FIFTH EDITION

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GEMS

THEIR SOURCES, DESCRIPTIONS AND IDENTIFICATION

R WEBSTER

REVISIONS EDITED BY PETER G READ

Gems

Suite of rubies and pink sapphires from Vietnam (photo by Shane F McClure, GIA Gem Trade Laboratory)

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Fifth Edition

Robert Webster FGA
Revised by **Peter G Read** CEng, MIEE, FGA, DGA

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Preface to the Fifth Edition

When, after three reprints of the 1983 fourth edition of Webster's *Gems*, the publishers decided it was time to embark on a fifth edition, they contacted several gemmologists to canvas nominations for the task. I was only just recovering from the effort of producing *Gemmology*, a vastly expanded update of my original paperback *Beginner's Guide to Gemmology*, and offered several possible names. When none of these avenues proved fruitful, the publishers again contacted me, this time with the proposal that I consider attempting such a revision myself. I countered this with the comment that while I would be very happy to act as the overall editor of a fifth edition (as with the Butterworth-Heinemann Gem Book series), the revision work involved with so large a book would be more sensibly shared out among a group of authors/ gemmologists, each member tackling his or her own speciality subjects. This was agreed to by the publishers and led to the approach subsequently adopted.

Because of the high regard and affection in which Webster's great work is held, I had little difficulty in finding willing contributors. As a result, the bulk of the thirty-nine chapters, identification tables and appendices were revised by the fifteen specialists named in this edition. It is interesting to note that these include contributors from Australia, Canada, Germany, Thailand, Vietnam, the UK and the USA, making this a truly international collaboration. Driven by my own interests in gem testing equipment and techniques, I have taken advantage of my position as editor to revise a few of the relevant chapters in Part 2 of this volume.

In addition to the necessary updating of chapters by the contributing authors, the contents of three chapters have been rearranged, 'Composite and Artifically Coloured Stones' becoming 'Composite Gemstones', 'Colour in Gemstones' becoming 'Colour and Colour Enhancement', and 'Opal' being extracted from 'Gems of the Silica Group' to form a separate chapter. I have also reintroduced Table 1 from the third edition, which contains a comprehensive list of gemstone constants.

I have been privileged to know both Robert Webster and Basil Anderson, and I trust that this fifth edition of *Gems* will live up to the high standards set in Robert Webster's three earlier editions, as well as those of the fourth edition, which was revised by Basil Anderson. In keeping with the tradition set by the very first two-volume publication, which included contributions and advice from Webster's colleagues in the London Chamber of Commerce's Gem Testing Laboratory, this edition is enhanced by contributions from colleagues in the Gemmological Association and Gem Testing Laboratory of Great Britain.

Peter G Read

Preface to the Fourth Edition

When approached by the publishers with the suggestion that I should undertake the revision, which had clearly become needed, of Robert Webster's great book, I was under no illusion that the task would be an easy one if it were to be carried out with the care and completeness that the work demanded. Nevertheless, I felt compelled to accept the heavy assignment, partly as a memorial tribute to an old and valued colleague, and partly also because the seed from which *Gems* eventually grew to such an imposing stature was planted as long ago as 1953 as a joint project from the London Gem Testing Laboratory, in which not only Robert Webster but C J Payne and myself were to be actively involved. In my diary for that year the 36 intended chapters of this ambitious proposition were listed and allocated to what seemed the most appropriate authors. C J Payne and I actually got so far as to write a chapter apiece, but our will to continue gradually dwindled, partly because the removal of the Laboratory from its old gloomy quarters at 55 Hatton Garden to new accommodation in itself provided a distraction and also resulted in an increase in routine work and better facilities for research, and partly because the excellent revision carried out by F C Phillips on Herbert Smith's classic *Gemstones* had diminished the urgent need for an up-to-date work on gemmology. Robert Webster, however, quietly persisted in his determination to compile a book on a more comprehensive scale, and to that end contributed long serial articles to *The Gemmologist* on the microscope, X-rays, and luminescence suitable for eventual incorporation in the projected work. As his colleagues and friends we were quite content to supply him, where needed, with data from our records and occasional specialised advice. But the sheer slogging hard work, the painstaking gathering of facts, and eventually the unusual ordering of the book with its description of species preceding that of the gemmological techniques needed for their study, were all Robert Webster's work, and in 1962 the first edition appeared in two volumes, a form which had obvious disadvantages for the reader.

In earlier and less scientifically inventive days the lapse of some six or seven

Preface to the Third Edition

Since the second edition of *Gems: Their Sources, Descriptions and Identification* of 1970, there has been a considerable increase in the number of man-made gem materials now available as gemstones or having a potential in that direction. This has made necessary a completely rewritten chapter on synthetic gems, and this has been necessary, too, with the text on composite stones of which there are now a number of new types.

The chapters on diamond have been revised in order to bring the discussion more in line with modern knowledge. In the cases of emerald and ruby and sapphire new sources of supply have necessitated additional text to the chapters on these gemstones. Minor adjustments have been made to other parts of the text and some new and unused gem materials have been mentioned where it is known that cut stones are in the hands of collectors.

The alteration of place names, particularly those of the new republics of Africa and Asia, has caused problems. Where possible these new names are put in the section headings, but they may not be continued throughout the text, for the older names are still in current circulation and are much better known. Thus 'Siam rubies' are understood by all, but 'Thai rubies' may well cause raised eyebrows, and even more so with 'Sri Lanka rubies and sapphires' in place of 'Ceylon rubies and sapphires'.

New designs of testing instruments are described and something is told of the more unusual instruments and techniques used by highly equipped laboratories coupled to universities, museums and large industrial concerns which have these types of apparatus for research and control. These are often made available when normal gem-testing methods fail to provide an answer. The author tenders his thanks to Mr Alan Jobbins and Mr Brian Young of the Institute of Geological Sciences for their assistance in making these additions.

Again I am indebted to those many friends who have sent criticisms and fresh information, and, rather belatedly, my thanks to Mr Ove Dragsted of Copenhagen for allowing me to use the colour plate of *tugtupite* at a critical moment in the production of the second edition. Thanks, too, to De Beers

Consolidated Mines Ltd, for the information on the Botswana diamond mining; Messrs Eickhorst & Co of Hamburg for the illustrations of the diamond colorimeter and dark field illuminators, and to Gemmological Instruments Ltd and P W Allen for illustrations of new types of instruments. I also acknowledge the help given by Mr Charles Schiffman of Lucerne in making certain criticisms and providing a new picture of the Gübelin spectroscope, Mr Monnickendam for advising on diamond classification, and Professor Hermann Bank for his helpful advice.

Robert Webster

Preface to the Second Edition

Experience with the two volumes of the first edition has shown that a single volume would be more convenient to the user. Despite the production of a book having a greater weight, *Gems: Their Sources, Descriptions and Identification* is now produced complete within a single cover.

The arrangement of the text has not been altered except that additions have been made to various chapters so that new information could be incorporated, in particular that on synthetic stones. New tables on plastics and their identification, drawn up by Mr H Lee, will provide more help in dealing with the identification of these difficult materials, and separate tables on refractive indices and specific gravities have been included to supplement the comprehensive main table of constants. The new blue zoisite gemstone, Tanzanite, has called for an alteration in the text. The section 'Thulite', which was previously the only gem material of the zoisite species, has now been entitled 'Zoisite' in order to cover more conveniently the new variety.

My thanks go to the many friends all over the world who have sent me items of information, or pointed out errors of omissions in the first edition. Dr Kurt Nassau has been most helpful in advising on the newer synthetic stones and Mr Craig C Smith gave valuable information on the new chrome chalcedony found in Rhodesia. The staff of both western and eastern headquarters of the Gemological Institute of America gave helpful advice, and I must give my thanks to Mr B W Anderson for his ever-ready assistance, advice and criticism. I thank Mr H Lee and Mr Dennis Smith for their help in proof reading this second edition.

New coloured plates, with a somewhat different outlook, replace those of Hallwag used in the first edition, as these earlier plates are no longer available. The new plates have been provided by the courtesy of De Beers Consolidated Mines Ltd; Messrs Garrards Ltd (The Crown Jewellers); Messrs Christie, Manson, and Woods; and The Institute of Geological Sciences through the staff of the Geological and Survey Museum, who prepared the coloured plates of the stones specially for this edition.

Robert Webster

Preface to the First Edition

For two decades, an earlier work of mine – *Practical Gemmology* – has proved a useful elementary textbook on the subject of gem materials and their testing, a study now known as 'gemmology'. During this period, new materials have been found and testing methods greatly improved, so that the simple expositions given in *Practical Gemmology* do not now cover the subject adequately and a new book has become a necessity.

The majority of books written on the subject of gems start with a detailed account of the physical and optical properties of gem materials. They then go on to the theory and use of instruments used in gem-testing before describing the gems themselves. In this work, the usual scheme is reversed and a more practical approach is made. A short introduction to the formation of such minerals in the earth leads to descriptions of the various gem materials.

Following this, there are chapters on synthetic stones, composite and imitation stones, and how gemstones are fashioned for the market. The first volume concludes with descriptions of pearl, coral, jet and amber, and other materials used in ornamentation which owe their genesis to organic processes. The second volume deals with the technical aspects of gem materials and is followed by descriptions of the various methods used in gem identification. The book is completed by a section containing tables and useful data.

The arrangement of describing the gemstones themselves before their technical aspects may be considered open to objection as some technical data must be included in the description of the stones. This is a minor point against the value of an arrangement which introduces the subject in the logical sequence of the finding in the rough state of the natural gems, the production of synthetic and imitation stones, and the fashioning of these various natural and man-made materials into a finished gemstone. Where possible, some simple explanation of the meaning of the technical references is brought out as the gem story unfolds.

One problem which besets any writer on gemstones is to select the order in which the gem materials are discussed. Whatever method is used, some criticism is inevitable. In this work the better-known jewellery stones are placed first, and are followed by the lesser-known stones in alphabetical order, unless, for some reason, the stones are better placed in a group forming a small subchapter.

In the technical section an endeavour is made to tell something of the history of gem-testing which has led to the present high standard of what has with some truth become known as 'scientific gemmology'. In this section, too, are details of the use and working of a number of special instruments not usually included in such books.

Throughout the compilation of this work considerable assistance has been received from many members of the Gemmological Association and of the jewellery trade. A special debt of gratitude is owed to Mr G F Andrews and Mr H Lee, who read and criticised the original manuscript.

I owe much to my colleagues Mr B W Anderson and Mr C J Payne for their encouragement and for unstintingly supplying me with much of their data accumulated in the archives of the Laboratory of the London Chamber of Commerce. Further, Mr Anderson freely handed over to me much of his unpublished work on the causes of colour, the hardness and the methods of determining the density of gemstones. These notes have been duly incorporated in the text. Likewise, Mr Payne allowed the incorporation of his articles on the method of refractive index determination by minimum deviation, and that on interference figures, both of which were published in *The Gemmologist*.

Mr Lee, with his technical knowledge of chemistry, gave considerable help on the chemical aspects of plastics, and the chapter on chemistry is based mainly on his information.

My thanks go to Dr W E Smith of Chelsea College of Science and Technology for his help with the chapter on the geology and the formation of minerals which forms the first part of the book. Dr W Stern advised on the part dealing with the marketing and industrial uses of diamonds, and Herr G O Wild of Idar-Oberstein gave information on a number of topics, particularly on the quartz gems.

Mr J Asscher, Jnr, of Amsterdam checked the notes on diamond polishing, and Mr C L Arnold and Mr G E Bull-Diamond likewise checked the part on lapidary working of gemstones.

A number of line drawings, particularly of crystals, were kindly prepared for me by Mr G A White of Norwich. Dr E Gübelin allowed the use of some of his excellent photomicrographs to illustrate the chapter on gemstone inclusions, which was mainly compiled from his published researches. It is appropriate here to mention that Plates I–XVI appeared in Dr E Gübelin's *Edelsteine*, and are reproduced by courtesy of Hallwag, Berne. Mrs V G Hinton kindly took the pearl surface photomicrograph specially for me, and Dr E H Rutland, Mr B W Anderson, Mr R K Mitchell and Mr H Lee assisted in the task of reading the proofs.

The Gemmological Association kindly allowed the incorporation in this work of my articles on emerald, ruby and sapphire, and marble, as well as a number of illustrations which had previously been published in the *Journal of Gemmology*. The chapters on the microscope, X-rays and luminescence are largely made up from my articles published in *The Gemmologist* and are reprinted, together with the illustrations, by courtesy of NAG Press Ltd.

Finally, the pictures of the pearl cultivation in Japan were supplied by Shell Photographic Unit and the Cultured Pearl Company, and those of diamond mining by the Anglo-American Corporation.

Robert Webster

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Introduction

The study of gems is of absorbing interest, not only to the connoisseur and to those whose business is to buy and sell jewellery but to the ordinary man and woman in the street, for it is they who appreciate gems for their beauty and for their power of adornment.

With the exception of pearl, coral and a few other organically produced materials, most gems are lustrous or brightly coloured minerals found in the rocks of the earth's surface. Many such minerals have been used for personal decoration, as charms or amulets, or for the embellishment of objects of virtue or utility, from times which predate written history.

The first of the three cardinal virtues of a gem is undoubtedly beauty: beauty through transparency and depth of colour as in the ruby or the emerald; through colour alone as in the turquoise; or through the splitting up of the white light into the spectral colours, the so-called 'fire', which is so well seen in the diamond. The 'play of colour' due to interference of transmitted light rays gives to the opal its unique appearance. Reflections from regularly arranged inclusions within the stone give rise to the cat's-eye and star-stone effects. However, much of the beauty of gemstones is latent until brought out by the work of the lapidary who cuts and polishes the stones in symmetrical forms.

For use in ornaments, a gemstone should be able to resist abrasive and chemical attacks which would tend to mar the polish and thus destroy the lustre. Durability is thus the second virtue and depends upon the hardness of the mineral. In general, gem minerals are hard minerals. Glass imitation stones are not durable: they are too soft to resist abrasion by sand and dust particles and the chemical action of the sulphur in the atmosphere.

Often of far greater influence than either beauty or durability is rarity. A mineral may be fairly common, yet really fine pieces suitable for fashioning into gemstones may be quite scarce. This is so in the case of the emerald. A flawless emerald of fine colour is exceedingly rare and may well command a higher price than a diamond of comparable size and quality. The law of supply and demand, often influenced by the caprice of fashion, governs to a great extent the rarity of gemstones. There are many stones which undeniably possess the qualifications of beauty and durability but are in little demand.

It used to be quite common practice to divide gemstones into two classes – precious stones and semi-precious stones – but the division was quite arbitrary. Precious stones are usually understood to be diamond, ruby, emerald, sapphire and pearl, with perhaps black opal and alexandrite. All of these are stones in fairly constant demand with a high value for fine specimens. Semi-precious stones are the peridot, aquamarine, topaz, tourmaline, zircon and amethyst in company with all other stones which do not command such high prices and for which the demand is more prone to the whims of fashion. Use of the term 'semi-precious' is now discouraged and the safer term *gemstones* is used for both the previous groupings.

It may surprise the uninitiated to know that ruby with its crimson colour and the lovely blue sapphire belong to the same mineral species. This is a species known as corundum, an impure form of which is the abrasive emery. The striking difference in colour of ruby and sapphire is solely due to a trace of a metallic oxide as an impurity. Similarly emerald, aquamarine and the blushing rose-coloured morganite are all colour varieties of the species beryl.

Changing the colour of gemstones by heat, by irradiation and by staining has become commonplace in species susceptible to such changes. While such treatment might improve the beauty of some stones, to the jeweller it poses problems of nomenclature and disclosure under modern legislation.

The turn of the century brought further problems for the jeweller. Extensive experiments carried out by scientists throughout the world began to produce results, and synthetic stones started to enter the field of commerce. At first only the ruby was so produced, then the sapphire, to be followed by synthetic sapphires of fancy colours. Later, gems of the spinel species were made synthetically in a galaxy of lovely colours. The 1930s saw the beginning of the synthetic emerald, and after the end of World War II new stones which had little or no counterpart in nature were synthetically produced by the scientist. Finally, the successful synthesis of the diamond was announced. Although at first the product was only of grain size and its use that of an abrasive, later synthesis produced stones of gem quality.

Part 1

Descriptions of Gemstones

1

The Origin and Recovery of Gemstones

Structure of the Earth

Gem materials are rare, and the finding of a single stone can be either the result of a happy accident or the culmination of a determined effort by perhaps hundreds of people. Gems are recovered at or beneath the surface of the earth and this chapter outlines some of the features of their sources and extraction.

The earth's interior consists of three main components (*Figure 1.1*). The outermost layer is the crust, beneath which is the mantle, and in the centre is the the core. The core has a diameter of about 7000 km (4300 miles) and probably consists of two parts, an inner solid region of diameter 2700 km (1700 miles) and density about 8 g/cm³, and an outer region about 2100 km (1400 miles) thick and density about 5.5 g/cm³, which behaves as a liquid.

Around the core is the mantle, about 2900 km (1800 miles) thick and, at about 3.5 g/cm³, much less dense than the core. This difference is probably due

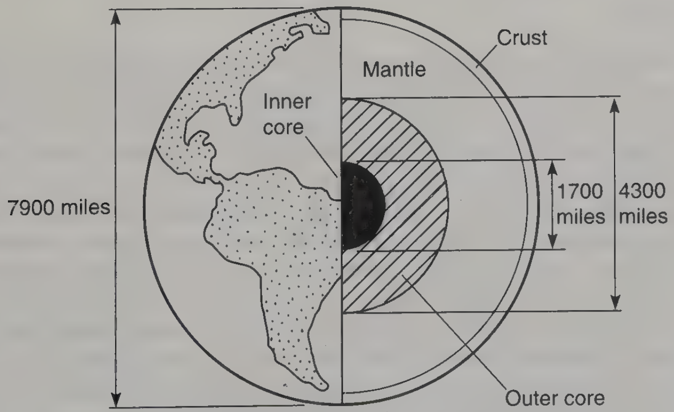

Figure 1.1 The structure of the earth

to a preponderance of iron in the core compared with the abundance of oxides and silicates in the mantle.

Above the mantle lies the earth's crust, a thin 'skin' of rock, less dense than the mantle and derived from it by geological processes operating for millions of years. The crust is seven-tenths covered by water and this points to a fundamental geological distinction between the two kinds of crust: oceanic and continental. The oceanic crust averages 6 km in thickness and 3.0 g/cm^3 in density; nowhere is it older than 200 million years. The continental crust averages 2.7 g/cm^3 in density and 35–40 km in thickness, but under mountain chains such as the Himalayas may reach 70 km. Large areas of the crust have been stable for at least 1500 million years and are called shield areas; and some parts of these shields have been dated to 3900 million years. The oceanic crust has a simple layered structure and relatively consistent composition; by contrast, the continental crust contains a range of simple to complex rock structures and has a very varied composition.

Rock Composition

Rocks in the earth's crust are composed of a variety of different kinds and quantities of minerals. A mineral is a distinct inorganic compound possessing a definite chemical composition and atomic structure. There are over 3000 listed minerals but only about 100 are common enough to be 'rock-forming' and only about 60 have the necessary qualities of beauty, durability or rarity for use as gems.

Some rocks consist of one mineral only, and the white ornamental marble, composed entirely of the mineral calcite, is a good example. Most rocks however are composed of two or more minerals and the relative abundance of these will control the overall chemical composition of the rock.

In detail the origins of rocks in the crust are many and varied, but they have been classified under three broad headings: igneous, sedimentary and metamorphic.

Igneous Rocks

Parts of the earth's crust are so hot that they are molten, and this molten rock is termed magma. When it cools, it forms igneous rocks, and if this takes place underground the rocks are described as plutonic or intrusive. If the magma reaches the surface of the earth before solidifying the resulting rocks are called volcanic or extrusive (*Figure 1.2*).

Most magmas consist of silicates of iron, magnesium, aluminium, calcium, sodium or potassium with varying amounts of dissolved gases and water, and on slow cooling a range of minerals may form. Generally, the slower the cooling the larger are the crystals formed. To start with, the individual minerals crystallise around local centres. Some minerals do so earlier than others and are able to develop good crystal outlines. However, the last minerals to crystallise rarely show good crystal shape since they can only occupy the irregular spaces left between the crystals already there. One example of a coarsely crystalline plutonic rock is granite (*Figure 1.3*). Although best known as a building stone,

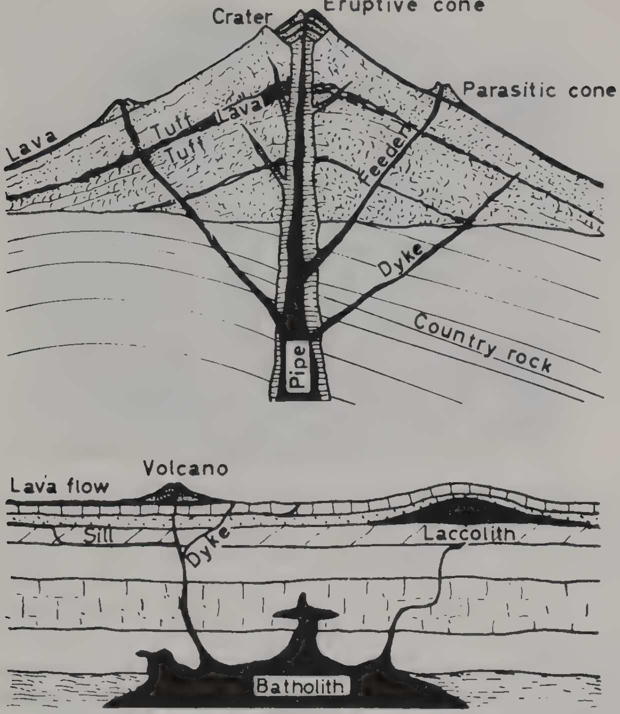

Figure 1.2 Forms of igneous activity. Volcanic lavas are commonly erupted through pipes or feeder conduits, or through steep-dipping sheet-like fissures (dykes). Tuffs consist of lava fragments deposited in a sedimentary fashion from air or water. Plutonic igneous rocks solidify underground in large masses many kilometres long and deep (batholiths), as lenticular masses (laccoliths), as dykes or sills (steep- or shallow-dipping sheets), or as plugs which usually form in volcanic pipes when extrusive activity ceases

granite has been used as a decorative stone mounted in jewellery. Typical granite consists of crystals of glassy-looking quartz, white or pink feldspar and white or brown glistening mica, all readily visible to the naked eye.

Rapid cooling of magma produces medium- to fine-grained rocks in which the crystals may only be distinguishable under a hand lens. However, some of these finer rocks carry with them a few large well-formed crystals, more or less evenly scattered throughout, and these are known as porphyries. Well-known porphyries include the 'Perfido serpentino' of Greece and the 'porphyrites leptosephos' of upper Egypt, rocks extensively used in prominent buildings around the Mediterranean.

When some lavas of granitic or silica-rich composition are extruded from volcanoes, the chilling may be so rapid that there is not sufficient time for crystals to form and the magma is quenched to a glass. One example of a glass of this type which is used for decorative purposes is obsidian. Depending on its

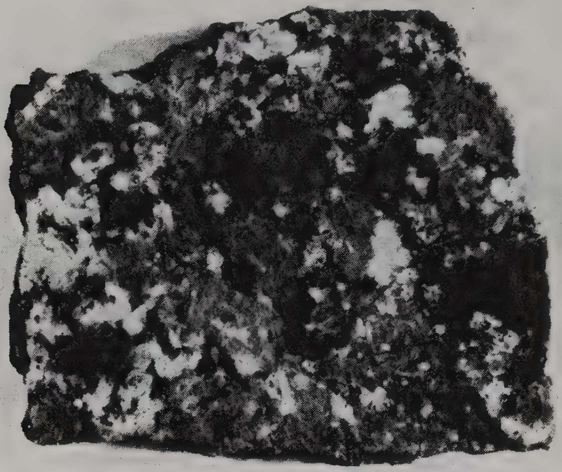

Figure 1.3 Granite from Aberdeen, Scotland, a typical igneous rock. The dark areas are mica, the grey areas are pink feldspar, and the light-coloured areas are quartz

composition, obsidian may be black, golden-brown or dark green in colour.

Towards the end of crystallisation of a granite – say when 80–90 per cent of the mass has solidified – what remains are residual liquids, very often water or gas rich, and containing many of the rarer elements that had not been accepted into the crystals of the main granite. These residual liquids may crystallise in place, forming miarolitic cavities in the granite lined with such crystals as beryl and topaz, or the liquids may coalesce to form veins across the host granite and out into the country rock. The veins solidify to form aplites (fine-grained) or pegmatites (coarse-grained) according to the conditions of crystallisation, and it is the latter that are a fruitful source of gem minerals. Some pegmatites contain crystals measured in metres and even gem-quality minerals can weigh many kilograms.

A pegmatite rock that has been used for ornamental purposes is 'graphic granite' which consists of intergrowths of quartz and feldspar in an angular pattern resembling the cuneiform script of ancient cultures around the Mediterranean.

Significant areas of the earth's surface are covered by basalt, a dark, fine-grained volcanic rock extruded as lava from volcanic pipes or through parallel fissures. In some areas such as the Deccan in India and in Brazil and Uruguay the basalts contain gas cavities which are now lined with gem-quality amethyst.

Some basaltic volcanic pipes extend to considerable depths in the crust but the deepest are those connected with kimberlites and lamproites – the host rocks for diamond. Kimberlite pipes probably originate at depths of more than 100 kilometres and, on their ascent to the surface, incorporate a range of country rocks and minerals including diamond.

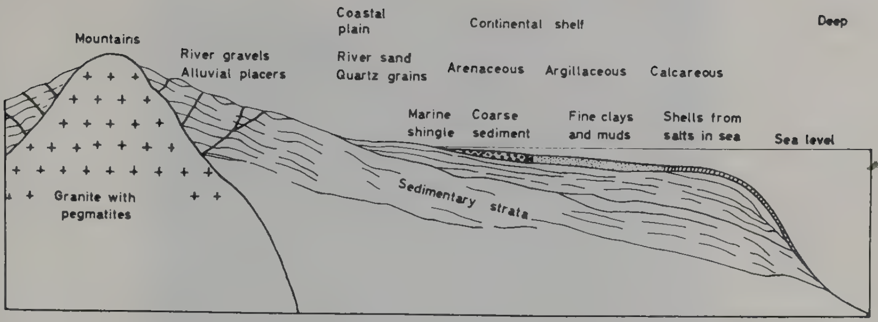

Figure 1.4 *The relationship between topography and different kinds of sediment*

Sedimentary Rocks

Sedimentary rocks result from the breaking down of earlier formed rock masses (*Figure 1.4*). There are three stages in the formation of typical sedimentary rocks. The first is the chemical and mechanical weathering of source rocks by the action of rain, wind or ice; by changing temperatures of day and night or winter and summer; and by the chemical breakdown in the atmosphere of unstable minerals.

The second stage is the transportation of the products of weathering by moving water or by wind. Rocks formed from sedimentary deposits transported by water are described as aqueous, while those derived from airborne transport are aeolian.

Thirdly comes deposition of the debris. Initially, fast-flowing streams will transport quite large and heavy particles, but when the flow rate decreases on flatter ground, these larger fragments are deposited and separated from the finer particles which are held in suspension longer – to be deposited even farther away from the source.

Sorting of the debris by water will depend greatly on the density of the minerals being carried. The more important gem minerals, being relatively dense, tend to fall into any depression in the river bed where water velocity is low, and there they form placer deposits. The river bed may be ancient, having long ceased to carry water, and by now be covered by more recent sediments and soils. It is in such old river courses that the water-worn pebbles of many gem materials are found. Such deposits are known as alluvials or gem gravels (*Figure 1.5*).

The distinction between sediments and sedimentary rocks is rather arbitrary. But when layer after layer of material is deposited, the sediments underneath start to compact and harden: gravels become conglomerates (*Figure 1.6*), rock screes become breccias, sands become sandstones, and muds become mudstones or shales.

The soluble products of weathering may be deposited by precipitation from water, by the action of organisms living in it, or by simple evaporation of mineralised water in places favouring rapid evaporation. Massive gypsum, calcium sulphate, is commonly formed in this manner and is the source of the

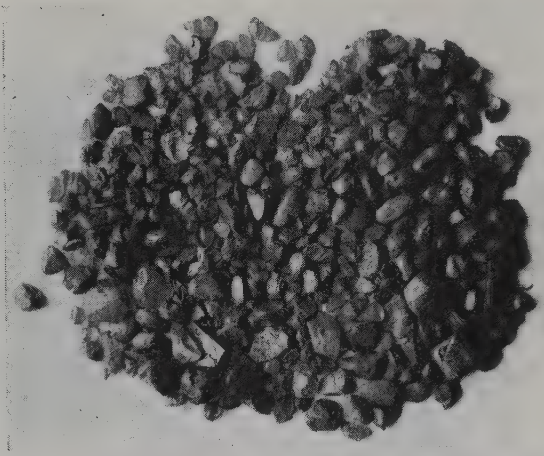

Figure 1.5 Water-worn pebbles from the Sri Lankan gem gravels

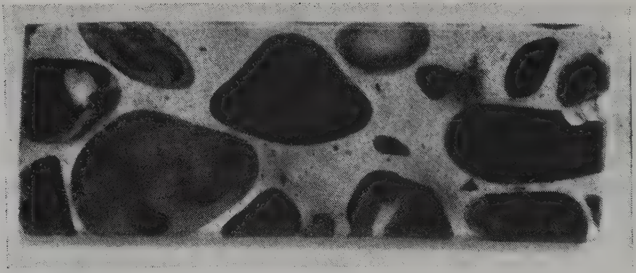

Figure 1.6 Conglomerates are the coarsest sediments, consisting of water-worn cobbles and pebbles in a finer matrix. Some are most attractive when cut and polished, and the figure is an example of the Hertfordshire pudding stone

ornamental material alabaster. Some limestones (calcium carbonate) are also formed in this manner and carbonate is common as a cementing material bonding the quartz grains together in sandstones.

Sedimentary rocks may accumulate in regions where vegetable or animal life existed. For instance, plant remains in some regions form peat and, through time, may become compacted to lignites or coals. When mixed with sands or clays and then compacted many plants and animals remain recognisable as fossils, and some are of importance as gem materials. In Australia shells and fragments of wood have been impregnated by precious opal; in the USA the woody tissues of quite large trees have been impregnated by silica, the

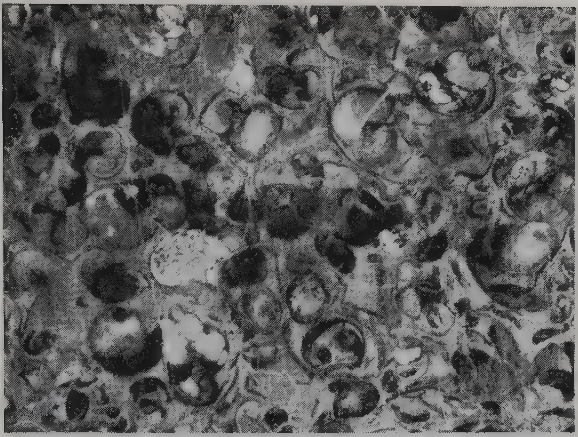

Figure 1.7 *Fossil shell limestone, Purbeck marble, containing masses of freshwater snail shells*

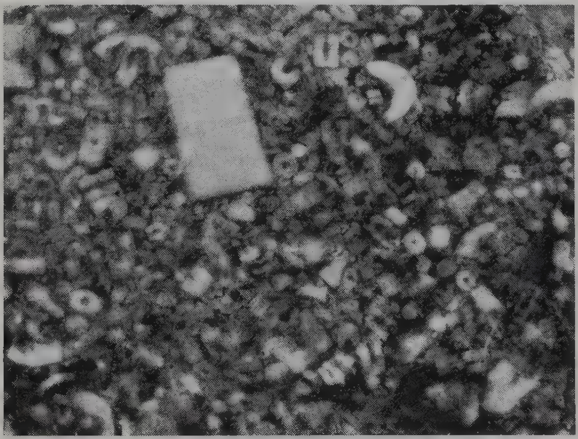

Figure 1.8 *Fossil limestone containing masses of crinoids (sea-lilies). Encrinital marble from Derbyshire, England*

spectacular reds, yellows and browns of the petrified forest in Arizona being caused by traces of iron and other metals. Fossil shells, corals or crinoids (sea-lilies) occur in an abundance of shapes and colours and, when cut and polished, make attractive marbles (*Figures 1.7, 1.8*).

Metamorphic Rocks

Heat and pressure from intrusions of igneous rocks, or from the compression and folding of the crust during mountain-building periods, may so alter the country rocks that new ones are created. Such an alteration is termed metamorphism, meaning literally a change of shape.

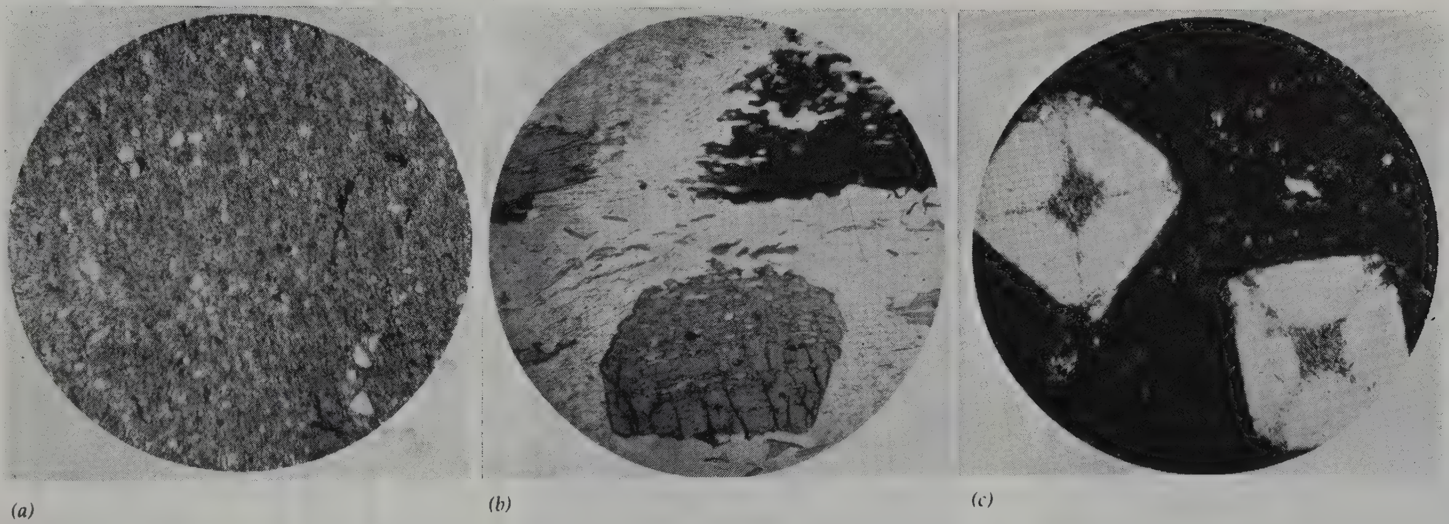

Figure 1.9 *Thin-section photomicrographs of metamorphic rocks: (a) grey slate, a product of regional metamorphism at low heat (b) garnet mica schist, a product of regional metamorphism at high heat (c) chiastolite (andalusite) slate, a product of contact metamorphism at high heat*

There are two main kinds of metamorphism: contact and regional. Contact metamorphism takes place locally around hot, if not molten, igneous bodies intruded into cool country rock. The zone of alteration in the country rock is called a contact aureole with the maximum alteration closest to the intrusion.

Regional metamorphism occurs over wide areas and incorporates both thermal changes and deformation. These are characteristics of the interiors of fold mountains where heat flow may be high over a wide area and the stresses and strains of mountain building create a range of compression, shearing and faulting in different parts of the fold belt.

The metamorphism of a pure limestone will produce a white marble such as that at Carrara in Tuscany, Italy. Here, the metamorphism has caused a recrystallisation of the calcium carbonate of the limestone to produce interlocking crystals of calcite; in thin section this is seen as a mosaic texture with the grains displaying no crystal faces (*Figure 1.9*). Sandstones behave similarly under metamorphism and pure varieties will transform to quartzites, again consisting of a mosaic of irregularly shaped grains. Some quartzites contain coloured minerals in sufficient quantity to form decorative golden-brown or green rocks, and the green aventurine quartz (which can resemble jade) is a well-known example (*Figure 1.10*).

Shearing and faulting during regional metamorphism break up the rocks along narrow zones, the smashed-up fragments being commonly angular and recemented to form a coherent rock. These are termed breccias, and decorative examples include some of the impure marbles from Italy, and fragments of agate and jasper cemented to form 'brecciated agate' or 'brecciated jasper' (*Figure 1.11*).

In addition to heat, igneous bodies commonly supply chemically active gases and fluids which interact with the surrounding country rock. New minerals are often formed in this process and, where boron and fluorine are introduced, such minerals as tourmaline and topaz may be formed. Limestones around large granite masses may be particularly susceptible to alteration and, if slightly impure, may give rise to a whole range of gem minerals including ruby, sapphire, spinel, garnet and diopside. Rocks containing a significant quantity of minerals resulting from the action of granite fluids on the country rock are called skarns.

At temperatures below those discussed above, much mineral-rich water travels through cracks and fissures in the country rock depositing minerals where conditions permit. Mineral lodes or veins of crystals or gem material can be formed in this way and are the source of some amethyst and turquoise. The veins may open out into cavities, called vughs (or vugs), the walls of which can be lined with crystals of considerable size and suitable for cutting into gems.

Such crystals have been deposited from the circulating water and are quite different from any of the constituents of the host rock. Rounded cavities of this nature are called geodes or 'potato stones' owing to their likeness to potatoes when removed from their host rock (*Figure 1.12*). The best-known potato stones come from the lavas of Mexico and some contain aqueous fluid as well as a lining of crystals. Other nodules derived from lavas may be completely filled with minerals such as finely crystalline quartz in the form of chalcedony or agate.

Mineral-rich water dripping from the roof of a cave may precipitate crystals at both top and bottom, forming stalactites and stalagmites respectively. With

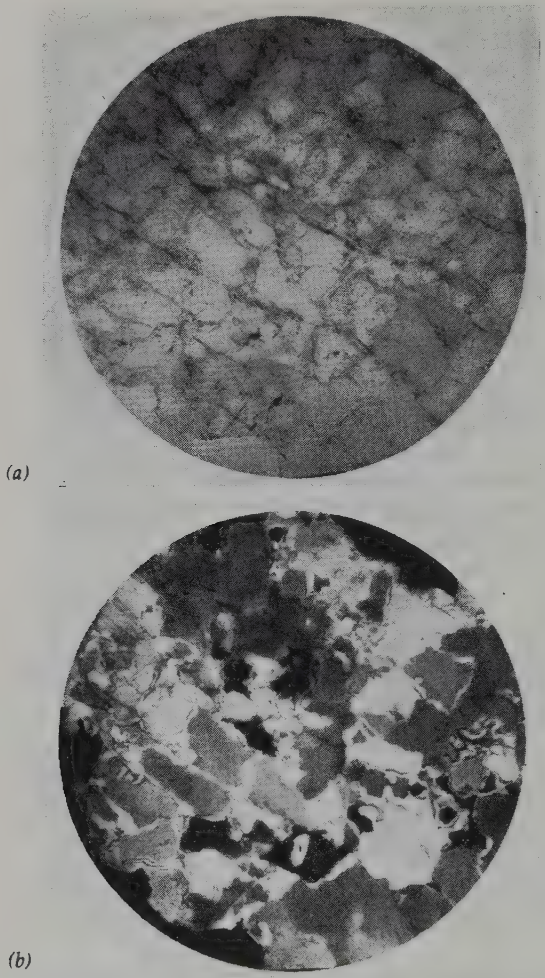

Figure 1.10 Thin-section photomicrographs of quartzite: (a) in ordinary light (b) in cross-polarised light, showing the individual grains

sufficient time the two structures may join and form a complete pillar between roof and floor. Further deposition of minerals may well occur in irregular sheets on pillar and floor and is commonly banded in structure. It is from such formations that the banded calcites, the 'onyx marbles' and the beautiful pink manganese carbonate rhodochrosite are obtained.

Rock Systems

In classifying an undisturbed sequence of sedimentary rocks, the geologist starts with the assumption that the oldest will lie at the base. Fossils and distinctive rock types are used to compare and correlate sequences from

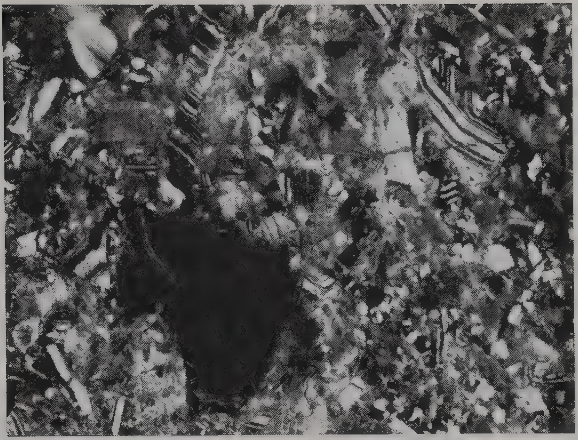

Figure 1.11 Brecciated agate

Figure 1.12 Quartz crystals in a geode: a typical potato stone

different areas and allow the relative ages of rocks to be established. Fossiliferous rocks are divided into systems, subdivided into stages and further subdivided into chronozones. This is a time-stratigraphic classification, built up initially on the basis of fossil studies, but augmented more recently by information from the small quantities of radioisotopes found in some rocks. These are summarised in *Table 1.1.*

The ages in years of some kinds of rock can be determined from the radioactive elements and their decay products contained in the constituent

Table 1.1
The relative ages of eras, systems and series of rocks

Era		*Period or system*		*Epoch or series*	*Age (in millions of years)*
Cenozoic		Quaternary		Holocene	
				Pleistocene	0–1.7
		Tertiary	Neogene	Pliocene	1.7–5
				Miocene	5–25
			Palaeogene	Oligocene	25–38
				Eocene	38–54
				Palaeocene	54–66
Mesozoic		Cretaceous			66–140
		Jurassic			140–210
		Triassic			210–250
Palaeozoic		Permian			250–290
		Carboniferous			290–360
		Devonian			360–410
		Silurian			410–440
		Ordovician			440–500
		Cambrian			500–590
Precambrian	Proterozoic	Late			590–1000
		Middle			1000–1700
		Early			1700–2500
	Archaean				>2500

Ages from the chart by Haq and van Eysinga published by Elsevier, 1987

minerals. Radioactive isotopes of uranium, potassium, rubidium and samarium each decay at known and constant rates into stable isotopes and are in effect isotopic clocks. Measurement of the relative amounts of the 'mother' and 'daughter' elements enables a calculation of the time taken for the stable daughter element to form, and this kind of dating is particularly useful in establishing the unfossiliferous sequences of rock prior to 600 million years ago – the Precambrian era. Some knowledge of these systems is desirable to understand references to certain gem-bearing rocks later in the book.

Gem Regions

Although the above survey is generalised and greatly condensed, it tells something of the context in which gems have been formed. By their very nature they are rare and are not evenly distributed throughout the crustal rocks. On the contrary certain areas seem to be favoured with an abundance of gem species while others are barren. Among the more fortunate are the very old shield areas of the major continents and, of these, Brazil, East Africa, and South India and Sri Lanka are exceptional.

Gem minerals also occur in major fold belts across the world, with emeralds coming from the Andes in Colombia, the Urals in Russia and the Himalayas in Pakistan, rubies also from the Himalayas in Pakistan and Nepal and their extension into Myanmar (Burma), and jades coming from the Rockies in western Canada, the mountainous South Island of New Zealand and, again, Myanmar.

The pegmatites of Madagascar provide a whole range of gem minerals such as beryl, tourmaline, garnet, topaz, and spodumene (kunzite). Comparable specimens come from pegmatite localities in California and Maine in the USA, and from Minas Gerais in Brazil.

Vast areas of New South Wales and Queensland, central Thailand and central Nigeria are covered with basaltic rocks which are associated with sapphires, rubies, zircons and spinels. Eastern and central Australia are also famous for their precious opal. The shield areas are again the locations for kimberlites and diamonds, the richest areas in gem-quality stones being southern Africa and Siberia.

Many other gem regions or districts could be cited here, but reference is more appropriately made to them where individual gem species are described.

Mining Methods

Gem gravels are one of the most abundant sources of fine gems. In many parts of the world gem minerals are weathered out of surface rock and washed downhill and downstream to be deposited some distance from the source. Flawed minerals are commonly destroyed during this transport and the ultimate deposits consequently contain high-quality gem material. Many deposits however are patchy and commonly in difficult terrain, making large-scale mining uneconomic. Consequently, much exploitation to date has been simple.

The method of recovering gem gravel from the dry beds of ancient rivers is to dig a small pit down to the gravel and, if conditions are right, drive short horizontal galleries from the base of the pit. Usually the broken-down ground containing the gemstones needs to be treated by washing in sluices, which floats away the less dense materials and leaves the concentrate which will contain any gems.

In the running water of streams and rivers, the gem pebbles are recovered by 'panning'. A shallow dish is used into which some of the gravel is placed with water and, by a gentle rotatory movement of the pan, the water is swirled over the edge carrying with it the lighter minerals. The gems are then hand picked from the minerals in the pan.

The first mechanised mining of gem gravels began in the Australian sapphire fields in the New England area in the 1970s. Large earth-moving equipment removes up to 20 metres of overburden before extracting the gravels which contain the sapphires. The gravels are broken up in a trommel (rotating drum) and sorted into size fractions before passing on to pulsating jigs. The jigs concentrate the heavy minerals from which the gems are separated by hand. Mechanisation of this kind is also being developed in South East Asia where the gem reserves are considered to justify the investment.

Emeralds present a different problem. They are neither as hard nor as tough as rubies and sapphires and have traditionally been mined straight from the veins in country rock by pick or by hammer and chisel. The black shales which contain emerald veins in the Colombian mountains are relatively soft and amenable to work in this way but more difficulty may be experienced where the emeralds occur in hard pegmatites. In this situation controlled blasting is used to loosen large blocks which are then processed by individuals working with drills or hammers. Great care is then taken to try and avoid cracking or breaking the emeralds. In recent years emeralds have also been recovered from some of the Colombian mines by 'terrace mining' where the earth and shale are cut away in steps or terraces.

Diamonds are extracted either from pipe-like bodies of kimberlite or from river alluvial or beach deposits. The mining of both kinds of deposit is very systematic because, unlike the coloured gemstones, all diamonds are used for one purpose or another and recovery is designed to be as complete as possible. Kimberlite pipes are mined from open pits to about 300 metres depth and then it is more economic to continue by a variety of underground methods. Beach deposits are mined in huge open pits behind banks of sand constructed to keep out the sea. Different kimberlites yield different proportions of gem to industrial diamond, but (for the reasons outlined above for gem gravels) the proportion of gem diamonds in the beach deposits is very high.

2

Diamond

Composition and Crystal Habit

Reputed to endow the wearer with purity, love and joy, the diamond – the 'Adamas' of the Greeks – is traditionally the emblem of fearlessness. Romantic in history and symbolic of love, diamond is the hardest of natural substances. It is crystalline carbon, akin in chemistry to graphite, which is one of the softest minerals known. What forces nature to marshal the carbon atoms to form the close-packed cubic arrangement which gives the diamond structure rather than the more open hexagonal packing of graphite is one of the many mysteries which diamond presents.

Diamond crystals belong to the cubic system of crystal architecture. When showing a perfection of form, they habitually take that of the octahedron, a form which may be described as two equilateral four-sided pyramids base to base. Such crystals usually have bright shining faces pitted with triangular markings called 'trigons' (*Figure 2.1*). The natural trigons have their points directed to the edge of the octahedral face of the crystal. Similar markings, called 'etch pits', follow the orientation of the face of the crystal.

A triangular-shaped form of crystal often occurs; this is due to twinning. These platy crystals may be described as octahedra in which half of the crystal has been rotated through 180 degrees. Such crystals are termed macles. Many diamond crystals assume nearly round forms owing in part to the curved form of the faces, this being particularly so in the case of crystals having 24 or 48 faces. The stepping of the octahedral faces also produces a tendency to roundness of form and to curved edges to the crystal. It is common to find these rounded crystals with a gum-like skin, called nyf. Stones showing a corrugated, grooved, or scaly appearance owing to this stepping are known as 'crinkles'.

Cube and dodecahedral forms (*Figure 2.2*) which have six square and twelve rhomb-shaped faces respectively are other habits assumed by diamond crystals. Many diamond crystals as found, particularly those of industrial grade used for purposes other than as gems, are so distorted in form that they may appear as

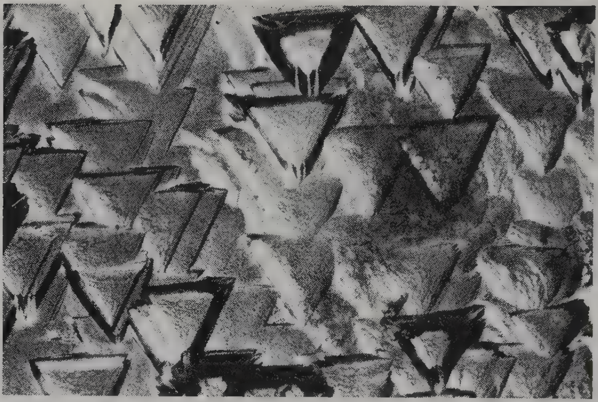

Figure 2.1 Trigons in diamond (by courtesy of De Beers)

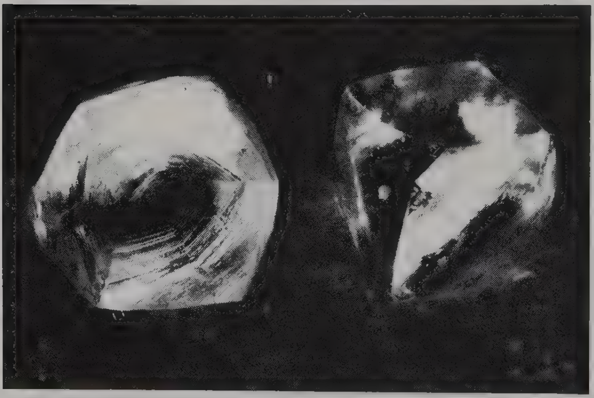

Figure 2.2 Dodecahedroid diamond crystals

irregular lumps like washing soda. However, to the inexperienced, even in these the adamantine lustre is characteristic of diamond (*Figure 2.3*).

Diamond Genesis

The last decade has seen significant advancements in the study and dating of inclusions in diamond. These studies have shown that, for the most part, diamonds are much older than the kimberlite or lamproite which carried them to the surface. For example, the diamonds in the Finsch mine in South Africa are of the order of 3300 million years old, whereas the kimberlite in which they are mined was emplaced just 100 million years ago.

Given that diamonds were formed before the emplacement of the kimberlites or lamproites, the study of both inclusions in the diamonds and the xenoliths (rock fragments that are foreign to the kimberlite or lamproite) in which diamonds are found has shown that diamonds are formed in two differing rock

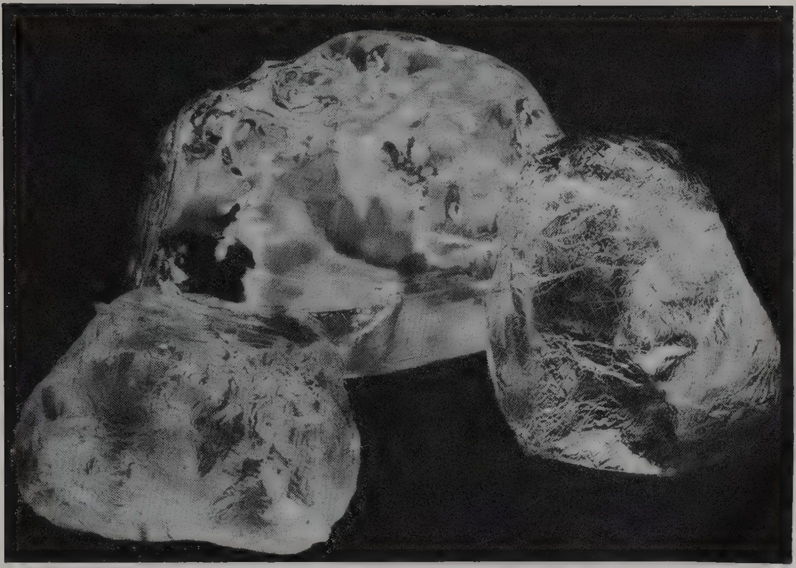

Figure 2.3 The Star of Sierra Leone diamond (left) with models of the only two larger diamonds found. The diamond was found in Sierra Leone, West Africa in 1972 and weighs 968.9 carats. Back centre is a model of the Cullinan, discovered in 1905 in South Africa. It weighed 3106 carats and is the largest diamond found. The Excelsior weighing 995.2 carats was found in South Africa in 1893. This picture shows how irregular a rough diamond can be, and this is particularly so with large diamonds (by courtesy of the Institute of Geological Sciences)

types – peridotite (P-type) and eclogite (E-type). Carbon isotope studies have also shown that the carbon from which the P-type diamonds form originates from a homogeneous source within the earth's mantle, whereas the E-type originates from sources on the earth's crust.

It is estimated that P-type diamonds form at a depth of 150–200 km in the upper mantle, whereas E-type diamonds appear to form at greater temperatures and depths.

India

Diamond first became known from India and it was from old Indian mines that the historically large diamonds such as the Koh-i-nûr and the Jehangir (*Figure 2.4*) were found. Of the very early days of diamond mining in India little is known. From statements made in an old Indian manuscript of the first century BC it is thought that diamond was known in India during the Buddhist period of about 400 BC. The first authentic mention of the Indian diamond fields was by Tavernier, a French jeweller and traveller, who visited the East between AD 1630 and AD 1668. Tavernier was not the first European to visit the mines, but he was the first to chronicle them.

The ancient Indian mines were situated in three main groups, the most

Figure 2.4 The Jehangir diamond: an 83-carat Indian diamond (by courtesy of Sotheby and Co)

important being those of the southern district. Although so important in the past they are now virtually abandoned. They stretched from the Godavari river near Hyderabad in the north to the Pennar river, which like the Godavari discharges into the Bay of Bengal, and it was here that the more historical stones were found. This area, usually referred to as Golconda, was one of the five medieval states formed by the distintegration of the Kingdom of the Deccan. Golconda existed as a state from AD 1347 to AD 1687 and the city of Golconda, now just ruins a few miles from Hyderabad, was the capital of the state. Golconda was not a mining area itself but was most probably a mart for the stones which were found in the many mines in the state and adjacent districts and transported to the city for sale.

The diamond fields of Andhra Pradesh, the modern name for the old states of Hyderabad, parts of Orissa and Andhra, comprise a vast area which includes parts of Anantapur, Cuddapah, Kurnool, Guntur, Krishna and West Godivari. These are now in the care of the National Mineral Development Corporation who are exploring the potential and, it has been said, have already opened up two mines. The source of the diamonds in Andhra Pradesh is debatable, although a kimberlite pipe had been found near Wajrakarur in 1880, and since 1961 three more pipes have been found. These apparently are barren and do not contain diamonds.

Particular mention must be made of the mines of Kollur, on the Krishna, for this is reputed to be the source of the Koh-i-nûr (Mountain of Light) diamond which now reposes in the front crosspatée of the Crown of Queen Elizabeth the Queen Mother, and also of the superb Hope blue diamond. Many Indian stones were cut as flat tablets, probably from cleavage pieces, which are called lasques. Maybe it is from this name that there originated the term 'laxey diamond' applied to rather shallow brilliants.

In the Bundelkhand district Madhya Pradesh, between the rivers Ken and Son, lie the northern group of workings. These have been mined to a limited extent in recent times. There are three types of deposits in this locality. They are (1) alluvial terraces of some of the river valleys; (2) in a conglomerate rock; and (3) in a volcanic pipe situated at Majgawan, which lies some 20 km south-west of Panna, in which well-shaped octahedral crystals of a light green colour are found. In 1955 the Panna Diamond Mining Syndicate was instrumental in the further working of this area and the Majgawan pipe. In 1951 the Syndicate ceased operations. Later the National Mineral Development Corporation took over the workings and developed the pipe mine at Majgawan and the workings around Ramkheria, putting in recovery plants at both places. These mines are now in production.

The eastern group, the third of the groups of Indian mines, lies around the Mahanadi valley in Madhya Pradesh and in the neighbouring Sambalpur district of Orissa. These mines have, in general, been abandoned.

Further to these main groups, Mohum Tagore mentions the districts of Himalayas, Surat, Chota Nagpur, and Berar as diamond-bearing localities. The truth of these assertions is debatable.

Apart from the Majgawan pipe, the Indian diamonds are found in sandstone or conglomerate, or in the sands and gravels of old river beds. The associated minerals are usually confined to quartz pebbles and variously coloured jaspers. Panna diamonds have been known for 200 years.

Borneo and Indonesia

That diamonds occur in Borneo and Indonesia (formerly the Netherlands East Indies) has been known since, it is said, about AD 600, and certainly since before the fourteenth century. The small stones, rarely exceeding one carat in weight, are found in the extreme west of the island. The principal deposits are in the vicinity of the Landek river near Pontianak and in the tributaries of the upper reaches of the river. Other deposits are along the upper reaches of the Sekajam river and near Sanggau on the Kapuas river. Another diamondiferous district lies in the south-east of the island in the area around Martapura near Banajarmasin. This is more important and stones up to 20 or more carats have been found in the swampy mining district. The principal workings are near Tjampaka on the Banjoe Irang river, and there are numerous occurrences along the Riam Kanan and Riam Kiwa rivers, and also along the coast rivers. Scattered finds have been made along the Pembuang (Serujan) and Kotawaringin rivers which lie to the south of the island.

The Borneo diamonds are won from alluvial deposits made up from the detritus from ancient rivers. The mining is carried out by Indonesians and some Chinese. It declined after 1930, but since the formation of the Indonesian Republic a fresh impetus to mining has been given. Some miners work alone while some work in family groups; yet others formed co-operatives of from 4 to 20 men in what are called *kongsies*, but the methods used are primitive. The production is absorbed by Eastern markets and many of the stones are cut at Martapura. Diamonds from Borneo are said to be harder than diamonds from other localities, excepting perhaps Australia, but this hardness may be due more to the variation of grain caused by twinning of the crystals than to an actual greater hardness.

A most curious and seemingly irrational superstition regarding certain diamonds prevails among the Malay and Chinese workers in the Borneo diamond mines. Certain well-crystallised diamonds enclosing a grey or black core occur and these are regarded as harbingers of personal good luck by the workers and are worn by them as an amulet. However, when one of these stones is found in a mine it is looked upon as the greatest sign of ill luck, and the mine, no matter how profitable, is abandoned. The mine owner may himself not be superstitious, but nothing will induce the workmen to work that mine again and a new site has to be chosen. The Malays know such stones by a name which means 'the soul of the diamond' and they say that once the soul has left the mine, it is dead.

Brazil

The discovery of diamonds in Brazil occurred at a place now called Diamantina, but which was formerly known as Tejuco. The pioneer explorers, the *bandeirantes*, when panning for gold along the Jequitinhonha river, frequently found bright pebbles at the bottom of their pans, or *bateas* as they are called. The larger ones they saved and used as chips in their card games and the smaller ones were discarded. These pebbles were diamonds, but their nature was unknown at the time.

Authorities differ as to the date these pieces were identified as diamonds and how this identification came about. Most give the date as 1725, although 11 years earlier has been mentioned as the true date. Who first spotted the white pebbles as diamond is again not certainly known. One version suggests that it may have been a priest who had been to India and had seen diamonds, or, according to Emmanuel, by an inhabitant of the state of Minas Gerais named Bernando Fonseca Lobo who had seen rough diamonds in a previous visit to the East Indies.

The influx of Brazilian diamonds to Europe during 1727 so shook the Dutch diamond merchants that they feared for their market. To counteract this they spread a report that the stones were only poor-quality Indian stones exported from Goa, in Portuguese India, to Brazil and then to Europe. The Portuguese merchants subsequently sent Brazilian diamonds to Goa and sold them as Indian stones, so turning the tables on the Dutch merchants.

Diamond is widespread in Brazil. Besides the initial find at Diamantina in Minas Gerais and at other places in this state, stones have been found in Matto Grosso and Bahia, where in 1754 a slave who had been transferred to the area saw the similarity of the soil to the diamondiferous earth of Minas Gerais. Goiás, Amazonas, Maranhão, Paraná, Piauí and São Paulo are other Brazilian states in which diamonds have been found.

Brazilian diamonds are won from a number of diverse types of rocks. In the so-called high-level plateau, the rocks comprise three series, all of which are probably Precambrian in age. The lowest stratum of these rocks is the Minas series, a metamorphosed rock which contains no diamonds. This series is overlaid by the much folded and faulted Itacolomy series, which is crossed by pegmatite dykes and intrusions of a much altered rock in which diamond occurs. This is generally known as the diamond matrix. The Itacolomy series is again overlain by the Lavras series which consists of conglomerates, phyllites, and sandstones in which diamonds are found.

Although diamond is mined on the plateau at 1200–1500 m above sea level, the greatest diamond recovery is from the detritus formed on the spot, known as *grupiáras*, and from the waterborne deposits from the plateau rocks. Diamond may also be mined from the alluvial deposits, either from the river beds or from the banks and terraces.

Most of the Brazilian diamond mining is carried out in a primitive manner. The miner stakes his claim and works it by stripping the overburden to reach the diamond-bearing gravel, called *cascalho*. He carries away the overburden, if it needs to be taken away, by laboriously carrying it on his head in a wooden platter some 400 mm in diameter, called a *corrombe*. When the diamondiferous gravel is reached, this also has to be similarly carried to the nearest water where it is washed on screens of different mesh in order to recover the diamonds. Mechanical dredges are now being used.

In river mining, the river bed is uncovered by diverting the river, or by building wing dams, so as to allow sections to dry out. The overburden is then stripped from the dried sections to get down to the diamond-bearing *cascalho*. Diving suits are often used if the river is deep. The material may, however, be brought up in sacks by unassisted divers. Either way the soil is put into the boat carrying the divers and panned by *batea* or screened in order to recover the diamonds.

During 1966 it was reported that systematic diamond mining on the Jequitinhonha river near Diamantina was being carried out, the gravel being removed by bucket dredge and then washed in circular jigs. By 1987 two large-scale bucket and vacuum dredges were in operation (*Figure 2.5*).

The majority of the Brazilian diamonds are of small size but of good quality. Large stones, as in other fields, are occasionally found. Indeed, what is probably the sixth largest diamond found, the Presidente Vargas of 726 carats (a carat is a fifth of a gram), is a Brazilian stone. Associated with the diamonds are many

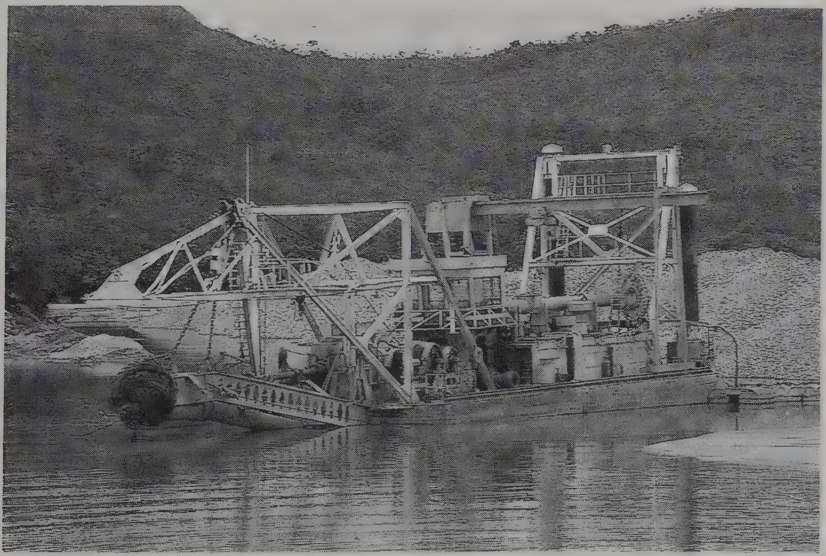

Figure 2.5 A large vacuum dredge used to remove diamond-bearing gravel on the Jequitinhonha river near Diamantina, Brazil (courtesy E A Jobbins)

bean-shaped pebbles which the miners call *favas* and consider to be indicators of the presence of diamonds. These *favas* are water-worn pebbles of tourmaline, kyanite, perovskite, rutile, chrysoberyl and anatase, among others.

In the state of Bahia an unusual type of diamond is found. This is carbonado (also called carbon), a black microcrystalline diamond mass, which owing to its lack of cleavage and consequent toughness was formerly used in the crowns of rock drills. Carbonado is obtained from the gravels of the Paraguaçu river and its tributaries, chiefly around Lençoes and Morro do Chapéu – the area lying some 320 km west of Salvador (Bahia), the state capital. The largest carbonado ever found in South America weighed 3078 carats, nearly as much as the Cullinan diamond. Splinters of carbonado are often used for drilling beads.

North America

As early as 1849, a straw-yellow crystal the size of a pea, which had been found in one of the gold-mining placer deposits in California, was identified as a diamond. Five years later a number of other diamonds were found by prospectors panning for gold at Cherokee, Butte County, in the same state. Some 500 stones have been recovered during gold mining in California. Diamonds have been found in almost every state of the United States. The largest of these alluvial stones were discovered in Virginia; they are the Dewey, found in 1885 weighing 23.75 carats, and the Punch Jones, which turned the scale at 34.46 carats. Geologists presume that these alluvial diamonds had been carried south from Canada by the sweeping action of ice-age glaciers, the probable source being, according to Hobbs, in the vicinity of James Bay, Canada.

During March 1948, great difficulty was found in drilling for water at Vassave township, county of Abitibe in the province of Quebec, and investigation showed that diamond grains were present. On this information the James Bay Diamond Syndicate was formed to work an area of some 800 ha in the Vassau–Lacorne–Preissac area of north-western Quebec province, Canada. Nothing further seems to have been heard of this enterprise.

A most interesting and important locality for diamonds in North America is at Murfreesboro, Pikes County, Arkansas. Here a peridotite pipe was studied by Branner and Brackett in 1889, but they found no diamonds and, from certain geological formations surrounding it, concluded the pipe to be barren. In 1906, a farmer who had a hunch that he would be lucky found diamonds in this same pipe. Since that time many diamonds have been recovered at Murfreesboro, among them the largest diamond found in North America, a crystal weighing 40.23 carats. The mine was operated by different companies until 1919 when the plant was burned down. It is now a tourist centre where amateurs may tour the diamond area and are allowed to keep any stone weighing under 5 carats they may find. A royalty must be paid on stones over that size.

There is a fairly authentic report of the finding of diamonds in the north of the state of Sonora in Mexico. The area is south of Douglas, in Arizona, and near the border with the Mexican state of Chihuahua.

In 1891, minute diamonds were found in the remains of an iron meteorite which fell at Cañon Diablo in Arizona. This led Henri Moissan to carry out experiments on diamond synthesis.

Australia

Diamond was first found in Australia at Sutter's Bar on the Macquarie river near Bathurst, New South Wales, in 1851. Later discoveries were made, during 1867, at Two Mile Flat on the Cudgegong river north-west of Mudgee. In the Bingara-Tingha district near the Queensland border an important diamond field was discovered in 1872. There are a number of other locations where diamonds have been found in New South Wales, and particularly at Copeton, which lies about 25 km from Inverell.

Small diamonds have been found in southern, central, and north Queensland. In the south at Stanthorpe and in the central Ruby Vale district, diamonds have been recovered during washing for sapphire. In the far north of Queensland diamonds have turned up during panning for gold and tin in the wild and rugged country at the source of the Gilbert river.

Until recently, Australian diamonds have been small in size and are usually yellow or off-coloured, but white and many fancy-coloured stones have been reported from the alluvial deposits. The stones are recovered as a rule during gold-mining operations. They are rarely cut as gems, but are mainly used for industrial purposes. The diamonds found in Australia are said to be, like those of Borneo, harder than the diamonds from other sources, but this apparent superior hardness may be due to twinning. Twinning may also occur locally within the crystal producing 'hard' spots which are frequently called 'naats' or 'knots'.

These alluvial Australian diamonds were usually accompanied by water-worn pebbles of topaz, quartz, zircon, black tourmaline, garnet, spinel, but rarely, except in the neighbourhood of Ruby Vale, by sapphire.

All this belongs to the past: the situation has now changed dramatically following intensive prospecting in the Kimberley district in the extreme north-east region of Western Australia. This exploration was carried out by a group of companies under the title of Ashton Joint Venture which began in 1972 following unsuccessful attempts of the kind by De Beers. Australia, far from being of minor importance in the diamond world, was destined soon to become one of the greatest producing countries for the mineral.

Attention was at first concentrated on one of no fewer than 28 pipes which were discovered in the Ellendale province. Some 18 000 stones were recovered from that locality, the largest weighing 6.47 carats, and it was thought from the quality of this sample that diamonds in this region would contain a high percentage of gem-quality stones. More recently, greater interest has been concentrated on alluvial deposits in Smoke Creek, which leads to a huge lamproite pipe known as AK-1. This is located near the man-made Lake Argyle (*Figure 2.6*). Smoke Creek is a small, mostly dry, old watercourse which in trials has yielded as much as 470 carats for every tonne of ore, which compares very favourably with yields from African sources.

The main source of diamonds in the district undoubtedly lies in the giant pipe AK-1 which covers a surface area of 45 ha, placing it as sixth in extent of all the

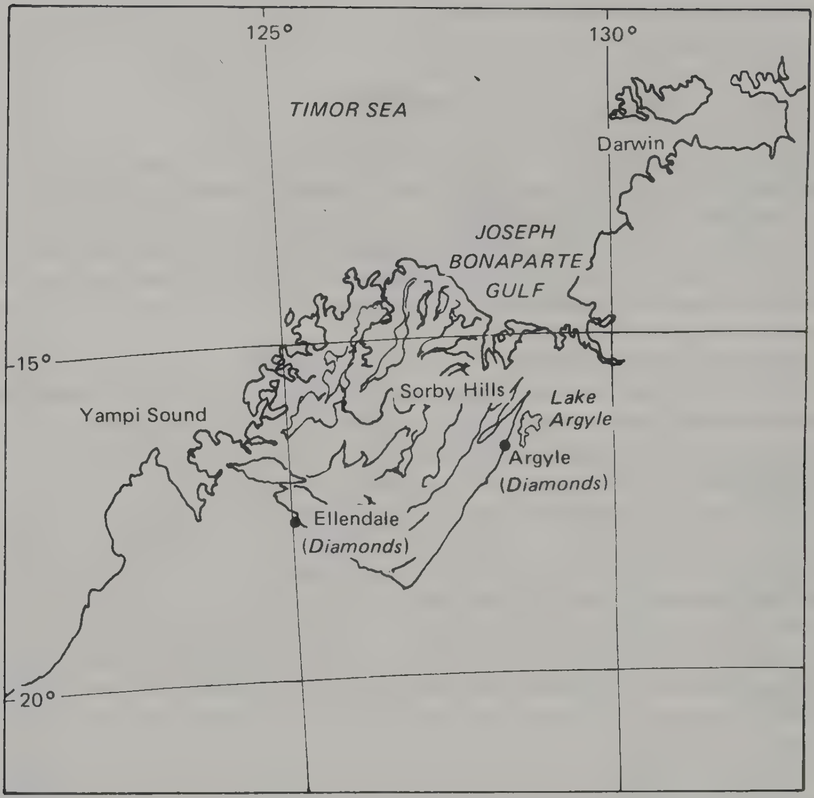

Figure 2.6 The diamond-producing localities in northern Western Australia

world's diamond pipes; the Premier mine, for comparison, occupies 32 ha. Initial samples of diamonds obtained from borings made in the AK-1 indicated that the percentage of gem-quality stones would be low, but there was no doubt that the volume of production would eventually be immense. Today Australia is the largest producer of gem diamonds (*Table 2.1*).

The first few months of 1985 saw a revolution in terms of fancy-coloured diamonds. Hundreds of deep pink stones emanating from the Argyle deposits appeared on the market. This source is now well known for these and an even greater number of brown stones.

The township of Kimberley in South Africa was founded in 1870 and was named after the Secretary of State for the Colonies at that time. Being the centre point of a group of the world's richest diamond mines, the name Kimberley soon became the most famous in diamond history. The district of Kimberley in Western Australia first became famous as a gold-mining area. That it should now become famous for its diamond production must, it seems, rank as a quite extraordinary coincidence.

South Africa

The known diamond fields of the world paled into insignificance when diamond was found in such profusion in South Africa. In the year 1866, the young son of Jacobs, a Dutch farmer of Hopetown which lies near the Orange river, found a shining pebble by the riverside. This pretty stone he showed to his mother, who in turn showed it, and indeed gave it, to a neighbouring Boer named Schalk van Niekerk. Van Niekerk puzzled over the stone and consulted his friend, the trader John Robert O'Reilly, who agreed to take the stone along to Lorenzo Boyes, the Civil Commissioner at Cape Town. Boyes sent it to Dr Guybon Atherston of Grahamstown, who determined it to be a diamond, the first diamond to be found on African soil. The stone weighed 21 carats and was exhibited at the first Universal Exhibition in Paris. It was later sold for £500.

In 1869 a diamond crystal weighing 83.5 carats was found by a Hottentot. This stone was cut into a pear-shaped brilliant of 47.7 carats and given the name Star of South Africa. It was bought by the Countess of Dudley to which fact the alternative name of the Dudley Diamond is due.

The identification of the glistening pebble found by young Jacobs as diamond sparked off, during 1867, a frenzied rush of diggers to the Vaal and Orange rivers. It was estimated that some 4000 of them and their hangers-on were at the diggings in 1869; but easy riches were for the few, disappointment was the lot of many. The best of these so-called 'wet diggings' were found during 1870 at a place called Klipdrift. This is now known as Barkly West on the Vaal river.

A few licensed miners operate around Windsorten and Noitgedacht on the Vaal river. They use few mechanical aids: a crane to hoist the dug-out ground and a circular gravity tank with revolving paddles driven by an internal combustion engine to concentrate the heavy minerals. This concentrate is then searched for diamonds after being spread on open tables.

In 1870 an observant overseer, De Klerk, noticed garnets in the ground of a farm called Jagersfontein, near Fauresmith in the Orange Free State. Knowing that garnets are associated with diamonds, De Klerk searched the ground and soon found a fine crystal of some 50 carats. This farm became the noted Jagersfontein mine. Within weeks similar diamondiferous areas were found at Dorstfontein farm at Dutoitspan, at Bultfontein nearby and at Koffiefontein. All these were in arid surroundings and hence were known as the 'dry diggings'.

During 1871 a further find of diamond was made at another nearby farm, called Vooruitzigt, owned by a farmer named De Beers. This became the De Beers mine, or, as it was earlier known, the Old De Beers mine.

Nearby, at a place called Colesberg Kopje – a name given to it by a band of prospectors who had come from Colesberg, a town on the Orange river – the celebrated New Rush mine, which was later renamed the Kimberley mine, was found during the same year. The town of Kimberley, named after the Secretary of State for the Colonies, lies alongside the mine. It is the centre of the diamond mines (*Figure 2.7*).

The year 1890 marked a discovery on the Wesselton farm, which became the Wesselton mine, famous for its cube-shaped diamonds – which being cross-grained are very tough and well suited for industrial purposes – as well as

Figure 2.7 The main diamond mines of southern Africa

gem-quality stones. This mine was originally called the Premier mine after the Premier Cecil Rhodes.

What is known today as the Premier mine is a mine which was discovered in 1902 and lies some 32 km north-north-east of Pretoria in the Transvaal. In this mine was found the largest diamond so far recovered from the earth's surface, the famed Cullinan, which in the rough weighed 3106 carats. The Premier is the largest mine in South Africa and is an elliptical kimberlite pipe measuring 1000 m by 300 m. The kimberlite of the pipe is surrounded by a red microgranite (felsite). Until 1932 when it was closed, the mine was worked by open-cast methods. It was reconditioned in 1949 and is now operated by shaft mining. *Figure 2.8* shows a day's output from the Premier mine.

Figure 2.8 This parcel represents a day's production at the Premier mine. It consists of gems and a large proportion of industrial diamonds (by courtesy of the Anglo-American Corporation of South Africa Ltd)

During 1960 Fincham discovered a diamond-bearing pipe some 65 km east of Postmasburg in northern Cape Province, and developed the mine called the Finsch, after Fincham and his partner Schwabel. At the time, searching for diamonds would have been illegal, for the location, Brits Farm, was on unalienated Crown land. Fincham first mined for asbestos, and it was the finding of garnets which gave him the clue that the ground was diamond bearing. When the restricting Act was amended in 1960, Fincham and his partner successfully started mining for diamonds. In 1963 the mine was taken over by the De Beers Company who now operate it as a shaft mine. Some 25 per cent of the diamonds found are of gem quality while the remainder are near-gem or industrial stones.

Diamondiferous Formations

The dry diggings consist of a typically yellowish-coloured soil in which the diamonds are found. At first this soil was thought to be parts of earlier river beds or the result of patches of river soil brought up by floods in earlier times which had settled in shallow areas. The diamondiferous yellow ground had a depth of some 20 m and lay on the top of a harder slate-grey earth called 'blue ground'. When this blue ground was reached, the miners considered the claim to be worked out and therefore abandoned it. However, one more inquisitive than his fellows – it has been said that it was Barney Barnato (see later) – did dig down into the blue ground and did find diamonds. It is believed that Barney Barnato kept quiet about his find and bought up the abandoned claims cheaply.

Later geological study produced a better understanding of these diamondiferous formations. It was found that the surface outlines of the diamond mines were elliptical or roughly circular and were in fact the mouths of pipes which reach down through the earth's crust to unknown depths. These pipes are filled with an ultramafic rock to which the name kimberlite has been given. Kimberlite, or blue ground, is a hybrid rock comprising fragments of high-temperature peridotite and eclogite plus megacrysts and a variable amount of wall rock material. At the surface, owing to the alteration by weathering, the ground takes on a yellow colour due to the oxidation of the iron content of the rock. Yellow ground is therefore simply oxidised blue ground. Diamonds are also found in lamproite formations (which are also pipes) which are ultrapotassic magnesium-rich igneous rocks.

Alluvial or waterborne diamond deposits are undoubtedly derived from some undisclosed pipes whose mouths are now covered by more recent strata, or which have been buried by geological upheavals in past ages. The alluvial deposits are usually mined by panning (washing) and screening the diamond-bearing earth and finally recovering the diamonds by sorting the concentrate on tables.

Dry Diggings

The dry diggings called for different mining methods. At first the pipe mines were worked as open pits, each claim being worked downwards independently with retaining walls between the claims acting as roadways. As the claims were dug deeper, and not always at the same speed, the walls were weakened by undercutting and mostly fell in, causing the abandonment of many claims.

When the roadways were finally demolished it became necessary to bring the blue ground up in a different manner. This was accomplished, particularly in the Kimberley mine, by constructing a vast system of wire ropes up which the buckets of blue ground were drawn from all parts of the rapidly deepening pit by means of windlasses surrounding the rim of the crater (*Figure 2.9*).

The Combines and Personalities

As the workings went deeper they became more difficult to work, owing to falls of rock, the abandonment of claims, and flood water. To counter this, individual workings gave way to amalgamations, creating fewer and larger holdings. Even so, work from above soon became impossible and open-pit mining had to be abandoned. Up to 1896 no miner in Kimberley was allowed by law to own more than ten claims, but with the necessity to combine in order to work a mine,

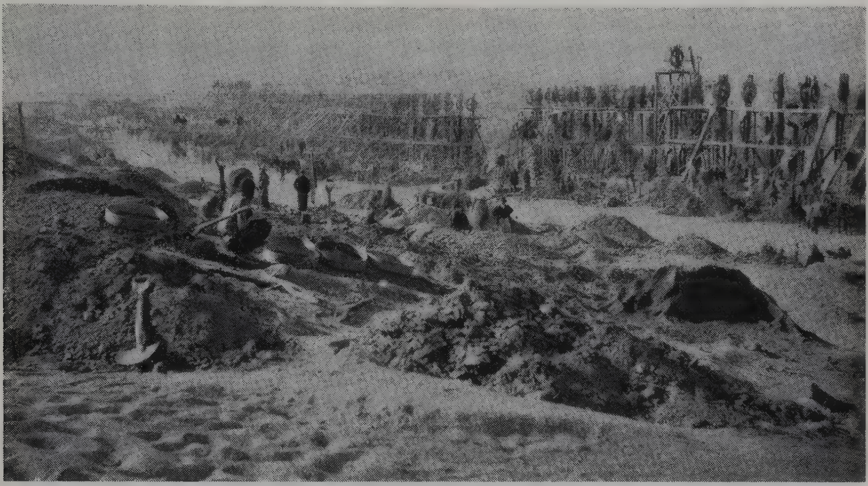

Figure 2.9 Early stages in South African diamond mining

this law had to be rescinded, thus leading to the disappearance of the individual and to the beginning of the combines.

The story of the combines brings in the personalities to which the South African diamond industry owes its origin, and among which the names of Cecil Rhodes and Barney Barnato are the most colourful. Rhodes, a shrewd businessman, a scholar, and a visionary, arrived in South Africa in 1870, at the age of 17 years, in order to join his elder brother as a cotton planter in Natal. Rhodes and his brother left Natal in 1871 for Colesberg Kopje, and with another brother, Colonel Frank Rhodes, secured three valuable claims. Cecil Rhodes was not content to leave his further education unfinished, and, leaving his brothers to run the claims, returned to England and studied at Oxford for a short time. In 1880, at the age of 26, he founded the De Beers Mining Company and was subsequently elected Member of the Cape Parliament for Barkly West. The next year he again returned to England and took a Master of Arts degree at Oxford. At the age of 31 he became Treasurer of Cape Colony.

Born in 1852, the son of a small shopkeeper in Whitechapel, Barnet Isaacs in 1873 followed his brother Henry to the diamond fields. Henry Isaacs had been a bartender and a music hall performer and took for his stage name the euphonious title of Barnato. His younger brother also liked the euphony of the new name and became Barnet Barnato, or more usually Barney Barnato. Barney did not do much digging but joined forces with Louis Cohen, the pair operating as field diamond buyers, 'kopje walloping' as it was then called. Cohen made his fortune, returned to Liverpool and departed from the picture.

Barney, with his brother Henry, founded the firm of Barnato Brothers and, in 1876, bought a claim; this was at a time when the Kimberley mine was becoming more difficult and dangerous to work and when fierce price cutting was rampant. Like Rhodes, Barney foresaw that the future of the diamond mines would depend upon centralised control of mining and selling. When Barney was 27 years old, and his brother two years older, the brothers floated the Kimberley Central Diamond Mining Company.

Thus began the epic struggle for financial control between Cecil Rhodes and Barney Barnato. For Barnato the fight was pure business, but the urge which gave so much power to Rhodes was his dream of the British flag from the south to the north of the African continent.

Cecil Rhodes and his friends, who included Julius Wernher, an ex-Uhlan, and Alfred Beit, approached the bankers Rothschild for financial backing, and this they obtained.

Barney's group could not resist the heavy backing ranged against them by the Rhodes group, who finally bought the controlling interest of Barney's remaining company, the Kimberley Central, for nearly $5\frac{1}{2}$ million pounds. In 1888, with the merger accomplished, the new company, under the title of De Beers Consolidated Mines Limited, put most of the South African diamond mines under unified control.

Cecil Rhodes never forgot his dream of a British Africa and stipulated that the surplus funds of the diamond industry should be used for the further development of Africa and the expansion into and colonisation of the country to the north. Barney at first objected to this and considered that the shareholders had first claim to all profits, but finally agreed under the scholarly and forceful arguments of Rhodes, as, indeed, he was bound to, as he had no controlling influence in the new company.

Subsequently, De Beers Consolidated Mines Limited completed the unification of the mines by buying control of the Griqualand West, Dutoitspan, and Bultfontein mines.

Mining Methods

At all pipe mines, the limit of open-cast working was soon reached and underground mining by shaft became universal. The mining methods are in general the same and vary only in local peculiarities. A main shaft is driven down through the hard surrounding rocks parallel to the pipe. From this shaft sublevels are driven horizontally across the pipe, tunnels being between 8 and 15 m below each other. At the end of each level a slot or chamber, 3–5 m wide and extending vertically to the level above, is cut from one side of the pipe to the other. The blue ground is worked backwards, working first a second slot, then a third, and so on through the width of the pipe. Each slot is worked one slot ahead of the level below it. By this stoping method of mining (*Figure 2.10*), the whole of the blue ground is removed. This proces is called 'chambering'.

Later a system of 'block caving' was used. Cone-shaped excavations are cut beneath a large volume of blue ground, 120 to 180 m thick, and this is then undercut above the cones. The unsupported overhanging blue ground then slowly settles into the cones, breaks up and is drawn through the cones into 'scraper drifts' where it is pulled out by mechanical scrapers (*Figure 2.11*). This method is less labour-intensive than chambering, and lends itself to mechanization.

The broken-down blue ground is loaded into trucks by hand and these are taken to ore passes and thence to the shaft bin by conveyor belts or endless rope buckets. Kimberlite is raised to the surface through the main shaft.

Figure 2.10 Blasting hard rock projecting into open mine at Bulfontein

Figure 2.11 A mechanical scraper pulling broken down blue ground along a scraper drift in the block caving method of mining (by courtesy of the Anglo-American Corporation of South Africa Ltd)

When freely exposed to the air, the blue ground disintegrates rapidly. Advantage was taken of this in the earlier method of treatment for the recovery of the diamond content. The blue ground was spread to a depth of half a metre over floors – levelled areas of the open veldt – and left for some months with periodical ploughing, and if necessary watering. When sufficiently decomposed, the ground was carted to washing and concentrating tables, the diamonds being picked out by hand from the concentrate.

More modern methods are now universally used. The blue ground on reaching the surface is passed through crushers where it is reduced to pieces of 25 mm or less in size and is fed to rotary pans fitted with revolving radial rakes. This mud puddle separates the heavy minerals, including the diamonds, from the lighter kimberlite gangue.

The tailings (the heavier minerals) from the pans, of which there may be a battery working with reduced sizes of crushed rock, are then brought to a dump by a belt conveyor. From this dump the diamondiferous concentrate is taken by truck to the pulsators which further concentrate the ore. The final concentrate is then passed over side-shaking grease tables. A modern innovation is a method of concentration by a heavy media separation plant which eliminates the pulsators (*Figure 2.12*).

Figure 2.12 *The bottom of a cone in the heavy media separation plant at the Premier diamond mine in which diamonds and associated heavy materials are separated from the lighter materials in the blue ground. The diagram shows the operation of such a plant (by courtesy of the Anglo-American Corporation of South Africa Ltd)*

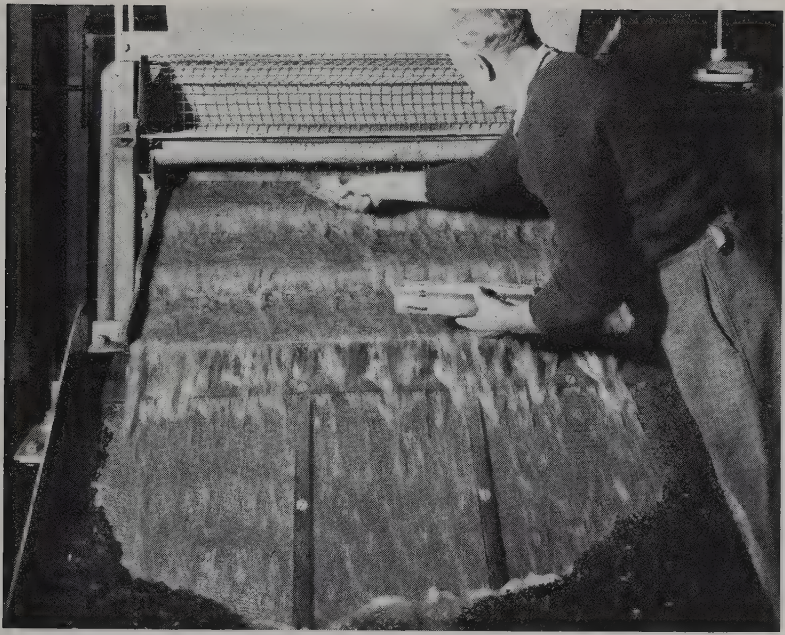

Figure 2.13 *Removing diamonds from the grease table at Kimberley (by courtesy of the Anglo-American Corporation of South Africa Ltd)*

It was discovered by Kirsten that as diamond is water-repellent, unlike most of the other heavy concentrates, it adheres to grease. This factor is made use of in the covered, sloping side-shaking grease tables. These tables are covered by a thick layer of petroleum jelly and the concentrate is passed in at the top, being washed down by a gentle flow of water. The diamonds stick to the grease while the other minerals pass out at the lower end as tailings.

Periodically the grease and the diamonds adhering to it are scraped off the table. The grease is boiled off and the larger diamonds are picked out by hand from any stray zircon or corundum which have a tendency to be caught by the grease. *Figure 2.13* shows a grease table. Some diamonds do not adhere to grease and for these 'non-stickers' other methods are used for recovery, such as electrostatic separation. The diamonds recovered by these processes are all sent to a central sorting office for grading.

To provide a continuous check on the efficiency of grease tables an optical separator is used which is based on the opacity of rock and the reflection and transmission characteristics of diamond. Much of the colour sorting of diamond crystals received from the mines is now carried out by optical separators which use photoelectric cells to sort the diamonds into colour grades. Such a machine, made by Gunson's Sortex Limited by Bow, London, has now been modified to operate by X-rays for use in diamond recovery at the mines. This machine (*Figure 2.14*) works on a similar principle to that devised by the Russians Krassov and Finne and depends upon the fluorescence of diamonds when in an X-ray

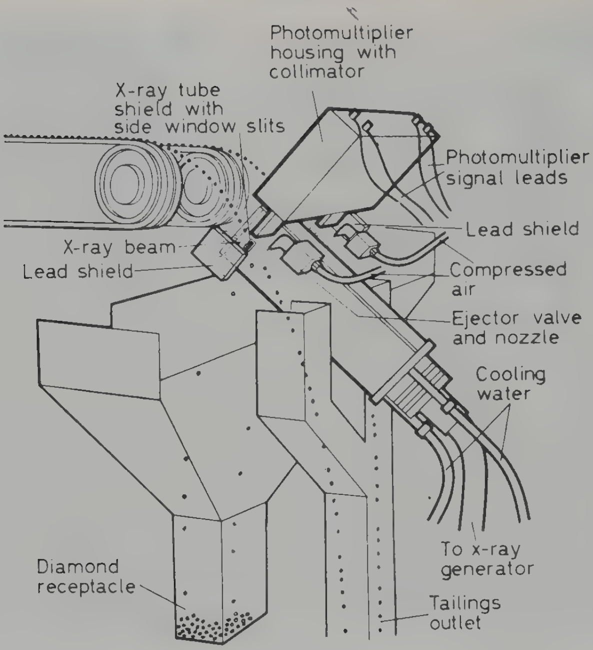

Figure 2.14 Diamond sorting by X-ray fluorescence

beam. X-ray sorting was introduced by the Russians as grease tables employing water could not be used in subzero temperatures.

Zimbabwe

The discovery of the diamond deposits of South Africa was the beginning of diamond finds over the greater part of the west and south-western part of the African continent.

Alluvial diamonds were discovered during 1903 in the Somabula Forest west of Gwelo in Matabeleland, Zimbabwe (formerly Southern Rhodesia). A little farther north of this locality there occur several pipes, but in most cases these are barren of diamond. These deposits have as yet little commercial importance, but prospecting is still proceeding.

Namibia

In 1908 diamond was detected near Lüderitz on the Atlantic coast of Namibia (formerly South West Africa). These marine beach deposits were later found in discrete areas stretching some 100 km along the coast north of the mouth of the Orange river. Diamonds may be found northwards along the Namibian coast as far as the Kaokoveldt, but the area is not mined. Some diamonds have been found in the small Possession Island, which lies some 3 km off Elizabeth Bay. The area is mainly operated by the Consolidated Diamond Mines of Namibia, a branch of the De Beers group. The main recovery plant is at Oranjemund at the mouth of the Orange river.

In 1927 extensive marine beach deposits were found in Namaqualand, south of the Orange river. Rich deposits were located some 25 m above sea level on a terraced beach in which the goatshorn oyster (*Ostrea prismatica*) is present in quantity. A minor diamond field was discovered in 1956 on the Skeleton Coast of Namibia. This area lies in the Kaokoveldt, south of the Kunene river, which forms the border with Angola.

These coastal fields are worked by the aid of mechanical excavators. The overburden, often 30 m in thickness, needs to be first removed. When uncovered, the diamondiferous gravel is removed by hand or by excavator and brought to a central treatment plant. *Figure 2.15* shows the overburden being removed by a mechanical shovel, and *Figure 2.16* shows a miner drilling into the diamondiferous conglomerate at Mittag, which lies just north of Oranjemund. The diamonds from these beach deposits are not water-repellent as they are coated with a microscopic film of salts. They are therefore treated by immersion and light milling in fish oil and caustic soda to enable them to adhere to the grease on the grease table (or belt). Alternatively, an electrostatic method is used to recover the stones. *Figure 2.17* shows some of the plant at the central recovery plant of the Consolidated Diamond Mines at Oranjemund.

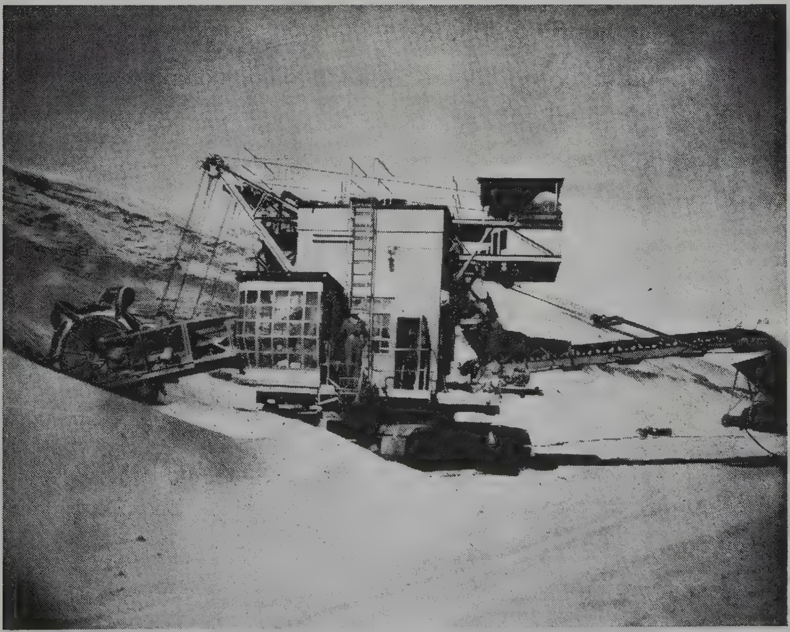

Figure 2.15 One of the big rotary scoops at the Consolidated Diamond Mines of Namibia. This giant which removes sand at the rate of 400 tonnes an hour is in a trench which is being prepared for mining in the east extension at Gemsbok Terrace (by courtesy of the Anglo-American Corporation of South Africa Ltd)

Figure 2.16 A miner drills a hole into diamondiferous conglomerate in a mining face at Mittage preparatory to blasting (by courtesy of the Anglo-American Corporation of South Africa Ltd)

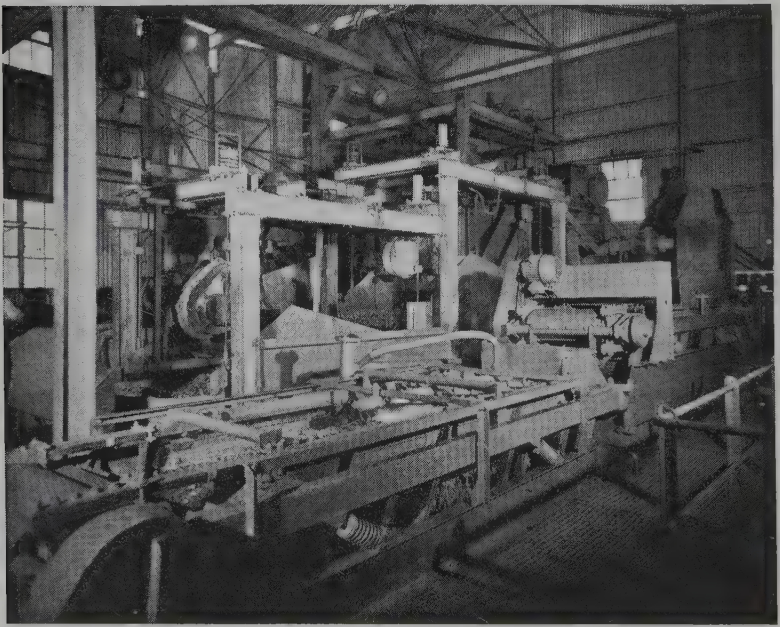

Figure 2.17 Screens at the central plant of Consolidated Diamond Mines (by courtesy of the Anglo-American Corporation of South Africa Ltd)

The origin of these marine alluvial diamonds is open to debate. Was the original source inland, or did the parent rocks lie submerged under the Atlantic Ocean? The size of the stones diminishes as the distance from the mouth of the Orange river increases. It is therefore thought that the source is inland, the stones having been carried by rivers of former geological ages to the sea to be later cast up on the beaches near the river mouths by ocean currents.

About 1964 the Marine Diamond Corporation commenced diamond recovery from the seabed off the Namibia mainland, and in 1967 the *Pomona*, a specially equipped barge, operated about a mile off the mouth of the Orange river. The sand of the seabed, up to 30 m below, is raised by airlift and suction dredge. The diamondiferous sand is then screened, washed, concentrated by heavy media separation, and finally sorted by hand. A larger computer-controlled barge operates today.

Zaire, Congo and Angola

In 1910 diamonds were found in the south-western part of the Congo in alluvial gravels in the valleys of the tributaries of the Kasai river. Farther west, diamond deposits have been located in the Kwilu basin. A more productive area was discovered around the Bushimaie river, which lies to the east of the Kasai river and some 600 miles north-west of Lubumbashi (formerly Elizabethville) in the district of Katanga, where uranium minerals vie with diamonds as the major export from the Congo. Near the Kundelungu plateau, just north of Lubumbashi, a number of kimberlite masses occur, a few of which have proved to contain diamonds. The town of Tshikapa is the centre of the diamond-mining operations in the Congo, which is the world's largest producer of diamond in terms of quality. Before the West African production came on the market, the Congo produced at least three-quarters of the crushing boart so widely used in industry.

During 1916 the Congo diamond fields were found to extend into the north-eastern part of Malange in Angola, particularly along the western bank of the Chuimbe river and both banks of the Luembe and Luana rivers. The Angola deposits are alluvial and are derived from an ancient drainage system which no longer exists.

Mining is carried out, in both Angola and the Congo, by removing the overburden to expose the diamondiferous gravel. This gravel is then excavated (*Figure 2.18*), taken to washing plants, and treated in a heavy media separator. The concentrates are processed in a recovery section for the extraction of the diamonds.

Ghana

The discovery, in 1919, of diamond at Abomoso near the Birim river opened up diamond mining in the Gold Coast, now called Ghana. Later prospecting disclosed diamond in the district south-east of Kade and about 100 km north-west of Accra, the capital. Diamonds from Ghana are mostly of industrial quality, although gem crystals are also recovered in some quantity.

Figure 2.18 Open-cast working in the Congo diamond fields

The Ghana deposits consist of gravels from 0.5 to 2 m thick and are interesting in that the rock formations in the area are steeply dipping metamorphosed igneous and sedimentary rocks of Precambrian age. The mining for diamond is carried out by removing the overburden and depositing it in previously mined sections. The exposed diamond-bearing gravel is mechanically loaded into one-tonne trucks and taken to the washing and recovery plants where, for the smaller diamonds, a method of 'skin flotation' is used. Much Ghana diamond gravel is worked by African leaseholders, but the main fields are operated by Consolidated African Selection Trust Ltd, though there are now American interests. Much illicit diamond mining and buying occurs which is detrimental to both the mining company and the leaseholders.

Diamonds are also found in the Ivory Coast.

Sierra Leone

The diamond fields of Sierra Leone were not discovered until 1930, when a small diamond was found by geologist Pollet in the gravels of the Gboboro stream near the village of Fotingaia in the Nimi Koro chiefdom. Next day another stone was recovered from the same site and, later, further finds were made in the gravel of a tributary of the river Moa in the Kennema district.

On hearing of these finds, the Consolidated African Selection Trust Ltd sent a prospecting party from the Gold Coast to Sierra Leone. They were well equipped with shaker trays and joplin jigs and with personnel skilled in diamond mining. During 1932 the prospecting party found diamonds north of the Bandafayi watershed in the Shongbo stream near Tongoma village. Small-scale mining operations showed the deposit to exceed expectations and, further, that the diamonds tended to gather in clusters on the bedrock. The company was granted the exclusive right to prospect for diamond over an area of 10 800 km² of the eastern district of Sierra Leone.

Further exploration showed that diamond was present in the gravels of the Sewa river, an area not included in the licence granted to the Gold Coast company, and in 1934 a new subsidiary company, the Sierra Leone Selection Trust, was floated and was granted the sole right to prospect for diamond in the colony. Owing to the vast expanse of diamond-bearing gravels, policing the area was almost an impossibility and illicit mining and buying was rife. During the early 1950s it was estimated that more diamonds passed out illicitly from Sierra Leone than were mined by the operating company. Much of the illicit buying is operated through the Republic of Liberia. In 1955, to alleviate this situation, a new agreement was entered into between the Sierra Leone Government and the Sierra Leone Selection Trust, enabling diamond mining to be practised legally by private persons under licence. A subsidiary company formed by the Diamond Corporation was granted the exclusive right to purchase diamonds from licensed diamond buyers and dealers in the territory.

It is interesting to note that the rock formations in Sierra Leone, unlike those of Ghana, are of Cretaceous age. The diamonds produced in Sierra Leone are in the main of good quality and are often of large size. Many of the crystals show excellent octahedral form with bright faces. Such crystals are called 'glassies' (*Figure 2.19*). Crystals of 100 carats or more are occasionally found: the Woyie River Diamond recovered in 1945 weighed 770 carats, but this was surpassed by the finding of the Star of Sierra Leone at the Diminco mine at Yengema in February 1972. This crystal weighed 968.9 carats and was the third largest diamond ever found (*Figure 2.3*). Natural bottle-green-coloured diamonds are often found and such diamonds will turn light brown on heating, in a similar manner to those stones which owe their colour to artificial treatment by particle bombardment (cyclotroned and neutroned diamonds). It is from this effect that it is suggested that uranium compounds might exist near the place where the diamonds were found.

Figure 2.19 A 'glassy' diamond crystal from the Sierra Leone diamond fields

The mining is carried on in a similar manner as in the other alluvial fields of Angola and Ghana. The Sierra Leone diamond fields are situated some 225 km east of Freetown, and in the mining area itself the Diamond Mining Company have constructed most up-to-date mining camps on the principle of a garden city.

West and Equatorial Africa

Among the first diamonds to be discovered in the old French West Africa were those in the Région Forestière of French Guinea (now the Republic of Guinea). A minute diamond found by Goor, in 1933, in a river in the N'Zérékoré district on the border of Liberia was probably the first. A year later, several workable deposits of diamond were found in the Makona river district and in the rivers of Haute Guinée.

The main workings of this diamond field are located some 75 km north-north-east of Macenta. The diamonds are mostly found in alluvial deposits in the upper courses of the smaller streams and in old terraces associated with such minerals as ilmenite, magnetite, zircon, rutile, corundum, monazite, epidote, topaz, spinel, staurolite, tourmaline and almandine garnet. The diamond crystals are usually octahedra or dodecahedra and are frequently of a brown colour, or a clear yellow or blue colour. The stones often contain black inclusions making them unfit for gemstones. The great preponderance of the diamonds from these fields are boart.

Diamonds have been recovered from ancient river terraces along the region of the Mambere river which runs through the western part of the Oubangui-Chari district of the Central African Republic. The diamonds – production is small in amount – are recovered by clearing the thick tropical underbrush of jungle and forest and removing some 2–5 m of overburden or topsoil to reach the diamond-bearing gravel, which is then removed and passed through old-fashioned joplin jigs to concentrate the heavy minerals for final sorting. Preliminary prospecting to gauge the depth of the overburden is carried out manually and dredging machines are used to test the gravel bed of the Mambere river. In Moyen Congo and Gabon districts of the Central African Republic, a few diamonds have been recovered, but mining in these territories has practically ceased.

Tanzania

In the area between Shinyanga and the southern shore of Lake Victoria in Tanzania (formerly Tanganyika), diamondiferous gravels 1 to 2 m thick exist over a large area underlain by granite. Claims in this locality were pegged as early as 1910, but mining did not begin until 1925. The workings were mainly at Mabuki, which lies on the railroad from Tabora through Shinyanga to the town and airport of Mwanza. The diamond deposits consist of diamond-bearing gravels on a kimberlite pipe, these outcrops being the most northerly kimberlite pipes in Africa.

Dr John Thorburn Williamson, a Canadian of Irish descent and one-time geologist to the Quebec Geological Survey, came to Mwanza in 1934. After a period on the Rand, where he became interested in diamonds and where he first formed his theory that the Tanzania diamond deposits must be derived from an original pipe somewhere in the area, he came to Tanganyika. Williamson thought that the pipe could be located by scientific study of the area and proceeded to work on these lines.

Sitting in the shade of a baobab tree at Mwadui, some 150 km from Lake

Victoria, Williamson found a diamond which was the clue to the finding of the Williamson pipe the next year. Thus successfully ended Williamson's hunch, and years of scientific prospecting, during which he never lost faith in his own convictions. The Williamson mine is the largest pipe mine in Africa. The main pipe at Mwadui is said to be eight times larger than the Premier mine in the Transvaal.

So far as is known, the Williamson mine is still being operated as an open mine, mechanical excavators scooping up the gravel and emptying their grabs into 5 tonne trucks. The trucks take the gravel to the concentrating pans to undergo the initial processing. Diluted to a mud-like consistency with water, the gravel and black soil are scoured by rotating rakes in wide and shallow pans. This causes the diamonds to sink to the bottom with the other heavier concentrates, but floats off the lighter materials which are drained from the top. Periodically the concentrate is shovelled out and taken in coco-pans to the jigs, where the final extraction of diamonds is carried out. The jigs in the sorting shed are manned by locals watched over by security men. The final tailings of concentrate are then hand-picked over by workers for any diamonds which have passed the jig. These workers wear only an overall which has one sleeve closed at the cuff allowing only the right hand to be free for picking out the diamonds. The free hands are carefully watched by security guards. This primitive and outmoded method is being replaced by modern diamond recovery equipment.

The Williamson mine has supplied a number of large diamonds, including one of 240 carats, and small green and pink crystals; the largest pink weighed 54 carats in the rough and gave a stone of 23.6 carats. This stone was given to Queen Elizabeth II when she was Princess Elizabeth. In 1958 a shaft was sunk alongside the pipe to a depth of 380 m from which exploratory tunnels were driven into the pipe to see if payable diamond exists.

Lesotho

During 1958 diamonds were discovered somne 2800 m up in a valley in the Maluti Mountains of the Mokhotlong area which lie west of the Drakensberg mountain range. This locality is in the landlocked former British Protectorate of Basutoland, now Lesotho, and is surrounded by the Republic of South Africa. The mining was carried on by primitive methods. Lesotho became famous when, in 1967, a miner's wife picked up a diamond weighing 601.25 carats. It was the largest diamond ever found by a woman. This crystal was cut into 18 stones. Two other large diamonds, one of 527 carats and the other of 338 carats, have also been found in Lesotho. The mine was closed when diamond prices slumped in the late 1970s.

Botswana

The search for diamonds in the then Bechuanaland, now Botswana, may be said to have commenced in 1955 in the area west of the Limpopo river. A few diamonds were found along the dry Motloutse river at Foley in the

Bamangwato tribal territory. Later searches were carried out to the headwaters of the dry river bed. Diamonds were found along the river course but the traces petered out and there was no sign of a pipe from which the diamonds could have come. The De Beers geologist, Dr Gavin Lamont, did find traces of a large shallow valley which he connected with a suggestion made years earlier by Du Toit that an earth folding had occurred along this line and would have thrown the source of the Motloutse river much further west.

This was proved when a group of pipes were discovered in the area of Letlhakane. One of these, found in 1967, is now the Orapa mine and is the second largest pipe mine, only being surpassed by the Williamson mine in Tanzania. Sampling showed that diamonds were in payable quantity and in 1969 a pilot recovery plant was put in operation. Although Orapa was said to have come into production in July 1971, it was not officially opened until 1 May 1972. Mining is carried out by the open-cast methods. Since then production has largely increased in Botswana's diamond mines, with Orapa producing 15 000 carats a day in 1981, though only 15 per cent of this was suitable for gems. In contrast 40 per cent of the diamonds produced from the nearby Letlhakane mine are considered to be of gem quality. A further large diamond mine at Jwanang which is jointly owned by De Beers and the Botswana government is now producing a high proportion of gem-quality diamonds. These mines are together among De Beers's most important present-day sources of diamonds.

Other African Mining Areas

Presumed to be of detrital origin and derived from the pre-existing Witwaters formation farther to the north, a number of small greenish diamonds have been recovered during the mining operations for gold in the Rand banket. During 1957 French uranium prospectors found six diamonds in the Hoggar area of the south-east Sahara.

Guyana

Diamonds were discovered in the gold washings of the Puruni and Mazaruni basins of British Guiana, now Guyana, during 1887. The diamonds, small in size, are found in a gravel of ferruginous clayey or sandy nature which is overgrown with tropical jungle. The nature of the terrain makes transport difficult and recovery of the stones uneconomic. Diamonds are also found in the Cuyuni, Potaro and Berbice rivers and their tributaries.

The diamonds of Guyana are usually worn and pitted octahedra, these crystals being most common in the Meamu-Apiqua district and in the Potaro deposits. The finest quality and the best shapes come from the Kurupung and Eping districts. The commonest colour of Guyana diamonds is white with a slight yellow tinge, followed by Capes, and light and dark browns. Unusual colours are rare as are blue-white stones, but occasionally a small aquamarine-blue or deep green stone is encountered, mainly from the Potaro district.

The mining in Guyana is carried out in a primitive manner by local miners, who are known as ‘pork-knockers’. These miners work on their own behalf and trade the stones they find with shops which supply them with their tools and necessities of life. The largest stone said to have been found in Guyana was a crystal of 56 carats and was recovered in the Potaro district in 1926.

During 1948 a diamond deposit was found on the Ireng river which lies along the Guyana–Brazilian frontier, which led to a miniature rush by miners from both sides of the frontier.

Bolivia

Diamonds have been found in the foothills of the Andes in Bolivia. The diamonds were discovered in the river gravels of the Rio Tuichi and have been reported from the Rio Tequeje, Rio Unduma and some other tributaries of the upper Rio Beni. The diamonds are found in gravel beds of from 1 to 3 m thick overlying a bedrock of Permian age.

Venezuela

The finding of diamonds along the Cuyuni and Paragua rivers in the area known as Gran Sabana of the state of Bolivar in Venezuela may be said to be an extension of the diamondiferous fields of Guyana. The exploitation of these deposits is hindered by their inaccessibility but some mining and marketing of Venezuelan stones is carried out. Diamonds from the Paragua river are coated with iron oxide, but fine-quality stones can be cut from them. Green diamonds are frequently encountered at Icabaru. Fancy colours, such as yellow-green, brown, reddish-brown, pink, light blue and black, are common in Venezuelan diamond deposits.

Russia

The first recorded discovery of diamond in Russia was in July 1829 when a German mineralogist from Freiberg, who was at the gold-bearing and platinum-bearing deposits in the Ural mountains, identified as a diamond a stone found by a 14-year-old Russian boy named Paul Popoff of Kalinskoje. A few other small diamonds were found in the gold and platinum washings and in the recovery plant for these metals. The find had no commercial significance.

It is said that from 1941 scientific methods were applied to diamond recovery in the Soviet Union, but the literature is not clear. However, industrial diamonds are said to come from Molotov Ablast which is situated on the confluence of the Kama and Chusovaya rivers at the foothills of the Ural Mountains and on the European side of the range. The Uralian diamonds are described as being of the ‘Brazilian type’ and this supports the view expressed by Alexander von Humboldt more than a century ago.

As long ago as 1898 it was known that there were diamonds on the mid Siberian plateau located between the Lena and the Yenisei rivers, and in 1936 Professor W S Sobelew recognised that the geology of the area bore some resemblance to that of the dolerites of the Karoo formation of South Africa. Further research awaited the end of World War II, but a few diamonds were recovered in 1945. Russia, needing diamonds for industrial purposes, then sent out expeditions to trace the diamond sources. The first useful diamond placers were found in 1949. In 1954 a young woman mineralogist attached to one of the survey teams found the first kimberlite pipe, and by 1959 some 120 pipes had been found in Yakutia. The most reported is the Mir pipe, but it is said that the Aichal pipe, found in 1960, may surpass it in diamond content. The diamond area, mainly along the Vilyui river and its tributaries, is covered by marshy primeval woods known as taiga, and this makes transportation difficult. At present it seems that only open-cast mining is carried out. The broken rock is taken to the treatment centre at Mirny, a town which has developed since the finding of diamonds in the neighbourhood, it being linked to the Lena river by a 300 km motorway. At the recovery plant the rock is washed by water jets which remove the gangue material leaving mainly pyrope, garnet and diamond. The concentrate used to be hand-picked for diamond but the sorting is now done mechanically. An interesting method of recovery which has been reported from Russia is by the Krassov and Finne's automatic sorter in which the diamondiferous concentrate is passed down a hopper where it passes an X-ray beam. The beam makes the diamonds fluoresce so that they are detected by a photoelectric device which operates an air jet to separate the diamonds from the gravel. A form of impure, dark-coloured diamond like carbonado has been found in Yakutia in Siberia and has been named *yakutite*.

China

In 1955 an important source of diamond was discovered in Hunan province and, from this and a diamond pipe found in Liaoning, over 2 million carats are now being produced annually. As a result many diamond cutting schools and factories are now being established in China.

Sorting and Grading

When diamonds have been recovered from the mines they are sent to centres for sorting into grades. More than 80 per cent of the world's diamonds are sent to London to be sold through the Diamond Trading Company. Very few of the diamond mines of the world are not under the care of the corporation which was first conceived by those great names in Kimberley in the 1890s. This corporation ensures that supply and price are maintained at an economic level. World gem diamond production is shown in *Table 2.1*.

The work of sorting is a specialised process that is now, and has been ever since mining started, carried out by hand and eye, although since the late 1970s automation has been introduced for weighing and for the colour sorting of some of the smaller sizes and lower qualities. The first sorting may be simply into two groups: that of cuttable goods, crystals which can be fashioned into gemstones; and industrials, stones which are suitable only for industrial uses (these will be discussed later). Some 80 per cent by weight of all mined stones

Table 2.1
World gem diamond production in thousands of carats
(compiled by US Bureau of Mines)

	1976	*1977*	*1978*	*1979*	*1980*	*1991*	*1992*
Angola	255	265	525	562	750	1 215	1 300
Australia	–	–	–	–	–	17 978	18 000
Botswana	358	404	418	659	765	12 000	12 600
Brazil	214	274	291	305	305	600	900
Central African Republic	172	178	199	205	180	300	300
China	–	–	–	–	–	200	200
Ghana	228	230	142	125	100	210	210
Guinea	25	25	25	27	27	85	85
Guyana	6	7	7	6	4	3	3
India	17	15	14	13	12	3	3
Indonesia	3	3	3	3	3	8	15
Namibia	1 609	1 901	1 803	1 570	1 482	1 120	2 000
Russia	2 000	2 100	2 150	2 200	2 250	7 500	8 000
Sierra Leone	433	423	353	419	400	175	175
South Africa	2 858	3 099	3 078	3 539	2 403	3 800	5 000
Tanzania	219	204	146	145	120	56	56
Venezuela	195	204	269	247	250	90	90
Zaire	498	533	640	294	470	3 000	3 000

are of too poor quality for cutting and are classed as industrial quality. There is no distinct division between gem and industrial grades in respect to the marginal qualities (known as 'near gem'), for they may be classed as either depending on the demand.

The sorting and subsequent valuation of gem diamond depends upon four factors: size, colour, shape and quality (purity). Stones of good weight, acceptable colour and normally of octahedral shape are termed 'stones', to which may be added 'shapes' which have many desirable features such as colour and size but which may not be quite so useful from the point of view of cutting. Macles and flats (thinner macles) form another category. Farther down the scale are mêlée which are crystals less than 1 carat in weight, and finally 'sand' which includes stones which can total as many as 120 to the carat. Cleavages are stones irrespective of weight which have been broken and therefore are of a highly irregular shape. Coated stones are crystals which have a dark coating on the surface (usually diamondiferous). Frosted or eroded crystals are those in which the coating has worn away leaving a dull or pitted surface.

The grading of diamonds for colour is carried out by trained personnel who have gained their knowledge purely by experience. In the case of diamonds, for all but small low-quality stones, colour grading must be done by the eye alone, for no mechanical aids have been found which will function so well. There are many divisions and subdivisions into which diamonds may be colour graded. Generally the grouping used is as follows: extra collection colour; collection colour; finest white; fine white; browns and greens (varying from light brown to light green); top Capes (stones having a yellowish tinge); Capes; and yellows.

The above classification refers to white diamonds, for the colours mentioned are just tinges and not a strong colour. Diamonds may be found having pronounced colours, and these are called fancy stones and may be highly prized.

Brown is a common shade, canary yellow less so, while pink, red, blue, and green shades are rare. The colour is thought to be due to lattice defects and not to trace elements as in most other gemstones.

The term 'blue-white' is not so often used as formerly; it indicates stones which tend to show an indefinable bluish tint. This has been explained as not being a colour in the usual sense but being due to a fluorescence induced by the ultra-violet component of daylight. It is usually the best diamonds which show this effect well. Stones which are flawless and limpid are said to be 'first water', a term the origin of which is not understood.

Consideration of the internal cleanness, that is freedom from flaws or inclusions, adds a further complexity to the sorter's task. There are so many ways of classifying diamonds into groups, differing in England as well as abroad, that enumeration of them would confuse the reader rather than assist. Anyway such grouping is the job of the diamond sorter.

The actual selling of the diamond rough, as the mined crystals are called, is, in London, carried out by the Diamond Trading Company holding 'sights' once a month. The graded and valued diamonds are made up into parcels of shapes, sizes and other grades, ready for the sights. The procedure at the sights is something of a ritual. Clients are shown into the buying rooms and the buyer or his broker will then be offered, in accordance with his application, 'a parcel of goods' as it is termed. Generally the parcel will consist of a collection of white papers (folded stone papers) each containing one or more of a particular category of stones – the whole being contained in a blue envelope. The buyer considers the parcel offered by selecting and examining several of the stones in a north light (which is best for colour appreciation). It must be appreciated that north light is only applicable to the northern hemisphere, for if the buyer is in a location south of the equator then south light is needed. The buyer must purchase the whole parcel and cannot pick and choose.

The rough crystals so purchased from the Diamond Trading Company are then fashioned into faceted stones suitable for mounting into jewellery, the brilliant cut being the best for showing to perfection the fire and brilliance of a diamond. The trap cut, usually in the so-called emerald-cut modification, is favoured for some diamonds, though such a style does not show the diamond's fire to the best advantage (*Figure 2.20*). The styles and methods of cutting diamonds are discussed in Chapter 21.

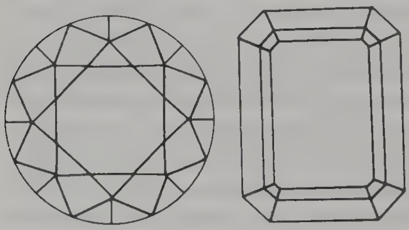

Figure 2.20 The brilliant cut (left) and the trap cut (emerald cut) (right) used for diamonds

The cut diamonds are then graded and valued, a slightly different scheme of classification being used for cut stones from that outlined above for the rough crystals. The classifications and values of cut diamonds are based upon the so-called 'four Cs', that is, colour, clarity, cut and carat, the last being the weight of the finished stone. A carat, which is one-fifth of a gram, is the weight used for diamonds and other gemstones.

The *colour* in this context implies not diamonds which have a definite colour – stones which are called 'fancy-coloured diamonds' – but those diamonds which appear white but which often have a faint tinge of yellow or brown. The hint of colour is often so slight that only a diamond expert could tell, and it certainly does not detract from the beauty of the stone. The diamond merchant uses various notations to classify diamonds; it may be by letters or numbers or certain trade and mine names. The so-called Jagers are the true blue-white or over-blue stones whose colour is due to their being very fluorescent. The scale then goes down to the Cape stones which have a trace of yellow or brown in them, and in the lower grades this is obvious.

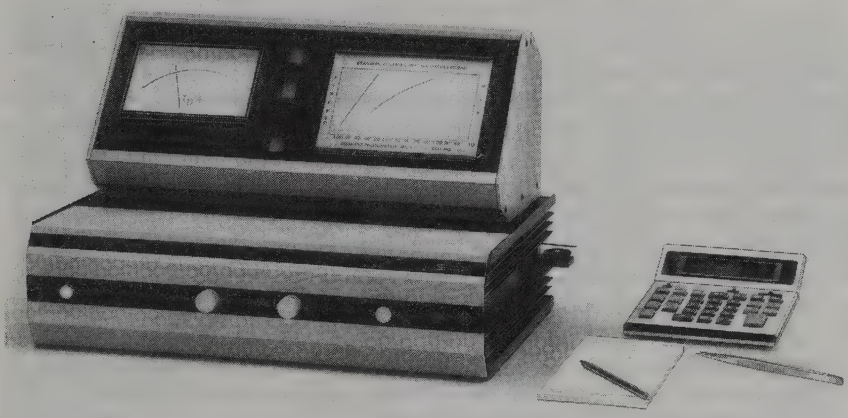

Figure 2.21 Diamond colorimeter (by courtesy of Eickhorst of Hamburg)

Many attempts have been made to standardise the colour grading of diamonds. The most successful seems to be the colour grading cabinets designed by the Gemological Institute of America and Eickhorst. These consist of a housing with a 'daylight' fluorescent lamp, the diamonds being laid on a small shelf and compared with a standard set of graded diamonds. There have been attempts to develop electronically controlled colorimeters: early models included two German instruments, which operate on the intensity of the 415.5 nm absorption line in Cape series diamonds, which Anderson had suggested was more intense the deeper the colour of the diamond (*Figure 2.21*). These instruments do not operate with some diamonds, including those of the brown series which do not have a 415.5 nm absorption line. More recently spectrophotometers have been introduced with computer programs which take into account all visible absorption characteristics. However, these are still in the evaluation stage and it is acknowledged that fluorescence characteristics are not accounted for by this method.

The *clarity*, or *cleanliness*, of a diamond depends on the included particles,

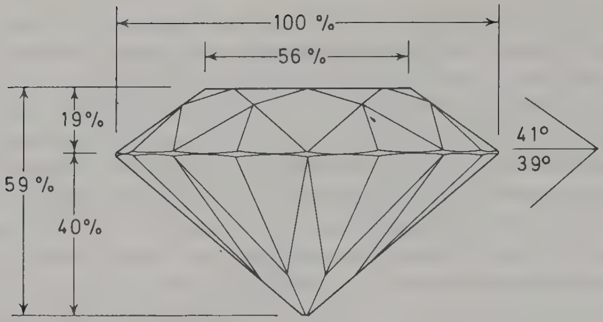

Figure 2.22 The correct proportions for a brilliant-cut diamond

cracks, etc., in the stone. Most diamonds contain minute imperfections included in them when they were formed by nature. When such imperfections do not materially interfere with the passage of light through the stone, they do not affect its beauty and have little effect on its value. A diamond is said to be 'clean' if no inclusions are visible to the trained eye when the diamond is examined under a colour corrected lens magnifying ten times. Breathing on the diamond will often allow a better view of the colour.

The clarity, often called *purity*, of a cut diamond may be classified, as in the case of colour, in a number of different ways.

The *cut* or, as it often called, the *make* of a diamond depends upon the proper proportions of the cut stone and upon the accurate alignment of the facet edges. A well-proportioned diamond should have, in order to throw back all the light entering from the front, proportions as near as possible to those shown in *Figure 2.22*, where the diameter of the stone is reckoned as 100 per cent. Any surface blemishes on the stone would detract from the make of the stone. There is no classification of make. A diamond proportion gauge produced by the Gemological Institute of America, based on the optical profilometer used in industry, is used to check and measure the depth and angles of cut stones, and the use of a spotlight will allow reflections from the facets of a diamond to show on a screen and provide a guide to the symmetry of the cutting.

Grading Cut Diamonds for Colour and Purity

Partly due to the rapid growth of investment buying of diamonds by those in search of financial security there has in recent years been an ever-increasing demand on the part of diamond purchasers for some form of written guarantee of the quality of the stones in which they have invested. There are indeed sound reasons for taking precautionary measures before purchasing an important diamond since the layman is quite incapable of appraising small differences in the colour, purity and cutting between two diamonds of the same size, even though after expert grading one may prove to have a market value twice as high as the other.

The Gemological Institute of America (GIA) was a successful pioneer in this field, and their certificates are sought after and accepted throughout the diamond markets of the world. In 1969, after lengthy and thorough preparative work particularly in the field of inclusions in diamond, the Scandinavian countries, led by Herbert Tillander of Helsinki, evolved their own classification scheme under the title 'Scan DN', which has been received with the respect it deserves. Very late in the day, after previously having opposed the issue of diamond certificates by laboratories, The European Jewellers' Organisation, CIBJO, decided to issue its own rules for the classification of diamond colour, clarity and cut based on measurements and observations made in a manner approved by the organisation. Very sensibly, the colour grading used corresponds exactly with that employed by the GIA, though the nomenclature is different. It was further decided that the issue of certificates should be carried out only by independent trade laboratories approved by CIBJO. The system used by the International Diamond Council (IDC) is also aligned with the GIA colour grades and uses a nomenclature the same as that of CIBJO. The system is used by the HRD laboratory in Belgium.

The certificate is completed with statements as to the exact weight in carats to two places of decimals, the style of cutting, dimensions in millimetres, height and width of the table, symmetry and polish, thickness and finish of the girdle, and ultra-violet fluorescence.

On each certificate are printed diagrams of the cut of the stone as seen from the crown and from the pavilion, enabling the grader to mark the position of any defects. The grader in each case retains a record of any extra details concerning the stone which may in the future if necessary aid in its identification.

Colour Grading

The grading of colour is carried out by direct comparison with one of a series of carefully selected 'masterstones', seven in number in the case of the CIBJO laboratories, which are issued to each officially accredited laboratory. In Great Britain this is the Gem-Testing Laboratory.

Comparison is carried out under standardised lighting conditions. Although the nomenclature used to describe the various grades differs in each of the four main systems (GIA, Scan DN, IDC and CIBJO) the actual grades are identical. The GIA uses a simple series of letters of the alphabet in which D represents the top grade; the Scan DN system employs terms derived from time-honoured trade practice, 'river', 'top Wesselton', etc.; whilst CIBJO recommends descriptive colour terms, of which the top grade is 'exceptional white +'. The American Gem Society (AGS) – founded by Robert Shipley Snr in 1934, three years after he founded the GIA – uses a numerical code. In carrying out a comparison between the stone under test and the masterstones, the ruling is that where no difference can be detected between the stone tested and a masterstone that colour is conclusive; but if the colour of the stone tested lies between those of two masterstones the colour of the darker masterstone shall be held conclusive.

A comparison between all the main systems for colour grading diamond at present in use is shown in *Table 2.2*.

Table 2.2
Colour grading standards for polished diamonds

UK	*Scan DN*	*GIA*	*AGS*	*CIBJO/ IDC*
Finest white	River	D	0	Exceptional white +
		E	1	Exceptional white
Fine white	Top Wesselton	F	2	Rare white +
		G		Rare white
White	Wesselton	H	3	White
Commercial white	Top crystal	I	4	Slightly tinted white
Top silver cape	Crystal	J	5	
Silver Cape	Top Cape	K		Tinted white
		L	6	
Light Cape	Cape	M	7	Tinted colour
		N		
Cape		O	8	
		P		
		Q		
		R	9–10	
Dark Cape	Yellow	S–Z		

The masterstones are chosen as representing grades in the depth of the yellowish tint most commonly seen in gem diamonds. Where brownish stones are encountered the nearest match in depth of tint to a masterstone must be decided upon, while stones which have a distinct colour are termed 'fancy-coloured' and separately described.

Fluorescence presents another problem in colour grading, since a highly fluorescent stone may give an unduly favourable conception of its body colour when viewed, for example, in sunlight, which will stimulate its fluorescent power. As an initial precaution the special standard lighting used in the colour grading arrangements is designed to contain a minimum of ultra-violet rays. In addition, the strength of fluorescence as displayed under long-wave ultra-violet light is recorded as being none, slight, medium or strong. The stones graded are placed table-facet down and are viewed parallel to the girdle in several orientations.

Purity Grading

For purity grading, the system of abbreviated symbols which has been understood and applied by diamond dealers for many years has been adhered to, but with an attempt to ensure that each such descriptive term should be made to apply so far as possible to a universally agreed standard. To assist in the understanding of each term more clearly than can be achieved by words alone, Herbert Tillander organised a series of photographs and also line diagrams of standard brilliant cut marked with defects in illustration of each grade. These are to be found in Eric Bruton's valuable book *Diamonds* together with an in-depth discussion of the whole grading process.

The terms used in purity or clarity grading are as given below, it being understood that the diamond has been examined with a 10 × achromatic aplanatic lens (loupe, from the French for magnifying glass) in normal light by an experienced professional grader:

Flawless	Free from internal and external characteristics.
Internally flawless	Free from internal characteristics; only possesses external characteristics.
Loupe clean (LC)	Absolutely transparent and free of inclusions.
VVS1/VVS2	Very very small inclusion or inclusions, extremely hard to find with a 10 × loupe.
VS1/VS2	Very small inclusion or inclusions, hardly to be found with a 10 × loupe.
SI1/SI2	Small inclusions, easy to find with a 10 × loupe, not visible with naked eye through the crown.
P1	Piqué. Inclusion(s) immediately visible with 10 × loupe. Difficult to find with naked eye through crown side, and not impairing the brilliancy.
P2	Large and/or numerous inclusions easily visible to the naked eye through the crown side and which slightly reduce the brilliancy of the diamond.
P3	Large and/or numerous inclusions very easily visible with the naked eye through the crown side and which reduce the brilliancy of the diamond.

A modern practice is to render black inclusions in a diamond less visible. This is carried out by drilling a very small hole down to the inclusion with a laser beam and then decolouring the inclusion with acid introduced down the hole. It is only done with low-grade stones. This laser channel is only five-thousandths of an inch in diameter and often cannot be seen with a lens (*Figure 2.23*). Special low-power binocular microscopes, often fitted with dark-field illuminators, which may make detection of inclusions easier, are made for the examination of diamonds (*Figure 2.24*).

A more recent treatment is to fill fractures in diamonds with a glass that has a similar refractive index to that of the host. This treatment, which was developed in Israel, may be identified by observing the alternate colour flashes from within the treated area as the stone is turned. A fractured diamond before and after treatment can be seen in *Figure 2.25*.

Figure 2.23 Two laser drill holes (reflected between facets) reaching inclusions within a diamond (courtesy GIA)

Industrial and Scientific Uses

The use of diamond for industrial and scientific purposes is increasing year by year as newer and often unusual needs for this hard material become available. The earliest use of diamond in industry was as an abrasive powder, and in many ways this is still the most important. Small and badly coloured diamonds and those of low grade structurally, collectively called bort (boort, boart or bortz), are crushed in a steel mortar to produce a powder which is used to charge the saws and laps used in the polishing of gem diamonds and other materials. The powder is produced in a variety of grades from coarse (80–120 mesh per linear inch) through medium (150–200 mesh) to fine (300–400 mesh). Finer 'diamond dust' is graded into 'subsieve' sizes of 20 microns (a micrometre or micron is one-thousandth of a millimetre) down to as small as two or even one micron. Sets of phosphor-bronze wire sieves are used for grading the diamond powder, the finest sieve retaining particles of over about 400 mesh. Subsieve sizes are prepared by either air sifting, centrifuging, elutriating (grading particles by means of an upward current in a liquid), or setting in oil (sedimentation). The diamond powder may be used as a paste in oil, rolled into metal, or bonded by sintering into metal or carbide wheels or shaped pieces.

The use of diamonds for rock drilling, which has so improved geological prospecting and mining, is said to date from 1863 when the diamond drill was first used by Professor Leschot. The cutting head of these tube drills by which a core is drilled out from the rock is set with suitable diamonds. Carbonado, or 'carbons' as they are called, were formerly used for rock drills but as they have become very scarce suitable industrial-grade diamonds are now used. Ballas, a

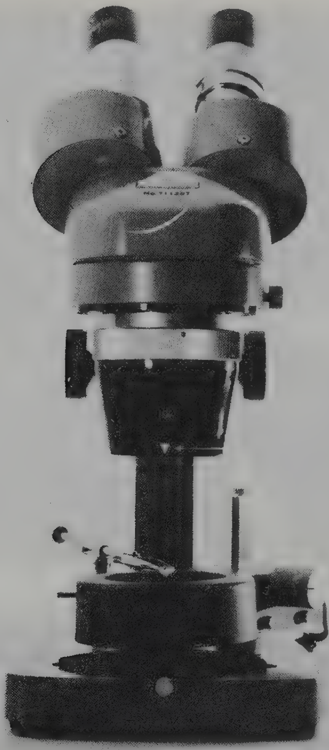

Figure 2.24 A microscope with dark-field illumination for use in diamond examination (by courtesy of Eickhorst of Hamburg)

multicrystalline diamond with the crystallites arranged radially producing a rounded form (shot ballas), has, like carbonado, no cleavage and therefore has a great resistance to abrasion and thus is suitable for rock drills. Ballas is an exceedingly scarce form of diamond and is found in Brazil and in the Jagersfontein and Premier mines of South Africa.

The diamond-set glass cutters, called vitriers, used by glaziers incorporate octahedral-shaped crystals, from 10 to 60 per carat in size, set into the face of the working end of the tool at a correct angle so that the edge and tip of the octahedron perform the cutting action. Small diamond crystals, chips from the fashioning of larger diamonds, called splints, or small diamonds ground to the shape of a cone and mounted in a suitable penholder-shaped metal grip, are used to 'etch' on glass or metal. Such tools are termed 'writing' or 'pencil' diamonds. Fine metal wires, such as those used for the filaments of the electric lamps, are drawn to a small diameter by pulling the wire through diamond drawing dies. Industrial-type diamonds are set staggered fashion across the cutting edge of circular or reciprocating saws used in the cutting of building stones.

A diamond set in a suitable steel holder is used for the truing of abrasive wheels used in the metal industries. Diamond-tipped turning tools, using single

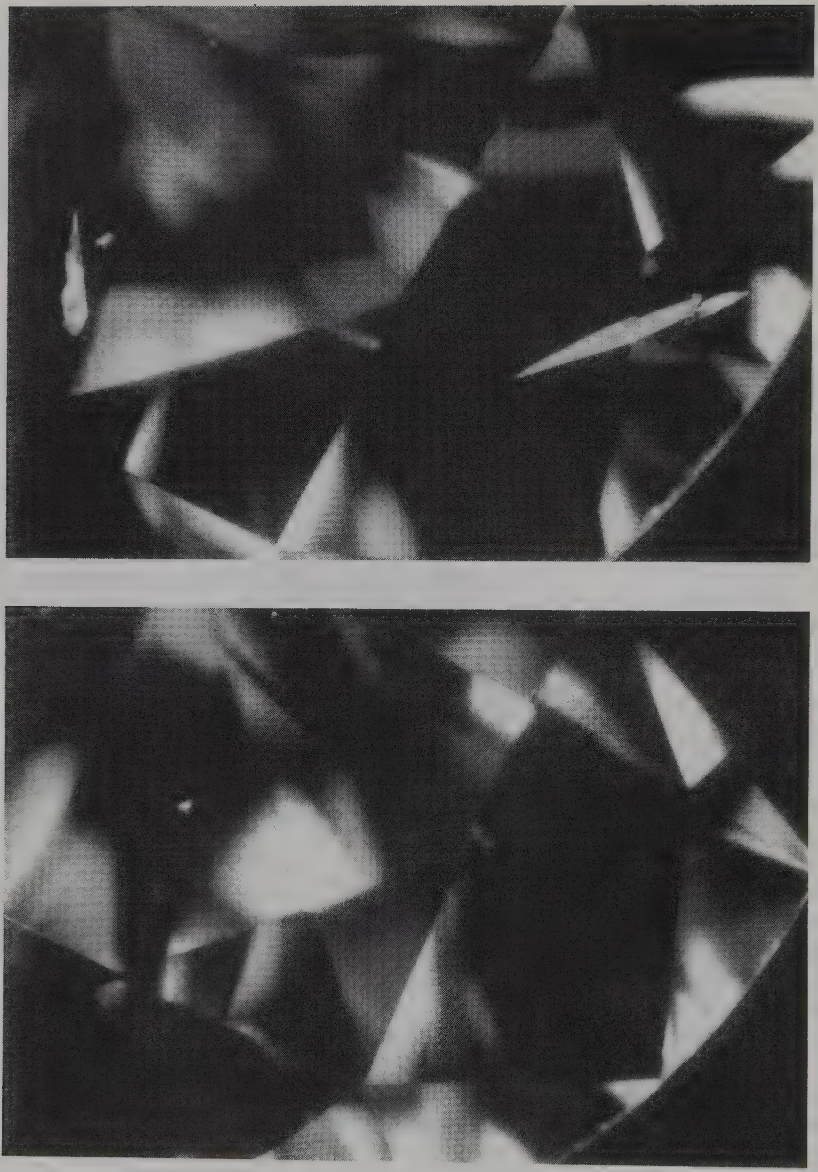

Figure 2.25 Two fractures reaching the surface on the crown of a diamond. Top: Before fracture filling. Bottom: After treatment

shaped and polished diamonds, are used in lathes for the turning of non-ferrous metals and plastic materials, and suitably shaped and polished diamonds are used in many of the modern indenter hardness testers. A diamond of similar type to that used for wire drawing is made use of as the orifice of pressure-type oil burners of boiler furnaces. The resistance of diamond to abrasion and the action of acid avoids the increase in diameter leading to wasteful consumption of fuel, through the grit and acid contained in the oil. Ordinary orifices of metal will not stand up to such abrasion and chemical action as does the diamond. Some diamonds behave as a radiation counter – like a Geiger counter – and the suggestion is made that this type of counter might be of exceptional advantage in certain types of medicine.

Chemical and Physical Properties

The atomic structure of diamond is of considerable interest, for each carbon atom lies at the centre of a regular tetrahedron and is joined to four other carbon atoms which lie at the corners of the tetrahedon. The structure is therefore a system of interlacing hexagons with each atom linked (covalently) to four others (*Figure 2.26*). It is owing to the nearness of the atoms, 1.54 ångströms (1 Å equals 0.10 nm), and the fact that the whole crystal is in effect one molecule, that any breakdown of the structure involves the breaking of the strong atomic bonds. Hence the chemical stability and the hardness of diamond, the hardest mineral known, with a value of 10 on Mohs's scale of hardness. The Mohs scale is based on one mineral scratching another and does not show the great difference in the hardness of diamond. *Figure 2.27*, showing the Mohs hardness against the Knoop indenter hardness number for a variety of gemstones, and two of the diamond simulants, illustrates the great hardness of diamond.

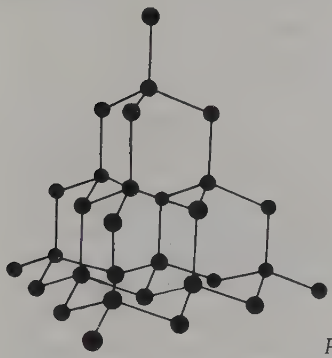

Figure 2.26 The atomic structure of diamond. A trigonal axis is vertical

Despite its hardness diamond has four directions of weakness along which the crystal will split fairly easily leaving smooth surfaces. The cleavage, as this effect is termed, is, in the case of diamond, parallel to the faces of the octahedron. In such a direction the atomic bonds are fewer than in other directions, and hence the cohesion is weaker along these planes. *Figure 2.28* illustrates the cleavage of diamond. Cleavage is of value in the fashioning of diamonds for it enables large crystals to be divided easily by splitting them along the cleavage direction. On the other hand, cleavage may be a

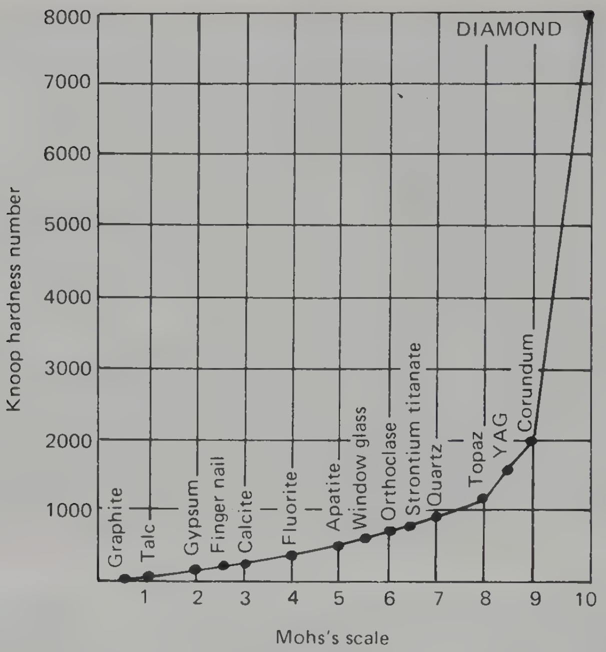

Figure 2.27 Diamond is the hardest substance known to man, natural or synthetic. The old Mohs's scale gives no idea of relative hardness, so it is here compared with an indentation hardness scale (by courtesy of The Retail Jeweller)

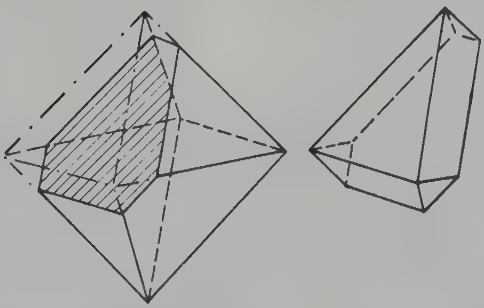

Figure 2.28 Cleavage of a diamond octahedron showing the cleaved piece removed

disadvantage in that a cut stone if inadvertently knocked along a cleavage direction may develop flaws or even split in two. Such a mishap, however, is rare.

The specific gravity (SG) of diamond is 3.515 and owing to the purity of the crystals it varies little from this value. The exception is in the case of the crypto-crystalline variety known as carbonado which can have much lower

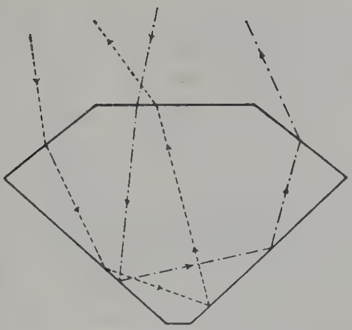

Figure 2.29 *The paths of a ray of light passing through a diamond. This shows the returning of those rays which enter at the front by total internal reflection at the back facets*

values of SG; values from 3.5 to as low as 2.9 have been recorded for this material.

Effects of Light on Diamond

Optical Properties

What causes the estimable brilliancy of a diamond? The answer lies in certain optical properties inherent in diamond, the first of which is the adamantine lustre due to the combined effect of the high polish the gem will take and the quality of the light reflected from its surface. The second cause is the ability of a well-cut diamond to return a ray of light which enters it from the front. A ray of light entering a diamond is bent – refraction as it is called. The measure of this bending is known as the refractive index, and is for diamond 2.417 (for yellow light) as against unity for air. Further, owing to the relatively high refractive index the rays are 'totally reflected' from the surfaces of the rear facets and returned through the front of the diamond. *Figure 2.29* illustrates this effect.

The third optical effect which makes diamond so attractive lies in the 'fire' exhibited by the stone. Fire, scientifically known as dispersion, is the breaking up of white light entering the stone into the spectrum colours, and in the case of diamond this is pronounced. The effect is caused by the differing amount of bending suffered by each of the different-coloured light rays which collectively make up the white light entering the stone. Hence, diamond will have a different refractive index for each coloured ray, each of which must, of course, take a slightly different path through the stone. In diamond the red ray (with a wavelength of 687 nm) has an refractive index of 2.407; the violet ray (wavelength of 397 nm) has an index of 2.465. The violet ray is always bent more than the other colours of the spectrum when entering an opticaly denser substance. A measure of the dispersion is the difference between the refractive indices of the red and blue rays. In general the dispersion of gemstones is measured by the difference in refractive index of the stone for the red ray (687 nm), which is the B line of Fraunhofer's solar spectrum, and the Fraunhofer G line in the blue at 430.8 nm. This gives the dispersion of diamond as 0.044. The dispersion of the light rays through a well-proportioned brilliant is

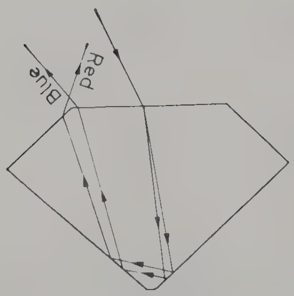

Figure 2.30 The paths of different-coloured rays of white light through a diamond. This shows the splitting up of the light by dispersion which gives the fire to a stone

illustrated in *Figure 2.30*. It is this play of spectrum colours flashing out which makes diamond such a beautiful gemstone.

Absorption Spectra

Visible light which has passed through a diamond, if examined carefully with a spectroscope (an instrument which analyses light into the spectrum colours), will often show dark lines obliterating certain parts of the spectrum. As will be explained in Chapter 33, such absorption bands are distinctive for many coloured varieties of other gemstones and provide a means of testing them. This is so in the case of diamond, but a diamond, unlike other gems where the absorption spectra are due to chemical elements in the stone, either fundamentally as in the chemical composition or as an impurity, owes these absorption lines to the crystalline structure, or to faults in the structure of the crystal.

Before enumerating the absorption spectra of diamond it may be an advantage to describe another phenomenon, that of photoluminescence (fluorescence), for this effect and the absorption lines have some definite relationship. Photoluminescence may be explained as the emission of a visible glow of light when the stone is bathed in a beam of invisible ultra-violet light, cathode rays, or X-rays. It is the effect seen when diamonds are bathed in the so-called long-wave ultra-violet light that has the greatest interest with regard to the 'tie-up' with the absorption spectra.

The absorption spectra of most diamonds, according to early work by Anderson, may be divided into two main groups. These are, first, diamonds of the Cape series, stones which fluoresce with a blue light and have body colours which vary from colourless to yellow. In this group the strongest absorption line is one at 415 nm in the violet part of the spectrum, a line first observed by Walter in 1891. This line varies in strength with the depth of the body colour but is nearly always present even in colourless diamonds. When this line is strong other lines are associated with it at 478, 465, 452, 435 and 423 nm, all of which are in the blue and violet parts of the spectrum. Of these only that at 478 nm is readily visible.

The second group consists of those diamonds which have a brown, greenish-yellow or green body colour, and which exhibit a green glow under ultra-violet light. Such stones show an absorption spectrum whose prominent line is a narrow one at 503 nm in the green of the spectrum. Other weak lines at

537 and 495 nm may be present. Diamonds showing both blue and green fluorescence are not uncommon and in such cases the 415 nm line will also be seen.

There are also certain colourless, bright yellow and brownish-yellow diamonds which show a yellow fluorescent glow under ultra-violet light. In these stones no discrete bands are observed at room temperature except for, maybe, a weak line at 415 nm. Blue (type IIb) diamonds absorb slightly in the red which is difficult to observe with the hand spectroscope.

It is not uncommon to observe the fluorescent glow in diamond to be localised in bands or zones, generally with some reference to the crystal form. It is of interest to note that when a strong blue fluorescence is shown, this glow when examined by a spectroscope is found to be banded.

Ultra-Violet Rays

Under the long-wave ultra-violet rays (emission at 365 nm) the glows exhibited by diamond, as mentioned above, may be a blue, a green or a yellow, although a reddish glow may occasionally be observed. The blue fluorescence may vary widely in intensity and in shade of hue from a very weak, practically indiscernible, mauve glow to a particularly bright sky-blue fluorescence, and likewise the strength of the glows of other colours can vary also. This unpredictable response of diamond to excitation by long-wave ultra-violet light has been found by Webster to have a practical application as a means of identifying a multi-stone piece of diamond jewellery. If the glows of the stones are photographed the pattern of differential luminosities forms an identity certificate for the piece (*Figure 2.31*), for even if a facsimile piece of jewellery was made up it would be outside the bounds of probability that the stones in the new piece would fluoresce similarly.

Several ingenious suggestions have been made, and some have been put into practice, to enable the identity of an individual important diamond to be established in the event of its being stolen and later recovered. It can be presumed that a record has been kept of the exact weight and dimensions of such a stone but something more definitive is greatly to be preferred.

One of the methods which has been put into practice is that of the 'Gemprint', which was developed at the Weiszmann Institute of Science in Israel and is commercially available through Gemprint Ltd of Chicago. This employs a low-power laser beam which is focused by a lens on to a pinhole in a screen and thence through a collimating lens on to the table facet of the diamond in question. This is fixed in an adjustable holder and is critically positioned in such fashion that the reflection from the table facet returns through the pinhole, thus establishing a unique position for the specimen. A pattern of tiny spots due to the reflection and refraction of rays from the various facets is then recorded on a Polaroid film and is found to be unique for every specimen, and incidentally establishes the stone as diamond as each substitute material yields a different and distinctive effect. The Gemprint firm keeps a central register of every diamond recorded by this system.

Another identification technique was perfected by the now defunct Okuda Company of Tokyo. In this an individual code was printed on the table facet of the diamond concerned which included the specimen's colour and clarity grades

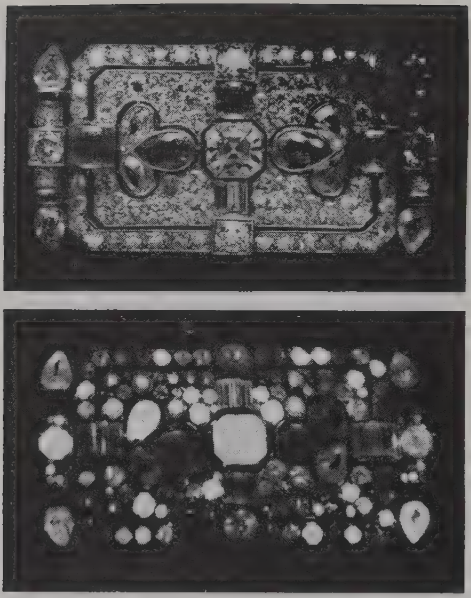

Figure 2.31 A diamond ornament in ordinary light (top), and the same piece taken when the diamonds were fluorescing under ultra-violet light. The differential effect may be used as an identity certificate

as well as its exact weight by a process which deposited the record on the stone in fused metallic letters and figures. This code was small and needed a magnification of 30 × to enable it to be read under the microscope.

If the diamond is recut after being stolen the above methods would lose their validity. Distinctive inclusions are hardly likely to be present in a fine diamond, but a possible scheme which would not be vitiated by a moderate degree of recutting would be to prepare a photographic record in colour of the pattern caused by strain birefringence when the diamond is viewed through the table and the girdle between crossed polarisers under some standard low magnification.

Many diamonds show an afterglow (phosphorescence) after exposure to ultra-violet light or sunlight, but what a given stone will do is unpredictable. Diamonds which show a bright blue glow do invariably, however, show a yellow afterglow varying in strength with the strength of the blue glow. This is an effect unique to diamond. Some pink diamonds show an orange fluorescence and a persistent orange phosphorescence. Anderson states that this glow when examined by a spectroscope will be seen to be discrete with a bright line at 575 nm and others with diminished strength at 586, 598, and 618 nm. The bright line at 575 nm is sometimes seen to be accompanied by an additional bright line at 537 nm. These latter have been seen, too, in diamonds coloured by atomic bombardment.

Under the short-wave ultra-violet light (emission 253 nm) the fluorescent effects are in general similar to those observed when the long-wave lamp is used, but the glows are very much weaker and in many cases not observable especially in the case of mauve fluorescing stones. Under X-rays most diamonds show a rather uniform bluish-white glow; the exceptions are those diamonds which show a yellow glow under ultra-violet light and show a similar glow under X-rays, but this is not always so. If a yellow and blue glow are present simultaneously the result will be a green glow.

It was found by Robertson, Fox and Martin in 1934 that certain diamonds were more transparent to ultra-violet light than others. They therefore classified diamonds into two types – type I and type II. Type I are transparent down to about 300 nm while type II are much more transparent and pass ultra-violet light down to about 225 nm. In 1952 Custers subdivided the type II diamonds into type IIa and type IIb. The type IIa are said not to phosphoresce when irradiated with short-wave ultra-violet light, while the type IIb when similarly irradiated show a bluish phosphorescence and will also conduct electricity. In these type IIb diamonds sometimes the afterglow is red, and this is so with the famous Hope blue diamond. The electrical effects shown by type IIb diamonds are due to the presence of boron atoms.

During 1959 Kaiser and Bond found the reason for the difference in the absorption of ultra-violet light to be due to free nitrogen in type I diamonds, and this type has been divided into two sections by Dyer and others in 1965): type Ia in which the nitrogen has been shown to be in groups of two or more atoms, and type Ib in which the nitrogen is dispersed in substitutional sites in a paramagnetic form. Any nitrogen in type II diamonds is in extremely low concentrations. There is some evidence that well-formed diamond crystals depend to some extent on the presence of nitrogen; and, further, it is noticeable that large diamonds which are found do not show any good crystal form and are almost surely type II diamonds.

X-Rays

The transparency of a substance to X-rays is a function of the atomic mass of the elements which make it up. The higher the atomic mass of the elements the less transparent it is to X-rays. Diamond is pure carbon (atomic mass 12) and is remarkably transparent to X-rays, whilst zircon which has the heavier zirconium atom (atomic mass 91) and silicon (atomic mass 28) and indeed all colourless stone and glass which simulate diamond are much more opaque to X-rays (*Figure 2.32*).

Flaws and Light

To be of the best quality, diamond must be clean, that is free from flaws and spots – inclusions as the gemmologist calls them. These imperfections may, however, be so small as to be undetectable under a lens magnifying ten diameters (the stone is then said to be flawless, internally flawless or loupe clean) or the flaws may be so obvious as to mar severely the beauty of the stone. Further, if just one large imperfection is in the wrong place in a cut diamond it may suffer reflection from all the back facets so that to the eye the stone may appear full of flaws.

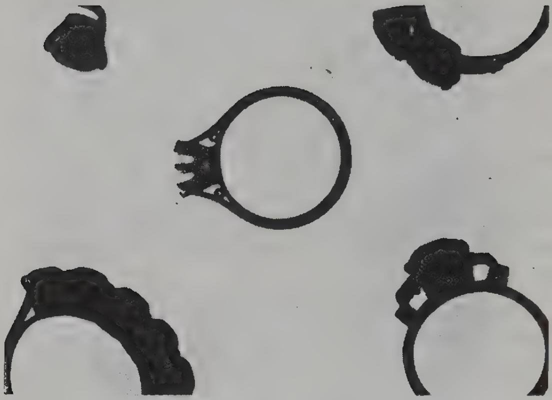

Figure 2.32 A radiograph of a diamond ring (centre), two zircon rings, a tie pin and a five-stone synthetic rutile ring showing the difference in transparency of the diamond

A most important study of the internal features of diamond has been made by Gübelin who has identified in diamond inclusions of graphite, hematite, magnetite, garnet, enstatite and zircon among others. Diamond itself is a common imperfection in diamond. Cleavage cracks and feathery marks often mar the transparency of diamonds, and both these and other otherwise clear inclusions may appear as black spots when seen at such an angle that light is totally reflected at their surfaces.

Artificial Coloration

The artificial coloration of diamond has attained some commercial importance owing to the colouring effect produced when the stone is bombarded with particles of atomic size. The production of a green colour in diamond by bombardment with radioactive particles from radium compounds has been known since early in the present century. Owing to the expense of the method and the ease with which such artificial coloration can be detected – for the stones themselves become radioactive from the treatment – 'radium-greened' diamonds are not commonly encountered. With the advance of atomic science since World War II other methods of colouring diamonds by particle bombardment, using modern high-voltage particle accelerators, have led to some commercialisation of artificially coloured diamonds.

Cyclotrons using protons (a particle in the nucleus of all atoms) and deuterons (the nucleus of the heavy hydrogen atom) produce in diamond a green colour, provided the heat generated by the impact of the particles is dissipated (usually by the use of a jet of liquid helium), otherwise a brown colour is produced. In any case a brown or yellow colour may be produced by subsequently heating the greened stones at a controlled temperature.

More recently a similar type of coloration has been produced by using neutrons (uncharged particles in the nucleus of most atoms) generated in an atomic reactor (atomic pile), and such artificial coloration of diamond is now carried out commercially both in Great Britain and in the United States of America. The diamonds come from the pile green in colour and can be altered to brown or yellow by subsequent heating under controlled conditions. Unlike 'cyclotroned' diamonds in which the colour is little more than skin deep, the 'piled' diamonds are coloured throughout.

By the use of electrons (the unit negatively charged particles planetary around the nucleus of all atoms) a light green or an aquamarine-blue colour has been induced in gem diamonds. More scientific information on bombarded diamonds will be given in Chapter 31.

A type of colour alteration sometimes practised, usually for fraudulent purposes, is to paint the rear facets of off-coloured yellowish diamonds in order to make them appear whiter. Scientifically it is well known that when two complementary colours mingle white is produced; it is this effect which is used in the whitening of diamonds. Off-coloured Cape diamonds are those usually experimented with. A film of blue or violet dye is put on the back facets of the stone: the blue (or violet) and the yellow colour of the stone combine to give a whiter effect. The film is so thin as not to be readily seen except where it has caught up on the raw edge (the unpolished girdle or setting edge of the stone). As the treatment is usually carried out by using a water-soluble dye, a thorough washing in hot water will dissolve the colour and unmask the fake. Should a coloured lacquer be used solvents such as acetone or amyl acetate, or even acid, may be needed to remove the colour. Similarly pink diamonds have been imitated by painting the back facets with a pink dye or enamel.

Synthesis and Simulation

For more than a hundred years some of the leading scientists of each generation made strenuous and ingenious endeavours to transform the soft black common forms of carbon (charcoal or graphite) into its intensely hard transparent form of diamond. A number of these early workers quite honestly believed that they had achieved that goal, but in no case were these claims substantiated when the processes involved were repeated by other workers.

The first published announcement of a repeatable method for making diamond came from a team working for the General Electric Company of America. This was in February 1955. Some months later workers in the big Swedish electrical firm ASEA claimed that they had succeeded in making synthetic diamonds some time earlier but (since their target was for gem-quality stones) they had postponed publishing their results. Before long the general processes employed by the American team were being used by other companies, in particular by De Beers, and the synthetic grits produced eventually became equal in importance with those produced from natural diamonds of industrial quality.

The American team persevered in secret in improving their process and were able in 1970 to announce that they had succeeded in growing transparent diamond crystals of gem quality in a variety of colours and sizes large enough to be used in jewellery. The vast cost of production, however, made such stones more costly than those found in nature.

More recently the firm of Sumitomo in Japan started commercial production of gem-quality synthetic diamond in small sizes. However, the main market for these is in industry where they are used for heat sinks etc. De Beers have now produced large synthetic diamond crystals and many of these have been cut into fine stones, but no commercial gem-quality production is envisaged.

The subject of synthetic diamond will be dealt with in greater detail in Chapter 18, which covers all forms of synthetic gemstones. For the present we will concern ourselves with the many past and present-day diamond simulants which may deceive the public or the unwary jeweller.

In the past, the natural gemstone most plausibly used to represent diamond was white zircon which, when well cut in brilliant style, displays a considerable amount of fire, while the highly refractive lead glass imitations known as 'paste' could be deceptive when fresh and unworn, though after wear they quickly become scratched and tarnished. When in any doubt the jeweller, before the days when he became trained in the use of non-destructive tests now available to gemmologists, used the destructive method of applying a hard file to distinguish paste from diamond, thus often ruining an attractive piece of jewellery. As for zircon, given a little scientific knowledge and the ability to use a 10 × pocket lens there is one feature which enables it to be distinguished from diamond quite easily. In diamond, as in all transparent materials crystallising in the cubic system, a ray of light entering the stone is refracted but passes through and emerges as a single ray (apart from the dispersion into spectrum colours which provides the fire). In zircon, on the other hand, which crystallises in the tetragonal system, there is only one direction, known as the optic axis, in which light passes through as a single ray. In all other directions it shows double refraction: i.e. it is split into two rays and produces *double* images of the back facet edges when viewed with a lens through the front of the stone (*Figure 2.33*). Owing to the extreme pressures under which it was formed, diamond, though a singly refracting mineral, shows what is termed 'strain birefringence' when examined between crossed polarisers, whereby patches of light and shadow are seen as the stone is turned. This is, in itself, a characteristic effect. As a further caution it should be said that a spurious 'doubling' of the back facet edges has sometimes been observed in diamonds which have been cut in the wrong proportions (*Figure 2.34*).

Since the 1930s the problem of distinguishing diamond from its simulants has become more and more acute owing to the production, one after another, of man-made stones which in some cases have optical properties rivalling diamond itself.

The first 'scare' (which seems absurd to us today) was raised by the emergence of synthetic white spinel (made from the Verneuil flame-fusion process) which had a brief but intense spell in the limelight when an enterprising jeweller named Jourado exploited well-cut and attractively mounted specimens for sale for which he made extravagant claims as to their similarity to diamond in cleverly worded advertisements. So effective was Jourado's campaign that the London Chamber of Commerce thought it wise to broadcast reassuring statements over the radio network! Synthetic white spinel has a limpid purity and takes an excellent polish, and it is still effectively used as a substitute for

Figure 2.33 Doubling of the back facets seen in a zircon. This is due to double refraction

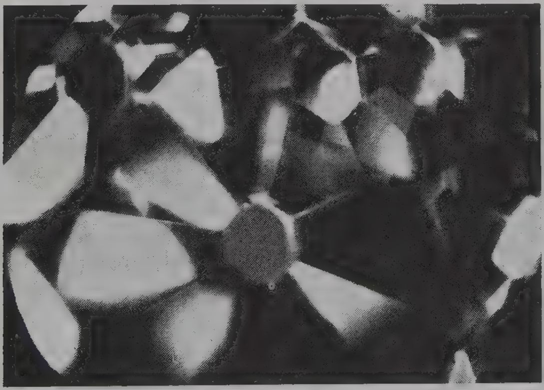

Figure 2.34 False doubling of the back facets seen in a badly cut diamond

small diamonds in multiple gem settings: moreover, it is singly refractive. But it gives a refractometer reading of 1.726, has a low degree of fire, and has a hardness of only 8 on Mohs's scale.

Since the Second World War there has been a succession of synthetically produced diamond substitutes (many of which do not occur in nature). These are briefly described here but are dealt with more thoroughly in Chapter 18, which deals with all types of synthetic gemstones.

Synthetic rutile (first produced by a modification of the Verneuil process in 1948) had a brief rise to fame. This had a yellowish body colour and, having six times the dispersion of diamond, exhibited a spectacular play of colours. It had very high refractive indices and a large double refraction which made it instantly recognisable by a gemmologist. In 1955 there followed strontium titanate ($SrTiO_3$). At that time this material was thought not to occur in nature; however, in 1987 grains of natural strontium titanate were found in the USSR and named tausonite. Synthetic strontium titanate was also made by an adaptation of the Verneuil process and posed the first serious problem as a diamond substitute even to a knowledgeable jeweller. The new material had a pure white colour, was singly refracting, and had a refractive index almost precisely the same as diamond for sodium light. However, the fire, which is four times that of diamond, gives warning to the experienced eye that the stone is not what it pretends to be, while for unmounted stones its high SG (5.13) is a revealing feature. The worst defect of strontium titanate (for which the names 'fabulite' and 'diagem' were coined) is its relatively low hardness, which is listed as 6.5 on Mohs's scale: moreover, it is somewhat brittle. Strontium titanate has no fluorescence under ultra-violet light, and often shows characteristic tiny 'centipede' surface markings on the pavilion facets.

The next serious claimant as a diamond substitute appeared in 1969 when a series of hard transparent synthetic stones having a garnet structure but containing no silica were developed, mostly by a technique of rotating and pulling a seed crystal in a melt, devised by Czochralski. One of these, popularly known as YAG (standing for yttrium aluminium garnet), was found to show the appearance of properties of a plausible diamond simulant, and was soon being manufactured on a very large scale. Two of the selling names adopted for this material were 'diamonair' and 'diamonique', but fortunately the general tendency in recent times has been to revert to more meaningful terms. The chief trouble with such obvious 'fancy' names is that they give the purchaser no clue as to the properties of the merchandise. To aid the reader in these matters, a glossary is provided amongst the appendices of this book. YAG has a cubic structure and resembles diamond in being isotropic. It has a refractive index of 1.834, which is too high to be measured on the standard refractometers, and its dispersion is 0.028, which, though lower than that of diamond, gives it a fair degree of fire when cut in the correct proportions, while its hardness is 8.5 on Mohs's scale which guarantees its excellent wearing properties. Another of the synthetic garnet series considered as a diamond substitute has been gadolinium gallium garnet, colloquially known as GGG. This has a high refractive index (1.97) and dispersion 0.0446 (on a par with that of diamond), but has been more written about than actually used.

In 1976 a new contender for the claim to be the most successful simulant of diamond made its appearance and its success has been phenomenal and is readily understood. This was synthetic cubic zirconia, at first marketed as 'phainite' or as 'djevalite', but now universally known by its correct name or abbreviated to CZ. In nature zirconium oxide is found in its stable monoclinic form as the mineral baddeleyite, but when combined with a proportion of some other oxide such as CaO or Y_2O_3 and fused at a very high temperature a stable cubic form can be induced to crystallise. The properties of CZ vary somewhat according to the stabilising oxide used, but can be broadly given as: hardness 8, SG 5.65, RI 2.15, and dispersion 0.060. The preparation and properties of all these diamond substitutes will be more fully discussed in Chapter 18.

The threat to jewellers of possible mistaken acceptance as true diamonds of some of the simulants mentioned above (especially since the advent of cubic zirconia) spurred the inventive powers of instrument makers to provide testing apparatus to aid the jeweller to distinguish quickly and with certainty between diamond and any of its substitutes, preferably without removing the stone from its setting and without risk of damage to the stone. A series of infra-red reflectivity meters appeared on the market in which the high reflectivity of a clean diamond surface enabled it to be distinguished at once from any of its rivals. More recently still the ingenious exploitation of another outstanding attribute of diamond, its high conductivity for heat, was made possible by means of a delicate probe. The use of these modern instruments is clearly explained in Chapter 32: meanwhile a brief run through of some of the more readily observed features by which diamond can be identified may prove useful.

The distinctive appearance of a well-cut diamond should be completely familiar to every jeweller. It is based on the effects of its adamantine lustre, the perfect flatness of its polished facets, giving undistorted reflections, and its fire, these in turn being the products of its incomparable hardness, its high refractive index and the skill with which it is cut. Examination of the girdle will often reveal 'naturals', i.e. parts of the original crystal deliberately left unpolished to act as a guide to the cutter (*Figure 2.35*), and if these show the typical 'trigons' common on an octahedral diamond surface this gives sure confirmation that the stone is diamond. Tiny 'nicks' in the girdle may also sometimes be detected, revealing signs of the octahedral cleavage of the mineral. When diamond is

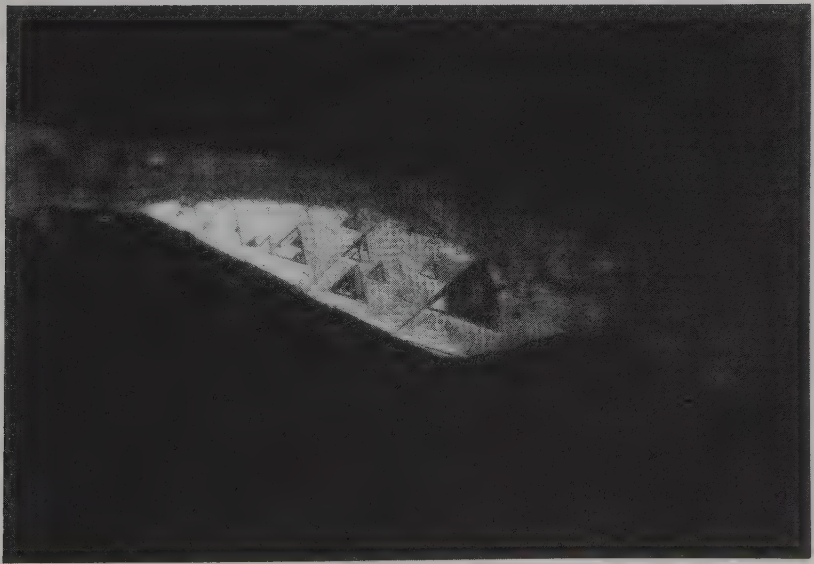

Figure 2.35 A 'natural' surface near the girdle of a faceted diamond (photomicrograph by John I Koivula, GIA Gem Trade Laboratory)

viewed with a lens between crossed polarisers there is seen a typical display of light and shadow due to 'strain birefringence'. Admittedly synthetic spinel may show a similar effect, but experience will enable the viewer to note a difference in the patterns shown. Under long-wave ultra-violet light diamonds will show a very varied degree of fluorescence. If all the 'diamonds' in a multi-stone setting show a similar fluorescence they are certainly not diamonds. Any diamond showing a bright blue fluorescence shows a yellow afterglow of short duration. To see this effect the diamond should be quickly removed from the rays and viewed within the darkness provided by cupped hands. This technique is worth practising as it is a decisive test. Under X-rays almost all diamonds show a blue fluorescence, and a brief exposure on film will show diamonds to be far more transparent to X-rays than any other gem.

Finally, a reminder that the unique hardness of diamond enables it to scratch a polished surface of synthetic corundum, whereas no substitute can do this. Unless great care is taken, however, the diamond itself may suffer some damage, and with so many other distinctive features to rely upon the hardness test must be considered as crude and seldom necessary.

In conclusion, one other diamond fake should be mentioned, though it is seldom encountered. This is a diamond doublet, in which the top half (crown) of the stone consists of diamond which is cemented on to a pavilion of some other colourless stone. When such stones are viewed obliquely through the table facet a shadow of the edges of the facet can be seen on the underlying cement layer, revealing the fraud. The photograph reproduced as *Figure 2.36* shows this effect very clearly.

A list is given in the appendices of the largest and most notable diamonds known at the present time.

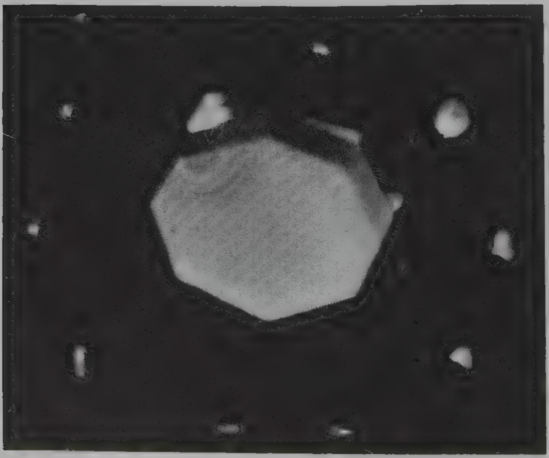

Figure 2.36 Reflection of the edges of the table facet on the cement layer seen in a diamond doublet

Special Methods for Differentiation between Diamond and its Imitations

The potential danger of confusion between diamond and its simulants became so much more apparent when cubic zirconia appeared on the market that a great stimulus was given for the production of special apparatus to make the distinction rapid and certain even in the case of mounted stones, and without involving more than a rudimentary knowledge of gemmology. The numerous examples of reflectance meters involving a beam of infra-red light appeared in good time to provide powerful aid of this kind, but since they have a more general application these are dealt with in a separate chapter (Chapter 32).

The most ingenious and effective specific means of differentiating diamond from all other gemstones makes use of one of its outstanding properties, its thermal conductivity, which is higher than for any other substance – higher even than for copper or silver. The Ceres Diamond Probe was the first to exploit this property in identifying diamond even with small specimens and (importantly) even in the case of mounted stones. The probe consists of two tiny ceramic thermistors (i.e. resistors which vary with temperature) mounted in a copper tip in a convenient holder. One thermistor acts as a miniature heating element which is charged by a battery, while the other measures the temperature of the probe. When the instrument is switched on the tip of the probe warms up in two or three seconds. If it is gently applied to the surface of the stone to be tested and this is highly conductive as in the case of diamond, the heat is carried away quickly and the other thermistor registers the fall in temperature: the needle of the instrument then swings to the right and a green light flashes. With any other stone the needle of the meter swings to the left and a red light flashes. The probe of the Ceres instrument is delicate and needs handling with care, but even very small stones can be checked for diamond with its aid.

As with most successful instruments, others of essentially the same kind were soon to make their appearance, amongst them the British-made Rayner Diamond Tester. In some cases there may be an improvement in the matter of robustness. To anyone handling diamond jewellery the high cost of such equipment is a matter of relatively small importance compared with the value of the goods tested.

Another property of diamond which has been exploited as a test is its affinity for grease or greasy liquids. The GIA made ingenious use of this in producing a Diamond Pen which was charged with a specially prepared liquid which left a coherent mark when drawn across the table facet of a diamond, but which broke up into droplets on the surface of all other stones.

The account of special apparatus included in this text is sufficiently comprehensive at the time of printing. The reader would be well advised to keep abreast of later developments by studying the relevant journals.

Immersion Contrast

When the most successful diamond simulants are immersed in a liquid of high refractive index such as pure methylene iodide (RI 1.742) or refractometer contact fluid (RI 1.81) all except strontium titanate show a dark ring diminishing in width as their refractive index approaches near to that of the liquid. This constitutes a convincing visual means of differentiation (*Figure 2.37*).

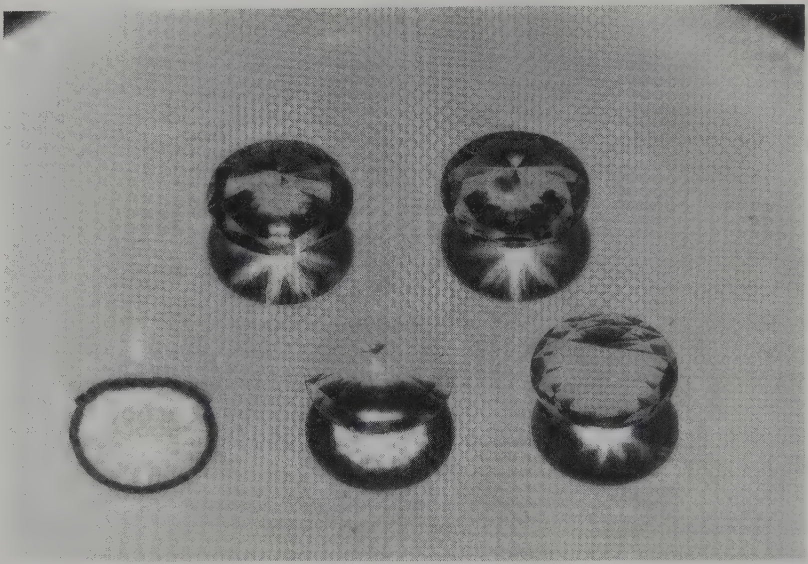

Figure 2.37 *When light is placed over stones immersed in di-iodomethane (methylene iodide), different stones show differing patterns: top row (left to right) strontium titanate, diamond, bottom row YAG, GGG, CZ (Courtesy GIA)*

3

Ruby and Sapphire*

Introduction

Varieties

It is difficult for the layman to believe that ruby, with its intense red colour, and the royal blue sapphire are the same mineral, composed of the gas oxygen and the light metal aluminium. Corundum, as this mineral is called, would if pure be perfectly colourless. Indeed some stones found in nature are practically colourless, but pure water-white stones are rare, a tinge of colour nearly always being present. The marvellous colours of ruby and sapphire are due to traces of one or more metallic oxides incorporated in the stone as impurities (a case where purity is not necessarily a virtue). Indeed, corundum may be found in many colours beside red and blue. Colourless (or white as it is often called), yellow, violet, green and even brown are common, and an attractive, though rather rare, orange colour may be met. The orange are sometimes called *padparadscha*, from the Sinhalese word for 'lotus flower', and fine pieces are quite valuable.

Asterism is common in corundum, and star-stones come in virtually all colours. Cat's-eye corundums are possible, but are extremely rare. Occasionally colour-changing sapphires are encountered. The best pieces are coloured by vanadium and change from a bluish-green in daylight to a purplish-red in incandescent light.

Origin of the Names

The names ruby and sapphire mean red and blue respectively; the first is derived from the Latin *ruber* and the second from *sapphirus*, the latter being derived from a Greek word of similar spelling. Similar words are found in Persian and Hebrew, and the primary derivation, though uncertain, may have been Sanskrit. The name corundum is derived from the Hindu word *kurand* or *kuruvinda*.

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*Revised by Richard W Hughes.

Legend and Lore

Ruby

The legend and lore of ruby and sapphire are quaint, like that of most gems. The lucky owner of a fine ruby was said to be assured of a life lived in peace and concord with all men; neither his land nor his rank would be taken from him, and his house and garden would be saved from damage by tempests.

According to the Judaeo-Christian view, ruby, the natal stone of July, is the most precious of the twelve stones God created when he created all creatures, and this Lord of Gems was placed on Aaron's neck by God's command.

The high esteem placed on ruby is further indicated by the names applied to it in Sanskrit. These were *ratnaraj*, which may be translated as King of Precious Stones, and *ratnanâyaka*, Leader of Precious Stones. The Hindu peoples described the glowing hue of the ruby as an inextinguishable fire which burned within the stone, and asserted that this inner fire could not be hidden and would shine through the clothing or any material wrapped around the stone. If placed in water, the inner heat would cause the liquid to boil.

Ruby was said to preserve the health of the wearer, for it removed evil thoughts. Although associated with passion, it was also thought to control amorous desires, to dispel pestilential vapours and reconcile disputes.

Some Indian beliefs were that making offerings of large rubies to the images of gods in worship of Krishna allowed rebirth as an emperor; offerings of smaller stones resulted, naturally enough, in a smaller reward, the rebirth as a king rather than emperor.

Rubies, and other red stones whose colour suggests blood, were thought to be a remedy for haemorrhage and inflammatory diseases. Such stones were believed to confer invulnerability from wounds. The Burmese believed that it was not sufficient to simply wear the stones: they must be inserted into the flesh and become, so to speak, part of the wearer's body. Doing this was thought to give protection against wounds of various kinds. Such beliefs persist in the orient to this day, but (thankfully for the wearer) usually take the form of an amulet worn around the neck or a tattoo on the body.

Sapphire

The gem of the soul and autumn, sapphire, the natal stone for September, was said to preserve the wearer from envy and to attract divine favour. Fraud was banished from its presence and necromancers honoured it more than any other stone, for it enabled them to hear and understand the most obscure oracles. The ancients thought sapphire to be endowed with the power to influence spirits, to be a charm against carnality, to be capable of making peace between foes and to protect its owner against captivity. The Sinhalese respect the star sapphire as protection against witchcraft.

Tradition is that the law given to Moses on the Mount was engraved on tablets of sapphire or perhaps lapis lazuli, but this seems unlikely owing to the lack of pieces of suitable size of either of these materials. The religious significance of sapphire was further enhanced in the twelfth century, when the Bishop of Rennes lavished encomiums upon the sapphire and began the use of this stone in ecclesiastical rings.

Rubies and Sapphires of Individuality

Because large rubies of fine quality are so incredibly scarce (large rubies of low quality are more common), there are few true rubies which have been named. Most famous 'rubies' of antiquity are in fact red spinels, such as the Black Prince's 'ruby', which graces the front of the Imperial State Crown, and the Timur 'ruby' which is also part of the Crown Jewels. The Persian and Russian crown jewels also have a number of fine large red spinels masquerading as rubies.

Among the notable true rubies are the Chhatrapati Manick ruby, an oval cabochon of ~40 carats, and the 43 carat Peace ruby, a crystal found in 1919. Unfortunately the Peace ruby did not live up to its potential after cutting. Another crystal, but not of top gem quality, is the 167 carat Edwardes ruby in the British Museum (Natural History Section), and the 100 carat De Long star ruby in the American Museum of Natural History. Apart from these, there are few rubies to which names have been applied. Probably the finest star ruby on public display is the Rosser Reeves ruby, at the Smithsonian. Weighing 138.7 carats, it was found in Sri Lanka. One of the finest faceted rubies in existence was the 15.97 carat stone formerly owned by Alan Caplan. In October 1988 this stone sold at Sotheby's New York for $3 630 000, a record price for ruby.

Among sapphires there are a number of fine stones, among them the St Edward's sapphire and the Stuart or Charles II's sapphire, both of which are companions to the Black Prince's ruby in the Imperial State Crown. The American gem dealer Harry Winston had, in his possession several lovely large sapphires, one the so-called Catherine the Great's sapphire and another gorgeous stone weighing 337.10 carats. In the American Museum of Natural History is a 536 carat star sapphire known as the Star of India and a smaller black star called the Midnight Star, weighing 116 carats. That sapphires can attain a large size is amply illustrated by the work of Norman Maness, who spent 1800 hours carving a 2302 carat sapphire into the form of the head of Abraham Lincoln.

Judging Quality of Rubies and Sapphires

Next to red diamonds, rubies are probably the most expensive gem in the world in sizes over three carats. The ideal for ruby is that of a red traffic signal, a highly fluorescent red of high intensity. Unlike diamond, small amounts of silk in a stone actually help the colour because they scatter light into areas it would not otherwise go. This helps cover up the extinction which would otherwise be found. Thai/Cambodian rubies suffer the double deficiency of too much iron, which cuts the fluorescence, and no silk to scatter light.

Top prices for blue sapphire are paid for stones of an intense blue verging on the violet. Large sapphires are more common than large rubies. Colour zoning can be a problem in sapphire: look for stones which have no major zoning problems. Many blue sapphires are too dark in colour, especially those from basalt sources such as Thailand and Australia. Such stones are generally inexpensive. Similarly, sapphires which are too light in colour are also inexpensive. The best stones are those which are well cut, eye clean and, most importantly, with intense blue colours. Orange sapphires should be rich in colour without blackish areas.

In star-stones, transparency is an important factor. Too much silk results in a lowering of colour intensity, because the length of light paths through the stone is reduced due to scattering off the silk. The ideal star-stone contains just enough silk to show a star, but not enough to cause the colour's intensity to be reduced. A stone can be expensive if its colour is good, *even if the star is poor*. In contrast, stones with sharp stars but poor colour are not valuable.

Chemistry and Crystallography

Chemical Composition

The mineral corundum is a crystallised form of aluminium oxide (Al_2O_3), traces of impurities modifying the water-white colour of the pure mineral. Ruby varies in shade from near colourless through pink through all shades of red to a deep crimson. All other colours are properly termed sapphire, with the colour prefix.

Coloration of Ruby

The colour of ruby is due to a trace of chromic oxide (Cr_2O_3), which enters the crystal structure by a small-scale replacement of some of the alumimium atoms. This is known as isomorphous replacement. The amount, about 1–3 per cent, determines the depth of colour, but the presence of iron in the ferric state (Fe_2O_3) also modifies the tint, reducing the fluorescence and giving to the rubies from Thailand the brownish tinge so typical of them. The finest rubies will be a strongly fluorescent red, resembling the colour of a red traffic signal. Such stones often contain extremely fine particles which serve to scatter light onto all facets and reduce extinction (facets which are dark). In the past in Myanmar (Burma), this colour was termed 'pigeon's blood', but the term has little meaning today as so few people have seen the blood of this Burmese bird.

Coloration of Sapphire

While there is evidence of two or more possible causes for the blue of sapphire, the colour of most apparently results from a combination of iron and titanium, where they have replaced aluminium in the corundum structure. In a process termed molecular charge transfer, an electron temporarily jumps from an atom of iron to a neighbouring titanium atom, absorbing light in the process. The temporary reaction can be written as follows: $Fe^{2+} + Ti^{4+} \rightarrow Fe^{3+} + Ti^{3+}$. While titanium apparently always occurs as Ti^{4+}, iron may occur in either *ferrous* (Fe^{2+}) or *ferric* (Fe^{3+}) states. Ferrous iron is necessary to initiate the charge-transfer reaction, and can be obtained by heating in a reducing atmosphere, while the Ti^{4+} needed can be obtained via heat-induced diffusion from exsolved rutile (TiO_2). These facts are crucial in corundum heat treatments.

The coloration of yellow sapphire is more complex. In some it may arise from oxygen→metal charge transfers ($O \rightarrow Fe^{3+}$), or ion pair transitions on individual ions of a pair (Fe^{3+} Fe^{3+}). In others, it apparently results from colour centres. Green results from a mixture of yellow and blue; orange is a mixture of red and yellow; violet a mixture of red and blue. The dark brown colour of black star sapphires results from the dark colour of exsolved hematite.

Crystallography of Corundum

Corundum crystallises in the trigonal crystal system, but the habit or shape varies greatly with a change in locality and/or colour. Three shapes are common, as follows (see *Figure 3.1*):

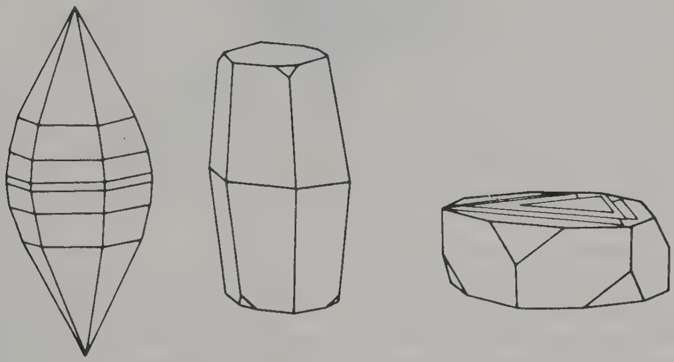

Figure 3.1 Some habits of corundum crystals

1. Spindle-shaped bipyramids (common to sapphire and some ruby).
2. Columnar hexagonal prisms (common to sapphire and some ruby).
3. Tabular prism/rhombohedron combinations (common to mostly ruby).

Combinations of any of these three main habits are also possible.

Ruby crystals often show a different habit from that of sapphires. Rubies from Myanmar (Burma) may show a hexagonal prism terminated at both ends by a basal pinacoid, with rhombohedral faces at alternate corners. These rhombohedral faces may be more or less developed or entirely absent, especially in the large, and usually opaque, crystals from Tanzania and Madagascar. In many ruby crystals the prisms are flattened and, although they may be of large diameter, are relatively thin. Such crystals often exhibit a stepped or platy appearance, as though the crystal was composed of a number of thin plates. Basal planes of many crystals are traversed in three directions by fine parallel striations, which take the form of hair-like lines crossing at angles of 60/120°, dividing the area into small triangles.

Sapphire (and some ruby) takes the form of a hexagonal bipyramid of twelve triangular faces, six above and six below, meeting at a girdle. This habit may occur in combinations of bipyramids of different inclinations, with the girdle sometimes formed by a narrow hexagonal prism. The ends of many bipyramidal crystals are capped by the flat basal face and such forms are aptly

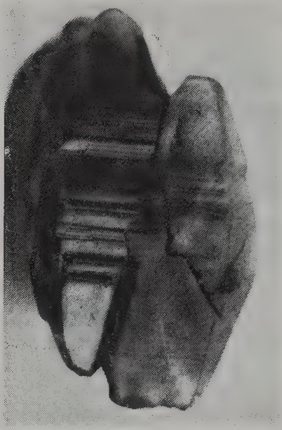

Figure 3.2 Crystals of sapphire from Sri Lanka (parallel group)

described as having a barrel-shaped habit. The hexagonal bipyramidal habit is common in the sapphire crystals from Sri Lanka (see *Figure 3.2*), and in this form the faces are often deeply striated horizontally, owing to repeated oscillation between different pyramids or between the pyramid and the basal pinacoid. Sapphires from Yogo Gulch, Montana in the US tend to take a tabular habit.

Physical Properties

Specific Gravity

The specific gravity (SG) of the purest corundum, the synthetic colourless sapphire, is 3.989, but the natural ruby and sapphire usually have SGs approximating to 3.997, there being little variation for specimens from different localities. An exception is the iron-rich yellow, green and blue-green sapphires (from Australia, Thailand, etc.), which may have SGs as high as 4.00.

Hardness, Fracture, Cleavage and Parting

Corundum is a hard stone, rating 9 on the scale of hardness devised by Mohs. Indeed the impure material (emery) is used as an abrasive. Despite the hardness of the mineral, ruby and sapphire need to be handled with some care, for they are slightly brittle and if dropped on a hard surface or given a sharp blow tend to develop internal flaws and cracks. The type of fracture seen when corundum is broken varies from uneven to conchoidal.

There is no true cleavage in corundum, but a parting (false cleavage) may be present. This occurs parallel to the basal plane or to the rhombohedral faces of the crystal, and results from a lack of adhesion due to exsolution of thin planes of hematite (basal) or boehmite (rhombohedral).

Effects of light

Refraction

Unlike cubic or amorphous minerals, a ray of light entering a crystal of the trigonal system (such as ruby and sapphire) in directions other than the *c*-axis breaks into two rays. This double refraction may cause the edges of the rear facets to appear slightly doubled. Like all minerals of the tetragonal, hexagonal and trigonal systems, there is only one optic axis (direction of single refraction) in corundum. Thus corundum is uniaxial.

In corundum there will be two indices of refraction. The ordinary ray has a constant value (usually ~ 1.7687 in pure material), while the extraordinary ray has a value varying between 1.7606 and 1.7687. Natural corundums do not vary much from these values, except in the case of the iron-rich yellow, green and blue stones which may reach values of 1.78 and 1.77. Since the ordinary ray is the high value, corundum is negative in sign.

The maximum difference between the RI of the ordinary ray and that of the extraordinary ray is termed the birefringence. Corundum has a birefringence of 0.008 (a fuller explanation of the optics of gem materials will be given in Chapter 32).

Pleochroism

The fact that there are two rays in these stones has an effect on the colour, for each of these rays may absorb light differently and as the stone is turned it may show a slightly different shade of colour. This effect is termed dichroism, and is seen moderately well in all rubies and sapphires, except in the colourless and yellow stones. The most attractive colour in both ruby and sapphire is that of the ordinary ray; this is a deep purplish-red in ruby and a deep royal blue in sapphire. Ideally, both rubies and sapphires should be cut with the *c*-axis at right angles to the table facet, to display the best colour.

Lustre

The lustre of ruby and sapphire is higher than glass (vitreous), but lower than diamond (adamantine). Thus it may be called sub-adamantine.

Dispersion

The dispersion of the stones is only 0.018 (B to G). Hence corundums show little fire and the beauty of the stones lies in their colour nuances alone.

Absorption Spectra

Three major types of absorption spectra are found in corundums: those due to chromium, to iron and to vanadium (*Figure 3.3*).

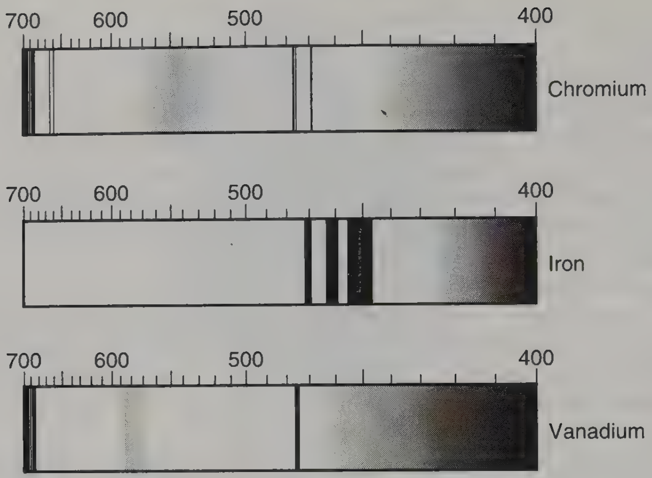

Figure 3.3 *The three major spectra of corundum (illustration ©1992 by Richard W Hughes)*

Chromium

The chromium spectrum is most common to ruby but, like all three spectral types, can be found in corundums of any colour which contain enough chromium. It is characterised by general absorption in the deep violet, transmission in the blue, an absorption band in the green centred at 550 nm, and transmission in the orange and red. There are three narrow lines in the blue, two of which (468.5 and 476.5 nm) are of equal strength and the third (475 nm) is much weaker. A number of fine lines are seen in the red, the strongest being a close doublet at 692.8 and 694.2 nm, which may reverse into fluorescent lines. Other weaker lines are at 659.2 and 668 nm in the orange. A Cr spectrum can be seen in any natural or synthetic corundum with enough Cr content and is of no diagnostic value.

The fluorescent doublet of ruby is best seen when light is scattered from the surface and may be viewed in a spectacular manner when the incident white light is filtered with a blue filter (such as a copper sulphate solution), which only passes blue light. Then the light scattered from the ruby is examined with a hand spectroscope; the bright lines are seen on a black background. Alternatively, the ruby bathed in blue light may be viewed with a filter (gelatine or glass) which only passes red light, causing the stone to appear like a glowing coal on a black background. This technique is known as crossed filters and is shown in *Figure 3.4*.

Iron

The absorption spectrum due to iron is most common to blue, green and yellow sapphires, but can be seen in any sufficiently iron-rich corundum. It consists of three lines of increasing intensity at 451, 460 and 470 nm. In iron-rich stones the 451 and 460 nm lines may merge into one. With decrease of iron content these bands, usually known as the 450 nm complex, decrease in intensity till, in the case of the rich blue sapphires, only the 450 nm line may be seen, and then only with difficulty. Many pale yellow and blue sapphires from Sri Lanka contain little iron and may show only a weak 451 nm line, if at all. The complete iron complex is proof of natural (or heated) origin. A weak 451 nm line has been seen in certain Verneuil and flux-grown (Chatham) synthetic sapphires.

Vanadium

Vanadium in corundum produces a greenish to red colour change and gives a spectrum somewhat similar to that of chromium. However, instead of the three narrow lines in the blue, only one is seen at 475 nm. In addition, the broad absorption band, which in ruby is centred at 550 nm, in vanadium-coloured corundums is centred at 585 nm. This is what produces the colour-change effect. Narrow lines are also seen in the red, similar to a chromium spectrum. The vanadium spectrum is extremely rare in natural corundums, being observed by the author on only three occasions, two Burmese colour-changing sapphires and one from Umba. But it is common in the Verneuil colour-changing synthetic sapphire.

Other Spectra

The other colours of sapphire have absorption spectra reminiscent of the colour nearest to them. Thus the purple and violet stones show chromium plus iron spectra. Pale stones may not show any diagnostic spectra.

Luminescence

The luminescence of chromium-coloured corundums (rubies, purple and violet sapphires) is a strong crimson (or sometimes orange) light which is the same whatever radiation is used. It can be excited by either short- or long-wave UV, or even simply blue light. This is due to the excitation of the chromium ion, the glow being mainly due to the intense emission from the doublet at 693.5 nm. This red glow can be seen spectacularly when a stone is viewed between crossed filters (see *Figure 3.4*). When rubies are viewed through the Chelsea colour filter this fluorescent red may also be seen and this is a convenient method to adopt when picking out rubies from a mixed parcel of rubies and garnets, the latter not fluorescing.

The fluorescence of ruby has been suggested as a test for distinguishing between rubies from Myanmar (Burma) and those from Thailand/Cambodia, and for distinguishing synthetic stones from natural rubies. While Thai rubies do tend to fluoresce less than those of Myanmar, some iron-rich Burmese stones also have weak fluorescence. In addition, rubies from virtually all sources except Thailand/Cambodia have a strong red fluorescence, as do most synthetic rubies. Thus the fluorescence test should not be used to distinguish between Burmese

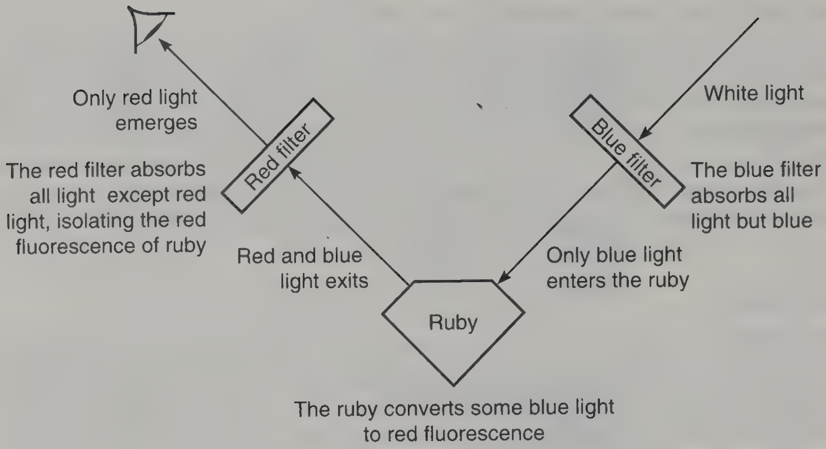

Figure 3.4 The crossed filters technique for observing fluorescence in ruby (illustration ©1992 Richard W Hughes)

and other rubies, nor is it reliable for separating natural and synthetic rubies.

In the case of blue sapphires, UV fluorescence is practically non-existent. Exceptions are Sri Lankan stones containing traces of chromium. These show a red or orange glow under long-wave UV light. Under short-wave UV, some blue sapphires show a weak blue glow, particularly heat-treated Sri Lankan stones. Observation has shown that it is the colourless portions of the stone that fluoresce, exactly similar to the Verneuil synthetic corundum. Magnification of the fluorescence reveals it to occur in angular bands which follow the growth structure of the stone. These are angular bands in natural corundums and curved bands in the Verneuil synthetics.

Most sapphires are inert under X-rays, except the Sri Lanka, Montana and some Indian (Kashmir) stones which may show a dull red or yellowish-orange glow. It has been reported that under bombardment by cathode rays (fast-moving electrons) Kashmir sapphires show a greenish-blue glow, Myanmar (Burma) stones show a strong dark purple, Thai stones show a weak dull red, and sapphires from Sri Lanka a vivid red.

The iron-rich green and yellow sapphires show no luminescence of any kind, but yellow and orange stones from Sri Lanka show a strong apricot-yellow glow under ultra-violet light, X-rays and gamma rays. The cause of this particular luminescence is not known. Such stones when bombarded by X-rays turn to a rich topaz colour, however weakly yellow they were originally. This colour is not permanent and reverts on exposure to about $3\frac{1}{2}$ hours' sunlight or quickly when the stone is heated to about 230°C. Colourless sapphires may also suffer this change of hue after irradiation, but the shade of yellow attained is usually lighter; and further some blue sapphires will change to a dirty amber colour.

Inclusions

Much work has been carried out, particularly by Gübelin in Switzerland, on the nature of inclusions in corundum, with a view to identifying the locality from which the stone originates. It is the writer's opinion that while in some cases the evidence so obtained is sufficient to give an indication, in many cases there are insufficient grounds to formulate a satisfactory conclusion. Apart from other factors, this is the primary reason why most gem testing laboratories refuse to certify the locality of a stone.

The inclusions of corundum vary tremendously from one source to another. In a book of this type it is impossible to even begin describing the possibilities of the major sources, let alone the minor ones. Rather than try to describe corundum's inclusions source by source, the author has made a general listing of the inclusions that can be found in any corundum. For a specific listing of the inclusions of corundum by source, the reader is directed to the periodical literature or to the works of Eduard Gübelin and John Koivula, particularly their *Photoatlas of Inclusions in Gemstones*.

The general inclusions of corundum are as follows (*Figures 3.5, 3.6, 3.7*):

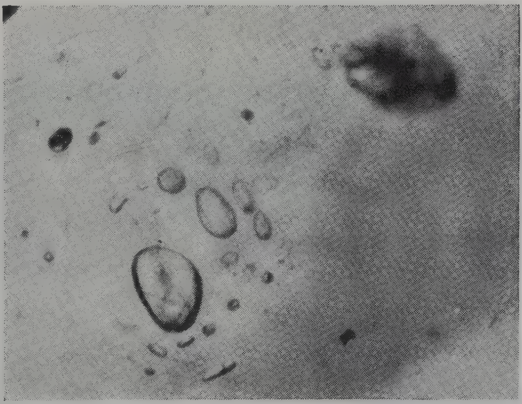

Figure 3.5 Rounded crystals in a Burma (Myanmar) ruby

1. Straight angular growth lines following various crystal faces, often in a hexagonal pattern and often featuring associated minute exsolved needles or particles following these growth lines. The lines vary in thickness and spacing, are never curved (if examined parallel to the face along which they grew), and always lie inside the stone. They are associated with crystal faces, not with cut facets. Sharp lines are seen best with dark-field illumination, or better, immersion with light-field shadowing illumination. Broad bands or ill-defined patches are best seen with immersion and diffused light-field illumination. In rubies, the colour often occurs in treacle-like swirls when looking in directions other than along the crystal faces.
2. Exsolved rutile needles and/or hematite plates ('silk') forming parallel to the hexagonal prism (three directions, intersecting at 60/120° in the basal

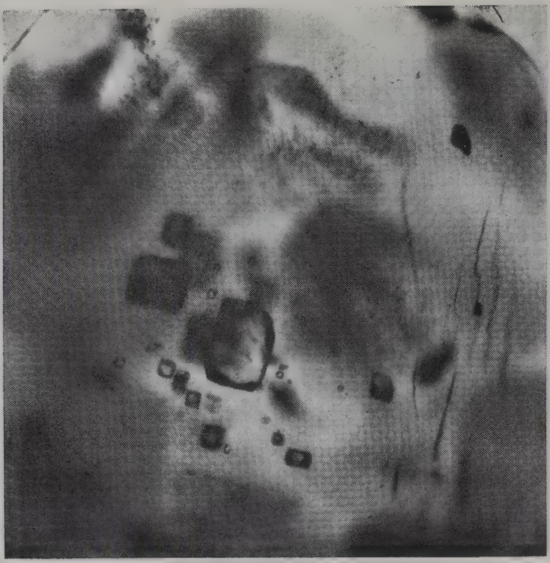

Figure 3.6 Silk and inclusions in a Burma (Myanmar) ruby

Figure 3.7 Feather in a sapphire

plane). These may form dense clouds. The rutile forms knife-shaped twins with tiny re-entrants at the broad end. Hematite tends to be more platy. Sizes vary greatly, some being much longer than others, some appearing as mere dots, some broad, some narrow. Overhead fibre-optic illumination is often best, looking down the *c*-axis. Minute exsolved particles are often best seen with the fibre-optic light guide from below or to the side of the stone.

3. Solid inclusions (crystals) of various types, including zircon, calcite, uranium pyrochlore, mica, apatite, spinel, garnet, etc., best viewed in dark-field illumination or via fibre-optic lighting. Crossed polars and immersion may also be useful.
4. Primary liquid- and/or gas-filled cavities (known as 'negative crystals') of various configurations (one, two or three phase).
5. Secondary liquid inclusions in patterns of infinite variety and thickness; often referred to as fingerprints or feathers. Produced by the healing of fractures, their patterns may often be wispy or veil-like, and so are easily confused with flux incisions in synthetic corundums. Their surfaces should be examined under high magnification with fibre-optic lighting to see if liquid (natural) or flux (synthetic) fills the small channels. As natural stones healed over a much longer priod of time, their healing patterns are often far more detailed. The higher viscosity of a flux also produces a more coarse and less detailed healing in flux synthetics.
6. Polysynthetic twinning along the rhombohedron (in three directions, but only two in any one plane) meeting at 86.1 and 93.9°. These lie about 30–60° off the *c*-axis. Growth twins may also be seen along other faces. Immersion between crossed polars will separate true twinning from sharp colour zoning. True twinning planes will show interference fringes and appear light against a dark background.
7. Long white exsolved boehmite needles which form at the junctions of intersecting rhombohedral twinning planes. Thus their directions and angles are the same as that described in 6. Rhombohedral twinning with the boehmite needles has yet to be seen in the flux-grown synthetic corundum and so is extremely important for identification.
8. Rhombohedral parting (due to exsolved boehmite) and basal parting (due to exsolved hematite).
9. Wavy parallel cracks ('fire marks') near the facet junctions due to overly rapid polishing. These are more commonly seen on synthetic stones, as less care is taken in the polishing process, but may sometimes be seen in natural corundums, too.

Methods of Fashioning

Faceting

Rubies and sapphires may be faceted in many different styles; mostly the mixed cut is used, the brilliant-cut crown being backed with a step-cut pavilion. For fine stones the step cut is often employed, and if the material is poor in quality or much flawed it may be cut into beads or even carved. Pale stones are often mounted with a closed setting and the back of the stone is sometimes foiled with a suitable colour. In Sri Lanka it was formerly the practice to place under a blue sapphire the blue part of a peacock's feather instead of foil.

Star-Stones

Star-stones must be cut as cabochons in order to exhibit the attractive optical effect of asterism. The cause of the asterism is exsolved rutile or hematite 'silk', multitudes of tiny oriented needles or plates. These inclusions form via exsolution – the unmixing of a solid solution. At high temperatures, the corundum may absorb more impurities, but as the crystal cools, the impurities can sometimes be squeezed out of solution. Since they are still in a solid, the impurity atoms only crystallise where there is space and this is determined by the host structure. In corundum, exsolved rutile and hematite crystallise in three directions in the basal plane, parallel to the faces of the hexagonal prism.

When a stone contains enough of such inclusions, it can display a six-rayed star effect if it is cut as a cabochon with the base of the cab parallel to the basal pinacoid (parallel to the layers of silk). The hematite crystallises parallel to the first-order hexagonal prism while the rutile follows the second-order hexagonal prism (30° off the first-order prism). If a stone contains enough of both hematite and rutile silk, it can display a twelve-rayed star. This is fairly common in black star sapphires, but is rare in other colours.

To observe the star effect, one must examine the stone in direct sunlight, or under a single, intense light, such as a fibre-optic light, pen light, or spot light.

Synthesis and Simulation

Ruby was the first major gemstone to be synthesised, this occurring in the mid nineteenth century. Today corundums of all colours are made synthetically by a variety of processes, for both gem and industrial use. Star corundums have been synthesised since the late 1940s, and are also made in all colours.

A description of synthetic and imitation corundum could be the subject for an entire book by itself, such is its complexity. The subject will be taken up in greater detail in Chapter 18. For a detailed treatment of synthetic, assembled and imitation corundums and their identification, see *Ruby and Sapphire (Corundum)* by R W Hughes. The following is a brief description of the identifying features of each major type of synthetic corundum.

Melt-Growth Processes

Verneuil (Flame-Fusion) Process

Various manufacturers (all colours, including six-rayed stars).

1. Curved growth lines (thin striae or bands), seen best at roughly 90° to the boule's length. These curved lines are *not* concentric.
2. Gas bubbles, round or elongated at 90° to direction of growth lines, from pinpoints to large distorted doughnut-shaped spheres or highly irregular worm-like distortions. Usually distributed in clouds which follow the curved growth structure of the boule. In blue stones, the gas bubbles may show concentrations of blue colour around them.
3. (a) Polysynthetic twinning along the *c*-axis ('Plato lines'), seen between crossed polars with immersion in sets of one, two or three directions.

3. (b) Polysynthetic twinning along the rhombohedron, sometimes with accompanying boehmite needles identical to natural corundums.
4. Induced fingerprints and feathers entirely similar to natural corundums.
5. Traces of the seed rod or seed crystal. Found at the base of the boule and featuring frosted surfaces at the seed junction.
6. Some varieties may show useful UV fluorescence. The V-doped colour-change type shows a diagnostic line at 475 nm. The full Fe spectrum (451, 460, 470 nm) is not seen.
7. Irregular colour distribution and rounded facet junctions of blue varieties in particular may cause confusion with surface diffusion-treated corundums.
8. Dense clouds of extremely fine, exsolved rutile silk in star material. The clouds do not show the straight angular zoning patterns that are common to natural stones. Instead, they may display curving bands (which are sometimes concentric).

Czochralski (Pulling) Process

Inamori (red, orange and red star), Novosibirsk (red) and others (red, blue and colourless).

1. Extremely fine and narrow curved growth lines (curved striae), which may be concentric.
2. Gas bubbles of various sizes, shapes and orientations.
3. Faint 'smoke-like' or 'rain-like' wisps of tiny particles, probably representing remnants of a flux used to aid melting during growth.
4. Small unidentified black prismatic crystals in groups (Inamori).
5. Extremely fine exsolved clouds of what may be rutile silk in the red star material (Inamori).

Floating-Zone Process

Hattori Seiko (red, orange, blue), Novosibirsk (red).

1. Gas bubbles of various sizes, shapes and orientations.
2. Irregular colour swirls.
3. Secondary lamellar glide twinning along the rhombohedron faces. Twin planes may intersect at 87 and 93°, and may also show long white needles (boehmite?) at the junctions of intersecting twinning planes. Best seen in immersion with crossed polars.
4. Rectilinear parting.

Solution-Growth Processes

Flux Process

Chatham (red, orange, blue), Kashan (red), Ramaura (red), Knischka (red), Lechleitner (overgrowths in various colours), Novosibirsk (red), Douros (red).

1. Primary flux-filled negative crystals, often only partially filled (two-phase) and featuring a characteristic crazed surface appearance. Primary flux in Ramaura stones often has a yellow-orange colour and may show distinct

growth striations on flux surfaces, open cavities and crystal faces which mirror the colour zoning.
2. Secondary flux-filled fingerprints, feathers, etc.
3. Tiny flux particles, often arranged in streamer or comet-like patterns (such as the 'rain' in Kashan stones).
4. Platinum plates, flakes, crystals, needles, etc. (Chatham, Knischka); black (platinum-rich?) growth planes (Chatham only, especially along the seed crystal).
5. Tiny, oriented, exsolved silk-like needles and/or particles in zoned clouds (Chatham and Knischka).
6. Polysynthetic and growth twinning in various orientations, but without the boehmite needles often present in the natural, Verneuil and Seiko (floating zone) synthetics.
7. Straight growth lines running parallel to crystal faces and meeting at specific angles. Unusual growth-line boundaries (Ramaura, Douros).
8. Chatham: rounded transparent crystals of low relief (possibly chrysoberyl).
9. Seed crystal, generally with trapped flux on the boundary. The boundary may be difficult to see in the Lechleitner overgrowth.
10. Knischka: primary negative crystals which often display a two-phase filling. These may be bipyramidal or irregular in shape and sometimes are surrounded by irregular bluish-white clouds.

Hydrothermal Process

Novosibirsk (Russia) only (red).

1. Extremely strong growth zoning (graining) parallel to the basal plane.
2. Small, highly reflective crystals of a gold colour, consisting of copper alloys.
3. Secondary healed fractures (fingerprints) believed to be liquid filled.

Simulants and Imitations

Although there are a number of materials which can have a similar appearance to ruby and sapphire (such as certain spinels, garnets, benitoite, etc.), all are easily separated by reference to the properties, such as RI and SG.

More dangerous are assembled stones, generally consisting of one or more parts of natural corundum, attached to other materials (generally synthetic corundum). They may show natural inclusions and colours because they are part natural. The key to identifying any assembled stone is to locate the separation plane where the stone is joined together. It must be a distinct join, completely unbroken around the entire stone. It is usually on the girdle, but may be on the pavilion or even the crown. The glue layer often shows curved brush strokes and flat gas bubbles. Since the glue's RI is quite different from corundum, it will stand out in high relief when the gem is immersed in di-iodomethane.

Various kinds of assembled star-stones are also possible. One of the most deceptive is simply taking a white star sapphire and coating it with red plastic.

Myanmar (Burma)

Historical Events

The most famous locality for fine rubies and sapphires is the district around Mogok in upper Myanmar (Burma) (*Figure 3.8*). This so-called Mogok Stone Tract is an area of some 1000 km².

When the Burma ruby mines were first discovered is quite unknown. The earliest heard of them is a Burmese legend of untold age, which relates of an

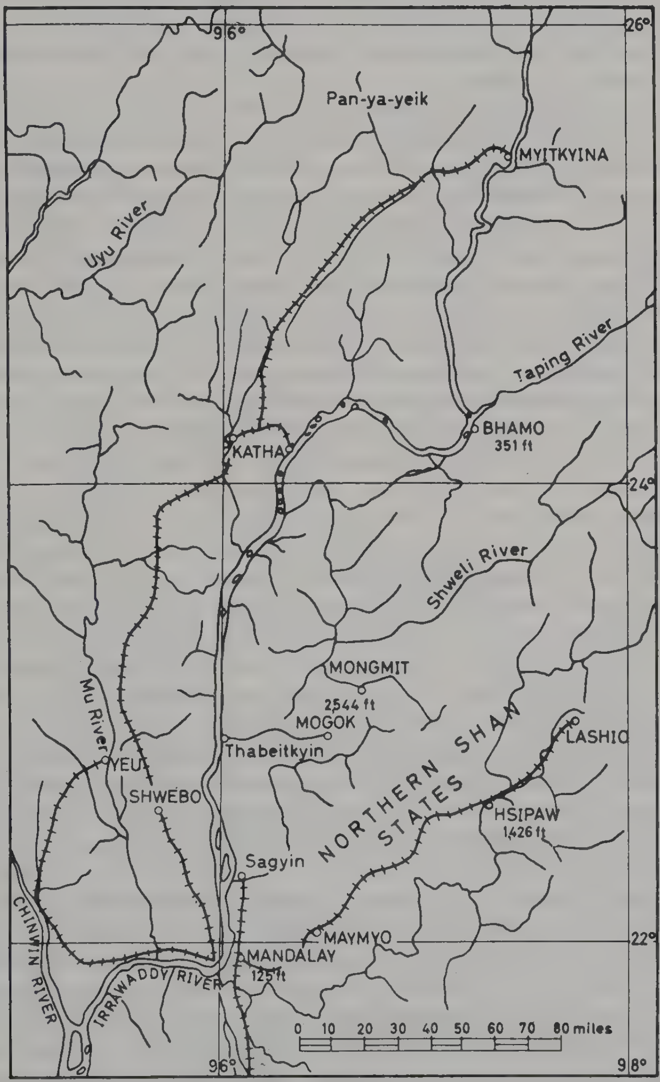

Figure 3.8 Sketch map of Upper Burma to show ruby localities (after J Coggin Brown)

inaccessible fever-stricken valley in the Chinese country, into which human beings could not descend, but into which lumps of raw meat were flung from the surrounding hills, to be retrieved by the vultures, and from which the adhering rubies were picked off. Similar stories have also been related about the diamond mines of India and the gem mines of ancient Sri Lanka. It has yet to be determined just how someone could throw a lump of meat such a great distance and so the only thing proven is that humans, both then and now, are suckers for a great story.

In any event, the mines do appear to be of great age, as a number of Stone and Bronze Age implements have been recovered among the detritus of the mining. The first specific written record of the mines is from 1597, when a Burmese king forced a Shan prince to trade the Stone Tract for a less valuable piece of property (Tagaung myo).

Mogok is located one day's drive north-east of Mandalay. The country, covered with dense forest, has long been so notoriously unhealthy that there often were shortages of labour. To alleviate this, one king (Bodawgyi) sent thousands of captives from Manipur to work in the mines. This was about 1780, and subsequently the mines became a place of exile for those who incurred the king's displeasure. Shortly after this, the district was placed in charge of *so-thuygis (so* or governors) who allowed mining on payment of a tax, with a stipulation that all stones mined of an individual value of 2000 rupees and over were the property of the king. This went on for some years and the *so* enriched themselves greatly by oppressing the miners and forcing them to sell their stones for little or nothing to themselves. As they held absolute powers of life and death, the *so* were well placed to terrorise the unfortunate miners. Things went from bad to worse, and the miners deserted their villages and left the district.

King Mindon Min then took over control of the mines but did such a bad job of administration 'that in 1863 another governor was appointed with the responsibility of collecting taxes of some £5000 a year from the miners. Matters became worse and a rebellion took place. Eventually the whole Stone Tract was beset by gangs of robbers and deserted by peaceful miners. As the king was getting no revenue, he made mining open to everyone, and miners were given the right to freely sell all stones under 2000 rupees in value – the king taking all stones above this value – to anyone within the Stone Tract, but not outside it. All stones not sold in the Stone Tract had to be sent under seal to a central ruby mart in Mandalay. Here they were offered for sale, and if sold the purchaser paid 10 per cent and the owner 5 per cent tax on the price. If no sale took place, the owner paid 10 per cent on the valuation and was then free to sell the stones anywhere.

This restored prosperity, but abuses again became apparent, because of the king's demand for more revenue, not only from the mines but from the governors, which they obtained by again oppressing the miners and swindling the traders who came to the mines to buy. Demands for more money grew apace and in 1885 King Thebaw appointed a governor whose business it was to find no less a sum than £16 000 per annum. The district again entered a state of chaos. Villages were raided daily by gangs of robbers, forcing villagers to travel in armed bands for self-protection. The road from Mogok to the river was infested with robbers. Three local bandits established a convoy system down the road and demanded up to 10 rupees a head for safe passage; those who did not pay were simply robbed or murdered. King Thebaw then decided to negotiate with a French syndicate for a lease of the mines. This was one of the deciding factors which led to the annexation of upper Burma by the British in 1886.

The Burma Ruby Mines Company

After the annexation, E W Streeter, author and Bond Street jeweller, who was said to have been negotiating with Thebaw, obtained a concession from the British government to work the mines. His concession was immediately challenged and was subject to a good deal of debate in Parliament (see Stewart's *The Pagoda War* for a lively discussion of the politics of the annexation). Eventually things were straightened out. The Burma Ruby Mines Company was immediately floated and, amid scenes of chaos in London, with people fighting over the forms, the issue was oversubscribed within hours; double the amount, £300 000, could easily have been raised. But shareholders had no idea of the troubles that awaited; they thought only of rubies.

The British government's annual rent for the mines was fixed at the tremendous sum of £30 000 plus 30 per cent of profits, in return for which the Company was to have the right to work any unoccupied land with use of machinery. Native miners were allowed to continue working by purely native methods, on payment to the Company of 30 per cent of the value of their finds. It was thought that the Company would have a monopoly of rubies and would be able to control the price of them. This was a mistaken idea as was soon evident; for native miners concealed the greater part of their finds. Smuggling was a simple matter and quite impossible to check; these stones coming on the market destroyed the Company's hope of controlling ruby prices in the market.

Thus a new arrangement was made whereby the native miner paid a fixed fee of 20 rupees a month per workman employed. The annual rent for the mines was reduced by 50 per cent, and was subsquently abolished altogether in view of the open market created by native miners selling their stones.

At the beginning the Company's engineers were confronted with a task of great magnitude. The ruby-bearing alluvials were found to lie deep under heavily waterlogged valleys, and a large portion of the ruby-bearing ground was under the town of Mogok itself. This entailed purchasing the buildings and re-erecting the town on another site. Heavy machinery and pumping plants had to be brought over a rough mule track through fever-stricken jungle infested with wild animals, ranging from tiger to elephant, and passing over mountains 1500 m high. It took over a year to make a road passable by light bullock carts, which took 3 weeks to make the journey and could not travel at all for 7 months of the year. Disease was common and machinery lay abandoned on the roadside for months owing to lack of transport.

These difficulties were eventually overcome and a good road was constructed. The company's engineer, A H Morgan, thought up a brilliant plan to drain the valley by constructing a tunnel, allowing access to previously flooded alluvials. At the mines a 400 kilowatt hydroelectric power station was opened, and five large washing mills, each dealing with some thousands of tonnes of earth per day, were put into operation. Subsequently, three more mills were erected 13 km away near Kyatypin, and the mines entered a period of prosperity.

The mines were worked by the open-cast method, there being no underground working at all. The first process was to take all the earth from grass level to bedrock and truck it away to large washing mills by hand labour and rope haulages. This method was subsequently superseded by a system of washing the earth down by large jets of water (monitor jets) under high pressure and passing it through a series of sluice-boxes, to which it was elevated by large gravel pumps, making a great saving in mining costs.

All went well and the Company was paying dividends until 1908, when inroads made by the Verneuil synthetic ruby caused profits to drop. America, the main market for fine stones, was in depression and prices of fine rubies fell; depreciation in lower grades was even greater in Bombay, the main market for lower grades. It was the beginning of the end. All through the lean years of World War I the Company struggled on. In 1925 it went into voluntary liquidation, and in 1931 the Burma Ruby Mines Co Ltd finally closed its doors for good, surrendering its lease to the government.

Reasons for the Company's Failure

Many have speculated about the reasons for the Company's failure, most concluding that it was just not meant to be, the difficulties being too great to surmount. But recent evidence uncovered by the author (RW Hughes) suggests that the Company owed its failure less to the difficulty of the task and more to that old devil we know – human greed. In a confidential report written in 1925, the head of the Geological Survey of India, J. Coggin Brown, pointed the finger for the Company's failure straight at the De Beers diamond cartel. He stated:

> At this juncture I cannot refrain from writing an opinion which I have already expressed verbally, that the influence of the De Beers diamond concern has had more to do with the present [1927] position of mining for coloured gems in Burma than appears on the surface. The reasons for this are obvious, and it is significant that there has always been a powerful representative of the great South African concern on the Board of the Burma Ruby Mines, Limited.

Brown went on to chronicle a number of bad decisions taken by the Board that resulted in missed opportunities. In 1992, the time of this writing, the company's equipment has lain fallow for over half a century. But the prospect of what might have been still haunts the mind. What if . . . ? Who knows. Perhaps if the company had succeeded, instead of diamond, ruby would today be considered 'a girl's best friend'.

Native Mining

After the failure of the Company, mining in Burma reverted to the age-old native methods. People were allowed to mine upon payment of a monthly fee, which was higher if water and explosives were used. In order to obtain a mining licence in Burma, it was then necessary for one's name to be on a very arbitrary list of registered miners, but those on the list were often willing to lend their names to the less fortunate for a consideration. A licensee usually employs three workmen, who receive as payment 50 per cent of the total profits for the month to share among them. Every market day they draw a very small advance for the purchase of food. If the month's work shows a loss, that amount is wiped out and they receive no further payment. If the mine shows a profit, this sum is deducted from the 50 per cent of the total profits of the mine.

Pit Mining

In the dry season these men mine by sinking a shaft down to the layer of *byon* (the name applied to the gem-bearing alluvial gravel); if no water is encountered, these pits are merely small round holes just large enough to allow a man to descend into them. They are sunk rapidly and contain no timbering. The pits are called *twinlons* and are usually from 6 to 12 m deep. Below this depth they are often unsafe, but in favourable ground may go down to 30 m. A second shaft is sunk parallel to the first, and is connected with it by openings at intervals for the purposes of ventilation.

One workman simply squats at the bottom of the shaft, loosens the earth with a tiny spade, and fills up a bamboo basket. This basket is hauled to the surface by the second workman by means of a bamboo crane known as a *maungdaing*. Light is reflected to the workman below with a mirror set at an angle above the hole. Until the *byon* is reached, the earth removed is discarded. Upon reaching the *byon*, side tunnels are driven by two workmen in every direction for about 12 m. Every scrap of *byon* is carefully removed and washed (*Figure 3.9*). The tunnels are allowed to fall in when finished with, but are

Figure 3.9 Washing the byon *in the Burma ruby mines (by courtesy of J R H Chisholm, a former editor,* Journal of Gemmology)

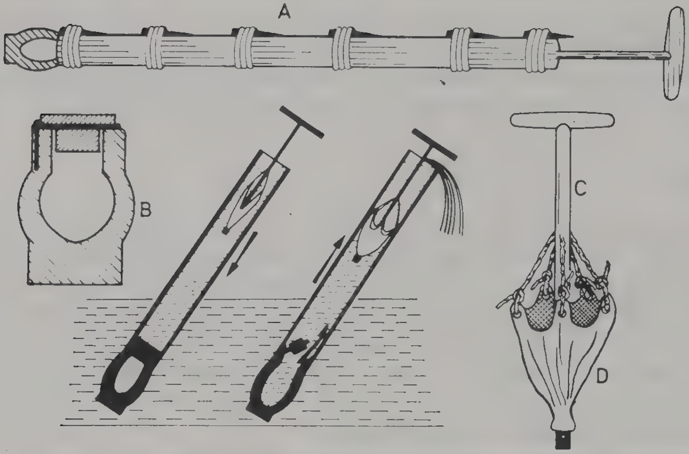

Figure 3.10 Details of the bamboo pump used by the Burmese miner for pumping out the pits: (A) complete pump, (B) detail of the end valve, (C and D) details of the plunger

consolidated so as to provide support for the top whilst the other galleries are being driven.

If the ground contains water and a *twinlon* would not stand, a square pit known as a *lebin* is put down. This has sides 0.5 m each way and is lightly timbered with brushwood and leaves held in place by thin sticks to keep the wet earth in place. Such pits may go down for over 60 m. Larger pits with sides of 1.5 m are known as *kobin*, while still larger ones with sides of 6–9 m are known as *imbye*. These large heavily timbered pits need a number of men to operate them and are expensive to work.

Water is removed from the wet pits by bailing with fuel-oil cans tied to the *maungdaing* or by the use of an ingenious bamboo pump, which is best explained by reference to *Figure 3.10*. Effective down to a depth of 6 m, the pumps are arranged in relays for greater depths.

Hillside Mining

In the rainy season when the pits cannot be worked, the hillside deposits are tackled. Miners make a cutting into the hillside, washing the loose earth away by means of sprays of water falling from bamboo pipes placed at a height above the ground. The light earth is allowed to wash away while heavier sands and gravels are led to narrow water courses. Here the heavier portion, containing the gems, is trapped in holes made in the channels and is sorted by hand. This method of mining is known as *hmyawdwin* and may be of any size from an insignificant cut to an enormous opening. The water to work the mines is often brought from long distances by channels cut in the rock, and even through tunnels, being carried over valleys on high bamboo aqueducts in bamboo mats luted with clay.

Caverns (Loo)

Deposits in the interior of the hills are contained in the cracks and crevices in the rocks, which may open out into large caverns of great beauty. These caverns are reached by long tortuous passages, so small that a man can scarcely worm his way along them, and such mines are called *loodwin* or *loo*. Some of the finest stones are found in such *Loo*.

Other Mining Methods

The local streams are worked for the gems by rudely damming them with logs and brushwood, and the gravel held up by this is dredged out by hand and small baskets. The return from this source is usually poor.

The *byon* removed from the mines is placed in a pear-shaped washing place called a *yebangwet* and is then broken up with water by men using hoses. The slurry formed is allowed to fall into a channel from the narrow end of the *yebangwet* where the heavy gravels are trapped in a series of holes dug in the floor of the channel. This heavy concentrate is removed and more highly concentrated by hand in small round bamboo trays. This residue is then sorted by hand for the gems.

In all the streams poor women armed with round bamboo trays may be seen scraping up the gravel from the bed, and sorting it for rubies. This is a hereditary right for women only and is known as *kanese*. It is free of all fee and licence and their work must not be interfered with. Usually their finds are small, but this custom caused havoc during the time of the Company, as it provided a convenient method for laundering stones stolen from the Company's mines. Dishonest workers would pass a stone across to the *kanese* women, who would then pretend to find it in the tailings.

Geology

Burmese ruby occurs embedded in a mother rock of white dolomitic granular limestone or marble, a common rock of the district. The exact formation of ruby at Mogok has been the subject of much conjecture over the years. Previously it was thought that the ruby formed through contact metamorphism but today it is generally accepted that the ruby is the product of regional metamorphism. Bands of clay within the limestone are thought to have supplied the alumina needed for growth of corundum. If magnesium is present, spinel grows; when the Mg is exhausted, ruby grows. Both star rubies and star sapphires are found at Mogok.

The sapphire from Myanmar is formed not in the marble, but in a syenite and in pegmatites. Both the ruby and sapphire are mined from secondary deposits. It is in the alluvial deposits derived from the weathering of the parent rocks that the gem corundums are mostly found; this is the *byon*. Rubies predominate around Mogok, whilst sapphires are more common at a site some 13 km away, near the village of Kathe, which is some 30 m higher than Mogok. At Bernardmyo, at an elevation of some 90 m above Mogok, rather dark-coloured stones are found in a hard black iron-cemented conglomerate. Bernardmyo is most famous for its peridot deposit.

Other Myanmar Ruby Deposits

Ruby has been found at localities in Myanmar other than Mogok. These include the Sagyin Hills near Mandalay and Namseka, near Mainglon.

In 1992, ruby was found at Mong Hsu, 250 km east of Mandalay. Since that date, large quantities of these stones have appeared in Bangkok. Mong Hsu rubies are of good colour, but generally heavily fractured. Cut gems rarely exceed two carats. They are characterised by blue cores, which may be removed by heat treatment.

Myanmar Today

In 1962, Ne Win staged a military coup and plunged the country into isolation. The Mogok mines were nationalised in 1968. Starting in 1991, the Ne Win government began to allow certain foreigners to visit the mines. What they found was that little had changed since the time of the British Company. The government runs several mines in the Mogok area, but smuggling is rife and little progress has been made. The mines (and the country as a whole) are operated in a manner similar to that of the Burmese kings, as almost a private concession, beholden only to Ne Win and his military cronies. What is not smuggled abroad is sold at the yearly emporium in Rangoon. While Myanmar still produces some of the finest sapphires, it has been eclipsed to a large degree by the recent ruby discoveries in Vietnam.

Thailand and Cambodia

Since the self-imposed isolation of Burma in the early 1960s, the most important sources for rubies and sapphires have been Thailand and Cambodia. The ruby deposits occur along the Thai/Cambodia border in Chanthaburi and Trat province in Thailand, and neighbouring Battambang province in Cambodia. The rubies tend to be brownish-red and somewhat dark in colour, while the sapphires are generally dark blue. Fine yellow sapphires occur at Khao Ploi Waen and Bang Ka Cha, while blue sapphires occur mainly at Khao Ploi Waen, Bang Ka Cha and Bo I Ram in Thailand and Pailin in Cambodia. Rubies are found in a wide area including Bo Rai, Nong Bon, Bo Waen and Tok Prom in Thailand and Pailin in Cambodia. The centre for the gem trade in this area is the Thai town of Chanthaburi.

All gem deposits in this area are derived from basalt, an iron-rich rock. The high iron content of the mother rock carries over into the corundums, which are also generally darker than the ideal. The stones are found in a coarse yellow or brown sand, overlaying a bed of clay or basaltic rock. The beds are mostly within 2.5m of the surface, but some of the mines are over 6 m deep. These deposits have only been worked to any extent since the late nineteenth century. The mining is by simple methods and many miners are descended from Shans from Burma.

Blue sapphires are also found in western Thailand at the town of Bo Ploi, in Kanchanaburi province. In the late 1980s mining at Bo Ploi was expanded dramatically, but has since fallen off.

Vietnam

The gem trade was stunned in the late 1980s by the discovery of rubies and sapphires in Vietnam. In what surely must rank as the discovery of the century, tin and gold miners found rubies of a fine colour at Luc Yen, north-west of Hanoi, in 1986. Then, one year later, stones of a similar colour were found at Quy Chau, in Nghe An province, west of the provincial seat of Vinh. Vietnam, which had never previously been known for gemstones, suddenly found itself with what many experts believe are the two finest ruby mines in the world.

Vietnamese rubies are striking in their similarity to those from Myanmar, except that, unbelievably enough, they tend to be of *better* clarity than the Mogok stones. Stones of Luc Yen are derived from a crystalline limestone while those in Quy Chau come from either pegmatites or limestones. Each source produces rubies with small blue patches and zones, similar to rubies from Jagdalek, Afghanistan. In addition to ruby, Quy Chau produces some beautiful orange sapphires, the colour of papaya, as well as dark blue sapphires and yellow chrysoberyl. At Luc Yen are found rubies ranging from the lightest pink to a rich intense red, as well as some off-red spinels and blue spinels. Cobalt-blue spinels have also been reported in Vietnam, along with pink and green tourmaline and colourless topaz. In southern Vietnam, near the town of Dalat, are found dark blue sapphires associated with basalts.

India

Kashmir

Sapphires of a magnificent colour, possessing a fine cornflower blue with a slight milky appearance, are found near the Zanskar district of Kashmir. The mines are near the village of Sumjam in Paddar district. The deposits were said to have been first discovered by an avalanche laying them bare in 1881, but there is reason to believe that the local inhabitants knew of them much earlier. The deposits lie in a small valley about one kilometre long by one-half wide near the Zanskar range of the north-western Himalayas. The valley, on a tributary of the Chenab, lies approximately midway between Srinagar and Jammu at an elevation of 4500 m, and except for a few months of the year is under deep snow. Sapphires occur in a pegmatite vein in association with tourmaline, garnet, kyanite and euclase. The pegmatite veins penetrate lenses of actinolite-tremolite rock in a crystalline limestone; the sapphires are found in pockets of kaolin derived from the pegmatite.

When first discovered the sapphires were extracted from the face of a precipice at the head of the valley. This 'old mine' was most productive from about 1881 to 1887; it was not until some years afterwards that the whole floor of the valley was found to be covered with a thin layer of white pegmatite, overlain by a few feet of ordinary earth, which carried sapphires in immense quantities, but these stones were of lower quality. Owing to the severity of the climate work was carried on in a desultory way until 1924, when the mines were reopened after the deposits came under the Kashmir Mineral Survey. They closed again after a few years. Today the mine lies abandoned, although every few years the Indian government makes noises about reopening it.

The crystals are well-formed spindles and sometimes of large size when found in the rock, but the stones found in the valley are water-worn and rarely show crystal form. Colour occurs in thin layers just beneath the crystal faces on top of a colourless core; thus the weathered material from the valley floor tends to be much lighter, similar in appearance to *ottu* sapphires from Sri Lanka. Crystals frequently enclose green tourmaline. Cut stones, which make excellent night stones, often contain rutile silk, and also contain inclusions of green and brown mica. Most distinctive are the small black crystals enclosed in larger cavities.

Other Indian Occurrences

Rubies are found in several India states. Facet-grade ruby is said to occur in the Kangayam area of Tamil Nadu. Karnataka state (Mysore) is another important source of ruby in India. This source produces mainly cabochon and bead quality. Facet qualities are rare. Star rubies of low quality are found at both of the above sources. India exports large quantities of this low-grade star material. Owing to the heavy cracking, ruby beads manufactured in India are frequently dyed to improve the colour.

Sri Lanka

In the south-west part of the island of Sri Lanka (formerly Ceylon) are found corundums of many colours – blue, violet, purple, yellow, orange, white, and red, from a light pink through a deep crimson. No other source produces a greater variety of hues. Although most Sri Lankan rubies tend towards pink, and the blue sapphires tend to be light in colour, large specimens of fine colour are occasionally found. Star-stones, too, are plentiful on the island, and the world's museums contain some spectacular specimens in both red and blue colours, including the Rosser Reeves star ruby (138.7 carats) at the Smithsonian. The 392 carat star sapphire owned by the State Gem Corporation of Sri Lanka is one of the finest in existence.

Pit mining is carried on in Sri Lanka in a similar manner to the Burmese system. The miner searches for the small and scattered localities by observing the surface for signs of rolled pebbles. These localities are often in the rice fields, and having found what he hopes will be a good spot, the miner sinks a pit which goes down maybe 15 m to reach the gem-bearing stratum, known as *illam*. Sometimes the gems are found embedded in boulders of semi-decomposed gneissic rock. If the miner is not successful with his first pit, he must fill it in and start another somewhere else. If he strikes gem gravel, then it is brought to the surface and panned by the use of a finely woven basket. The concentration in the bottom of the basket is known as *dullam* and is searched for gems, which are then sold.

Virtually all Sri Lankan gems are cut and polished by native craftsmen on the island. Squatting outside a cottage, or in a back alley, the cutter fashions the corundum gems on a small wooden wheel mounted at the end of a horizontal shaft which is rotated by a drawstring bow, which he saws back and forth. For polishing, a chamois leather pad is fixed over the vertical lap, and the stone is usually held in the hand while being cut and polished. Sri Lankan cutting is often poor, with too much emphasis on retaining weight, but a few firms on the island do better work. Much blue sapphire from Sri Lanka is parti-coloured and the wily native cutters cut such stones with the blue colour at the bottom of the pavilion, so that by total internal reflection the stone when viewed from the top appears a good blue colour; such stones looked at sideways are found to be colourless at the top with a patch of blue near the culet and are termed *ottu*. Some blue sapphires from the island contain a trace of ruby and although they are a good blue colour in daylight they change to purple in artificial light.

In common with many stones of other species that are found in Sri Lanka, the corundum often show included small crystals of zircon, surrounded with circular dark areas where stresses from the zircon have affected the surrounding host mineral. These inclusions are usually known as 'zircon haloes'. In addition to corundums, many other gems are found in Sri Lanka. No other country produces a wider variety.

Starting in the late 1970s, Thai traders began descending on Sri Lanka and buying up a milky corundum locally termed *geuda*. This was brought back to Thailand and heat treated, producing clear stones of deep blue and yellow colours. Unfortunately, such heated stones were accepted by many traders as natural, thus encouraging the practice. Today over 90 per cent of all rubies and sapphires from all sources are heat treated. The result has been the disappearance of natural-coloured rubies and sapphires from the market.

China

With the opening up of China and the conversion to a market-oriented economy, gem deposits are being actively explored. Corundums occur in several locations, the most important of which are the sapphire deposits of Hainan Island in the south and Shangdong province in the north. In both locations the sapphires occur in blue, green and yellow colours and tend to be dark owing to their iron-rich basalt origin.

Afghanistan and Pakistan

There is a small deposit of ruby at Jagdalek, in Afghanistan, some 50 km east of Kabul. This mine is believed to be centuries old. Material found here is of good colour, being derived from a marble, and some faceting material is produced. Stones often contain small blue patches in the ruby, similar to Vietnamese rubies.

Rubies are also found in the Hunza valley in northern Pakistan. In this district, mica schists are traversed by crystalline marbles in which ruby crystals up to nearly 50 mm in length are found, together with well-formed spinel crystals and chrome diopside. Though the colour is good, little faceting material is found, most being of cabochon grade. So free are these stones from the traces of iron which are usually present in natural rubies that the stones, when tested in the London Gem Testing Laboratory, showed a pronounced red afterglow following a fluorescence test under X-rays.

Australia

Corundum, mainly of blue, green and yellow colours, and some ruby, are found in Queensland and New South Wales. All of the Australian deposits are derived from basalt flows and thus tend to be dark owing to the high iron content. Heat treatment can lighten this colour somewhat by removal of the rutile silk.

Queensland Fields

The Queensland sapphire fields are located around Anakie and cover some 500 km^2. Ruby Vale is a prominent locality for Queensland corundum and at Willows, some 350 km west of Rockhampton, a 217.5 carat yellow sapphire was found in 1946. The Anakie deposits, discovered in 1879, are along the banks of creeks and not in the beds of the present streams, the stones being found in a clayey, or loose and friable, alluvium. Owing to the arid nature of the area, sluice-boxes are not often used and the mining is carried on by hand-picking and by the use of hand-sieves. The Lava Plains area of Queensland also produces some blue sapphire.

New South Wales Fields

The New South Wales deposits, which are centred around Inverell, west of the New England Range, lie in the north-east part of the state. The sapphires are found in an alluvial deposit of recent age, and here the mining is carried on by dredging and the sapphires are reclaimed by the use of sluice-boxes and pulsators. During the past three years, production in the New England district has dropped dramatically.

Although Australian blue sapphires are usually rather dark and somewhat inky, the yellows are of an attractive greenish-yellow; Australia produces probably the best of the green stones. The greenish tinge of the stones is due to iron, and this is shown by the strong 450 nm complex seen in the absorption spectrum, by the slightly higher RI and SG and by the lack of luminescence under UV light. Australian corundums usually show dark feathers, but also show strong colour zoning. Some sapphire is found, too, in the north-east part of the island of Tasmania.

In 1978, rubies of poor cabochon grade were recovered from a shallow subsurface deposit on the Hart Range, north-east of Alice Springs.

United States of America

The only important locality for gem corundum in the United States of America is in Montana, where fancy sapphires are found as water-worn pebbles in the gravel bars of the Missouri river, and at Yogo Gulch, near Utica, where flat gemmy crystals of light to medium blue are found in a nearly vertical and much weathered dark-coloured fine-grained igneous dyke. Yogo crystals are usually small (less than 0.30 carats rough), but when a large piece is found the colour is extremely fine; this is quite rare. On the other hand, stones from the Missouri River and from Rock Creek often cut to well over 1.00 carat, but the colour tends to be more greenish or yellowish. Many attempts have been made to mine the dyke at Yogo, including several recent ones, but all have failed, largely because of the small size of the recovered sapphires.

Small rubies of poor quality have been found in Macon County, North Carolina, the stones being found in the sands of Cowee Creek. Blue sapphire is said also to occur in Colorado and Idaho.

Africa

Many gemmologists and dealers believe that Africa is the source of the future. It is a large, little explored continent with tropical areas full of well-sorted sediments, and the potential appears great. Since the 1960s, Africa has been home to many important gem discoveries, including diamond, ruby, sapphire, zoisite (tanzanite) and green garnet, to name but a few.

Kenya

In the year 1973, American geologists Tim Miller and John Saul discovered ruby in Kenya's Tsavo West National Park, in the area of Mangari. Although material clean enough to facet was rare, the colour of the material was excellent. In a scandal reaching to the highest levels, the Kenyan government illegally took control of the mines. The mines were eventually restored to their rightful owners, and today the so-called John Saul mine continues to produce good cabochon-grade material, along with some faceted stones. Much of the material is brought to Bangkok for cutting and heat treatment.

Sapphires of blue, green and yellow colours are mined over a widespread area in the Turkana district of north-western Kenya. These are believed to be derived from basalt flows and are generally dark in colour.

Tanzania

There are three major corundum-producing areas of Tanzania: Longido, Umba and Morogoro. The first discovery of corundum in Tanzania dates back to the early 1900s. A German officer stationed on the Kenyan border at Mt Longido found ruby in the area. The material has quite a unique appearance, occurring in a bright chrome-green zoisite rock. Most of the material is too heavily included for faceting; instead it is cut as cabochons or often used as a carving material. Faceting material is extremely rare from this deposit, which is still worked to this day.

But Tanzania's main claim to corundum fame is the fancy corundum found at the Umba river valley in north-eastern Tanzania, near the Kenya border. Corundum was first discovered at Umba in the 1950s, by a Tanzanian of Greek origin. The occurrence is quite interesting, with the corundums mined from several pits in and around a greyish-green serpentine pipe measuring about 2.5 km long and 1 km wide. The sapphires and rubies of Umba occur in various colours, including reds, oranges, blues, greens, yellows and mixtures of these colours which defy conventional description. Parti-coloured stones are also found. Currently (1992) there is said to be no production at Umba.

Other sources of gem corundum in Tanzania include the ruby deposits in the western Uluguru mountains near Morogoro, which started producing in the 1970s. The mines from Morogoro are spread over a large area, including Matombo, Kitonga, Epanko, Ruaha, Lukandẹ, Mayote and Kitwaro. Mostly cabochon-grade material is produced here, including star material.

Nigeria

Starting in the late 1970s, corundums of a blue, green and yellow colour began appearing in world markets. These are basalt-derived stones and tend to be dark in colour. The mines are located in the Kaduna district.

Malawi

During 1958, the existence of corundum on the Chimwadzulu hill in southern Malawi (formerly Nyasaland) was reported. In 1965, a claim was pegged for the mining of these sapphires and rather pale rubies by a London consortium. A number of stones were mined by the company, but the mines were eventually taken over by the Malawi government. The corundum occurs *in situ* in an amphibolite rock and the cut stones vary in colour from pink to yellow, orange and green to a good blue colour.

Other African Sources

Sapphires of various colours were once found in Namaqualand in Namibia and opaque ruby suitable for cutting into cabochons was found in the north-eastern Transvaal. Similar red crystals are found in Madagascar at Gogogogo, east of the Linta river in the south-western part of the island. The matrix is said to be a green mica schist. Sapphire is also said to have been found in Madagascar.

In earlier days a small number of corundums of various colours were found in the Somabulu forest in south-western Zimbabwe and a deposit of sapphire has recently been found in a pegmatite mine and in alluvial gravels in north-eastern Zimbabwe. Many of these African sapphires have rather unusual colours, including some which show a colour change, and the usually stumpy hexagonal crystals often show a core of different colour.

Other World Corundum Occurrences

Corundum is of widespread occurrence, but the above-mentioned occurrences are the important gem localities for ruby and sapphire. Sapphires of dark blue colour have been found near Jauru, by the Coxim river, in Mato Grosso, Brazil.

Ruby and sapphire are found in the Rio Mayo, a tributary of the Patia, and in the sands of the Platayaco, in the Caqueta territory of the South American republic of Colombia. Gem corundum has been mentioned as being found in Norway and Finland: in the latter poor-quality star-stones are produced. There are said to be occurrences in Czechoslovakia, the Ural Mountains of Russia, and in Romania and Borneo.

4

Emerald, Aquamarine and Other Beryls

Chemical and Physical Properties

Emeralds and aquamarines are colour varieties of the mineral known as beryl, which, besides these well-known gemstones, may be found in other colours to give such attractive if lesser-known gems as the lovely rose-pink morganite, the rich yellow heliodor and the colourless goshenite.

Beryl is a silicate mineral in which the silicate molecule combines with the metals aluminium and beryllium. The chemical formula is $Be_3Al_2(SiO_3)_6$, but considerable replacement of the beryllium and aluminium ions occurs. Beryl of non-gem quality is mined as the raw material for beryllium which is now increasingly used in industry.

Beryl crystallises as six-sided prisms which belong to the hexagonal crystal system. The terminations, in the case of emerald, are usually flat faces joining the prism faces, producing the hexagonal prism of solid geometry. With the other colour varieties, and in a few cases emerald also, small pyramidal faces bevel the junction of the flat (basal) face and the prism faces. The atomic structure is formed by Si_6O_{18} groupings as independent sixfold rings formed by six SiO_4 tetrahedral groups linking through oxygen atoms. These rings are further bonded with the fairly small aluminium and beryllium atoms which serve to bind the rings tightly together, both laterally and vertically, and create vertical channels occupied by water and charge-compensating ions of the alkali metals such as lithium and magnesium. This strength of bonding cancels out the possibility of prismatic cleavage and allows only an ill-defined and poor cleavage parallel to the basal plane. The hardness of beryl is 7.5 on Mohs's scale. In view of the importance of the beryl gems, and for the reason that the different varieties have slightly different physical properties, the varieties will be discussed individually.

Emerald

Lore and History

The name emerald is derived from a Persian word, which later appeared in the Greek as *smaragdos* and then as *smaragdus*. From this derivative the altered forms *esmeraude*, *émeraude* and *esmeralde* were derived, the present form not making its appearance until the sixteenth century. The name emerald has always been used for a green-coloured mineral, but often not for the emerald we now know.

A stone that was offered nearly 4000 years BC in Babylon, the earliest known gem market, emerald was dedicated by the ancients to the goddess Venus. The birthstone for May, emerald is steeped in superstition and lore. It is the symbol of immortality and the symbolisation of faith, and by changing its colour is said to reveal the inconsistency of lovers. Emerald is said to be beneficial to the eyes.

Historically the earliest known locality for emerald was the group of mines by the Red Sea in Egypt, the so-called Cleopatra's emerald mines. These mines were probably worked some 2000 years BC and from them came most of the emeralds used in the ancient jewellery. The location of these mines was completely lost during the Middle Ages and was not rediscovered until 1818 when Cailliaud, who had been sent by the Viceroy of Egypt to search for them, at last found the ancient workings. The mines are in the hillsides of Djebel Sikeit and Djebel Zabarah in northern Etbai: the hills lie parallel to, and some 27 km inland from, the Red Sea and about 160 km north-east of Aswan, the ancient Syene. There are hundreds of shafts in the ancient mines, some of which had workings extending to a depth of some 44 m, and in which tools and appliances dating back to the times of Sesostris (1650 BC) were found. Sporadic attempts have been made since the rediscovery to work the mines but, owing to the poor quality of the flawed crystals found in the micaceous and talcose schists which form the mother rock, the workings have been found unprofitable. The emerald mines of Djebel Zabarah were recently rediscovered by the Italian-led Castiglioni expedition. The story of this expedition, together with a description of the mines and their emeralds, can be found in the July 1990 issue of the *Journal of Gemmology*.

Colorisation

Emerald owes its verdant green colour to traces of the chromium (Cr^{3+}) and vanadium (V^{3+}) ions. Chromium also gives ruby its magnificent red colour. The mechanism of this change of colour is considered to be due to the difference in intensity and in the wavelength position of the broad absorption band which is such a characteristic feature of the absorption spectra of chromium-coloured minerals. The sharp bright lines in the red shown by the fluorescence spectrum of emerald tend to prove the small-scale isomorphous replacement by the chromium atom, as in ruby. Traces of iron are usually present in emerald and this again may have some bearing on the final shade of colour, as indeed it may have on certain other properties.

Austria

Said to have been known since the time of the Romans, there is an occurrence of emerald in a very inaccessible spot some 2300 m above sea level, on the east side of the Legbach ravine, a branch of the Habachtal, in Salzburg, Austria. The occurrence is of little importance, but mining by irregular methods has been carried on intermittently through the years, and in 1937 the mine was reopened on a small scale. Since World War II some crystals have been seen but whether these are from the 1937 working or from a resumption of mining since the war is not certain. The simple hexagonal crystals are found in a mica and chlorite schist, a type of mother rock similar to that of the Uralian source. Thus the inclusions seen in the Habachtal emeralds are in general similar in type to those seen in the Russian emeralds, that is tremolite rods and mica plates with rounded outline. The specific gravity of the Salzburg emeralds approximates to 2.73 and the indices of refraction are ordinary 1.591 and extraordinary 1.584, showing a double refraction of 0.007.

Colombia

Who first discovered the lovely green crystals found in the Andes of Colombia, which give to this South American country the honour of being the source of the world's finest emeralds, will never be known. It is quite evident that the native Indians realised something of the value in the emeralds which they had used for barter with other neighbouring tribes, and which probably extended to those as far north as Mexico, and south to Bolivia and Peru. Despite 300 years' diligent search no other emerald-bearing areas outside Colombia have been found in the Andean ranges, or in Central America or Mexico. The so-called 'Peruvian' or 'Mexican' emeralds were in all probability products of the ancient Colombian mines.

Europe first knew of the fabulous emeralds from South America when Pizarro ruthlessly conquered and despoiled Peru, taking from the Incas an immense quantity of emeralds, many of incredible size being sent to the Queen of Spain. Subsequently the old native workings in Colombia were found by the Spanish invaders and worked by them; they shipped the stones, both those mined and those taken from the Indians, to Spain where they were later sent to Paris for sale.

The emerald mines of Colombia are situated in the Cordillera Oriental, the eastern range of the Andes. They lie north to north-east of Bogotá, the Colombian capital, in the departments of Boyacá, Cundinamarca, and Santander. Colombian emeralds are mined from two zones: the western zone that hosts, from north to south, the Peñas Blancas, Cosquez, Muzo and Yacopi mining regions, and the eastern zone that hosts the Chivor/Somondoco and Gachala mining regions.

The Chivor Mines

The first indication of the source of the South American emeralds came in 1537 when Gonzalo Jiménez de Quesada conquered Colombia, and was presented with nine green stones by the inhabitants of the town of Guachetá. Although the Indians carefully guarded the whereabouts of the mines, a youngster gave the invading forces the information that the emerald mines were at Somondoco, the mines now best known as El Chivor, so Chivor should be the first to be revealed of the famous South American emerald mines.

The Chibcha Indians of the high plateau of Colombia mined emeralds from Chivor before the Spanish conquest; the stones recovered were traded for gold from the Indian tribes across the Magdalena river. Some time after the Spanish subjugation of Colombia the *conquistadores* worked the mines of Somondoco. In 1592 Francisco Maldonaldo de Mendoza built an extensive viaduct, remnants of which still exist, in order to supply the water necessary to wash the mining debris away. Within 100 years the mines were abandoned, either because of the lack of a successful yield or because of the discovery of the fruitful mines at Muzo some 250 km to the north-west. Chivor died out as a mine and the prolific growth of tropical vegetation effectively hid the workings for over 200 years.

After a long search the Somondoco-Chivor mines were rediscovered by Don Francisco Restrepo in 1896. Restrepo had nothing to go on except a note in a chronicle written by a friar on the Spanish Conquest, which said 'The mines of Chivor are situated on the point of a ridge from which the llanos of the Orinoco can be seen.' The Chivor Mining Company was formed by Restrepo but, although the state tax was paid for 20 years, the mine was not successfully worked. The rights to the emerald mining at Chivor passed to a German commercial group just before World War I and they, after having the report of R Scheibe, sent, during 1911 and 1912, Fritz Klein to test the mine workings. The outbreak of war in 1914 stopped further exploitation by the company. In 1919 the mines passed to an American company, the Colombian Emerald Syndicate Ltd, which was converted in 1926 into the Colombia Emerald Development Corporation of New York, and in 1927 P W Rainier took over the management of the mine for the lessors. The mine had many vicissitudes with periods of inactivity and bursts of frenzied activity. It was being worked in 1937, but little is known about the war years; indeed there was little knowledge at all concerning the mine until 1950 when R W Alderton became manager. At the end of 1951, owing to litigation and depredations by the local banditry, Chivor ceased working and was for all intents and purposes closed. After some years in receivership the Chivor, Colombia's only privately owned emerald mine, is once again producing variable amounts of commercial emerald.

The emeralds of Chivor are found near the summit of the mountain overlooking the headwaters of the mighty Orinoco river. When the Spaniards mined for emeralds they chose the western slopes; recent mining, however, is carried out on the slopes facing the east. Until tunnel mining commenced, mining was of the traditional terrace type, in which the emerald-bearing veins were exposed by digging horizontal terraces in step-like formation along gullies, and washing the debris away with water released from a lake-like reservoir above the cuttings.

The emeralds are found in vein-shaped cracks some 200 mm wide and varying in length up to 70 m. The crystals are usually in 'strings' or in 'nests' (pockets) containing anything from a few to over a hundred crystals. As the emerald pockets are approached there are showings of *moralla*, an uncrystallised form of green beryl, and this gives an indication that the miner may soon find a pocket of *canutillos*, the Columbian miners' name for good-quality emerald crystals.

The crystals, usually of a good blue-green colour, are unfortunately often shattered owing to the force of earlier geologic cataclysms. The crystals take the usual hexagonal prismatic form but often show small pyramidal faces. Often they are found loose in the pockets owing to their having been weathered out from the parent rock, and such emerald crystals are covered with a tenacious coating of limonitic red iron oxide. This coating needs to be cleaned off by acid in order to see the quality of the emeralds, which are then sorted into five qualities or grades.

The emeralds of Chivor have an SG of 2.69, and median refractive indices of 1.579 for the ordinary ray and 1.579 for the extraordinary ray, with a birefringences of 0.005–0.006. Chivor stones usually show a fairly strong red under the colour filter and a red fluorescence when bathed in ultra-violet light and therefore behave somewhat like the synthetic stones. The inclusions seen in Chivor emeralds (*Figure 4.1*) are the three-phase types common to South American emeralds, but most typical of Chivor stones are inclusions of well-formed crystals of pyrites.

The Muzo and Cosquez Mines

The world's most beautiful emeralds are said to come from the mine at Muzo which, with the mine at Cosquez, 10 km to the north-north-west, is owned by the Empresa Colombina de Minas (Ecominas) of the Colombian government and leased to private enterprise on a ten-year lease basis. Emeralds from the

Figure 4.1 Three-phase inclusions in a Chivor mine emerald

Muzo and Cosquez mines may be legally marketed by the lessees after the value of their production has been determined by representatives of Ecominas.

The geology of the area is fundamentally similar to that of Chivor, but the emerald-bearing veins, containing calcite, quartz, dolomite and pyrites, run through a black carbonaceous limestone and shale which form the country rock. The crystals, embedded in the vein material, have the simple forms of the hexagonal prism closed with basal pinacoids. The Spaniards mined Muzo by driving adits, but the method of terracing and washing away the debris is now employed. In contrast, until relatively recently, lack of water and hard emerald-bearing rocks have made tunnelling the chosen method for mining emerald at Cosquez.

The yellowish-green stones from the Muzo district have a warm velvety appearance which is most prized. The specific gravity of the Muzo emeralds is generally slightly higher than for the Chivor stones; the SG is 2.70 and the median indices of refraction are for the ordinary ray 1.580 and for the extraordinary ray 1.570, the double refraction being 0.005–0.006. Muzo stones usually show the typical three-phase inclusions (*Figure 4.2*) of a bubble of gas in a liquid and a cubic crystal of sodium chloride (common salt), contained in a flat cavity having spiky or jagged outlines with tail-like appendages (*Figure 4.3*). Pyrites crystals, so common in Chivor stones, are not seen as an inclusion in the emeralds from Muzo and Cosquez, but occasionally there is seen in Muzo emeralds yellowish-brown prismatic crystals of the rare-earth mineral called parisite, a fluocarbonate of cerium, a species whose type locality is the emerald mines of Muzo.

Figure 4.2 Three-phase inclusions in a Colombian emerald

While best-quality Muzo emerald tends to have a well-saturated slightly yellowish-green colour, Chivor emeralds tend to have a slightly less saturated bluish-green colour. Although Cosquez emerald occurs in a range of colours and clarities, in best qualities it has a dark, slightly bluish-green colour. Owing to poor security, little is known of the Cosquez mine. However, a recent informed estimate suggested that more than 150 000 carats of emerald are being mined annually from the Cosquez mine. Large amounts of pale green emerald are presently being mined from the Yacopi mine, 15 km to the south of Muzo.

Figure 4.3 Spiky flat cavities in a Colombian emerald

Figure 4.4 End and side views of two trapiche emeralds from Colombia

During 1964 a new type of emerald crystal was encountered (*Figure 4.4*). Originating from Colombia, it consists of a central hexagonal prism of green colour from the prism faces of which six prisms of similar colour appear to have grown outward. The interstices between these 'radial' prisms are filled with a fire-grained mixture of colourless beryl and albite. The whole forms a complete hexagonal prism that may attain a length of 250 mm and a width of 10 mm. The crystals are called 'trapiche emeralds' from the Spanish word for cane-crushing gears. The green sections of the crystals are cut into small stones which characteristically have a cloudy appearance and show fine straight striations internally. These trapiche emeralds are found in both the Chivor and the Peñas Blancas mines of the Muzo district. In the stones from the Chivor mine the central core is green but in the Muzo stones it is black owing to the presence of carbonaceous inclusions.

Brazil

The belief in medieval times that there was a fabulous source of emeralds in Brazil contributed in no small degree to the opening up of the interior of this vast country. The first expedition set off in 1554 under the leadership of one Bruzo Espinoso and a Jesuit priest. This expedition, and also a second under Martin Carvalho in 1567, failed to find the source of the coveted gem. The name of Sebastio Fernandes Tourinho brings interest to the stories of the search for emerald in Brazil, for he made three journeys into the interior, the first in 1555 and the third and most important in 1572. Taking his followers into the 'barbarous forests of the Rio Doce' he eventually reached the watershed dividing the rivers flowing east from the tributaries of the Jequitinhonha and the Arassuahy. There he was said to have found many stones of diverse colours, and finally emeralds themselves. On his return to Porto Seguro the stones were sent to Portugal where they were pronounced to be 'emeralds from the surface baked by the sun, and stones that the earth had rejected as refuse'. It was suggested that better stones would be found by digging deeper.

This 'digging deeper' suggestion led to more expeditions which were in the main organised by the Governor of Bahia. In 1574 Antonio Dias Adorno left with 650 followers and many slaves but failed to find anything but 'baked emeralds'. Twelve years later Martin Cao searched along the Rio Doce das Esmeraldas but found no emeralds; however, he made a name for himself by his inhuman treatment of the Indians he took as slaves. Marcos de Azeredo Coutinho took out an expedition in 1612 and he did find green stones which were reported by Portugal to be emeralds. Coutinho died without revealing the secret of the locality. Five more expeditions, two led by the sons of Coutinho, failed to find the emerald area; but in 1674 a sixth expedition under Fernao Dias Paes Leme from São Paulo did find Coutinho's locality of the green stones. Leme died without suffering the disappointment of knowing that the stones never were emeralds but only green tourmalines. The last expedition was organised in 1713, but its only claim to success was the discovery of the alluvial gold of the Rio das Contas.

Eventually the source of the Brazilian emerald was found at Brumadinho in Bahia, and emeralds were later located in the Rio Doce area. Therefore, were Coutinho's emeralds genuine or were they misidentified in Portugal? More recently deposits of emeralds have been found at Vitoria da Conquista in Bahia, at Itaberai in Goiás and Ferros in Minas Gerais. In 1913 a find was made at Brumado, formerly Bom Jesus dos Meiros, in Bahia, where the crystals were found in cavities in an altered marble capping a mountain. The crystals, often much flawed, are hexagonal prisms with basal pinacoids, and the edges truncated with small pyramidal faces. The yield is small and the mining primitive. About 1964 an extensive find of what appears to be a source of excellent grade of emerald was made in the Carnaiba Mountains near Campo Formoso in Bahia. These emeralds are found in a mica schist.

According to Dr Deitmar Schwartz, emerald occurs in four of Brazil's eastern states: at Itabira, Capoeirana, Santana dos Ferros (Minas Gerais), Fazenda das Lajes, Santa Terezinha de Goiás, Pirenopolis, Porangatu (Goiás), Fazenda do Pombo, Acude do Sossego, Brumado, Carnaiba; Salininhas, Socoto (Bahia), and Taua (Ceará). The SG of Brazilian stone varies from 2.68 for Brumado emerald to 2.76 for Santa Terezinha emerald. Median refractive indices vary from a low 1.573 (ordinary ray) and 1.570 (extraordinary ray) with birefringence 0.005–0.006 for Brumado emerald, to a high 1.595 (ordinary ray), 1.580 (extraordinary ray) and birefringence 0.008 for Santa Terezinha emerald. The Brazilian emeralds which appeared on the market about 1900 were a pale yellowish-green, and so resembled ordinary green beryl that at first they were rejected as imitations. Brazilian emeralds may be fairly free from inclusions which further tends to give the impression that the stones are just green beryl rather than true emerald, but the existence of a chromium absorption spectrum effectively proves that the stones are true emeralds, by traditional definition. When the internal features of schist-type Brazilian emeralds are examined they are usually included by two-phase tubes and partly 'healed' fractures, as well as one- and two-phase cavities of less regular outline. Included minerals tending to characterise emerald from specific Brazilian mines include: Santa Terezinha mine, chromium spinel, pyrite, calcite-dolomite, talc; Belmont mine, Itabira, biotite-phlogopite mica, quartz, tremolite, dolomite, andesine, apatite, hematite; Fazenda Piabas mine, Socoto, biotite-phlogopite mica, talc, chlorite, actinolite-tremolite, allanite, apatite, quartz, feldspar, calcite-dolomite, tourmaline, hematite, molybdenite, pyrite, chromite, beryl. One of the difficulties, indeed dangers, of Brazilian emeralds is that the Brazilians are prone to impregnate all their crystals with colourless oils and plastics to make the flaws less visible and to 'improve' the colour. The danger is that when these impregnators dry out or decompose the emeralds become much less desirable.

Green beryl crystals which seemed to have been first found about 1962 and later came on the market emanate from the district of Salininha, near Pilão Arcado, Bahia. These crystals posed a problem in nomenclature for they were found to be coloured by vanadium and there was only the merest trace of chromium present. At that time it was considered that these crystals should not be called emerald and should be known as green beryl, despite their pale emerald colour.

Russia

The source of the Uralian emerald was found quite accidentally when in 1830 a peasant noticed some green stones at the foot of a tree torn out by a storm. After the discovery large government mines were sunk in the dense forest amid marshes some 90 km north-east of the town of Sverdlovsk, which in the heyday of the Russian Empire was known as Ekaterinburg. The mines are on the Asiatic side of the Ural Mountains and on the Takovaya river. The crystals – which are generally large, cloudy and of poor colour, although smaller stones of good colour form valuable stones – are found in a mica schist which is interfoliated with chlorite-actinolite and talc schists. The crystals are found in this locality in association with the other beryllium minerals chrysoberyl and phenacite, and with common beryl. In recent years the Malysheva mine, in the old Takovaya river mining area, has once more begun supplying Western gem markets with this historic emerald.

Russian emeralds have an SG rather higher than the emeralds from sources previously discussed, ranging between 2.71 and 2.75. The median refractive

Figure 4.5 Large actinolite crystal in a Russian emerald

indices are 1.588 for the ordinary ray and 1.580 for the extraordinary ray, the double refraction being 0.006–0.007. While actinolite needles, as single individuals (*Figure 4.5*) or dishevelled groups, and biotite-phlogopite mica plates were described as characteristic inclusions in previous editions of this book, a recent examination of 100 newly mined and 20 older Uralian emeralds, by Schmetzer *et al.* (*Gems and Gemmology*, Summer 1991) indicated that the characteristic inclusions of Uralian emerald (healed fractures, tubes parallel to the *c*-axis, flat cavities at right angles to the *c*-axis, growth banding, and biotite-phlogopite mica) are common to emeralds from other sources.

Australia

The first discovery of emerald in Australia was in 1890 when W A Porter, while prospecting for tin, found green crystals in a dyke offshoot from a griesen granite where it had taken on the form of pegmatite. The locality is some 14 km north by east of Emmaville in New South Wales. Professor David inspected the site in 1891 and found the crystals to have an SG of 2.67, and to be intercrystallised with topaz frequently penetrating fluorite as delicately acicular prisms, or sometimes embedded in a kaolinised rock and occasionally surrounded by mispickel. In that year a crystal weighing 23 carats was found completely embedded in mispickel. In 1891 and 1892 the mine was worked by the Emerald Proprietary Mines, who mined some 25 000 carats of emerald each year. Since then the mines have closed down and have only been worked sporadically by prospectors. Pale green Emmaville emerald has an SG of 2.67, and median refractive indices of 1.575 for the ordinary ray and 1.570 for the extraordinary ray, the double refraction being 0.005.

In 1909, a tin prospector named Ryan found in a biotite schist and in pegmatite dykes another source of emerald at Poona, a place some 65 km north-west of Cue in Western Australia. In 1912 the state mining engineer made an independent discovery in the area. He secured several promising stones that were cut in Sydney and in London.

In the same year Pearl opened up one of the deposits and found them nearly worthless, but two fine stones were sent to Paris for cutting, one of which weighed 5 carats and was sold for £100 to the Montana Sapphire Syndicate, who resold it for £170. This Montana Sapphire Syndicate then took over the mine and spent £5000 on equipment but the outbreak of World War I stopped the project. After this war the mines at Poona remained more or less dormant until the Star Emerald Syndicate commenced development. Since 1936 Poona emeralds have been intermittently mined by a series of hopeful entrepreneurs. The most recent lessee, Poona Emeralds, ceased commercial mining in 1990.

The Poona emeralds are associated with quartz, albite, oligoclase, topaz, tourmaline and fluorite, and the micas biotite, muscovite, lepidolite and zinnwaldite. The stones are mostly pale in colour and badly flawed, but some are found which are a fine colour, including one embedded in a small quartz leader in the dark biotite schist. Batchelor reports one fine stone of 30 carats from the same locality.

Poona emeralds have an SG of about 2.69, and median refraction indices of 1.578 for the ordinary ray and 1.572 for the extraordinary ray, with a double refraction of 0.005–0.007.

Good-quality emerald has also been mined from two pegmatites that intrude peridotite 50 km west of Menzies, and 150 km north-north-west of Kalgoorlie, Western Australia. Menzies emerald contains 0.33 per cent chromium, and has an SG that ranges from 2.71 to 2.75, and median refractive indices of 1.581 for the ordinary ray and 1.573 for the extraordinary ray, with a double refraction of 0.008.

A few small crystals of emerald which reached some 10 mm in length were found in the Wodgina district of Western Australia, but they were too turbid and flawed to be worth cutting. In 1961 there was a newspaper report of an emerald find in the 'Pilbara field'. This may of course be a continuation of the Wodgina deposit as both lie near by and just south of Port Hedland on the north coast. In South Australia a few poor emeralds have been found near Mt Crawford near Williamstown, where they occur with aquamarine and heliodor in pegmatite. The occurrence at Mt Remarkable in the same state, which was mentioned by Bauer, seems debatable, for there appears to be no record of it in the South Australian Department of Mines publications.

South Africa

In the year 1927 beryl crystals, many of which had the colour and other qualities of true emerald, were found some 20 km east-north-east of Gravelotte station in the Leysdorp district of the Letaba area of north-eastern Transvaal. The deposits are associated with acid pegmatite inclusions in biotite, chlorite and actinolite schists belonging to the Swaziland system. The gemmy crystals occur almost invariably in the biotite schists at or near contact with the pegmatite bodies. Associated with the emeralds are such minerals as quartz, apatite, schorl, molybdenite, pyrite and feldspar.

The crystals have unusual prismatic form and range in size up to 50 mm or more in length, but most often they are variable in colour, cloudy, cracked and flawed. Some clear pieces, however, have been sold for £100 per carat for cut stones. The flawed material is usually cut into cabochons.

In 1929 some five companies operated in the area, including the Beryl

Mining Company's Somerset mine which was worked by a shaft and by open-cast mining. This mine was installed with mechanical treatment plant capable of treating up to 200 tonnes of emerald-bearing schist per day. This recovery plant used a modified form of tube mill to separate the emerald crystals from the enveloping mica schist. During the period before World War II the only consistent producers were the Somerset mine and a mine operated by Cobra Emeralds Ltd, and in 1930 some 5.5 kg of emerald crystals were being sent to London cutters each week.

During the slump, of 1930 and 1931 most of the workings were abandoned, or at least ceased working, and this included the Somerset mine. In 1934 increased demand opened a new interest, but the only consistent producer was the Cobra Emerald Mining Company. Mining during the war years to all intents and purposes ceased, except perhaps for the winning of crude beryl for beryllium. After the war the mine restarted, but until recently productivity has been marred by the trade boycott with India which took much of the poorer flawed material for cutting into cabochons to be used in native jewellery.

At one time an emerald cutting project was started in Johannesburg but the endeavour did not bear fruit. In 1947 there was talk of reopening the Somerset mine by the Beryl Mining Company, which, it seems, is still in existence, as is the Cobra Emerald Mining Company with their New Chivor mine. Other mines operating in the Gravelotte district include the New Hope and Lone Hand mines.

It is said that emeralds have been recovered from biotite schist at Uitvalskop in the Schweizer Reneke district of Transvaal, and near Baviaanskop in biotite and in lenses of quartz. There is, too, a report of emeralds being found in the Kalahari desert, but no details are forthcoming.

Transvaal emeralds have a somewhat higher refractive index than for most other emeralds, typical values being 1.593 for the ordinary ray and 1.586 for the extraordinary ray, the birefringence being 0.007; the SG is near 2.75. The inclusions are typically brownish mica plates and if these are profuse they tend to make the stones dark or even brownish. When observed, silver-grey molybdenite inclusions suggest Gravelotte as a possible source. The South African emeralds rarely show red through the Chelsea colour filter and hence have at times been rejected as imitations.

Zimbabwe

During 1956 the prospectors Contat and Oosthuizen discovered emeralds in the Belingwe district in the southern part of the country. The occurrence is located in the Mweza Greenstone Belt, in the Sandawana Valley, on the south side of the Mweza Range, the crystals being in a tremolite schist bordering pegmatite dykes. The crystals are usually small although cut stones of one or two carats have been obtained, the stones being of excellent green colour. Sandawana emeralds have an SG of near 2.75, and median refractive indices of 1.590 for the ordinary ray and 1.584 for the extraordinary ray, with a double refraction of 0.006. The inclusions are rather typical tremolite needles, either as short rods or as fine, often curved, fibres, and garnets having a yellowish limonite halo. Some Zimbabwean stones have been seen to show colour zoning.

Zimbabwean emeralds seem to be inert under ultra-violet light and show a weak reddish under the Chelsea colour filter. Emeralds are found over a fairly wide area but the stones from other mines do not seem to compare with the stones from Sandawana valley. Other mines are the adjacent Machingwe mine, the Belingwe mine and the Mustard, Flame Lily and Cohen's Luck claims which lie in the Filabusi Greenstone Belt to the north-west of Sandawana, and the Chikwanda, Novello, Twin Star and Mayfield claims in the Victoria Greenstone Belt to the north-east. The legal position in Zimbabwe, where it is an offence to deal in uncut emeralds without a licence, has led to a unique situation. Analyses of some stones from the Mustard and Pepper claims have shown 1 to 2 per cent of chromium oxide but, as the spectroscope has not apparently shown up the chromium lines, the stones are, for economic purposes, just green beryl.

India

The emerald has been held in high esteem in India from ancient times but, until the find in 1943, a source of true emerald in India was not known. A number of references are extant as to Indian emerald sources, but despite careful investigation no proof of an emerald locality in India was forthcoming. The locality called Canjargum or Cangagam, given as a source of Indian emeralds, seems to refer to the aquamarine mines of Padyur near Kangayam in the Coimbatore district of Madras. It is interesting to note that some small green rolled pebbles, which the natives had regarded as emeralds, had been found at Ajmere, Rajasthan, which is perhaps better known as the old state of Rajputana. Although these stones were officially understood to be ordinary green beryls, in the light of the 1943 discovery there must always be doubt whether or not emerald has been mined in days long past.

Even if emerald was mined in India in the past it would not account for the vast quantities of emerald used in native jewellery for some 1500 years. Coggin Brown refers to old Sanskrit writings which tell of emeralds from 'a mountain situated on the edge of the desert near the sea coast', a description which could well apply to the mines of Djebel Sikeit and Djebel Zabarah alongside the Red Sea. In more recent times the emeralds from the mines in Siberia were the source of the emeralds used in Indian jewellery, and in the nineteenth century much poor-quality emerald was exported to Asiatic countries from the stone markets of London and Paris. Much of the emerald mined in the Transvaal was sent to India.

The finding of emerald in the Awawalli mountain range of Rajasthan in 1943 was the result of the wartime search for beryl and mica as strategic minerals. During the search some small green crystals were found in the Kaliguman area of Udaipur, and these were identified as emeralds. A mining lease over the Kaliguman area was granted by the Udaipur authorities, then the independent state of Rajputana, to Sir Bhagehand Soni and his partner Seth Banjilal Thulia, the latter an emerald merchant of Jaipur. The first mining efforts in 1954 met with immediate success and crystals up to 100 mm in length were recovered. The emeralds are found in bands of biotite (mica) schist. Further searches followed this first successful attempt at emerald mining in India and other finds have been made in both Udaipur and Ajmere-Merwara. In 1947 quarrying was

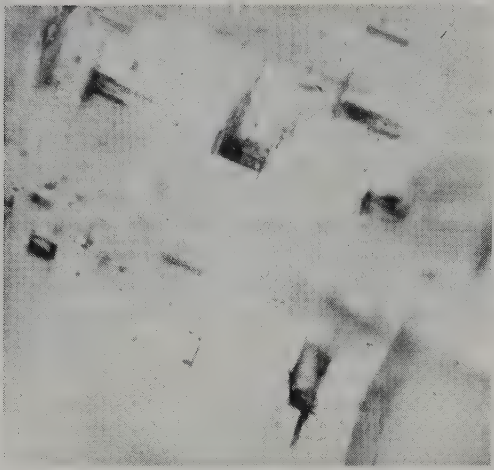

Figure 4.6 Comma-like two-phase inclusions in an Indian emerald

begun at the Rajgarh mine, which is some 25 km south of Ajmere, in which the emeralds are found in a soft talcose-biotite schist. Another source is near Bhilwara.

The Indian emeralds vary greatly in quality; the stones from the Rajgarh mines, and other sources in Ajmere-Merwara, in general have a better quality than those from the Kaliguman mines, although good stones of large size have been recovered from the first discovered locality. The SG of Indian emeralds is commonly 2.73–2.74, and the median refractive indices are 1.595 for the ordinary ray and 1.585 for the extraordinary ray, the double refraction being 0.007. The inclusions seen in Indian emeralds are typically characteristic and are of a type not reported from the stones of any other locality. These inclusions consist of two sets usually running at right angles to each other. Oriented parallel to the vertical axis of the crystals are oblong cavities containing a liquid and a bubble of gas. These cavities are characterised by having a shorter columnar projection on the edge of one end, giving them the appearance of 'commas' (*Figure 4.6*). Gübelin has shown that these cavities are groups of negative hexagonal crystals, one being remarkably longer than the other. The second type of inclusion Gübelin found to be biotite tablets and these are oriented parallel to the basal plane. Like the South African emeralds the Indian stones may not exhibit a red residual colour through the colour filter. The Indian stones are marketed mainly in Jaipur.

Pakistan

With the opening up of the remote, mountainous northern area of Pakistan many commercial gem and ornamental materials have been found, among which is emerald. Emerald was first found in Pakistan in 1958, when the

Mingora deposit was discovered in the Swat Valley, located 200 km north-east of Peshawar in the south-eastern foothills of the Hindu Kush Mountains. Mingora (Swat) emeralds are of pneumatolytic-pegmatitic origin and are commonly associated with faults and fractures, limonitic zones, calcite nodules and veinlets and quartz veins and stockworks in a greyish sheared talc-chlorite-dolomite schist. Other commercial emerald deposits have subsequently been discovered at Gujarkili, in the Swat district, and Khaltaro in the Gilgit agency. According to Gübelin, the colour of Mingora emerald ranges from best Colombian colour to average commercial colour. A high iron content quenches any fluorescence and provides these emeralds with their high SG (2.57–2.78), high refractive indices (ordinary ray 1.595–1.600, extraordinary 1.588–1.593), and high double refraction (0.008–0.009). Liquid and mineral inclusions in Mingora emerald superficially resemble those in emeralds from other localities, except that some Mingora emerald closely resembles Colombian emerald in that they are both included by calcite and jagged three-phase inclusions parallel to the *c*-axis of the crystal.

Tanzania

During 1969 a gemstone miner was shown some emeralds which came from a source then unknown, but in 1970 it was reported that the location of this new emerald deposit was near the village of Maji Moto, on the southern shore of Lake Manyara, about 100 km south-west of the town of Arusha. These emeralds, which are found together with alexandrite, partly in pegmatites and partly in mica schist, are a fine grass-green in colour, sometimes with a yellowish tinge and sometimes with a bluish-green hue, and these best-quality crystals may weigh up to about 8 carats. It is said that the stones from the mica schist show pink under the Chelsea colour filter while those from the pegmatites are practically inert. Some crystals reach 100 grams in weight but these larger crystals are turbid and only useful for cutting into cabochons. The stones were found to contain mica flakes of several types, mineral inclusions of apatite, orthoclase and quartz, two- to multi-phase prismatic negative crystals of triangular to hexagonal cross-section, and partly healed fractures. Lake Manyara emerald has properties consistent with those of emeralds from other biotite schist localities. Their SG is typically 2.72, with median refractive indices 1.585 for the ordinary ray and 1.578 for the extraordinary ray, and double refraction of 0.006. The stones are dichroic and show a chromium absorption spectrum typical of emerald.

Zambia

About 1970 a 'new' source of emerald was found in the African state of Zambia (formerly Northern Rhodesia). These emeralds probably were mined from the old Miku mine 56 km south-west of the Copperbelt town of Kitwe. Subsequent exploration identified a major Zambian emerald deposit, the Kafubu emerald field. This 170 km^2 rectangular area is located near the Kafubu river, immediately south-west of the Zambian Copperbelt, and 5 km to the south-east of the Miku mine. To date most Zambian emerald has been mined from the Kamakanga, Fwaya-Fwaya, Pirala, Libwente, Dabwisa and Nkabashila prospects in the Kafubu emerald field. Zambian emeralds are found, sometimes within quartz-tourmaline veins, in pegmatitic contact zones within a talc-chlorite-amphibole-magnetite schist. Although the quality of Zambian emerald may be similar to that of Colombian emerald, its mode of occurrence resembles that of South African and Zimbabwean emerald. The reported SG of Zambian emerald ranges from 2.74 to 2.80, and the median refractive indices range from 1.586 to 1.602 for the ordinary ray and 1.580 to 1.592 for the extraordinary ray, with a double refraction of 0.006–0.01. Zambian emeralds are inert to ultra-violet light, show a reddish residual colour through the Chelsea filter, and have a fairly strong chromium spectrum. Identifying inclusions in Zambian emerald include black dravite tourmaline, magnetite, biotite-phlogopite mica, orange-red rutile, chrysoberyl, hematite, and apatite.

Nigeria

Problematic gem-quality blue-green beryls, which Hanni suggests be termed blue-green emeralds, are being mined from near Jos in the Rafin Gabas Hills district of Nigeria's central Plateau state. Here, blue-green beryls occur with other coloured beryls, topaz, and smoky quartz in narrow stringers and thin layers forming a stockwork over the roof zones of granitic hills. Moderately saturated blue-green Nigerian beryls, coloured by combinations of up to 0.08 per cent chromium, 0.06 per cent vanadium and 1.2 per cent iron, have a median SG of 2.67, refractive indices which range from 1.570 to 1.574 for the ordinary ray and 1.564 to 1.568 for the extraordinary ray, a double refraction of 0.006, and an absorption spectrum that displays features of both aquamarine and emerald coloured by both chromium and vanadium. Inclusions include complex growth zoning, partly healed two-phase fractures, and two-phase jagged cavities oriented parallel to the *c*-axis.

Madagascar

Emerald, with characteristics comparable to those of Zambian emerald, occurs in mica schists of the Ankadilalana mine, near Kianjavato, on the south-east coast of Madagascar. Blue-green emeralds, containing an emerald component due to chromium and an aquamarine component due to iron, have been mined for the past five years from mica schists in the Morafeno region, 30 km south of the central east coast city of Manjaray. These partly transparent emeralds have an SG of 2.68–2.71, refractive indices of 1.588–1.591 for the ordinary ray and 1.580–1.582 for the extraordinary ray, and a double refraction of 0.008–0.009. Inclusions include colour zoning, two-, three- and multi-phase partly healed fractures and negative crystals, brown mica, tremolite-actinolite rods and needles, and undetermined colourless crystals.

Norway

Emeralds have been found at Byrud Minnesund, Eidsvoll, at the southern end of Mjøsa lake, some 55 km north-north-east of Oslo. The crystals are found embedded in granite, and are nearly always turbid. The SG of Eidsvoll emerald is 2.76, with refractive indices of 1.590 for the ordinary ray and 1.583 for the extraordinary ray, and a double refraction of 0.007. The dichroism was found to be distinct, the absorption spectrum strong, and under the Chelsea filter it shows a bright red. Observation by microscope of the internal features of this stone showed that it was filled with masses of inclusions, mostly 'mossy' in character, but combined with a vast number of interconnecting cavities rather like vesicles. To these masses of inclusions is due the turbidity of the stone, which would preclude such a stone being successfully cut with facets, although as a cabochon it was quite attractive.

North Carolina, USA

That emeralds could be found near Hiddenite in Mitchell County, North Carolina has been known for about a century, certainly before 1875. They are locally called 'green bolts'. The original mine was apparently worked by A E Hidden, famous as the discoverer of hiddenite from the same area. In 1881 Hidden formed the Emerald & Hiddenite Mining Company. There are some 14 or 15 mines in the area; those most important are the Crabtree Mine near Little Switzerland, which as far as can be ascertained was first worked about 1884 and is still in production and is operated by shaft mining. It is from this mine that the attractive cabochons of emerald crystals in a white albite feldspar are cut. They are called 'emerald matrix'. Two of the mines, the Ellis and the Rist, are of recent origin. They are adjacent to the township of Hiddenite. Robert Crowningshield reports that a stone of 13.14 carats was cut from a crystal of 59 carats found in the Rist mine. It is said to be the largest American faceted emerald. The SG was found to be 2.73, and the refractive indices were ordinary 1.588 and extraordinary 1.580, and the stone fluoresced red under long-wave ultra-violet light.

Other Occurrences

In September 1967 R Webster was shown by a jeweller from Maputo (Lourenço Marques) two very nice emerald crystals which were said to have come from a mine in the north of Mozambique. These emeralds could have come from either the mica schists of the Morrua district, or the Maria 111 mine that is associated with the Alto-Lingonha pegmatite region, 260 km west-south-west of Maputo. Mozambique emerald has an SG of 2.73, median refractive indices of 1.592 for the ordinary ray and 1.585 for the extraordinary ray, and a double refraction of 0.007. It is included by brownish mica, and has *c*-axis-oriented two-phase negative crystals and growth tubes that often have basal fractures.

Reports of emerald in the Harrach and Bouman rivers of Algeria, and also *in* *situ* in the neighbourhood, have not been substantiated. The crystals may be tourmaline. There is another story that emeralds have been found in Libya, probably around Ghadames. Although much prospecting is being carried out in parts of Libya there is no confirmation.

Despite more recent discoveries, Colombia is undoubtedly still by far the most important world producer of fine emeralds. The Cosquez, Muzo and other major mines which were taken over by the government in 1973 have since been leased to private companies and have returned to full production. Exact figures for their output are not available, but for 1988 official Colombian exports of about 1 906 000 carats of rough emerald were valued at just over US$93 million.

South Africa, Zimbabwe, Zambia, India, Pakistan and recently Russia are also important producers of emeralds, but no exact statistics of production are available from these sources.

Effects of Light

The elements responsible for the intense slightly yellowish-green to bluish-green of gem-quality emerald are chromium, vanadium, and iron. As the concentrations of these colouring elements vary widely, from deposit to deposit, this influences the colour and optical properties of the emerald. It will be noted from the values of refractive indices given for emeralds from different localities that the species beryl shows double refraction, and since the index for the extraordinary ray is less than for the ordinary ray the sign of the refraction is negative. The dichroism of emerald is distinct, with the 'twin colours' blue-green for the extraordinary ray and yellowish-green for the ordinary ray.

Absorption Spectra

The absorption spectrum is that typical for chromium-coloured minerals, showing fine lines in the red part of the spectrum, a weak diffuse central absorption with absorption of the violet, and rather weak lines in the blue. In chromium-dominant emerald there is a distinct difference between the absorption spectra for the ordinary ray and for the extraordinary ray. In that of the ordinary ray only two narrow lines can be seen in the red and they are of almost equal strength. These two lines consist of the main doublet (683 and 680 nm) and a clear-cut line at 637 nm; the central weak absorption patch covers from about 625 to 580 nm, and there is a narrow line in the blue at 477.5 nm which may only be seen in very chrome-rich stones, when another line at 472.5 nm may also be noticed. The absorption of the violet commences at about 460 nm. In the spectrum of the extraordinary ray the doublet is rather stronger, particularly the 683 nm line of the pair; the 637 nm line is missing and in its place are two rather diffuse lines at 662 and 646 nm, these being bordered on the short-wave side by characteristic transparency patches. The broad absorption region is now nearer to the red and is much weaker, and there are no lines in the blue.

Chromium does, however, efficiently mask absorptions due to both vanadium and iron in the visible region of the electromagnetic spectrum, for the approximate positions of the green colour producing absorptions in the violet and orange-red of the emerald absorption spectrum are nearly identical for chromium (ordinary ray 430 and 593 nm, extraordinary ray 416 and 628/644 nm) and vanadium (ordinary ray 434 and 618 nm, extraordinary ray 426 and 630 nm). In addition, vanadium does not produce the 680, 683 nm doublet and 660 nm absorption in the extraordinary ray, and 637 and 476 nm absorptions due to chromium. The 371 and 426 nm absorptions, in the respective ordinary and extraordinary rays, due to iron are also effectively masked by the general absorption of chromium below 460 nm.

Fluorescence

Emerald, although a green stone, transmits a considerable quantity of deep red, which is also a region of fluorescence, and it is this fluorescent red light which mainly gives the red colour seen when emeralds are viewed through the Chelsea colour filter. Should this fluorescence be suppressed or dimmed by a fluorescence 'poison', for example iron, such emeralds may not show red through the filter; this may well be the reason for most South African and Indian emeralds remaining green when viewed through such a filter. The majority of the emerald imitations and simulating minerals show green through the filter, but there are exceptions, such as the older type of soudé emerald, and certain varieties of natural minerals, particularly the emerald-green fluorite, the demantoid garnet, and green zircons, which show reddish through the filter. The earlier synthetic emeralds, owing to their chrome-richness and freedom from impurities such as iron, show a fiery red appearance through the filter. Although this strong red residual colour can betoken a synthetic emerald it must not be taken too literally, for some natural emeralds from the Chivor mines of the Bogotá region of Colombia behave similarly, and, further, some modern synthetic emeralds contain iron and do not fluoresce at all.

Cutting of Emerald

Traditionally, the cutting of emerald is performed on a copper lap charged with diamond dust and the polishing is carried out on a similar lap with rottenstone as the agent. The best-quality emeralds are almost universally fashioned in the trap-cut style with the corners truncated, giving an elongated octagonal outline, a style which has, owing to the common use for emerald, become known as the emerald cut.

It is the style of cutting which, owing to its few plane facets, shows the saturated deep velvety green of emerald to best advantage. Although the mixed cut, with a brilliant-cut top and a step-cut pavilion, has been used for emerald, such a fashioning is rare and is said to give a glassy look. Poor-quality and badly flawed emeralds are cut *en cabochon* or as beads, and much Indian jewellery is set with such stones, which are usually of poor-quality emerald. Native-cut stones are often 'doctored' by boiling in fat which has been suitably coloured. Such treated emeralds tend to show spots at a later date, so if any suspicion is aroused it is best to soak the stones for some time in warm alcohol when some of the false material will dissolve and unmask the trick, and, incidentally, show the true colour of the stone.

An emerald cut with the table facet at right angles to the optic axis, that is at right angles to the length of the prism, will give a yellowish-green colour due to the ordinary ray. At right angles to this direction, that is with the table facet cut parallel to the prism (and of course the optic axis also), the colour is more bluish-green due to about 50 per cent of the extraordinary ray. This latter colour is often less pleasing to many than the paler shade due to the ordinary ray. Emeralds are often carved, especially if the material is of good colour, but marred by many fissures and flaws.

Oiling of Emeralds

A very widespread practice amongst those engaged in the wholesale trade in emeralds is to treat them with some form of fine oil in order to disguise the very frequent appearance of flaws. The benefit to the seller is obvious, since undoubtedly the effect of skilful oiling on emeralds of indifferent quality is to upgrade them considerably in terms of their appearance and hence their apparent value. To those who purchase such stones for the purpose of using them in the manufacture of jewellery, often without knowledge of their having been doctored in this way, there may come a nasty shock when, as a finishing touch for the manufactured jewel, they subject the piece to ultrasonic cleaning. Such treatment will usually empty any flaws which reach the surface of the stone of any oil content, with a disastrous effect on appearance. Should this risk be avoided by the manufacturer it will be the retailer's turn to be unwittingly storing up eventual trouble for himself, since a customer who was careless enough to forget to remove her emerald ring before washing up in hot water laced with detergent may well be dismayed at the altered appearance of her emeralds, and return the jewel to the shop where she bought it for some sort of explanation and possible replacement.

This form of treatment for emeralds is so prevalent and so difficult to detect without spoiling the stone in the course of a test that it is likely to continue. All that the gemmologist can do is to let the dangers attached be known in all departments of the trade, and to warn strongly against the ultrasonic cleaning or the heating of jewellery containing emeralds as the effect is likely to be deleterious whether the stones have been oiled or not.

The actual technique employed in the oiling process is normally kept secret for obvious reasons. In some cases little care has been taken and traces of oil can be seen on close inspection to be oozing from flawed parts of the stone. At the other extreme, responsible dealers such as those in Colombia dealing extensively in emeralds may employ oiling methods only with the agreement of their customers, and use great care and skill in carrying out the process. In a visit with a trade party to Bogotá, the emerald 'capital', Eric Bruton was able to learn details of one such routine from a highly qualified specialist in the treatment of emeralds. It was revealed that the oil preferred for the treatment is cedar oil, which has a refractive index close to that of emerald. The polished emeralds are first placed in small beakers of hydrochloric acid in a vacuum chamber for a considerable time. The acid is then removed from the stones and they are subjected to ultrasonic treatment to remove any oxide left by the polishing and any calcite from the stones. The next stage is to immerse the stones in cedar oil which has been warmed to reduce its considerable viscosity. The oil pots are placed in the vacuum chamber, by which means the air is withdrawn from the flaws and replaced by the oil. There is then a final treatment in which the stones are held for several hours at a temperature of 83 °C. The expert who explained this process was confident that emeralds after undergoing such careful treatment would withstand ultrasonic cleaning with no ill effects, but it is highly advisable for any jeweller to avoid such risk of serious trouble.

In recent years commercial techniques for impregnating surface-reaching fractures in emeralds, with either a colourless chemically set epoxy plastic such as Opticon®, or colourless glass (Yehuda treatment), have become commercially available. Careful low-power microscopy, using diffused transmitted light, should allow the gemmologist to recognise any unnatural fillers in surface-reaching fractures of fracture-filled emerald.

Synthesis and Simulation

Emerald is synthetically produced and marketed as a gemstone. The methods of the production and the characters of the synthetic product are fully described in Chapter 18 on synthetic gemstones. The more common imitations of emeralds are the composite stones, such as the garnet-topped doublets which consist of a slice of red garnet forming the crown of the stone fused to a base of green glass. The more important, however, of these composite stones are the so-called soudé emeralds in which two pieces of colourless quartz (or beryl) form the top and bottom of the stone and are cemented together with a green-coloured layer. In the earlier types this was a layer of green gelatine, but in later types a sintered layer of some copper compound is used. More recently the rock crystal has been replaced by two pieces of synthetic colourless spinel. These soudés readily give themselves away if they are immersed in water or other liquid and viewed sideways, when the clear colourless top and bottom with the dark line of the coloured layer between will show. The earlier type with the coloured gelatine layer shows red under the Chelsea colour filter. Glass imitations of emerald can be very effective and of good colour and appearance, and they are often embellished with 'flaws' and 'feathers' produced by layers of bubbles or by included extraneous matter. The so-called Ferros emerald is of glass.

Pale natural emeralds are often painted on the back with a green pigment in order to enhance the colour. When the stones are set with open backs, this is easily detected and easily removed. When, however, the stones are in closed settings the problem is not so easy and examination by microscope may be necessary in order to see the patchiness of the blobs of colour below the stone. Some paints used for this treatment fluoresce under ultra-violet light and so indicate a painted stone. Further, the strength of the absorption spectrum may indicate the true colour of such backed stones, for the backing may not be paint but a coloured metal foil. Rock crystal as well as pale emeralds are also treated in order to give an 'emerald' stone. The so-called 'Indian emeralds' are simply green-dyed crackled quartz.

Aquamarine

The most acceptable colour for aquamarine (a name which means sea water) is a clear sky-blue, which even in the darkest shades rarely reaches the hue of sapphire. Much aquamarine has a bluish-green colour, which, while not so prized today as it was formerly, does have a charm of its own. Under this group may be described also the clear green beryls which owe their colour to iron and do not have the verdant green of the chromium-coloured emerald. The other is the colourless variety, to which the name goshenite (after Goshen in Hampshire County, Massachusetts) has been applied. This name is fast becoming redundant, and the name colourless, or white, beryl is now more commonly used.

The hexagonal crystals of aquamarine are often of large size and, owing to oscillation between the first- and second-order prisms, are often striated parallel to the prism edge. At times this striation is so pronounced that the hexagonal outline is obscured and the crystal assumes a ribbed cylindrical form. Further, due to erosion, many aquamarine crystals exhibit a tapering form.

Aquamarine, unlike emeralds, are found in large crystals of flawless clarity from which large water-clear stones can be cut. Indeed, cut aquamarines need to be of some size for the colour to be sufficiently intense to produce a good-coloured stone, small stones rarely having a depth of colour sufficient to be attractive. Practically all the lovely blue aquamarines seen in jewellery are the result of heat treatment of greenish-yellow stones, or even certain stones of a brownish-yellow colour. The blue colour is induced by heating to a temperature between 250 and 720 °C for a varying time, and the resulting colour is permanent. Some aquamarines show chatoyancy.

The SG of aquamarine lies between the range of 2.66 and 2.80, as some Madagascan stones have higher densities owing to a trace of alkali metal in their composition. The refractive indices for aquamarine vary from 1.572 to 1.590 for ordinary ray and 1.567 to 1.583 for the extraordinary ray; the birefringence, negative in sign, 0.005 for the lower indices and increases to 0.007 or 0.008 for the stones with higher indices. The fire (dispersion) of the beryls (including emerald) is 0.014 (B to G).

Aquamarine has, like all the beryls, a weak basal cleavage and a tendency to brittleness. The lustre is vitreous and aquamarines exhibit a distinct dichroism, the 'twin colours', the strength of which depends on the depth of the colour of the stone; they are deep blue and colourless, the extraordinary ray giving the attractive blue colour. The absorption spectrum, which is ascribed to iron, is not very pronounced. There is a somewhat broad band in the violet at 427 nm and a feeble diffuse band in the blue-violet at 456 nm. Further, the extraordinary ray, which can be isolated by the use of a polaroid disc, shows these bands more strongly, and in such conditions there may be detected a narrow and delicate absorption line in the middle green at 537 nm. This line is seen in natural greenish aquamarines, and in yellow and colourless beryls, but is not seen in the heat-treated blue aquamarines. Aquamarine does not exhibit luminescence.

True colourless beryl is not common; nearly all the so-called colourless beryls have a trace of green, pink or yellow. Indeed, all the colourless beryls, like the blue and sea-green stones, show, when viewed through the Chelsea colour filter, a strong greenish-blue colour. In such a way aquamarines may be picked out from a parcel of similar-looking stones.

An important factor in the colour shown by aquamarines when cut as gemstones is the effect due to the strong dichroism shown by all blue or blue-green beryls. By far the stronger colour in beryl is carried by the so-called extraordinary ray, which means that the fine blue of this ray must always be diluted by the pale ordinary ray.

The best direction for the stone to be cut from a prismatic aquamarine crystal from the point of view of colour is also that naturally adopted by the lapidary from consideration of size and shape, which is that the table facet must be cut parallel to the length of the prismatic crystal which is the normal habit of beryl. In the case of the deep blue beryls of the 'Maxixe' type which are mentioned in the next section there is a curious reversal of the two rays: the ordinary ray carries the deeper colour. This contributes to the almost sapphire-blue colour of some of the attractive beryls which startled the trade when they appeared on the market in 1973.

Occurrences

Of the many Brazilian states providing valuable sources of pegmatitic aquamarines and other coloured beryls, Minas Gerais is the most important. Four districts in Minas Gerais – Teofiloni–Marambaia, Jequitinhonha River valley, Aracuai River–Capalinha–Malacacheta, Governador Valadares – are major sources of aquamarine. The most famous and prolific deposits are those found in the north-eastern regions of Minas Gerais, where the river Jequitinhonha and other subsidiary streams have transported and deposited the beryl, topaz, quartz and other minerals of gem quality from the weathered pegmatites where they had grown, often as crystals of considerable size. Alluvial deposits are more favourable sources for the prospector than the original unaltered rocks, since the hard and heavy gem minerals have become segregated by their tumbling in the streams from the unwanted softer and lighter materials, which have been ground into particles of sand and clay. In addition, any flawed portions of crystals will have been broken away, leaving sound, clear gem material for the miner to recover.

The largest and most important deposits for aquamarine are grouped near Marambaia in the bed of the Mucuri stream and along the Jequitinhonha, where the sites known as Lavra Batadal and Lavra Papamel were found. In these a layer of the brown gem gravel *cascalho* several metres in thickness is covered by some 6 m of laterite clay and a thin layer of fragmented feldspars. It was in Lavra Papamel that in 1910 an aquamarine crystal of record size was recovered. This measured 480 mm in length and 400 mm in girth and weighed 110 kg. The crystal was perfectly transparent from end to end and had a blue central portion surrounded by a greenish-yellow exterior. This famous crystal was purchased for US $25 000 by a dealer in Idar-Oberstein. It is indeed unfortunate that, with the notable exception of relatively rare deep blue aquamarines from the Santa

Maria and Coronel Murta deposits on the Jequitinhonha River, faceted Brazilian aquamarines need to be of at least 10 carat size to attain their deepest blue colour.

Since 1982, the dominance of Brazilian aquamarine on world markets has been challenged by the marketing of small, deep blue aquamarines from newly discovered deposits in the African countries of Kenya, Zimbabwe, Nigeria and Zambia. These new African aquamarines have the decided commercial advantage of producing deep blue colours in stone sizes of less than 5 carats.

The Ural Mountains dividing European from Asiatic Russia, as well as being a famous source for such rare gems as emerald, alexandrite and demantoid, have been well known as a provider of fine beryl crystals, some of them of immense size. In particular, sources in the neighbourhood of Sverdlovsk, especially Mursinka, have provided many splendid aquamarines. Blue, green and yellow beryls are found in granite in the Adun-Chalon Mountains in the Nerchinsk district of Transbaikalia, and other splendid beryls occur with topaz at Miask.

Madagascar is another very famous source for fine beryls of all colours (except emerald) and is particularly noted as the home of crystals of the rose-pink beryl known as morganite. Some of the morganites are unusually large for this variety and have provided cut specimens of the huge sizes which are the delight of museums. An example is the cut-corner step-cut flawless morganite in the British Museum (Natural History) in South Kensington. This stone weighs 598.7 carats, but is outweighed by a step-cut aquamarine from Russia, oval in outline, which weighs 879.5 carats. There are said to be fifty known sources of beryl, not only coloured but also colourless, on the island.

Of the many localities in the United States of America, mention may be made of the following: Stoneham, Albany and Paris, Oxford County, Maine; Haddam Neck, Middlesex County and New Milford, Litchfield County, Connecticut; Pala, San Diego County, California; Mount Antero, Chaffee County, Colorado; Hurricane Mountain, Yancy County, and Grassy Creek, Mitchell County in North Carolina.

Aquamarine is found in Myanmar (Burma) but is not common in Sri Lanka.

Gem aquamarine is found at Rössing in Namibia and recently aquamarine of rather weak colour has been found in Zimbabwe. The Coimbatore district of Madras, India, as well as Rajasthan (Rajputana) and Kashmir are Indian localities where aquamarine has been found. Unimportant sources, not necessarily of gem quality, are the Shinyanga district of Tanzania, the San Luis mountains of Argentina, several localities in China, at Fykanvatu at the head of the Glåmfjord, Norway, and in the Mourne Mountains of Northern Ireland.

Simulants

The most effective imitation is provided by synthetic spinel coloured pale blue by cobalt. These synthetics have an entirely different refractive index (1.728) and SG (3.63) from those of aquamarine, but the quickest and easiest test for the busy jeweller is to place the suspected stone close to a strong light and view it through a Chelsea filter held close to the eye. The synthetic spinel shows a distinct red under the filter whereas aquamarine shows a decided green appearance.

Imitations in pale blue glass are sometimes deceptive to the eye but are quickly distinguished by their single shadow edges on the refractometer. The only natural stone closely resembling aquamarine is blue topaz, which gives refractometer readings of 1.610 and 1.620 compared with the 1.574–1.580 which are the most common values for aquamarine.

Other Beryls

Blue Beryls

Gemstones of a satisfactory blue colour are scarce in nature. Sapphires, justly the most famous of all blue gems, are said to be the most popular of precious stones, but the price of fine sapphires is enormously high. Many of the gems sold in jewellery under that name, though genuine, are so dark in colour that they appear almost black in artificial light, which is the light in which they are needed to give of their best. Hence the immediate popularity of the handsome blue form of zoisite discovered in 1967 in Tanzania to which the name tanzanite has been given. In 1973 there appeared on the market a number of very attractive deep blue beryls in quite important sizes, and for a time these were readily fetching prices up to £100 per carat. Then came disappointment: the initial fine blue colour of the stones was found to fade slowly but irretrievably when exposed to sunlight or strong artificial light. The origin of these blue beryls was hard to place: it seemed there might be several sources, but apparently all were from Brazilian localities. They all showed certain strange differences in their optical characters from those found in normal aquamarines, and these reminded knowledgeable gemmologists of similar effects shown by blue beryls from the Maxixe mine located in the Piaui area south of Arassuahy in Minas Gerais which earned a brief notoriety following their discovery in 1917.

The features concerned were as follows. First, of the two dichroic colours shown by the stones the deeper tint belonged to the ordinary ray (the extraordinary ray being almost colourless) whereas in all normal aquamarines the deeper colour belongs to the extraordinary ray. Secondly, the presence of strongly marked absorption bands in the red end of the spectrum at 695 and 655 nm, with weaker bands showing at 628, 615, 581 and 550 nm, somewhat resembled the bands seen in zircon. Thirdly, the colour faded rather rapidly under bright light and no simple method was found to restore it.

The original Maxixe stones had other subsidiary features of technical interest. They showed little crystal form and had a high content (2.80 per cent) of the rare heavy alkali metal caesium as well as 0.39 per cent boron. The SG was also high for beryl (2.80) and the refractive indices (1.5844 and 1.5920) were also high.

Possible reasons for these anomalies and the similar effects shown by the recently promoted dark blue beryls have been thoroughly investigated by Kurt Nassau and his colleagues and a summary of the results will be found in Chapter 31 which deals with colour in gemstones.

Pink Beryls

The lovely pink-, rose- and peach-coloured beryl is called morganite, after the American banker and gem lover J P Morgan, and Nassau states the colour is due to manganese, not lithium as thought. The alkali metals caesium and rubidium are often, by small-scale replacement, impurities in pink beryl and tend to raise the SG and refractive indices. Most, but not all, pink beryls have an SG from 2.80 to 2.90 although some may be as low as 2.71. The refractive indices lie between 1.578 and 1.600 for the ordinary ray and between 1.572 and 1.592 for the extraordinary ray, the double refraction varying between 0.008 and 0.009. A few pink beryls (those with low density) have refractive indices only a little higher than for aquamarine. Some colourless beryls (rich in caesium) also have this higher density and indices of refraction. Morganite is heat-treated to drive off the yellow tinge.

The dichroism of morganite is distinct, the twin colours being a pale pink and a deeper bluish-pink, the stronger colour being that for the extraordinary ray. There is no characteristic absorption spectrum and the luminescence under ultra-violet light is a weak lilac, but under X-rays there is an intense, but not bright, crimson glow.

A pure pink-coloured beryl is found in the state of Minas Gerais in Brazil, and in fine large crystals from Tsilaizina, Anjanabonoina and Ampangabe in Madagascar where the stones are found in pegmatite dykes and alluvial deposits derived from them. The best-known source of gem morganite in the United States of America lies in San Diego County, California, where pink beryl of a pale rose to a peach colour is found in the Stewart, Katerina, Pala Chief, San Pedro and White Queen mines of the Pala district. Other deposits are those of the Himalayas, San Diego and Esmeralda mines in the Mesa Grande district. Morganite crystals usually assume rather short prisms, and are thus tabular in habit.

A red variety of beryl, called bixbite, which owes its colour to manganese, is found in the Thomas mountains in Utah. The small, badly flawed, hexagonal crystals have chiefly a rarity value. The largest fine-quality stones weigh under 2 carats.

Pink beryl is simulated by pink topaz, kunzite, natural and synthetic pink sapphire and spinel. Garnet-topped doublets and pastes are also made in a pink colour.

Yellow Beryls

The yellow beryls, to which in the case of the rich golden-coloured stones the name heliodor (from the Greek meaning sun and gift) has been applied, have a colour varying from a pale lemon to a rich gold. The yellow colour is said to be due to iron. The physical and optical constants of the yellow beryls differ little, if at all, from those of the aquamarine. There is an unconvincing absorption band in the blue to be seen in deep yellow beryls; and, most probably due to the iron content, no luminescence is exhibited. Some heliodores show chatoyancy.

Yellow beryls are obtained from practically all the localities mentioned for aquamarine. Particular localities are Madagascar, Brazil and Namibia. In

Namibia, heliodor is found in association with aquamarine and a yellowish-green variety at Klein Spitzkopje near Rössing on the Otavi railway east of Swakopmund, and also between Aiais and Gaibes on the Fish river. Some yellow beryls have been reported to show radioactivity due to their containing a trace of uranium oxide. A deep yellowish-red variety of beryl, called 'berilo bocade fogo' (fire-mouth beryl), comes from Santa Maria do Suassui in Minas Gerais.

Many localities in the United States of America produce yellow beryl but the only one of importance is the Merryall or Roebling mine at New Milford, Connecticut.

Dark Brown Beryl

An unusual dark brown beryl with a star effect (asterism) and a bronzy schiller was said to have been first discovered in the Governador Valadares area of Minas Gerais about 1950. The weak asterism is said to be due to oriented ilmenite, and these and other coarser agglomerates cause the dark brown colour, for clear patches show that the body colour is that of pale green aquamarine. The schiller appears to be due to the structure of thin layers parallel to the basal plane, and these seem to act as mirrors. These star beryls neither show fluorescence nor exhibit any typical absorption spectrum. Black star beryl is reported from Alto Ligonha, Mozambique.

Inclusions

The inclusions seen in beryls (*Figures 4.7–4.10*), other than emerald which has already been discussed, are various and the colour varieties do not seem to favour any particular type of inclusion. The most common inclusions seen in beryl are long straight tubes in parallel arrangement, and which lie parallel to

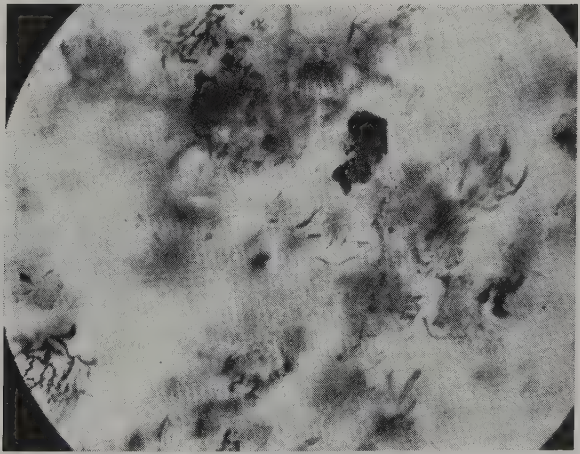

Figure 4.7 A type of inclusion, probably ilmenite, seen in aquamarine

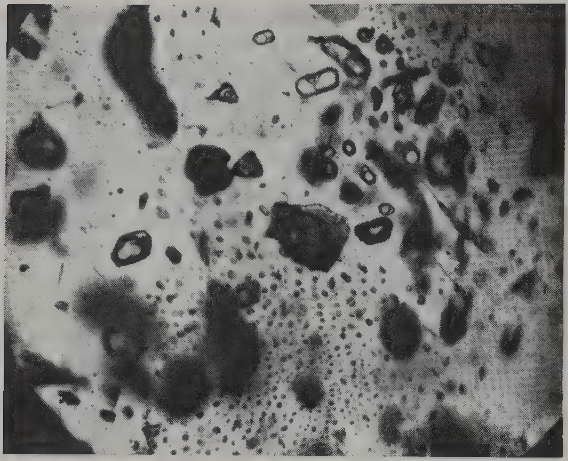

Figure 4.8 *Various inclusions seen in a yellow beryl from Madagascar*

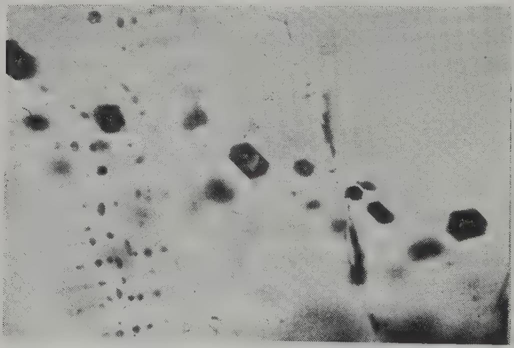

Figure 4.9 *Negative crystal cavities with a gas bubble in an aquamarine*

the prism faces. These tubes are either hollow or filled with liquid which may give to them a brownish colour. Some beryls show feathers of negative crystal cavities, some of which may contain a bubble of gas. An intriguing object sometimes seen in aquamarines is a flat inclusion, which under low-power magnification looks like a snowflake and when viewed by oblique illumination looks like a metallic disc. These inclusions have been aptly described as 'chrysanthemum' inclusions.

Cutting of Beryls

Aquamarines, morganites and yellow beryls need to be cut as stones of some size if the colour is to be strong enough for the stones to be attractive. In

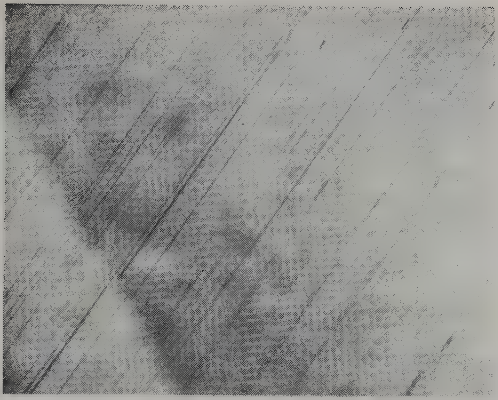

Figure 4.10 Tube inclusions in a Zimbabwean aquamarine

modern practice it is usual to cut beryls into the trap-cut style (the emerald cut) and such stones are mounted as important centre stones in rings, brooches, pendants and earrings.

John Sinkankas, in his book *Emerald and Other Beryls*, published in 1981 by Chilton (condensed by Peter Read in 1986 into the book *Beryl* for the Butterworths Gem Book series), has provided the most complete account available of all aspects of the beryl minerals. This work should be consulted by anyone wanting information in depth on this important group.

5

Chrysoberyl and Spinel*

Chrysoberyl

Varieties

The mineral chrysoberyl produces gemstones which are predominantly green, greenish-yellow or brown in colour, but two varieties of chrysoberyl, the alexandrite and the cat's-eye, have, owing to their peculiar optical properties and rarity, a prized position in jewellery. The most common colour of chrysoberyl is a transparent greenish-yellow which in Victorian and Edwardian periods had a vogue in jewellery. Such stones were often called 'chrysolite', a name which, owing to its use as a specific term for the mineral olivine in certain fields of mineralogy, leads to confusion. Therefore, in present-day gemmological nomenclature the term is discontinued. The brown stones are sometimes faceted and a colourless chrysoberyl is occasionally encountered. Some brown stones have been found which have higher constants, actually nearer those of sapphire.

The most important and interesting of the chrysoberyls are the alexandrites. These stones exhibit a colour change, for the stone appears a grass-green colour in daylight, but under artificial light the hue of the stone is a raspberry red.

The other important chrysoberyls are the honey-yellow to greenish- or brownish-yellow stones which, when cut with a domed surface (cabochon), show a mobile streak of light. This is the cat's-eye effect, or chatoyancy as it is called. Such stones are popularly called cat's-eyes and the name cymophane has been applied to the cat's eye chrysoberyls. The colour of chrysoberyl cat's-eye varies from a dark yellowish-brown to a pale yellow, a honey-yellow colour being the most prized shade.

A number of other species, such as quartz, tourmaline, apatite, scapolite and diopside, exhibit chatoyancy, but the term cat's-eye used alone is, in the

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*Revised by Richard W Hughes.

jewellery trade, restricted to the chrysoberyl cat's-eye. In the other species which have stones showing a chatoyant effect the name cat's-eye is prefixed by the name of the species, for example quartz cat's-eye; indeed it is the quartz cat's-eyes which are most similar to the true cat's-eyes in colour if not in sharpness of ray.

Fine specimens of both alexandrite and cat's-eye are valuable gemstones. Occasionally the alexandrite variety is found which shows chatoyancy and such stones are highly desired. Star chrystoberyls are known, but are rare.

Judging Quality in Chrysoberyl

Most expensive of the chrysoberyls are the alexandrites, which are among the most expensive of all gemstones. Even mêlée can fetch hundreds of dollars per carat, and fine stones of over one carat are priced in the thousands. The ideal in alexandrite is a stone which displays a daylight colour like the finest Colombian emerald, shifting to the colour of a fine Burma ruby in incandescent light.

Cat's-eyes are next in value. The finest stones should have the colour and transparency of honey. Transparency is of great importance, as is the quality of cutting. Fine stones have a straight, sharp eye and a deep, rich colour.

Yellow and brown chrysoberyls should possess a rich, intense colour, should be clean to the eye, and should be well cut. As the gem is relatively inexpensive, cutting is important.

Chemical Composition

The chemical composition of chrysoberyl is a double oxide of beryllium and aluminium ($BeAl_2O_4$) and therefore has some similarity to spinel. It is the small-scale replacement of the alumina by chromic oxide which gives the green colour to alexandrite, and, as well be explained later, accounts for the intriguing change of colour of this variety of chrysoberyl when it is viewed in artificial light.

Crystallography

Chrysoberyl crystallises in the orthorhombic system, and is found, especially in the clear yellow stones, as prismatic crystals which are usually flattened parallel to one pair of faces (the macropinacoid faces). Some crystals, particularly alexandrite from the Ural Mountains, are twinned as 'trillings' (cyclic twins, or 'flowers'), the three intergrown crystals giving an appearance of hexagonal symmetry. Much gem chrysoberyl is found as water-worn pebbles, and this is usually so in the case of the chrysoberyls found in the Sri Lankan gem gravels.

Specific Gravity, Hardness, Cleavage and Fracture

The specific gravity (SG) of chrysoberyl is generally between 3.71 and 3.72, but may go as high as 3.80 or as low as 3.64. Brown stones may go up to 3.755, while colourless gems may be as low as 3.703. One Brazilian alexandrite showed an SG of 3.68. Zimbabwe alexandrites have been reported with SGs as low as 3.64.

Hardness is 8.5 on Mohs's scale, and until the discovery of bromellite (beryllium oxide) chrysoberyl was the third hardest of all known natural minerals. Chrysoberyl has three directions of cleavage, but they are weak and have little consequence. Fracture surfaces are either uneven or conchoidal (shell-like).

Effects of Light

Refraction

The optical characters of orthorhombic crystals, such as chrysoberyl, are doubly refractive and biaxial. In orthorhombic minerals, the unit cell or building block of the crystal possesses three dimensions, each of a different length than the other two. As a result, there are three RIs, one corresponding to each dimension of the unit cell. These RIs are denoted by the symbols α, β and γ. α is the lowest RI, γ is the highest, and β is intermediate, corresponding to the unit cell dimension intermediate between the other two. Optic sign in biaxial minerals is determined by the position of β relative to α and γ. If β is closer to α, the stone is positive; if β is closer to γ, it is negative; if β is halfway between, the crystal is neutral. Chrysoberyl is usually positive, but may also be negative in sign. There are two directions of single refraction, termed optic axes.

The RI values of chrysoberyl vary little at 1.75–1.76, with the birefringence being between 0.008 and 0.010. Some typical values for chrysoberyl are given in *Table 5.1.*

Table 5.1
Chrysoberyl refractive indices and specific gravities

	γ	β	α	γ-α	SG
Yellow stone	1.753	1.747	1.744	0.0094	3.709
Yellow stone	1.755	1.746	1.744	0.011	3.72
Alexandrite (Urals)	1.759	1.753	1.749	0.0094	
Alexandrite (Sri Lanka)	1.755	1.749	1.745	0.010	
Alexandrite (Myanmar)	1.755	1.748	1.746	0.0085	3.706

Unusual Stones

Rarely are the values in *Table 5.1* exceeded. A specimen of brown chrysoberyl did give the surprisingly high values of γ 1.770, β 1.764, α 1.759, the SG of this unusual stone being 3.755. An alexandrite weighing 14.17 carats cut from a crystal said to have come from the southern part of Jacuda, Bahia, Brazil, was found to have an SG of 3.68 and refractive indices of α 1.747 and γ 1.756. A small colourless chrysoberyl had an SG, low as would be expected, of 3.703. Yellow-green chrysoberyls from Anakie, Queensland, Australia have unusually

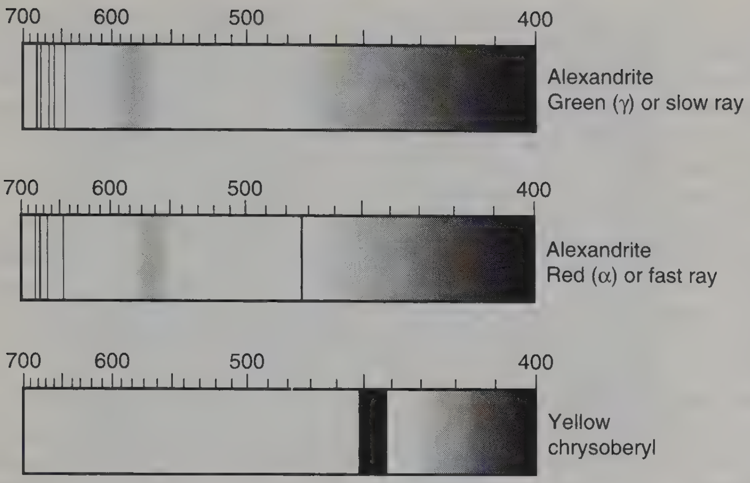


Figure 5.1 *Spectra of alexandrite and yellow chrysoberyl (illustration © 1992 Richard W Hughes)*

high values and could possibly be confused with yellow sapphires. Their lower SG and biaxial character allow separation, however.

Dispersion

The fire shown by chrysoberyl is small, as the dispersion is only 0.015 (B to G).

Pleochroism

The three optical directions of biaxial stones may absorb light differently, and hence show different colours. This trichroism is particularly apparent in the case of alexandrite. Alexandrites show a deep red (or rarely, purple) for the γ-ray. One alexandrite specimen from Mogok, Myanmar (Burma) exhibited an anomalous pleochroism (trichroism) with the α-ray purple, the β-ray grass-green, and the γ-ray blue-green. Yellow and brown chrysoberyls show pleochroism more in depth of colour rather than a different hue, the effect varying from weak in the pale greenish-yellow stones to strong in those of brown colour.

Absorption Spectrum

The absorption spectrum shown by yellow and brown chrysoberyls consists of a strong band at 444 nm, due to ferric iron, which gives the gem its colour. The absorption spectrum of alexandrite is more complex and, further, varies slightly with direction owing to the gem's trichroism. The remarkable colour change of alexandrite results, not from the trichroism, but from an anomaly in the gem's absorption spectrum (*Figure 5.1*).

The colour change can be better understood by comparing alexandrite's spectrum with that of ruby and emerald, where Cr^{3+} also substitutes for Al in the crystal structure. Each of these materials contains a broad absorption band; the band in ruby is centred at 550 nm, in alexandrite at 580 nm and in emerald at 600 nm. The position of this band causes the colour to shift from the purplish-red in ruby to a blue-green in emerald. In alexandrite, where the band is between the red of ruby and green of emerald, the stone is balanced between them. It can be green when the light source is balanced (daylight), but when the light is reddish (incandescent) alexandrite appears red.

Alexandrite is strongly trichroic and the spectrum differs with direction. The spectrum shown by the green (γ or slow) ray consists of a narrow doublet at 680.5 and 678.5 nm, of which the 680.5 nm is the stronger. Weak narrow lines may be seen at 665, 655 and 649 nm. The broad absorption band absorbs light from about 640 to 555 nm and there is an absorption of the blue and violet below 470 nm.

The red or purple (γ or fast) ray shows the doublet weaker and it is the 678.5 nm component which is the stronger. Only two other lines are seen in the red, at 655 and 645 nm, and 'transparency patches' may sometimes be seen in this region, similar to emerald. The broad absorption now lies between 605 and 540 nm and, further, in favourable conditions a line may be seen in the blue at 472 nm. The absorption of the violet commences at 460 nm. In the usual practice of observing absorption specra, when Polaroids are not normally used to separate the rays, only a mixed spectrum may be seen which may vary slightly when the stone is viewed in different directions.

Luminescence

The iron-rich yellow, brown and dull green chrysoberyls exhibit no luminescence when irradiated by UV light or X-rays, although some pale greenish-yellow stones have been seen to glow with a faint greenish light under short-wave UV.

Alexandrite shows a weak red glow under both long- and short-wave UV, a very dim red under X-rays, and, as reported by Michel, an orange glow under cathode rays. The red fluorescence of alexandrite can be well seen by the crossed-filter method (see *Figure 3.4*), and it has been inferred that in borderline cases the presence of a red glow and a faint chromium absorption spectrum would prove the stone to be an alexandrite and not a green chrysoberyl. Such a supposition makes little sense, for the variety alexandrite is properly defined by the presence of a green-to-red colour change, not by the supposed colouring agent.

Inclusions

Probably the most common internal feature of chrysoberyl is the clouds of tiny needles which run parallel to the *c*-axis. These needles have been identified as exsolved rutile in the chrysoberyls from southern India, but it remains to be seen whether this is true in all cases. Some authorities believe them to be hollow tubes. If enough are present a cat's-eye gem can be cut.

The yellow and brown chrysoberyls show various types of internal imperfections, the most common being cavities filled with liquid and a bubble of

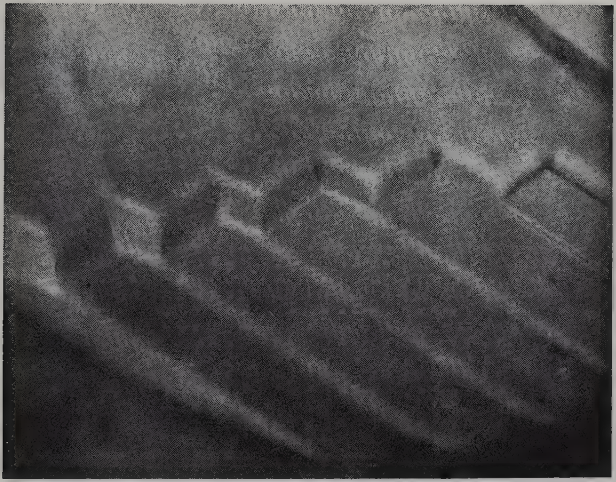


Figure 5.2 Stepped twin planes seen in a yellow chrysoberyl

gas – the so-called 'two-phase' inclusions. Flat liquid-filled cavities and long tubes are other inclusions. An unusual type of structure seen internally in the yellow and brown chrysoberyls are 'stepped twin planes'. These planes, which appear to lie parallel to the brachydome (one of the dome-shaped facets which cap the prism), are not always easy to see and oblique lighting conditions may be needed (*Figure 5.2*).

Solid inclusions in chrysoberyls include mica, actinolite and goethite needles, quartz and apatite. Primary and secondary two- and three-phase cavities, which may contain both water and carbon dioxide, are also common.

The internal features seen in the alexandrite, especially Russian stones, usually consist of feathers and other inclusions similar to those seen in some rubies. They may also display any of the above inclusions.

Occurrences

The finest alexandrites were first found near the Takovaya river in the Ural Mountains some distance north-east of Sverdlovsk (Ekaterinburg) during the year 1830. The stones, small in size and blue-green in colour, are found associated with emerald and phenakite in a mica schist. A further source of alexandrite was discovered later in the southern Urals. The two strongest dichroic colours shown by alexandrite are red and green which are the colours of the old Imperial Russia and the gem was named after Czar Alexander II, who came of age on the day alexandrites were first found in Russia. Today these mines produce little.

Much larger specimens of alexandrite are found as rolled pebbles in the gem gravels of Sri Lanka. The hue of these Sri Lankan stones compares less favourably with the Uralian alexandrites, being yellowish-green in comparison with the bluer green of the Russian stones. In artificial light the Sri Lankan stones are a browner red as against the violet-red of the stones from the Urals. Despite the larger sizes the Sri Lankan stones are less prized than the stones from Russia, because of their poorer colour change. But the gem gravels of Sri Lanka are home to the finest cat's-eyes. Transparent yellow and brown chrysoberyls are also found here.

Other than Sri Lanka, the most important current source of chrysoberyl gems is Brazil. All varieties are found here, including transparent yellow and brown gems, fine cat's-eyes, and recently the world's most important alexandrite deposit, in Minas Gerais, at Lavra de Hematita. Discovery of alexandrite at Hematita set off a boom in sales of this once rare gem, along with a property dispute over ownership of the mine. But for the first time since discovery of the Ural deposits, the world again had a chance to buy fine examples of this rare colour-changing gem. Chrysoberyl is also found in Brazil in the Malacacheta district.

Alexandrite has been found at two different places in the Mogok Stone Tract of Myanmar (Burma). Cat's-eye is also found at Mogok, as well as yellow and colourless chrysoberyl. Zimbabwe, Zambia and the shores of Lake Manyara in Tanzania are other sources of alexandrite.

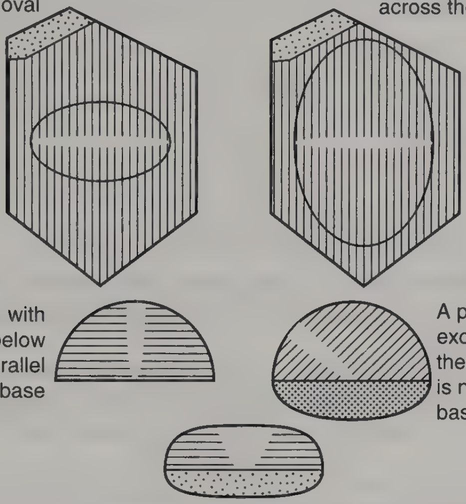
Other sources include the Somabula forest in Zimbabwe and Madagascar. The author (RW Hughes) recently bought one piece of yellow chrysoberyl at Vietnam's new ruby mines at Quy Chau. Chrysoberyl cat's-eyes have also been reported in Orissa state and from southern India.

Cutting of Chrysoberyls

The usual cut for yellow chrysoberyls and alexandrites is the mixed cut, with a brilliant crown and step pavilion. The full step cut, so favoured today for important stones, is not often used for chrysoberyls. Orientation is crucial for alexandrite, owing to the trichroism. The best colour change is seen when the table facet is perpendicular to the direction of the strongest 580 nm spectral band. Generally this means cutting the table perpendicular to the *c*-axis. Since the rutile silk runs parallel to the *c*-axis, it is generally impossible to orient a cat's-eye gem properly to get both chatoyancy and the best change of colour. Thus the rarity of cat's-eye alexandrites.

In order to display chatoyancy, cat's-eye chrysoberyls must be cut *en cabochon* (with a domed top). The chatoyant effect is due to the reflection of light from the fine canals or needles and may be likened to the streak of light seen on a reel of silk. It is essential that the stone is cut with the inclusions running parallel to the base of the cab in order to have a stone with a well-centred ray (*Figure 5.3*). In addition, on oval stones the silk must run parallel to the width so that the eye will run along the length. This is a problem in many crystals, for the shape of the rough does not lend itself to cutting large ovals. Many Sri Lankan cat's-eyes are disfigured by poor cutting, where ovals are cut but the eye goes across the width of the oval rather than down the length. Such stones are generally worthless unless recut.

For the eye to be seen properly, the stone must be viewed under one light source only, such as the direct rays from the sun or a single tungsten lamp; multiple lights confuse the ray, as do fluorescent tube lights.



In properly cut cat's-eyes the eye should run along the length of the oval

In poorly cut stones, to save weight the eye often runs across the width of the oval

A properly cut stone, with no excess material below the girdle and silk parallel to the base

A poorly cut stone, with excess weight below the girdle and silk which is not parallel to the base

If the dome of the cab is too flat, the eye will be diffuse and visible only from straight above

Figure 5.3 Crystal of chrysoberyl showing the needles or tubes running the length of the crystal and a cabochon stone cut from it giving the cat's-eye effect (illustration © 1992 Richard W Hughes)

Synthesis and Simulation

Alexandrite chrysoberyl has been synthesized by a number of different processes, including Czochralski, floating-zone and flux. Inamori in Japan has also produced an alexandrite cat's-eye. Identifying features of these synthetic chrysoberyls are as follows.

Melt-Growth Processes

Czochralski (Pulling) Process

Inamori (alexandrite, alexandrite cat's-eye), Novosibirsk (alexandrite).

1. Gas bubbles.
2. Extremely fine curved growth striae.
3. Synthetic cat's-eye alexandrites show extremely fine, white acicular inclusions or particles at right angles to the direction of the eye. Also found are undulating fibrous inclusions. The short-wave UV fluorescence is a weak chalky yellow confined to the surface of the stone, underlain by a weak red-orange fluorescence. This has not been found in natural alexandrites.

Floating-Zone Process

Hattori Seiko (alexandrite), Novosibirsk (alexandrite).

1. Gas bubbles.
2. Colour swirls in a random pattern.

Solution-Growth Processes

Flux Process

Creative Crystals (alexandrite), Novosibirsk (alexandrite).

1. Primary flux-filled negative crystals, often only partially filled (two-phase) and usually displaying crazed surfaces. They are generally of a white or very pale yellowish colour.
2. Secondary flux-filled negative crystals (healed fractures).
3. Platinum plates, needles and crystals, resulting from corrosion of the crucible walls. These have a random orientation, are opaque and of extremely high relief.
4. Straight growth lines which may meet at angles following the crystal faces. These may appear very sharp and often resemble the 'venetian blind' growth zoning of flux-grown synthetic emeralds.
5. Layers of dust-like inclusions parallel to seed face.

Imitations

Both synthetic corundum and synthetic spinel are made in shades of colour, complete with colour change, to imitate the true alexandrite. Such synthetic stones, besides having the features of their synthetic origin, have different refractive indices, SG and absorption spectra. Spinel being singly refractive does not show dichroism, and corundum – the most common imitation – although showing fairly strong dichroism, never shows the intense green ray as seen in genuine alexandrite. The synthetic colour-change corundum has rather a greyish-blue colour in daylight and a more purple colour in artificial light.

An unusual type of imitation alexandrite is a composite stone in which two pieces of rock crystal (colourless quartz) are cut to form the crown and pavilion and are joined together with a gelatine filter suitably dyed so as to produce a colour change in artificial light. Glasses may be encountered which have apparently been intended to imitate the alexandrite, but these stones do not necessarily change colour and owe their peculiar appearance to swirls of different coloured glass.

The best imitation of cat's-eye is the quartz cat's-eye, a stone which has similar colour nuances to the chatoyant chrysoberyl. The SG of the quartz cat's-eyes (2.65) is much lower than for chrysoberyl; thus, the quartz gem will float in di-iodomethane (3.32) while chrysoberyl will sink. If the stone is mounted the SG test cannot be carried out and recourse must then be made to the refractometer.

The only other natural cat's-eyes which resemble chrysoberyl cat's-eyes are the somewhat uncommon prehnite cat's-eye and the yellow tourmaline cat's-eye. Both of these stones will float in di-iodomethane, a liquid with an SG of 3.32. Chrysoberyl will sink in this liquid. A doublet with a transparent cat's-eye top and a more opaque base has been reported. Bleached tiger's-eye is another chrysoberyl cat's-eye imitation.

There are two types of glass which are made to imitate cat's-eye. The first, a fibre-optic glass sold under the trade name 'Cathaystone', can be identified by its peculiar structure under magnification. When viewed parallel to the fibres, it shows a structure of tiny hexagonal fibre bundles. The other glass is made by Iimori in Japan, and is sold under the name 'Victoria cat's-eye'. Unlike chrysoberyl, it will float in di-iodomethane.

The yellow transparent chrysoberyl is not imitated although glasses are made with a similar colour. The greenish-yellow synthetic spinels, which are coloured by manganese and which show such a brilliant fluorescence, might be mistaken for yellow chrysoberyl if the examination was cursory.

Spinel

Varieties

The mineral spinel produces a lovely suite of gemstones which, unfortunately, are overshadowed by their more opulent cousins, the ruby and sapphire. Next to ruby, spinel is perhaps the most beautiful of all red gems, varying from the lightest pink to the deepest 'garnet' red. A beautiful 'flame' orange is also found. The other important spinel colour is blue, ranging from a magnificent cobalt-blue to a more subdued blue-green. Violet and purple colours are also common.

Pure colourless natural spinel is most rare (or non-existent); natural white spinels always show a trace of pink, which is clearly evident when such stones are viewed side-by-side with the water-white synthetic spinel. A true green-coloured spinel is also a rarity: the so-called green spinels are iron-rich and far too dark to make attractive gemstones. Such stones, called ceylonite or pleonaste, are essentially black. True black spinels have been found in the ejected masses from the crater of Monte Somma, Vesuvius, as well as in the corundum mines of Thailand, where they are locally termed *nin*.

Star spinels have been found in Sri Lanka, with either four or six rays, depending on how the stone is oriented. Mark Smith of Bangkok, who specializes in the rare and unusual, once showed the author (RW Hughes) the truly extraordinary – a cat's-eye spinel. This was not simply a misoriented star, but was a stone with silk running in only a single direction.

The terms 'ruby spinel' or 'spinel ruby' are ambiguous and should not be used.

Judging Quality in Spinel

Next to ruby and the rare red diamond, spinel is the most expensive of all red gems. Red spinels are judged in a similar manner to ruby. The finest stones are a rich, fluorescent red, the colour of a red traffic signal. Stones above one carat may go as high as $2000 per carat.

Cobalt-blue spinels are quite beautiful, but usually small in size. These generally sell for less than $1000 per carat, unless of exceptional size and quality.

Quality of fancy spinels depends on the richness of the colour. Good stones should be 'eye clean' and well cut. They generally fetch less than $50 per carat.

Lore and Unique Stones

The derivation of the name spinel is obscure, but it probably originated from the Latin *spina*, meaning a thorn. Another possible derivation is from the Greek word meaning a spark, alluding perhaps to its fiery colour. In olden times red spinel was often known as Balas ruby, a name derived from Balakshan, another form of writing Badakshan (in northern Afghanistan), or from Balkh the district capital, whence the earliest stones were said to have come.

The historic Black Prince's ruby, which is set in the front of the Imperial State Crown, is an uncut red spinel, as is the Timur ruby, another historical stone in the possession of the British Royal Family. This latter stone is unique in that it has engraved upon it inscriptions which give the names and dates of six owners, from Shah Jahangir (1612) to Shah Durr i-Dauran (1754).

Chemical Composition

Spinel is an aluminate of magnesium, $MgAl_2O_4$, or as it is sometimes written $MgO{\cdot}Al_2O_3$, in which magnesium may be replaced by ferrous iron or manganese, and aluminium by ferric iron or chromium Gem spinel is just one of an isomorphous series in which the magnesium may be wholly replaced by ferrous iron or zinc, or partly by manganese and ferrous iron. The members are shown in *Table 5.2*. Other members of the spinel group are magnetite (Fe_3O_4) and chromite ($FeCr_2O_4$), and there are a number of other minerals which are replacements of the double oxides. Thus even in the more restricted gem material some variation is to be expected in the chemical, physical and optical properties.

Table 5.2
Members of the spinel series

Species	*Formula*	*RI*	*SG*	*Colour*
Spinel	$MgAl_2O_4$	1.719	3.55–3.63	Various (most gems)
Gahnospinel	$(Mg,Zn)Al_2O_4$	1.805	4.0–4.62	Dark green
Gahnite	$ZnAl_2O_4$	1.725–1.753 +	3.58–4.06	Blue, dark blue
Hercynite	$FeAl_2O_4$	1.835	4.40	Dark to black
Ceylonite (pleonaste)	$(Mg,Fe)Al_2O_4$	1.77–1.78	3.63–3.90	Dark colours
Picotite	$Fe(Al,Cr)_2O_4$	–	4.42	Dark green to black
Galaxite	$MnAl_2O_4$	1.92	4.04	Dark red to black

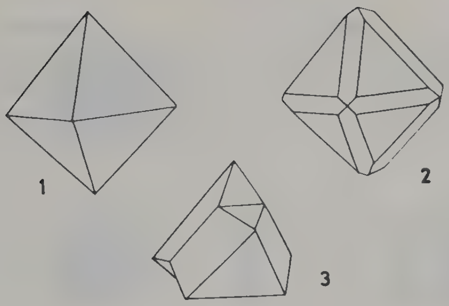


Figure 5.4 *Crystals of spinel: (1) octahedral crystal, (2) octahedral crystal with the edges truncated by the dodecahedral faces, (3) contact twin crystal, the 'spinel twin'*

Crystallography

Spinel is a cubic mineral and when it is found as crystals they are invariably of octahedral form and often have brilliant faces (*Figures 5.4*). Some crystals have the edges of the octahedral faces truncated with the faces of the dodecahedron, and many crystals are twinned on the plane of the octahedral face producing flattened triangular forms. This is a type of contact twinning and is called the 'spinel twin' owing to its common occurrence in spinel. The highly lustrous and often perfect octahedral crystals of spinel which are found in the Mogok Stone Tract are called by the Burmese *anyan nat thwe*, which means 'spinels cut and polished by the spirits'. Much spinel is found as water-worn pebbles in alluvial gravels.

Hardness, Cleavage, Fracture and Specific Gravity

Spinel is comparatively hard, rating 8 on Mohs's scale. It shows an imperfect cleavage and a conchoidal fracture and has a brittle nature. The specific gravity varies from 3.58 to 3.98, but gem spinels range from 3.58 to 3.61, pale pink stones having lower values. Iron-rich ceylonites have an SG of 3.63 to 3.90, 3.80 being a usual value. In 1937, Anderson and Payne reported the existence of a zinc-rich gem spinel for which the name gahnospinel was suggested. These spinels varied in colour from pale to dark blue and ranged in SG from 3.58 to 4.06, with an RI of 1.753.

Effects of Light

Refraction

Spinels display a vitreous lustre and take a brilliant polish. The mineral has a single RI, ranging from 1.712 to 1.80. Normal gem material is fairly constant at 1.718, but red stones rich in Cr may rise to 1.74. Ceylonites have the highest values at 1.77 to 1.80. Gahnospinels vary in RI between 1.725 and 1.753, and higher.

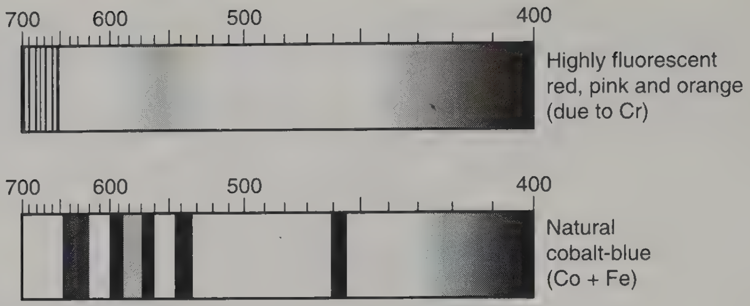


Figure 5.5 The absorption spectra of natural spinel (illustration © 1992 Richard W Hughes)

Absorption Spectrum

The absorption spectrum of red and pink spinel is typical of stones which owe their colour to chromium. This spectrum is characterised by a broad absorption in the yellow-green centred at 540 nm, and absorption of the violet (*Figure 5.5*). There is an absence of lines in the blue window; any lines in the red are difficult to see, except in richly coloured specimens. The lines in the red may be seen as bright fluorescence lines; these differ from those shown by ruby in that they are a group of fine lines. Anderson has aptly labelled this an 'organ-pipe' spectrum, owing to the appearance of the fluorescent lines. There may be as many as ten or more of these lines in strongly fluorescent stones; those at 686 and 675 are strongest, separated from each other by a large gap. Three weak lines are on the long-wave side of the strong pair, and five on the short-wave side.

Blue spinel owes its colour to ferrous iron, or more rarely cobalt, and shows a spectrum having the most important lines in the blue, particularly a strong band at 458 nm. There is a narrower band at 478 nm, together making a pattern quite distinctive from that of blue and green sapphire. Weaker and less easily seen lines are at 443 and 433 nm, and in the orange, yellow and green at 635, 585, 555 and 508 nm. The 458 nm line has not been found in the synthetic, making it important for identification.

In the case of pale blue and mauve spinels, and zinc-rich gahnospinels, a similar type of spectrum to the deep blue stones is seen, but is weaker.

Luminescence

The luminescence of spinel shows considerable variation. Natural red and pink spinels show a red glow under UV light. This is stronger under long-wave than short-wave UV; the red glow is moderate under X-rays. In no case is phosphorescence seen. Dark blue spinels are completely inert under any radiation.

Natural pale blue or violet-blue spinels exhibit a green glow under long-wave UV light and X-rays, but are practically inert under the short-wave UV.

Purple and pale violet spinels fall into three classes:

1. Those stones, generally deep purple, which glow
   red under LW UV
   inert under SW UV
   red under X-rays.
2. Those stones which glow
   orange to red under LW UV
   inert under SW UV
   green under X-rays.
3. Those stones, generally pale violet, which glow
   green under LW UV
   inert under SW UV
   green under X-rays.

Inclusions

Liquid inclusions are rare in spinel. Spinel crystallizes in the cubic system; as such it tends to grow equally in all directions and so does not develop the stress cracks common to non-isometric crystals. In addition, the metamorphic environment from which many spinels grow is akin to plastic; it lacks the liquids of other geological environments, such as pegmatites.

Common spinel inclusions include 'spangles', which are included crystals with surrounding iridescent stress fractures. But the most common inclusions are the octahedral crystals, alone or in rows, which may be of another member of the spinel group, or may be cavities filled with calcite or dolomite (*Table 5.3*). Such octahedral crystals appear like a fingerprint made up of tiny octahedra, where each octahedron is oriented along definite crystallographic directions in the host crystal (*Figure 5.6*).

Thin films, often containing iron staining and commonly associated with

Table 5.3
Spinel inclusions

Inclusion type	*Description*
Solids	Octahedral crystals of spinel-group minerals, often in rows Plates of graphite, along the spinel's octahedron faces Calcite and/or dolomite Apatite prisms Limonite Quartz Olivine Phlogopite mica Sphene Uranite
Cavities (liquids/gases)	Primary and secondary liquids are rare in spinel, but unhealed cracks are common. Primary cavities may be filled with calcite or dolomite
Growth phenomena	Growth zoning parallel to the octahedron faces, seen most easily under immersion between crossed polars
Twinning	Growth twins on the octahedron faces are common
Exsolved solids	Needles of sphene, following the octahedron edges

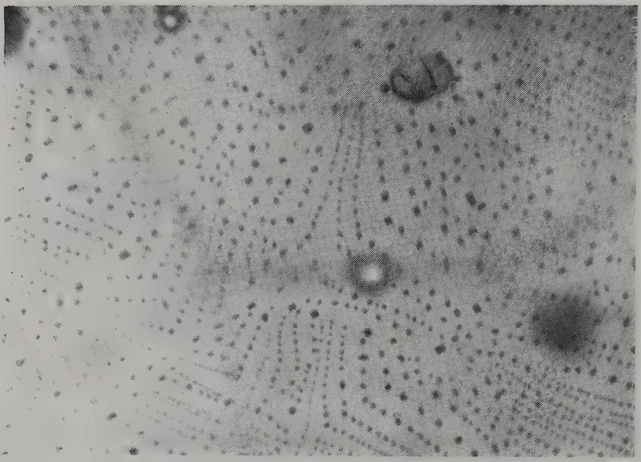


Figure 5.6 Octahedral inclusions arranged according to the crystal directions of the host mineral, seen in a blue spinel

fairly large octahedral crystals, are a common spinel inclusion. Sri Lankan spinels may show 'zircon haloes', a central inclusion surrounded with brown stain markings which may appear like wings. The cause of these surrounding brown markings was previously ascribed to staining by radioactivity from the zircon crystal which forms the centre, but more recently they have been ascribed to stress cracks caused by the unequal thermal expansion of the central inclusion and the host mineral.

Spinels showing asterism used to be quite rare because the cloudy rough in Sri Lanka was discarded. But when cutters realized such rough had value, former rarities became common. Star spinels vary in colour from red to black, red being the more valuable. The star, owing to exsolved sphene needles, may be either four or six rayed, depending on how the rough is oriented. If a six-rayed star is seen on top (base parallel to cube face), there will be alternating four and six-rayed stars around the girdle. If a four-rayed star is on top (base parallel to the dodecahedron), only six-rayed stars will be seen at the girdle. Fine clouds of unidentified particles forming in an octahedral pattern have been seen in Burmese spinels.

Occurrences

Spinel is commonly found in association with gneiss, serpentine and allied rocks, and is generally found with corundum. Much gem spinel is found in alluvial gravels and not so often *in situ.*

At Mogok, Myanmar (Burma), spinel occurs in alluvials, and in crystalline limestone rocks. The finest red, pink and orange spinels are found here, but all colours are produced. The mineral is found both as perfect octahedral crystals of sometimes large size, and as massive lumps and broken fragments without any outward sign of crystal form. The reason given by Halford-Watkins for perfect spinel crystals being found side-by-side with the harder ruby, which is in a water-worn condition, is that the spinel crystals are localised in certain parts of the deposits and only occur in any quantity in isolated patches. Thus they have not had to travel so far as the rubies.

The other important world gem deposit of spinel is Sri Lanka, where it is found in some quantity as water-worn pebbles. A full range of colours is produced in Sri Lanka, with the blues and violets being particularly fine in quality.

Minor sources include the Amboseli district of Kenya, the Jemaa district of Nigeria, and the Matombo district and the Umba Valley in Tanzania, all in Africa. In Asia, spinel is found at Hunza in Pakistan, in the Pamir Range in Tajikistan, and at Luc Yen in Vietnam. Contrary to what has been previously published, to the best of the present author's (R W Hughes) knowledge there is *no* gem spinel mined in Thailand other than black. Also contrary to what has previously been written, the author *has* found spinel in a parcel of sapphire from Yogo Gulch, Montana.

Spinel is found, again in association with ruby and sapphire, in Afghanistan. Other localities are Australia, Sweden, and Brazil.

Cutting of Spinels

Spinel is generally cut in a similar way to corundum. In antique jewellery in Myanmar, one still occasionally encounters uncut red spinel octahedra mounted in rings, earrings and bracelets without any treatment whatsoever from the lapidary. But watch out for octahedra offered by unscrupulous dealers that have polished faces to 'improve' them.

Synthesis and Simulation

Spinel has been made for several decades by the Verneuil process in a variety of colours, except red. The red colour was found difficult to make and was never made commercially. Generally it is made to imitate other gemstones, but with the rise in prices of natural red and blue spinels, the danger is always there. Recently a flux-grown synthetic spinel made in Russia has been marketed. It is produced in red and cobalt-blue.

The identifying features of synthetic spinels are as follows.

Flame-Fusion Synthetic Spinel

Varieties

1. Colours: red, pink, yellow-green, green, light and dark blue, and colourless.
2. Phenomena: colour change (green to red), imitation moonstone (white with schiller).
3. Imitation lapis lazuli, consisting of a sintered synthetic spinel powder coloured blue by cobalt, with real gold specks added to imitate the fool's gold (pyrite) of natural lapis.

Chemical Composition

1. Most colours (except red): ratio of Al_2O_3 to MgO is 2.5:1.
2. Synthetic red spinel: ratio 1:1. Imitation moonstone type: ratio 4:1.

Refractive Index

1. 1.728 ± 0.003 for most colours.
2. 1.722 to 1.725 for synthetic red spinel.
3. 1.725 for the imitation lapis type.

Specific Gravity

1. 3.63 to 3.67 for most colours.
2. 3.60 to 3.66 for synthetic red spinel.
3. 3.52 for the imitation lapis type.

Polariscope Reaction

Generally weak anomalous double refraction which is often seen in a characteristic cross-hatch pattern; it is caused by the strain from the excess alumina.

UV Fluorescence

The following are approximations only and considerable variation from these reactions may be found. The key feature is that many synthetic spinel varieties fluoresce pale chalky colours under SW. This has not been found in the natural.

Variety	*Reaction*
Pale pink	chalky green (SW)
Red	red (LW and SW)
Pale blue	orangy red (SW); red (LW)
Pale blue-green	intense yellow (SW)
Yellow-green	chalky green (SW)
Colourless	bluish-white (SW)
Imitation moonstone (white)	bluish-white (SW)

Features of Rough

1. Boules are generally of 20–40 mm diameter and up to 100 mm or more in length, with slightly flattened sides. The boules do not need to be split lengthwise. Such boules may weigh hundreds of carats and can produce cut stones of up to 100 carats.
2. Side surfaces have a fine-grained frosted texture similar to that of Verneuil synthetic corundum, but the top convex surface may display numerous tiny octahedron faces under magnification.
3. Boules may show cubic tension (cleavage?) cracks on the surfaces.

Magnification

1. Gas bubbles, sometimes with torpedo shapes and sometimes featuring slightly formed cube/octahedron crystal faces. When elongated, they usually run at 90 ° to the slightly convex top surface of the boule. Long, parallel hose-like tubes are common.
2. Virtually all (but not all) synthetic red spinels display obvious curved growth lines which appear as broad swaths of colour, in contrast to the tightly packed curved striae of Verneuil synthetic rubies. The curved growth lines are seen at roughly 90 ° to the boule's length. Curved growth lines are rather rare in other varieties, but have been seen in synthetic blue spinels and might possibly be found in other varieties, too.
3. The imitation moonstone synthetic spinel features a mirror-like coating on the back of the cabochon. The schiller-like effect is caused by exsolution of excess alumina (4:1 ratio), which produces multitudes of tiny needles, and can even result in a star of sorts.
4. Solid crystals of alumina, thought to be due to exsolution.
5. Strain knots when viewed between crossed polars with magnification.

Spectrum

1. Red: identical to the natural (with a broad band at 540 nm), except that only a single fluorescent line at 686 nm is seen.
2. Cobalt-blue: strong transmission in the blue and red, with broad absorption lines at 544, 575, 595 and 622 nm. The 458 nm line present in the natural is lacking.
3. Green (with yellow fluorescence): a strong line at 422 nm and a vague band at about 445 nm.
4. Greenish-blue: a strong line at 422 nm, a vague band at about 443 nm, and an extremely weak cobalt complex at 544, 575, 595 and 622 nm.
5. Colour-change type: broad absorption from 400 to 480 nm, narrow transmission band from 480 to 520 nm, broad absorption band centred at 580 nm, narrow line at 685 nm.
6. Lapis lazuli imitation (reflected light): vague lines at 452 and 480 nm, broad band centred at 530 nm, broad lines at 585 and 650 nm.
7. UV spectrum, synthetic red: generally UV transmission (315 nm) stronger than visible-region transmission.

Flux-Grown Synthetic Spinel

Novosibirsk (Russia): red, cobalt-blue.

Magnification

1. Primary flux-filled negative crystals.
2. Straight angular growth lines following crystal faces (generally along the octahedron).
3. Crystals often have one flat face (cube face?) at the tip of the octahedron, forming a base from which the growth started.

6

Topaz and Tourmaline

Topaz

A long-held error had been to suppose that all yellow stones were topaz and that all topaz was yellow. Even in present enlightenment, occasionally the yellow to reddish-brown citrine quartz is still sold under the misnomers 'topaz', 'quartz topaz', 'Scotch topaz' and 'Madeira topaz', and the term 'precious topaz' is reserved for the true topaz. This confusion of names dates to antiquity, for in older days all yellow stones were called topaz.

There are two theories as to the origin of the name topaz. The Roman writer Pliny in the first century AD suggests that the name was derived from the Greek word *topazos*, meaning to seek, and was apparently derived from the name for a somewhat elusive island in the Red Sea. This island is probably the one now known as the Island of Zeberget (or St John) from which the brownish-green to yellow-green peridot has been mined. It seems, therefore, that our modern peridot was in earlier days called topaz. Another and more likely derivation is that the old Sanskrit word *tapas*, meaning fire, was the root from which the modern name has sprung.

The first use of the name topaz for the precious topaz of today's jeweller appears to have been made by Henckel in 1737 when he described the Saxon deposits. In the light of the confusion relating to nomenclature that has occurred, it seems a pity that Henckel did not select another and newer name for the mineral.

Chemical and Physical Properties

Topaz crystallises in the orthorhombic system as prismatic crystals with the faces of the prisms often deeply striated parallel to their length. In the terminal faces considerable differences in habit occur. The brown crystals from Brazil are simply terminated with four low-angled triangular faces forming a pyramid. In

Figure 6.1 *Topaz crystals from New Hampshire, USA*

the crystals from Utah these pyramidal faces are steep, and in the Japanese and some African crystals and those from a number of other localities, which are usually colourless or blue, a number of pyramidal and dome-shaped faces occur, with two of the dome faces often so enlarged that they meet at the top of the crystal to form a ridge, thus giving a chisel-shaped appearance to the crystal. In some cases the basal pinacoid is present producing a flat-topped crystal. *Figure 6.1* shows some topaz crystals.

Topaz crystals are usually terminated at one end only, the other being the cleaved basal plane where the crystal has been broken from the rock on which it had grown. Doubly terminated crystals are rare but not unknown. On looking down the length of a topaz crystal the outline is seen to be lozenge-shaped (diamond-shaped), but if, as sometimes occurs, the second-order prism is predominant, a pseudo-tetragonal or square outline is seen.

Topaz crystals occur in cavities in highly acid igneous rocks, such as granite or rhyolite; the supposition is that topaz is deposited by the action of hot fluoriferous gases after solidification of the magma. (It is of interest to note that the geochemistry of fluorine in groundwater has been proposed as useful in delineating areas of fluorine-bearing gem minerals such as topaz.) Topaz is also a common occurrence in zones of contact metamorphism and in granitic pegmatite dykes, especially those carrying tin. Pegmatites are the major primary source of gem topaz, with huge, gem-quality crystals sometimes being found in cavities or 'pockets'. A 300 kg transparent topaz recovered from a pegmatite in Minas Gerais, Brazil, is displayed in the American Museum of

Figure 6.2 Garimpeiro washing eluvial gravels in a stream, Minas Gerais, Brazil (photo by Robert C. Kammerling, GIA Gem Trade Laboratory)

Natural History in New York, and faceted stones in excess of 20 000 carats have been cut from such gemmy crystals. Topaz occurs in association with such other minerals as apatite, beryl, cassiterite, feldspars, fluorite, mica, quartz and tourmaline. Much topaz is found as water-worn rolled pebbles in river gravels, and may be recovered as are other gem materials from such secondary sources (see *Figure 6.2*).

Most topaz is colourless, the pale blue colours being next in abundance, and may rarely be chatoyant. Stones of a green colour, resembling the sea-green aquamarine, are said to emanate from Russia. Brownish crystals are found in a number of localities, but the highly prized brownish-yellow to orange to yellow-brown 'sherry topaz' and vivid pinkish-orange to red-orange 'imperial topaz' crystals which cut into such fine jewel stones are found only in Brazil. Natural pink-coloured crystals are rare, one relatively new source for these (as well as reddish-brown, tan, and colourless crystals) being near Katlang, Pakistan. Much of the pink topazes used in jewellery are without doubt Brazilian stones which have been altered to pink by heat treatment.

Although topaz is a hard mineral (at 8 on the scale of hardness devised by Mohs), it will break easily in a direction at right angles to the length of the crystal, for it has an extremely good basal cleavage. This cleavage in topaz is a danger in that the least knock or blow given to the stone may start internal fissures or flaws. As many topazes are fashioned into long oval or drop (pear) shapes owing to the prismatic shape of the crystals, there is a great tendency for such stones to develop cleavages across them, or even to break into two parts (*Figure 6.3*). Topazes need to be treated with great care, even when set in

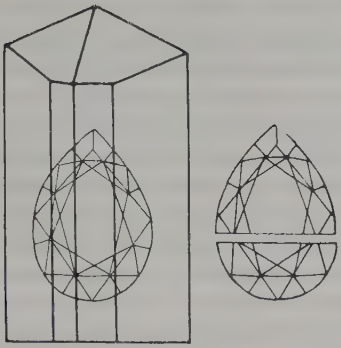


Figure 6.3 Stylised topaz crystal showing a drop-shaped stone cut from it and the liability of the stone to break in two owing to the extremely good basal cleavage of topaz

jewellery, and mountings should be designed to give them additional protection.

Topaz is in composition a fluosilicate of aluminium; the chemical formula is expressed as $Al_2(F,OH)_2SiO_4$, that is the fluorine and the hydroxyl (the OH group) can substitute for one another by isomorphous replacement. In theory, therefore, there could be a pure hydroxy topaz – $Al_2(OH)_2SiO_4$ – but in fact there is always some hydroxyl and fluorine in the chemical make-up. Fluorine has the tendency to raise density and to lower the refractive index of a mineral, while hydroxyl operates in the reverse way.

Effects of Light

Refraction

The sherry-brown and pinkish-orange imperial topazes from Brazil, and the heat-treated pink stones derived from them, have an SG near 3.52 and refractive indices near 1.629 and 1.637 with a birefringence of 0.008. Similar to slightly higher values are reported for the pink topazes from Pakistan. The light blue, light green and colourless stones, and the yellow stones from Russia, eastern Germany (Saxony), the United States of America, and elsewhere, have a higher SG – near 3.56 – and refractive indices of about 1.609 and 1.619, the birefringence for these stones being greater at 0.010. These values indicate a richness in hydroxyl for the Brazilian stones and a richness in fluorine for the topazes from elsewhere. In all cases, the refraction is biaxial and positive in sign. Although these two groups of topaz are fairly well defined, there have been cases where intermediate values of refractive indices have been measured. Stones with such properties, that is with a refractive index measurement of 1.62–1.63, are rare. With a birefringence of 0.010 the doubling of the rear facet edges of topaz should be fairly easy to detect. This could, however, be overlooked, for the doubling, although parallel, may be superimposed and thus not obvious.

Translucency and Pleochroism

Topazes are usually transparent, except in cases where abundant inclusions produce a cloudy effect. The limpid transparency of the water-clear stones is aptly described by the Brazilian and French names used for them; these are *pingo d'agoa* and *goutte d'eau*, both meaning drops of water. Topaz has a vitreous lustre, a characteristic slippery feel, but little fire, the dispersion being 0.014 (B to G). The stones take a fine polish and thus can have a high lustre.

The pleochroism of topaz is distinct but not strong, except in the case of the 'fired' pink-coloured stones when the effect is pronounced, one ray being colourless to pale yellow and the others two shades of pink. Dark rose-red stones exhibit red to dark red, yellow to brownish-yellow, and rose-red, while pink stones from Pakistan display the trichroic colours yellow, purple, and deep mauve to violet. The sherry-coloured stones exhibit brownish-yellow, straw yellow, and orange-yellow for the three optical directions. The blue stones show colourless, pale pink and blue. When viewed through the Chelsea colour filter, the blue stones show a greenish-blue, but this is nowhere near the strong blue effect exhibited under similar conditions by aquamarine.

Absorption Spectra

The topazes, with two notable exceptions, show no observable absorption spectra which can be used in their identification. The sherry-coloured crystals from Ouro Prêto in Brazil are said to contain a trace of chromium, but this element rarely appears to show in the absorption spectrum of such stones. When, however, such stones are heat-treated to about 450 °C – producing the pink-coloured topaz – the chromium takes its place in the crystal lattice and then gives rise to a chromium fluorescence and absorption spectrum. The main characteristic of this very weak spectrum is a feeble doublet about 682 nm, which can be seen as a faint absorption line, or more readily as a fluorescent (or emission) line by scattered light. It can be seen better if the incident light is passed through a flask of copper sulphate solution or similarly coloured gelatin filter. Similarly, the pink stones from Pakistan, also coloured by chromium, exhibit a very weak line at 682 nm.

Luminescence

The luminescence of topaz appears to vary in some accordance with the two types, the hydroxyl-rich and the fluorine-rich. The blue and colourless stones may show a weak yellow or greenish-yellow under long-wave ultra-violet light. Under the short-wave lamp the glow is very much weaker or may not be detected at all. Leiper has found in some colourless and bluish topazes a lemon-yellow fluorescence under the short-wave lamp and that the glow tended to show a definite orientation, three main types of orientation of the glows being noted. The effect is suggested as being a useful guide for ascertaining the best cutting directions in order to obtain the best blue colour from bluish crystals. Under X-rays the blue and colourless topazes show a greenish-white to a violet-blue fluorescence. Under X-ray bombardment the stones are found to take on a brownish-yellow colour component, which, however, is not stable.

The sherry-brown and heat-treated pink stones, which with the exception of the irradiated blue stones are those most commonly found in jewellery, may show a strong orange-yellow glow under long-wave ultra-violet light, and a similar but much weaker glow is seen under short-wave ultra-violet light. Some yellow and pink topazes show a dull greenish-white reaction to the short-wave lamp. Under X-rays the glow is brownish-yellow to orange in colour. This is an entirely different effect to that seen when the colourless and blue stones are so irradiated. Natural-colour pink stones from Pakistan fluoresce a very weak dark red to long-wave ultra-violet light and a distinct milky-green to short-wave ultra-violet light.

Effects of Heat and Irradiation

Topaz becomes strongly electrified by either heat or friction and retains this charge for several hours. Some specimens will become highly electrified by gently stroking with the fingers. In some Brazilian crystals quite a gentle pressure between the finger and thumb in the direction of the principal axis is quite sufficient to electrify them.

It was recorded by the Greeks that yellow topaz decolorised when strongly heated, but as the yellow quartz variety known as citrine behaves similarly, it is difficult to be sure whether the material was the true topaz or quartz. If the reddish-brown crystals from Ouro Prêto, Brazil, are slowly heated to about 450 °C the crystals first become colourless but on cooling develop a colour which may vary from a salmon pink to a purple-red, depending on the intensity of the original colour and on the strength of the heating.

It was said that the process was first discovered by a Paris jeweller, Dumelle by name, who communicated his discovery to the French Academy of Sciences. Dumelle's process consisted in heating a topaz in a sand bath to a temperature of 500 °C and leaving it to cool in the sand. Another method is to enclose the crystal in many wrappings of tinder which are then fired, the heat from the burning tinder being sufficient to 'pink' the topaz. Slow heating and slow cooling are essential to prevent the crystal from being fissured and made cloudy; too much heat or too rapid a heating will cause the stone to become completely decolorised, this occurring at over 600 °C. The cause of the change of colour from brown to pink is due, as mentioned earlier, to the trace of the element chromium present in the brown stones entering the crystal lattice under the influence of heating. Many of the paler brown topazes from other localities, probably all of the fluorine-rich type, tend to fade in sunlight. This is particularly so with such crystals from the Urulga river in Russia and those from Japan and the Thomas Range in Utah, USA. Some fluorine-rich topazes have been seen which have a rather strong yellow-brown colour and this has prompted the suggestion that such stones have been laboratory irradiated.

Not long after the appearance on the market (in 1973) of cut specimens of deep blue beryl, which were subsequently found to owe their colour to irradiation with gamma rays, cut specimens of topaz of an almost equally fine blue colour began to enter the market, and gave rise to a considerable degree of speculation as to their origin and the permanence of the blue coloration. Eventually, research by Nassau established that these attractive stones also owed their colour to some form of gamma radiation, but that, unlike the treated blue beryls, the colour in this case was unaffected by exposure to sunlight.

It is now known that such enhanced colours can be produced in topaz by treatment in gamma-ray facilities like those used to sterilise food and medical instruments. The treatment produces both blue- and yellow-causing colour centres, so irradiation is followed by heating to remove the less stable yellow colour component. Light blue topaz produced by this method has been referred to in the trade as Cobalt Blue. Higher doses of gamma irradiation may produce a 'steely' greyish-blue colour. Today, it is believed that there is little commercial production of gamma-irradiated blue topaz, although some processors first treat topaz with gamma rays as a pre-screening procedure, as material that picks up a blue colour under these relatively low doses of radiation is likely to turn a darker blue upon exposure to the higher energies associated with other irradiation treatment processes.

Linear accelerators or 'linacs' are now one of the preferred enhancement methods for inducing blue colour in topaz. These permit higher energies (or higher doses) than gamma treatment, so darker colours are often obtained. As with gamma treatment, linac treatment must be followed by heating to remove an unwanted yellow to brown colour component. Unlike gamma irradiation, however, linac treatment may produce short-lived residual radiation in topaz so it cannot be released from the radiation facility for typically a few weeks after irradiation. The material called Sky Blue in the trade is typical of the colour produced by this method. There is little if any unwanted 'greyishness' associated with material so treated.

In 1981, specimens of topaz that were dark blue and perceptibly radioactive made their appearance. The latter indicated that the process used involved neutron bombardment in a nuclear reactor. Subsequent research has shown that the main emitters are the radionuclides tantalum-182, scandium-46 and manganese-54, which are produced during the treatment process.

Nuclear research reactors are now regularly used to produce blue coloration in topaz. Material so treated generally comes out blue, and therefore does not require a subsequent heating step. The most typical reactor-produced colour is a medium to dark greyish-blue that is often described as 'inky' in appearance. A trade name often heard for this material is London Blue. Heating may be used, however, to remove the inky cast, resulting in a lighter but more saturated colour.

Because treatment in a nuclear reactor renders topaz radioactive, it must be stored for a period of time until this induced radioactivity decays to a safe level, normally one to two years. Many countries have regulations to control the sale and distribution of reactor-treated gems. In the United States of America, where there is a large market for blue topaz, the Nuclear Regulatory Commission (NRC) has licensed a number of facilities, including the Gemological Institute of America, to test topaz and other gems for residual radioactivity prior to their distribution to the public.

Most recently, combined treatments have been used to produce some darker blue colours in topaz that do not suffer from the inkiness of the London Blue material. Such a combination of treatments usually begins with irradiation in a nuclear reactor, this being followed by linac treatment, and then heating to remove unwanted secondary hues. Among the trade names used for such material are Super Blue, Swiss Blue and American Blue.

The radiation treatments used to produce attractive blue colours in topaz have greatly increased the availability of this material, which has become one of the most popular of all coloured gemstones.

It should be noted that irradiation in nuclear reactors has also been used to produce green colours, such material being marketed as Ocean Green Topaz. Additionally, a predominantly blue coloration has been produced in topaz by coating the surfaces with a thin film of gold. These stones, marketed as Aqua Aura topaz, display both the blue to greenish-blue transmission colour of the gold as well as a superficial thin-film iridescence.

Inclusions

Much topaz is inclusion-free. Internal features that may be seen in the colourless, blue and brown fluorine-rich types of topaz are usually tiny cavities containing two or even three immiscible liquids with distinct dividing lines. These cavities are often drop-shaped and the bubbles, one of which could possibly be carbon dioxide, may be inside one another (*Figure 6.4*). Such inclusions may also contain a solid phase (*Figure 6.5*). Occasionally these cavities may be flattened out into thin films of liquid. Because of its easy cleavage, flat breaks may be noted in fashioned gems.

Crystalline inclusions typical of topazes of pegmatitic origin include monazite (*Figure 6.6*), muscovite mica (*Figure 6.7*), spessartine garnet (*Figure 6.8*), albite feldspar, brookite, and quartz. A rare type of inclusion which has been observed in topaz from the tin workings of Nigeria is cubic crystals either singly or as groups (*Figure 6.9*). These, as well as octahedrons, rhombic dodecahedrons and their combinations have been identified as fluorite crystals. The hydroxyl-rich sherry, imperial and pink stones from Ouro Prêto usually show long tube-like cavities running the length of the *c*-axis of the crystal.

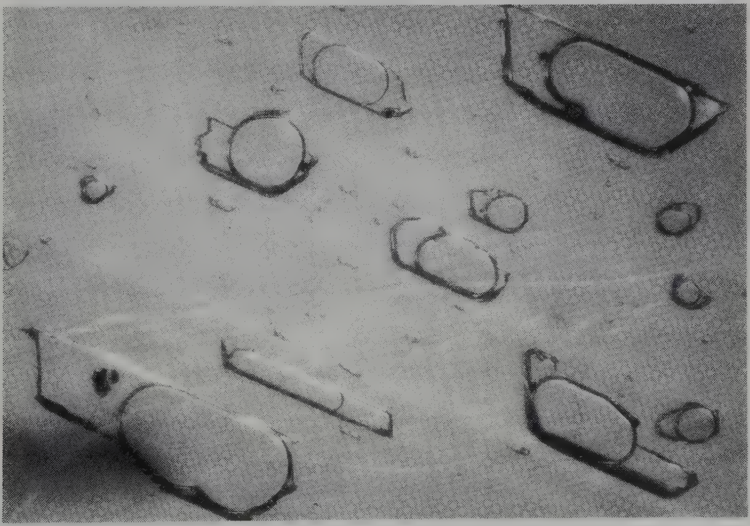


Figure 6.4 Cavities with two immiscible liquids in a blue topaz (photomicrograph by John I Koivula, GIA Gem Trade Laboratory)

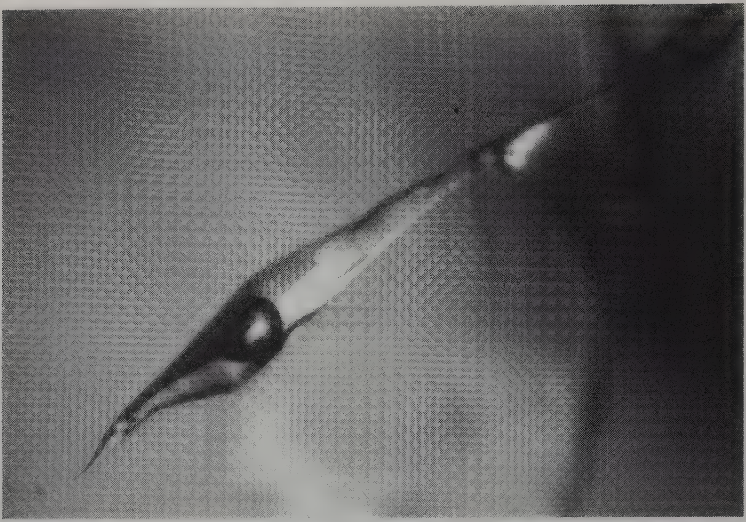


Figure 6.5 Three-phase inclusion in topaz: the solid phase is a salt crystal (photomicrograph by John I Koivula, GIA Gem Trade Laboratory)

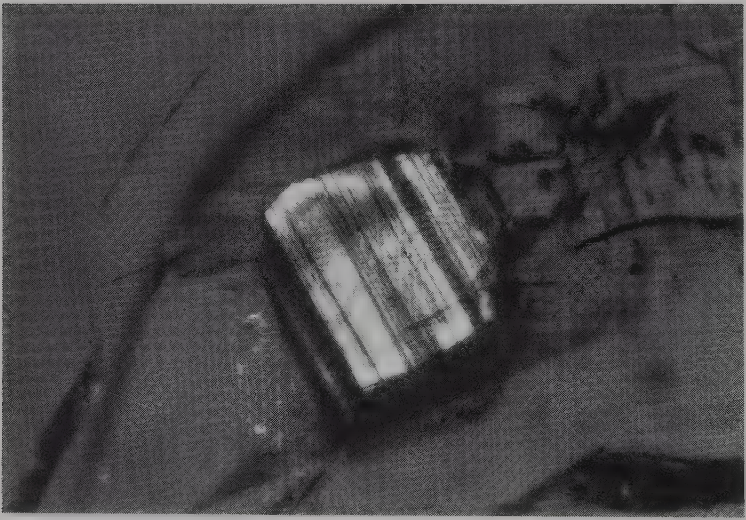


Figure 6.6 Monazite crystal inclusion in topaz of pegmatitic origin (photomicrograph by John I Koivula, GIA Gem Trade Laboratory)

In the mid 1980s, faceted Brazilian topazes containing eye-visible brownish-yellow acicular inclusions appeared on the gem market. These stones – mostly colourless but also some blue – were being marketed under the name 'rutilated topaz' because of their superficial resemblance to rutilated quartz. Investigations carried out at the GIA revealed the essentially parallel inclusions to be not

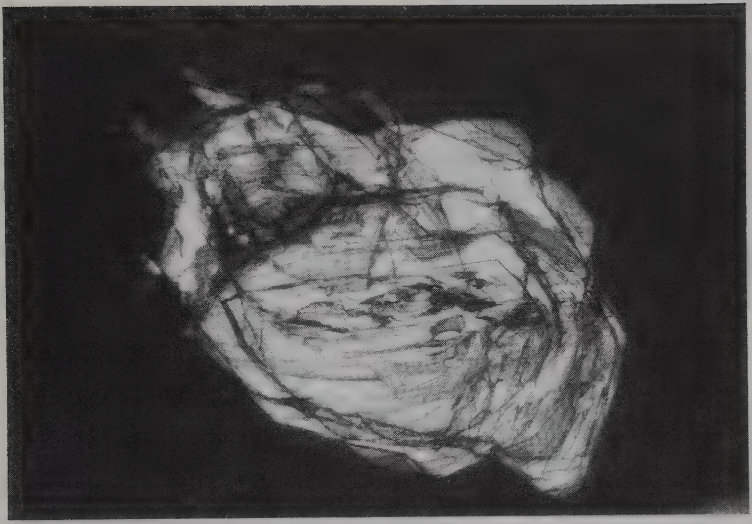


Figure 6.7 *Muscovite mica, another typical inclusion in topaz (photomicrograph by John I Koivula, GIA Gem Trade Laboratory)*

Figure 6.8 *Spessartine garnets in a topaz from Minas Gerais, Brazil (photomicrograph by John I Koivula, GIA Gem Trade Laboratory)*

rutile needles but surface-reaching ribbon-thin etched dislocation channels that were partially to totally filled with epigenetic iron staining (*Figure 6.10*). Subsequent experimentation showed that heat treatment could alter the limonite staining to hematite, thereby changing the colour to a dark red-brown and making them more prominent.

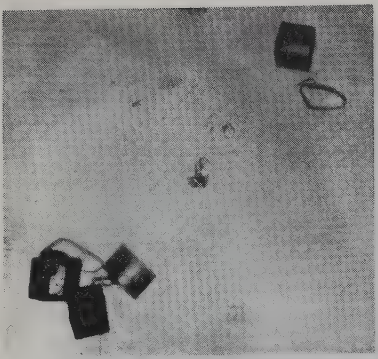


Figure 6.9 *Cubic crystals in colourless topaz from Nigeria*

Figure 6.10 *Brazilian topaz containing limonite-stained etched dislocation channels (photo by Maha DeMaggio, Gemological Institute of America)*

Occurrences

The earliest known source of topaz was probably that of Schneckenstein, near Auerbach in Saxon Voigtland (eastern Germany), where the crystals, of pale wine-yellow colour or completely devoid of colour, are found in drusy cavities in association with quartz and tourmaline. Traditionally the most sought-after topaz for jewellery purposes has been the sherry-brown material from Brazil which makes such attractive pink stones when heat-treated. The locality for these crystals and including the colours now called imperial topaz is just west of Ouro Prêto in the state of Minas Gerais. The topaz is found as groups of detached crystals embedded in clay or scaly kaolin in cavities all along a range of hills that form a belt about 20 km long and 6 km wide running east–west from the Saramenha mine, roughly 4 km west of Ouro Prêto, to the Olaria mine, about 25 km to the west of the city.

Natural-colour pale blue as well as colourless topazes, in the form of crystals and rolled pebbles, are abundant in many places in Brazil. Colourless material, used to produce blue stones through irradiation, are found throughout the Teófilo Otoni-Marambaia and Araçuaí-Salinas pegmatite districts. Very large quantities of colourless material are also mined in Rondonia in western Brazil. Yellow and colourless topaz is found at La Paz, San Luis Potosi, and Durango in Mexico. Colourless, pale blue, reddish and wine-yellow crystals are found in the Pikes Peak region of Colorado, in southern California, Texas, New Hampshire, and in the rhyolite Thomas Range of Utah.

Blue, colourless, and pale brown topazes are found in Tasmania and, with tin, in the Gilbert Ranges of northern Queensland. Here the crystals are commonly highly included, but the rolled pebbles are found flawless. New South Wales and northern Queensland also produce topaz. Well-formed crystals occur in pegmatite veins and as pebbles in the river gravels near Takayama, Naegi, and Hosokute in Mino province, Tanokamiyama in Omi province, and Ishigure in Ise province of Japan.

The gem gravels of Sri Lanka produce a fair amount of good-quality topaz; colourless material such as that mined at Polwatta near Matale in central Sri Lanka is especially prized for irradiating to blue colours. The ordinary alluvial deposits of the ruby mines of Mogok in Myanmar (Burma) produce similar material. A considerable occurrence of fine yellow, blue, and (mostly) colourless topaz of magnificent gem quality and large size has been recovered from a large pegmatite dyke at Sakangyi some 32 km west of Mogok. Pink crystals, typically stubby to tabular in habit and heavily included, are found in narrow calcite veins and tension gashes at Ghundao Hill and areas on adjacent mountains, about 65 km north-east of Peshawar near the town of Katlang in Mardan district, Pakistan. In India, colourless topaz is mined at Patnagarh in Orissa and has been found in Quaternary sediments in an area of the Thuong Xuan region of Thanh Hoa province of central Vietnam.

Topazes of many colours are found in Russia. Blue and green crystals are found on the eastern slope of the Urals at Alabashka near Sverdlovsk, the gem centre once again known as Ekaterinburg, and beautiful magenta-coloured crystals are found near the Sanarka river in the Ilmen mountains. Pale brown crystals, which like those from Japan and Utah fade on exposure to sunlight, are found near the Urulga river north of the Borshchovochnoi mountains in the Nerchinsk district of eastern Sakha (formerly Siberia) in the Russian Federation. In the Adun-Chalon mountains of the same district topaz is found in good crystals. Kamchatka, in the extreme east of Sakha, also produces topaz of yellow, blue and greenish colour. Colourless topaz as well as blue, pink, red and yellow crystals come from the pegmatites of Volynya, Ukraine. In the People's Republic of China, fine-quality pale blue-green and richly coloured yellow to red topaz crystals up to 240 mm long have been found in the Xilingeleimeng region of the Inner Mongolia Autonomous Region. The pegmatite region of Altay in the Xinjiang Uygur Autonomous Region as well as Guangdong, Guangxi, Hunan and Yunnan provinces have also produced topaz.

In the African continent topaz is abundant. Except for the blue-coloured material and the colourless material used to produce irradiated blue colours it has little gem importance. Well-formed colourless and blue crystals are found near Klein Spitkopje in Namibia; the crystals are obtained from pegmatite dykes, and topaz is also obtained from the gem gravels of the Miami district in Zimbabwe. Blue and colourless topazes, as crystals and as rolled pebbles, are found around the tin workings in western Plateau state of central Nigeria. The crystals are here found in veins and fissures in the contact metamorphosed aureoles caused by the younger of the granitic intrusions of the plateau. The water-worn rolled pebbles are found in streams and alluvial gravels, and in the past local inhabitants placed colourless pebbles of topaz in the indigo dye pots which are such a feature of Nigeria. This superficially coloured the pebbles a blue shade and they were then sold to unwary tourists who thought they had a fine blue topaz. Today, however, this material is generally sold to be colour-enhanced through irradiation. Topaz crystals have also been found near Tamanrasset (Fort Laperrine) in the Hoggar district of south-eastern Sahara. The pegmatites at Mahabe and Soarano and the alluvial deposits of the Saka river of Madagascar supply topaz.

Of interest, but scarcely of gem importance, is the topaz found in the Mourne Mountains of Northern Ireland, the Cairngorm Mountains of Scotland, and St Michael's Mount and Lundy Island off the Cornish and Devon coasts.

Cutting of Topaz

The mixed cut is a style of cutting often used for topaz, and, owing to the long prismatic shape of the crystals, the stones are cut as rather longish oval or as pear-shaped (drop-shaped) stones. In order to minimise the risk of breakage, it is often recommended that the table be placed at 12 to 15 degrees off the basal plane of the crystal.

As a result of its pleochroism, brown topaz shows a darker colour at each end of the long axis of the stone. Moderately rich-coloured topazes are cut in the trap-cut style (a cut-corner rectangular step cut commonly called the 'emerald cut'). Many pale pink topazes have been set, particularly in old jewellery, in a closed setting with the back of the stone painted with red colour, or with the settings containing a red foil. It has been recorded that topaz, despite its strong cleavage, has been cut as a cameo.

Because of its easy availability, irradiated blue topaz is one of the gem materials used in the mass production of so-called 'fantasy' cuts, that is, stones that combine aspects of faceting and carving.

Synthesis and Simulation

Topaz has been synthesised for academic interest, but not for commercial exploitation as a gem material. The process was carried out by the action of hydrofluorosilicic acid on silica and alumina in the presence of water at a temperature of 500 °C. What is sometimes incorrectly called 'synthetic topaz' in the gem trade is a synthetic corundum or synthetic spinel of suitable colour. Except for the natural and synthetic corundum and spinel having colours similar to those of topaz, the other natural stones which are most likely to be mistaken for topaz are tourmaline, danburite, spodumene, aquamarine, morganite, scapolite, apatite, beryllonite, brazilianite, euclase, transparent feldspars such as labradorite and orthoclase, and quartz. All of these materials will float in di-iodomethane (methylene iodide) (SG 3.32) whereas topaz will sink.

Glass imitations of topaz are also encountered. These may coincidentally have both a refractive index and an SG quite close to topaz. The single refraction of the glass, however, would serve quickly to separate it from the doubly refractive topaz.

Tourmaline

Tourmaline is one of the more scientifically interesting minerals, and as a gemstone surpasses all others by its range of colour. Some crystals of tourmaline exhibit two, or more, colours in the one crystal (lengthwise or radially) and stones cut from them show this 'parti-coloration'. Some tourmaline grows as parallel aggregates of thin, nearly fibrous crystals and this material when cut *en cabochon* shows a cat's-eye effect.

The derivation of the name tourmaline is obscure but it is generally believed to have originated from the Sinhalese *turmali*, a name applied by the local jewellers to the yellow zircon. The use of this name for tourmaline was said to have come about owing to a parcel of tourmaline being sent by mistake under this name to stone dealers in Amsterdam in 1703, and the name may well have stuck. The red to pink colours of tourmaline are sometimes known as rubellite, the blue as indicolite or indigolite, the colourless as achroite, and the brown and yellow as dravite (even when they do not belong to this species); a peculiar reddish-violet variety is called siberite. Rarely, green tourmaline is called verdelite. In practice, the majority of green to yellow tourmalines are simply called tourmaline with the colour as prefix, and indeed, this preferable type of nomenclature is now used extensively. The tendency to use the fancy varietal names mentioned in order to enhance sales is a natural one, but should not be encouraged by the gemmologist. There is an opaque black tourmaline which the miners call schorl; seldom has it been cut except for mourning jewellery.

Tourmaline crystallises in the trigonal system. The crystals are usually of a long prismatic form and are vertically striated, an effect probably due to oscillation between the first- and second-order prisms. Acicular crystals are sometimes referred to as tourmaline 'pencils' (*Figure 6.11*). In some tourmalines, however, the prism tends to be short and the habit is then tabular. The crystals usually show a characteristic rounded triangular section when viewed down their length. The prisms are capped by rhombohedral or scalenohedral faces which may differ in their angle with the prism at opposite ends of the crystal; thus one end appears flatter than the other. This feature is known as hemimorphism and is an outward sign of polarity in the crystal (*Figure 6.12*).

This polarity of tourmaline crystals is also displayed by the phenomenon of pyroelectricity shown by some crystals, which, when heated to about 100 °C, develop positive electricity at one end of the crystal and negative at the other. This electrical charge enables the crystal to attract to itself small pieces of paper or wood ashes. Indeed, it was owing to this

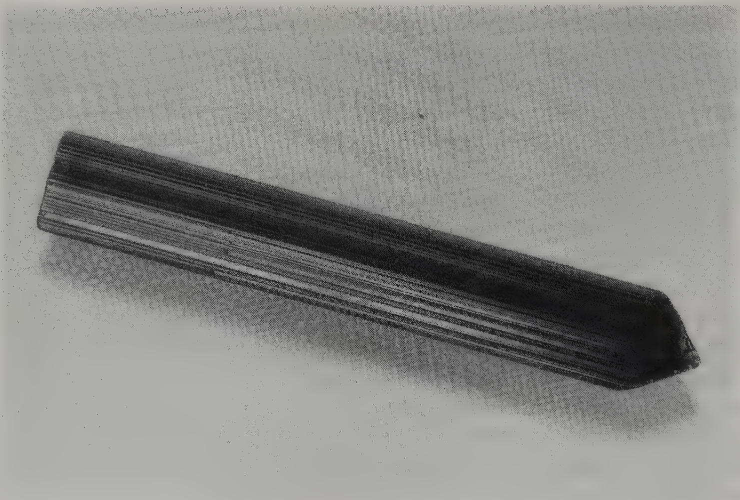


Figure 6.11 *A typical long prismatic, vertically striated tourmaline 'pencil' (photo by Maha DeMaggio, Gemological Institute of America)*

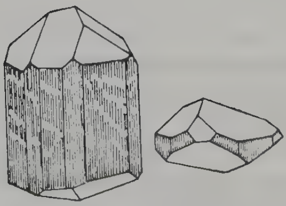


Figure 6.12 *Tourmaline crystals*

property that the Dutch merchants applied the name *aschentrekker* to such crystals brought from Sri Lanka. It is also the cause of cut tourmalines collecting dust, when in a heated shop window or museum display case, to a much greater extent than other gemstones. It must be mentioned that the iron-rich tourmalines, such as the black schorl, do not exhibit this pyroelectricity to any extent.

Another property, also due to the polarity of tourmaline crystals, is that a charge of electricity may be induced when pressure is applied in the direction of the vertical crystal axis. This effect is termed piezoelectricity, and has been made use of in certain depth-recording apparatus for underwater craft, specially cut tourmaline plates being used for this purpose.

The chemical composition of tourmaline is extremely complex. A general formula can be written as $WX_3Y_6B_3Si_6O_{27}(O,OH,F)_4$, where W is sodium, calcium, or potassium; X is magnesium, aluminium, ferrous or ferric iron, lithium, aluminium, or manganese; and Y is aluminium, ferric iron, chromium, or vanadium.

In most gem tourmalines the W position is sodium, the Y position is aluminium, and the X position is chiefly occupied by lithium and aluminium; to this species the name *elbaite* has long been given. Where X is ferric iron, the species name is *buergerite*, which occurs in dark bronzy brown to black colours and has little importance as a gemstone. If X is ferrous iron it becomes *schorl*, a well-known name for black tourmaline which has occasional use as a gemstone in mourning jewellery, while where X is magnesium, the term *dravite* is used. This is often not a very attractive brown colour and is again of little attraction as a gemstone, exceptions being some deep red stones and similarly dark-toned green stones from African sources. The name *tsilaisite* has been proposed (but not generally recognised) for a hypothetical end member where the X position is occupied primarily by manganese.

If X is magnesium and Y is chromium, the species name is *chromdravite*, crystals of which display an intense dark green colour. In *ferridravite*, the X is primarily magnesium and Y is ferrous iron; this is typically black. Finally, there are two further species discovered and analysed by Dunn and coworkers. Of these *uvite* is a tourmaline in which W is calcium, X is mainly magnesium, and Y is aluminium. This species is usually brown but is occasionally found as green or even colourless crystals. The latest addition to the tourmaline group has been named *liddicoatite* as a compliment to the well-known gemmologist Richard T. Liddicoat, chairman of the board of governors and past president of the GIA. This can be described as the calcium analogue of elbaite and, as in elbaite, is found in attractive colours suitable for cutting as gemstones.

The fact that species of the tourmaline group cannot all readily be distinguished by standard gemmological tests makes it obvious that, for the ordinary gemmologist, these tourmalines can safely be regarded as one gem material distinguished only in terms of colour and quality.

The pale green and pink tourmalines belonging to the elbaite species have a remarkable tendency to exhibit both these colours in the same crystal, the change in colour being longitudinal in some cases (*Figure 6.13*) and concentric in others (*Figure 6.14*). Polished pieces may show a slight variation in refractive index and even in inclusions where one colour passes into another.

Attractive bright green tourmalines owing their colour to chromium and/or vanadium have been found in Tanzania. These are commonly referred to collectively as chrome tourmaline; very rarely, cat's-eye stones are cut from such crystals containing needle-like inclusions.

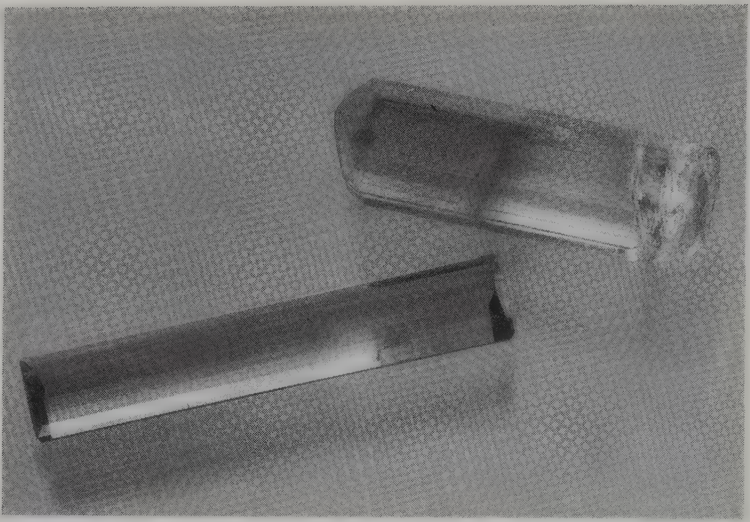


Figure 6.13 *Faceted and rough tourmaline showing longitudinal colour zoning (photo by Maha DeMaggio, Gemological Institute of America)*

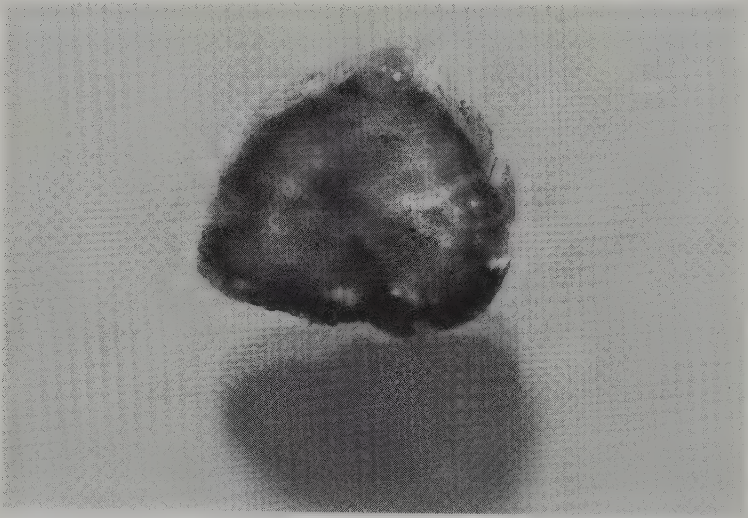


Figure 6.14 *Section of a tourmaline crystal showing concentric zoning (photo by Maha DeMaggio, Gemological Institute of America)*

The mineral has no distinct cleavage and the fracture is subconchoidal to uneven. The hardness varies to some extent and may be given as 7 to 7.5 on the Mohs scale. Owing to the complex nature of the chemical composition the SG of gem-quality tourmaline varies and has a typical range from 3.01 to 3.26. The various colours, however, fall into fairly well-defined groups. The mean values for the various colours are as follows: pink 3.03, red 3.05, pale green 3.05, brown 3.06, dark green 3.08–3.11 (but chromdravite 3.40), blue 3.05–3.11, yellow to yellow-orange 3.10 and black 3.15, but this may go to over 3.2.

Tourmaline is of common occurrence in more siliceous igneous rocks such as granites and granitic pegmatites (the primary source of gem elbaite tourmalines), and metamorphic gneisses, schists, granulites and similar rocks. The mineral occurs in zones of contact metamorphism as a result of fumarole action by the mineralising effect of hot gases in the fluid magma. It is associated with quartz, mica, corundum, apatite, spodumene, scapolite, topaz, albite feldspar, beryl, garnet, amblygonite and cassiterite. In granitic pegmatites, tourmaline is found in cavities, frequently attached by the base, and growing freely in groups, and tourmaline crystals may be found interpenetrating quartz crystals (*Figure 6.15*). It is also found in secondary deposits (eluvial, colluvial, and alluvial).

Effects of Light

Lustre

The lustre of tourmaline is vitreous and the transparency varies from perfectly transparent through all stages of translucency to opaque, as in the black schorl. Much of the clear material is marred by many cracks and flaws and such tourmaline is usually cut into beads or carved into figurines.

Figure 6.15 Tourmaline crystals in association with quartz, from the Himalaya Mine in Mesa Grande district, southern California, USA (photo by Bill Larson, Pala International)

Refraction

The refractive indices of tourmaline are approximately 1.622–1.641, but vary somewhat with stones of different colours. The birefringence, too, is variable and may be as low as 0.013 or as high as 0.024; a common value is 0.019. The double refraction is strong enough for a clear doubling of the rear facet edges to be seen when viewed by a hand lens through the thickness of the stone. Exceptionally high birefringence, ranging from 0.031 to 0.033, was shown by dark red tourmaline crystals found in Kenya, as described under 'Occurrences'. Chromdravite from Russia shows exceptionally high RI (1.772–1.778) and low birefringence (0.006) values. Some tourmalines that have been overheated and/or subjected to thermal shock during polishing may exhibit multiple shadow edges on the refractometer that seem to 'float' above the true values. Experiments have shown that this phenomenon, known as the 'Kerez effect' or 'satellite readings', can be removed by careful repolishing.

Tourmaline is uniaxial and therefore only one shadow edge moves on rotation of the stone on the prism of the refractometer; this edge is that of the lower index, for the optical sign of tourmaline is negative. The fire shown by tourmaline is small, for the dispersion is only 0.017 (B to G).

The dichroism of tourmaline is one of its most outstanding features. It is specially marked in the dark brown and dark green stones, when the ordinary ray is so strongly absorbed that it does not penetrate the stone at all, so that sections cut parallel to the vertical crystal axis can be used for the production of plane polarised light. Indeed, they were so used in the early polarisers known as the 'tourmaline tongs'. In some cases the ordinary ray is so strongly absorbed that only a single edge due to the extraordinary ray is visible on the refractometer and may well give the impression that the mineral is singly refractive. Also such absorption may mask the doubling of the back facet edges when the edges are viewed through the stone.

The paler-coloured tourmalines such as the pale pinks, and particularly the yellow stones, show only a weak dichroism. The variation in dichroic effect shown by different tourmalines requires that the stones be cut with it in mind. Light travelling through a tourmaline in the direction of the vertical crystallographic axis is always deeper in colour than light travelling at right angles to this axis. Therefore dark stones need to have the table facet cut parallel to the vertical axis (*c*-axis), to lighten the colour, and pale stones with the table facet at right angles to this, that is at right angles to the vertical axis, in order to get the most promising colour out of the stone.

Absorption Spectra

The absorption spectra shown by tourmalines are usually so weak that they lack value as a means of identification. In the green tourmalines the red part of the spectrum is almost completely absorbed up to about 640 nm, and the yellow and green are freely transmitted except for a faint absorption region near 560 nm. In the green part there is a fairly strong and narrow band centred at 498 nm (attributed to ferrous iron). These are accompanied by a weaker and vaguer band at 468 nm. A strong band in the violet at 415 nm has been observed in some green and particularly in blue tourmalines. Red and pink tourmalines typically show a broad absorption region in the green, usually centred near 525 nm, within the long-wave end of which may be seen a narrow line at 537 nm. There are also two bands in the blue, almost as narrow as the lines in the blue of the spectrum seen in ruby. In tourmaline these lines are at 458 and 450 nm. Such a spectrum is seen most completely in the 'siberite' variety. Dark brownish-red to red iron-rich dravites from Zambia exhibit a broad band from about 520 to 590 nm, another at 460 to 470 nm, and a 445 nm cutoff of the blue and violet, while the manganese-rich yellow stones from this country can show an absorption cutoff in the short-wave range to about 410 nm, a strong band centred at 419 nm and a narrower band at about 423 nm.

Luminescence

Tourmaline is almost always inert to long-wave ultra-violet light. Under short-wave ultra-violet, some yellow stones show an extremely weak glow too indistinct to recognise the colour. Red and pink stones from a number of localities may show a blue to violet glow under short-wave ultra-violet light and X-rays (when they may even show slight phosphorescence). Colourless stones from Afghanistan may luminesce a bright violet while some golden-yellow, brown and green tourmalines from Tanzania have been found to exhibit a fairly strong yellow glow under short-wave ultra-violet light.

Effects of Heat and Irradiation

The influence of heat on tourmaline is variable; the result is usually to lighten the colour. Such heating is commonly used on dark blue and green Brazilian stones, a process referred to as 'opening the colour' (*abrir a cor*). Experiments have shown that some pink to red tourmaline loses colour when heated to 260 °C, while other material is colour-stable even over 400 °C. At about 700 °C pink tourmaline decolorises completely and the green-coloured stones lighten in colour. The colour of some of the distinctive blue to green tourmalines from Paraíba, Brazil, results from heat treatment which removes a manganese-caused pink colour component from the stones. Another interesting application of heat treatment is that certain dark green stones from Namibia lighten to an attractive emerald-green colour. Heating can, however, have the negative effect of making tourmaline more brittle.

Irradiation may also be used to alter the colour of tourmalines. Such treatment may produce pink to red to purple colours from colourless or very pale pink, green, or blue stones. Radiation treatment may also develop or intensify a yellow colour or cause some yellow stones to turn orange, while some uniformly green stones may become red and green parti-coloured. As noted above, heating may cause a reversal to the original colour.

Inclusions

The inclusions seen in tourmalines are in general irregular thread-like cavities called trichites that occur singly or in loose, mesh-like patterns (*Figure 6.16*).

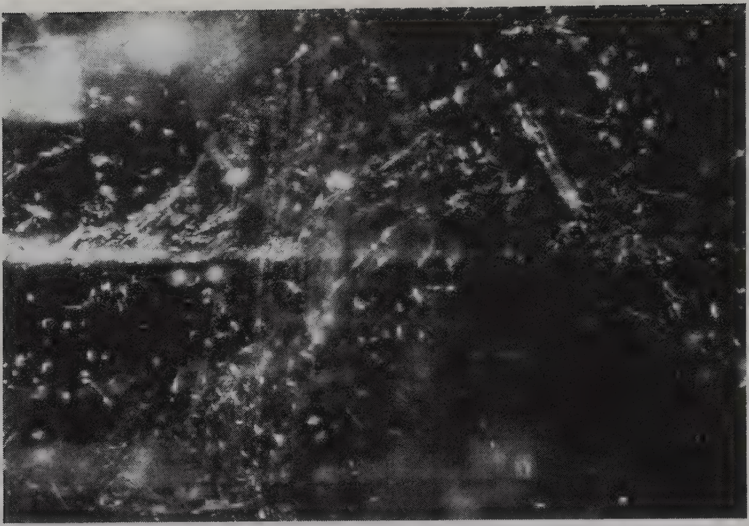


Figure 6.16 Thread-like fluid-filled trichite inclusions in tourmaline (photomicrograph by John I Koivula, GIA Gem Trade Laboratory)

Under high magnification these are resolved into tubes filled with liquid and often containing a gas bubble (two-phase inclusions). Hollow tubes running parallel to the length of the crystal are also common and if profuse are the cause of the chatoyant effect seen in tourmaline cat's-eyes; sometimes these tubes contain mineral inclusions. Eppler, however, takes the view that the inclusions causing the chatoyancy in tourmaline are crystal fibres.

Flat films are another common inclusion, most typically in red tourmalines, and if these happen to be viewed at such an angle that the incident light is totally reflected from them they appear as black patches (*Figure 6.17*). Crystalline inclusions identified in tourmaline include mica, hornblende, apatite

Figure 6.17 Flat film inclusions in tourmaline

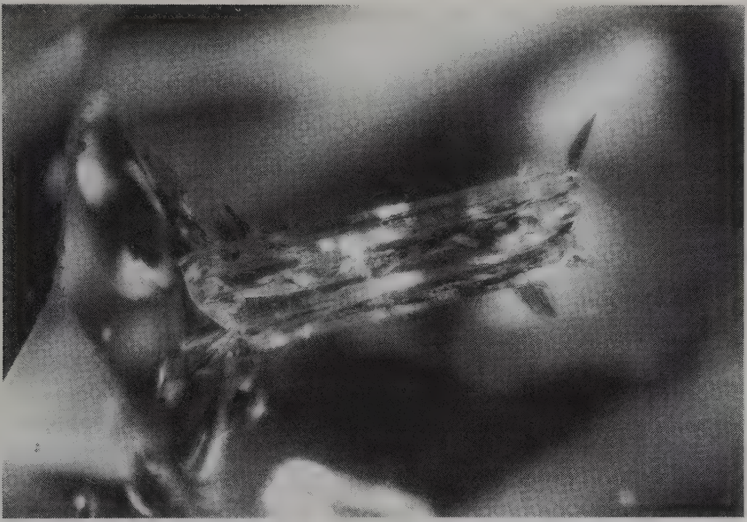


Figure 6.18 *Apatite crystal inclusion in a green tourmaline (photomicrograph by John I Koivula, GIA Gem Trade Laboratory)*

Figure 6.19 *Tourmaline inclusion in a red tourmaline from Zambia (photomicrograph by John I Koivula, GIA Gem Trade Laboratory)*

(*Figure 6.18*), quartz, microlite, tourmaline (*Figure 6.19*) and zircon. The tourmalines from Paraíba, Brazil sometimes contain yellow metallic-appearing inclusions, possibly a sulphide mineral.

Occurrences

A principal locality for gem tourmaline is near Mursinka in the Ural Mountains of Russia where good-quality crystals, usually blue, red or violet-red in colour, are found in the yellow clay disintegration product of the granite in which they had formed. The village of Shaitanka, some 70 km north of Sverdlovsk, produces red crystals; these are found in druses in a coarse-grained granite. Another Russian locality is Nerchinsk in Transbaikalia where tourmaline is found near the Urulga river.

Sri Lanka, probably the original source of tourmaline as a gemstone, supplies stones of yellow and brown colour from the alluvial deposits in the south-east of the island; these have been identified as uvites. Brown to green tourmalines have also been found in the Elahera gem field in central Sri Lanka. About 32 km south-east of Mogok in Myanmar (Burma) there is an extensive alluvial deposit of decomposed gneiss and granite carrying fine red tourmaline. The deposit lies on the banks of the Nampai river near the town of Mainglon and has been worked spasmodically, often in the past by Chinese miners, for in olden times this red tourmaline was much esteemed in China where it was used for making the distinctive button for a certain grade of mandarin. Mogok also produces some pink elbaites and brown uvites. Tourmaline, including pink, light blue and light green colours, is one of the gem minerals reported from the granitic pegmatite dykes in the Altay Mountains of the northern Xinjiang Uygur Autonomous Region of China. Tourmaline is also found in Inner Mongolia and Yunnan province. The pegmatites of Kolum district of the Nuristan region in eastern Afghanistan provide some exceptional gem elbaites, primarily bright blues and greens as well as pinks and parti-coloured. Several deposits of tourmaline occur in the Shingus and Dusso areas of Gilgit division, northern Pakistan, while attractive stones have come from the Hyakule and Phakuwa pegmatite mines in the Sankhuwa Subha district, Kosi zone of eastern Nepal.

Brazil produces tourmalines of many colours, particularly green, blue and red crystals, and many which show zonally arranged colours (parti-coloration). The crystals are found primarily in the north-eastern state of Minas Gerais, in regions encompassing what are known as the Araçuaí-Itinga, Araçuaí-Salinas and Governador Valadares pegmatite districts, and in areas surrounding the cities of Capelinha, Itambacurí, Minas Novas, Poté and Turmalina. In the 1980s, a new gem deposit was discovered in the state of Paraíba, also in north-eastern Brazil, near the village of Sao José da Batalha. Here in a decomposed granitic pegmatite were found colours not known previously in tourmaline, including deeply coloured 'electric' bluish-green to greenish-blue, dark violetish-blue, and purple. Chemical analysis has shown that copper, not previously known as a colouring agent in tourmaline, was responsible for the blue colour component, while manganese- or iron-titanium charge-transfer mechanisms shift the colour towards green. Manganese produces pink and thereby contributes to violetish-blue to purple colours.

Much gem tourmaline is found, in a wide range of colours including the dark green which lightens to an emerald-green shade on heating, in the pegmatites at Klein Spitzkopje near Rössing on the Otavi railway east of Swakopmund in Namibia. The gem gravels of the Somabula Forest in Zimbabwe, and Alto Ligonha in Mozambique, are other sources. Malawi produces green and pink tourmalines. In Tanzania there are found green tourmalines which contain chromium and/or vanadium. These show, unlike normal green tourmalines, a strong red residual colour when viewed through the colour filter. Tanzania has also produced yellow to orange and colour-change tourmalines, the latter appearing dark green in daylight and red in incandescent light. In the early 1970s a deposit of small euhedral tourmaline crystals, transparent but very dark red in colour, was discovered by J M Saul under a meadow of Osarara, Narok district, Kenya. The crystals had a normal SG of 3.07 but the birefringence was found to be exceptionally high. Typical values for the refractive indices were 1.623–1.655. Analysis indicated that the crystals could best be described as iron-rich dravite tourmalines. Attempts to lighten the deep red colour of the stones by heat treatment or by radiation have not been successful. Kenya has produced attractive orange-yellow and brown stones from the Voi-Taveta area. At Chipata in Zambia, dark red crystals similar to those from Kenya have also been found with a similarly high birefringence (0.030) and mean SG of 3.05. Zambia has also produced some rare, bright yellow, yellowish-brown, and greenish-yellow tourmalines (birefringence 0.023–0.028 and SG 3.13) approaching tsilaisite in composition, with up to 9.2 per cent MnO. In Nigeria, the pegmatites south-east of Keffi in western Plateau state have produced green, pink, red, violet, yellow and watermelon (see later) elbaite tourmalines.

The island of Madagascar has supplied much gem-quality tourmaline. The crystals are obtained from pegmatites in the central part of the island, one of which is the famous Anjanaboina deposit, and include all colours, the red being the most prized; the colourless crystals are the rarest. Blue, brownish-purple, rose-pink, yellow, brown and green material are found in the Madagascan deposits.

The Pala region of San Diego County, California, produced much tourmaline from the pegmatites of the district. One famous mine, the Himalaya in Mesa Grande district (*Figure 6.20*), continues to be worked commercially in the 1990s; a gem pocket found in 1989 produced about 500 kg of tourmaline, the majority of which was suitable for mineral specimens. The colours found at Pala vary from jet-black 'schorl', through the deep blue, to greens and pink to pale red. Colourless material has also been found at Pala. It can be said that nearly all the colours assumed by tourmaline are found in the San Diego deposits, with only brown-coloured material not well represented. Two or more colours are commonly present in a single crystal, and some are characterised by concentric or layer-like zoning parallel to the *c*-axis of the prismatic crystals. Some of these mixed-coloured tourmalines are of deep blue to black cores surrounded with single or multiple layers that may be colourless, blue, green, or pink, or any combination of these colours, such as a pink central portion surrounded by a rim of green-coloured material, a type called 'watermelon' tourmaline.

Another type of parti-coloration is where the colours vary in layers parallel to the basal plane of the crystals (that is, perpendicular to the *c*-axis), which may be green at one end and pink at the other, with perhaps a zone of colourless material in the centre or other variations of this theme. The colours in some of the zoned (parti-coloured) crystals are sharply bounded from one another, whereas in other crystals the colours appear to merge gradually and intergrade with distances of about 2 mm or less. It should be noted that parti-coloured stones tend to be somewhat more fragile at the colour boundaries.

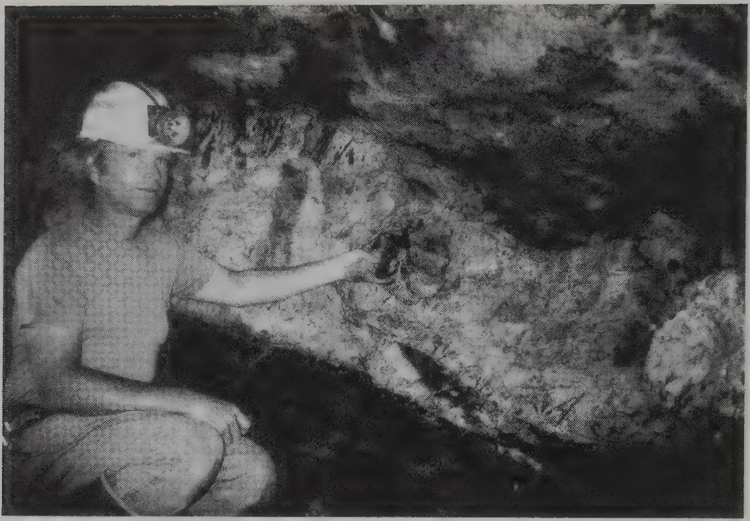


Figure 6.20 Mine manager holding recently recovered tourmaline crystal in the Himalaya mine, Mesa Grande district of southern California (photo by Bill Larson, Pala International)

During the early years of the twentieth century, Pala tourmaline was principally marketed in China. This was particularly so with the pink and red varieties which were highly prized by the Chinese who carved and polished it into many different forms. With the collapse of the Manchu dynasty in 1912 this Asian market was eliminated, and much of the mining for gem tourmaline ceased in southern California.

Much gemmy tourmaline has been found in Maine, USA, mainly at Hebron and Paris (Mount Mica) where tourmaline of a bluish-green colour is abundant and pink crystals are rare. At Auburn in the same state is found an attractive lilac-coloured tourmaline, as is also the deep blue, green and parti-coloured crystals. Haddam in Connecticut is another American locality for elbaite, while San Luis Potosi in Mexico has produced buergerite. Pegmatites in Western Australia and on Kangaroo Island have also produced gem-quality material.

Cutting of Tourmaline

The mixed cut – a step-cut pavilion with a brilliant-cut crown – is commonly used for tourmaline. With the deeply coloured blue and green crystals as well as with longitudinally zoned parti-coloured material, the trap cut is used to a great extent. This has the advantage of providing maximum yield from the rough and, with the dark iron-colour stones, minimising the negative effects of the strong pleochroism. The watermelon type of concentrically zoned material is often fashioned as thin, polished slabs for use in drop earrings and cuff-links. Much flawed tourmaline (and the crystals may be of considerable size) is fashioned into beads or carved into small figurines. Tourmaline is also a popular

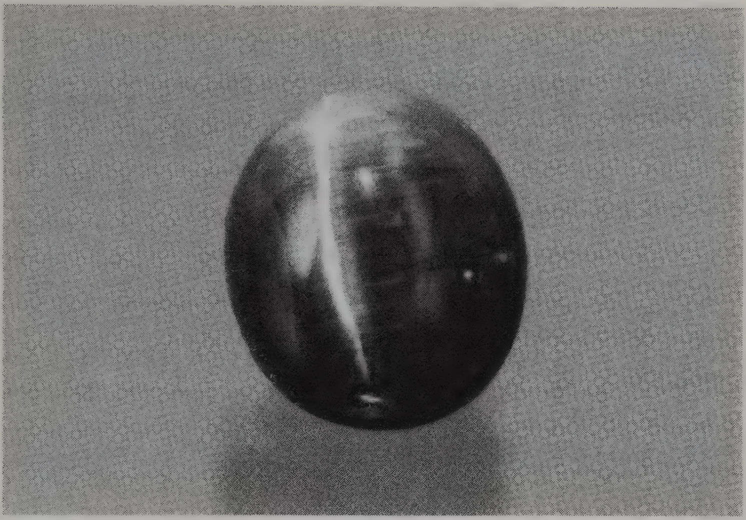


Figure 6.21 *Cat's-eye tourmaline containing parallel hollow tubes (photo by Maha DeMaggio, Gemological Institute of America)*

gem material for 'fantasy' cutting. Crystals with appropriate inclusions for showing the cat's-eye effect are cut as cabochons (*Figure 6.21*).

Synthesis and Simulation

Small tourmaline crystals, too small for cutting into gemstones, have been synthesised hydrothermally through the recrystallising of glass formed from melted natural material. Tourmaline has rather distinctive properties and is not commonly confused with other gems. Some tourmaline from Sri Lanka exhibits pleochroism similar to that seen in andalusite, a gem with refractive indices in the range of tourmaline. The andalusite's lower birefringence (0.008–0.013) should serve to distinguish it from this tourmaline. Lazulite, a deep blue gem, also has refractive indices in the range of tourmaline but exhibits a higher birefringence, about 0.031. Bright greenish-blue to bluish-green apatite from Madagascar looks much like some of the distinctive tourmaline from Paraíba, Brazil and has even been sold under the misleading name 'Paraíba apatite'; similarly coloured apatite has recently been reported from Minas Gerais, Brazil. Irradiated topaz that has not been annealed subsequent to irradiation has also been used to imitate Paraíba tourmaline.

Occasionally, assembled stones employing tourmaline are encountered. One type exhibits chatoyancy, being made by cementing a transparent crown to a fibrous pavilion. Another relatively recent type is a faceted stone consisting of a tourmaline crown and glass pavilion. A related type, misrepresented as natural crystals, consists of tourmaline with concentric colour zones cemented to a lighter-coloured piece of glass. Beryl triplets employing a bright blue cement have also imitated Paraíba material.

7

Zircon, Peridot and Spodumene

Zircon

The mineral species known as zircon furnishes a suite of gemstones with a range of colour varying from colourless, through yellow, red, orange and brown, yellowish-green, a bright leaf green to a dark green, and a sky blue. The colourless, golden-brown and sky-blue stones owe their colour to heat treatment, are the most important in jewellery, and show off to the best advantage the adamantine lustre of zircon.

The name zircon is said to have been derived from the word *zargoon*, which in Arabic means vermilion and in Persian gold-coloured. Hitherto, zircons have been variously known as 'jargoon' or 'cerkonier'; the first name is said to have been derived from the Italian word *gaicone*, which is probably a corruption of *zargoon*. Yellowish-red and orange-red stones have had the names 'hyacinth' and 'jacinth' applied to them, but these names are better discontinued. The colourless stones from material found at Matara in Sri Lanka were, in the eighteenth century, regarded as inferior diamonds and were called by the misnomer 'Matara diamonds'.

Chemical and Physical Properties

Zircon has been of sustained interest to gemmologists owing to its variation of SG and refractive indices, and it was not until the work of Chudoba and others during 1937 that the mystery of these variations was finally solved.

The composition of the mineral is a silicate of zirconium ($ZrSiO_4$). Zircon forms mixed crystals and shares habit with the uranium mineral coffinite, $U(SiO_4)_{1-x}$, and the thorium mineral thorite, $(Th,U)SiO_4$. In older specimens alpha particles from U and Th have partly or wholly broken down the crystal lattice of the zircon. Where the lattice has entirely degenerated from the crystalline state, the stones are virtually amorphous and known as metamict.

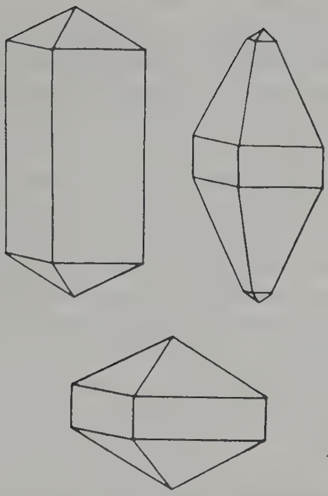


Figure 7.1 *Zircon crystals*

Where the process has not begun (or may be very little advanced) the term 'high zircon' is used. Intermediate stages are known. Physical and optical properties vary widely from the high to the metamict (low) types.

Zircon crystallises in the tetragonal system and the crystals take the form of a combination of a square prism terminated at either end by a square pyramid, or a combination of pyramids of different inclinations. The end of the crystal may be terminated by a small basal face. The crystals may assume a pseudo-octahedral habit, but usually the prism is elongated and the habit is prismatic. Twinning according to the rutile law, giving geniculate forms, is occasionally seen. The forms of zircon crystals are shown in *Figure 7.1*.

The hardness of high zircon varies from 7 to 7.5 on Mohs's scale and may not be consistent throughout the entire stone, a factor which sometimes leads to difficulty in polishing. The cleavage is very imperfect and negligible; the fracture is markedly conchoidal and the stones by nature are brittle. This brittleness is well shown by the abrasion of the facet edges when zircons have been kept loose in a stone packet for some time, an effect termed 'paper wearing'. To avoid this the zircons sent from Bangkok are wrapped in 'strings' of tissue paper, each stone in a little twist of paper so that it cannot rub against another.

The specific gravity of zircons shows considerable variation. High zircon has an SG in the range 4.6–4.8; low zircon falls in the range 3.95–4.20, many stones being near 4.00.

Effects of Light

Refraction

High zircon has refractive indices of 1.92 for the ordinary ray and 1.98 for the extraordinary ray; the birefringence, which is uniaxial and positive in sign, is 0.059. From the high type the values decrease, both in the indices and the birefringence, until the low type is reached, and this has a refractive index of

1.78. Such stones are practically isotropic. They have a hardness of 6.5 on Mohs's scale.

Zircon, despite its pronounced double refraction, in general shows practically no dichroism. Some blue zircons, probably owing their colour to heat treatment, show distinct dichroism of deep sky blue to colourless or yellowish-grey. Red and brown specimens show light and dark shades of those colours. The dispersion, or fire, of zircon is approximately 0.039 and is appreciably higher for the extraordinary ray. Further, the amount of fire does not decrease from the high type to the low type, an effect for which it is difficult to account. Zircon approaches diamond in fire; hence well-cut colourless zircons may be mistaken for diamond if care is not taken. The strong double refraction shown by zircon will provide a sure test for zircon as against diamond, for the back facet edges will appear doubled when looked at through the stone with the aid of a hand lens.

Absorption Spectrum

A characteristic of zircon is the remarkable absorption spectrum exhibited by the mineral, a spectrum which was first observed by Church in 1866. This absorption spectrum shows at its best many strong narrow bands and fine lines throughout the spectrum, but the spectrum, which is due to uranous uranium, varies considerably in the number of bands which may be seen. The greenish-brown zircons found in Myanmar (Burma) exhibit the richest spectrum, over forty lines having been recorded in one such stone. Sri Lankan zircons show a smaller number of bands, fourteen being about the usual number which can be seen; while the orange stones from Uralla, New South Wales, show only a few bands. The red stones from Auvergne, France, appear to be devoid of bands. The heat-treated colourless, sky-blue and golden-brown zircons from Indo-China show the zircon spectrum extremely weakly: usually only the strong persistent line at 653.5 nm may be seen, and that only as a fine 'pencil' line, which affords clear indication of the species.

The main bands in the spectrum of zircon are at 691, 683, 662.5, 660.5, 653.5 (the strongest and most persistent), 621, 615, 589.5, 562.5, 537.5, 516, 484, 460 and 432.7 nm. The spectra of the low-type zircons, which are practically amorphous, are less sharply defined. The absorption spectrum of the metamict zircons shows a woolly band at the 'persistent' line wavelength of 653.5 nm. Heating such low-type zircons will cause the band to sharpen and other lines to appear. There are some rare variations of the low-type absorption spectrum, one of which is notable in showing three broad strong bands in the red at 691, 669 and 653.5 nm, the centre band being the strongest. Another type, which curiously has been found only in zircons which have a refractive index of 1.82 and an SG of 3.98, shows a vague band at 655 nm and another at 520 nm.

Fluorescence

The fluorescence of zircon is variable. Some stones are practically inert and some fluoresce most strongly; the colour of the glow is always a mustard yellow of varying intensity. Under X-rays the glow emitted by zircons varies not only in intensity but also in colour. Most stones show a whitish or violet-blue glow but some show a greenish or a yellowish light; a fluorescence spectrum may be observed. It must be emphasised that great care must be taken in exposing the heat-treated types of zircons to radiations of any kind, for prolonged exposure will cause such zircons to revert to their original brown colour.

Effects of Heat

Most interesting is the influence of heat on the different types of zircons. Both the low type and those intermediate between them and the high type, if heated to about 1450 °C, tend to increase in density to the normal value near 4.7 with normal refractive indices and with a sharpening of the absorption lines. This heating causes the dissociated silica and zirconia to recombine as crystalline zircon; the amount of heating needed to bring the low type back to the high type depends upon the completeness of the original dissociation. It is said that in some cases heating will never cause the stone to return to the completely high type. This may only be due to the lack of a continuous and long heating.

Sri Lankan zircons are mostly some shade of green. On heating to a dull red heat for about an hour they become much paler, while the rarer reddish-brown stones from this locality may turn colourless under such heat treatment. The most important heat treatment of zircons is carried out on the reddish-brown crystals found in Vietnam, for it is the rough material from this locality which produces, after heat treatment, the colourless, blue and golden stones which are so popular in jewellery.

The heating of the zircon rough is carried out using crude clay stoves burning charcoal as a fuel. The stoves are provided with grates and suitable apertures to maintain the draught, which may be further increased by the addition of a tall iron chimney. The zircon rough (crystals and rolled pebbles) is placed in a fire-clay crucible which holds about one kilogram of rough zircon (*Figure 7.2*). The crucible is closed to produce a reducing atmosphere and the cooking is carried out for between one and a half and two hours at a temperature between 900 °C and 1000 °C, but these figures may be varied somewhat by the operator from his own personal experience of the behaviour of the type of rough being treated. From this treatment only about 30 per cent of the stones are suitable for fashioning into gemstones.

The poor colour, but clean, blue stones from the first heating are then subjected to a further heating in the closed crucible, and this tends to turn them colourless. Such treatment is critical, for underheating tends to produce colourless stones which have a great tendency to revert to a brown colour; while overheating produces a cloudy effect. From the above description it is seen that heating in a reducing atmosphere may produce the sky-blue or colourless zircons.

Heating the zircon rough in a perforated crucible which allows free access of air – that is, in an oxidising atmosphere – to a temperature of about 900 °C, produces golden-yellow and colourless stones with sometimes stones of a red colour. The residue of 'off-colours' from the primary firings in a reducing atmosphere are often again heated in the oxidising crucible, when some of the stones assume the water-white or golden-yellow colours.

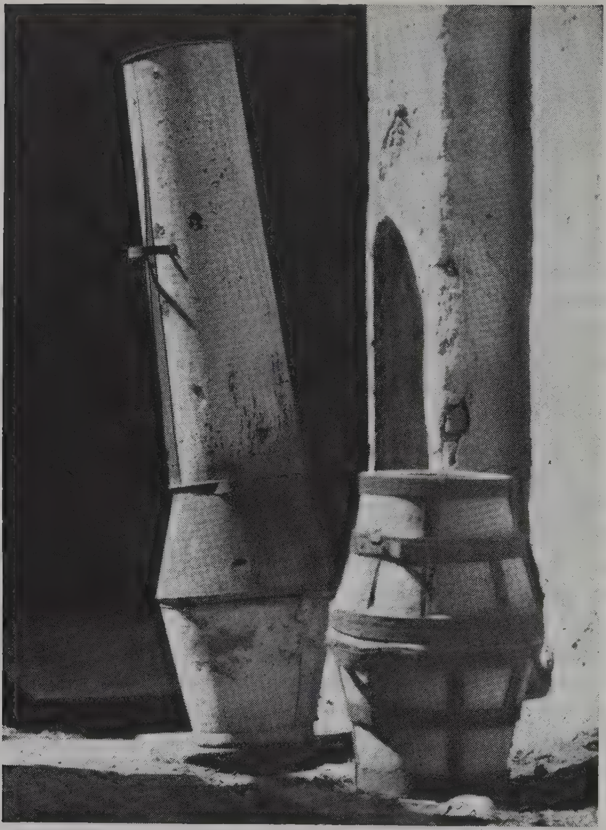


Figure 7.2 Heating rough zircon: left, a tall funnel filled with coal; right, one kilogram of rough zircon being heated (by courtesy of George Lindley & Co (London) Ltd)

Although many of the heat-treated blue stones are fairly permanent in colour, a number tend to revert in part to their original brownish hue. Such partially reverted stones have an unpleasant greenish-blue or brownish-blue colour. Reverted stones may sometimes be returned to their blue colour by judicious heating, but this may not occur in every case. A successful result was obtained on a completely reverted blue zircon (which had been, while set in a ring, thrown into an open fire) by heating to about 800–900 °C after it was packed in a crucible with wood charcoal.

Inclusions

Metamict zircon shows the most characteristic inclusions. Most prominent are tension fissures meeting at an angle of 57.5° and probably due to the degeneration process. They echo the original crystal's prism and dipyramidal faces. Also due to isotropisation are disc-shaped tension fissures. Unequal

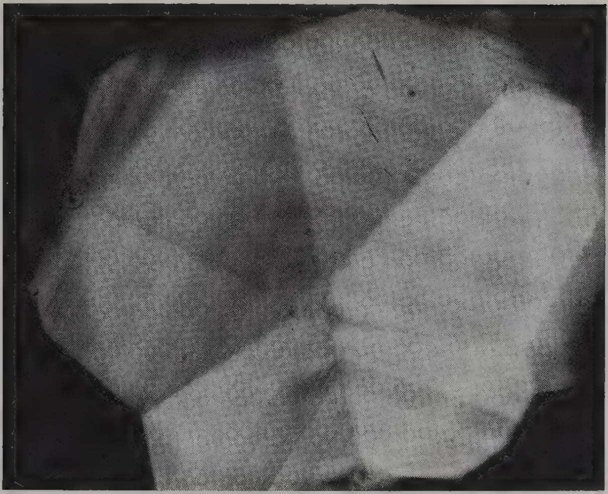


Figure 7.3 Zonal lines typical of low-type zircons

isotropisation may give rise to parallel stripes which also suggest tetragonal form (*Figure 7.3*). Ilmenite may be found in fractures and some healing fissures are reported.

Occurrences

The sources of zircon are world-wide, the mineral being a common accessory constituent of igneous rocks, but the gem-quality zircons are found in more localised areas. Zircon is prolific in the gem gravels of Sri Lanka, and the mineral is found in gem quality in the Mogok Stone Tract of upper Myanmar. Red zircon is found in Expailly, France, and well-formed brown crystals are obtained from Arendal in Norway. Gem-quality material has been found at Uralla, Sapphire, Inverell and other places in New England, New South Wales, Australia. Crystals with sharply defined forms and very bright lustre are found in the Ilmen Mountains of the southern Urals. Zircons from the Harts Range, Northern Territory, Australia show no or very few radioactive trace elements. Thus there is little or no radiation-related structural damage. Yellow, brown, pink and purple colours are found in sizes suitable for faceting. Reddish-brown zircon is reported from decomposed alkali basalts near Jemaa, Nigeria.

The most important localities for gem zircon are those of Vietnam, the mining areas of which in some cases pass into the neighbouring territory of Thailand. The most important localities for the Vietnam and Thailand zircons, which are generally cut and marketed at Bangkok, are the Kha, Champasak and Pailin districts (*Figure 7.4*). The Kha districts are the only areas where mined rough produces blue, golden and colourless stones after suitable heat treatment. Near-white rolled pebbles of zircon have been found at Emali, in Tanzania. A greyish-green chatoyant zircon weighing 125.47 carats was reported in 1992.

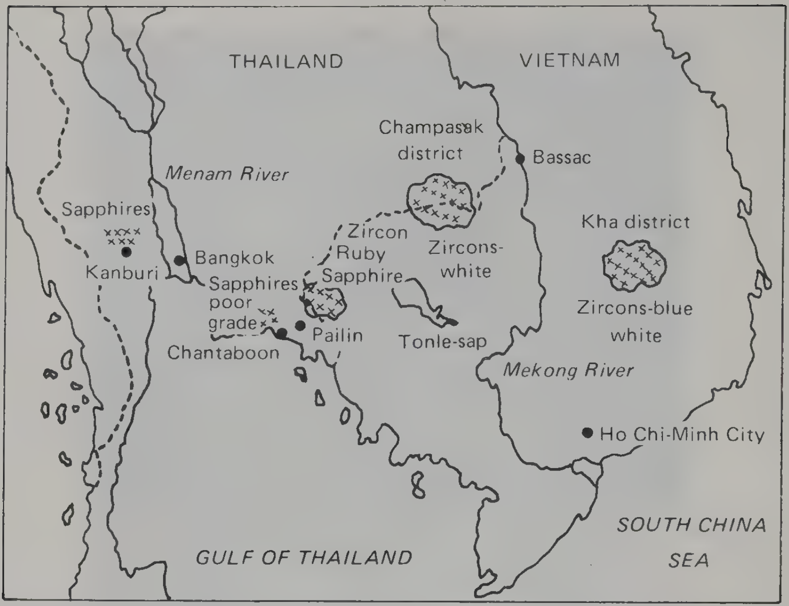


Figure 7.4 Location of zircon mines (by courtesy of George Lindley & Co (London) Ltd)

Cutting of Zircon

In order to obtain the best optical effect with zircon, the stones are usually cut into a modified brilliant cut which has a second set of pavilion facets. The octagonal and four-sided trap cuts are now extensively used for specimen zircons of the blue and golden colours, for some of the greens and yellows, and also the browns of natural colour. The natural-coloured stones are, however, more usually cut in the mixed-cut style.

Simulation

Apart from suitably coloured glass, the only stone which simulates zircon, and it is the sky-blue zircon which is imitated, is the synthetic blue spinel. The lack of double refraction and the orange residual colour shown by the synthetic stone when viewed through the Chelsea colour filter easily distinguishes it from the natural heat-treated blue zircon, which shows a greenish colour through the filter.

A basaltic rock containing groups of flower-like radiating crystals of zircon and xenotime, a yttrium phosphate (YPO_4), is found in a hill named Maru-Yama, just north of Mount Funabuse in Gifu prefecture of Japan. The rock is called by the Japanese *kiku-ishi* which translated probably means 'chrysanthemum stone', the name which is more commonly used for the rock which is used as a type of ornamental stone. A similar rock is found, usually as boulders, in Vancouver Island of British Columbia, Canada.

Small crystals of zircon have been grown hydrothermally and are described in the chapter on synthetics (Chapter 18).

Peridot

The attractive green gemstone known to jewellers as peridot belongs to the mineral group olivine. The name peridot is French but of obscure origin.

At one time the stone we now call peridot was known as topaz, a name perhaps derived from the island of Topazios in the Red Sea. This island is now known as Zeberged (Zebirged) or the Island of Saint John, and was the only ancient source of peridot; it is said that the discovery of peridot on Zeberged was made by pirates but the location was lost for centuries. Peridot was not obtained from Zeberged again until the rediscovery of the mines in the 1900s.

The peridot used in jewellery has a rather oily bottle-green colour; some stones have a tinge of brown and are less highly prized. Very rarely a brown-coloured peridot is found and cut stones of this material may be said to be collectors' pieces.

Peridot may attain quite large size: there is a cut stone of 319 carats in the Smithsonian Museum in Washington, USA; one of 192 carats in the Diamond Treasury in Moscow; and another of 136 carats in the Natural History Museum in London.

Chemical and Physical Properties

Peridot is a variety of forsterite, $(Mg,Fe)_2SiO_4$. The minerals forsterite and fayalite form an isomorphous series within the olivine orthorhombic silicate group with forsterite as one end member, Mg_2SiO_4, and fayalite as the other, Fe_2SiO_4. The ideal iron content for gem peridot is in the region of 12–15 per cent. Some stones contain Cr and are a notably bright green, while others may contain Mn. An iron content of more than 15 per cent gives a dark colour which is unsuitable for gemstones. Traces of Ni also give a bright green. Peridot is idiochromatic, that is the colour is due to iron in the ferrous state. A peridot of orange colour has been reported.

Peridot is a comparatively soft stone, the hardness approximating to 6.5 on Mohs's scale. Hence, while peridots are eminently suitable for setting into brooches, pendants and earrings, their use for ring stones and for setting into bracelets is not always satisfactory, as they are then subject to a greater risk of abrasion with consequent loss of polish. There is also a distinct cleavage parallel to the vertical axis of the crystal.

The crystals of peridot belong to the orthorhombic system and are found as vertically striated flattened prisms, but well-formed crystals are rare. Peridot is most commonly found as rolled pebbles.

Effects of Light

The SG of peridot approximates to 3.34 and typical figures for refractive indices are α 1.654, β 1.671 and γ 1.689. The stones are biaxial and the sign of the refraction is positive. The amount of double refraction is usually 0.036, which is large enough for the doubling of the back facet edges to be seen easily when they are viewed through the thickness of the stone by a low-power hand lens. Peridot has a dispersion of 0.020. The lustre of the stones may best be described as oily and vitreous. The dichroism is weak, one ray being more yellowish than the others. Some chatoyant stones have been reported.

Absorption Spectrum

The absorption spectrum of peridot, which is due to ferrous iron, consists of three main bands in the blue. They are well separated and evenly spaced and are centred at 493, 473 and 453 nm, the band at 493 nm having a distinct narrow 'core' at 497 nm. The 473 nm band is also fairly narrow while the 453 nm band is broader and less well defined. In large specimens weak and vague bands may sometimes be seen at 653 nm in the orange and at 529 nm in the green. It is probably due to the iron content of the stones that peridot shows no luminescence under ultra-violet light or X-rays.

Inclusions

Peridot hosts a number of inclusions, some of them characteristic for particular areas. Rectangular biotite crystals characterise stones from Mount Kyaukpon, Myanmar. Blebs of natural glass have been found in Hawaiian stones (*Figure*

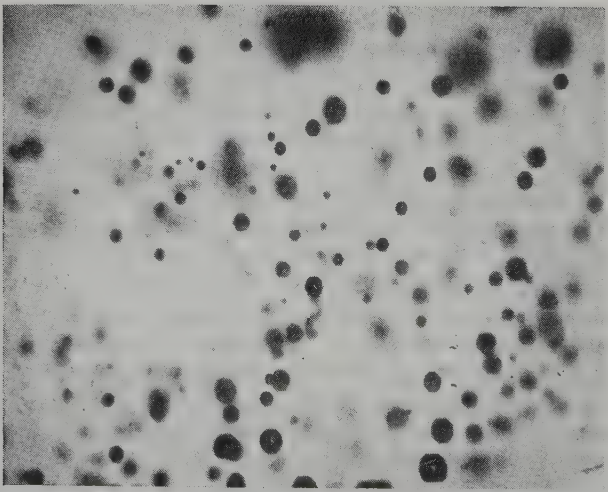


Figure 7.5 'Gas bubbles' inclusions seen in a Hawaiian peridot. These bubbles are actually glassy drops

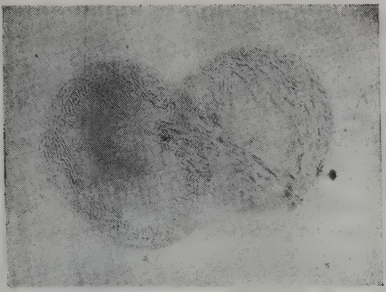


Figure 7.6 *Lily-pads, an inclusion seen in peridot*

7.5), together with grains of chromite; these latter, however occur in peridot from other places, including Arizona and the Island of St John. The characteristic discs known as lily-pads (*Figure 7.6*) are decrepitation haloes and often contain a chromite crystal at the centre. They occur in peridot from more than one source. Minute fluid droplets give a sleepy appearance to many peridot specimens from Myanmar.

Chromian spinel seems to characterise peridot from San Carlos, Arizona. Fluid inclusions are found in some stones but do not indicate particular deposits. Hercynite is reported from peridot found at Kilbourne Hole, Arizona. Chalcopyrite has been found in a peridot from Arizona.

Occurrences

The Zeberged occurrence (the name is a romanisation and can be variously spelt) is about 100 km south-east of the Râs Banâs peninsula in the Red Sea. Peridot crystals are found in outcropping peridotites with the larger ones occurring on the eastern slopes of Peridot Hill. Much of the finest Arizona peridot comes from the area of Peridot Mesa on the San Carlos Apache Reservation in Gila County where the crystals occur in vesicular basalt. Bright green well-formed crystals are found north of Mogok, Myanmar, on the northern slope of Kyaukpon in a weathered serpentine in which the crystals are loose.

Hawaiian peridot is found on beaches. Stones from Ameklovdalen, Sondmore, Norway are Fe-poor and a bright yellowish-green. Gem-quality peridot is found in China in the Zhangjikou-Xuanhua area of Hebei province. It is reported from Antarctica and from alluvial deposits near the Usambara Mountains in the Umba district of Tanzania.

Cutting of Peridot

Peridot is best cut in the trap-cut (step) style, although oval, round and pendeloque-shaped mixed-cut stones are common. In some peridots the large table facet is cut not flat but with a slight doming. It may be remarked that peridot may lose its polish after contact with hydrochloric or sulphuric acids.

Simulation

The characteristic oily lustre and strong double refraction of peridot serve to identify the stone from its counterfeits, although there are convincing imitations made in glass and in the composite stone made with a garnet top on a suitably coloured glass. In recent years a peridot-coloured synthetic corundum (a fancy-coloured synthetic sapphire) has been produced, and also a peridot imitation based on the soudé emerald type of composite stone, the top and base being synthetic colourless spinel and the join across the girdle containing a suitable green colouring matter.

Spodumene

The name spodumene is derived from the Greek meaning 'burnt to ashes', in allusion to the appearance of the crude non-gem crystals which often reach gigantic size. Such crystals are of value only as the source of lithium metal and its compounds.

The transparent gem crystals comprise the bluish or lilac-pink variety kunzite, the yellow and yellowish-green material for which no varietal name has been coined, and the rare emerald-green crystals which owe their hue to chromium. These are called hiddenite, after A E Hidden, the one-time superintendent of the mining company which operated the mine at North Carolina, USA, where the bright green crystals are found. Unfortunately, the pale yellowish-green material found at other localities has been sold as hiddenite, but the colour of this material is nowhere near the lovely green of the true chromium-coloured hiddenite.

Chemical and Physical Properties

Spodumene, a member of the pyroxene group of minerals, crystallises in the monoclinic system as flattened and corroded prisms characterised by vertical striations, and having an irregular capping reminiscent of mountain ranges (*Figure 7.7*). The crystals exhibit strong cleavage in two directions parallel to the prism faces, making the cleavages nearly at right angles to one another. In composition spodumene is a lithium aluminium silicate with the formula $LiAl(SiO_3)_2$. It is one of the few gemstones which contain lithium and on this account the green hiddenite has been called 'lithia emerald'.

The hardness of the gem is 7 on Mohs's scale and the SG values lie between 3.17 and 3.19. It is unusually resistant to abrasion.

Effects of Light

The refractive indices approximate to 1.660 and 1.675 with a fairly constant double refraction of 0.015. The refraction is biaxial and positive in sign. The stones have a vitreous lustre and exhibit little fire, the dispersion being only

Figure 7.7 A typical crystal of kunzite from Madagascar

0.017. In kunzite and hiddenite the dichroism is marked, the colours being violet, deep violet and colourless, and bluish-green, emerald green and yellowish-green respectively. Pleochroism in the yellow and yellowish-green stones is weak.

In kunzite no absorption spectrum can be seen clearly and used for identification; hiddenite, however, shows the typical absorption spectrum due to chromium. In the hiddenite spectrum the close doublet characteristic of the chromium spectrum is at 690.5 and 686 nm. Weaker lines in the red and orange are positioned at 669 and 646 nm, while the broad absorption is centred near 620 nm. There are no lines in the blue but a general absorption of the violet is present. The yellow and yellow-green spodumenes show a well-defined band in the blue at 437.5 nm, which is in the same position as in another pyroxene mineral, jadeite. There is a weaker narrow band at 433 nm. Both these bands are due to iron.

Kunzite shows a golden-pink or orange glow under long-wave ultra-violet light, and a similar but much weaker effect is seen under short-wave. Under an X-ray beam kunzite shows a very strong orange fluorescence with a strong and persistent afterglow. When the phosphorescence has died away the stone is found to have changed its colour to a bluish-green; this remains stable provided that the stone is kept away from a strong light. This induced colour is discharged, with emission of luminescence (orange light), if the stone is exposed for some hours to strong sunlight, or to heating at about 200 °C. The yellowish-green spodumene shows a weak orange-yellow fluorescent glow under the ultra-violet light, but this is extremely weak under the short-wave lamp. The glow is fairly strong under X-rays but, unlike kunzite, no phosphorescence seems to be present and there is no change of colour. The chromium-coloured hiddenite variety does not respond to ultra-violet light to any extent, but under X-rays a slight orange glow with some phosphorescence is seen.

Brownish-orange spodumene was found to have been irradiated, primarily by the isotope scandium-46. Neutron radiation is used in this case. A Geiger counter should be used routinely on spodumene of citrine-like colour. Isotopes with longer half-lives were also detected by gamma-ray spectroscopy. Wearing is not recommended.

Occurrences

The major localities for gem spodumene are in North and South America, Madagascar and Myanmar. Non-gem spodumene has been known to mineralogists for over two hundred years, but gem-quality material does not appear to have been discovered until about 1877, when it was reported that transparent yellow spodumene had been found in Minas Gerais, Brazil, and that this material had been sold as chrysoberyl.

About 1879 green and yellowish-green crystals were found at Stony Point, Alexander County, North Carolina in the United States of America. First thought to be diopside, the crystals were later found to be spodumene and, as mentioned earlier, were named hiddenite. The crystals range in colour from a rarely found colourless variety, through a light yellow to an emerald green. They were first found, in a pitted condition, in association with true emerald, loose in the soil, but later perfect crystals were found attached to the veins of the wall rock. The deposit is said to be now completely worked out and the few stones cut from the crystals rarely exceed two carats in weight. A true hiddenite of pale colour but in large sizes has recently emanated from Brazil. White spodumene and kunzite cat's-eyes are known.

The first discovery of a lilac-coloured spodumene was at Branchville, Connecticut, USA during 1879, where much-altered crystals of spodumene were found to have transparent spots of amethystine-coloured material. The material from this deposit had no gem significance. Over two decades went by before the finding of the lovely gemmy lilac-pink crystals of kunzite in California. This was during 1902 when kunzite was found in the White Queen mine on Hiriart Mountain in the Pala district of San Diego County, California. Since then much gem-quality kunzite has been obtained from other mines on Hiriart Mountain and adjacent Chief Mountain. The deposit spreads north-east into the adjacent Riverside County where kunzite has been found on Coahuila Mountain. The crystals found in these localities are in pegmatite and are often much altered to clay pseudomorphs. Yellow and yellowish-green spodumene accompanies the bluish-pink kunzite. Magnificant kunzite is found in the Vanderberg, Katerina, San Pedro and Pala Chief mines in the Pala district of San Diego County, California.

Spodumene, in the varieties kunzite and of greenish and yellowish colours, has been known in the island of Madagascar since the second decade of the present century. The crystals occur in pegmatite veins intersecting the Archaean rocks, and in the alluvial derived from them, in the western part of the island. Kunzite, the most important of the varieties, is obtained from Anjanabonoina.

Since the earlier find of yellow spodumene in Minas Gerais further pockets of gem-quality spodumene have been discovered in the pegmatite veins of the gem-bearing localities of this Brazilian state. The material is mainly light yellow or pale green in colour. The main source of the bluish-pink kunzite, which was found some time before 1926, lies on the outskirts of Cuité, a town alongside the Rio Doce river, not far from Governador Valadares. Yellow and green crystals, the latter classified locally as hiddenite – it is not the true hiddenite, for it is not coloured by chromium – have been found in this same locality. Several of the pegmatites north of Governador Valadares have been worked for kunzite which is found with tourmaline, beryl and mica. An unusual two-colour material, in pleasing lilac and green, has been found at a mine located near Santa Maria de Suassui, and another pegmatite a few miles from Governador Valadares is said to have produced both light green and light blue spodumene. Spodumene has been reported from the Mogok Stone Tract of upper Myanmar.

A blue spodumene weighing 35 carats has been reported. The stone had refractive indices of α 1.660, β 1.668 and γ 1.675 and an SG of 3.185, and showed orange-red under crossed filters. These values are very close to two other gemstones, euclase and fibrolite, which also have a blue colour. The refractive indices of these two stones are given for comparison: fibrolite α 1.658, β 1.659 and γ 1.676 with an SG of 3.25, and euclase α 1.656, β 1.660 and γ 1.675 with an SG of 3.10.

Spodumene from Afghanistan occurs as kunzite, yellow, blue and green varieties, often occurring as large crystals. Light pink stones showed strong bluish-pink fluorescence with red phosphorescence lasting about one minute after SW irradiation. Three-phase inclusions, growth tubes and cleavages are seen. Most of the spodumene shows tenebrescence, that is reversible darkening and lightening of colour with changes in lighting conditions. When mined, crystals are blue-violet or green, altering to purple or pink after a few days in the sun. Pink stones fade to virtually colourless when exposed to direct sunlight within several days (less than a week). Colour can be restored by irradiation by gamma rays or X-rays.

Cutting of Kunzite

Owing to the strong cleavage, brittleness and heat sensitivity, spodumene is a difficult stone to facet. Further, owing to the thin nature of some of the crystals it is not possible to cut well-coloured stones, since to get stones of good colour advantage should be taken of the strongest pleochroic colour. The deepest colour is seen approximately parallel to the length of the crystal, so for the best result the stones should be cut with the table facet at right angles to this direction. This is, of course, more important in the case of kunzite, which is usually cut very deep in order to enhance the colour. Some kunzites have a tendency to fade on exposure to strong sunlight. Some yellowish-brown spodumenes turn purple after heat treatment.

Simulation

Kunzite is simulated by synthetic pink spinel and by a suitably coloured glass, but distinction is easy as both of these stones are singly refractive, whereas in kunzite the double refraction is strong enough for the doubling of the rear facet edges to be seen with a hand lens. Further, glass and spinel are not dichroic. What may be a more convincing simulator of kunzite is a bluish-pink amethyst, but even here, apart from the differences in the indices of refraction and SG, the lustre of the amethyst is not nearly that of kunzite.

8

The Garnets

To the average layman garnet is the name for a low-priced red gemstone, a gemstone which is cut as small stones fashioned as 'roses', as the Bohemian garnets which were so prominently used in Victorian jewellery; or stones cut with dome-shaped forms as in the so-called 'carbuncles'. Garnet is, however, a much more important gemstone than this. Indeed, it may not be red in colour: orange and green varieties supply important and valuable stones.

Garnet is really the name for a group of minerals all of which have a common crystal habit and some similarity of chemical composition. In fact there are six members of the family, only five of which have been used in jewellery. These are the iron-aluminium silicate garnet known as almandine (almandite); pyrope in which the iron is replaced by magnesium; and grossular which has calcium with the aluminium. The rare rich orange-coloured spessartine is a manganese-aluminium silicate, and andradite, which has the lovely green demantoid as a variety, is a calcium-iron silicate. The garnet group is completed by the calcium-chromium garnet uvarovite, the emerald-green crystals of which would make attractive gemstones if they were ever found in sufficient size to cut.

Chemical and Physical Properties

Garnets crystallise in the cubic system, the forms being the twelve-faced rhombic-dodecahedron and the twenty-four-faced icositetrahedron (trapezohedron), and combinations of these two forms (*Figure 8.1*). The hexoctahedral form is sometimes found in combination, but cubic and octahedral forms are rare. The crystals show no cleavage, but there is sometimes a rather distinct parting parallel to the dodecahedral face; the fracture is subconchoidal to uneven.

The general formula given for the chemical composition of the garnets accords to $R_3''R_2'''(SiO_4)_3$, or may be written as $3R''O,R_2'''O_3,3SiO_2$, where the divalent metal (R'') may be calcium, magnesium, ferrous iron or manganese, and

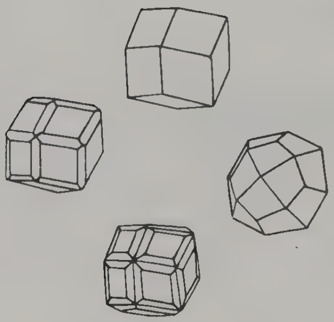


Figure 8.1 The crystal forms of garnet

the trivalent metal (R‴) aluminium, ferric iron or chromium. The atoms (ions) of the metals in each group have relatively similar size and thus may interchange in any amount producing a series – an isomorphous series. Garnet may be considered as consisting of two such series: (1) pyrope-almandine-spessartine, often called the 'pyralspite series'; and (2) uvarovite-grossularite-andradite, called the 'ugrandite series'; but even these two systems may have slight miscibility with one another.

This intermixture of the chemical composition of the garnets is the reason for the wide variation encountered in the constants of the various types of garnet, and this may be expressed more fully by the schematic diagram devised by Marie-Therese Mackowsky (*Figure 8.2*).

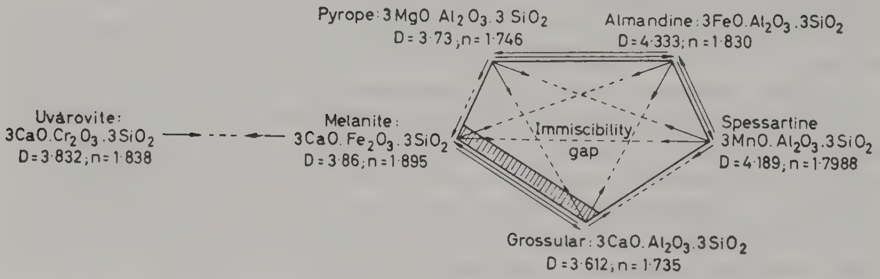


Figure 8.2 Schematic diagram of garnet families (after Mackowsky)

The diagram shows the complicated connections between the pure end members grossular, andradite (melanite), almandine, pyrope, spessartine and uvarovite. To understand the diagram it should be explained that where the arrows extend the whole distance, as for example between pyrope and almandine, a so-called unbroken series of mixed crystals exists, and both the exchangeable groups (here FeO and MgO) can be present in any proportions. Such isomorphous mixed series are found first between pyrope and almandine, and secondly between almandine and spessartine, making these form a group in which it is always the divalent constituent which is interchangeable. In a similar manner grossular and andradite (melanite) can interchange, but in this case it is the trivalent constituents of the molecule which are miscible with one another in all proportions.

It is otherwise with the only partly extended arrows which link each type of garnet (with the exception of uvarovite which occupies a somewhat separate position) with all the others: that is, apart from the exceptional case where a variety occurs quite pure, a certain percentage of the other constituents is included. Even here an unbroken series is not possible, for after a certain percentage (about 10 per cent) the miscibility comes to an end, and there is the so-called immiscibility gap. A garnet which, for example, was located in the shaded portion of the diagram, would, in addition to its main components grossular and andradite (melanite), contain also a mixture of pyrope, almandine and spessartine, and under certain conditions even uvarovite. The same can be deduced for all garnets from the diagram.

The diagram is marked with the appropriate indices of refraction and specific gravities and the chemical composition of each of the end members, though the figures for pyrope given by Mackowsky are too high for the pure mineral. Pyrope garnets containing more than 75 per cent of the pyrope molecule are in fact not found in nature. 'Pure' pyrope, as prepared artificially, has been found to have an SG of 3.582 and a refractive index of 1.714. It will readily be understood that the refractive index and SG of a given garnet will depend upon the proportions of the isomorphous mixture. It cannot be said with certainty, therefore, that a red garnet having a refractive index of 1.771 and an SG of 3.911 will consist exactly of 30 per cent almandine and 70 per cent pyrope, since the presence of a small percentage of andradite will shift the proportions in favour of almandine, and the presence of grossular would produce a lowering effect on the values of the physical data.

Although garnets are, from their crystal structure, singly refractive, many garnets display local double refraction when examined between crossed polars in a polarising microscope. Usually this anomalous double refraction is confined to dark streaks, often in two directions at right angles, but some garnets show a convincing 'four times light and four times dark' during a complete revolution of the microscope stage carrying the stone. This optical anomaly is ascribed to stress due to the isomorphism, but as idocrase, a tetragonal mineral, has an atomic configuration similar to garnet, it might well be that at least some garnets are tetragonal in structure.

Pyrope Garnet

The pyrope garnet is usually blood-red in colour but this hue may be tinged with yellow or purple. The pyrope, if pure, would be colourless and have the formula $Mg_3Al_2(SiO_4)_3$, but the stones always have some iron and usually some chromium to which the red colour of the stones is due.

The theoretical values of SG and refractive index for pure pyrope garnet are 3.51 and 1.705 respectively, but the lowest refractive index for pyrope as found in nature – and as a gemstone – is 1.730 and the SG 3.65. From these limits the values rise with the increasing content of the almandine molecule, until what may be called almandine is reached. Thus there is a continuous series from pyrope to almandine, going through an intermediate series which for the sake of convenience is, in this book, made a separate group. The highest refractive index for the pyrope garnet may be said to be 1.75 and the SG 3.80, but this division is quite arbitrary.

The fear that there may be difficulty in distinguishing between some low-value pyrope garnets and the high-value red spinels, not only on account of the overlap of refractive index, but for the reason that many bright red pyropes show a chromium absorption spectrum not very dissimilar to that of red spinel, is not justified. In practice no such difficulty arises as the red spinel fluoresces under ultra-violet light whereas pyrope garnet, owing to the iron it contains, does not. Further the absorption spectrum of red spinel shows the group of chromium emission lines in the deep red which are not seen in pyrope. The lowest SG of pyrope at 3.65 is higher than the highest SG for red spinel at 3.61.

The hardness of the pyrope variety of garnet is 7.25 on Mohs's scale and the dispersion (fire) is, for the B to G interval, 0.022.

The absorption spectrum of pyrope garnet which normally contains some, and often a considerable amount, of the almandine molecule which gives a red colour to the stone, may show the typical almandine garnet spectrum characterised by its three main bands centred at 575, 527 and 505 nm. However, in the rich crimson stones, such as those from Czechoslovakia, Arizona, and Kimberley, there is a profound difference in the spectrum owing to the trace of chromic oxide which gives to these pyropes their brighter colour. In such stones the chromium absorption spectrum becomes prominent and masks that of the ferrous iron, the almandine spectrum. This chromium absorption spectrum consists of a narrow and very weak doublet in the deep red at 687 and 685 nm. Other lines at 671 and 650 nm may be seen in exceptional stones. There is a broad spectrum centred near 570 nm which is nearly 100 nm wide and which covers two of the most prominent almandine bands, but allows the remaining almandine band at 505 nm to be seen. It will be recalled that the centre of the broad absorption in the spectrum of red spinel is at 540 nm. In common with all chromium spectra the violet end is absorbed beyond about 440 nm.

Pyrope garnets are comparatively free from internal imperfections. Any inclusions are usually small rounded irregular crystals with a very low relief. Gübelin states that Bohemian garnets frequently contain quartz crystals, or crystals – possibly of augite – arranged in a circular pattern. Such a circular arrangement of inclusions is common in the 'snowball' garnets of Glen Calvie, Ross and Cromarty, Scotland, where the phenomenon is said to indicate that the garnets have been rolled along by differential movement of the matrix of the rock during dynamothermal metamorphism, whilst the crystals were still in active growth. Some Arizona pyrope garnets have included needles and octahedral-shaped crystals.

Occurrences

The association of pyrope as a mineral with diamond is well known, and the finding of pebbles of this garnet in river beds or on the surface of desert sands has been known in several cases to lead to important discoveries of diamond pipes or deposits. In the Kalahari desert, for example, acute observers have found that the huge mounds raised by colonies of termites provide samples of mineral fragments brought to the surface from levels far below by the termites searching for food and moisture over the centuries. Thus the finding of pyrope garnets in these mounds was an important clue to the discovery of what became the giant Orapa diamond mine by Dr Gavin Lamont, the geologist in charge of a prospecting team. In Russia the discovery of pyrope garnets by prospectors in 1953 led to a concentrated search in the neighbourhood leading to the first kimberlite pipe in the upper Markha river.

The best known occurrence of pyrope garnet was in an area of some 70 km² near Trebnitz in the north-eastern part of the old kingdom of Bohemia, now Czechoslovakia. The crystals, which are found in conglomerates, volcanic breccias and tuffs and in various alluvials derived from them, are fairly free from flaws but seldom show crystalline faces. These Bohemian pyropes gave rise to a considerable local cutting industry and jewellery manufacturing centre which can be traced as far back as the sixteenth century. The centre reached a nadir of mining and manufacturing activity, however, in the last half of the nineteenth century, particularly during the Victorian era. The sudden demise of the area by the end of the century can be traced in part to the shift towards new jewellery fashions, as well as the discovery of even better-quality material in the diamond mines of South Africa. These African pyropes are found in the kimberlite of the pipes and in the river gravels, the best materials being found in the De Beers and Kimberley mines.

Pyrope garnet is found in many places in the United States of America, particularly near the border of Utah and Arizona in several separate locations. Termites excavating their architectural complexes were largely responsible for early mining of this material, to be discovered and eventually marketed by Indians or travellers in the area. Pyropes were also reportedly found on the Navajo Reservation in New Mexico as well as in Santa Fe.

Since the recent discovery of East African intermediate pyrope-spessartine gems, there are reports of some stones falling into the pyrope classification from that area. They range in colour from typical dark red to slightly orangy-red as well as some pale pink.

Other sources of pyrope include Russia, among the diamond pipes, and Australia, in the district of New South Wales and Anakie and Ruby Vale in central Queensland. China, near Donghai in northern Jiangsu Province; Myanmar (Burma); Rio Mina, Clavers in Cordova and San Martin and Quines in San Luis, Argentina; and Gravata as well as the Mucuje and Utinga rivers in Argentina, also have been reported as sources of pyrope.

Pyralspite: the Intermediate Series

There are two series of garnets which do not fit the end-member names in the garnet family. The first, along the pyrope-almandine series, range in colour from blood-red to violet-red, with tones usually in the moderate to light categories. These gems are technically neither pyrope nor almandine, but are intermediate between the two. The refractive index may range from 1.75 to 1.78 with SGs from 3.80 to 3.95. However, because these garnets are in a solid-solution series, the limits are admittedly arbitrary. Attempts have been made to provide a name

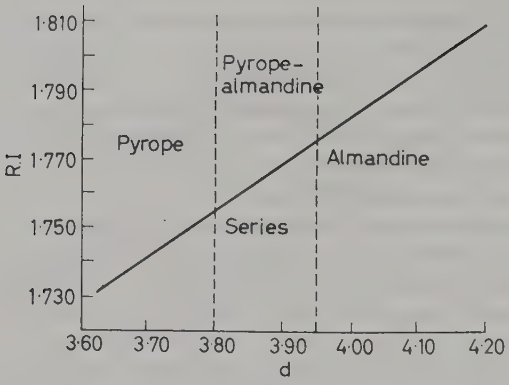


Figure 8.3 *Graph of the pyrope-almandine series (after Anderson)*

to these stones, but none of 'pyralmandite' (proposed by Fermor), 'rhodomacon' (Campbell), 'umbalite' or 'pyrandine' (Anderson) has generated universal acceptance. *Figure 8.3* shows the relation of refractive index to SG of this series and illustrates the suggested division between the groups.

In this group lies the lovely rhododendron-red garnet, exhibiting SGs between 3.80 and 3.95 with refractive indices in the range 1.75–1.78. Such stones are called 'rhodolite' after their colour, a name originally ascribed to stones found in Macon County, North Carolina during the late 1890s. But similar stones are also found in Zimbabwe, Orissa (India), Madagascar and Sri Lanka, as well as the striking gems found in Kenya and the Kangala and the Mwaki Jembe mines in Tanzania; consequently, names suggesting the location of a particular site have not been acceptable for such intermediates. The name 'rhodolite' is tied to the hue of the stone (violet-red) and is used in the gem trade to refer to such intermediates, while 'pyralspite' seems to be more acceptable to petrologists and mineralogists.

The Zimbabwean rhodolites occurring near the Limpopo river of the Beit Bridge area bordering on the Transvaal studied by Ian Campbell revealed a similar violet-red coloration with refractive indices clustering about 1.755 and SGs at 3.85.

Star rhodolite garnets from East Africa are rare, but several have been reported and photographed (Rouse, *Garnet*, 1986, Plate 21; and *Gems and Gemology*, spring 1989, Figure 10, p. 49).

Inclusions among these intermediate garnets have followed almandine, as well as the absorption spectrum. In addition, because of the iron content, there is no fluorescent response under ultra-violet lighting.

A second intermediate garnet type was discovered when the gem dealers of Nairobi refused to buy stones that did not fit the colour requirements of rhodolite. The hues ranged from orange to reddish-orange, generally with pinkish overtones. These 'rejects' were called *malaya*, a Swahili word meaning 'prostitute' or 'out of the family'. By 1979 gem dealers and consumers world-wide were introduced to these gems in extensive advertising campaigns.

The interesting feature of these stones, from a purely mineralogical point of view, was that they represented a curious mixture of spessartine and pyrope, a combination not previously known to exist. Moreover, a number of these garnets were found to change colours under daylight and incandescent lighting, possibly owing to the presence of trace minerals of vanadium and chromium in varying amounts.

Schmetzer and Bank (1981) reported that these stones were of two types. In type I specimens, there was considerable mixture of spessartine-pyrope without an almandine component. In the type II stones, the spessartine-pyrope had varying amounts of the almandine component, quite similar to known samples which had occurred in Ratnapura, Sri Lanka. Both the refractive index and the SG of such stones place them within the intermediary category.

Almandine Garnet

The term 'almandine' is derived from a small city in Asia Minor called Alabanda whose gem activities were known to Theophrastus as early as the late fourth century BC and to Pliny during Roman times.

Theoretically, pure almandine, $Fe_3Al_2(SiO_4)_3$, should have a refractive index of 1.83 and an SG of 4.25, but all the almandines of jewellery contain some of the pyrope molecule, and in addition grossular and spessartite are also present. So in practice garnets may be called almandine if they have an SG higher than 3.95 and a refractive index greater than 1.78.

The colour of almandine garnets is usually dark toned with a more intense red, which usually inclines to a violet-red hue. It has been primarily on account of their dark colour that many almandine garnets have been fashioned in the cabochon form with the back hollowed out. Such a practice was instituted in Roman times in order to decrease the thickness of the stone and hence lighten the colour.

The hardness of almandine is about 7.5 on Mohs's scale, and the dispersion (fire) equals that of pyrope in having a value of 0.027 for the B to G interval. There is no dichroism, although there may be an anomalous double refraction when viewed between crossed polars.

The striking absorption spectrum of almandine garnet, which was first described by Church in 1866, provides a ready test for identification. Ascribed to ferrous iron, the spectrum consists of three main absorption bands centred at 576 nm (in the yellow) and some 30 nm broad, and two bands in the green at 526 and 505 nm which are near enough to each other to merge with one another in the case of deeply coloured almandines. There are several other bands in the complete spectrum but a weak broad band in the orange at 617 nm and another in the blue at 462 nm are usually clearly seen as 'outriders' to the main group of three bands. Other bands which have been measured in almandine garnet are at 476, 438, 404 and 393 nm, some of which can only be seen photographically, and all of which are too weak to affect the general appearances of the so-characteristic three- (or five-) band spectrum of the almandine garnet. These bands to a greater or lesser degree may be seen in all stones of the pyrope-almandine series.

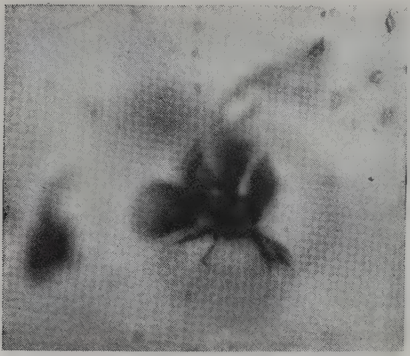


Figure 8.4 'Zircon halo' in a Sri Lanka almandine garnet

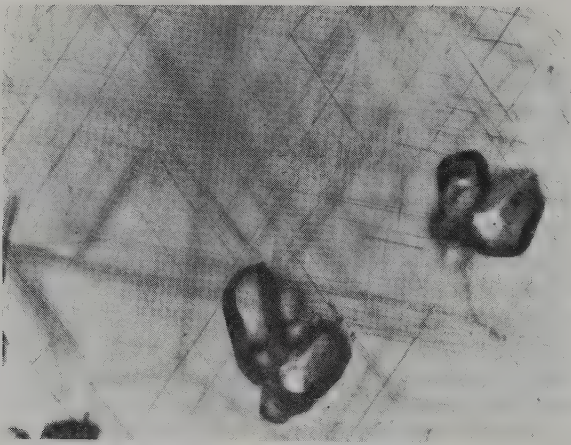


Figure 8.5 Well-formed crystals in an almandine garnet

Inclusions

The inclusions seen in almandine and garnets of the pyrope-almandine series consist of the following types. 'Zircon haloes', like those seen in Sri Lankan sapphires, also occur in the Sri Lankan garnets (*Figure 8.4*). Another type consists of a number of dot-like crystals dispersed all over the stone. Some stones show a large number of lumpy crystals, many of which show crystal form (*Figure 8.5*) or irregularly shaped 'lumps' (*Figure 8.6*). Some crystal inclusions have been identified as apatite, spinel, quartz, biotite and phlogopite flakes from the mica group, in addition to pyrrhotite (magnetic pyrites), ilmenite, fluorapatite, chalcopyrite, plagioclase, muscovite, and sphalerite (a high-property zinc mineral).

The most common inclusions in almandine, however, are the ubiquitous needles, which have been identified as rutile and usually run parallel to the edges of the dodecahedron (*Figure 8.7*). They are often oriented so that they intersect each other on the same plane at angles of 70° and 110°, but they may

Figure 8.6 Large irregular lumpy crystals and crossed needles in an almandine garnet

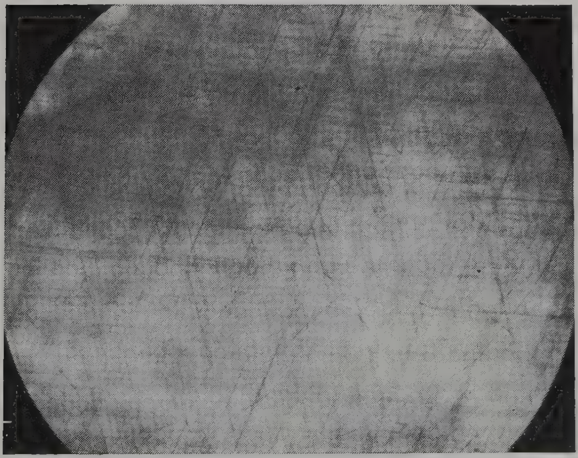


Figure 8.7 Rutile needles are a common inclusion in almandine garnet and when thickly disseminated through the stone may produce asterism (star effect)

also occur at seemingly random angles, exhibit short or long needles, or reveal fine to moderately thick coarseness. When such needle-like inclusions are thickly disseminated throughout the stone, they may reveal a four-ray star.

Occurrences

Almandine garnet is a mineral formed during the metamorphism of rocks and is commonly found in schists. The localities for almandine are world-wide but gem-quality material is more restricted in its location. India is one of the best-known producers of almandine garnet and is thought to have been one of the major sources for ancient jewellery containing almandine. Examples as early as 3200 BC have been found in Egypt, indicating some trade connections at that early date.

The current Indian sources include the mica schists of Rajmahal in Jaipur state, the Sarwar district of Kishangarh state and the Ajmer-Merwara, all of which are in what used to be called Rajputana (now Rajasthan). Another Indian source is in the Warangal district of Hyderabad; but there are many other locations in India, with the exception of western India, which seems devoid of garnet occurrences (Iyer, 1961). Some of the Indian almandine is asteriated and is a major source for star garnet. Almandine is also found on the north-east coast of Sri Lanka, at Trincomalee.

There are many other sources of gem almandine, including Idaho in the United States (another source of star almandines), the Swat Valley in north-west Pakistan, Myanmar (Burma) and Thailand (orange-red almandines), the rivers of the Northern Territory of South Australia, and Brazil in the gem-rich states of Minas Gerais and Bahia.

Some gem-quality almandine has also been obtained from the Zillertal in the Austrian Tyrol, and much garnet is found in Scotland, but rarely in gem qualities.

Spessartine

The colour of this rather rare garnet ranges from a yellowish-orange to an intense aurora-red to a deep orangy-red. Some of the stones have a somewhat similar appearance and colour to some hues of hessonite garnets of the grossular garnet species and thus may be mistaken for them.

The formula for pure spessartine is $Mn_3Al_2(SiO_4)_3$, but usually some of the manganese is replaced by ferrous oxide (FeO), and some of the aluminium by ferric oxide (Fe_2O_3). The hardness of spessartine is 7.25 on Mohs's scale; the SG has the small range from 4.12 to 4.20, and the refractive index lies between 1.79 and 1.81. The dispersion is 0.027 for the B to G interval.

The absorption spectrum of spessartine has a practical value in identifying the stone. The spectrum, due to manganese in the manganous or divalent state, consists of weak bands at 495, 485 and 462 nm. These are followed by a very strong band at 432 nm and others at 424 and 412 nm which is very intense, but these last two bands may be somewhat masked by the general gloom of the violet end of the spectrum which is to some extent absorbed. The key bands of the spectrum are the 432 nm line and the intense 412 nm line if it can be seen. These two bands are important for the other bands may well be masked, or confused, by the bands of the almandine garnet spectrum which is universally present.

Manganese, at least in traces, in many minerals acts as an activator of luminescence, but despite the manganese in spessartine garnet there is no fluorescence shown by the stones when under a beam of ultra-violet light or X-rays. This is most probably due either to the manganese being in too great a concentration or, perhaps more likely, to the poisoning of the luminescence by the iron of the almandine molecule which always replaces some of the manganese.

The inclusions seen in spessartine garnet are to some extent typical of the variety. They consist of wavy feathers, formed by minute liquid drops, and have a peculiar 'shredded' appearance.

Spessartine (often known as spessartite) was first found at Schaffenburg in the Spessart district of Bavaria, hence the name, but the occurrence appears to have had no gem significance. Perhaps the most famous source of the material has derived from the Rutherford mines in Amelia, Virginia in the United States. The pegmatite mines produced gem materials as early as 1873 and continued, sporadically, until about 1968. The Morehead mine, located nearby, was also a producer of spessartine, some with fine 'flesh-red' colours. Another important source of spessartine has been the Surprise and Hercules mines in the Ramona district of San Diego County, also in the United States. Other mines have also produced gem materials in the same vicinity. Other sources of spessartine include Madagascar, Sri Lanka, Myanmar (Burma), Brazil, India (in Narukot, Bombay), and numerous other regions.

Grossular Garnet

The name grossular is little known in the jewellery trade for the title is the mineralogical name for the calcium-aluminium group of garnets, which, if pure, would have the formula $Ca_3Al_2(SiO_4)_3$. Within the grossular species there are several significant gem varieties that require attention, particularly hessonite, tsavolite and the massive hydrogrossular.

The hessonite garnets range in colour from a brownish-yellow through a brownish-orange to aurora-red. The stones have a hardness of about 7.25 on Mohs's scale and an SG approximating to 3.65. The single refractive index varies from 1.742 to 1.748, and the stones have a dispersion of 0.027 over the B to G interval. Hessonite garnet does not have a characteristic absorption spectrum, but may show, owing to the inclusion of some of the almandine molecule, a slight trace of the almandine spectrum. Hessonites, sometimes known as 'cinnamon stones' (from the spice island of Sri Lanka, an early source of the gem), do not exhibit luminescence when under ultra-violet or X-rays.

The internal structures shown by hessonites when they are examined microscopically, or even by a hand lens, are so pronounced as to be characteristic for the gem. The stones show a granular appearance owing to the inclusion of many small transparent crystals having rounded outlines or a fused aspect, and which are often accompanied by peculiar treacly streaks ('treacle') which give to the stone's interior an oily appearance (*Figure 8.8*). The included shapeless crystals are said, by Gübelin, to be either apatite or zircon, the latter showing well-marked relief while the apatite crystals, which have an index of refraction near to the garnet, show only low relief.

Hessonite garnet is common in the gem gravels of Sri Lanka and practically all the gem material is obtained from this locality. Some hessonite is found in Mexico, producing some fine brownish-orange colours with minimal brown. Hessonite is also found in the state of Minas Gerais in Brazil. The Jeffrey mine located in Quebec, Canada has been a significant producer of the gem, although

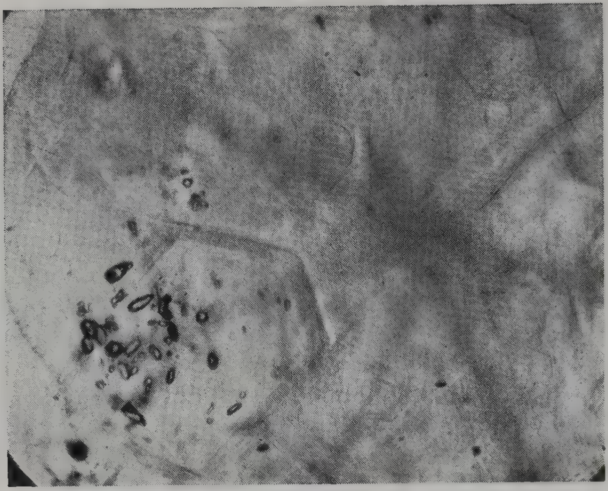


Figure 8.8 *Characteristic 'eroded' crystals, probably in this case of zircon, and the peculiar oily streaks often called 'treacle' seen in a hessonite garnet*

colours tend to the pale yellowish hues for a large percentage of the production. The area has also produced other colours, from colourless through to white, pink, orange and green. The green grossulars have been most rare from this site, however. Another source of hessonite has been Tanzania, with some colourless materials found there, grading into the typical hessonite yellowish-brown.

East Africa has also been associated with the remarkable green garnet, tsavolite (called 'tsavorite' in the United States). The colours of the green garnet range from a pale yellowish-green to an intense emerald-green, and it is found in Tanzania as well as Kenya. The Swat area of northern Pakistan is another source. The African tsavolites occur in beds of graphite-bearing gneiss traversed with bands of marble. Although chromium and vanadium were present in these garnets, the reported 3.3 per cent of vanadium oxide was undoubtedly the dominant partner in producing the fine green colour. In the spectrum, no chromium lines were detected, while broad absorption maxima due to vanadium were measured at 610 and 430 nm. The SG of these garnets ranged between 3.57 and 3.65 and the refractive indices between 1.739 and 1.744. Amongst inclusions noted were groups of yellow fibres reminiscent of the demantoid garnets, but lacking their curved horse-tail distribution. Faint veil-like inclusions have also been observed, composed of very small liquid inclusions arranged in a single plane.

Massive Hydrogrossular Garnet

Another variety of grossular garnet which needs to be mentioned is the massive variety. The most important of the massive grossular is the green-coloured material which is found in the Transvaal, and which has been marketed under the erroneous name 'Transvaal jade'. The material is found on Buffelsfontein and the adjoining farm of Turffontein, which are some 65 km west of Pretoria in almost featureless country belonging to the norite margin of the Bushveld. While the best and most commonly used material is a bright green in colour, some of the material is greyish or bluish, and some pink. It differs from true grossular in having water (H_2O) in its chemical composition.

In general appearance the material is a homogeneous compact rock in which no minerals are recognisable. The texture is horny and the fracture somewhat conchoidal or splintery with a wavy lustre. The rock contains black specks which have been identified as magnetite although some chromite may be present. The colour of the green material is reported as due to chromium and the pink to manganese.

In a study of these garnet rocks, Hall mentions that the green and pure pink material are nearly pure garnet, but that the grey-coloured rock contains up to 25 per cent of zoisite. Hall states that the origin of the rock is not certain, but that there is some ground for regarding the rock as xenoliths of garnet hornstone derived from an original aluminous calcareous sediment by contact metamorphism combined with metasomatism.

The refractive index of the material, only a diffuse shadow edge being visible on the refractometer, varies from 1.70 to 1.73, the lower value being for the pink stones. The SG ranges from 3.36 to 3.55, the pink material varying from 3.36 to 3.41 and the green 'Transvaal jade' from 3.42 to 3.55. Except for the possibility of a weak chromium spectrum showing in the case of the green material, the absorption spectra of the massive grossularites show little that would aid in their identification. While the material does not exhibit any luminescent glow when irradiated with ultra-violet light, a strong orange-yellow light is seen when the material is placed in a beam of X-rays. This X-ray luminescence is, in the case of the green material, most useful, for neither jadeite nor nephrite, nor any other jade simulant, exhibits this glow which is thus diagnostic.

A crystalline, massive form of grossularite – probably similar to the so-called 'Transvaal jade' of South Africa – occurs in the Whitehorse Copper Belt, Yukon, Canada, and a number of occurrences of massive green grossularite are reported from California and other states of the North American continent. Massive white grossularite has been found with jadeite in Myanmar (Burma), and has been carved by the Chinese.

Grossular garnet has a great similarity in its chemistry and structure with the mineral idocrase and a mixture of these two minerals can, and does, occur. This does pose problems in nomenclature, but if it can be shown by SG and absorption spectrum that it is mainly grossular or mainly idocrase, then the specimen can fairly be called the name of the main constituent. Intermediate types should be described as grossular-idocrase intergrowths. Such material has emanated from Pakistan and California, and probably southern Africa. Green hydrogrossular is found in New Zealand and Utah, USA.

Andradite Garnet

Andradite is a species of garnet which was named after M d'Andrada, a Portuguese mineralogist who described and named 'allochroite' in 1800. Under the modern species of andradite, many varieties are found, including the titanium-rich melanites as well as the striking gem varieties of green demantoid and yellow andradite.

In composition pure andradite is a calcium-iron-silicate with the formula $Ca_3Fe_2(SiO_4)_3$, but partial replacement of the calcium by magnesium and manganese, and the iron by aluminium, is universal. The beautiful demantoid garnet owes its attractive green colour to replacement by a trace of chromic oxide.

The opaque black melanites were used for mourning jewellery, or materials for inlay, but in recent years the availability of massive quantities of black onyx (most often dyed black chalcedony) has satisfied the demand.

The important green andradite garnet called demantoid, so named from its adamantine lustre, suffers from the defect of the low hardness of andradite, which is only 6.5 on Mohs's scale. The SG varies from 3.82 to 3.85, and the single refractive index from 1.888 to 1.889. The colour dispersion of demantoid is 0.057 for the B to G interval: thus the stones have a greater fire than diamonds, but the effect is to some extent masked by the body colour of the stone. It was first found, in Russia, in 1868 and used throughout the century, as supplies lasted, in fine jewellery specimens.

Demantoid garnets show reddish when viewed through the Chelsea colour filter, and the stones are characterised by an absorption spectrum consisting of a strong band at 443 nm, which generally appears as a cutoff owing to the general obscurity of the violet end of the spectrum, and only in the paler stones can any violet light be seen beyond this band. This band is due to iron (ferric oxide) which to some extent gives the green colour to the stone, but iron greens are dull greens and the bright green of demantoid is caused, as mentioned earlier, by the trace of chromium. Therefore, in fine demantoids a chromium absorption spectrum may be seen, the lines being the strong doublet near 701 nm, a weak but sharp line at 693 nm and two bands in the orange at 640 and 622 nm which are vaguer and broader than usual in chromium spectra. Demantoid does not exhibit any luminescence under ultra-violet light or X-rays.

The internal features of demantoid are characteristic inclusions of byssolite (asbestos) fibres with a radiating arrangement or as 'horse-tails' (*Figure 8.9*). Such inclusions are diagnostic for demantoid for they are not seen in any other green stone.

The Ural mountains of Russia are the main source of gem demantoid, the stones being found on both the European and the Asiatic sides of the range. The finest examples are found in the gold washings of Nizhne-Tagilsk in the Sissertsk district and in serpentine beside the Bobrovska tributary of the Chusovaya river. The garnets were first found as pebbles in the Bobrovska stream but were later traced to their mother-rock, a serpentine, where they occurred in narrow veins accompanied by asbestos fibres, dolomite, magnetite, and clay. Well-formed crystals are rare. Although the Ural supply was exhausted in the late nineteenth century, some material continues to trickle out. Few other sources provide demantoid; however, Zaire, Korea and San Benito County in California have been mentioned for some few gem and mineral specimens. Those stones from Korea were reportedly found as idiomorphic crystals revealing the unusual (211) dodecahedral habit. Chemical analysis confirmed its identity and the physical and optical properties demonstrated the usual high degree of constancy for this particular variety of green garnet. The

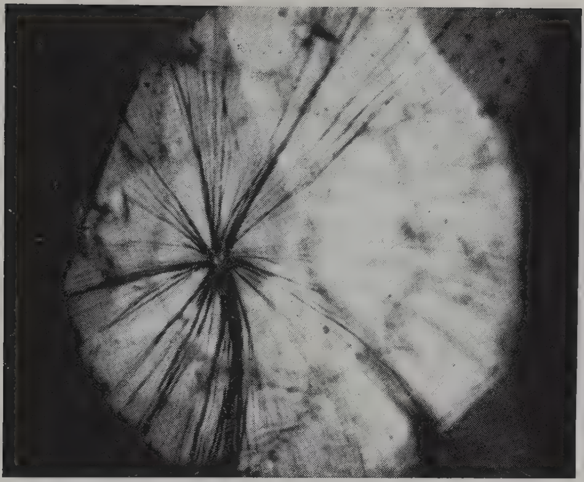


Figure 8.9 Radiating or 'horse-tail' inclusions which consist of asbestos fibres are a characteristic of demantoid garnet (by courtesy of V G Hinton)

refractive index was 1.8889 for sodium light with the SG only varying slightly, between 3.82 and 3.83. Unfortunately, most of the crystals were very small, and few would be large enough to cut tiny stones. The green colour was determined, as usual, to be due to chromium.

Demantoid often grades into yellow when the chromium element is lacking in sufficient strength to produce the green colour. Very often, demantoid sources provide much more greenish-yellow and yellow andradite than the green demantoid. The yellow colour is attributed to the ferric iron in the andradite, but it may be modified also by the presence of titanium or manganese as well. Unfortunately, fine pure yellow andradites without the modifying influences of either the green or the brown are unusually rare. The use of name 'topazolite' is objectionable as applied to yellow andradite, and such materials should be called yellow demantoid or yellow andradite.

In recent years an andradite of unusual iridescence has been found from Mexico. Cut in cabochon, iridescent lamellae oriented in three directions exhibit all the colours of the rainbow on a reddish-brown body colour. These interesting stones are reported to be a mixture of andradite, grossular and almandine. They display two types of lamellae, one rich in iron and the other rich in aluminium. The iridescence depends on the spacing and the thickness of the lamellae. The source is a calcite mine about 145 km north-east of Hermocillo, Sonora, Mexico, and similar materials have been reported by Ingerson and Barksdale in 1943 in Adelaide, Nevada, and Kamihogi, Japan.

Uvarovite Garnet

The chromium-calcium garnet, $Ca_3Cr_2(SiO_4)_3$, would provide a valuable addition to the green gemstones were there available crystals sufficiently large to cut. Coloured by chromium which is an inherent part of the composition, the stone has the fine bright green colour which chromium gives to a mineral. The hardness of the crystals is 7.5 on Mohs's scale and the SG is 3.77. The refractive index is 1.87 which is near to that of demantoid. The small crystals are found in association with chromite in serpentine, or occurring in granular limestone, in the Ural mountains, particularly at Saranovskaya near Bisersk and in the vicinity of Kyshtymsk, north-east of Zlatoust. Jordansmühl in Silesia, the Himalayas and the Pyrenees are other localities where the uvarovite garnet is found and there is considerable uvarovite found with chromite in California.

An emerald-green chrome garnet near uvarovite in composition is found at Orford, Sherbrooke County, Quebec, but again the crystals are far too small to be of value as gemstones.

9

Moonstone and Other Feldspar Gemstones

Chemical and Physical Properties

The feldspar, sometimes written as felspar, groups of minerals are important for the place they take in the formation of rocks, but several varieties of the various groups supply gem materials, the most important of which is the lovely moonstone.

The feldspars, which are all closely allied in form and habit as well as in the mode of their occurrence, are aluminous silicates of potassium, sodium, calcium, or barium, but are practically without magnesium or iron. They are usually divided into four subgroups: (1) orthoclase and microcline (potassium aluminium silicate); (2) albite (sodium aluminium silicate); (3) anorthite (calcium aluminium silicate); and (4) celsian (barium aluminium silicate), this last having no interest to the student of gemmology.

Orthoclase and microcline give the gemstones moonstone and amazonite respectively, while the albite and anorthite produce by isomorphous replacement a series – the plagioclase series – in which occur a number of gem or ornamental minerals. The hardness of the mineral is about 6 on Mohs's scale, and the crystals, which are monoclinic in orthoclase and celsian and triclinic in the plagioclases, have two directions of easy cleavage which are nearly at right angles to one another. The angle does, however, vary somewhat in the different varieties. The measurement of these angles aids the petrographer and the mineralogist in their work of identification of the feldspars, but these 'cleavage angles' are of less importance to the gemmologist who approaches the problems of identity in a different manner. For a clearer understanding of the feldspars, the different groups of the family which have varieties useful as gem minerals need to be discussed separately.

Orthoclase

The monoclinic potash feldspar, $KAlSi_3O_8$, known as orthoclase, is transparent and colourless in its purest form and such material, called adularia, is found in small crystals in the locality of the St Gotthard in Switzerland, but is of no gem significance. The crystals of orthoclase often exhibit, in the opaque non-gem material, one of three types of twinning, but as the gemmy material is so rarely found as euhedral (well-formed) crystals, their discussion is not warranted here. Green, orange and yellow stones are found.

The important orthoclase feldspar gem is moonstone, a gem which is characterised by the beautiful blue schiller shown by the better-quality specimens. This lovely sheen, termed adularescence, is due to a combination of orthoclase and albite – one end member of the plagioclase series – arranged in layers. Light reflected from these layers, if they are not too thick, produces by interference effects the blue schiller, in recent studies called 'Rayleigh scattering' (E Fritsch and George Rossman in *Gems & Gemology*, summer 1988). If the layers are thick the sheen is white and the stone far less attractive. It must be pointed out that in order to obtain the best effect it is necessary for the stone to be cut so that the plane of the base of the cabochon lies parallel to the plane of the layers.

The SG of moonstone varies from 2.56 to 2.59. Indian stones give the higher values between 2.58 and 2.59 while the stones from other localities, particularly those of Sri Lanka, give values below 2.58 and are generally nearer to 2.56. The hardness of orthoclase is 6, orthoclase having been selected by Mohs for the standard 6 on his scale. The refractive indices are, for the greatest and least indices, 1.525 and 1.520 respectively. The double refraction is 0.005 and is negative in sign. Orthoclase has a vitreous lustre which may be pearly on cleavage surfaces, and the fire is small, the dispersion measured over the B to G interval being only 0.012. There is no characteristic absorption spectrum to be observed in moonstone, but the luminescent glows shown by the gem – under long-wave ultra-violet light there is generally a bluish glow of weak intensity, or may be no glow; under the short-wave lamp there is a weak orange glow; and under X-rays a whitish to violet glow – may have some value in distinguishing moonstone from its simulants.

Inclusions

The inclusions seen in moonstones are often characteristic and usually consist, especially in Sri Lankan stones, of peculiar straight lath-like cracks which run parallel to the vertical axis of the crystal. From these cracks, which are most often in pairs or multiple, numerous branching cracks extend for a short distance in the direction of the *b*-axis, after which they taper off in an oblique direction. Such 'stress cracks' may appear like grotesque insects of the centipede type (*Figures 9.1* and *9.2*).

Another kind of inclusion, which may be just a modification of the stress crack type, appears to have the main body of the crack in the form of a cavity or negative crystal (*Figure 9.3*). Some Myanmar (Burma) stones may show oriented needles (*Figure 9.4*); a profusion of such needles may well be the cause of the cat's-eye effect seen in some moonstones.

Figure 9.1 Stress cracks producing a pseudo-insect seen in a moonstone (by courtesy of the Journal of Gemmology*)*

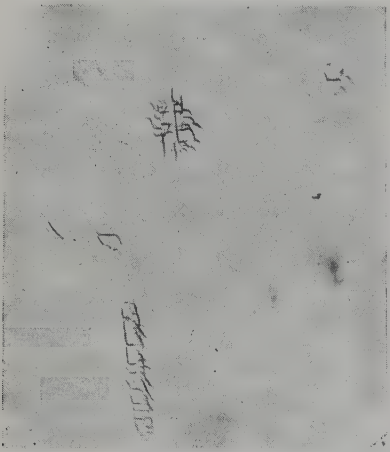


Figure 9.2 'Chinese aeroplanes': stress cracks seen in a moonstone (by courtesy of the Journal of Gemmology*)*

Occurrences

The most important source of moonstone is Sri Lanka, where the mineral with either a white or blue 'flash' occurs in peculiar adularialeptynite dykes at Weergoda near Ambalangoda in the Southern Province and in the Dumbara and Kandy districts of Central Province. Water-worn pebbles, probably derived from the dykes, are found in the gem gravels in the southern part of the island. The mineral is also found in the Coimbatore district of Madras, India, and the mineral from this locality is characterised by variations in body colour from white to reddish-brown or plum-blue. Other localities are Madagascar, Myanmar (Burma), Tanzania and at a number of places in North America, particularly in the states of Colorado, Indiana, New Mexico, New York, North Carolina, Pennsylvania, Virginia and Wisconsin. A green moonstone comes from India.

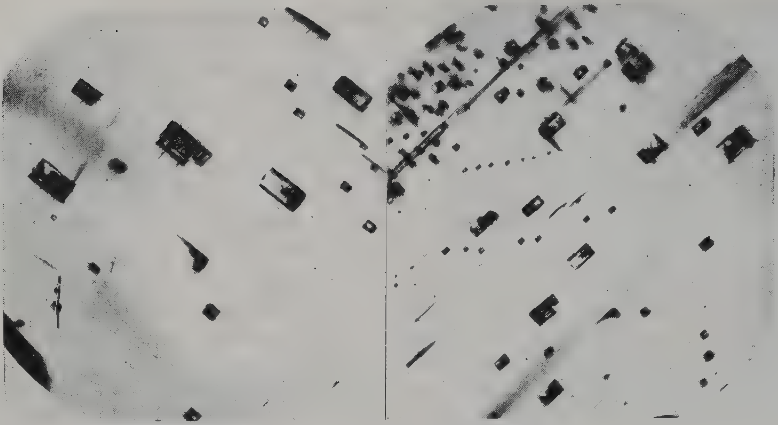


Figure 9.3 *Stress cracks like negative cavities in a moonstone (by courtesy of the* Journal of Gemmology*)*

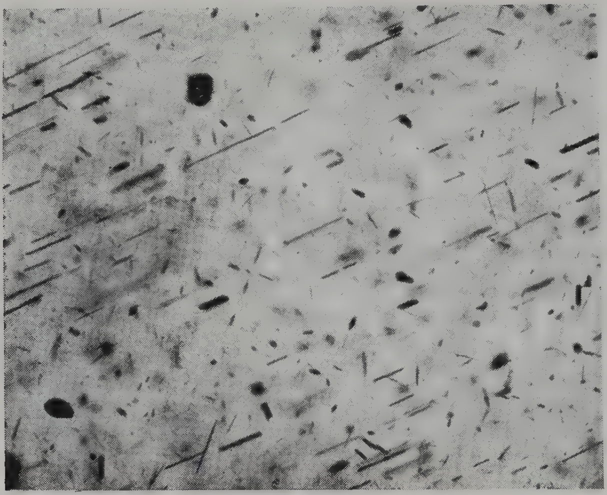


Figure 9.4 *Oriented needles in a moonstone (by courtesy of the* Journal of Gemmology*)*

Synthesis and Simulation

The major imitations of moonstone, apart from a very unconvincing glass, are the synthetic white spinels which have been schillerised by secondary heating, and by a similarly heat-treated amethyst. A white chalcedony which shows a pale blue-moon effect when cut cabochon has been miscalled 'moonstone'.

Yellow Variety of Orthoclase

A transparent clear pale yellow to golden-yellow variety of orthoclase, which is rich in iron, emanates from the pegmatites at Itrongay, Madagascar. The crystals are found loose in the soil surmounting the weathered part of the pegmatite and they are usually broken or with their faces corroded and dull. The stones faceted from this yellow orthoclase have a vogue with collectors. Facetable pieces of rich yellow orthoclase have recently been found in this area, some specimens as large as 2500 carats. The SG of this type of orthoclase, the colour of which is due to the iron it contains, is 2.56, which is quite a normal value, but the indices of refraction are slightly higher, the least and the greatest indices being 1.522 and 1.527 respectively. The double refraction of 0.005 is the same as that for the normal type of orthoclase.

The yellow orthoclase shows an absorption spectrum due to iron, which consists of two broad and diffuse bands in the blue and violet. These are a weak band at 448 nm and a stronger band centred at 420 nm. There is a further strong band in the near ultra-violet at 375 nm, but this can only be observed photographically. The Madagascan yellow orthoclase shows a weak reddish-orange glow under both long-wave and short-wave ultra-violet light, and a similar and stronger glow under X-rays. An unusual yellow orthoclase from Myanmar (Burma), which showed a cat's-eye effect, behaved similarly except that the glow under X-rays was more yellow in hue.

A glassy variety of orthoclase feldspar, called sanidine, is found near Brohl and the Laacher See, which lie north-west of Koblenz in the German Rhineland. There is said to be another source near Rieden near Bavaria. Both colourless and pinkish-brown stones have been cut from the Rhineland material, the brown stones being quite attractive. The constants for these brown sanidines, as determined by Professor Bank, give the following range: α 1.516, β 1.521, γ 1.522 to α 1.520, β 1.525, γ 1.526, with a negative birefringence varying from 0.005 to 0.007. The SG is 2.57 to 2.58.

Microcline

The only gem variety of microcline feldspar is the verdigris-green to blue-green material to which the name amazonite or amazon stone is applied. Microcline has the same chemical composition as orthoclase, namely potassium aluminium silicate, and accords to the formula $KAlSi_3O_8$. The mineral differs from orthoclase in forming triclinic crystals, but the inclination of the third axis is very small and thus the crystals of amazonite strongly resemble those of orthoclase. Indeed, it is from this very small change of angle to the triclinic system of crystallisation that the mineralogical name microcline is derived.

Microcline occurs in translucent to opaque well-formed crystals, or as massive material of greyish-white, flesh to brown-red or green colour. It is the bright verdigris-green to blue-green material that is alone used as a gem material for beads and cabochon-cut stones, but the material is not suitable for carving owing to the easy cleavages.

Like all feldspars, microcline has two directions of good cleavage and this constitutes a danger in fashioned material which may break with some facility along these directions if the stones are carelessly handled. Incipient cleavage cracks give polished surfaces a shimmering effect due to reflections from these cracks, and this is very evident when the stone is rotated. This effect and the mottled texture readily differentiates amazonite from other green ornamental minerals.

Amazonite is usually slightly harder than orthoclase and may reach nearly 6.5 on Mohs's scale. The SG varies from 2.56 to 2.58, and the material, which is optically negative in sign, has for the greatest and least indices of refraction values of 1.522 and 1.530, values which are slightly higher than for orthoclase. The birefringence is 0.008. Microcline, or rather the amazonite variety, shows no distinctive absorption spectrum. The material usually shows a yellowish-green glow under long-wave ultra-violet light, is inert under the short-wave lamp, and exhibits a weak green glow with a fairly long afterglow when irradiated with X-rays.

The green microcline feldspar owes its varietal name amazonite to the Amazon river, but although the mineral is found in Brazil it is not known to come from the vicinity of the Amazon. Green microcline is found in the pegmatite veins of Sao Miguel de Piracicaba and from Joahyma and in the region of Ferros in the state of Minas Gerais.

The most important sources of the mineral at present are the Kashmir district and elsewhere in India. In the United States of America a good-quality amazonite was at one time mined at Amelia Court House, Virginia, but the mine is now closed as the best-quality material has been worked out. The most important North American locality is in Colorado where the mineral is found in well-formed crystals in scattered pegmatite pockets in a schist near Crystal Peak and at Pikes Peak. The green mineral is found in the Renfrew and Parry Sound districts of Ontario, Canada, and one of the earlier sources, and probably mined today, is near Miask on the eastern side of Lake Ilmen and in the Ural mountains of Russia. It is found in these localities mainly in the form of compact masses. Amazonite is also found in several of the pegmatites of Madagascar, notably around Anjanabonoina, Andina, Imody and Mahabe. Recently amazonite of good green colour has been found in the Sahara desert and Tanzania, in Kipawa, Quebec and in southern Africa.

Perthite

Perthite, which owes its name to the town of Perth, Ontario, Canada, where it was first found, consists of an intergrowth of albite or oligoclase in orthoclase or microcline. The component minerals are miscible at high temperatures but on cooling are thrown out of solution producing an interlaminated intergrowth of different feldspars.

Suitably cut this material makes a handsome ornamental stone exhibiting a rich golden labradorescence against a flash-red to reddish-brown or white background. Perthite is found in large masses at Dungannon, Hastings County and in the Nipissing district of Ontario, and also in a number of localities in Quebec.

Plagioclase Feldspars

It has already been mentioned that the plagioclase feldspars, known also as the soda-lime feldspars, constitute an isomorphous series between albite, the

Table 9.1
The plagioclase feldspars: range and composition

Albite	90 to 100 per cent albite with	0 to 10 per cent anorthite
Oligoclase	70 to 90 per cent albite with	10 to 30 per cent anorthite
Andesine	50 to 70 per cent albite with	30 to 50 per cent anorthite
Labradorite	30 to 50 per cent albite with	50 to 70 per cent anorthite
Bytownite	10 to 30 per cent albite with	70 to 90 per cent anorthite
Anorthite	0 to 10 per cent albite with	90 to 100 per cent anorthite

sodium aluminium silicate, $NaAlSi_3O_8$, and anorthite, the calcium aluminium silicate, $CaAl_2Si_2O_8$. The mineralogist has applied various names to minerals falling into certain positions in the series and in *Table 9.1* is shown these subvarieties and the range of composition of each.

In these groups are certain feldspars which have a value as gem materials, and for convenience these particular minerals will be discussed separately. However, the characters of this feldpar series – all members of which crystallise in the triclinic system not necessarily as good crystals but usually as crystalline masses – must first be given. The plagioclases, especially the oligoclase (sunstone) and labradorite, exhibit repeated twinning giving fine lamellae which appear on the basal cleavage surfaces as fine striations (*Figure 9.5*). The refractive indices and SG increase from albite, with an SG of 2.605 and refractive indices α 1.525, β 1.529 and γ 1.536, to anorthite, which has an SG of 2.765 and indices of refraction α 1.576, β 1.585 and γ 1.588. The optical orientation of the plagioclases also changes with composition and this affects the optical sign which alters in different subvarieties. The variations in SG, refractive indices and optical sign are shown in *Figure 9.6*.

Albite

The albite variety of feldspar also produces a moonstone, the so-called albite moonstone, but the variety is not at all common. One type is called peristerite,

Figure 9.5 The striations seen on the basal cleavage face of sunstone due to repeated twinning

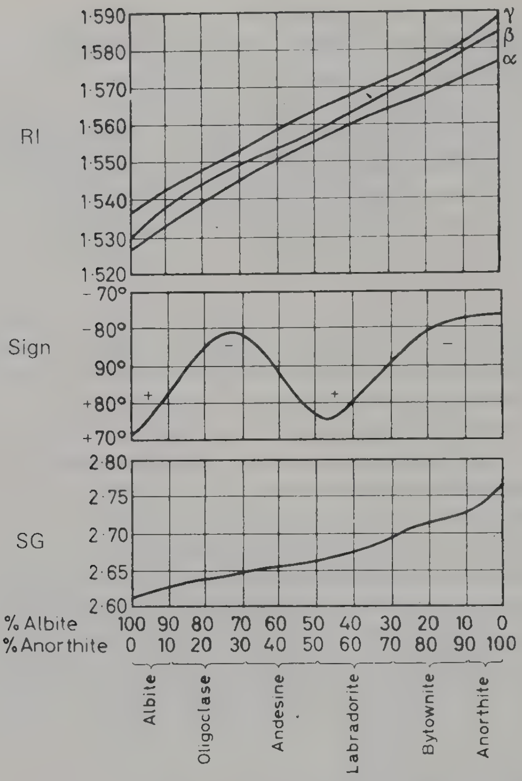


Figure 9.6 Graph showing the relation of refractive indices, optical sign and SG for the various percentage compositions of the plagioclase feldspar series

sometimes known as 'pigeon stone'. Peristerite is an ornamental feldspar with a white, cream, fawn or brownish-pink body colour showing a celestial-blue flash of iridescence or play of colour. A sample of this variety gave an SG of 2.617 and an index of refraction near 1.54. The mineral showed a very weak brownish glow under both ranges of ultra-violet light, and a weak glow of indeterminate colour with a persistent afterglow when the stone was irradiated by X-rays.

The most beautiful peristerite is said to be found at Monteagle, Hastings County, Ontario, and this material has been fashioned into beads and cabochon stones. An ivory-white peristerite is found in some quantity in the Villeneuve mine, Labelle County and at Buckingham, Quebec. Other Canadian sources are at Bathurst, Lanark County, near the mouth of Eel Greek, on the north shore of Stony Lake, Burleigh, and at Bromley, Renfrew County, Ontario.

A transparent feldspar, nearly colourless with a tinge of blue or yellow, has been cut from material found in Kenya. The mineral is an albite/oligoclase and a specimen gave values of refractive indices of α 1.535, β 1.539 and γ 1.544, the SG being 2.63. The material showed a faint whitish glow under long-wave ultra-violet light, was inert under the short-wave lamp, and under X-rays exhibited a bright lime-green glow with a persistent phosphorescence of similar hue.

Oligoclase

The gem mineral of the oligoclase variety of feldspar is sunstone, or as it is sometimes known aventurine feldspar, a mineral which owes its attractiveness to the inclusions of red and orange, and occasionally green, microscopically thin platy crystals of goethite or hematite or both which are disseminated in parallel orientation through the near colourless oligoclase matrix (*Figure 9.7*), and which gives to the mineral a rich golden or reddish-brown colour and specular reflections.

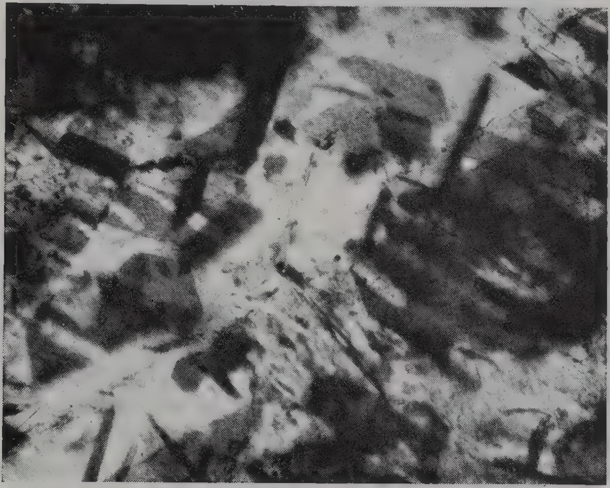


Figure 9.7 Platy crystals of hematite or goethite are responsible for the golden colour and reflective iridescence of sunstone

The SG of sunstone varies from 2.62 to 2.65, the most common value being near 2.64, and the least and great indices of refraction are near 1.54 and 1.55. The mineral is for practical purposes inert under ultra-violet light but shows a whitish glow when irradiated with X-rays.

The source of the best sunstone is at Tvedestrand and Hiterö on the south coast of Norway, where the mineral is found as irregular masses in veins of white quartz traversing gneiss. Another locality is at Verkhne Udinsk on the Selenga river near Lake Baikal in Russia. Sunstone is found in several places near the contact of the Bancroft sodalite and nephelene syenite in Hastings County, Ontario, and there are other Canadian localities in Lanark, Renfrew and Haliburton Counties of Ontario. Sunstone of a brownish-pink colour is found in a pegmatite dyke east of the French river on the north-east side of Lake Huron, and from Kangayam, southern India.

In the United States of America sunstone is found in the states of Maine, New Mexico, New York, North Carolina, Pennsylvania and Virginia, but the localities are relatively unimportant.

Some aventurine feldspar or sunstone may be adularia (orthoclase) with included platelets of hematite, and the so-called spangled sunstone from Modoe County, California, is now stated to be labradorite with coppery inclusions of goethite.

About 1887 a clear colourless to pale variety of oligoclase was found at the Hawk mica mine near Bakersville, North Carolina, and from this material some faceted stones were cut. No information as to the properties has been given but from the description of the mineral it may well be similar to the Kenya albite/oligoclase which was mentioned under albite.

Andesine

During 1967 a massive green material, somewhat resembling jade, was determined as andesine feldspar by American workers.

Labradorite

The member of the plagioclase group known as labradorite is noted for the brilliant play of colour which flashes out over large areas of the grey-coloured mineral. This play of colour, or schiller, is only seen on the easier of the two cleavage surfaces, or on polished surfaces nearly parallel to this plane. The most beautiful colours which flash out from the grey-coloured labradorite are blues and greens which rival the iridescence seen on the wings of some tropical butterflies. Yellows, gold, reds, and purple are some of the other colours shown by specimens of labradorite.

The optical effect which produces these brilliant colours on the otherwise grey material is mostly due to interference of light from the fine lamellae of the repeated twinning, to which must be added some colour effects produced by the platy inclusions which probably give to labradorite the grey colour. These platelets, which are said to be the iron oxide magnetite, are accompanied by profuse needle-like inclusions (*Figure 9.8*). Like the hematite inclusions in sunstone these magnetite platelets may also produce flashes of coloured light due, like the schiller, to interference effects. Some labradorite does, indeed, have hematite inclusions like sunstone and thus produces an aventurescent labradorite. A colourless labradorite darkened by needle-like inclusions, and which has a pronounced blue flash and some degree of chatoyancy when cut in the correct direction, is called 'black moonstone'.

The SG of labradorite approximates to 2.69 and the greatest and least refractive indices are near 1.568 and 1.560, the birefringence being 0.008. No characteristic absorption spectrum is observed in the material, nor does it exhibit any luminescence. While the flashes of colour show best in flat polished plates, an effect like opal is shown by carved labradorite, the carving breaking up the broad flashes into more pin-point gleams which in such work, carved despite the strong cleavage of the feldspars, is most effective. A labradorite from Finland has been called Spectrolite.

A clear near-colourless to yellow transparent labradorite which does not show a play of colour is found at Millard County, USA. This variety has an SG

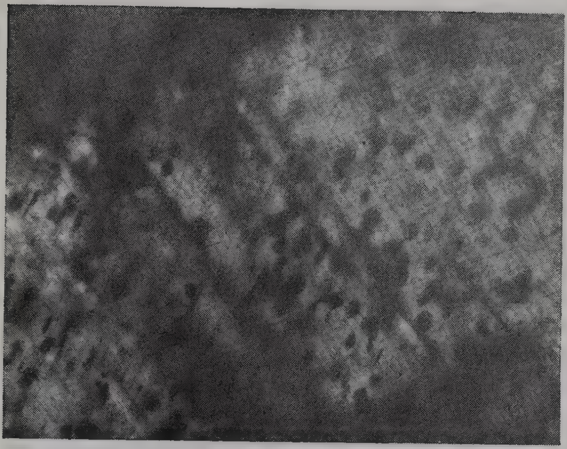


Figure 9.8 Magnetite platelets and needle inclusions which give to labradorite its grey colour, and sometimes chatoyancy

near 2.68 and refractive indices for the greatest and least shadow edges of 1.572 and 1.565 respectively. A similar material comes from Mexico and Australia. A transparent type of labradorite from Madagascar shows the blue flash and needle-like inclusions as found in 'black moonstone'. These types of labradorite show little in the way of luminescence under ultra-violet light, but under X-rays a bright greenish glow is seen.

The normal rock-like labradorite is found as extensive rock masses in the vicinity of Nairn on the coast of Labrador, hence the name applied to this variety of feldspar. Other sources are in Newfoundland, along the shore of Lake Huron, at Cape Mahul, at Abercrombie and at Morin in Quebec, Canada. There are sources of the mineral in the Ukraine, especially at Gorodishch in the Zhitomir district, and in the Ural mountains in Russia. Labradorite is found in small quantity in Arkansas, New Mexico and Vermont in the United States of America.

Bytownite and Anorthite

A reddish faceted stone has been identified as bytownite. The stone had an SG of 2.739 and refractive indices of 1.56–1.57; there was observed an absorption band at 573 nm. A pale yellow bytownite is found at Plush, Oregon, USA, and there has been a report that some feldspar from Oregon has unusual red and 'andalusite' colours. Irregular pebbles of bytownite have been found along the Arizona/New Mexico border west of Reserve. The hardness is said to be 6 on Mohs's scale, and the refractive index just over 1.57. The SG is probably about 2.73. Anorthite has been cut for collectors.

Laurvikite (Larvikite)

The Norwegian rock known as laurvikite, so named from Laurvik in southern Norway, is a material extensively used for building façades. It is often referred to as labradorite, but is actually a rock chiefly characterised by its rhomb-shaped feldspars which give a pearl-grey iridescence. The material actually consists of crypto-perthite or anorthoclase or both, plagioclase being absent, with biotite and aegirine-augite.

Sunstone Labradorite from Oregon

New labradorite sunstone, ranging in colour from pale yellow, pale pink, medium orange and deep red to some rare greens, was discovered in 1980 and is currently being mined commercially. Studies of the material indicate the presence of rare pleochroism and aventurescence in these transparent and translucent gems. The cause of colour in these stones is still under investigation, but it is speculated that it is due to intervalence charge transfer involving copper. The location of the material is in central Oregon, 255 km south-east of Bend. The feldspar is An70 labradorite, a high calcic plagioclase, and the aventurescence is due to the native copper in these gems. Because of the copper inclusions, the colour in the gems is not materially affected by changes in light intensity, and the sunstones do not 'die' in low-light conditions.

10

Gems of the Silica Group

The quartz gems comprise several different groups. They include the fully crystalline quartz, to which belong the lovely amethyst and the ubiquitous rock crystal; the crypto-crystalline quartz or chalcedonies, the best known of which are the agates; and the impure but colourful jaspers, to which are allied the hornstone, chert and flint, materials which have no gem significance despite the use of flint by early man.

Quartz

Chemical and Physical Properties

At temperatures up to 870 °C quartz is the stable modification of crystallised silica, SiO_2. At approximately 573 °C the structure alters from the stable (alpha quartz or low quartz) to beta quartz or high quartz. This alters to the modification tridymite at 870 °C, the alteration involving volume change; at 1470 °C a change to cristobalite takes place. Quartz (trigonal), tridymite, which may be monoclinic and pseudo-hexagonal (or triclinic), and the tetragonal cristobalite are all polymorphs of SiO_2; other polymorphs exist. At temperatures over 1728 °C cristobalite melts.

Quartz is a member of the trigonal system, most commonly with the near-universal forms of the prism with positive and negative rhombohedra. Where the two types of rhombohedron are present the positive usually predominates; the names major and minor are sometimes used. Small modifying forms are also seen; these include the trigonal pyramid and the positive trigonal trapezohedron, with other less common trigonal trapezohedra with positive right and positive left faces. Overall the identifying of forms can be difficult in quartz, particularly in striated or rounded zones. Some crystals have equant habit in which both positive and negative rhombohedra are equally developed

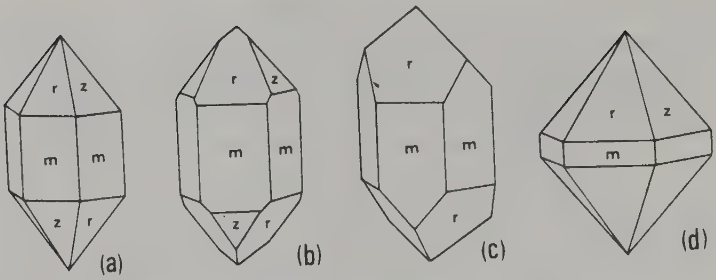


Figure 10.1 *Prismatic habits of quartz*

with no prism form present or, when present, poorly developed (*Figure 10.1*). The name quartzoid has been used for this type of crystal which resembles a hexagonal pyramid. Prism faces are nearly horizontally always striated and this feature helps in correct identification of the morphology; the notably brighter lustre and larger size of the positive rhombohedron compared with its negative counterpart is also useful. The presence and situation of vicinal faces and growth hillocks are closely studied in the context of quartz crystal synthesis.

Twinning in quartz is almost universal. The various types include Dauphiné and Brazil twinning with parallel axes: in the former type the twinned portions are related geometrically and are of the same hand. They are related by a rotation of 180° around the *c*-axis (*Figure 10.2*). In general both portions in

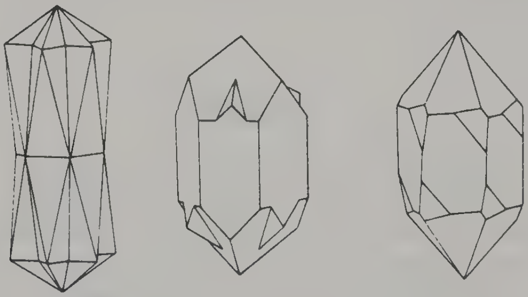


Figure 10.2 *Examples of Dauphiné twinning*

Dauphiné twinning are of similar size. Its presence can only be detected by chemical etching or by X-ray diffraction. Brazil twinning, also including penetration, involves the relationship of two portions, of opposite hand. Brazil and Dauphiné twinning are present simultaneously in most crystals. Brazil-law contact twins are known with right- and left-hand individuals joined with large re-entrant angles. Brazil-law twins can be recognised in polarised light.

Twinned crystals with inclined axes include the Japan-law type and its various subtypes. All twinned crystals with inclined axes are contact twins with the *c*-axes inclined at 84° 33′.

Quartz belongs to the trigonal trapezohedral class of the trigonal system.

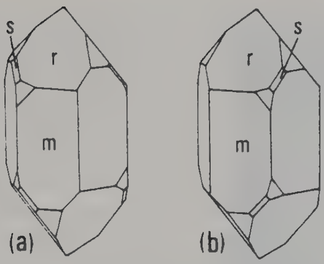


Figure 10.3 (a) Left- and (b) right-handed twinning in quartz

Crystals in this class show the property of enantiomorphism – a relationship between two identical but non-superposable objects or mirror-images. This relationship can give crystals a right-handed or left-handed form (*Figure 10.3*); in quartz it appears as a helical arrangement of the SiO_2 tetrahedra along threefold axes. The analogy of a corkscrew may be useful; its helix is right-handed when it is thrust into the cork away from the observer and turned clockwise; seen from the side with the axis of the helix held vertically, the thread of the corkscrew slopes upwards to the right (Frondel, 1962). The identification of hand can usually be done by examining the position of the trigonal pyramid in the upper corner of the prism face below the positive rhombohedron. If the pyramid is in the upper right corner the crystal is morphologically right-handed; if it is in the upper left corner the crystal is left-handed. The two types are found in almost equal numbers in nature. Some texts distinguish between structural hand and morphological hand but this need not concern us here.

If a quartz crystal is mechanically stressed along certain directions it will develop a surface electrical charge (piezoelectricity). Applying an electrical field will give mechanical strain in the crystal. This phenomenon is the basis of many electronic devices. Quartz will also develop a surface electrical charge with change of temperature (pyroelectricity).

The hardness of quartz is designated 7 on Mohs's scale and varies slightly with direction. There is no distinct cleavage and the fracture of single crystals is conchoidal. The specific gravity is close to 2.651 at room temperatures, varying only slightly with the presence of impurities. The refractive index is 1.544 for the ordinary ray and 1.553 for the extraordinary ray, with a birefringence of 0.009. The dispersion is 0.013. Quartz shows no fluorescence.

Quartz rotates the plane of polarisation of light travelling parallel to the *c*-axis either to the right or to the left. The normal uniaxial interference figure is unique for quartz in that the arms of the black cross do not meet in the centre (*Figure 10.4*). This is a most useful test for rock crystal spherical beads which can quickly be passed between crossed polars when the characteristic figure can be seen (*Figure 10.5*).

Rock Crystal

The colourless water-clear quartz is known as rock crystal and receives its name from the hardy mountain climbers of ancient Greece who first came upon it

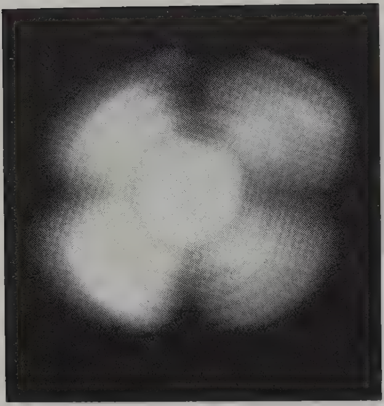


Figure 10.4 Interference figure of quartz showing the central gap in the arms of the black cross

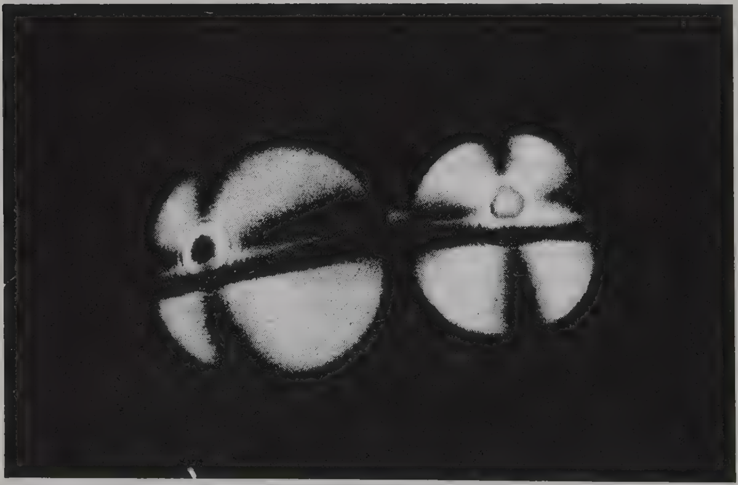


Figure 10.5 The unique interference figure of quartz as seen in two necklace beads placed between the filters of a polariscope

gleaming in hidden caves near Mount Olympus. They called it *krustallos* meaning ice, for they believed it to be water so frozen by the Gods as to be forever solid. Crystals of colourless quartz are abundant and show considerable variation in size, from crystals so minute that it would take about 4000 to make a gram to gigantic crystals weighing more than 500 kg.

Cutting of Rock Crystal

Rock crystal is cut into faceted stones and as beads. The large crystals provide a suitable medium for large carved and engraved pieces and many exquisite works of the glyptic art made in rock crystal are extant from Grecian and Mycenaean times, and from the Middle Ages. The peoples of China and Japan excel in the carving of this material and some fine engraving on rock crystal has been carried out during the present century by German and Bohemian artists.

The rondels, the small flat beads sometimes used for separating coloured stones in necklaces, are usually made of rock crystal, and the halves of the composite stone known as soudé emerald are usually pieces of rock crystal, often selected for the natural flaws they contain.

Rock crystal is ground and polished, mostly by Japanese workers, into crystal-gazing balls, although most of the crystal-gazing balls are moulded and polished glass. Quartz spheres over 75 mm across are rare, but there is an exceptional specimen in the United States National Museum which has a diameter of 325 mm and weighs 49 kg. The distinction of quartz spheres from those made of glass, apart from the much colder feel of the quartz ball, may be made by looking through the ball at a dot or pin-hole in a sheet of paper. Quartz, except for one position along the optic axis, will, owing to double refraction, show the dot doubled, whereas glass will not do this. The ball must be turned and viewed in different positions 90 degrees removed, to ensure not going down the optic axis, before the ball is identified as glass.

Inclusions

Rock crystal may contain two-phase inclusions (often gas or liquid CO_2 with varying mineral neighbours) but several minerals give rock crystal an unexpectedly exotic appearance. Reddish or golden rutile crystals in hair-like form produce rutilated quartz or Venus hair stone (*Figure 10.6*) and other long slender invaders may include dark colours of tourmaline or actinolite. In some cases the actinolite fibres are sufficiently dense to colour the host green. Reticulated (net-like) needles give sagenitic quartz. Other rock crystal inclusions are blue anatase (particularly in Norwegian material), ilmenite, the sulpho-salts boulangerite, giessenite and heyrovskyite (these particularly from Alpine cleft material), brownish-yellow bundles of goethite crystals, red plates of lepidocrocite, reddish hematite, yellowish-green chlorite group minerals, golden-yellow pyrochlore, and orange spessartine. The copper mineral chrysocolla may be brown or blue; also giving blue inclusions is dumortierite. Thin cracks may give interference colours in white light (rainbow quartz). Sometimes the cracks may be filled with dyes (firestones).

Occurrences

Rock crystal is found the world over and only some of the more important localities are mentioned here. Fine specimens, usually crystal groups, come from the Swiss and French Alps and from Hot Springs, Arkansas, USA. Doubly terminated crystals, often containing black inclusions of petroleum, are found in Herkimer County in the state of New York. The most important source for rock crystal is in Brazil, where the best technical quartz is obtained in Goiás, Minas Gerais and Bahia. Madagascar is another source of large crystals, as is the area around Mount Kimpu in the Kai province and elsewhere in Japan. Large crystals are found in New South Wales and rutilated quartz is found in Tingha in the same Australian state. Very large quartz crystals are found in Sakangyi in the Kathe district of upper Myanmar.

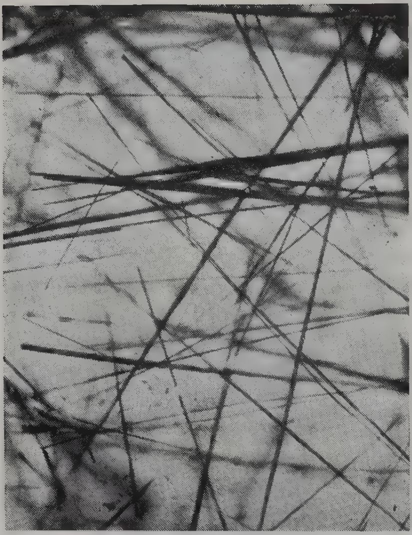


Figure 10.6 *Rutile needles in quartz (Venus hair stone)*

White Quartz

White quartz, the so-called milky quartz, owes its milkiness to the presence of a multitude of very small cavities containing water or carbon dioxide in liquid condition. Sometimes the milkiness is only skin deep on the crystal and such crystals are called quartz *en chemise*. Much vein quartz is white quartz and this type is often gold-bearing. Such material with included gold grains has been cut as plates or cabochons, perhaps as souvenirs of the mining camps. Milky quartz is little used as a gemstone.

Brown and Smoky Quartz

Quartz crystals of a clear brown colour and varying in hue from a light brown to so dark a brown as to appear black – then known as morion – are fairly common but do not have a great appeal as cut stones. Brown quartz crystals have been found in the debris of a weathered granite in the Cairngorm mountains of the Scottish Highlands. Faceted stones of this brown quartz are known as cairngorms and were traditionally used to embellish the accoutrements of the picturesque Highland dress. The supply from the Cairngorm mountains is now virtually exhausted and much of the cairngorm used for Scottish jewellery today is amethyst from Brazil which has had the colour altered to brownish-yellow by heat treatment. Some brown quartz has a smoky tinge and is then known as smoky quartz.

The usual inclusions seen in brown quartz are the two-phase negative crystal cavities in which the liquid phase is usually carbon dioxide, as is shown by the disappearance of the bubble when the quartz is heated to between 30 and 31 °C, which is the critical temperature for carbon dioxide and above which it cannot exist in the liquid state. Brown quartz shows quite a distinctive dichroism, one ray being brown and the other pinkish-brown. The stones shows no absorption spectrum of diagnostic value, nor do they luminesce under ultra-violet rays or X-rays.

The colour of smoky quartz arises from the operation of a colour centre involving an aluminium impurity. Natural irradiation ejects and traps one of a pair of electrons, leaving a hole colour centre with absorption of light giving the brown colour. Heating restores the trapped electron and removes the colour.

Some natural smoky quartz or irradiated synthetic quartz turns greenish-yellow on heating before it loses its colour entirely. The greenish-yellow colour is stable to light. In this case the cause of the colour centre is not known and no Fe is present. Re-irradiation returns it to the smoky colour.

The most important sources for brown quartz are in the Swiss Alps where, in 1868, in the Canton Uri, a single cavity yielded some 1400 kg of crystals. Very fine crystals of smoky quartz are found at Pike's Peak, Colorado; other North American localities are in Auburn County, Maine and Alexander County, North Carolina. Butte, Inyo, Kern, Riverside and San Diego Counties of California also supply brown quartz. Japan and Hinojosa in the province of Cordoba, Spain, have produced smoky quartz; there are some localities in New South Wales, Australia.

Citrine

The yellow quartz, called citrine, varies in colour from a light golden-yellow to a reddish-yellow and owes its colour to a trace of ferric iron (Fe^{3+}). Natural yellow quartz is somewhat rare and the best material comes from Brazil. Citrine shows perceptible dichroism. Most of the yellow and brownish-yellow quartz which in the past was often sold under the misnomer 'topaz' is heat-treated amethyst.

Amethyst

The violet and purple varieties of quartz provide the most prized, and in many respects the most interesting, of the large family of quartz minerals. Amethyst, the name by which this variety of quartz is known, is of ancient derivation. Pliny stated that the gem was so called from the colour being near to, but not quite reaching, that of wine. The name is also said to have been derived from the Greek word *amethustos,* which is translated as 'not drunken'; and was given to the stone from the belief that a wearer would not suffer unduly from excess consumption of alcoholic liquors. As an amulet, amethyst was believed to dispel sleep, to sharpen the intellect, to be an antidote against poison, and to preserve the wearer against harm in battle.

In ecclesiastical circles amethyst has always been held in high esteem and many of the finest specimens of this beautiful variety of quartz are set in the finger rings of bishops. There are two fine amethysts in the British regalia: a large faceted orb set below the cross and surmounting the Star of Africa in the sceptre, and another fine stone set below the cross which surmounts the orb.

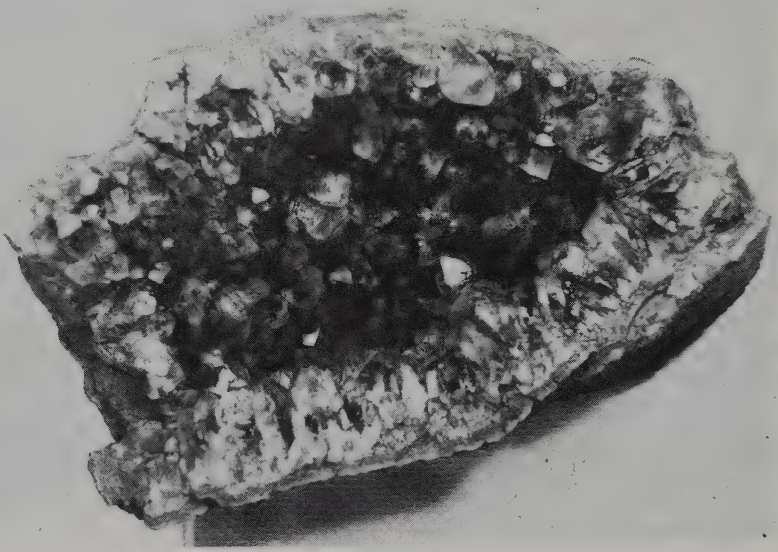


Figure 10.7 Typical amethyst geode

Amethyst crystals are found lining vughs or the inside of hollow cavities (*Figure 10.7*). It is characteristic of amethyst crystals found in these drusy masses to show only the rhombohedral tops, the prism faces being absent, and it not infrequently happens, especially with South American stones, that the three alternate rhombohedral faces are the only ones developed, giving crystals with a cubic aspect. Further in these druses the faces of the rhombohedra are often arranged in parallel position. It is also characteristic of amethyst that quite often only the tips of the crystals are deep coloured, the remainder grading into milky quartz or rock crystal. Thus, although amethyst is always violet in hue, the range of colour is very wide and may vary from nearly colourless with a faint mauve tint to a glorious purple.

Coloration

We have seen that the yellow colour of citrine comes from Fe^{3+}. The colour of amethyst arises from the natural (or artificial) irradiation of Fe-bearing quartz. Either divalent or trivalent Fe may be involved and, provided that growth occurs in certain directions rather than others (e.g. in the positive or negative rhombohedron) a successful purple coloration will be achieved. The mechanism is a colour centre.

Much amethyst on heating lightens in colour: if Fe^{3+} was present before irradiation, a yellow citrine colour will develop. If Fe^{2+} was present, a green colour develops ('prasiolite'). Heating to 350–400 °C may produce a bicolour amethyst-citrine ('ametrine') occasionally. Some amethyst when heated will give the prasiolite colour, perhaps via a colourless intermediate stage. The change to green occurs at 400–500 °C.

Effects of light

Amethyst shows distinct dichroism, the twin colours being bluish-violet and reddish-violet for the ordinary and extraordinary rays respectively. However, the brown heat-treated amethyst does not show dichroism, and thus treated stones may be detected from those of natural brown or yellow by their lack of dichroism. Under the Chelsea colour filter amethysts appear a reddish colour, the stronger the more pronounced the body colour of the stone. There is a wide absorption of varying intensity in the yellow-green region of the spectrum from about 520 to 550 nm, but the spectrum of amethyst cannot be called distinctive and is of little aid in identification. The amethyst is practically inert as regards any luminescence, but a blue glow has been seen with some amethyst when bathed in short-wave ultra-violet light.

Inclusions

The inclusions which may be seen in violet quartz are most commonly feathers made up of negative cavities. A quite common imperfection in amethyst is a mark like a thumb-print or tiger stripes (*Figure 10.8*) which is ascribed to rhombohedral twinning or to the partial healing of separations occurring along the planes of the major rhombohedral faces. Very few amethysts are free from parti-coloration with angular zones of colour, and even in the heat-treated brown stones this zonal colour marking is seen. Cacoxenite crystals are often seen in amethyst.

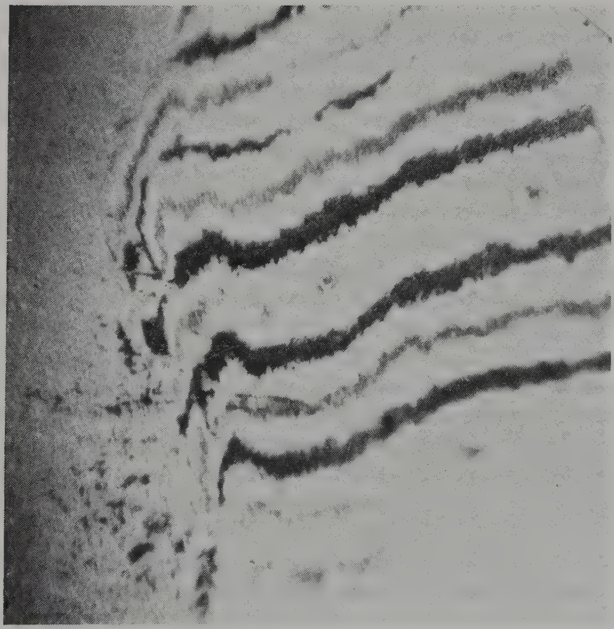


Figure 10.8 Tiger stripes inclusion in amethyst

Occurrences

The most important source of amethyst in earlier times was Russia, where crystals of a lovely rich colour were found in cavities just beneath the turf and in association with beryl and topaz. The location is Reshev and Alapayev in the neighbourhood of Sverdlovsk in the division of Perm along the western borders of the Ural mountains. Beautiful as it is, the Russian amethyst usually tends to take on a more crimson tint when viewed by tungsten light. Amethyst was also found in the neighbourhood of Idar-Oberstein on the Nahe in the German Rhineland. Amethyst is found in the Kaokoveldt 65 km inland from Cape Frio in Namibia, and in the Osborn district of Western Australia. Lusaka, Zambia, is another source.

Because of the discovery in the latter part of the nineteenth century of a vast amount of mauve quartz in Brazil and in neighbouring Uruguay, the value of amethyst fell greatly. The most important area for this South American amethyst is in the Serra do Mar which stretches from Rio Grande do Sul, the southernmost state of Brazil, into northern Uruguay around Rivera and Artigas. The crystals are here found in amygdaloidal cavities in a melaphyre. Other Brazilian localities are Campos dos Cristaes near Diamantina, Ribeirão da Paciencia at Itabarava near Ouro Preto, and at Bom Jesus dos Meiras in the state of Minas Gerais. Rolled pebbles which have weathered out from the geodes are found in the Minas Novas district, and another source is at Coimbra on the headwaters of the river Negro, a tributary of the river Parana in the state of Matto Grosso. At the time of writing three areas in Brazil are producing most of the amethyst: Maraba (the most prolific producer), Pau d'Arco (some of the finest material) and Rio Grande do Sul (which has the longest sustained production). Amethyst is also found in the state of Guanajuato in central Mexico and many fine amethysts are found in the Aztec graves.

In the United States of America amethyst has been found in a number of localities. On Rader Creek, east of Butte in Jefferson County, Montana, large groups and single crystals are found in a dyke, and a limited number of fine crystals have been found in North Carolina and in Oxford County, Maine. In the state of California there are a number of deposits in Amador, Mono, Lake and San Benito Counties. Amethyst is also found in Texas, Virginia and Pennsylvania, and in the Yellowstone National Park. The source in the Keweenaw Peninsula on the south shore of Lake Superior may be classed as a link with Canada, for across the lake on the north and Dominion side there is a fine deposit of good-quality violet quartz at Thunder Bay. Amethyst is found on the shores of Lake Nipigon and along the shores of the Bay of Fundy in Nova Scotia, and some amethyst is found in the trap-rock of Dubawnt lake in the North-West Territory.

In India geodes containing amethyst are worked from the deposits of the Deccan trap-rocks. Other Indian localities are the Sutlej valley in Bashahr and in the bed of the Narbada stream near Jubbulpore, but Indian sources are not important. Good-quality amethyst is found in the gem gravels of Sri Lanka, but little material is found in Myanmar. Excellent amethyst of a dark violet-red colour is found in the pegmatites at Ambatomainty, Ampangabe and Tongobory in Madagascar. A deposit of good amethyst has been reported from near Pretoria in South Africa and in Zimbabwe. Fine crystals of amethyst are obtained from an occurrence at Tsunagi, Echigo province and Fujiya in Hoki province, Japan. Unimportant are the deposits of amethyst which are found in Cornwall, England and in Cork and in Achill Island off County Mayo, Eire (Ireland). Amethyst was formerly obtained in the island of Sark in the Channel Islands and was sold as 'Sark stones'. The deposit is now exhausted and the 'Sark stones' sold to tourists are material from Brazil. Amethyst is also found in New South Wales, Australia, and has been reported from China.

Much massive quartz of an amethystine colour is used for carving. It is usually heavily flawed and very patchy in colour. The transparent crystals are usually cut in the mixed-cut style or for important stones the trap-cut style is used. Amethyst is often fashioned into beads.

Simulation

Amethyst is imitated in glass, and often in a glass which has a low refractive index containing pronounced swirl marks. Synthetic corundum is made in a colour to imitate amethyst, and a soudé-type composite stone is made which can be very deceptive, for the top, if not the base as well, is made of quartz and will thus give a refractometer reading for amethyst. Pale amethyst is often mounted in a closed setting with paint or foil below in order to enhance the colour.

Rose Quartz

Less common than the other varieties of crystal quartz is the pink-coloured rose quartz. It varies in colour from a strong rose-pink to a nearly white, and is nearly always cloudy with fissures and never entirely clean, although some material has been found which is sufficiently clear and transparent to cut into faceted stones. The material is mainly used, however, for the production of figurines, ashtrays and other small carved objects.

Rose quartz is found as cores in large pegmatite dykes as solid masses of rose-coloured rock made up of large crystal units which do not show good boundaries but with occasional contact faces between the individual crystals. In some localities, such as Governador Valadares in Brazil, well-formed crystals of rose quartz have been found; they have no gem significance but make attractive mineral specimens.

Current thinking ascribes the colour of rose quartz to a charge transfer between the Ti^{4+} state of titanium and the Fe^{2+} of iron. This is brought about by irradiation. Some rose quartz is known to fade, and it is thought possible that colour centres involving a phosphate impurity are responsible in this case.

Very fine near-transparent crystallised rose quartz is found in several places in Brazil. The host pegmatites often contain gem-quality tourmaline with some Na substitution bodies. These deposits are concentrated in the state of Minas Gerais, particularly in the Jequitinhonha valley near Aracuai and Itinga and the Rio Doce basin.

Much rose quartz contains microscopic needles of rutile oriented in definite crystal directions in the host crystal. These needles produce a star effect when the stone is looked through in the correct direction at a source of light. This effect is termed diasterism and differs from the epiasterism of the star sapphire in which the star is produced by reflection of light which is directed from above. Use is made of this diasterism of rose quartz in the production of an ingenious imitation star sapphire. Some asterism in rose quartz is produced by sillimanite needles. A description of these objects is given in Chapter 19. Star rose quartz is sometimes cut as round beads each of which reveals a star when seen in a bright light.

Despite the fact that much of the material may be marred by cracks the density of rose quartz does not vary very much from rock crystal. Rose quartz shows a fairly strong dichroism in the deeper hued material, but the effect falls off greatly the paler the material and in the very pale samples little or no dichroism can be observed. There is no distinctive absorption spectrum and rose quartz shows very little luminescence or none at all under ultra-violet light. A faint bluish glow is usually visible when the stone is irradiated with X-rays and an appreciable darkening of the colour of the stone may be observed at the irradiated spot.

The best rose quartz comes from the Alto Feio in the Rio Grande do Norte and other places in the valley of the Jequitinhonha of Brazil. Other localities are at Tsileo, Amparikaolo and south of Mania in Madagascar, and at Warangal, Hyderabad and Chhindwara of the Central Provinces of India. The material is also found at Goto in Iwaki province, Japan, in Namibia, in Bavaria in Germany, in the Ural mountains in Russia, and in Maine and South Dakota in the United States of America.

Quartz Cat's-Eyes and Crocidolite

Quartz cat's-eyes, which in the best specimens may closely resemble the chrysoberyl cat's-eyes, owe their chatoyancy to a multitude of slender crystals or channels oriented parallel to the principal axis of the host quartz. Such stones, which are cabochon-cut in order to show the cat's-eye streak of light, may be honey-yellow, brownish to grey-green in colour, and the sharpness of the ray varies considerably with different specimens. Quartz cat's-eyes are found in the Sri Lankan gem gravels and in India and the poorer greenish specimens come from the Fichtelgeberge in Bavaria; there is the possibility that similar material may be found in Australia.

When cut correctly the silicified asbestos called tiger's-eye or crocidolite shows a cat's-eye effect, but most of the material is cut into flat plates, beads and cabochons or carved as cameos. The surface of this subtranslucent to opaque yellow to golden-brown stone with a golden silky lustre shows a series of lustrous yellow bands alternating with brown banding which reverse in colours as the stone is turned.

The original mineral of the veins was a blue asbestiform variety of riebeckite, known as crocidolite, and this has altered by decomposition into silica. The mineral is therefore a quartz pseudomorph after crocidolite, changing its composition but not its form. The residual fibrous structure, now welded into a solid mass by silica, is usually stained by hydrous iron oxides (limonite) which give to the mineral its delightful golden-brown colour. If some of the original blue asbestos is present a variegated blue silicified crocidolite is produced giving a parti-coloured effect which is very pleasing. Such stones are sometimes known under the name zebra, and if the mineral has not changed at all the blue stone is then known as hawk's-eye. The tiger's-eye is cut from the lovely golden-brown stone produced by oxidation of the iron content of the original asbestos. This oxidation can take place either before or after silicification occurs.

Heating the golden-coloured crocidolite will turn the brown limonite into reddish hematite and produce a red stone. The material is sometimes dyed but such treated stones are readily distinguished by their unnatural colour. The major source is Griqualand West, South Africa.

Quartzites

When quartz has been formed from pre-existing rocks by the metamorphic process, as detailed in Chapter 1, the rock quartzite is produced, although some quartzites are formed by silica cementation of quartz grains (sand or sandstone). Quartzite, which is used for ornamental purposes, is a rock consisting of a granular interlocking mass of quartz crystals with irregular boundaries. Often the quartzite rock contains small crystals of mica or an iron mineral, and such a rock may exhibit a schiller and is then known as aventurine quartz. One variety of aventurine quartz has included platy crystals of the green chrome mica fuchsite, and this green aventurine quartz is often used for beads and other small articles of jewellery. The amount of green mica present in the quartzite can vary and one type is so impregnated with fuchsite mica that it is practically opaque and may be said to be a quartz schist. This type is often banded with lighter and darker green zones and may readily be mistaken for the green copper mineral called malachite.

The iron-coloured types of aventurine quartz vary from a creamy white to a reddish-brown in colour, and a grey quartzite with mica inclusions comes from Chile. A fine reddish-brown type is found at Cap de Gata near Almería on the south coast of Spain. Much of the white to brownish quartzite comes from Russia, particularly from the Korgon mountains in the Tomsk area. A close-grained quartzite of bluish-white colour with veins or splotches of brownish-red, and containing small cubic crystals of pyrites, is used for the carving of small ornaments, particularly at Idar in West Germany.

India supplies most of the green aventurine quartz. Some Indian localities are Belvadi in the Hassan district of Mysore and at nearby Sindagere, the first named place producing a rich bluish-green material and the other a banded type. Other sources in India include the Coimbatore and Nellore districts of Madras. A large-grained quartzite of delicate pale aquamarine-green colour banded with deep purple is found in Nellore district. Some green aventurine is found in Siberia and in Tanzania.

The refractive indices of quartzite correspond to those of crystal quartz, but owing to the confused mass of disoriented crystals with which the rock is composed, only a vague shadow edge at 1.55 will normally be seen on the refractometer. Again, owing to the inhomogeneity of the material and to the presence of impurities, the SG may be as low as 2.64 and as high as 2.69. Green aventurine quartz shows a red residual glow through the Chelsea colour filter, and thus may be distinguished from malachite which appears green. A chromium-type absorption spectrum is shown by green aventurine quartz, but the lines in the red are rather vague and the broad absorption in the yellow-green region is not pronounced. This type of aventurine quartz shows a greyish-green glow under ultra-violet light, whereas the other types of aventurine quartz are inert.

Chalcedony

Chemical and Physical Properties

Generally speaking the name chalcedony is applied to any fine-grained quartz with a fibrous microstructure. It almost always displays a more or less distinct banding, though a microscope may be needed to detect some examples (*Figure 10.9*). The name agate is used for the important subvariety of chalcedony which displays a distinct banding with successive layers differing in colour and degree of translucency. All gradations exist between agate and ordinary chalcedony.

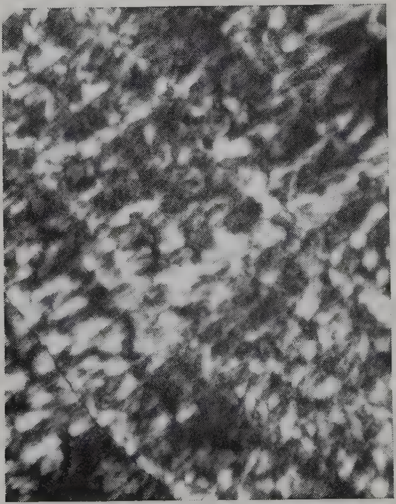


Figure 10.9 A thin section of striped agate seen under a microscope in polarised light

The individual fibres of chalcedony and its subvarieties are not physically separable; they occur as parallel or subparallel aggregates, as laths or as spherules. The fibre direction is perpendicular to the layering and to the free surface while the banding is parallel to the free surface or parallel to the walls of the cavity in which the chalcedony occurs.

The hardness of chalcedony is somewhat variable and lower than that of coarsely crystallised quartz, at 6.5. The specific gravity, which also varies owing to porosity and water content as well as to the presence of other substances, is usually 2.57–2.64.

Chalcedony is about 90–99 per cent SiO_2 with the higher content in the lighter coloured material. Brown and reddish subvarieties are relatively high in

Fe_2O_3. Water in chalcedony is not essential but is held by capillary forces; (OH) is also present and may be held as a substitution for O in (SiO_4) tetrahedra in a strained region between adjacent interlocking fibres. The hypothesis that opal is contained in chalcedony as an interstitial material between the fibres of quartz is not borne out by investigation.

The refractive index of chalcedony lies in the range 1.530–1.539, most commonly near 1.534, for the ordinary ray. It is hard to state a precise value for the extraordinary ray but values range upward from about 1.538. In practice a small birefringence can sometimes be seen but this amounts only to 0.004 at the highest. This and other anomalous optical properties arise from the disoriented aggregates of fibres.

Chalcedony fractures readily across the banding to give a splintery surface with a waxy lustre. Most chalcedony shows pale colours, often with a greyish tinge. Tyndall scattering is responsible for a bluish colour seen in some specimens by reflected light. As banding becomes more distinct the boundary between chalcedony and the agate subvariety is crossed.

When chalcedony or agate display spectral colours (iris effect) the structures contain elements giving a periodic effect and acting as a diffraction grating. Twisting of the fibres is known to occur and if adjacent fibres are in twist phase a periodic planar variation in refractive index is produced perpendicular to the fibre elongation direction; this may produce the diffraction effects. The name iris agate has been used for specimens with this property.

The fibrous nature of chalcedony enables it to take up dyes and such material, often with brighter colours than untreated chalcedony, is widely available commercially.

The luminescent response of chalcedony to ultra-violet light varies considerably. Mostly the glow seen is bluish-white, but in some varieties, particularly those from Wyoming in North America which contain traces of a uranium mineral, the glow is bright yellowish-green. The short-wave lamp is usually best for exciting fluorescence in chalcedony, for many agates do not glow at all under the long-wave lamp. The banded agates will often show the fluorescent light in bands or in patches.

Chalcedony is deposited in a variety of environments and deposition is commonly at low temperatures. Light-coloured material with no marked banding is often found as a late hydrothermal deposit or an alteration product in acidic to basic igneous rocks, tuffs and breccias. It is very common as crusts, as vein and cavity fillings.

Chrysoprase

The most prized of the chalcedonies is the green material chrysoprase. It varies in colour from a lovely apple-green to a dingy greenish-yellow and owes its colour to the presence of disseminated particles of a hydrated nickel silicate. Chrysoprase is usually cut into cabochons, or as beads, and for intaglios and cameos. The material was popular in the Victorian era and the stones were often cut as low cabochons with a narrow rim of facets around the edge.

Although intaglios and cameos in chrysoprase are said to date from Greek and Roman times, where the material used came from does not seem to be known, or even if the material was truly chrysoprase. In 1740 chrysoprase was found in several places in the vicinity of Zabkowice in Silesia and this locality supplied the bulk of the mineral. A small quantity of chrysoprase is obtained from the Ural mountains. In 1878, and in later years, four occurrences of good-quality chrysoprase were discovered near Visalia in Tulare County, California. The material was found in narrow veins irregularly distributed in serpentine and varied from an opaque green material to that of a beautiful translucent emerald green. There was active mining for this chrysoprase at Visalia until about 1911, after which the mines closed down as the gem had waned in popularity and the demand was insufficient to warrant mining, especially as the more easily recovered material had been mined. Water-worn pebbles of good colour have been found near Nickel mountain in western Oregon.

Chrysoprase is found associated with nickel ores in several of the Brazilian states, including Minas Gerais and Goiás. An important Australian source was discovered in Marlborough Creek some 145 km from Rockhampton in Queensland in 1965. The mineral was found in veins 50–200 mm thick, and the nickel content was found to be unusually high (up to 2.35 per cent) and in consequence the colour is deeper than for most samples from other localities. The product has proved popular and in plentiful supply.

Although it cannot be strictly called chrysoprase, which is coloured by nickel, a chromium-green chalcedony very much like chrysoprase was found in 1955, but only in recent years has it been marketed. This material, which shows red under the colour filter, is found in the Great Dyke of Zimbabwe just north of Mtoroshanga. It has a sharp one-band spectrum in the red. The material has been called mtorolite.

Simulation

The dearth of the material led to the imitation of chrysoprase by staining agate green, either by the precipitation of nickel salts or by using chromium salts. The latter is more common, and such stained chalcedony may be detected readily by the brownish-red residual colour shown when the stone is viewed through the Chelsea colour filter (chrysoprase shows green) and by three vague lines in the red part of the spectrum due to chromium which are seen when the absorption spectrum of the stone is examined. Nickel staining is more difficult to determine, but whatever type of staining is used, it is sometimes possible to see a mosaic-like veining which has been brought up by the staining. This effect is due to the sheaf-like nature of the crystal fibres which lie at right angles to the layers of the chalcedony. In order to get the best penetration of the dye solutions in staining agate, it is necessary to slab the mineral parallel to the layers and then the outlines of these aggregates of crystals tend to show up. This is illustrated in *Figure 10.10*. Chrysoprase is imitated by a suitably coloured glass which, however, usually shows profuse bubbles.

Other Chalcedonies

Plasma is microgranular or microfibrous chalcedony coloured various shades of green, including apple-green and leek-green. Particles of various silicate

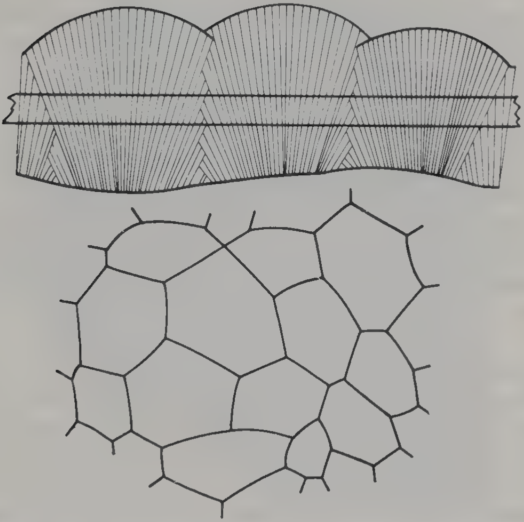


Figure 10.10 The upper part of the illustration depicts the sheaf-like microcrystals in chalcedony showing how the material is 'slabbed' for staining. In the lower portion are shown the mosaic-like markings which are seen by transmitted light after staining

minerals (chiefly of the chlorite group) disseminated through the material are responsible for the colour, which may be varied by the presence of white or yellowish patches. India, Madagascar, Egypt and the north-western states of the USA have commercial deposits of plasma.

More translucent than plasma, and coloured leek-green, is prase, the colour coming from fibrous hornblende aggregates or from disseminated chlorite. Vermont and Pennsylvania have deposits of prase, and the material is found world-wide. The name buddstone has been given to a green chlorite-rich chalcedony with white veining, found in southern Africa.

The names heliotrope, now obsolescent, and bloodstone, still in common use, are used for a type of chalcedony or plasma with spots of iron oxide or red jasper resembling blood spots against a dark green background. Good-quality material comes from the Deccan trap-rocks, India and from Brazil and many other countries.

Uniformly coloured light brown to dark brown translucent chalcedony is known as sard. It may have reddish or orange tints. Good-quality material is blood-red in transmitted light and blackish-red in reflected light. Uniformly coloured red to reddish-brown or flesh-coloured chalcedony is known as cornelian or carnelian; the boundary between sard and cornelian is a matter of individual judgement. The colour of cornelian is caused by colloidally dispersed hematite. India has produced most of the finest sard and cornelian since the fourth century BC but there are many other sources world-wide. Much commercial material comes from various deposits in Brazil and Uruguay. Some beaches on the east coast of England produce cornelian. Other reddish chalcedonies may have been coloured by heating since if they contain disseminated iron compounds the heating will oxidise them.

Amethystine chalcedony is reported from à single locality in central Arizona. It is marketed as 'damsonite'.

The red mineral cinnabar is an occasional inclusion in chalcedony. Such a material can be a translucent white chalcedony with streaks and clouds of bright red or pink cinnabar, or it can be so impregnated with the mercury mineral as to be completely red. This variety of chalcedony is known as myrickite. Blue and green chrysocolla is another mineral which impregnates chalcedony to give a stone of intense sky-blue colour which is called chrysocolla quartz. Most of these colourful impregnated chalcedonies come from the United States of America.

Some translucent chalcedony when cut in the cabochon form has a schiller which resembles to some extent the true moonstone. A translucent chalcedony of lovely blue colour is found about 130 km north-east of Okahandja in Namibia, and an attractive blue and white banded chalcedony also comes from Namibia. This is sometimes called 'lace agate'. A blue chalcedony has also been found in Cornwall, England. Chalcedonic pebbles abound along the Vaal and Orange rivers in South Africa.

The so-called 'fire agate' is a botryoidal growth consisting of platy crystals of an iron mineral over layers of chalcedony. With careful polishing away of the uninteresting brown outside layers, the rainbow colours of the iridescent layers appear. This material has been set in jewellery.

Agate

Agate is a subvariety of chalcedony in which successive layers in the banding are different in colour and translucency (*Figures 10.11, 10.12*). It occurs filling cavities, and individual bands are concentric to the external surface of the mass or nodule. Layers show sharp angles on occasion, echoing the plan of a fort, and the name fortification agate may be used; landscape agate, ruin agate and star agate are also familiar names.

Sizes of agate vary a good deal and may reach hundreds of kilograms. Colours are generally pale though varied; natural colours are green, yellow, red, reddish-brown, white and bluish-white, among others. Heating may change brown colours to red, and oil immersion may heighten translucency.

Some types of agate have their own names. Onyx is used for agate with milky-white or white bands alternating with bands of black or dark brown; white with brown bands may also be called sardonyx. Cameos are made from onyx with the figure carved in white in relief against the black background. The name jasp-agate refers to the alternation of translucent chalcedony with opaque red jasper layers.

Much agate is dyed to give strong and commercially acceptable colours. The material is sawn and shaped before dyeing. Immersion in a hot sugar solution followed by immersion in concentrated sulphuric acid and heating gives black; a blue colour, once called Swiss lapis, is produced by immersion in potassium ferrocyanide and subsequent warming in a solution of ferrous sulphate to give a

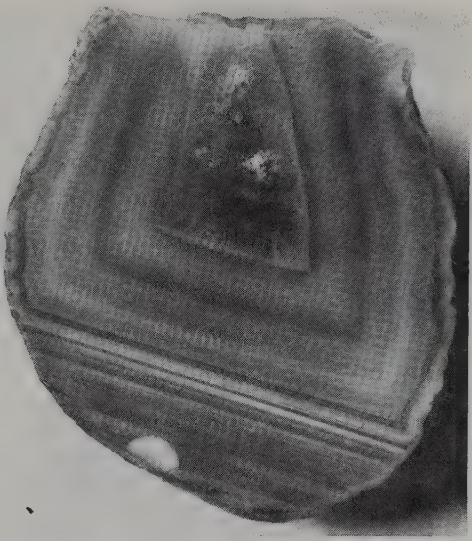


Figure 10.11 Section of an agate nodule showing the centre filled with crystalline quartz, from Montrose, Scotland

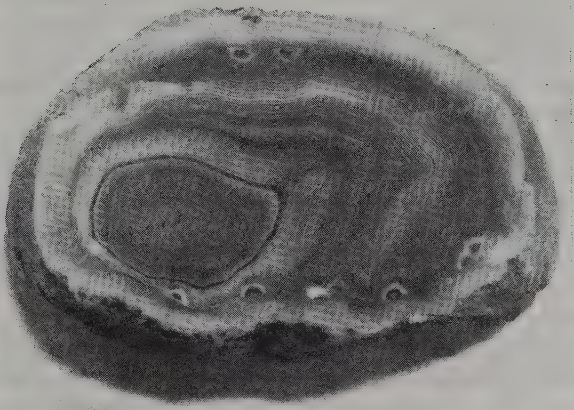


Figure 10.12 An agate showing the banding

precipitate of Berlin blue. Chromium alum or potassium dichromate may be used to give green or bluish-green, and nickel compounds give a brighter, apple green. Impregnation with iron compounds and heating may give reddish-brown and red colours. Yellow to greenish-yellow is obtained by heating dry agate that has been treated with concentrated hydrochloric acid.

Although it seems hardly possible to imagine, a pagoda-like shape may be obtained from some Myanmar agate when the piece is slit across the whitish bands. The name pagoda stone has been used for these attractive curiosities.

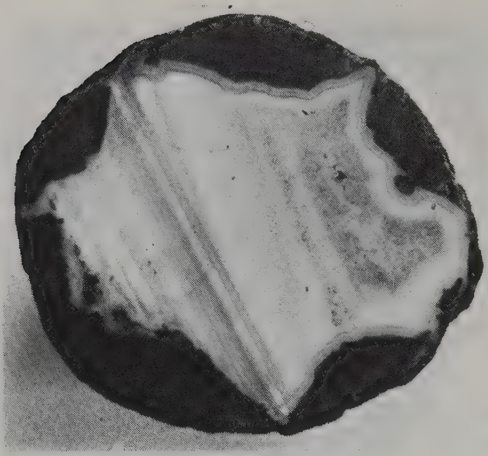


Figure 10.13 *A section through a 'thunder egg'*

Agate geodes are found in basic lavas and other igneous flow rocks and have probably been formed by silica deposition in cavities created by gases. The smaller cavities are near-spherical; larger ones, known as amygdules, are elongated and flattened. Characteristic chalcedony nodules, locally known as thunder eggs (*Figure 10.13*), are recovered from rhyolitic lavas and tuffs in the north-west of the United States. Some show a central five-pointed star or a cavity in the middle. Agate banding involves a rhythmic deposition of silica on cavity walls according to one of several theories. Alternatively a silica gel process is possible. Here a cavity may contain liquid colloidal silica with metallic salts; percolating acid water may later enter the cavity and alter the colloidal solution to a gel. Diffusion within the gel leads to the formation of Liesegang bands giving bands of colour. This process can be repeated experimentally.

Occurrences

Agate nodules are of world-wide occurrence. Agate was collected in the desert regions around Jebel Abu Diyeiba in Egypt over 3000 years ago. From ancient times India has supplied agate, and the material was also found along the Achates river in Sicily, a river now known as the Drillo. The name agate was derived from the earlier name for this river. The agate cutting industry of Idar-Oberstein in the valley of the Nahe in the German Rhineland was said to have commenced in the fifteenth century, and the agate used was obtained from the hills around the twin towns. The Brazilian and Uruguayan deposits of the Rio Grande do Sul are the most important source of agates. Much colourful agate is found in the United States of America, particularly in the western states of the country, and the 'Scotch pebbles' from Montrose, the Ochil mountains and elsewhere in Scotland are well known.

In recent years a remarkable supply of geodes has been recovered from marly clays overlying the carboniferous limestone near Dulcote in the Mendip Hills, England. These have attractive fillings of red agate, quartz, calcite, and other minerals, and 33 per cent of the nodules consist of agate of cutting quality.

Figure 10.14 Dendrite

Thin-walled chalcedony geodes containing a large air space may also contain water whose movement can be heard or seen if the shell is thin enough. Evaporation of the liquid is responsible for the air space. The best examples are from the agatised areas of Brazil and Uruguay; they occur also at Monte Tondo, Vicenza, Italy and elsewhere. The name enhydros is used.

Moss agate is a pale bluish, grey or yellow translucent to subtransparent chalcedony containing dendritic inclusions of various oxides (*Figure 10.14*). Their colour varies; most are black but red and green dendrites are also seen. The name Mocha stone is used synonymously with moss agate and comes from Mocha in the Yemen.

The best-known locality for green moss agate is the Deccan trap of India. Dendritic agates are found in a number of localities in North America, particularly in Montana, Oregon, Idaho and in the Sweetwater agate beds near Granite mountain in Wyoming where the local agate contains traces of a uranium mineral and in consequence fluoresces a strong green colour under ultra-violet light. Moss agate is found in many places and some of the 'Scotch pebbles' from the Ochil mountains of Scotland show red and green moss. Moss agate is imitated by placing some chemical, like manganese dioxide, with a thin gelatine on one surface of a glass plate. When a chemical 'tree' has grown on the gel the excess water is driven off by gentle heat and a second plate of glass to act as a cover is cemented on. The whole may then be ground and polished in cabochon form. The readily seen join between the two pieces of glass exposes the fake.

Chalcedony as a Fossilising Agent

Chalcedony often replaces other materials and thus acts as a fossilising agent. Agatised wood is a chalcedony pseudomorph after wood and this fossil wood is cut and polished for ornamental purposes. Bone has also been fossilised with agate, and at Tampa Bay, Florida, there is much chalcedony pseudomorphous after coral, and attractive cabochons are cut from this agatised coral, which is often artificially dyed blue and pink. Algae (seaweed) and small mollusc shells may be fossilised by silica, and like the fossil marbles, such material is cut and polished for ornamentation. The process of replacement by silica, as in the case of the petrified wood, is that the original substance is replaced particle by particle with silica so slowly that the original form remains. In the case of fossil wood this is done so that even the tree rings are still visible.

Jasper

Jasper, which is the archetypal collectable beach pebble, consists of massive, fine-grained quartz, fairly dense, containing significant amounts of other materials, particularly iron oxides. Most commonly, jasper is a dark brownish-red, but it may be yellow or black. Variegated types are found. Banding is often present, the bands being planar rather than concentric as in agate. Finely divided hematite is responsible for the red colour and goethite for the brown and yellow colours. The presence of clay may give white, yellowish or greyish material with a porcellaneous appearance.

When the agent causing colour is present only in small quantities, jasper grades into a translucent fine-grained material for which the names chert, hornstone and novaculite have been used. This material may range from near-colourless through yellow to reddish or brown.

Jasper, unlike agate and chalcedonies, occurs as extensive beds of sedimentary or metamorphic origin. Jasper grades into or is combined with other types of quartz which may traverse it or be combined with it as a breccia. Jaspilite is a metamorphic rock containing alternating layers of jasper with black or reddish hematite. Jasponyx is thin-banded jasper with alternating dark or light bands; the names band jasper or ribbon jasper are also used. Lydian stone or touchstone (basanite), a black fine-grained jasper, is used for testing the streak of gold alloys.

Jasper occurs as a cavity filling or as nodules or veins in iron ores. It occurs in altered igneous rocks and in detrital deposits. Large bedded deposits provide a good deal of ornamental jasper. It may occur in variegated red to brown colours as a petrifying agent of wood; orbicular varieties (*Figure 10.15*) and jaspers displaying spherules of different colours are used as ornaments.

Chemical and Physical Properties

Owing to the impurities present, the SG of the jaspers varies somewhat widely and any value between 2.58 and 2.91 may be found. Most of the jaspers have an SG which is just below that of crystallised quartz (2.65) but a few specimens have shown SGs which are higher. Specimens of the red and green ribbon jasper from Russia were found to have an SG between 2.7 and 2.8, and a piece of heavily pigmented brown material from Siberia gave the high value of just over

Figure 10.15 An orbicular jasper

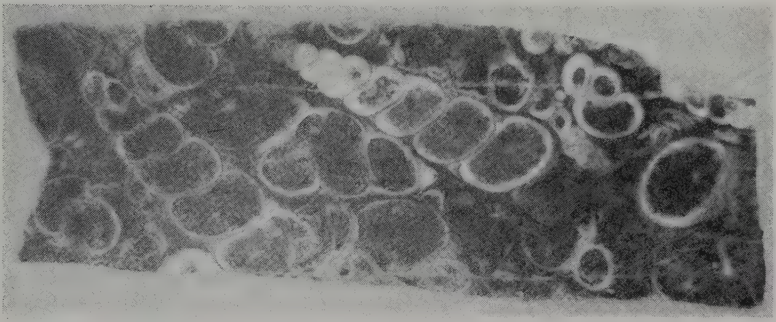


Figure 10.16 Turritella agate

2.9. The hardness of jasper is very little below that of quartz, and as a rule the material is tough although it may break easily along veins or laminations. The refractive index is approximately 1.54 and the material shows no characteristic absorption spectrum or typical luminescence.

Petrified dinosaur bone from Colorado, Utah and Wyoming in the United States of America is used for ornamental purposes. Fossil 'dinny bone' is used in West Germany for such carvings as small tortoises where the markings of the fossil bone give some realism to the carving. Turritella agate (*Figure 10.16*), often used for ornamental purposes, consists of shells of the turritella which have been agatised. The so-called 'picture jasper' found at Biggs Junction in Oregon is probably a jasperised rhyolite, and when suitably cut shows 'scenic' designs in light and dark-brown colours, and sometimes with black 'trees' formed by dendritic inclusions. A similar material is found in the Namib desert.

Occurrences

Jasper is of world-wide occurrence. Ribbon jasper is said to occur at Okhotsk in eastern Siberia and other varieties are found in the vicinity of Troitsk and Verkhne Uralsk in the southern Urals. India and Venezuela supply a red jasper but the most varied types of this impure quartz are found in the United States of America. Of the many American localities mention may be made of the Morgan

Hill district of Santa Clara County, California, where orbicular jasper is found in quantity; other jaspers are also found in California. Arizona, Idaho, Nevada, Oregon and Washington produce much jasper, and jasp-agate is found in the gravels of the Pecos river in Texas. The most famous locality for jasperised wood is the Arizona petrified forest.

11

Opal

The most highly prized of the silica gemstones is the opal, but not all opal exhibits the beautiful play of colour seen in the specimens mounted in jewellery. Without these colour nuances opal is quite a common mineral and, except in certain cases, has no value in ornamentation. Four types of opal are highly prized and met with in jewellery. They are the white opal which has a light or white body colour with a fine play of colour; black opal which has a black or dark blue, green or grey body colour with vivid flashes of colour springing from the dark stone; fire opal which is transparent to translucent with an orange-red to red body colour which may or may not show a play of colour; and lastly, there is the water opal which shows brilliant flashes of colour in a clear colourless (water-white) stone. Other types of opal are occasionally encountered in ornamental pieces and these relatively unimportant types will be mentioned in appropriate places.

Opal has met with many vicissitudes during its long history. From Roman times until the early seventeenth century it was held in high esteem, but during the eighteenth and nineteenth centuries it fell into disfavour in the belief that the stone was a bearer of ill-fortune, a belief which was probably based on a Teutonic superstition. Others say that this disfavour came from the influence of Sir Walter Scott's novel *Anne of Geierstein* in which opal played such a malignant part. It seems more probable, however, that Scott conceived the idea of an opal of evil influence from an already existing belief.

Chemical and Physical Properties

Opal, unlike the silica minerals discussed in Chapter 10, is not crystalline. It is formed of minute spherical particles constituting a gel which has the formula $SiO_2.nH_2O$, that is silica with chemically combined water which may vary from 1 to 21 per cent, but is about 6–10 per cent in precious opal. Opal is found filling nodules, as veins or seams in rock, as botryoidal masses in cavities or as stalagmitic forms. The hardness of the gemmy varieties varies from 5.5 to 6.5 on Mohs's scale and the fractured surface may be conchoidal or irregular.

Effects of Light

Opal has a single index of refraction which varies from 1.44 to 1.46, and the SG varies from 1.98 to 2.20; the black and white opals have a value near 2.10 and the fire opals are slightly lower at 2.00. It can show no dichroism, and the absorption spectrum has little value. In the case of fire opal the absorption spectrum is just a colour filter cutting off all the colours except the red and orange. Under both long- and short-wave ultra-violet light opals showing a play of colour exhibit a luminescent response which may vary from white, to bluish, brownish or greenish with often a persistent green phosphorescence. The black opals are, however, generally inert, and the fire opals usually show a greenish-brown response. Much common opal shows a green fluorescence, and often phosphorescence, which is due to the inclusion of some secondary uranium mineral. Such uraniferous opal is common in the United States of America. The green opal from Silesia, which is coloured by nickel, is inert.

What causes the vivid coloured flashes which spring out from a piece of coloured opal? When opal is looked through at a source of light no play of colour is seen, the stone appearing a uniform colour which is generally creamy white or dingy yellow, and it is only when the light falls on the stone that the beautiful colours are seen.

About 1964 experiments carried out by German and Australian scientists using electron microscopy showed that the fine structure of opal consists of a regular stacking of uniform spheres of amorphous silica with regularly arranged 'voids' between. The arrangement of these spheres and voids forms a three-dimensional cubic lattice producing a three-dimensional diffraction grating. Under such conditions, Bragg diffraction of light occurs causing pure spectrum colours to appear at different angles. The size of the spheres decides the longest wavelength of light which can be diffracted (*Figure 11.1*); thus regular sheets of small spheres may only diffract blue light and not green, yellow, orange or red. Larger spheres may diffract green, blue and violet light, while still larger spheres may give red light and all the other colours of shorter wavelength. In all cases the size of the spheres in gem opal is suitable to diffract light through 180°. Opals are best viewed on a black background which absorbs any light transmitted through the stone, which otherwise may be reflected or scattered back, diluting the coloured flashes. Thus the effectiveness of black-based opal doublets and black dyed opal is explained.

The play of colour of opal is a diffraction effect, and the term opalescence so often applied to the colours seen in opal is incorrect. Opalescence is correctly applied to the milky effect seen in common opal, some moonstone and in the so-called opal glass. It is due to the scattering of light from small particles in the stone.

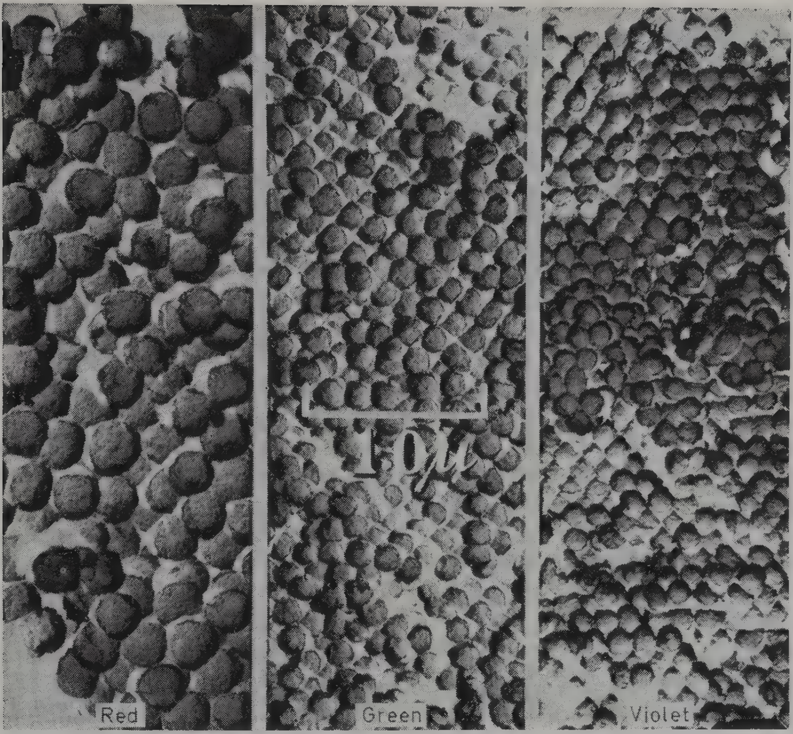


Figure 11.1 *Electron micrographs of precious opal illustrating the maximum colours produced by spheres of different sizes*

Varieties of Opal

Several of the common opals, mainly those with pronounced colour, have been cut as gems. Apart from the fire opal already mentioned there is a green opal, not unlike chrysoprase in appearance, which owes its colour to nickel. An attractive cherry-red opal, a rose opal and much yellow opal is found and occasionally cut. Opal is a common petrifying agent and much opal is pseudomorphous after wood. An opalised wood, yellow in colour with black markings, is found at Washoe County, Nevada, and attractive cabochons have been cut from it. This material is noted for its green fluorescence under ultra-violet light, a fluorescence activated by the presence in the opal of traces of a uranium mineral. The most interesting pseudomorphs in opal are the opalised freshwater and marine shells, belemnites and bones from prehistoric animals which are found in Australia. Opal is often found as pseudomorphs after gypsum, glauberite, calcite and other minerals. Opalised crystal aggregates of such minerals, particularly glauberite, are known as 'pineapple opal' and form attractive mineral specimens.

Hyalite is a colourless transparent variety of opal that closely resembles melted glass; it is sometimes called Müller's glass. When this type of material shows a play of colour it is then the prized water opal. Common opal is translucent to opaque and of various hues. When milk-white, yellowish or greenish it is called milk opal. Hydrophane is a curious type of light-coloured but opaque opal that becomes transparent and exhibits play of colour when soaked in water. Cacholong is an opal with either a porcelain-like or a mother-of-pearl-like lustre which is so porous that it will adhere to the tongue. Menilite is an opaque greyish to brownish concretionary type, and tabasheer is an opal-like silica found within the joints of bamboo. Jasper opal is red, reddish-brown or yellow-brown and closely resembles ordinary jasper. A violet-coloured opal is found in Mexico, and a blue-green chrysocolla opal is known and may come from Taiwan.

Backgrounds for Opals

Thin seams of opal in dark- or light-coloured sandstone are often cut so that the top of the stone is brilliant precious opal on the sandstone which forms a strong backing for the opal. Likewise, a thin piece of good opal on potch may be cut so that the potch acts as a backing. Such opals might well be mistaken for opal doublets but careful examination of the edge of the stone by a lens will show the slight irregularity of the matrix and opal and the absence of a distinctive join as seen in opal doublets. Such stones are rightly termed true opal. Opal when in small areas in the other rock may be cut complete with the matrix and such stones are known as opal matrix. Sometimes opal forms in ironstone and the opal matrix cut from this shows patches of coloured opal in a chocolate-brown matrix, and a similarly appearing type of opal occurs where the ironstone and opal have impregnated roots of the gidgee tree (an acacia). The stones cut from this material are called gidgee opals. Such iron-impregnated stones have a higher density than true opal and may range in SG from 2.65 to 3.00.

In order to make use of thin films of opal, which often show a fine play of colour, they are made into the so-called doublets by backing them with pieces of potch, black onyx or a black glass called 'opalite', which is obtained from Belgium. The cement used to join the pieces has a high melting point so that it will not be affected by such heat as boiling water. An ingenious triplet is made where an ordinary opal doublet is completed with a coverglass of rock crystal which fits over the top of the opal. Water opals always show their play of colour better when they are on a dark background, so it is common to mount such opals in a closed setting with a piece of black, or preferably purple, silk below. An imitation opal made of small fragments of real opal set in a black resin has been encountered.

Occurrences

Czechoslovakia

There is little doubt that the opal known in Roman times came from the mines near Czerwenitza in Czechoslovakia (formerly in Hungary). These mines lie some 10 km north of Prešov, a town some 30 km north of the important centre of Košice in the eastern part of Slovakia. The mines are in the Libánka and

Simonka mountains, and at the foot of the latter is the small settlement of Dubnik (Opalbanya) which may be said to be the opal centre. There is a further mine lying to the east of Košice at Nagy-Mihály.

The Hungarian opal (for the opal from Czechoslovakia is still better known under the old name) is found in nests in a greyish-brown andesitic lava. The mining in this area is known with certainty to have been carried on since the fourteenth century and in former times was worked by open cuttings. Today, however, a network of levels has been tunnelled into the mountains. The Czechoslovakian stones have a milk-white background upon which small points of red, blue and green form a mosaic of changing hues, the so-called harlequin opal. The stones from this locality supplied the world before the discovery of the Australian opal fields.

The mining in the then Hungarian opal deposits was, until 1788, carried on successfully by the peasants of Czerwenitza, but in that year the Hungarian government claimed a monopoly of the mines and instituted underground working. The government endeavour was unsuccessful and was soon abandoned and for several decades the mines were unworked. They were then farmed out to individuals and successfully operated until the rich Australian fields were discovered.

Mexico

Opal, especially the fire opal, was probably known to the Aztecs. The Mexican occurrences are in the states of Queretaro, Hidalgo, Guerrero, Michoacan, Jalisco, Chihuahua and San Luis Potosi, the mineral being found in cavities of volcanic lavas rich in silica (*Figure 11.2*). The yellow and hyacinth-red fire opal is found in a trachytic porphyry at Zimapan in the state of Hidalgo, and hyalite (with probably water opal) comes from San Luis Potosi. The mines of Queretaro, which were first discovered in 1835 and have been systematically worked since 1870, are the most important. The centre of the opal trade and for the cutting of opal is the town of Queretaro; the lapidaries there use home constructed apparatus and turn out quite good specimens of polished opal. Opals of many different types are found in Mexico but, except for the fire opal, the stones do not have the quality of the opals from Australia. A cherry-red opal with no play of colour and a yellow-coloured opal are found in Mexico and sometimes cut. In North America, what is termed in England 'fire opal' is often called 'cherry opal'. Fire opals from Queretaro are believed to have formed at about 160 °C from hydrous silica gels contained in fluids with small variable amounts of NaCl and CO_2. These results have been obtained from a study of the fluid inclusions. Queretaro opal has been found to contain inclusions of hornblende, limonite pseudomorphs after hornblende, goethite, hematite, fluorite, quartz, cristobalite, kaolinite and pyrite.

Honduras

The opal was found in Honduras prior to 1843, the year in which the deposits of Gracias a Dios were first described. It is considered highly probable that the pre-Colombian Quiche procured the opals used in the jewellery from the sources in Honduras. The mines are near the town of Gracias in the western part

Figure 11.2 An opal mine in Mexico

of Honduras and the opal is found in veins and bands in a dark reddish-coloured trachyte. Another source is near the town of Erandique some 40 km south of Gracias. The opal from Honduras is unimportant commercially. Some opal is found in Guatemala and Brazil (see p. 252).

Australia

The credit for the first, but unrecorded, discovery of opal in the Australian continent is generally considered to belong to Mingaye, a German geologist, who in 1849 found opal near Angaston in South Australia. It was in 1872, however, that the first recorded discovery of opal was made in Australia. This was the boulder opal, thin veins of opal ramifying through hard jaspideous brown-coloured greasy boulders, and was found at Listowel Downs in central Queensland; in 1878 a company was floated to market this opal. The boulders occur at various depths and are very hard and difficult to break, but the thin veins of opal are usually brilliant. The material is principally used for cameo carving.

Two subvarieties of the boulder opal are the sandstone boulder and the yowah nut. The first of these consists of concretions made up of shells of coarse sandstone and hard siliceous clay with layers of opal between them or filling the centre. The yowah nuts – which are found not far from Yowah Homestead, hence the name – are small boulders about the size of a walnut and are found in a unique formation consisting of a regular band containing the nuts packed in like a conglomerate. The opal, like the larger boulder opal, is found either as a central kernel or as thin veils surrounding an ironstone centre or traversing the nut, but never reaching to the outer edge.

Opal may be found in a free sandstone in the form of veins or pipes varying in thickness up to 25 mm or more. This type is known as sandstone opal and seems to have been first found in Queensland in 1889. In the same year four prospectors, travelling in the semi-desert country 1100 km inland from Sydney, wounded a kangaroo and while following the tracks of the wounded animal came across loose opal on the ground. This find was the beginning of the famous White Cliffs opal field in Yungnulgra country about 100 km north-west from the town of Wilcannia and some 200 km from Broken Hill in New South Wales. Although Wilkinson in 1877 reported a find of opal in a soft vesicular basalt on Rocky Bridge Creek, a tributary of the Abercrombie river, the White Cliffs find was the first important opal discovery in New South Wales. The 'float' opal (loose opal on the surface) first encountered at White Cliffs indicated the presence of opal *in situ*. Examination revealed that a fine-grained siliceous sandstone occurring at depths of 8–13 m, called the 'bandstone', was a marker horizon for opal. Above and below this bandstone, which generally contains no opal, are fine-grained clayey sandstones and in the underlying bed opal is most abundantly found. The colourful precious opal is found in irregular patches in the thin veins of potch – the miners' term for opal which may be colourful but does not show the play of colour, or as they say is 'not alive' – which fills the joints and bedding planes of the sandstone. This opal is called seam opal. It is in the opal from this district that the fossil molluscs, crinoids, belemnites and the bones of ancient vertebrate animals are found completely petrified with opal.

Originally known as Wallangulla, Lightning Ridge, just beyond the town of Walgett in north-east New South Wales and about 65 km south of the Queensland border, is the famed locality for the black opal first found here in 1903. The rock formation is here similar to that of White Cliffs, except that there are four levels of bandstone, beneath each of which there is the white opal-rich clayey sandstone which the miners call the 'opal dirt'. The opal itself is usually found at Lightning Ridge in the form of isolated nodules to which the miners have given the name 'nobbies'. These nobbies may be opal replacement after sponges or corals.

Other opal fields in Queensland, situated mostly in desert country and suffering from lack of water supply, are the Hayricks opal mine which lies north-north-west of Quilpie, some 1000 km from Brisbane, and isolated occurrences throughout the desert area of south-central Queensland. The Hayricks opal mine, so called because it is situated amidst a striking group of sandstone mesas, supplies opal which is found in cracks in ironstone boulders, and is won by driving tunnels into the hillside. In New South Wales, apart from White Cliffs, and Lightning Ridge which are the only two important localities in the state, mention must be made of the find at Tintenbar 8 km north of Ballina. Opal was found here during 1901 but was not considered as a commercial possibility until 1919. The opal occurs in cavities in a decomposed basalt or is weathered out from the cavities and lies loose in the soil. The Tintenbar opal has a transparent matrix upon which the play of colours flash out, but the stones have a marked tendency to craze and for that reason the mine soon ceased operation. Other New South Wales sources are at Purnanga and Grawin, which must be considered as extensions of the White Cliffs and Lightning Ridge deposits respectively, and at Tooraweanah, Warrumbungle mountains where opal is found filling vesicles in a trachyte. Milparinka and Brindingabba near Hungerford on the Queensland border are other locations.

Seam opal, similar to that found at White Cliffs, was discovered during 1915 at Coober Pedy (Stuarts Range) in the Stuarts Range mountains of South Australia. Coober Pedy is an aboriginal name meaning 'a man in a hole' which is literally true, for all the miners' homes are underground excavations in the hillside. The precious white opal is associated with gypsum in the sandstone. Coober Pedy opal has a slight tendency to crack if it is brought up into the hot atmosphere from depths greater than 25 m, for in summer the temperature gets up to as high as 55 °C.

In 1930 opal was found at Andamooka (an aborigine word meaning 'no name') which lies some 600 km from Adelaide and 430 km south-east of Coober Pedy. This field, which covers only a small area, is comparatively easily worked, for the opal lies close to the surface of the band which is itself not far from the surface. Andamooka has become quite famous, not only for the type of black opal which is mined there, but for the lovely 'Andamooka opal', which when found in 1949 weighed, before cutting, no less than 190 g and which was eventually cut into a cabochon 70 mm long and weighing 203 carats. This lovely opal was set into a necklet which was presented to Her Majesty Queen Elizabeth II. In 1945 a new opal locality at Amberooka 485 km north of Coober Pedy was discovered, where opal very different in appearance to most other Australian opal was reported found. This opal is semi-transparent with a blue body colour and a strong play of colour in green. In the same year there was reported the discovery of another opal deposit 15 km north-west of Coober Pedy.

The 1960s brought the problem of the 'treated' opal. Certain unsaleable and previously discarded opal from the Andamooka diggings of South Australia was found to be susceptible to treatment, giving it a dark background which brought out the small patches of colour. The principle used was similar to that carried out in the colouring of chalcedony to produce black onyx. One version states that the treatment is by soaking preformed stones in sugar solution, or glucose, and then 'carbonising' with sulphuric acid followed by low heating. The darkened stones are then lightly polished. Another method mentioned is by burying the stones in cinders, covering the whole with motor car sump oil and setting fire to it. The fact that a given opal is treated cannot be surely proved, but the peculiar mosaic-like patches of colour indicate this type of opal. Unfortunately there is a natural opal with an oolitic structure which can appear similar to the treated opal.

In Australia the mining of opal is carried out by the sinking of a shaft, usually 1.5 by 0.75 m, down to below the steel-like band of hard rock, which is known as 'shincracker' as the pick is liable to cause fragments to fly off and strike the miners' shins. Penetrating the band the miner, who is known as a 'gouger', comes to the layer of opal dirt and works into this layer. Above the shaft a windlass is fixed and by a rope and crude bullock-hide or metal bucket removes the earth, or as the miner calls it the mullock, to the dumps on the surface (*Figure 11.3*). At the bottom of the mine, which may go down to 25 m or more, the opal is gouged out with knives or small gougers, or with the 'spider', a steel spike or twisted piece of fencing wire made primarily to hold the candle used to light the workings and which is just jabbed into the sandstone wall by the side of the miner. The miners mostly sell all the opal they find in the rough, just nipping off a piece from the edge to see its quality; in the case of boulders splitting with a 'tomahawk' is often carried out. Much Australian opal is now cut at the fields, particularly at Lightning Ridge. The practice of picking over old mine dumps for

Figure 11.3 *Opal mining at Andamooka. The miner turning the windlass is hauling up a bucket which a miner below ground has filled*

overlooked opal is another form of 'mining'. Such procedure is termed noodling.

A beautiful dark opal, with a splendid play of colour on a dark iron-impregnated sandstone, comes from Queensland. The stones are cut with the back consisting of the dark 'ironstone' matrix. These stones are not doublets for they are in one piece, but they do pose problems in nomenclature under existing British legislation. The SG of these pieces depends on the thickness of the ironstone matrix at the back. Values determined have varied from 2.6 to 2.8.

Opal forms in both sedimentary and volcanic environments, but the microstructure is generally distinctive and characteristic of one or the other environment. The occurrence of gem opal in sedimentary rocks appears to be unique to Australia, where the material forms in horizontal layers in or near a bentonitic horizon. Opal from volcanic rocks apparently forms from more concentrated silica solutions and at higher temperatures than opal in sedimentary rocks. The limited occurrence of natural gem opal is due to the specialised conditions necessary for its formation.

Brazil

Opals of good gem quality from unspecified localities in the state of Piauí in Brazil appeared on the London market in the early 1970s. During 1973 at the request of the state government the geology of the district was investigated by Lenzell and Jobbins, who eventually published an account of their findings in a paper by Jobbins (1980).

The chief primary source for these opals was in the Pedro II area in the state of Piauí and occurs where flat-lying Mid Devonian sandstones are intersected by intrusions of quartz-dolerite. The opals were found in and above the altered zone and in veins in the sandstone, while alluvial opals of poorer quality derived from the original sources were found up to 10 km distant, the area being drained by the Rio de Matos and its tributaries.

The best Brazilian stones are similar to some Australian stones of medium quality and have similar properties, some figures quoted being SG 2.09 and RI 1.458.

Other Occurrences

Fine-quality precious opal is found at Virgin Valley, Humboldt County, Nevada, in the United States, where it is located in racks and seams in opalised wood. Opal from this deposit, which was discovered about 1906, often tends to suffer from cracking or surface crazing. Large flawless opals comprising the contra luz, hydrophane and crystal opal are reported from Opal Butte, north-eastern Oregon, USA. Fire, blue and dendritic varieties are also found. Opal occurs in rhyolite geodes embedded in decomposed perlite. The material varies in stability. A dendritic opal, white and multi-coloured, occurs in many places in the United States, Zimbabwe and South Africa. The non-iridescent green opal called prase opal which is coloured by nickel is found at Kosemutz and Zabkowice in Silesia, Poland.

A number of unusual opals have been reported, which from their characters could engender doubt as to their exact nature. The first of these opals, which most likely originate from Jalisco in Mexico, are stones which are extremely porous, so porous that the determination of the SG is well-nigh impossible. A number of these opals have been 'blackened' by treatment with black plastic. These porous (hydrophane type) opals may be found to have not only a low SG but a low refractive index as well, usually about 1.39. Some opals are said to be treated by smoke, but these are not common and little is known about either the opals or the process. It is known that an opal of hydrophane type has been synthetically produced, so far only experimentally, but in the future this type of opal may pose problems. Another type of opal is one in which the play of colour is in circular areas, or in structures suggesting that the opal has replaced organic material, or perhaps coral. This is termed oölitic opal and has been confused with the carbon-stained opal from Andamooka, in Australia. An imitation opal has been mentioned in which a hollow-backed cabochon of rock crystal is filled with plastic and opal chips; and another where a flat-based cabochon of rock crystal has cemented to the base a piece of iridescent shell, most likely that from the *Haliotis*.

A variety of opal simulants are described in Chapter 19.

12

Turquoise and Lapis Lazuli

Turquoise

The gem turquoise, which owes its beauty entirely to its superb colour, has been used for ornamentation from remote antiquity. It was certainly known by 3000 BC and possibly prior to the first dynasty of ancient Egypt. Turquoise was also a prized gem of the lost civilisation of ancient Mexico.

The derivation of the name turquoise, by which the stone has been known since antiquity, is clouded in mystery. Turquoise (turquois in the USA) is reputed to have been derived from the French *pierre turquoise*, or in old French *tourques*, which means 'Turkey stone', not because the stone came from Turkey, but because the Persian material, and perhaps that from the Sinai peninsula, entered Europe by way of Turkey. Another version of the derivation is that the name Turkey implies coming from the Orient, as it was a term of uncertain value indicating strange or foreign. That the Turkish people were conversant with turquoise is certain, particularly the material from Persia which they called by the Persian name *firuse*. Pliny, that great Roman recorder, mentions *callais* (*callaina* or *callaica*) as being a pale blue stone which may have been turquoise.

Chemical and Physical Properties

Turquoise, which is mostly found in arid regions, occurs as incrustations, nodules, botryoidal groups and veins. The mineral has only been found in distinct crystals, of the triclinic system, at once place, that is at Lynch in Virginia, USA, in 1912. The usual formation consists of a cryptocrystalline aggregate with the crystallites so fine that the material may be considered to be practically amorphous, and the mass is to some extent porous. The chemical composition of turquoise is that of a hydrous copper aluminium phosphate with some iron, but the composition is to some extent variable. The formula is given as $CuAl_6(PO_4)_4(OH)_8 5H_2O$, with some alumina replaced by ferric oxide. The sky-blue perfection colour, known in America as 'robin's egg blue' (the

American robin is a red-breasted thrush), has been ascribed to copper and to copper and iron in the more bluish-green varieties.

A possible theory is that a complex amino-copper ion, which might have originated from an animal source, is responsible for the blue colour of turquoise, and that the alteration of the blue colour to green might well be due to dehydration. The colour of American turquoise is said to fade more readily than does the Persian material owing to the greater porosity of the former, perhaps because of the greater readiness to dry in the case of porous material. A story is told that merchants, in order to find out whether a stone is likely to fade, carry them against the skin underneath the armpit; this does not seem to be a satisfactory test if the loss of colour is due, as is most likely, to loss of water. It has been recorded that miners bury turquoise in moist earth before offering them for sale, and that some stones regain their colour if soaked in water or in weak uric acid.

The hardness of turquoise is slightly less than 6 on Mohs's scale, and the SG varies from 2.60 to 2.90, the lower ranges from 2.60 to 2.70 being usual for the more porous American stones, and from 2.75 to 2.85 for the fine compact Persian material.

The mean refractive index of turquoise approximates to 1.62. Actual determinations on the Virginian crystals (by Schaller) gave the principal indices as 1.61 and 1.65, biaxial and positive in sign. Turquoise shows an absorption spectrum consisting of a vague band at 460 nm and a line at 432 nm, which together form a distinctive pattern. The line at 420 nm is too far in the violet to be seen. At best turquoise is only feebly translucent and the spectrum must usually be seen by reflected light. The fluorescence of turquoise under long-wave ultra-violet light varies from greenish-yellow to bright blue, while under short-wave ultra-violet or X-rays there is no response. Some imitations however exhibit a strong blue glow under the short-wave rays. Gilson Created Turquoise (see later) under long or short ultra-violet rays shows an unhelpful dull blue glow.

Although somewhat soft, turquoise takes a good polish, and because it is practically opaque with a wax-like lustre, scratches on the surface are scarcely noticeable. There is no advantage in faceting turquoise, so that the cabochon cut is nearly always used except for the small flat pieces so commonly used for inlay work which is a feature of some oriental and Mexican work. Turquoise is used for carvings and for the panel-like pieces which are produced. Turquoise is so often disseminated throughout the limonite matrix that no stone large enough to cut can be got from the rough material. The stone is then cut complete with the matrix, which may be brown limonite or fawn sandstone. Such pieces are termed turquoise matrix. Much Victorian jewellery is set with turquoise. Blue turquoise is often engraved with Persian or Arabic inscriptions and the incised design inlaid with gold.

Occurrences

Iran (Persia)

The finest turquoises come from the district of Nishapur, 25 km west of Mashhad in the province of Khorassan in Iran. The chain of mountains which extend from west to east between Kotshan and Nishapur consist of nummulitic limestone and sandstone associated with clay slates and interbedded with large masses of rock salt and gypsum. These rock masses have been broken through by volcanic rocks of Tertiary age. The turquoise is confined to the 2012 m peak called the Ali-mersai where the gem material is found in the mother rock, a porphyritic much weathered trachyte, and is cemented together by the brown iron ore known as limonite, the turquoise being found between the layers of limonite and also in the debris (scree) at the foot of the mountain. Many hundreds of mines, which have a long history, have been worked in this area. In many cases Persian turquoise is found as a pseudomorph after feldspar and the cut stones are often characterised by small patches and veins of whitish material. Good-quality Persian turquoise has a fairly constant SG of 2.79. The stones are marketed at Mashhad and usually exported to Russia and India.

Tibet

Much has been written of the turquoise as the national stone of Tibet where turquoise of a green colour is the more highly prized. There appears to be some doubt whether the stone is found in Tibet. Berthold Laufer states that the first European author to report the indigenous occurrence of turquoise in Tibet proper, as far as he could ascertain was the Capuchin friar Francesco Orazio della Penna di Billi (1730). Laufer also states that according to Sarat Chandra Das the finest turquoises are obtained from a mine in the Gangs-chan mountains (Chang Chenmo range?) of Nagari-Khorsum in west Tibet. It is further recorded that green turquoise occurs in several mountains of the great state of Derge in eastern Tibet, but the exact locations were not given. In Tibet the material is known by the name *gyu*, which is pronounced 'yu'; whether this word was derived from the Sanskrit or the Chinese is not clear (*yu* is the name for jade in China).

India and China

The peoples of ancient India do not seem to have been acquainted with turquoise, which does not appear to have entered India until the Mogul period of the fourteenth century, although there has been the suggestion that the gem entered both India and China through the agency of the Arabs after the conquest of Persia in AD 642. The Mogul name for turquoise is said to have been *kiris*.

The existence of true turquoise in India is doubtful. From the presence of blue streaks in the copper ores of Ajmir it was earlier thought that turquoise could be found in India, but later work suggests that these blue streaks are a secondary copper ore. According to ancient literature and the evidence of recent archaeological finds, turquoise has been known in China for over 3000 years, and Marco Polo speaks of the existence of turquoise in the province of Caindu, which has been identified with the present Chinese province of Sichuan, a territory then largely inhabited by Tibetan tribes. Today turquoise of gem quality is mined at Yunxian and Zhushan in Hubei province, where it occurs as compact nodules in tension fractures in silicified limestone associated with powdery black shale.

Egypt

The Egyptian turquoise from the Sinai peninsula is historically the most important source, if not commercially important, for there is little doubt that the mines of Maghârah and Serâbît el Khâdim were the source of the turquoise used in Egypt over 3000 years ago. True there is little proof that the mines were worked for turquoise or for the copper ores, for malachite, azurite and chrysocolla were also found in the mines although little now remains. Turquoise was undoubtedly used for ornamentation, not only in the Old and Middle Kingdoms, but as early as the Baderian period. The ancient name for turquoise was *majkat*, which in early translations was transcribed as malachite; this accounts for the absence of the name turquoise in old records. It is interesting to note that the site of the port through which the Egyptians brought the turquoise, with which the Pharoahs and their ladies were adorned, was found in 1947. This is a low mound on the edge of the Merkhah plain about 100 m from the Gulf, from which the mines of Serâbît el Khâdim are but 27 km inland.

The turquoise district of Sinai lies along the south-western coastlines of the peninsula bordering on the Gulf of Suez and is some 650 km². The deposits are in country which is rugged and bare and remarkable for the pronounced faulting which produces canyon-like wadis or valleys. Although the rainfall is only 25 mm per year, a heavy shower converts these wadis into raging torrents. There are six mines in the area: Wadi Maghârah (or Egma), Wadi Shellal, Jebel Ham'd, Um Bogma, in which area extensive mining for manganese has recently been carried on, Abu Hamad and Serâbît el Khâdim. Abu Hamad, some 10 km in extent, Wadi Shellal and Um Bogma are poor deposits. Jebel Ham'd has not been worked for many years because the spirits of seven Bedouin who were buried by a fall of roof which had been undercut are said to haunt the place. Wadi Maghârah, the valley of the cave or grotto, is the site of ancient workings which were believed to have been worked out about 2000 BC. Spasmodic working is carried out by destitute Bedouin who break up the sandstone at promising points by the use of home-made gunpowder, made from sulphur, saltpetre and charcoal locally obtained. A yellow seam of sandstone, consisting mainly of coarse grains of yellow quartz cemented by an iron-red clay, is believed locally to indicate the presence of turquoise. This sandstone is called Al'erg Safra and directly below it is the *baloota*, a bed of paler sandstone often dirty white in colour. There are a number of stopes at this mine, the larger ones having names: the largest, Al Yahoodiah (the Jewess), is of immense size, and the next largest, called El Higgigah (the Pilgrimage), with Al Gâneyn (the two rich ones, or brothers), have produced pieces of turquoise of large size even in recent years. Equally important in ancient times was the mine at Serâbît el Khâdim, 4 km north of an ancient temple dedicated to Hathor, Goddess of Turquoise; this mine is also spasmodically worked at present times.

Turquoise commonly occurs in arid regions where rocks such as sandstones (often extensively fractured) are in juxtaposition with copper deposits and a source of alumina and phosphorus, such as a volcanic lava. The copper may come from minerals such as malachite, azurite or chrysocolla or from a copper sulphide finely disseminated through a lava. The alumina may result from the decomposition of feldspar and phosphorus from the breakdown of the calcium phosphate, apatite, in a trachytic lava or from decomposed organic matter, e.g. fossils. Meteoric waters seeping through fractures may pick up carbonic acid and even sulphuric acid from the decomposition of pyrite (FeS_2) in shale or igneous rock. These percolating solutions facilitate the formation of the turquoise. The resulting minerals commonly accrete around a nucleus and concretionary forms build up, or they may form veins in the fractured rock.

The Egyptian turquoise is more often greeny-blue than the sky-blue colour of the material from Persia, but some fine blue material is obtained from Sinai and this is characterised by the polished surface showing small circular areas of deeper blue colour. The SG of Egyptian turquoise varies between 2.7 and 2.9, the purer blue-coloured material having the higher density which is usually not far removed from a value of 2.81. Some of the Egyptian turquoise is said to suffer from fading, but as a rule the material is fairly stable. The wily Bedouin are said to have a trick of polishing with an oily rag, and it is said that local lapidaries even paint the stones.

United States of America

In the western hemisphere turquoise is found in some profusion in the south-western states of the North American continent, and these were probably the sources which supplied the turquoise used by the Aztecs of Mexico, and perhaps even by the Toltecs who preceded them. The Aztec use of turquoise for decoration was mainly by inlaying, often on a wooden base with a wax or gum as a cement. Superb examples of such work are in the British Museum, one gruesome piece being the front of a human skull, completely covered with a mosaic of turquoise and lignite with the eyes of polished pyrites and the teeth of white shell. The Pueblo Indians of the American south-west also featured the inlaying of turquoise, and this may be a survival of the ancient Mexican art. The Apache Indian, who called the turquoise by the name *duklij*, highly prized the gem for its talismanic value. One of its supposed powers was to aid the warrior or hunter by assuring the accuracy of his aim, for if a turquoise was affixed to a gun or bow the missile fired from the weapon would go straight to its mark.

The turquoise used by the Aztecs is supposed to have been obtained mostly from the mines in New Mexico, probably from a trachyte rock in the Los Cerrilos mountains near Santa Fé, and from Nevada, Arizona and California. The sources in Lower California (Baja California) are not too well described but workings have been reported near the town of Rosario on the west coast of the peninsula. Nevada is a major source of turquoise, particularly in the Toiyabe range near Austin and at Columbus east of Tonapah.

In California the turquoise is found mainly in the Mohave (Mojave) desert in San Bernardino County, where the mines were worked in ancient times, not by the Californian natives but by the Pueblo people from Arizona and New Mexico who probably entered California and worked the mines seasonally. These miners worked exposed turquoise veins to a depth of about 4 m as open pits, by breaking and crushing the waste mass with hafted stone axes and hammers and throwing the muck out with a hand scoop made from a tortoise carapace or the shoulder blade of an animal. Heavy stone-pointed picks weighing up to 5 kg were used to break out the rock and there is some evidence that wedges were also used. No signs of the fire and water method of breaking rocks were found in the Californian mines, although there is ample evidence that such a method was used in Arizona and New Mexico. The mines of California are in the area of the Turquoise mountain, 15 km north-east of Silver Lake. Little turquoise is now mined in California.

Turquoise has been found in the state of Colorado, particularly at the Hall mine near Villa Grove and the King mine near Manassa, where it is found in a felsite porphyry; at the Turquoise Chief mine near Leadville in Lake County, where it is found in Algonkian granite; and lastly in a stream bed near Creede, Mineral County. The material from Colorado varies considerably in quality from a firm compact turquoise of good colour to a soft semi-compact material useless for high-class gems.

The turquoise is said to have been formed by meteoric waters leaching the constituents from alkali feldspars, neighbouring copper ores and apatite and depositing them in fractures. A characteristic of American turquoise is that it is lighter in colour, is more porous and chalky, and has an SG which lies between 2.6 and 2.7. The find of turquoise in triclinic crystals in Virginia has already been mentioned.

Other Occurrences

A number of occurrences of turquoise have been reported in the Uzbek Republic of the former USSR, particularly near the Kansaisk lead mines near Kuraminsk and in the Karatube mountains. It is also reported from Oelsnitz in Saxony and in Silesia. Turquoise-blue minerals including rashleighite, andrewsite and henwoodite have been found in various localities in Cornwall, including the Bunny mine and Gunheath clay pit near St Austell, the old wolfram mine at Castle-an-Dinas and at Liskeard. Recent research has shown all these minerals to be members of the turquoise-chalcosiderite series and the earlier names are discredited. Most Cornish turquoise is porous and friable, and compact material is hard to find.

Turquoise has also been reported from the Chuquicamata mine in northern Chile, some of which is said to equal in colour the best Persian turquoise. The mineral has been found near Bodalla on the south coast where it occurs in black cherts in the Wagonga series. Occurrences have also been reported from Victoria and Queensland. A 'turquoise' from a mountain near the town of Dayboro, about 65 km north-west of Brisbane, was found to have properties similar to variscite. The material has an SG near to 2.5 and a refractive index of 1.58. There is an unconfirmed report of a turquoise deposit in Namibia.

Simulation

The material found exclusively in an ancient Celtic grave at Mane-er H'rock near Lockmariaquer in Brittany, so often mentioned in literature under the name callainite, is probably a variety of variscite having a better transparency and a bluer colour than is usual for this mineral. Naturally occurring minerals which may have a strong resemblance to turquoise are lazulite, chrysocolla and wardite, and mention must be made of the so-called 'bone turquoise' or odontolite, which is a fossil tooth or bone coloured blue with vivianite. These are separately described in Chapter 17. It has further been suggested that a blue massive variety of the rare fluoride mineral prosopite bears a striking resemblance to turquoise. Accordingly an account of this mineral has been added to the same chapter.

It is not surprising that turquoise, so highly prized by the peoples of ancient Egypt, should have been one of the first gems to be imitated in base material. One of these early types consisted of an artificial frit composed of a crystalline compound of silica, a copper compound, which may be malachite, calcium carbonate and soda (natron). This frit, called by Vitruvius caeruleum and by Theophrastus kyanos, was, in addition to its use as a pigment, carved into small objects. Faience, perhaps better expressed as a glazed siliceous ware, was used for making beads, necklace pendants, rings, amulets and small animal figures. The material was known from pre-dynastic times (before 4777 BC) and was still being produced as late as the Roman period about 51 BC. The broken surface of faience consists of two, sometimes three, layers. There is always an inner core with an outer coating of coloured vitreous glaze, which, when present, is very marked on account of the difference in colour and SG. The core consists of a fine gritty material and the glaze is a thin coating of true glass, and the special layer is probably used to enhance the glass.

Although glass has been reported to have been used prior to the eighteenth dynasty (1567–1328 BC), no clear confirmation is forthcoming on this point and in some quarters it has been disputed. Of these ancient blue glasses imitating turquoise most were found to be coloured by copper compounds: one, from the tomb of Tutankhamun, was coloured by cobalt and two of the Ptolemaic period by iron.

Imitations of turquoise are made in glass, enamel, stained chalcedony and, rarely, porcelain. The stained chalcedonies are considerably more translucent than true turquoise and have an SG of 2.63, a refractive index of 1.53 and a hardness of 6.5 on Mohs's scale. Glass imitation turquoises usually have an SG near to 3.3, although lower values have been recorded. Glass imitations usually show small bubbles just below the surface or as pit marks on the surface. Porcelain imitations are not common but have a typical china lustre, are usually glazed, and have a fairly constant SG of between 2.3 and 2.4.

Many artificial products made to imitate turquoise have been marketed. The so-called 'Viennese turquoise' is made by pressing together a precipitate of aluminium phosphate coloured blue by copper oleate. Another type is composed of malachite, aluminium hydroxide and phosphoric acid carefully mixed and ground to a fine powder, which, after heating to over 100 °C, is compressed with great force. A German product, first produced in 1957, was found to be a mixture of bayerite and copper phosphate with the dark veinings of the matrix due to some amorphous iron compound. This material is marketed under the name neolith. Some turquoise imitations from the United States of America were found to consist of grains of some natural minerals, including a copper mineral bonded with a styrenated alkyd type of plastic. It is reported that a suitably dyed jasper is another imitation of turquoise (cf. 'Swiss lapis' in Chapter 10 and later in this chapter).

The SG of these 'pressed' and 'bonded' pieces is always lower than for natural turquoise. The pressed types give, when a 'snap' SG is taken, a value of about 2.4, but on soaking the value reached may be near 2.6. The plastic bonded types vary considerably in SG and range from as low as 1.85 to as great as 2.5, but are usually between 2.0 and 2.4. The refractive index of the Viennese turquoise is shown by a vague shadow edge at 1.45, that of the German types at about 1.55, and the plastic bonded types near 1.56.

The easiest test for these pressed and bonded imitations is to place a spot of hydrochloric acid on an inconspicuous part of the specimen. The acid turns to a yellow-green colour which will stain a piece of filter paper (blotting paper) when the acid is soaked up by it. Such an effect does not occur with true turquoise, or with the resin-bonded true turquoise mentioned below. Carefully applied the test does not damage the stone except for the possibility of taking away the polish at the spot where the acid was applied. These imitations blacken or fuse to a black glass when heated and do not decrepitate like true turquoise does. Further they do not show the turquoise spectrum.

An extension of the bonded types is the resin-bonded true turquoise which is produced in Arizona from local material got from the Turquoise mountain in Cochise County and near Morenci. Turquoise is also bonded with sodium silicate or colloidal silica which reduces the specific gravity, but is otherwise not easy to detect. Such material is durable and does not lose its colour. Some of these pieces may have faked cracks suitably coloured to imitate true turquoise matrix. This bonded real turquoise does show weakly the turquoise absorption spectrum of the two bands in the blue-violet. Resin-bonded turquoise may be readily identified by the lower SG which may vary from 2.18 to 2.55 and also by a simple chemical test which can be carried out on a very small scraping removed from some inconspicuous part of the specimen. To do this the scraping from the specimen is placed in a micro-test-tube which is then strongly heated. If the material is resin-bonded a liquid, probably yellowish in colour, will condense in droplets on the walls of the cooler part of the tube, and, usually in a position between the hot part and the liquid condensate, there will appear a narrow ring of sublimate consisting of feathery crystals of phthalic anhydride (*Figure 12.1*). Further, an unmistakable odour is given off which, although not unduly strong, can best be described as 'itchy'.

The phthalic anhydride is best confirmed by rubbing in the sublimate, by means of a glass rod, a very small quantity of resorcinol and one drop of concentrated sulphuric acid and gently reheating *in situ*. Wash out with water into a small beaker and make this alkaline with sodium hydroxide or sodium carbonate when the characteristic yellow solution with a strong green fluorescence is produced. This procedure is in fact always the safest when testing for alkyds, as when these occur in a heavily polymerised molecule direct heating of the original substance with resorcinol will often lead to a negative result.

A further test for resin-bonded turquoise is to approach, but not touch, the specimen in an inconspicuous area, with a hot needle or electrically heated probe, when the resin will give off a typical acrid odour of hot plastic. In the case of wax-impregnated material the wax may be seen to melt locally.

The colour of some turquoise tends to bleach on exposure to the sun, or to turn greenish with time. Soaking the stones in ammonia is said to improve the colour, but the effect is rarely permanent. Poorly coloured stones are occasionally stained with Prussian blue, but such staining may be detected by the loss of colour at the place where a spot of ammonia has been applied.

Figure 12.1 Feathery crystals of phthalic anhydride produced when alkyd resins are heated in a test tube (photo: G Wild)

Specimens of turquoise are sometimes oiled or waxed and are considered commercially acceptable, and presumably the method of hardening the soft friable American turquoise by impregnating with colloidal silica is also acceptable. Some turquoise which has lost its colour may sometimes be brought back to a good blue by treatment with solvents, but the results cannot be predicted.

Clever fakes of turquoise have been made of coloured clay, and a 'reconstructed turquoise' is said to have been made from finely powdered ivory with copper stain and cement. Doublets have been made with a low cabochon of turquoise-coloured opacified glass with a back of blue-stained chalcedony. Cabochons cut from bone and suitably coloured, usually with phosphate of iron, are easily detected by their low SG (about 2), by their effervescence with acid and by their organic structure. Other imitations of turquoise are blue-dyed howlite; surface-stained limestone; and blue-dyed and plastic-treated marble beads. Recently there has been produced a completely plastic turquoise imitation which can be easily detected by its low density. A so-called 'synthetic turquoise' is described in Chapter 18.

Lapis Lazuli

The beautiful blue stone called lapis lazuli has been known from ancient times. The mineral owes its name, as do several other blue minerals, to the Persian word *lazhward*, meaning blue. The colour of lapis lazuli varies from a blue tending to a greenish-blue to a rich purple blue, the perfection colour being a dark blue of extraordinary depth and intensity. Owing to the inclusion of iron pyrites within the stone most specimens show bright brassy specks, which, if not too prominent, are valued as a sign that the stone is genuine. In olden days the stone was known as sapphirus, a name which is now applied to our sapphire, the blue corundum.

Chemical and Physical Properties

Unlike most of the gem materials, lapis lazuli is a complex aggregate of several minerals, particularly hauyne $(NaCa)_{4-8}(SO_4,S)_{1-2}(Al_6Si_6O_{24})$, to which the stone owes its beautiful colour, sodalite $Na_8Cl_2(Al_6Si_6O_{24})$, nosean $Na_8(SO_4)(Al_6Si_6O_{24})$, and lazurite, which is an isomorphous combination of hauyne and sodalite. These four minerals all belong to the cubic system; they are members of a group of rock-forming minerals known as feldspathoids which are produced when the silica content of the rock is insufficient to form completely true feldspar. There is always calcite present which produces the whitish parts of the poorer-quality material, and, as previously mentioned, the iron pyrites. A small amount of diopside, augite, mica and hornblende are generally present. Lapis lazuli is therefore a rock and not a true mineral.

The indefinite nature of the mineral's composition naturally affects the physical properties. The refractive index is generally shown as a somewhat vague shadow-edge at about 1.50 on the refractometer scale. The constant of specific gravity, although having a rather wide range, has a diagnostic value. The commercial type of lapis lazuli has an SG which varies from 2.7 to 2.9; this figure may even be higher if much pyrites is present. The hardness is 5.5 on Mohs's scale. The material is decomposed by hydrochloric acid giving off the obnoxious smell of rotten eggs (hydrogen sulphide). Under the long-wave ultra-violet lamp lapis lazuli generally shows spots or streaks of an orange or copper-coloured glow, stronger and more pronounced in the material from Chile than in that from Afghanistan. The fluorescence is less pronounced and more pinkish when the short-wave lamp is used, and shows as ill-defined yellowish streaks when irradiated with X-rays.

Before the nineteenth century powdered lapis lazuli produced the pigment ultramarine, but since 1828 this pigment has been synthetically produced by calcining a mixture of china clay, sodium carbonate, charcoal and sulphur in the absence of air.

Lapis lazuli is formed by metamorphic action on impure limestone through contact with intrusive igneous rocks, causing a recrystallisation to marble with the formation of a number of new minerals including lapis lazuli.

Occurrences

The most famous locality for lapis lazuli is in the Badakshan district of the mountainous north-eastern part of Afghanistan, the mines having been intermittently worked for 6000 years. They were visited and described by Marco Polo in 1271, but owing to their remoteness and inaccessibility little is known of them. The mines are at Sar-e-Sang on the upper reaches of the Kokcha river, which is a tributary of the Oxus, the lapis being found in a black and white limestone.

What are probably the same mines or a part of them were described by the Russian academician Fersman, who was one of an expedition in 1930 to find the 'lazurit', which legend said existed in the Pamirs. The expedition found the route exceedingly difficult and after reaching some 3500 m the party had to leave its horses and continue on foot along one of the rivers which had the name Liadjuar-Dara, which means River of Lazurit. On reaching the height of 5000 m they found a great glacier field covered by immense stone falls from the adjacent steep wall of marble and gneiss. In this snow-white marble were veins and nests of lapis lazuli, some bright blue, some delicately blue with beautiful passages into violet and green tints. That the locals knew of this place was given credence when one of the guides said that he had heard of it from his father and that he, with others, had previously tried to reach the place but all had contracted mountain sickness and turned back.

The Afghanistan mines are worked in a primitive manner. The rock is heated and then quenched in order to obtain pieces of such size, about 5 kg each, convenient for bringing out of the inhospitable locality. A quantity of this material reaches Pakistan and is made up into jewellery at Lahore.

Amidst the wild and uninviting Sayan mountains light blue boulders of lapis lazuli are found in the rapid Slyudyanka river, which flows into the southern end of Lake Baikal bordering on Mongolia. This deposit, scattered in irregular accumulations of crystalline limestone, was exploited in the Bystraya river valley during the middle of the nineteenth century, but towards the end of the century the mines were neglected and the place became overgrown with dense woods. Whether the mines have again been opened is not known.

A paler colour lapis lazuli is mined in the Chilean Andes, the most important localities being those at Ovalle Cordillera, Coquimbo province and farther north near Antofagasta. On Italian mountain, high in the Sawatch range of the Colorado Rockies, is found lapis lazuli in stringers in limestone rock measuring up to 200 mm and outcropping for a distance of 100 m along the face of the mountain. As in the case of the Afghanistan lapis lazuli the formation is due to contact metamorphic action. Folding and faulting of the mountain occurred in Cretaceous times with the intrusion of igneous rock, a diorite. The deposit was discovered in 1939, but the rock is only worked spasmodically owing to the short season, the high altitude and the necessity of moving badly fractured overburden to ensure safety in working. The material is almost black to an intense blue, contains narrow veins and spots in calcite, and is heavily charged with pyrites. It lacks the texture and hardness of good quality lapis, has a waxy to subvitreous lustre and has an SG varying from 2.82 to 2.85.

An occurrence of lapis lazuli has been found near the summit of Antonio Peak in the San Gabriel mountains in southern California about 65 km east of Los

Angeles, and also in Cascade Canyon, San Bernardino mountains. Material of a blue-grey splotched with bright blue and white, and containing pyrites inclusions, is found in Baffin Island north of the Labrador peninsula, Canada. It has little merit as a gem material for it is somewhat porous and does not take a good polish. Lapis lazuli is also found in the Mogok region of Myanmar; the actual locality is the Dattaw valley. Lobito Bay in Angola and Pakistan (SG 2.81–2.84) are other sources.

Cutting of Lapis Lazuli

An opaque stone valued for its colour only, lapis lazuli is rarely faceted, but the material is fashioned into seal stones, beads and small carved objects, and is used as inlay material, often with a lighter-coloured mineral such as the stalactitic marble best known as 'onyx marble'. It has been said that in order to improve the apparent colour of Chilean lapis, the lap for the final polishing is charged with ultramarine powder.

Simulation

Lapis lazuli is imitated by the so-called 'Swiss lapis' or 'German lapis', which is a type of jasper stained blue by the action of potassium ferrocyanide and ferrous sulphate which produces Prussian blue or Berlin blue. This imitation does not show the brassy specks of pyrites, but often shows glistening flakes of transparent quartz. The material, which has an SG varying between 2.38 and 2.60, is generally harder than true lapis and has an inferior colour to the real material.

A sintered synthetic spinel coloured blue by cobalt has been produced in Germany. The imitation, of good lapis colour, has an index of refraction of 1.725 and an SG near to 3.52. Many specimens of this imitation are complete with brassy specks, but these are in fact gold pieces incorporated in the powder before the sintering.

Paste imitations of lapis lazuli are not often seen. There have been cases of an opacified blue glass which contained spangles of copper crystals, as in goldstone, and these glass imitations purport to be imitation lapis lazuli, but the gaudy nature of these glasses is sufficient to identify them. It has been recorded that pale-coloured lapis lazuli has had the colour enhanced by staining, but such treated stones never show the glorious colour of the best lapis lazuli. It is practically impossible to achieve a true synthesis of a rock such as lapis lazuli consisting as it does of a mixture of a number of minerals in different proportions and states of aggregation. Experiments to this end were, however, carried out by Dudzic in Canada and a US patent was obtained for his process in 1970, while in the mid 1970s Pierre Gilson began producing Gilson Created Lapis, a handsome material having the appearance and many of the properties of the natural material. A fuller description will be found in Chapter 18.

Some lapis lazuli has been dyed and it has been found that this dye will come off and stain a swab moistened with nail-varnish remover (amyl acetate). One imitation is composed of crushed lapis lazuli bonded with plastic and with included pyrites. The application of a hot needle will generally unmask this fake. Another recent imitation is largely composed of barium sulphate with included pyrite, the mass being bonded with polymer. Yet another recent imitation is a dyed calcite marble. Some lapis lazuli beads are heated in molten paraffin wax which enhances the colour after light polishing.

Unlike its imitations, lapis lazuli will show a fairly bright whitish glow when under a beam of short-wave ultra-violet light (253.7 nm). A further test for lapis which has been suggested is that the rock gives off hydrogen sulphide when moistened with hydrochloric acid.

13

The Jades

History and Lore

As a result of some 40 years of controlled archaeological research in China it is now known that the ancient Chinese have been working tough green materials, which they call *yu,* for over 7000 years, i.e. since neolithic times. These green materials include the minerals which today we know as jade. The name jade does not signify one mineral but may refer to either of two mineral species, nephrite and jadeite, which have no relation to one another except that of appearance. Jadeite, often confusingly known as Chinese jade, is found in Myanmar (Burma), but this material did not enter China until the eighteenth century and therefore was not the *chen yu,* or true jade, which was so cleverly carved by the Chinese craftsmen of ancient dynasties. Their jade certainly included the mineral nephrite which would have come from Khotan in central Asia in later times, but other more ancient sources have been postulated and these include Siberia, Manchuria and other localities.

The nephrite variety of jade, owing to its toughness, has been used for tools and weapons and for ritual ornaments, not only by the Chinese but by the early inhabitants of the Swiss lake dwellings, by the North American Indians, by the Aztecs of central America and by the Maoris of New Zealand, who used the nephrite found in such profusion in the South Island.

The name jade was apparently first derived from the end word of *piedra de hijada,* the Spanish name for jade. The Spanish adventurers in the time of Cortes brought back the jade pieces which they found to be so widely distributed among the Indians. It was they who brought back the name *piedra de hijada,* which means stone of the flank or loins, or by another derivation colic stone. It is suggested that the flat polished pebbles with rounded edges resembled the kidneys, and were, therefore, thought to be efficacious in disorders of that organ. Howard Hansford states that the Spaniards knew the stone as *piedra de los riñones* ('kidney stone'), a name which was translated into Latin as *lapis nephriticus,* and this gives the word nephrite.

Nephrite

Chemical and Physical Properties

Often known as greenstone, nephrite consists of an interlocking mass of fibrous crystals having monoclinic symmetry, the felting of the crystals giving to the mineral its toughness (*Figure 13.1*). The mineral is a silicate of magnesium and calcium with some iron in the ferrous state, the composition corresponding to the formula $Ca_2(Mg,Fe)_5(OH)_2(Si_4O_{11})_2$, the colour deepening to deep green with the increase of iron to magnesium content, and with less iron and more magnesium the colour lightens to a creamy buff, the so-called 'mutton fat' jade. The mineral is in fact a member of the tremolite-actinolite series of the amphibole family, the lighter-coloured varieties being nearer to tremolite and the darker to actinolite.

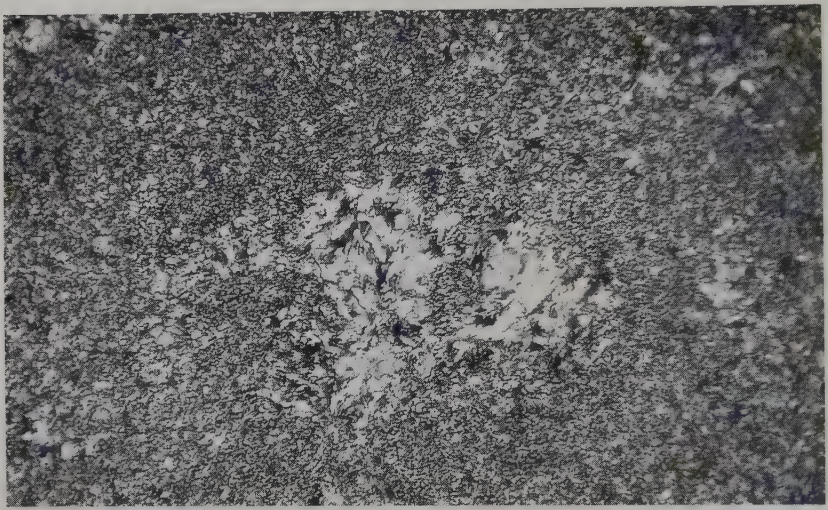


Figure 13.1 *Photomicrograph of a thin section of nephrite showing the interlocking fibrous texture (New Zealand specimen under cross polars)*

Nephrite often assumes a brown colour, caused presumably by oxidation of the iron content. Indeed many pebbles and boulders of nephrite are covered with a brown skin where the material has weathered on the outside. This weathering is often apparent along cracks penetrating the interior and producing a brown coloration along their margins. The Chinese carvers (*Figure 13.2*), so adroit at getting the most out of any material, often used the brown weathered zones to incorporate colour schemes into their carvings. Thus they might choose a small weathered pebble for carving into a snuff bottle, and, cameo fashion, incise into the brown skin to produce a two-colour effect.

The hardness of nephrite is 6.5 on Mohs's scale, but owing to the felted nature of the crystal aggregate the mineral is extremely tough. The SG is near to 3.00 (2.90–3.02), a value considerably lower than for jadeite (3.3). The refractive indices of the individual crystal fibres have been found to vary between

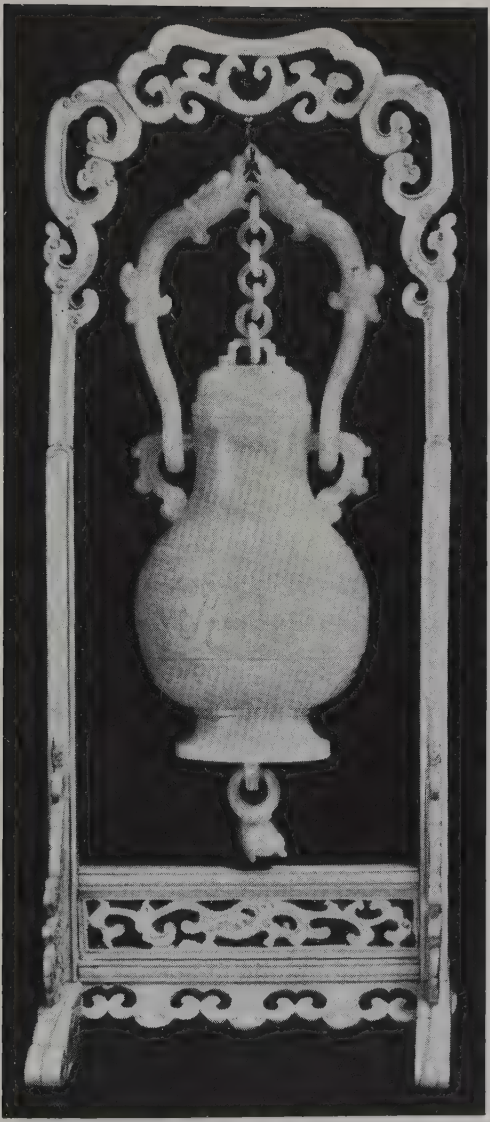


Figure 13.2 Chinese carving in nephrite. White translucent jade hanging vase, with carved handle depicting dragons. The cover is suspended from the top with a seven-linked chain. From the bottom is suspended a parrot on a ring perch. The vase and all its linked parts are carved from one piece of jade

1.600–1.627 and 1.614–1.641, thus giving a birefringence of 0.027. In practice, owing to the aggregate nature of the crystals, only a vague reading at about 1.62 can be seen on the refractometer, and for the same reason the marked dichroism of the individual fibres is masked. Nephrite shows a very indistinct absorption spectrum of a doublet in the red about 689nm; however, two vague bands at about 498 and 460 nm and a fairly sharp line at 509 nm are often seen. The mineral shows no luminescence under ultra-violet light, and through the colour filter the stone appears green.

There is one type of nephrite, of a yellowish or greyish-brown colour, which deserves mention. This is the so-called 'buried' jade which has so much importance from an archaeological angle. These ancient jades from neolithic and early historical times, which have been buried through the intervening ages, are supposedly from indigenous sources of nephrite. The material has, after the long burial in the yellow loess of China, altered in colour and perhaps in composition from the original material. The changes may have been caused by general weathering in the zone of circulating groundwater, or, when in tombs, by the proximity of bodies and their decomposition products. It is also of interest to note that similar colour changes can be induced in nephrite by heating at moderate temperatures.

Occurrences

The occurrences of nephrite are wide, the material being found in many parts of the world, either *in situ* or as alluvial boulders and pebbles with a brown skin due to weathering. Among the earliest known and most important sources of nephrite from the Chinese carvers' point of view is along the northern slopes of the Kuen Lun mountains near Khotan in eastern Turkestan, where it is found *in situ* as a layer some 7–14 m thick between hornblende-schist and gneiss, or as alluvial boulders in the beds of the Keriya, Yurungkash and Karakash rivers. An occurrence of dark green nephrite in the Lake Baikal district of eastern Siberia was discovered by Alibert in 1850, where boulders of large size are found in the rivers Onot, Bistraya, Bielaya, Kitoi and Slyudyanka, south of Irkutsk, the primary source probably being in the Sayan mountains. The jade from this locality is often marked with small black spots of graphite, a mineral mined nearby. Nephrite has been reported from the Pamir district which lies south of the Kirghiz steppes and north of Chitral.

The nephrite found in New Zealand which is variously termed 'New Zealand greenstone', 'Maori stone or jade' or 'axestone', and by the Maoris *pounamu*, is found *in situ* in talc and talc-serpentine rocks in the Griffin range; west of Lake Wakatipu in the province of Otago; at Mount Cook in the Southern Alps, and in the small island of D'Urville which lies in Cook Strait separating the North and South Islands. Much boulder material is found in the glacial debris of the river valleys of north Westland. These alluvial pebbles are often flattened in form and admirably suit the fashioning of the Maoris' grotesque ornaments called *hei tiki*, and for the flattened club known as the *mere*. New Zealand nephrite is mostly of a dark green colour and the creamy-buff 'mutton fat' nephrite is rarely, if ever, found there.

The finding of worked pieces of nephrite in the Swiss lake dwellings led to speculation as to the source of the material which at the time was only known from distant lands. Nephrite-bearing rocks are found at Poschiavo in eastern Switzerland. In 1884 nephrite was rediscovered in Europe at Jordansmühl (now known as Jordanow) in lower Silesia which is now part of Poland. Nearby Reichenstein, a place which is now known as Dzierzoniów, also supplies nephrite which is lighter and greyish-green in colour, but some Silesian nephrite is a creamy-white to a sand colour with green patches. Occurrences of nephrite have been reported from southern Liguria in north Italy and in the Harz mountains of Germany.

North of the Arctic Circle in north-western Alaska nephrite is found at Jade mountain, 240 km from the mouth of the Kobuk river, and in the basins of the Noatak and Kobuk rivers. The jade which is taken out from this inhospitable region is sent via Kotzebue Sound or by air. The nephrite of this region occurs in a series of outcrops of ultra-basic rocks intruded mainly in schists and limestones, but the jade from this locality has also been won from gravel deposits of the Kobuk river some 15 km below Shungnak village. Some nephrite from Alaska is fibrous and shows chatoyancy when cut as beads or cabochons.

In recent years the nephrite variety of jade has been found east of Wind River range of the Rocky mountains at Lander, Wyoming in the United States of America. Some jade is found as large boulders of alluvial deposition and is exposed by natural erosion as the terrain, isolated and with few habitants, is situated at high elevation and subjected to severe storms and blizzards during much of the year. The jade varies much in colour and only a small quantity is the prized green. In addition to the widespread alluvial jades there are also deposits *in situ*, including the celebrated 'black jade' found in the Crooks mountain area. Some Wyoming jade is chatoyant. Alluvial nephrite is also found in California, particularly at Placer County, where the Chinese miners panning for gold also found jade boulders in the river; it is thought that many of these boulders were taken back to China. Nephrite also occurs in veins near Bagby in Mariposa County. Jadeite is found at Clear Creek, San Benito County. Nephrite pebbles are found on the coast of Monterey County, Marin County and San Luis Obispo County. The last named is said to have a deposit of nephrite *in situ*. Nephrite, with jadeite, has been reported from a location 10 km east of Mount Vernon in Washington, and the mineral is said to occur in the Amazon valley.

For many hundreds of years nephrite has been known by the Indians living along the tributaries of the Lower Frazer river and was used by them for making tools until the arrival of the white traders who introduced iron tools. There is a story that in the 1890s the placer miners, many of whom were Chinese, recognised that the boulders seen in the creeks were jade and made shipments of this nephrite to China. Boulders of nephrite were found in Wheaton Creek about 1938 but the jade from here was only mined for about 15 years. There was a revival of interest in British Columbian jade later but it did not really start until about 1960 and the mining is to some extent controlled by local mining laws. The nephrite jade is found as pebbles, cobbles and boulders, the latter of several tonnes in weight. The colour ranges from yellow-green to dark spinach green. About 1965 nephrite was found in Ogden Mountain, west of Manson Creek, in central British Columbia, and some 400km north-north-west of the town of Prince George. Beautiful green nephrite has also been marketed from the Atlin, McDame and Dease Lake areas.

That the alluvial nephrite found at Amargoza, Bahia, Brazil was worked by native Indians seems probable from the abundance of artifacts made from this material found in the region. An occurrence of dark green nephrite of good quality has been reported from the Mashaba district of Zimbabwe and a paler material from Tamworth, New South Wales, Australia. Large deposits of dark green and 'black' nephrite are found at Cowell, South Australia. Nephrite is also found in Taiwan (Formosa) and Korea.

Since 1965 there has been marketed, usually under the name 'Wyoming jade' or 'Snowflake jade', a 'jade' which is really a mixture of the tremolite variety of amphibole and albite feldspar. The values of SG determined on these intergrowths varied from 2.80 to 2.95, but were fairly constant at 2.84. The refractive index, as far as could be measured on a refractometer, was about 1.56.

Jadeite

Chemical and Physical Properties

Jadeite consists of an aggregate of interlocking crystals of the monoclinic system, which unlike nephrite are more granular than fibrous, and, owing to slight differences in hardness of the grains, shows on the polished surface a 'shagreened' or dimple effect (*Figure 13.3*), although modern diamond-powder polishing produces an even mirror-like finish. Jadeite is one of the pyroxene group of minerals and is thus allied to spodumene, diopside and enstatite.

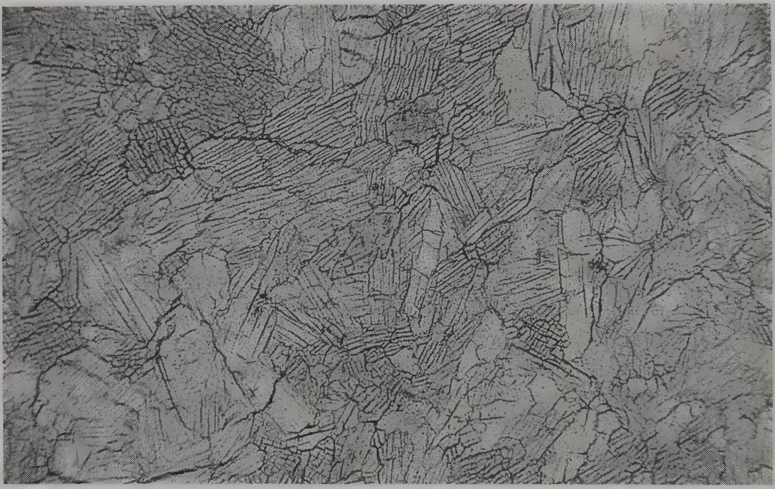


Figure 13.3 Photomicrograph of a thin section of jadeite showing the interlocking granular texture (Myanmar specimen under plane polarised light)

The composition of jadeite is a sodium aluminium silicate and accords to the formula $NaAl(SiO_3)_2$, but a varying percentage of the diopside $CaMg(SiO_3)_2$ and/or kosmochlor (ureyite) $NaCr(SiO_3)_2$ molecules are often present. Jadeite has a hardness equal to quartz, that is 7 on Mohs's scale, the SG lies between 3.30 and 3.36, and the refractive indices for the single crystals are near 1.654 and 1.667, but on the refractometer only a vague shadow edge will be seen at about 1.66. The SG of chloromelanite is usually higher than normal and may reach 3.5.

Absorption Spectrum

The absorption spectrum of jadeite is characterised by the presence of a strong line in the blue-violet at 437 nm. Accompanying this strong absorption band are similar but much weaker bands at 450 and 433 nm, and occasionally a vague band at 495 nm may be seen. The band at 437 nm is diagnostic for jadeite, but in the rich emerald-green material which is coloured by chromium this band, owing to the absorption of the violet due to the chromium spectrum, may not clearly be seen. However, the emerald-green jadeite will show lines in the red which are so characteristic of chromium coloration. These lines are at 691.5 nm, which is probably an unresolved doublet with lines at 694 and 689 nm. This main band is accompanied by weaker bands at 655 and 630 nm. Under long-wave ultra-violet light the paler-coloured green and the yellow, mauve and white jadeite show a whitish glow of low intensity, the darker-coloured jadeite being unresponsive. Very little is seen under the short-wave lamp. Under X-rays the paler shades show a white or yellowish-white glow, but it has been noticed that the colourless, pale yellow and mauve stone often exhibits a strong violet or blue-violet glow. Green jadeite shows green under the Chelsea colour filter.

Colour Range

Jadeite is found in most colours from pure white, through pink, brown, red, orange, yellow, mauve, blue, violet and black, to an extensive range of shades of green, and mottled green and white. The most highly prized colour, ascribed to chromium, is a rich emerald-green of great translucency. Jadeite, therefore, has a much greater range than has nephrite. A jadeite containing a considerable amount of the oxides of iron is called chloromelanite; it is dark green to black in colour. The mauve colour in jadeite has been ascribed to the presence of manganese and the duller greens to iron.

Occurrences

The only important commercial source of jadeite is upper Myanmar (Burma) where it is found *in situ* in dykes of metamorphosed rock of the Uru valley (a tributary of the Chindwin river). Tawmaw, Mainmaw, Pangmaw and Namshamaw are the chief dykes; the primary deposit at Tawmaw outcrops for a distance of about 6 km. The tough mineral is difficult to mine and the Chinese formerly used fire to break up the deposits. This is now superseded by modern methods of drilling and blasting. Alluvial jadeite boulders and pebbles are also mined from the Uru and other rivers of the Myitkyina district, particularly at Pakhan, Hweka and Mamon. The boulders are generally covered by a brownish skin due to weathering, and as with nephrite weathered boulders, this brown overlay is often made use of by the Chinese carvers in order to obtain a two-colour effect. Both the rock and the boulders were marketed through the Chinese province of Yunnan; hence the Burmese jadeite is sometimes called

'Yunnan jade'. The blocks were 'mawed' before sale, that is a flat of about 25 by 40 mm was polished on the piece in order to show something of the colour of the material, but as the colour may not be, and rarely is, uniform throughout, there is speculation as to how the piece will turn out. Burmese jadeite is now marketed through Yangon (Rangoon) and Thailand.

Jadeite was discovered in the south-western part of San Benito County, California in the mid 1930s. The mineral is found near Clear Creek as boulders and nodules in serpentine with pumpellyite and lawsonite. Stream boulders of jadeite are found at Williams Creek and on the north fork of the Eel river, Mendocino County and Trinity County, and a similar occurrence has been found in a glaucophane schist at Valley Ford, Sonoma County. There is a report of the finding of doubly terminated jadeite crystals along Russian river near Cloverdale in Sonoma County but this occurrence can have no gem significance. The occurrence of jade at Leach Lake mountain, which is sawn into slabs and exported to Germany for carving into art objects, is a nephrite-jadeite mixture found in placer and bedrock deposits. The jade from California ranges in colour from white through pale green to dark greyish-green to dark bluish-green and is generally semi-opaque.

Jadeite has been reported from China and Russia in the Polar Urals and Prebalkash. There is, however, a well-authenticated report of the finding of jadeite near the village of Kotaki in Niigata prefecture, Japan, but the material does not yield a high-quality gemstone.

Jadeite of various colours has been found in the Motagua Valley of Guatemala. This could be the source of the material used for carving by the Aztecs and other ancient civilisations of central America.

Whilst on a visit to Myanmar during 1963 Dr E Gübelin became interested in some bright green 'jades' nicely patterned by dark green to black spots and veins. He ascertained that the material apparently came from a place called Maw-sit-sit near Namshamaw in upper Myanmar, and that the Burmese called the stone *maw-sit-sit* after the place name. Subsequent investigation indicated that the black spots (chromite) are often surrounded by dark green kosmochlor (ureyite) – a chrome-rich analogue of jadeite, with bright green jadeite and a chromian amphibole with minor albite and zeolites. The refractive indices recorded varied from 1.52 to 1.54 and the SGs from 2.46 to 3.15.

Cutting of Jade

The jades are fashioned mainly as carvings (*Figure 13.4*), as beads or as cabochons, the smaller carved pieces being used for ring stones, brooches or drop ear-rings. The modern method of jade carving is that the rough jade piece is sawn into slab form of the requisite size, the design is marked out in pencil and the carving is carried out by the use of carborundum-tipped grinding tools (or diamond tools) driven from an electric motor, either through a fixed head, or through a flexible drive in a similar fashion to a dentist's drill.

Far different and more exacting were the methods used by the Maori and Chinese craftsmen, who cut their jade by the use of thin laminae of sandstone or a slate charged with sand and water and carved with wooden or stone pencils using the same abrasive. The Maoris used a pointed stick with sand and water or a flint splinter in the end of a cleft stick and rotated by crossed strings. The

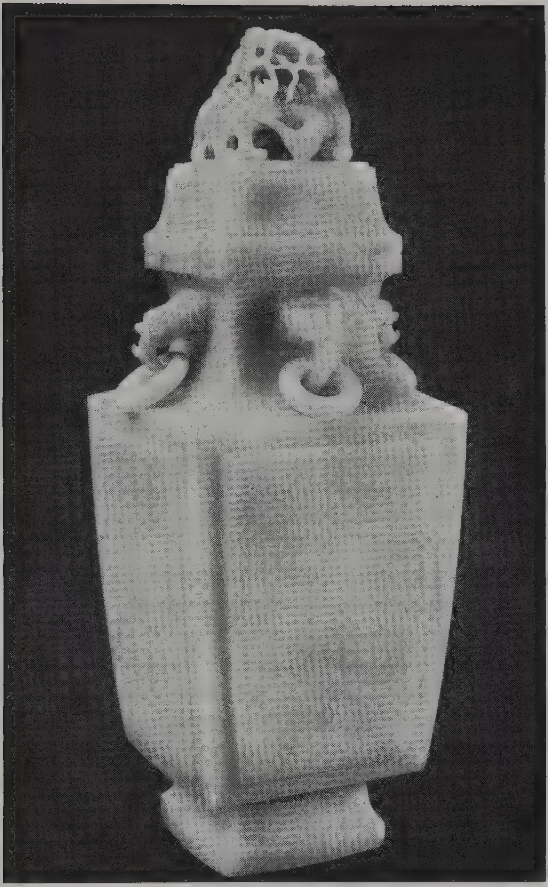


Figure 13.4 *A large vase and cover in Imperial sodden snow jade (nephrite), 380 mm in height: Chinese, Ch'ien Lung period (by courtesy of Sotheby and Co)*

Chinese had access to a most perfect drill in the hollow bamboo rod charged with sand and water. Gradually metal tools took the place of stone and bamboo until today the methods of carving are mechanised, but it must be said that modern workmanship, with all its aids, does not surpass the beauty of the work of the ancient craftsman; it may be faster, but the real beauty of jade carving was when time stood still.

Simulation

Many different minerals may simulate jade to a remarkable degree and a note of these minerals needs to be given. An example is the bowenite variety of serpentine which is found in Kashmir, Afghanistan and China. From the latter country many specimens of carved light yellowish-green bowenite have been exported to Western countries under the name, or rather misnomer, 'new jade'. Bowenite comes from Xinyan county, Laoning province. Bowenite is also found at Milford Sound on the west coast of Otago county, New Zealand, near to where the true nephrite occurs. It is a translucent deep green material with a pronounced similarity to jade and this New Zealand material was worked by the Maoris who called the stone *tangiwaite*. The bowenite variety of serpentine has more translucency and a greater hardness than is usual for serpentine, the hardness being near to 5.5 on Mohs's scale. The refractive indices have a mean about 1.52 and the SG is consistently near to 2.58 for the pale apple-green material and up to 2.62 for the darker green stone. The lower hardness – bowenite can be scratched with a knife blade – distinguishes this material from the true jades. The so-called 'Korea jade' is bowenite.

The massive prehnite of green colour can be a most convincing jade imitation. The material has an SG varying between 2.80 and 2.95 and is thus only a little less dense than nephrite. The hardness is 6 on Mohs's scale and the mean refractive index is 1.63, which are again not far different from nephrite. However, prehnite shows a distinctly reddish tinge when viewed through the colour filter, whereas the jades show green.

The so-called 'Transvaal jade', a massive grossular garnet, is easily distinguished from the true jades by its higher SG (3.48) and the refractive index (1.73), even if its somewhat different appearance to the jades did not give a clue to its identity. Under X-rays the green grossular garnet shows an orange fluorescent glow and is alone among the jade-like minerals to do so.

The particular sheen seen in the green variety of microcline feldspar, sometimes miscalled 'Amazon jade', is completely different from the lustre of jadeite or nephrite. The lower SG (2.56) and refractive index (1.55) are sufficient to identify such pieces.

The massive green variety of idocrase (sometimes intergrown with grossular garnet) known as californite has a jade-like character and may pass for the genuine material, especially as the SG is a little lower than for the crystal idocrase and varies between 3.25 and 3.35, thus overlapping the values for jadeite. The refractive index at 1.72 is, however, distinctly higher than for jadeite and will distinguish the material if the refractive index can be obtained.

The bluish-green smithsonite, which has been sold under the trade name Bonamite, is generally too translucent to be readily mistaken for jade. It is a zinc carbonate and thus will effervesce with acid, and, moreover, has a high SG of between 4.30 and 4.35; this 'heaviness' should be apparent even in a small specimen.

The green aventurine quartz miscalled 'Indian jade' is so manifestly different in appearance to the true jades that no confusion should arise, but the green chalcedony known as chrysoprase, or even the chalcedony artificially stained green, can approach jade in appearance. The lower SG (2.6) and the refractive index (1.55) readily separate this quartz mineral from the true jades. In this connection it is interesting to mention that some years ago there was a discovery of so-called 'jade' in Baker County, Oregon, which turned out to be the quartz known as plasma.

A decomposition product of basic igneous rocks, saussurite, is often of a grey-green, yellow-green or moss-green colour and is often variegated white and green and may closely resemble some of the jades. Saussurite is essentially a rock composed of albite and zoisite, together with variable amounts of sericite mica and calcite, etc. The hardness is near 6.5 on Mohs's scale and the SG is usually between 3.0 and 3.4, but may go as low as 2.8 when little zoisite is present. Likewise the refractive index can vary from 1.70 to as low as 1.57. Pectolite is another jade substitute.

Agalmatolite or 'figure stone' is a massive variety of the mineral pinite, an alteration product of iolite. The lower SG, about 2.80, confirmed by the low hardness of 2.5 on Mohs's scale, precludes any confusion with the jades. Some agalmatolite may be steatite (soapstone), which is even less hard. 'Styrian jade' or pseudophite does not have the typical colour of jade and moreover cannot be confused with it, as the Mohs's scale hardness is only 2.5, the SG about 2.7 and the refractive index 1.57.

Smaragdite, a foliated variety of amphibole often derived from diallage, has an emerald-green colour of considerable depth. The material is with difficulty distinguished from true jadeite, indeed chloromelanite may be a form of smaragdite, and it has been suggested that the material is so near jadeite that distinction is unnecessary. The SG of the material is 3.25.

There has been reported from New Guinea the finding of a chrome-rich precious stone said to be of a dark green colour with lighter-coloured veins and to be a chrome-rich jadeite intergrown with picolite, quartz, opal and limonite, and to have been derived from an olivine rock. The material has an SG of 3.35, and is named astridite after Queen Astrid of Belgium.

A beautiful green rock from the Barberton district of Transvaal and from Zimbabwe is verdite, which is a massive mica rock essentially composed of the green chromian muscovite called fuchsite. It often exhibits yellow and red spots, has a refractive index near 1.58 and an SG of about 2.9.

The serpentinous calcite known as verd-antique, or Connemara marble, could, to the uninitiated, be mistaken for a jade. This serpentine marble is quite distinctive with its green patches veined with white streaks and is easily distinguished from jade by the effervescence produced when the specimen is touched with a spot of acid. Further, the strong absorption band in the blue part of the spectrum at 465 nm may assist identification.

Pale jadeite has been artificially stained a fine green colour resembling Imperial jade. The colour may be seen to be concentrated along cracks in the stone and the absorption spectrum shows two broadish bands in the red part of the spectrum which are diagnostic. Such green-stained jadeite is prone to fade. A mauve colour is produced by staining, and in this case the stones are said not to fade, but the mauve colour is rather too pronounced and the stones look unreal. Mauve-stained jadeite shows absorption bands at 598 nm (broad) and 547 nm (moderate), but these have been seen weakly in natural mauve jadeite so cannot be a conclusive sign of staining. John Koivula found that many lavender jades of a pinkish-purple shade lose their colour when heated in the range 220–1000 °C. Furthermore, these jades showed a bright orange fluorescence under long-wave UV light. Lavender jades of a bluish-purple shade did not bleach and showed a weak brownish-red in these conditions. If, therefore, a lavender jade fluoresces bright orange and/or reveals traces of dye it should be treated with caution.

In the 1990s the bleaching of jadeite has become prevalent in Far Eastern markets and probably world-wide. The process involves two stages: firstly, the removal of brown (iron) staining by immersion in acids such as hydrochloric; and secondly, the impregnation of the treated jadeite with polymers such as Opticon and by paraffin wax (which has long been used for enhancing surface polish). Dealers refer to material so treated as 'grade B jade' or simply as 'B jade'. As well as removing the iron staining the immersion in acids also opens up the minute cracks between the grains and these may become easily visible under the microscope. Subsequent infillings of the cracks by resins may also be detectable under the microscope. The SG of the resin-treated jadeite is generally in the 3.22–3.25 range and it floats in di-iodomethane (3.32) whereas most natural jadeite will sink. Treated jadeite subjected to a hot needle or thermal probe may melt and produce a plastic smell, but finer material may not react in this fashion. Many natural jadeites do not react to UV radiation, but much bleached and impregnated jadeite shows a bluish-white to yellowish-green fluorescence to long-wave UV radiation – a useful but not conclusive test. Briefly, SG, luminescence and microscopic examination can help in testing but are not conclusive. To positively detect the presence of impregnating resins (Opticon, phthalates and others) and wax it is necessary to resort to infra-red spectroscopy – a very expensive technique used only in sophisticated laboratories.

An ingenious jadeite triplet has been made. In these stones a cabochon core is cemented into a hollow-cabochon top by the aid of a green-coloured cement, and the base closed in by a third piece of jadeite, white jadeite being used for the three component pieces. Such stones are very effective and are less easily detected than the green-stained cabochons, providing that the seam of the joining is masked by the setting. The absorption spectrum shown by these triplets is similar to that shown by the green-stained jadeite, that is one or two broadish bands in the red part of the spectrum. The chance of such stones fading is less likely.

Serpentine, probably a type of the bowenite variety, is also stained an Imperial jade green colour, and quite large carved pieces as well as bead necklets have been encountered in this stained serpentine. The material is much softer than jadeite and the broad bands seen in the red part of the absorption spectrum clearly indicate that the material has been stained.

A suitably coloured and opacified lead glass makes a convincing imitation of jade. The SG of these pieces is generally higher than for jadeite – it is usually about 3.7 – but the nature of the pieces is obvious when the surface is examined by a lens, for such a glass will show pit marks where included gas bubbles have been cut across. Some of the plastics are made to simulate jade by their colouring, and as far as that is concerned are quite effective. The exceptionally low SG and the ready sectility quickly distinguishes them.

In 1984 General Electric of America announced the synthesis of jadeite. Colours produced included greens and lavender with textures resembling natural material in many respects. There were no significant differences in refractive indices, specific gravity or fluorescence, but the 437 nm absorption line was not seen in synthetic material. The hardness was 7.5–8 in contrast to 6.5–7 for natural jadeite. At present GE has no plans for commercial production, but a similar process has been patented in Japan. In view of the high cost of production and the ready availability of natural material it seems unlikely that synthetic material will be encountered on a commercial basis.

The reddish variety of dumortierite in quartz and a quartzite, stained by either rhodonite or rhodochrosite, have both been sold under the misnomer red (or pink) jade. Said to come from Italy and sold under the trade name of Oxalite, or Oxolite, is a material which is understood to be made from calcined beef bone and bears a resemblance to ivory, or if coloured green, imitates jadeite.

14

Marcasite and Hematite

Marcasite

The marcasite of jewellery, then usually pronounced as 'marcazeet', is, so far as the stone by this name used in jewellery is concerned, a misnomer, for the true marcasite of the mineralogist rarely ever appears in jewellery, the mineral pyrites being used almost exclusively. The confusion over the name is due to the fact that in the early eighteenth century, when minerals were not accurately determined, marcasite and pyrites were habitually mistaken for one another.

Chemical and Physical Properties

Marcasite and pyrites have the same composition, iron sulphide (FeS_2), but are dimorphous, that is they crystallise in different systems, marcasite in the orthorhombic system and pyrites in the cubic system.

The marcasite of the mineralogist is the unstable form of iron disulphide and crystallises in rhombic crystals which are often twinned and with spear-shaped habit, or are aggregates of flattened twin crystals in crest-like forms to which the name 'cockscomb pyrites' is given. The colour of the mineral is bronze-yellow and the SG lies between 4.85 and 4.90. Marcasite is of world-wide occurrence, and many specimens of the spear-shaped habit are found in the chalk between Dover and Folkestone and in the corresponding rocks on the Pas-de-Calais side of the English Channel.

Pyrites, the jeweller's 'marcasite', has been used in jewellery for hundreds of years. It was apparently first used in ancient Greek jewellery and has been found in the tombs of the Incas, often as large polished pieces which were probably used as mirrors. Hence pyrites has been called *pierre des Incas*. Marcasite, as the jewellery trade knows the mineral, has had many vicissitudes; its first real vogue in more recent times was during the mid eighteenth century and its popularity was said to be due to the Comtesse du Barry. The material again became fashionable during the middle of Queen Victoria's reign. Marcasites are usually set in silver for the stone does not harmonise with gold, and today the stone is much used in inexpensive jewellery.

Pyrites forms crystals which may be cubes and which have striations on each face running in a direction at right angles to those of the adjacent faces; this proves that the crystal does not have the full symmetry of the cubic system (*Figure 14.1*). Another common form of crystallisation is that known as the pyritohedron which consists of twelve five-sided faces (*Figure 14.2*). Many of the crystals of pyrites possess brilliantly lustrous faces and this is particularly so with the crystals which come from the island of Elba and some other localities. Frequently pyrites is found massive or radially fibrous and in fibrous nodular forms with a botryoidal surface. Such nodules can be picked up from the chalk of the South Downs in Sussex, England, and are often thought by the finder to be 'thunderbolts' (meteorites), which of course they are not. Such pyrites nodules are occasionally brought in to jewellers by their customers asking whether they are gold, or contain gold. It is true that some pyrites does contain a small quantity of gold but, excepting the so-called 'auriferous pyrites', the gold content has no commercial value and would not pay to refine. It is owing to the brassy appearance of much pyrites that the name 'fool's gold' has been applied to the mineral.

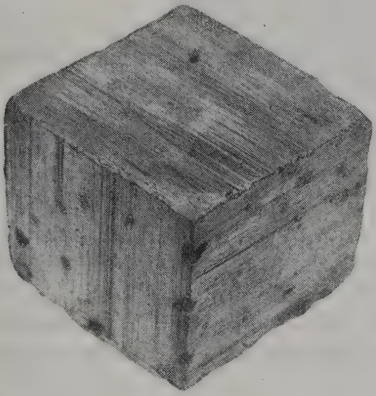


Figure 14.1 Striated cube of pyrites

Figure 14.2 A double pyritohedral crystal of pyrites

Pyrites has a brass or bronze-yellow colour and a high metallic lustre when polished. The hardness of the mineral is 6 to 6.5 on Mohs's scale, and the material is somewhat brittle. The SG varies between 4.95 and 5.10, and the 'streak' or mark made by pyrites when rubbed across an unglazed porcelain plate (a streak plate) is greenish-black or brownish-black.

Cutting and Setting

The marcasites used in jewellery are pyrites cut and polished to a circular outline with a low pyramid of six faces on top and with a flat base, in fact a flattened rose cut. These marcasites are, in the best jewellery pieces, hand set, the stones being held in place by small grains turned over from the setting on to the edge of the stone. In cheaper pieces they may be simply cemented in. The mineral is cut and distributed mainly from the Jura Alps in France.

Marcasite (pyrites) is a durable stone which does not rust like cut steel. Owing to the fibrous nature of the mineral a sharp knock may crack the stone which may then loosen it from the setting so that it may readily fall out, but with normal use and care such accidents should not occur. Much modern marcasite-set jewellery is mounted in silver which has been rhodium-plated to prevent the silver tarnishing.

Simulation

Imitations of marcasite are few. In some old jewellery roses of cut steel have been used, the mounting being ordinary white metal and not silver. These earlier steel pieces were produced in Birmingham and Wolverhampton in England and the jewellery pieces were of fine workmanship and good design. During the early part of the nineteenth century a Frenchman invented a process for the making of these steel pieces. The French type can be distinguished from the older English type by the steel studs on the base whereby they were fixed to the mount.

The modern imitations of marcasite are almost invariably mounted glass (paste) which are usually only cemented in the mount and not set by rolling over the mounting metal. The vitreous lustre, the moulded look of the facet edges and the pit marks of cut-through glass bubbles are certain indications of their nature.

Hematite

Chemical and Physical Properties

The compact type of iron oxide (Fe_2O_3) called hematite, or by the older spelling haematite, owes its name to the red colour of the powdered mineral which resembles dried blood. The German name for this iron oxide is *blutstein* (bloodstone) and has a similar derivation, but this term is confusing, for the English bloodstone is a variety of green chalcedony flecked with red spots of jasper.

Hematite is found in various states of compactness, and varies from a soft red paint ore which was used by early American Indians to deck their faces before

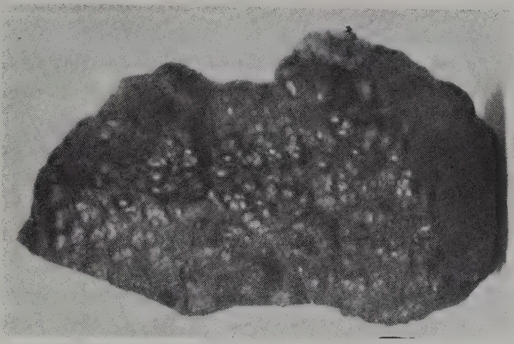


Figure 14.3 Mass of kidney ore hematite

battle, and today as a pigment, through various degrees of compaction, most of which are used as an ore of iron for smelting, to a hard compact form which may be cut for jewellery.

The compact forms of hematite are found in large nodular masses made up of radially fibrous crystals producing a reniform nodule. Such nodular masses, from their shape, are often known as kidney ore (*Figure 14.3*). Hematite is occasionally found in the form of lustrous rhombohedral crystals, the faces of which are often tarnished, giving a colourful iridescent surface. Beautiful groups of such crystals are found in the isle of Elba. As a point of interest there are found in the Ticino and Grison regions of Switzerland beautiful crystallised specimens of hematite composed of a rosette of platy crystals. These are known as iron roses. Around Cleator Moor in Cumberland, England, are found masses of kidney ore which break up into pointed fibrous crystalline fragments from which term 'pencil ore', sometimes given to hematite, is derived.

Hematite crystallises in the trigonal system and the colour of the compact material used in jewellery is blue-black. The hardness of these purer types may be as high as 6.5 on Mohs's scale and the SG varies from 4.95 to 5.16. The refractive index, according to a determination made by special methods, is 2.94 for the extraordinary ray and 3.22 for the ordinary ray, but the refractive index is too high to allow the constant to be tested by normal methods, and has, therefore, academic interest only. The easiest test for hematite, although in the case of one imitation there is a chance of misidentification, is to rub the edge of the stone on a streak plate (white unglazed porcelain) which, if the stone is hematite, results in a red streak on the plate. Indeed, powdered and purified hematite is the red polishing powder known as jeweller's rouge.

Cutting and Fashioning

The uses to which cut and polished hematite is put in jewellery are as modified trap-cut stones or as brilliant-cut stones, at least so far as the crown of the stone is concerned, for the bases of such stones are usually flat and left unpolished. To the unwary the brilliant-cut hematite when set may have the appearance of black diamond. Beads have also been produced and in this connection such forms have been used to imitate black pearl. The most common use of hematite is for the production of seal stones, and these are most commonly cut as intaglios. Cameos in hematite are also produced and are often cut as curvettes, that is the raised carving lies in the centre of a bowl-shaped depression in the stone, the outer edge being raised, probably in order to protect the carving to some extent. Such a style of fashioning is known as chevee in North America. Most of the fashioning of hematite is carried out at Idar-Oberstein in Germany from material imported from Cumberland, England.

Simulation

Hematite is cunningly imitated by various artificial materials which have colour and appearance very like that of the true material. The composition of such imitation hematite is not surely known and may consist of a number of different types. These imitations are sometimes attracted by a magnet; they may show a red streak, and 'intaglios' are pressed in and not carved which provides a distinction from hematite. Hematite is not usually magnetic, but in recent years some specimens from Brazil have been found to have a magnetic response. A synthetic 'hematite garnet' has been produced in Zimbabwe. In appearance like hematite, the material has an SG near 4.16, shows a deep red when a strong light is passed through it and reveals an intense almandine spectrum.

Psilomelane

Resembling hematite, for which stone it has recently been used as a simulant on account of the scarcity of hematite itself, is the mineral psilomelane. Usually found in botryoidal or stalagmitic forms, the mineral is regarded as a colloidal manganese oxide with the oxides of barium, potassium and sodium, and some water. The hardness can vary from 5.5 to 6.5 on Mohs's scale and the SG varies greatly, but specimens of gem material have been found to average about 4.35. Detection from hematite is by its more silvery lustre; by its brownish-black streak (that of hematite is red); and by the fact that a drop of hydrochloric acid placed on an inconspicuous part of the specimen will dissolve the area and release chlorine gas which has an irritating and suffocating smell. The material seems to form a perfect conductor for an electric current and this provides a test against the true hematite which, although variably conductive, is at best weakly so as against that of psilomelane.

Other Metallic Ores

Other metallic ores have been cut and polished, usually for the whim of collectors. Some of these are as follows.

Chalcopyrite

Chalcopyrite, or as it is better known copper pyrites, is more important as an ore of copper than as a gem material. The mineral is brass-yellow in colour and is usually found massive and less commonly as crystals which belong to the tetragonal system. Chalcopyrite is a sulphide of copper and iron ($CuFeS_2$) and has a hardness of 3.5–4 on Mohs's scale. The SG of the mineral is near to 4.2 and the mineral is distinguished from pyrites by its deeper yellow colour and lower hardness. The occurrences are world-wide.

Cobaltite and Smaltite

Cobaltite is a sulphide of arsenic and cobalt, CoAsS, which crystallises in the cubic system and may be found as cubic or pyritohedral crystals, or in massive form. The mineral is opaque and has a silver-white colour tinged with pink, and the lustre is metallic. The hardness is 5.5 on Mohs's scale, and the SG is between 6.0 and 6.3. Cobaltite is found in well-formed crystals at Tunaberg in Sweden and Skutterud in Norway. Other sources are Cobalt, Ontario, Canada; Dashkesan in Transcaucasia; and the Botallack mine, St Just, Cornwall, England.

Another mineral, smaltite, the cobalt arsenide, $CoAs_3$, has been cut. The mineral forms cubic crystals but is usually found massive; it has a tin-white to steel-grey colour and a metallic lustre. The hardness is 5.5 on Mohs's scale and the SG lies between 6 and 6.3. It is mainly found at Cobalt, Ontario, Canada, and to a lesser extent in Germany, France, Spain, Morocco and Chile.

Breithauptite, Chromite, Niccolite and Pentlandite

Chromite is an oxide of chromium and iron ($FeCr_2O_4$) and is iron-black to brownish-black in colour. The mineral crystallises in the cubic system but the material is usually found massive. The refractive index is 2.1 and the SG lies between 4.1 and 4.9. The hardness is 5.5 on Mohs's scale. Chromite is found in the United States of America, Asia Minor, Silesia, Austria, France, New Caledonia and Zimbabwe. Chromite is feebly magnetic.

Niccolite, the nickel arsenide, NiAs, is also known as kupfernickel, and is a pale red mineral with a metallic lustre. The hardness is 5–5.5 on Mohs's scale and the SG varies from 7.33 to 7.67. The crystal structure is hexagonal but crystals are rare and the mineral is nearly always found massive. Niccolite is found in central Europe, France, Canada and in the United States of America.

The bronze-yellow nickel iron sulphide mineral called pentlandite has been cut for the whim of collectors. It has a hardness of 3.5 to 4 on Mohs's scale and an SG of 5. It is not magnetic.

Another nickel ore which has similarly been cut is breithauptite. Copper-red in colour, the mineral is a nickel antimonide and has an SG of 7.54.

Columbite, Samarskite and Euxenite

Columbite and samarskite are two related minerals of a black colour and with a semi-metallic lustre. Columbite is a niobate and tantalate of iron and manganese and has a hardness of 6 on Mohs's scale and an SG varying from 5.2 to 8.0, with an increase of tantalum when the mineral merges into the pure tantalate of iron and manganese. Samarskite is an extremely complex mixture of the oxides of niobium and tantalum with rare earth oxides. Velvet-black in colour, the mineral has a hardness of 5–6 on Mohs's scale and an SG varying from 4.1 to 6.2.

The third of these gemmologically unimportant minerals is euxenite, a niobate and titanite of yttrium, erbium, cerium and uranium. The mineral is brownish-black in colour, has a hardness of 6.5 on Mohs's scale and an SG varying from 4.7 to 5.0. Euxenite is found in Madagascar, Norway, Brazil, Finland, Canada and the United States of America. A tantaliferous variety is found in Australia.

Domeykite, Algodonite and Bornite

Specimens of these copper minerals have been cut for collectors. Both domeykite and algodonite are copper arsenides found as irregular lumps in the copper mines of Michigan. The colour is tin-white to steel-grey but quickly tarnishes on exposure to the air. The hardness on Mohs's scale is 3.5 to 4, and the SG for domeykite is 7.2 to 7.9, and for algodonite about 8. Bornite, sometimes known as 'peacock ore' owing to the surface tarnishing with the production of iridescent colours, is a sulphide of copper and iron. The colour is usually copper-red, and the hardness 3 on Mohs's scale. The SG varies between 4.9 and 5.4.

15

The Natural Glasses

Natural glasses occur in a number of forms and compositions while consisting mainly of silica. Even today the precise origin of some of the natural glasses is uncertain. Many are used ornamentally and some large, clear pieces have been faceted.

There is considerable variation in the chemical composition, but obsidian may contain up to 77 per cent silica with 10–18 per cent alumina. Had a rock formed instead of obsidian it would have consisted of quartz, feldspar and mica.

Obsidian

Obsidian is formed by the rapid cooling of volcanic lava, which, had it been allowed to cool slowly, would have developed a crystalline structure. A network of curving cracks can be characteristic of some varieties of obsidian. The resulting texture is known as perlitic, and disintegration along the cracks gives bead- or ball-shaped pieces. The name marekanite has been used for these pieces, the name being taken from the Siberian locality. The name has also been used for similar material from Mexico which produces a spherulitic textured obsidian with radiating feldspar fibres, known as peanut obsidian. This is found in the neighbourhood of Sonora.

Obsidian is normally an opaque black or grey but may be yellow, red or greenish-brown. It may have an iridescent sheen caused by reflections from minute inclusions as seen in the silver and golden obsidians which are often polished into beads for necklaces. In the United States of America a variety of obsidian having spherulitic inclusions of a white mineral on the black groundmass is cut and polished. This material is called 'flowering obsidian'. A variety banded black and red is termed 'mountain mahogany' and is sometimes used for ornamental objects and for carvings. A transparent leaf-green obsidian has been mentioned, but green is a very rare colour and most transparent green obsidians are usually found to be moldavites or merely green glass. Red and blue obsidian has been reported.

Moldavite consists of approximately 75 per cent silica with 10 per cent alumina; it may also contain oxides of iron, potassium, calcium, sodium, magnesium, titanium and manganese. The hardness is near 5.5, the specific gravity ranges from 2.30 to 2.50 and the refractive index is 1.48–1.52. The absorption spectrum with vague bands in the orange and blue is little help in identification. A faint yellowish-green under X-rays is the only fluorescence. Profuse rounded or torpedo-shaped bubbles with swirls and striae are very characteristic of moldavite; the crystallites seen in obsidian are absent here. The name marekanite has also been applied to material from Mexico. Glassy pebble-like solid cores of unaltered glass, 25 mm or more across, from the decomposed obsidian of the American south-west, are known as 'Apache tears'. The transparent ones when cut produce stones of a grey or light grey colour and may show fine silky striations which give to the stone a cat's-eye effect. A brown-black obsidian from Hungary is called 'Tokay lux-sapphire'.

Chemical and Physical Properties

Obsidian has a hardness of near to 5. The fracture of obsidian is eminently conchoidal, and it is due to the facility with which the material can be broken into sharp-edged flakes that obsidian was so valued by Stone Age people who lived in areas where obsidian was common, the easily controlled flaking allowing the production of keen-edged spear points, knives and tools.

The lustre of obsidian is vitreous; the index of refraction lies between the limits of 1.48 and 1.51, but is most commonly near 1.49. Thin fragments viewed between crossed polars show the groundmass of the material to be isotropic but the field is speckled with bright points of light due to very small crystalline particles. These crystallites, owing to incipient crystallisation, are always present in volcanic glass. The SG of obsidian varies between 2.33 and 2.42, at least for the types used in jewellery.

When a thin sliver of obsidian is examined under the microscope the texture is seen to consist of a clear glassy ground containing many small crystallites. These may be round bodies which are called globulites, they may be rod-shaped when they are called belonites, or they may be coiled or twisted hair-like bodies termed trichites. When the small globulites are fused into chains the term margarites is used, probably in fanciful analogy to a string of pearls. It may take a fairly high magnification to resolve these bodies. Round or torpedo-shaped bubbles are present in some obsidian. These, which can generally be seen clearly with low-power magnification, are often in parallel arrangement, and it is this parallelisation of the bubbles and the crystallites which give to some obsidian the prized sheen (*Figures 15.1* and *15.2*).

Occurrences

Obsidian is widespread in occurrence, but most of the material used in jewellery is obtained from the North American continent. Important localities are the Glass Buttes, Lake County, where iridescent obsidian is found, and at Hampton, Deschutes County, Oregon. At Obsidian Cliff, Yellowstone National Park in

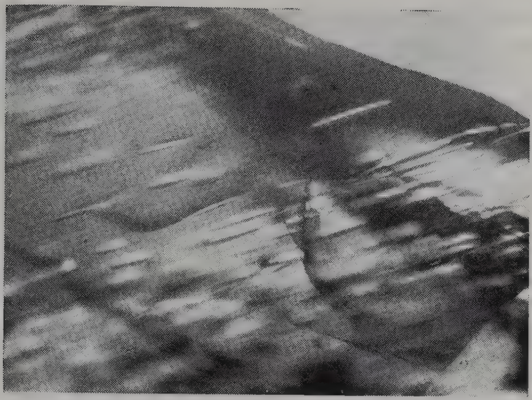


Figure 15.1 *Long torpedo-shaped bubbles in a golden obsidian*

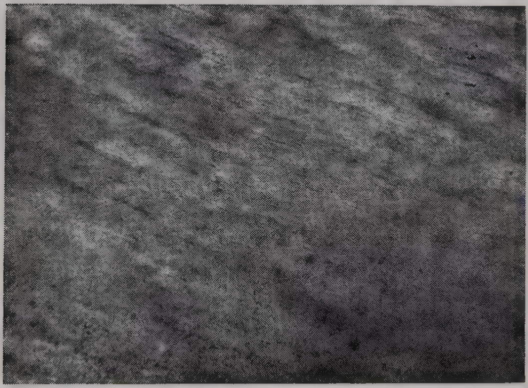


Figure 15.2 *Needle-like inclusions running in one direction in a silver obsidian. These are possibly the cause of the silver sheen*

Wyoming, obsidian has been quarried since the days of the North American Indians, who used it for arrowhead material. Arizona, Colorado and Nevada have deposits of obsidian, while California has many sites where the material has been quarried from ancient times. The best known of these Californian sources are Glass Mountain, Modoc County; Little Lake, Inyo County; and Obsidian Butte on the south-west side of Salton Sea in Imperial County. 'Apache tears' are usually found in New Mexico.

Obsidian was used by the Aztecs and their predecessors for the sharp points of their weapons, for mirrors and masks, and for dainty ear ornaments. They called the material *iztli* and surnamed it *teotetl* (divine stone) because of its manifold uses. The ancient Aztec obsidian pits were rediscovered by Humboldt during the opening years of the nineteenth century at Sierra de la Navagas in the state of Hidalgo, Mexico. Obsidian is found at several other places in Hidalgo, and in the other Mexican states of Jalisco, Queretaro, Michoacan and

Vera Cruz. The Maya obtained their obsidian from ancient quarries at La Joya, some 30 km east of Guatemala City, and the Indians of Equador had a quarry at Guamani.

Obsidian is present at those places where volcanic activity occurs or has occurred in the past. Such places are the Lipari Islands, Hawaii, Japan and Iceland – where the greyish obsidian which is cut and sold under the misnomer 'Iceland agate' is obtained – apart from the localities already mentioned.

Basalt Glass

Basalt glass, which is found mainly on the chilled margins of basaltic intrusions, or lining or filling vesicles or cavities in basalt, is semi-translucent to opaque and usually black or brown in colour. It contains about 50 per cent of silica. Basalt glass, which has a hardness of about 6, does not afford large flakes or show extensive conchoidal fracture when struck with a hammer, but breaks up into small irregular fragments and splinters. These glasses have a refractive index between 1.58 and 1.65 and a range of SG between 2.70 and 3.00. Under low-power magnification the texture is seen to be uniform and the structure cannot be resolved except under high power. Basalt glasses are not normally cut as gem material but some experimental cabochons have been cut from the light grey, navy-blue, bluish-green and brown pieces found near the headwaters of the Flinders river in northern Queensland. The pieces are often attractively mottled and spotted.

Meteorites

Those extraterrestrial objects called meteorites are hardly expected to enter the field of gems, but, as will be explained, one such type of suspected meteorite has been used for ornamentation.

A meteorite is understood to be part of a disintegrated stellar body which, travelling through space, has entered the gravitational field of the earth and crashed on to its surface; thus it may be said to have cosmic origin. There are two general types of meteorites: those whose constitution is mainly iron and nickel, known as siderites; and those which consist of olivine, pyroxene and a little feldspar and thus approach the basaltic rocks in composition. These are termed aerolites.

Tektites

It is not the metallic or stony objects from the skies which interest those who study gems, but a type having a glass-like constitution rich in silica, and which can be likened to the volcanic glass obsidian. These pieces, which are only suspected as being of meteoritic origin, have been given the name tektites.

The first noted occurrence of these glassy pieces was in 1787 in western Moravia and around České Budějovice near the Bohemian river Moldau, a river of which the Czech name is Vltava. Derived from the former name of the river,

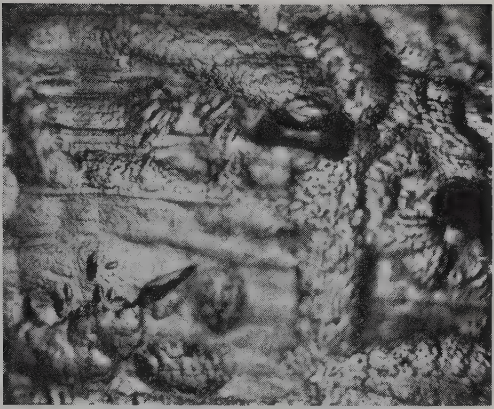


Figure 15.3 Surface structure of a moldavite pebble

the pieces were called moldavites. These lumps of glass, often peculiarly fissured on the surface – either reminiscent of alpine topography with craggy mountain tops, or with rounded crests having a botryoidal surface (*Figure 15.3*) – are transparent green, greenish-brown or brown in colour. The material has been cut as gemstones producing bottle-green stones. Cut moldavite has been sold under a variety of fancy and completely misleading names, such as 'bottle stone', 'obsidian', 'water chrysolite' and 'pseudo-chrysolite'. The stone has also been known under the name bouteillenstein.

Czech moldavites fall into three categories. Oval or spherical specimens from the Radomilice area of southern Bohemia are pale or bottle-green with few included bubbles and less obviously flattened. These are silica-rich and alumina-poor with little lechatelierite (i.e. near the silica glass composition). Moldavites from most other southern Bohemian finds are bottle-green, more flattened and with profuse bubbles (*Figure 15.4*). Their lechatelierite content is higher, with Si, Al and Fe content intermediate between the first type and a type found in Moravia, coloured brown and with more Al and Fe than other types.

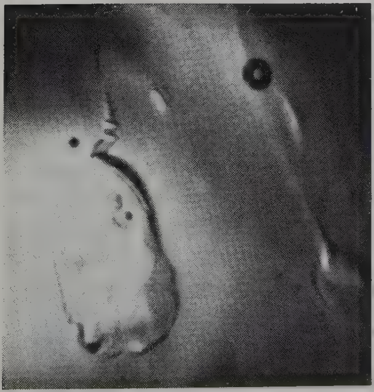


Figure 15.4 Internal structure of a moldavite

Moravian specimens have fewer bubbles and are spherical. Four different occurrences are reported. Some are found in Upper Miocene sediments and others in Pliocene and Pleistocene sediments. Slope lavas, possibly Pleistocene, and Holocene or Pleistocene alluvia house the remainder. Moldavite from Chlum nad Maisi in southern Bohemia has been used in jewellery in recent years.

Button-shaped glass pieces (australites) have been found in South Australia and Tasmania. The variety billitonite was found on Billiton Island between Sumatra and Borneo, and specimens tend to be dark brown (*Figure 15.5*).

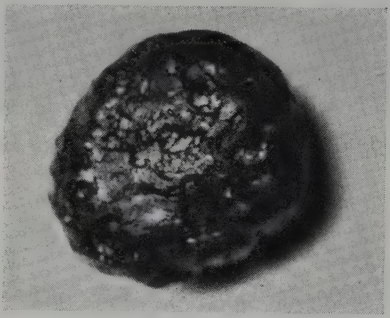


Figure 15.5 *A billitonite showing the surface structure*

Colombia produces colourless tektites but whatever the origin they tend to be button-shaped. The Jukes-Darwin field near Queenstown, Tasmania, produces silica-rich and alumina-poor colourless to olive-green to black specimens with specific gravity 1.85–2.30, with the varietal names darwinite or queenstownite.

Crater Glass

Other types of natural glasses exist which, although not of meteoritic origin, have had their genesis in meteoritic action. One type is obtained from meteoritic craters, the glass being formed by the intense heat generated by the impact of a meteor on to the earth's surface where the surface cover is siliceous, such as in a sandy desert.

Such glass, white, greenish-yellow or black in colour, is in general simply a fused quartz, about 90 per cent silica with some impurities, of which the most common is iron. The material is slaggy and contains numerous vesicles. The specific gravity of these glasses varies from 2.10 to 2.31, a range which is lower than for the previously mentioned moldavites and tektites. The value is in many cases lower than that for pure fused quartz (silica glass, 2.203), probably owing to the included vesicles. The refractive index varies from 1.46 to 1.54, the high values probably being due to a richness in iron. This crater glass has been found in many widely different places, mostly in localities known for their sandy deserts, such as Wabra in Saudi Arabia, Henbury in central Australia, and at Meteor Crater, Arizona, in the United States of America.

Plate 1
Suite of natural-colour diamonds (photo by Shane F McClure, GIA Gem Trade Laboratory)

Plate 2
Emerald crystals from the Ural Mountains, Russia (photo by Shane F McClure, GIA Gem Trade Laboratory)

Plate 3
Faceted zoisite from Tanzania in a range of colours (courtesy Pala International: photo by Shane F McClure, GIA Gem Trade Laboratory)

Plate 4
Green zoisite crystal from Tanzania (courtsey Pala International: (photo by Shane F McClure, GIA Gem Trade Laboratory)

Plate 5
Fashioned and rough tanzanite (courtesy Andrew Sarosi: photo by Shane F McClure, GIA Gem Trade Laboratory)

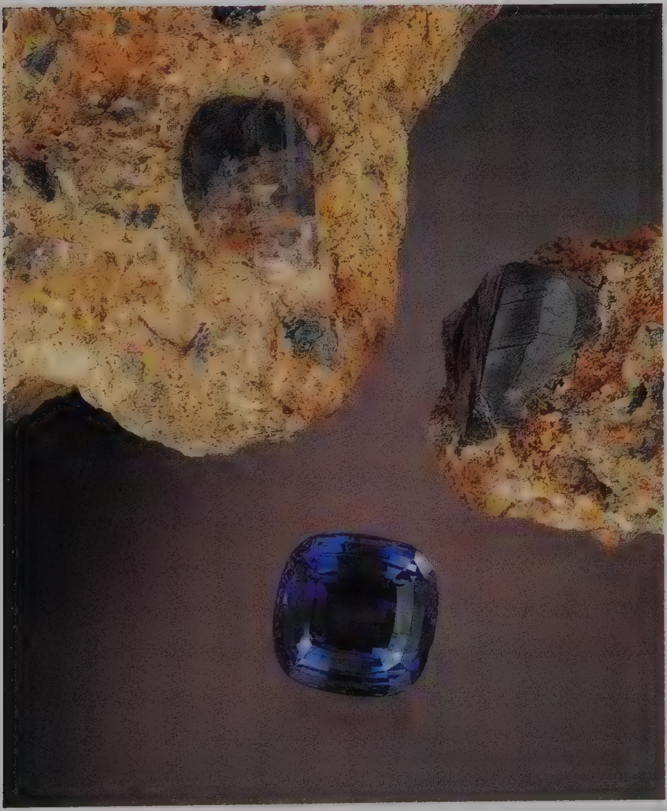


Plate 6
Tanzanite, faceted and in matrix (courtesy Gerhard Becker: photo by Shane F McClure, GIA Gem Trade Laboratory)

Plate 7
Suite of rough and faceted beryl (photo by Shane F McClure, GIA Gem Trade Laboratory)

Plate 8
Suite of less common to rare faceted gems: left (top to bottom) phenakite, rhodochrosite, apatite, taaffeite; centre (top to bottom) apatite, fluorite, enstatite, apatite; right (top to bottom) scapolite, euclase, sinhalite, sillimanite (photo by Shane F McClure, GIA Gem Trade Laboratory)

Plate 9
Suite of topazes (photo by Maha DeMaggio, GIA)

Plate 10
Suite of natural spinels (photo by Maha DeMaggio, GIA)

Plate 11
Suite of garnets (photo by Maha DeMaggio, GIA)

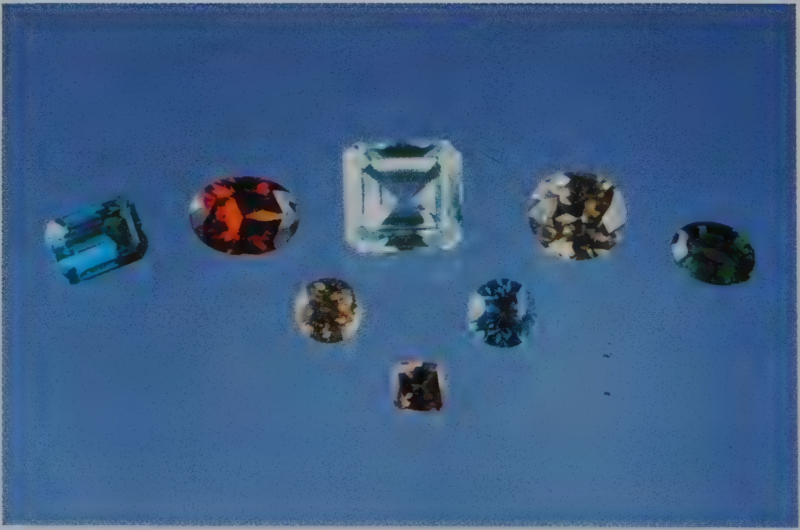


Plate 12
Suite of zircon gems (photo by Maha DeMaggio, GIA)

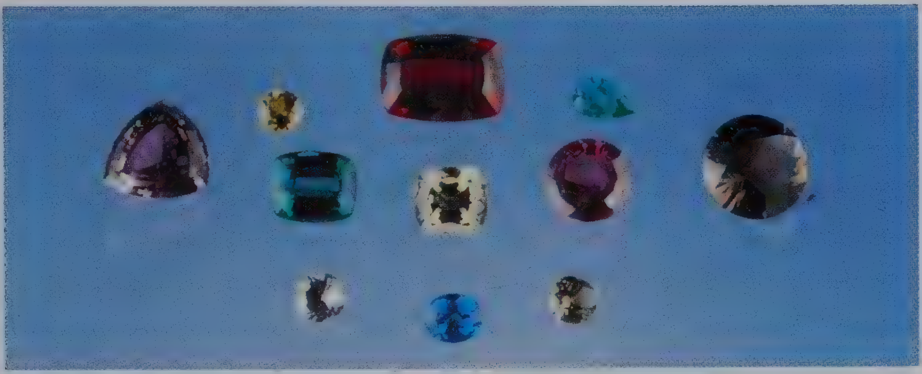


Plate 13
Suite of tourmalines (photo by Maha DeMaggio, GIA)

Plate 14
Suite of quartz gems (photo by Maha DeMaggio, GIA)

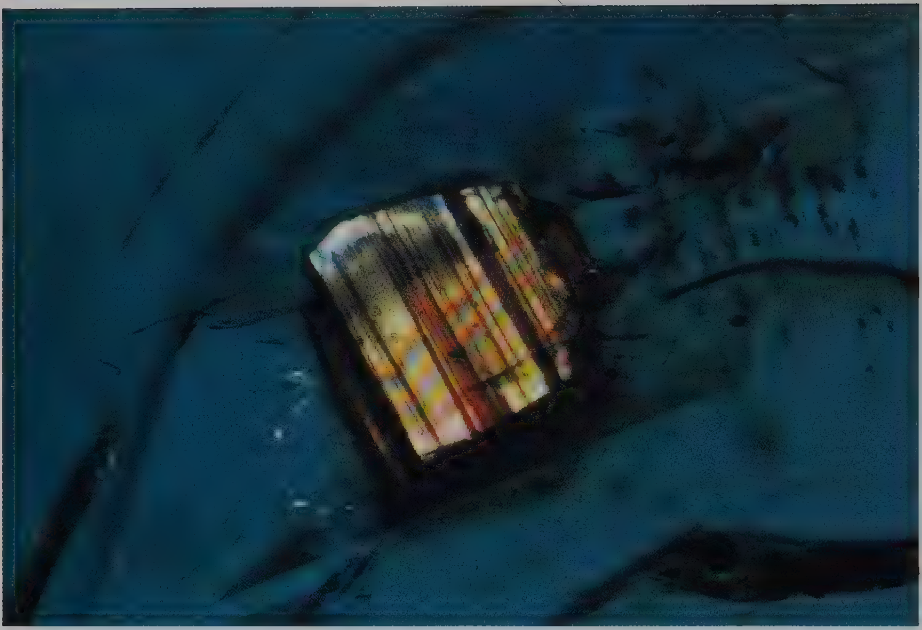


Plate 15
Monzanite crystal inclusion in topaz of pegmatitic origin (photomicrograph courtesy of John I Koivula)

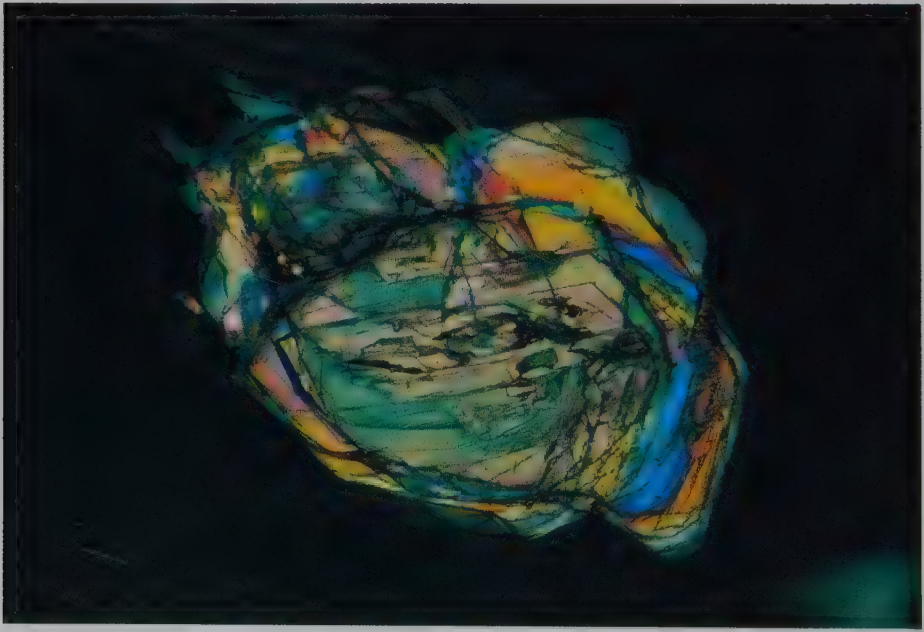


Plate 16
Muscovite mica, another typical inclusion in topaz (photomicrograph courtesy of John I Koivula)

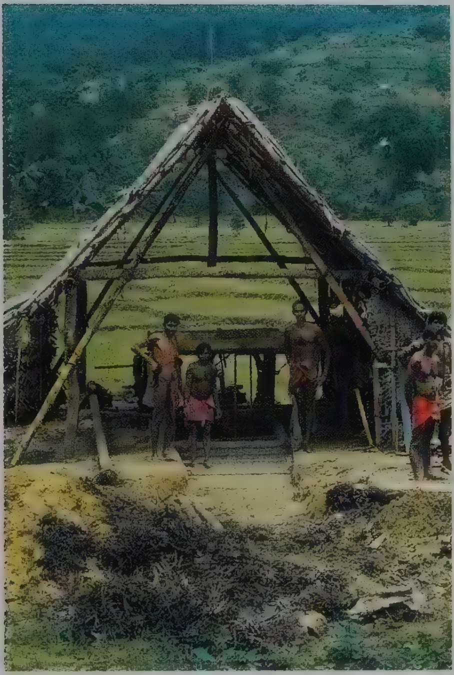


Plate 17
Gem mining near Ratnapura, Sri Lanka (photo by Robert C Kammerling, GIA Gem Trade Laboratory)

Plate 18
Examining gem gravels near Ratnapura, Sri Lanka (photo by Robert C Kammerling, GIA Gem Trade Laboratory)

Plate 19
Simple gem fashioning using bow-driven cutting wheel, Ratnapura, Sri Lanka (photo by Robert C Kammerling, GIA Gem Trade Laboratory)

Plate 20
Garimpeiro washing eluvial gravel in stream, 20 km east of Tres Barras, Minas Gerais, Brazil (photo by Robert C Kammerling, GIA Gem Trade Laboratory)

Plate 21
Washing gem gravels in a stream in the Mogok Stone Tract, Myanmar (Burma) (photo by Robert C Kammerling, GIA Gem Trade Laboratory)

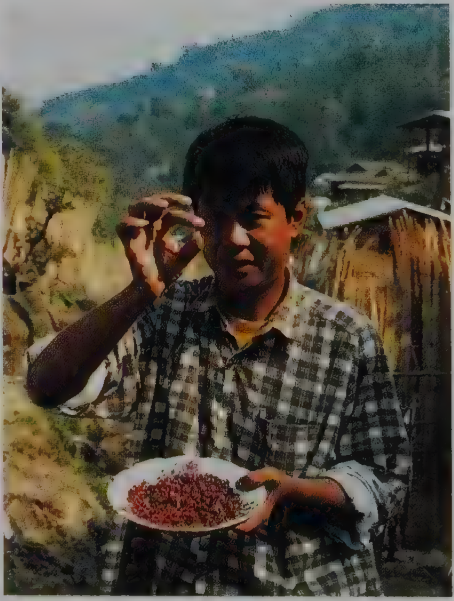


Plate 22
Examining part of two days' production at Thantya, a joint-venture primary ruby mine, Mogok Stone Tract, Myanmar (Burma) (photo by Robert C Kammerling, GIA Gem Trade Laboratory)

Plate 23
Nasute soldier termite in amber from the Dominican Republic (photomicrograph courtesy of John I Koivula)

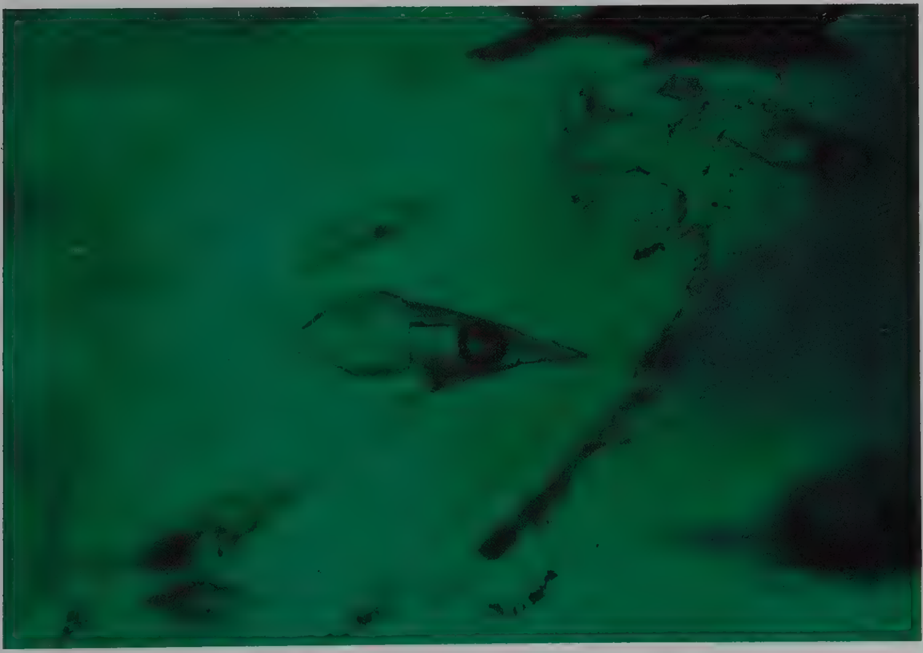


Plate 24
Three-phase inclusion in a Colombian emerald (photomicrograph courtesy of John I Koivula)

Plate 25
Uranium pyrochlore in a sapphire from Pailin, Kampuchea (Cambodia) (photomicrograph courtesy of John I Koivula)

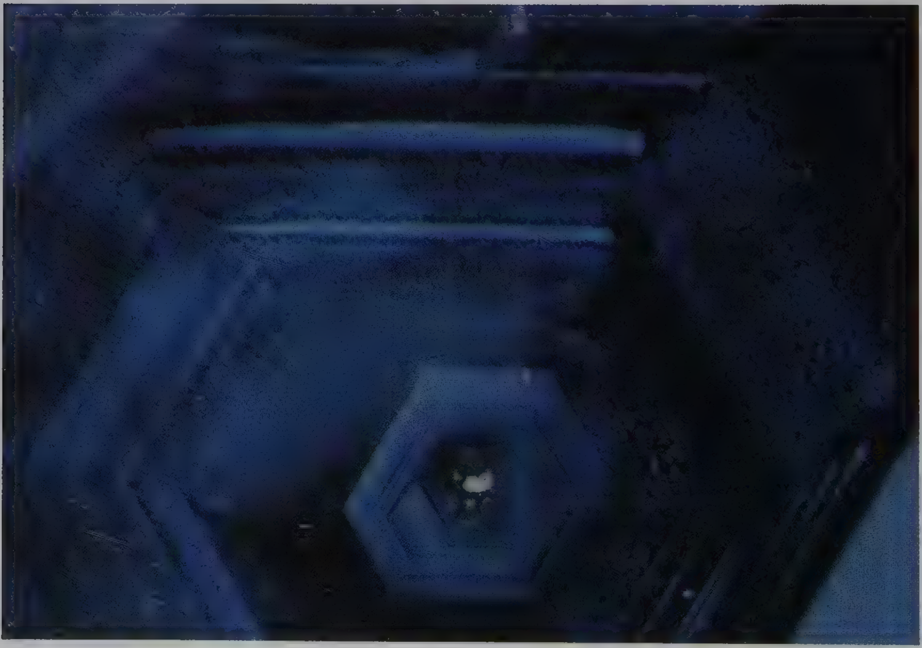


Plate 26
Montana sapphire with hexagonal zoning accented by rutile (photomicrograph courtesy of John I Koivula)

Plate 27
This ruby from Thailand hosts a layer of iridescent fluid inclusions (photomicrograph courtesy of John I Koivula)

Plate 28
Boehmite needles accentuate twin planes in a Thai ruby (photomicrograph courtesy of John I Koivula)

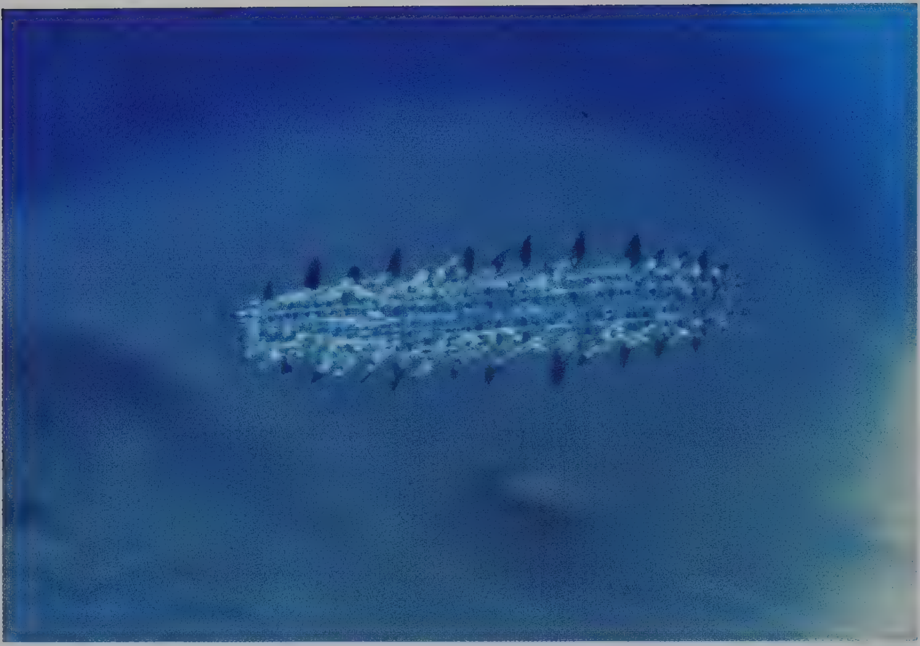


Plate 29
A so-called centipede inclusion identifies this orthoclase feldspar (photomicrograph courtesy of John I Koivula)

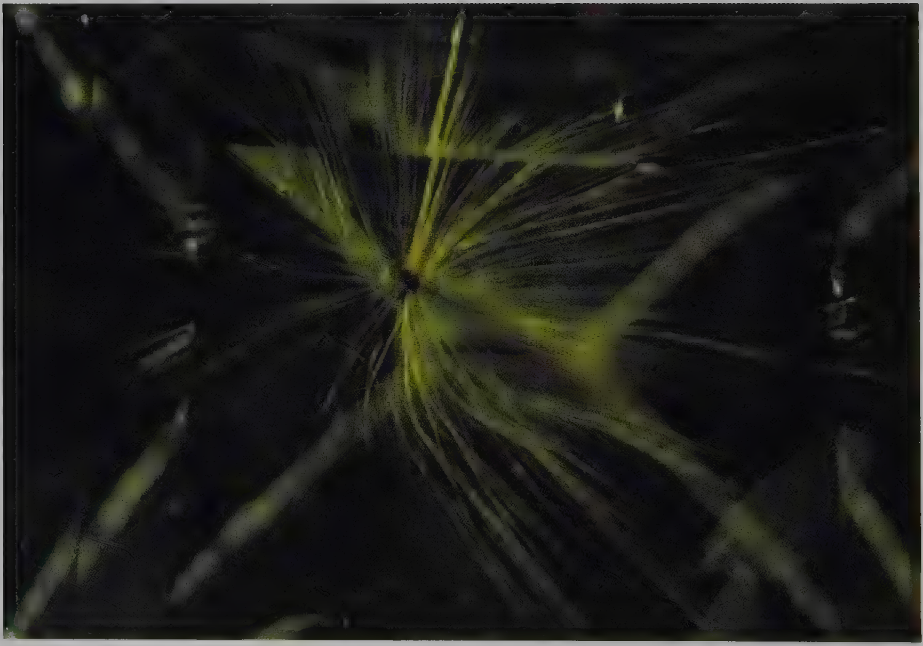


Plate 30
Demantoid garnet characterised by a horsetail of byssolite (photomicrograph courtesy of John I Koivula)

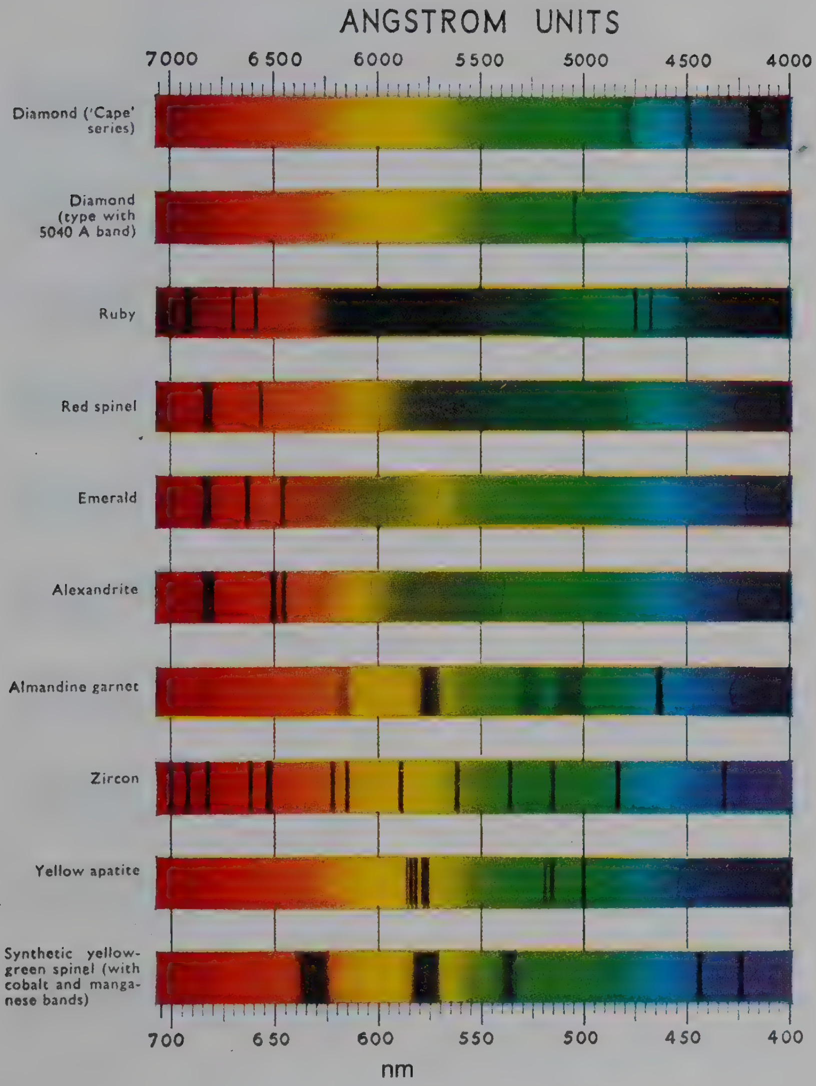


Plate 31
Absorption spectra of gemstones (as seen through a diffraction grating spectroscope)

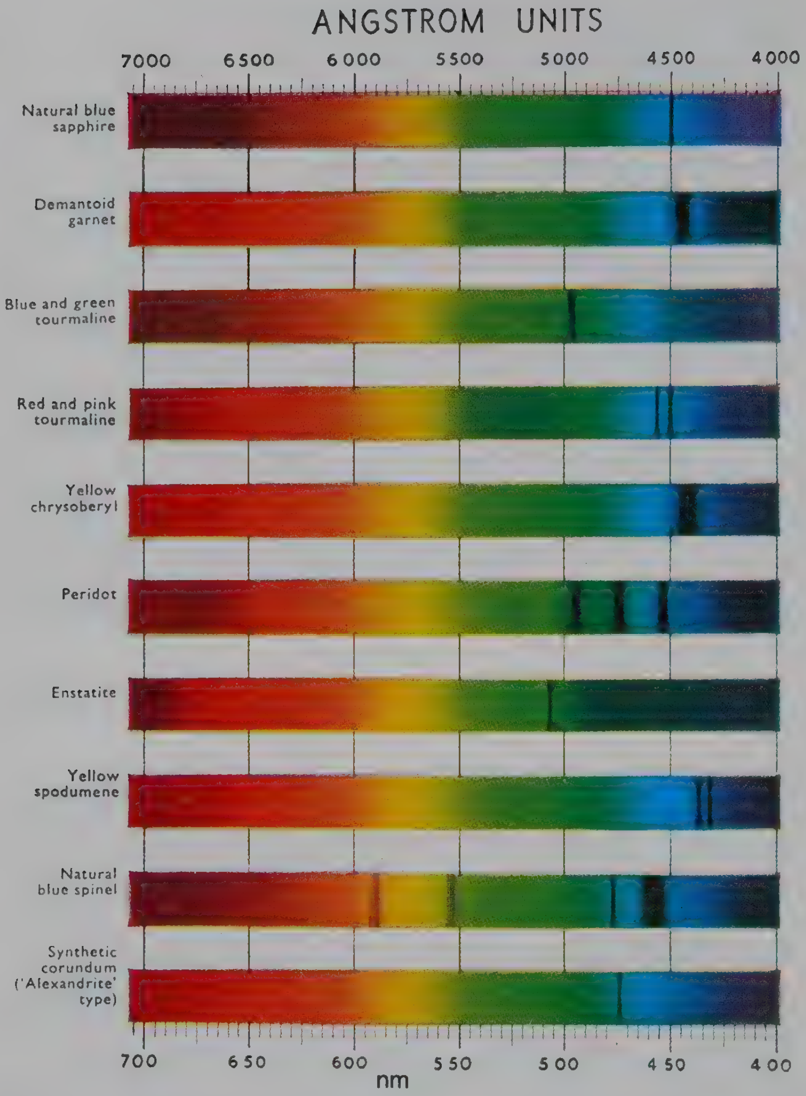


Plate 32
Absorption spectra of gemstones (as seen through a diffraction grating spectroscope)

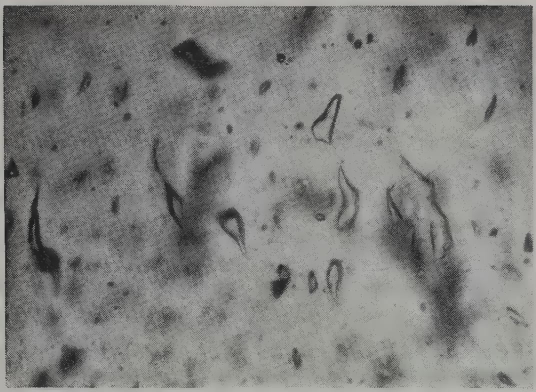


Figure 15.6 Internal structure of silica glass showing the irregularly shaped vesicles

Fused Sand Glass

Fulgurites or lightning tubes are thin tubes of fused sand caused by the intense heat set up when a lightning flash strikes and enters the sand of the desert. Scarcely a natural glass, but certainly a crater glass, is the fused sand formed by the experimental atomic bomb which was exploded in New Mexico during 1945. This material, which has been named trinitite, is vesicular and greenish in colour, and the constants for the material are similar to those for ordinary crater glass. Even after many years much of this fused sand is still radioactive. It may appear unlikely that such material would be used for ornament, but it is on record that some has been fashioned into gems – mainly as publicity for film stars. In view of the radioactivity present it would certainly be a risk to wear such objects for too long at any one period.

Silica Glass

A nearly pure silica glass of uncertain origin found in 1932 in the wastes of the Libyan desert is known as silica glass. The material is found as sand-blasted lumps up to 7 kg in mass. It is of a greenish-yellow colour and is usually cloudy rather than clear owing to the inclusion of vast numbers of irregularly shaped vesicles (*Figure 15.6*).

Silica glass consists of nearly pure silica (98 per cent SiO_2), and has a refractive index of 1.46, an SG of 2.21, a hardness of 6 on Mohs's scale and a vitreous lustre. The stones cut from this material lack brilliancy and have a dispersion of 0.01. Occasionally there are found included in such glass, either as strings or as single individuals, spherulites of the cubic modification of quartz known as cristobalite. A little of the material has been cut and polished for collectors, but its insipid tint and poor brilliancy does not allow the stones cut from silica glass to be at all attractive.

Lumps of glassy material, usually striped with greyish-blue and dark brown or black, are occasionally encountered. The material looks like an obsidian but it is actually a furnace slag and has an SG near to 2.82.

The properties of a green glass reportedly made from ash from the Mount Saint Helens eruption in 1980 were compared with those shown by a sample of melted black ash known to have been from that source. The green glass gave an RI of 1.508 while the black sample showed a variation over the range 1.500–1.526; SGs were 2.448 and 2.485 respectively. It was concluded that the green glass contained from 5 to 10 per cent of Mount Saint Helens ash at most, chemical analysis giving a conclusive separation from known material.

A transparent brownish natural glass from San Luis Potosi, Mexico, showed layered and botryoidal textures giving rise to an iridescent effect. Similar material has been described, misleadingly, as iris opal. IR spectroscopy showed that SiOH groups were present but that water was not.

16

Marble

Marble, which derives from the Greek word *marmaros* (Latin *marmor*), meaning a shining stone, may be defined as a crystalline aggregate of calcite and/or dolomite which often has a granular or saccharoidal texture. To the classical writers the term encompassed any stone used for decorative purposes, regardless of composition, even including the porphyries ('marmor lacedaemonium viride', the green porphyry from Greece) and granites ('marmor claudianum', a fine, pale granite from Egypt). This imprecise usage is still current among antiquarians, and even in modern commerce to a lesser extent.

The 'marbles' of commerce come from all over the world, being found in areas where detritus is poor, mainly marine sedimentation has occurred at some time. Taken in isolation the crystalline marbles may appear to be lithologically distinct, but they merely represent a product of metamorphism, the end result of a post-depositional and gradational mineralogical reorganisation of a limestone, and it is often a matter of subjective choice to separate them. The calcareous rocks are relatively easy to work, even with stone tools, and all cultures have used these stones for decoration to some extent. Their present variety and popularity, however, may be said to derive from the architectural fashions of Imperial Rome. Many of the stones to be found in Western *objets d'art* and furnishings, both antique and modern, still originate from within the bounds of the Empire, or its sphere of influence, and Italy remains the major marble processing country.

The stones dealt with in this chapter, so important as media for some of the more handsome clock cases, vases, boxes and other *objets d'art*, are grouped as the true calcareous marbles, the compact limestones and the travertine/onyx marbles.

Nomenclature

Names given to marbles are innumerable and confusing. Synonyms abound, and are coined at will to satisfy commercial pressures. Names commonly derive from the source, e.g. 'breccia di Seravezza', or the appearance, e.g. the Belgian 'rouge-et-gris', or are entirely fanciful, e.g. 'pavonazzo' (peacock) and 'Napoleon' marbles. They should be treated with caution as, for example, the 'Griotte d'Italia' is from France, and 'Molina rosa', named after a Spanish locality, is of Italian origin.

There is no universal or consistently employed system of nomenclature for marbles, and ancient names are 'pirated' for use by suppliers of stone from new sources which may have only a superficial resemblance to the original. The 'verde antico' (verd-antique) marble may be taken as an example. The original is a beautiful dark green serpentinite breccia containing fragments of white calcite marble from Thessaly, Greece. This was so prized in classical times that the name has become familiar and has been applied to most other green breccias, even some from the USA.

Nevertheless, there are a small number of terms which have relatively consistent meanings, although they are of little use alone in specific identification. Among these may be cited 'arabescato', patterns of swirling lines reminiscent of Arabic script; 'breccia', stone composed of angular fragments; 'cipollino', finely parallel banded stone, likened in structure to a section of an onion (Italian *cipolla*); 'Griotte', dark red marbles of the colour and often the appearance of a mass of Griotte cherries; 'lumachella', stones composed of oyster-like shell fragments; 'perlato', pale stones containing scattered rounded algal or shell fragments; and 'verde' or 'vert', mostly applied to serpentinite breccias. Many of the names are of Italian derivation, reflecting the pre-eminence of that country in marble working since ancient times.

Such is the variation in colour and textural combinations that it is impossible to adequately, and unequivocally, describe specific varieties. Identification therefore requires experience and access to good, well-documented reference collections.

Although marbles from around the world are now flooding into Western countries, most are used for large-scale architectural purposes, and will be unfamiliar even to experts. The marbles of most decorative artifacts of fine quality which will be encountered will still be from established sources in the Old World, and India.

True Marbles

True marbles are the product of recrystallisation of existing calcareous rocks by the agency of pressure and possibly heat produced by geological upheavals in past ages, a process known as regional metamorphism. When the country rock which suffers this metamorphic change is a very pure limestone, the resulting rock is a pure white, crystalline and translucent marble such as the famous Carrara statuary marble from the Apuan Alps of Tuscany, Italy.

Pure marble is white; other colours derive from impurities in the original limestone. Iron is the most abundant source of strong colour, giving red, brown, yellow, grey and green tints, depending on its quantity and oxidation state. Blue is a rare colour in marble. Most marbles which are traditionally described as blue, such as 'bleu turquin', a French synonym for the Bardiglio marbles from Carrara, and 'bleu belge', from Belgium, are really soft greys. A recent introduction is the 'azul Macauba' marble from Brazil, a white crystalline stone streaked and veined with brilliant blue, which is probably derived from sodalite impregnation. The less brilliant 'African blue' comes from Kenya.

Limestones often contain impurities rich in heavy elements, either disseminated through the stone or concentrated in original sedimentary layers. Such impure rocks may produce attractively patterned and coloured marbles. Because of their origin in mobile parts of the earth's crust, marbles have often been shattered and fragmented, resulting in brecciated or breccia marbles. The fissures so formed, subsequently filled with consolidating, often coloured mineralisation, produce the beautiful variegated or veined marbles. Examples such as the spectacular purple, grey and white 'breccia di Seravezza' from north-eastern Italy, and the pale pink and white 'breche rose' of Norway, may be cited.

Many limestones contain some magnesia in the form of dolomite ($CaMg(CO_3)_2$), and when quartz (silica) is also present the two may combine with water to form the mineral serpentine. Serpentinous crystalline marbles are known as ophicalcites and commonly show swirling, irregular banding in shades of green and white. Possibly the most familiar variety is the 'Connemara marble' from the Republic of Ireland, but other similar varieties occur in Sweden ('Ringborg' or 'Swedish green') and the USA, and the Scottish isle of Iona. The name ophicalcite has also been applied erroneously to the serpentinite breccias (the 'verde' marbles) because of their serpentine-carbonate mineralogy. The latter stones are hydrothermally altered ultrabasic igneous rocks of quite different origin from the true ophicalcites.

Some rare marbles contain scattered euhedral crystals of non-carbonate minerals, and can be extremely decorative, although only of use for small objects. Among these are the ruby marbles of the Mogok Stone Tract and Sagyin, Myanmar (Burma). Large crystals of pink grossular garnet occur in a creamy marble at Xalostoc, Mexico, the stone being known as 'xalostocite', 'landerite' or 'roselite' (*Figure 16.1*). In Britain, the Tiree marble from the Western Isles of Scotland contains small crystals of diopside in a pink to white marble groundmass.

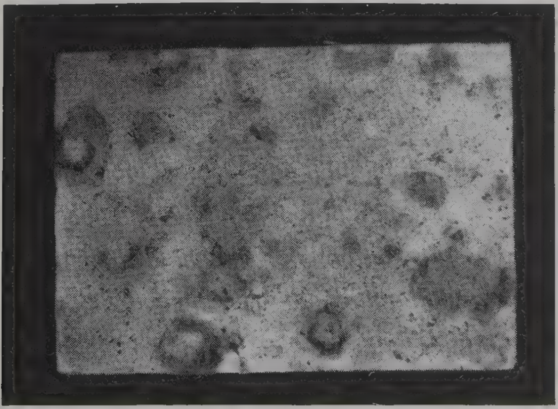


Figure 16.1 Xalostocite, a marble containing pink crystals of grossular garnet

Compact Limestones

Origins

Those compact limestones which are capable of taking a polish are known to the French as *pierres marbrier*, for which there is no English equivalent term, and so they are included with the marble for practical purposes. They are limestones, sedimentary rocks, which have become compacted through diagenetic processes which are less destructive to the original structures than true metamorphism. Apart from their ability to take a polish, they depend upon the original sedimentary structures and colourful variation in composition for their decorative effect, rather than the crystalline translucency of true marbles.

Many primary limestones owe their origin to organic processes, either biomechanical or biochemical, although the influx of weathered detritus is also important in giving variety of colour and structure. Secondary reworking and fragmentation of these limestones produce more heterogeneous sedimentary breccias and conglomerates. The stones dealt with in this section are mostly of shallow-water, submarine, mechanical origin. Biochemical rocks will be treated below with the travertines.

Sedimentary Breccias and Conglomerates

These are coarsely fragmental rocks produced by vigorous and rapid erosion or by slumping or collapse of existing strata, resulting in a chaotic mixture of fragments. In practical terms, breccias are composed of angular fragments, whereas in conglomerates the fragments are rounded. Because of their coarse structure, these stones show their best in large objects such as monolithic vases, columns and fire surrounds, and have been extensively employed as wall cladding in banks and other public buildings.

In nature they tend to form around unstable continental margins, and to be associated with mountain ranges such as the Appalachian Mountains of the south-eastern USA, and the Pyreneean-Alpine ranges of southern Europe. From the latter region come the pale pink and grey 'arabescato' from Bergamo, Italy, the coarse, more strongly coloured 'machiavecchia' from the Italian Alps, and 'libeccio' from Sicily. The strong coloration of the latter two is due to the admixture of dark red and brown terra rossa sediment which contrasts with the usually grey limestone fragments.

In the shallow waters of continental shelves, coral reefs may form, and the fragmented coral and coralline algal detritus from these, mixed with other sediment, forms important decorative marbles which are commonly highly coloured. Belgium has long been a major producer of such marbles from restricted reef knolls of Devonian age in the Namur region. Their predominant colours are dull red and grey, and they are known collectively as 'Belgian rouge-et-gris', with more specific varietal names such as 'rouge de rance' or 'rouge byzantin'.

Conglomeratic marbles are uncommon and represent near-shore deposits of the more stable continental shelf seas. They were more used in antiquity than at present, but can be found reused in later objects. Confusingly they are often designated as breccia in literature, as with the pale-coloured 'breccia polychroma' and 'breccia d'Aleppo' from northern Italy, and the dark green 'breche universelle' from Egypt. *Pietra dura* inlay work from India often includes a brown stone crowded with small yellow and green pebbles, from Sabalghar in Gwalior. This stone was popular with the seventeenth and eighteenth century Mogul craftsmen and continues to be used.

Fossil Marbles

Here are included a large variety of stones which are composed predominantly of accumulations of obvious fossil skeletal remains of a restricted variety of invertebrate animals and plants. The fossils visible may be shells (of the phyla Mollusca and Brachiopoda), coralline (corals, bryozoa and algae) or encrinital (the remains of crinoids, also known as sea-lilies). Representatives of other phyla are rarely sufficiently abundant to form rock-like masses.

Shelly Marbles

Species of the phylum Mollusca often live in communities of innumerable individuals, and probably form the most abundant group of sea-shells still to be found. The important rock-forming types lived in shallow waters affected by tidal and current action which concentrated into masses the skeletons of dead individuals. Oyster and clam shell accumulations lithify to form the type of stone known as lumachella. In these stones the arcuate white, grey or black shell may contrast with a residual matrix of buff or brown sediment. They have been exploited for use in small-scale items in Italy, in Spain, and along the Mediterranean coast of north-west Africa. In England the Jurassic Forest marble has been employed for ecclesiastical and domestic decoration. From Tortosa in Spain comes a type, brightly coloured in red and yellow, known as 'broccatello', and golden varieties called 'castracane' have been found in Asia and India.

Lumachella is also a name given to a variety of marble from Bleiberg, Carinthia in Austria and from Astrakhan in Russia. The marble consists mainly of fossil shells with iridescent surfaces so prominent in reds and greens that it has also been called 'fire marble'. Similar effects are shown by fossil ammonites from southern Alberta, Canada (*Figure 16.3*). The ammonites (*Placenticeras meeki*) occur in Upper Cretaceous dark grey shales, and the iridescent colours come from the nacreous layer of the shell. Again the common colours are red and green, but the better-quality pieces may show a complete range of colours. The shell consists chiefly of calcium carbonate in the form of overlapping platelets of aragonite. Trade names for this iridescent material include 'korite', 'ammolite' and 'calcentine'.

The gastropods, water snails, may also occur in rock-forming quantities, but such stones are very rare and of unusual patterning. The 'Purbeck' and 'Sussex' marbles of southern England, composed of masses of shells of the genus *Viviparus* with a grey, green or reddish matrix, may be mentioned for their importance in architectural decoration of the Early English period (*Figure 16.2*).

Coralline and Algal Marbles

Fossil coral marbles (*Figure 16.4*) produce intriguing marbles with diverse large-scale patterns. The more fossil-rich varieties of the Belgian 'rouge-et-gris' marbles, such as the 'rouge royal', may be the best known, with irregular pale

Figure 16.2 *Fossil marble: the Purbeck marble from Dorset, England*

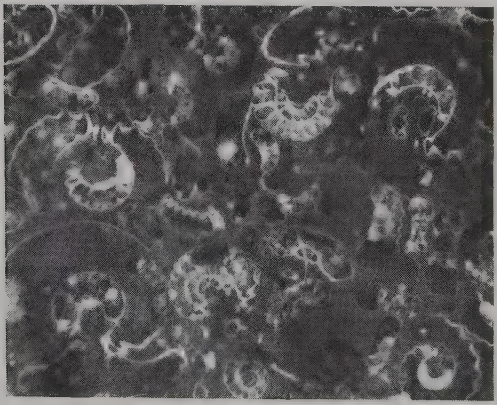


Figure 16.3 *A fossil marble containing ammonite shells*

grey, often black-rimmed, fragments of coral or coralline algae set in a dull red matrix. Other coral limestones, also of Devonian age from south Devon, England, were exploited during the nineteenth century (*Figure 16.5*).

Perhaps more common than true coral rocks are limestones resulting from the activities of lime-concentrating marine algae, with their muted grey and brown coloration and smaller, but commonly still irregular, patterning. The

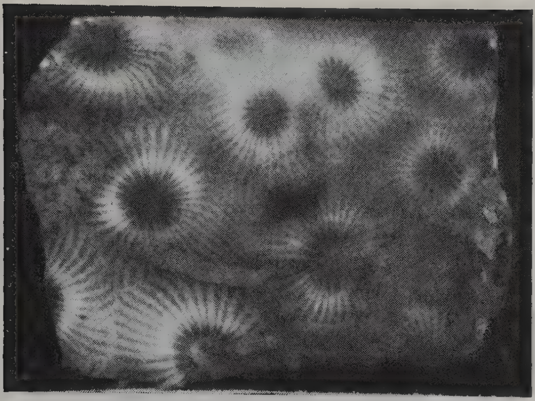


Figure 16.4 A fossil coral limestone

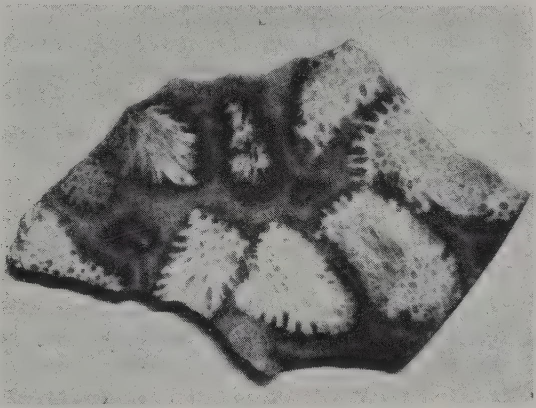


Figure 16.5 A limestone containing the fossil coral Favosites cervicornis *from Torquay, Devon, England*

Lower Carboniferous strata of western Europe are especially rich in these rocks; the 'Napoleon' and 'lunel' varieties from northern France are well known. Some of the English stones have similar appearances, but the rare brown 'rosewood' marble from Ashford in Derbyshire shows a regular fine parallel lamination reminiscent of wood graining.

Like the algae, lime-concentrating bacteria also inhabit very shallow waters, and develop spectacular mushroom-shaped masses known as 'stromatolites'. These masses are uncommon and of only limited extent, but have given rise to the 'Cotham' or landscape marble' from the Rhaetic of Gloucestershire, England. The term 'landscape' derives from the appearance of the stone in vertical section, where dark grey dendritic masses of the stromatolites rise from parallel laminated paler mudstone, giving the impression of views across ploughed fields with distant hedgerows. A contrasting pictorial effect is developed in the 'Florentine' or 'ruin marble' or 'paesina' (*Figure 16.6*). This is a fine even-grained yellow to brown calcareous mudstone where orthogonal fractures have

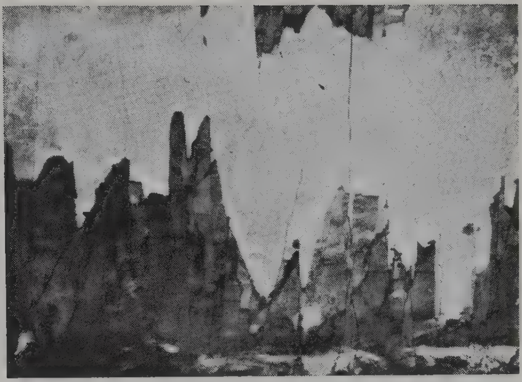


Figure 16.6 Florentine or ruin marble

allowed box-stone-like patterns of iron staining to occur, an effect, however, of chemical and not organic origin. Appropriate sections through the stone give images reminiscent of a ruined town. From the neighbourhood of São Paulo, Brazil, comes another pictorial limestone, with diffuse pink to purple areas in a grey ground. The effect here is of a sunset. All these stones are rare oddities, and may be found as furnishing inlay.

Encrinital or Crinoidal Limestones

The encrinital limestones are usually fawn to dark grey in colour, prettily marked in contrasting tints by fragments of the cylindrical stems of crinoids (sea-lilies). Such marbles are common in the Lower Carboniferous strata of Derbyshire, England – 'bird's-eye', 'Hopton Wood' and 'Derbyshire fossil' marbles (*Figure 16.7*) – and Belgium. In the latter area the stones are known as 'petit granit', referring to their granularity rather than to any supposed resemblance to granite. Northern Italy is the source of white speckled reddish-brown limestones called 'porfirico' from their remarkable superficial similarity to the purple imperial porphyry of Egypt.

Stones showing small-scale sedimentary structures supply attractive types. The well-known 'rosso Verona' and 'porfido ramello' types from north-eastern Italy, brownish-red intraformational conglomerates of rounded but irregular limestone fragments set in a contrasting marly matrix, are good examples. The French Pyrenees provide the 'campan' types, which have suffered a degree of metamorphism and shearing. In these, the pebbles are often flattened to almond-like shapes, giving their alternative and perhaps rather misleading name of 'amygdaloidal marbles'. They usually show grey-green colours but may be dark red, or of mixed colour as in the dark red and green banded 'campan mélange'. Of more sombre but equally striking appearance is the 'portor' or 'black and gold', a dolomitic dark grey limestone with sinuous chrome-yellow veining.

Many varieties of marble are of uniform appearance, being used for statuary, and as a foil to more spectacular material as background to inlaid table-tops and

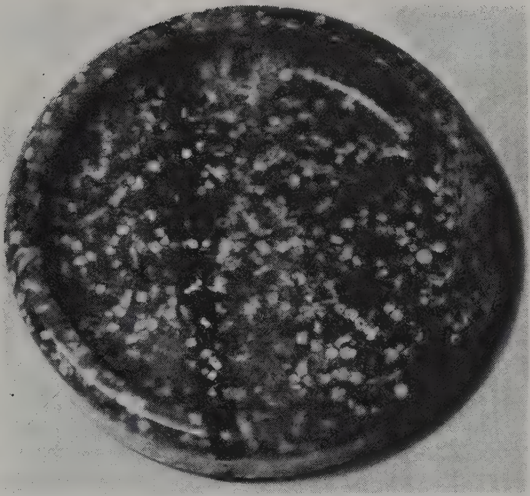


Figure 16.7 Encrinital marble from Derbyshire, England

pietra dura work, boxes and plinths for sculptures. They are usually fine-grained stones with little or indistinct patterning, and soft, pale, and essentially monochrome coloration. From Italy may be mentioned the 'botticino' and 'filetto' marbles, cream to yellowish stones marked by widely spaced stylolitic streaks of contrasting colour; 'Roman stone', despite its name, comes from Istria, and includes the greyish-buff 'auresina', 'nabresina' and 'repen zola' varieties. These are shell detritus stones similar in appearance to the English 'Hopton Wood' marble, but the shell fragments are rarely identifiable.

Fine-Grained Limestones

The so-called 'lava cameos' which are occasionally met as brooches or bracelets, and are either opaque grey or brownish-yellow, appear to be nearly always a fine-grained limestone. Sometimes they are imitated by glass.

Oolitic limestones (formed of ovoid or spherical concretionary carbonate grains) of Jurassic age may also be treated as marbles. A number of these stones are found in the upper reaches of the Loire valley of France. 'Comblanchien' and 'nuits St George' are two varieties. The latter is appropriately the colour of a pale red wine. In England, Portland stone, more familiar as a constructional stone, is sometimes polished.

Monochrome black marbles are often found in late nineteenth century clock cases and as tombstones of all dates. In Europe the majority of these stones have come from Belgium, the famous 'Tournai marble' being only one variety. 'Noir belge' (Belgian black) was found along the Sambre and Meuse rivers, and much black marble is also found in the departments of Nord and Pas-de-Calais in northern France. That from Nord is known as 'grand antique' and that from Pas-de-Calais as 'noir français'. The Republic of Ireland provides the 'Kilkenny black', England the 'Derbyshire black' and also formerly the 'Poolvash' marble from the Isle of Man. These stones are all relatively unaltered compact limestones, but the Carrara area of Italy can supply a black crystalline true marble.

Travertines and Onyx Marble (Stalagmitic Calcites)

Origins

Unlike the marbles of the previous section, the travertines and onyx marbles are predominantly of non-marine physicochemical or biochemical origin. They have formed subaerially or in shallow lakes on the land surface from lime-saturated waters, and the commercial varieties occur in limestone areas where flowing groundwater can dissolve the stone to deposit the lime elsewhere. Calcite is virtually insoluble in pure water, but all groundwater contains dissolved carbon dioxide, which makes it slightly acid and able to dissolve limestone. The resulting solution of calcium bicarbonate may become oversaturated when the waters reach the surface and carbon dioxide is lost to the atmosphere, precipitating the lime as a fine powder.

This process may be accelerated and the lime concentrated by algal or bacterial activity in lakes when sunlight is available, the resulting rocks being known as 'travertine'. The stones are fine-grained, irregularly laminated and often cavernous. Great thicknesses of travertine occur in Italy near Rome, where the stone is usually of a greyish-cream colour, and Siena. In the latter locality a wider range of coloration occurs, red, brown and yellow varieties being present. There is also a beautiful variety, 'silver travertine', of a clear silvery grey.

Travertines are usually opaque, but can grade into crystalline translucent types known as 'stalagmitic calcite' or 'onyx marble' (*Figure 16.8*) where either the water current or lack of sunlight prevents the growth of algae. They are commonly found as cave deposits on rock surfaces, and show a fine

Figure 16.8 A stalagmitic marble with wavy bands

concentrically laminated structure, strikingly coloured by periodic variation in the composition of the waters from which they are derived. The colours of the laminations come mainly from iron and manganese salts, and sudden alternations from colourless to white to browns, reds and black create striking effects. As in all marbles, the translucency is a factor of crystallinity: the coarser the calcite crystals, the more translucent the stone. Some finer varieties were even used for window 'glazing' by the Romans, much as white true marbles were used in the Middle East and India.

The nomenclature of the stalagmitic calcite stones is unsatisfactory. 'Stalagmitic calcite' is more a mineral than a rock name. 'Onyx marble' harks back to the ancient method of naming stones from their outward appearance, and not their composition. It is therefore ambiguous. Onyx, as now understood, is a variety of chalcedony, a banded silica hardstone, the only connection with the marble being in the structure.

One of the early names is 'alabaster' or 'alabastron', derived from the ancient district of that name in central Egypt, where it was exploited at an early date. This usage is still current in the Mediterranean area. The meaning was extended to include the vases and jars made from the stone, and was later translated by northern Europeans to mean the gypsum rock of similar patterning. Although these marbles are travertines in the broadest sense, better definition is needed.

The earliest, and still active, large-scale exploitation of 'onyx marbles' was in Egypt, whence it has been traded as 'alabaster', 'Egyptian alabaster' or 'oriental alabaster', the last name becoming generic for all varieties, wherever they came from. The expansion of international trade during the Roman Empire gave access to supplies in Turkey, and in Algeria and Morocco. From the latter areas come dark brown, almost red types. Considerable quantities come from the provinces of Oran and Constantine. The major quarries are situated close to Bon-Hanifa, a village about 15 km north-east of the town of Mascara. Bon-Hanifa lies near the ancient Roman town of Aquae Sirensis, which was noted for its hot springs, and it may well be that the deposits originated from these springs. The Constantine deposits lie about 15 km from Constantine, the capital of the department of the same name, and much of the marble from this locality is bright red in colour. On the Moroccan side of the border with Algeria lies another deposit of stalagmitic marble, which may be considered an offshoot of the Algerian deposits. Like the Oran marble, the colour of Moroccan marble is normally white with coloured veins, but material which is blue, grey, red or pink mixed with green is also found. Smaller deposits occur in Italy, the 'stalattite' of Fruili-Venezia Giulia; in France, the 'stalagmite de Bedat' of Ariege; and in the valley of Vintschgau near Laasee, Austria, where it is known as 'Tyrolese onyx'. 'Gibraltar stone' is from small deposits found within the caves of the rock, and has been used for tourist souvenirs (*Figure 16.9*).

The modern age has found deposits further afield in the New World. These stones are often of a pretty white to pale green, marked with brown and yellow, such as the 'Pedrara onyx' of northern Mexico, and other 'mexican onyxes' from Puebla and Oaxaco. In America these stones are sometimes called 'Tecali marble', a name originating from the Aztecs who deemed the stone too sacred for it to be used by the common people. The marble was almost solely devoted to the ornamentation of religious buildings or for the making of sacrificial vessels. Indeed 'Tecali' is but a corruption of the Aztec name Teocali given by

Figure 16.9 Gibraltar stone

the Mexican Indians to their temples. It is from the Mexican localities that most of the onyx marbles now used in England for ornamental pieces are derived. The province of San Luis in Argentina supplies the so-called 'Brazilian onyx', and limited occurrences are known in the USA, including the lemon-yellow 'Utah onyx' from near Lehi, some 30 km from Salt Lake City. Marble similar to that from Mexico has also come from Yavapai County, Arizona and is called 'Yava onyx'.

'Java onyx' is a stalagmitic marble usually dull white in colour or variegated with amber-coloured wavy banding. The rock, which is found around the town of Kediri (Wadjak) some 100 km south-east of Surabaja (Surabaya) in the Toeloeng Agoeng district of Java, does not have the translucency of many other 'onyxes'. A beautiful translucent banded material of bright yellow colour comes from the Karibib district of Namibia. It is locally called 'aragonite' but is actually a stalagmitic calcite.

Staining and Coating of Marbles

The true marble is a granular material and will be susceptible to staining; this is artificially carried out, usually by aniline dyes. Marble may also be coated by essentially colourless substances to mask small scratches or other irregularities and improve the surface appearance. Among the most commonly used materials are waxes, paraffin and plastics. Under magnification the effect of a needle probe in depressing a surface may reveal how soft it is, while the proximity of a heated needle or tiny hot filament may cause a coating to soften and flow.

Calcite

Chemical and Physical Properties

Pure calcite is colourless and the mineral, which is a calcium carbonate ($CaCO_3$), crystallises in the trigonal or rhombohedral system, commonly with rhombohedral or prismatic habit. The hardness of the pure calcite is 3, and is the standard 3 for Mohs's scale, but from the admixture of impurities some marbles may be slightly harder. The purest true marbles, such as the white statuary marbles from Carrara, break with a saccharoidal or granular surface, while the fracture in limestones is usually much smoother. The refractive indices of calcite are 1.658 for the ordinary ray and 1.486 for the extraordinary ray, but in the compact and granular marbles the most pronounced edge seen in the refractometer is that of the extraordinary ray at 1.48, which can sometimes be seen to move upwards on rotation of the specimen. The ordinary ray is seen with difficulty, much depending on the granular size of the calcite crystals. The limestones generally show an indistinct edge at about 1.50.

The specific gravity of pure calcite is 2.71, but in marbles and limestones there may be, and usually is, a lowering of the SG owing to the granular nature of the crystal aggregates, or the SG may be raised owing to the inclusion of other minerals. The range of SG for most marbles and limestones lies between 2.58 and 2.75.

As calcite is a carbonate, a spot of dilute hydrochloric acid placed on marble will produce an effervescence. This is a sure test for calcite marble against some other, but not all, marble-like rocks.

Effects of Light

The absorption spectra and the fluorescence under ultra-violet light of marbles are too vague to be of value in identification. The luminescent glow exhibited under short- or long-wave ultra-violet light, if any fluorescence is shown at all, is patchy, some of the veined material showing up the veins as a whitish glow. Some of the travertines, including Gibraltar stone, show a bright greenish-yellow glow and a strong phosphorescence under both wavelengths of ultra-violet light. Under X-ray stimulation most true marbles and many limestones show the typical orange glow shown by calcite.

Varieties of Calcite

A pink variety of calcite, cobalti-calcite, which owes its colour to cobalt, has been fashioned into cabochons as collectors' items. Concretions of calcium carbonate with pearly lustre, which have been formed by the agency of water in limestone caves, are called cave pearls. Despite its low hardness and strong cleavage, golden-yellow and colourless calcites have been faceted for collectors.

One kind of crystal aggregate consisting of fibrous crystals of calcite is known as satin-spar (see 'Alabaster' in Chapter 17). The material is found in veins and the fibrous crystals stretch across the vein from side to side. When polished with a flat surface the material shows a silky lustre. Calcite satin-spar –

which occurs at Alston Moor in veins from 20 to 100 mm in thickness, at Glen Tilt, Perthshire and in several states in North America – is now scarce.

Aragonite

Aragonite, a dimorphous form of calcium carbonate which crystallises in the orthorhombic system, has, despite its low hardness, been cut as faceted stones for the collector. The crystals are often twinned and then form pseudohexagonal prisms; they are usually white or colourless but may show tinges of brown, grey, green or violet. The hardness is 3.5 to 4 on Mohs's scale; the SG lies between 2.93 and 2.95; and the refractive indices are α 1.530, β 1.680 and γ 1.685, the negative birefringence being 0.155. A stalagmitic form like 'onyx marble' is said to occur, but whether it has been used in the arts is doubtful. The yellow stalagmitic marble found at Karibib, in Namibia, is stalagmitic calcite, although it is sold under the name 'aragonite'. The groups of pseudohexagonal crystals from the sulphur mines in Sicily are interesting owing to the rose-pink fluorescence they show under long-wave ultra-violet light and the green afterglow they show after removal from the rays. Transparent crystals of aragonite are found in many places, particularly in Bohemia, Spain and the north of England.

Aragonite is a major constituent of pearls in concentric layers of tiny overlapping crystal platelets.

17

Lesser-Known Ornamental and Gem Materials

The following descriptions of the lesser-known gemstones include those used for ornamental purposes, those rarer faceted stones occasionally met with in jewellery, and those which may be termed collectors' items. All the minerals which have been known as fashioned pieces in collections are included, even if their use for pure ornamentation is, as in many cases, impracticable, since there is a possibility of such stones being released from collections and proceeding via trade channels to other collectors, or even to the jeweller's junk box. It seems a sounder procedure to give them a short notice than to omit them. The rare mineral painite has been described in gem literature, despite only three crystals having been found, none of which has ever been cut into a gemstone. These stones are described in alphabetical order, and no grouping is made. A division into the rarer faceted stones and the ornamental stones has not been attempted, for so often one mineral will supply either transparent or translucent material suitable for faceting into stones, or translucent to opaque massive material which may be carved and polished into ornamental objects.

Actinolite

Better known as the constituent of the darker-coloured nephrite jades, transparent green crystals of this mineral are found in sufficient size to have been faceted into polished stones. Varying from pale to dark green in colour, which is due to ferrous iron, the crystals form bladed crystals of the monoclinic system. One of the amphibole group of minerals, actinolite has the formula $Ca_2(Mg,Fe)_5(OH)_2(Si_4O_{11})_2$; the crystals have a hardness of about 5.5 on Mohs's scale, and there are two directions of cleavage. The SG is about 3.05 and the refractive indices are 1.620–1.642 with a birefringence of 0.022. The pleochroism is yellow to dark green and there is a faint absorption line at 503 nm. A number of specimens from Tanzania gave a range of SG of 3.03–3.07 and the refractive indices as α 1.619–1.622, β 1.632–1.634 and γ 1.642–1.644. A cat's-eye specimen gave an SG of 3.00 and an index of refraction about 1.63. It is a matter of conjecture whether the stone should be called an actinolite cat's-eye (or even tremolite cat's-eye). A chromium-bearing actinolite called smaragdite, of emerald-green colour, is found in Tanzania.

Adamite

Transparent specimens of adamite ($Zn_2(AsO_4)(OH)$) occur in reddish, pink and violet colours at the Ojuela Mine, Mapimi in Mexico. The orthorhombic crystals have a hardness of 3.5 on Mohs's scale and there is one direction of distinct cleavage. The SG is 4.68 and the refractive indices are α 1.710–1.712, β 1.735–1.736 and γ 1.758–1.760, with a birefringence of 0.048–0.049; the optic sign is negative. The mineral was named after the French mineralogist M Adam and is also found in Tsumeb, Namibia and the USA. Adamite is readily soluble in acids.

Aegirine

Cuttable greenish-black aegirine and aegirine-augite have been found at the Langesundfjord in south Norway. Aegirine has the chemical formula $NaFeSi_2O_6$ (acmite) with a diopside content up to 25 per cent, while aegirine-augite has higher diopside contents between 25 and 80 per cent. Both minerals of the pyroxene group crystallise in the monoclinic system and have a hardness of 6 on Mohs's scale and distinct cleavage. The aegirine possesses an SG of 3.50 and the refractive indices are α 1.760, β 1.785 and γ 1.805 with a birefringence of 0.045. The aegirine-augite has an SG of about 3.45 and refractive indices of α 1.740–1.748, β 1.760–1.767 and γ 1.780–1.790 with a birefringence of 0.040–0.042.

Alabaster

The massive variety of the mineral gypsum is called alabaster, and is the variety of most importance in commercial gemmology, for the fully crystallised varieties have scant use in ornamentation.

Gypsum, a hydrous calcium sulphate ($CaSO_4.2H_2O$), when well crystallised produces excellent transparent monoclinic crystals, which are often twinned in swallow-tailed forms. These crystals, which are not used for purposes of ornamentation, are readily cleavable in one direction. Such crystals of gypsum are called selenite, for the crystals tend to show moon-like gleams from the cleavage surfaces.

A type of gypsum, generally white in colour, in which the mineral fills veins in rock formations with parallel fibrous crystals stretching across the vein from side to side, is known as satin-spar (although a similar formation of calcite is also so-called). Satin-spar is occasionally cut as polished slabs, cabochons or beads. Pretty as they can be, the low hardness – gypsum has a hardness of about 2 on Mohs's scale – precludes its use to any extent.

The massive rock-like variety of alabaster was known from the days of the Phoenicians, Assyrians and Egyptians, who made all kinds of beautiful vases and amphorae from it, and who were also the first to find out and use its beauty as a medium for direct and indirect lighting. The delicately wrought alabaster vases that were found in the tomb of Tutankhamun were used to illuminate the temples in the land of the Pharaohs. Today the material is used not only for bowls for indirect electric lighting, but for small articles of utility, such as powder boxes, ashtrays, clock cases, paperweights and other ornamental objects.

Massive gypsum is usually deposited by the evaporation of an enclosed sea basin, or may be deposited from desert lakes. Gypsum is frequently formed in mineral veins where sulphuric acid, derived from the oxidation of pyrites and other sulphides, has acted upon limestone.

The purest form of alabaster is white and translucent but the material is often associated with a trace of ferric oxide which produces light brown and orange-coloured bands and veins, or with other impurities which colour the stone in yellows, browns and black in veins or patches of colour. The softness of the rock, especially when freshly quarried, enables it to be carved easily. Indeed, alabaster can be scratched by a fingernail, but to a slight extent the mineral hardens after exposure to the air and will then take a good polish. Alabaster, too, is sufficiently porous to allow it to be stained and such artificial coloration is often produced.

The hardness of gypsum is given as 2 on Mohs's scale, but most alabaster is found to be harder than 2. The fractured surface is more finely granular than the saccharoidal fracture of marble. The translucency varies from highly translucent to practically opaque and the material has a glistening lustre. The refractive indices are 1.52–1.53, and in the case of the massive variety – alabaster – a shadow edge about this value is moderately clearly seen on the refractometer scale. The SG of alabaster lies between 2.30 and 2.33. There is no absorption spectrum of value to be seen in alabaster, and the luminescence under ultra-violet light, usually a brownish shade, gives little aid to distinction. Under X-rays the material is inert.

Massive gypsum is of world-wide occurrence, but only in relatively few localities are quarries worked for ornamental alabaster. One of the important localities for alabaster is the quarries situated at Castellina, in the district of Volterra in Tuscany, Italy. The alabaster from this district is found in nodular masses embedded in limestone interstratified with marls. The mineral is mainly worked by mining through underground galleries.

The carving of Tuscan alabaster is carried out at Florence and Pisa and other cities of central Italy, and the industry dates from Etruscan times. The pure white Tuscan material is often carved into figurines having a religious significance. Some of this pure white material is, after carving, treated by immersion in cold water, which is then slowly raised to boiling point. The stone is allowed to cool very gradually and is afterwards thoroughly dried. This treatment is said to make the alabaster scarcely distinguishable from white marble. The material may be stained.

The most important quarries for ornamental alabaster in England are in the counties of Derbyshire and Staffordshire. The Derbyshire quarries are in the neighbourhood of Chellaston, where the mineral is found in thick nodular beds or 'floors' and in small lenticular masses termed 'cakes'. These deposits are close to the surface and are worked by open pit mining. The major Staffordshire quarries are at Fauld near Hanbury, and near Weston, which lies close to the Derbyshire border. Occasional thin bands of fine granular gypsum of a pinkish colour are found along the coastal plains of Glamorgan in South Wales. It is known as 'pink Welsh alabaster' but is not commercially important.

The anhydrous calcium sulphate ($CaSO_4$) anhydrite has also been used as a gem material. The hardness of anhydrite is about 3 on Mohs's scale, the SG is 2.9 and the refractive indices are 1.57 and 1.61 for the principal rays. The mineral, which crystallises in the orthorhombic system, is usually white in colour, but may be blue, and is found at many different localities in Brazil and Canada. A granular variety from Vulpino, Italy, and hence called 'vulpinite', is cut and polished as cabochons and for other ornamental purposes. Two SG determinations on vulpinite gave 2.901 and 2.93.

Amblygonite

Occasionally clear transparent colourless or yellow crystals of amblygonite have been cut for those who covet the unusual. The mineral is a fluophosphate of aluminium and lithium $(Li,Na)Al(PO_4)(F,OH)$, a mineral which, like topaz, has the fluorine replaceable by the hydroxyl group. Amblygonite forms large but rough crystals of the triclinic system which have a tabular habit and a perfect basal cleavage. The hardness is 6 on Mohs's scale and for the gem material the SG is between 3.015 and 3.033. The refractive indices for the cut stones so far examined approximate to 1.611 and 1.637 for the principal rays, the biaxial positive birefringence being 0.026. No clear absorption spectrum is seen with the yellow amblygonite and under the long-wave ultra-violet lamp the stones show a very weak greenish glow, but under X-rays the glow is a bright greenish-white. Apart from the physical and optical properties identifying amblygonite, microchemical tests will prove the phosphate content. Powder 'sneaked' from the edge of the stone will allow this to be done and will also allow flame tests to be carried out, for the powder introduced by means of a platinum wire into the colourless bunsen flame will colour the flame with the characteristic red of lithium.

The localities for amblygonite are São Paulo and Minas Gerais in Brazil – whence most of the gem material is said to have emanated – and Pala, California and Maine in the United States of America. Saxony, France and Australia (Northern Territory) are other localities. Pale mauve amblygonite is found in the Karabib area of Nimibia.

Analcite (Analcime)

At the whim of collectors some small colourless crystals of analcite have been cut. The mineral, which forms icositetrahedral crystals of the cubic system, is a hydrous sodium aluminium silicate with the formula $NaAlSi_2O_6.H_2O$. The hardness is from 5 to 5.5 on Mohs's scale, the SG is from 2.22 to 2.29 and the refractive index is 1.487. The mineral is a member of the zeolite group and is found in the United States of America, Czechoslovakia, Italy, Scotland, and in fine crystals from the Kerguelen Islands in the Indian Ocean. Australia and Japan are other localities for this mineral which may be said to have a world-wide occurrence.

Anatase

One of the polymorphous forms of titanium oxide (TiO_2) (rutile and brookite are the others), anatase is rarely cut as a gemstone. The mineral is brown or blue in colour and crystallises in the tretragonal system, usually as bipyramids so that the form can be said to be octahedral. It is owing to this that the alternative name octahedrite is sometimes used for the mineral. Anatase has a hardness of 5.5–6 on Mohs's scale, an SG which lies between 3.82 and 3.95, and refractive indices 2.493 for the extraordinary ray and 2.554 for the ordinary ray. The uniaxial negative birefringence is 0.061. Anatase shows no luminescence. The mineral results from the alteration of other titanium-bearing minerals and is also found in veins of hydrothermal origin. The localities for anatase are Isère in France, St Gotthard and Binnenthal in Switzerland, the Ural mountains of Russia and Minas Gerais in Brazil. Other localities are Massachusetts, North Carolina and Colorado in the United States of America, where blue crystals are found.

Andalusite

Not commonly met with in jewellery, andalusite, which is named after the Spanish province of Andalusia where the mineral was first found, supplies stones of a greenish-brown to a rich green in colour, the stones owing much of their attractivenes to the extremely pronounced pleochroism which they exhibit. The mineral is an aluminium silicate corresponding to the formula Al_2SiO_5, and is therefore polymorphous (that is it has the same chemical composition) with the minerals kyanite and fibrolite. The crystals, belonging to the orthorhombic system, have a prismatic habit with vertically striated prisms which are nearly square in section and capped with pyramids, but much of the gem material is found as water-worn pebbles.

The hardness of andalusite is 7.5 on Mohs's scale and the specific gravity varies from 3.15 to 3.17. The least and greatest refractive indices vary from 1.634 to 1.641 and 1.644 to 1.648, the biaxial double refraction varying from 0.007 to 0.011. The sign is negative. The dispersion is approximately 0.016 over the B to G interval, and the three pleochroic colours of the stones are yellow, green and red which may be variable in intensity. The absorption spectrum of andalusite varies in that the deep green viridine-like variety, believed to come from Brazil, shows a manganese spectrum, with an absorption band, graded in intensity, which ends in a knife-sharp edge at 553.5 nm, and which is followed by fine lines at 550.5 and 547.5 nm and fainter ones at 518 and 495 nm. There is a strong absorption in the blue and violet but a band at 455 nm can just be seen. This has been noted in the normal types of gem andalusite and these stones, particularly those from Sri Lanka, show this band to be accompanied by a narrow band at 436 nm. These last two bands are probably due to iron. Andalusite exhibits no luminescence under the long-wave lamp, but the brownish-green stones from Brazil often show a dark green to yellowish-green glow under the short-wave ultra-violet lamp and a greenish-yellow glow under X-rays.

Andalusite of a dull green is found in the gem gravels of Sri Lanka, but Brazil is the more prolific source of the gem material, where the stones are found in secondary deposits, either in the stream beds or on the slopes of the hills under several yards of clay and gravel. This is in an area some 15 km wide and 40 km in length near the town of Santa Tereza in the state of Espírito Santo. Andalusite is also found in the state of Minas Gerais. The gem mineral is rarely found in crystals with good form and most of the gemmy material is found as water-worn pebbles. The Brazilian stones usually show a very strong flesh-red and olive-green pleochroism, which is especially well brought out when the stones are cut with the table facet nearly at right angles to the vertical axis of the crystal. Such stones may closely resemble certain types of Brazilian tourmalines. A dark green andalusite is also found in Brazil, and so too are stones of a rose-red colour, although these are rare.

An impure opaque variety of andalusite in which the crystals contain carbonaceous inclusions with a cruciform arrangement is known as chiastolite (cross stone). Sections of such crystals are cut and polished for amulets and charms in several countries, and particularly in the Pyrenees, where the religious significance of the cross is profound. Owing to impurities chiastolite may have a lower hardness and SG than for the transparent crystals. Chiastolite crystals are found in the Nerchinsk district of Transbaikalia in Siberia, at Sallas de Rohan near Brieux in Brittany and Mount Howden, north of Bimbowrie in South Australia. Other localities are at Hof in the Fichtelgebirge and in the slates around Skiddaw in Cumberland, but here the needle-like prisms are too slender for fashioning into gems. Sources in the United States of America are Arizona, and Madera in Madera County, California. Other localities are in Maine, Connecticut, Massachusetts and New Mexico, and Fannin County, Georgia. Good examples of the chiastolite variety are found in the Chantaing U range, near Kyankse, south of Mandalay, in Myanmar (Burma), and there are sources in Zimbabwe.

Anglesite

A stone only cut for collectors is the orthorhombic mineral anglesite, a lead sulphate, $PbSO_4$. Usually white in colour although shades of yellow, green or blue may be found, the mineral has a hardness of 3 on Mohs's scale, an SG of 6.30–6.39 and refractive indices of α 1.877, β 1.882 and γ 1.894, biaxial and positive in sign with double refraction of 0.017. The lustre may be adamantine inclining to resinous or vitreous, and anglesite fluoresces with a weak yellow glow under short-wave ultra-violet light. The mineral has a world-wide occurrence and is found in large crystals at various places in the United States of America. Anglesite was originally found in the isle of Anglesey, hence the name, and fine crystals have been found in the Leadhill district of Scotland. Cuttable material comes from Bou Azzwr in Morocco.

Apatite

If apatite were not so soft, the mineral being the standard 5 on Mohs's scale, it would make a fine suite of gemstones as the colours range from white, yellow and green to blue and violet.

The mineral is a calcium phosphate, but there is always some fluorine or chlorine in the composition; hence the formula may best be written as $Ca(F,Cl)Ca_4(PO_4)_3$. In coarse non-gem, quality crystals, apatite reaches enormous sizes, sometimes hundreds of kilograms in mass, but the clear crystals from which gemstones are cut are never large. The crystals belong to the hexagonal system and their habit is usually stumpy prismatic, or in some cases tabular.

Lovely blue stones are found in the Mogok Stone Tract of Myanmar and in the gem gravels of Sri Lanka, some of which have a fibrous structure and when cut cabochon in the correct direction show a cat's-eye effect. Yellowish-green crystals found in the Spanish province of Murcia, probably in the Serra de Espuna, have been called 'asparagus stones', owing to their peculiar colour. From Arendal, in southern Norway, comes a beautiful bluish-green variety to which the name moroxite has been given. Well-formed prismatic crystals of yellow colour come from Cerro de Mercado, Durango in Mexico, and lovely violet-coloured stones are found in the Griefenstein in Saxony, Schlaggenwald in Bohemia and in the United States of America at Auburn, Maine and San Diego, California. Other localities are in Ajmer, Rajasthan and Devada, and Madras, in India, where sea-green material is obtained. A deep rich green apatite is found in Quebec and Ontario, Canada and marketed under the name 'Trillium'. There are many other sources of apatite, which is a widespread mineral, but the localities given are the better-known places where gem material is found. Well-formed green crystals in an orange calcite come from Mozambique and form lovely mineral specimens, the apatite often being clear enough to produce cut stones. Yellow and green cat's-eye apatite has been seen and an intense sapphire-blue material comes from Minas Gerais, Brazil. Yellowish-green, greenish-brown and reddish-brown apatites and apatite cat's-eyes have been found in the Umba valley in Tanzania. Green apatites from Rössing in Namibia have high refractive indices of 1.649–1.655 with a birefringence of 0.006.

The SG of apatite varies from 3.17 to 3.23, the blue stones generally being 3.18 and the yellow 3.22. The refractive indices are 1.63–1.64 with an exceptionally small negatively uniaxial birefringence of 0.002–0.004. The diochroism is usually feeble but distinct, except in the blue and some green stones. The blue stones show pronounced dichroism and the twin colours are blue for the extraordinary ray and pale yellow for the ordinary ray. The lustre is vitreous and the fire (0.013 B to G) is weak. Absorption spectra of apatite can vary considerably; both blue and yellow stones show absorption spectra attributed to the rare earths, but the yellow-coloured stones show strongly two groups of closely spaced lines, one a group of about seven lines at about 580 nm, which is just on the short-wave side of the D lines of sodium, and a group of about five closely spaced lines in the green of the spectrum at about 520 nm. The blue-coloured apatites show rather broader bands, the strongest being at 512, 491 and 464 nm, the last two being in the blue part of the spectrum. It is interesting to recall that the rare earth didymium is actually composite, containing the two elements praseodymium and neodymium, which are so often associated together. Thus the absorption spectrum will, in general, show bands due to the two elements, but the bands of one of the pair of elements may predominate. Webster has suggested, from the appearance of the absorption spectrum of yellow apatite, which is usually called a 'didymium spectrum', neodymium preponderates, while in blue apatite praseodymium is stronger.

The luminescence of apatite also varies. Results of the examination of a number of different coloured apatites are shown in *Table 17.1*.

Table 17.1

Colour	*Long-wave ultra-violet light*	*Short-wave ultra-violet light*	*X-rays*
Yellow	Lilac-pink	Weak lilac-pink	Pinkish-white to pinkish-yellow and mauve
Blue	Bright deep violet-blue to sky-blue	Bright deep violet-blue to sky-blue	Very dim pinkish-straw colour
Green	Greenish-mustard	Weak greenish-mustard	Yellowish-white to yellow
Violet	Greenish-yellow	Vague pale mauve	Very bright greenish-yellow with persistent phosphorescence

A massive sky-blue variety of apatite has been polished as an ornamental stone, and a variety with lapis from Siberia has been named lazurapatite.

Apophyllite

Valued as a gemstone by collectors only, the hydrated potassium calcium silicate having the formula $KFCa_4(Si_2O_5)_4.8H_2O$, known as apophyllite, forms crystals of the tetragonal system with varied habit and which have a perfect basal cleavage. Apophyllite is usually colourless or it may have a bluish, pinkish, greenish or yellowish tint. The hardness of the mineral varies from 4.5 to 5 on Mohs's scale, and the SG ranges from 2.30 to 2.50. The refractive indices are 1.535 and 1.537 and the small uniaxial birefringence may be either positive or negative in sign. The lustre is vitreous, although on the cleavage surface the lustre is pearly. There is no distinctive spectrum and normally the stones do not luminesce under ultra-violet light. A yellowish glow from apophyllite under short-wave ultra-violet light has been reported. Under X-rays the mineral shows either an orange or a weak bluish glow. Apophyllite is found in many places, particularly from the rocks of the Deccan trap of India. The mineral is also found at Guanajuato, Mexico (pink crystals on amethyst), Switzerland, Germany and a number of the states of North America.

Aragonite

The orthorhombic polymorphic modification of $CaCO_3$, aragonite has been found in transparent colourless, yellowish, yellowish-green and brownish-yellow crystals at Horuenec near Bilina in Czechoslovakia. Aragonite was named after the original locality in Aragon province, Spain and has a hardness of 3.5 to 4 on Mohs's scale. The SG is 2.93–2.94 and the refractive indices are 1.530–1.540 and 1.680–1.690 with a birefringence of 0.150; the optic sign is negative. An opaque, iridescent aragonite of ammonite shells comes from a location between Cardstone and Lethbridge in Alberta, Canada. Refractive indices are α 1.522, β 1.672–1.673 and γ 1.676–1.679 with a birefringence of 0.154–0.155. Aragonite frequently shows pseudohexagonal habit which is caused by combination and twinning. As a carbonate mineral it is easily soluble in acids.

Arandisite

An attractive apple-green material, arandisite is sometimes cut, together with the surrounding brown limonite. It is a basic silicate of tin but is considered to be a mixture of two constituents, perhaps colloidal and crystalline phases. The hardness is 5 on Mohs's scale; the SG is 4, but if with much limonite would be less; and the refractive index is 1.70, but can be higher in parts. It is a rare mineral and is found only at the Arandis tin mine, north of Arandis, Namibia.

Augelite

Colourless to yellowish crystals of this hydrated aluminium phosphate mineral which accords to the formula $Al_2(PO_4)(OH)_3$ have been cut as gems for collectors. The monoclinic crystals have a tabular habit, a hardness of 5 on Mohs's scale and an SG near to 2.7. The refractive indices are α 1.574, β 1.576 and γ 1.588. The mineral is biaxial and optically positive with a birefringence of 0.014. The stones have a vitreous lustre and do not exhibit luminescence under ultra-violet light. Augelite is found at White Mountain, California, in Bolivia and in Spain. Material from California has refractive indices α 1.570–1.575 and γ 1.590–1.591, with a birefringence of 0.02.

Axinite

The broad acute-edged triclinic crystals of axinite, which form such attractive crystal groups, may be found large and clear enough to cut into gemstones for those who crave the unusual. Axinite, named after the axe-like shape of the crystals, is usually a typical clove-brown colour, or more rarely honey-yellow or plum-blue, and the stones are characterised by the strong pleochroism they exhibit, the three colours being olive-green, violet-blue and cinnamon-brown for the three principal directions. The indices of refraction, biaxial and negative in sign, are approximately 1.68 for the greatest and 1.67 for the least, the birefringence being 0.010–0.012. The hardness of axinite is 7 on Mohs's scale and the SG varies from 3.27 to 3.29. The absorption spectrum of axinite shows three fairly obvious bands; a narrow band in the blue-green at 512 nm and two broader bands at 492 and 466 nm in the blue. No luminescence has been observed in gem axinite, but it has been reported that honey-yellow crystals from Franklin Furnace, New Jersey, USA may fluoresce red under short-wave ultra-violet radiations. This may well be due to included traces of manganese, as so many of the minerals from this noted zinc ore mining locality behave similarly.

Axinite is a complex calcium aluminium borosilicate ($Ca_3Al_2BSi_4O_{15}(OH)$), but much variation of the composition occurs owing to the replacement of the calcium by iron, magnesium and manganese. The mineral occurs in cavities in granite or diabase and especially in the contact zones of these rocks. Axinite is found in magnificent crystal groups at St Cristophe, near Bourg d'Oisans, Isère, France, from various localities in America, in Bahia, Brazil, and at the Botallack mine near St Just, Cornwall, England. During 1964 a new source of gem-quality axinite of reddish-brown colour, and in quite large crystals, was discovered at Mina la Olivia in Baja California, Mexico.

In 1974, Jobbins described an unusual magnesio-axinite from Tanzania, cut as a gemstone. This had refractive indices 1.660, 1.666 and 1.668 with the unusually low SG of 3.18. Analysis showed the specimen to have $Al_2O_3.SiO_2$ (44 per cent), MgO (6.9), MnO (0.4), FeO (0.03) and V (0.4).

A cinnamon-brown ferro-axinite has been found in Sri Lanka. The SG is 3.178–3.314 and the refractive indices are α 1.656–1.675, β 1.660–1.685 and γ 1.668–1.685. The pleochroism is α reddish-brown, β dark violet, γ colourless to yellowish.

Azurite

The somewhat unstable basic copper carbonate ($Cu_3(OH)_2(CO_3)_2$) is known as azurite from the typical azure-blue colour. Like malachite, to which mineral it slowly changes, azurite is a secondary ore of copper found in the oxidised portions of copper veins. It is found as prismatic monoclinic crystals of varied habit, often in spherical radiating groups, and as such is found at Chessy, near Lyons in France – hence the alternative name chessylite for the mineral. It is common in botryoidal or stalagmitic groups and massive in veins with malachite. Indeed it is rare to find azurite without its alteration product – malachite – and even the crystals become pseudomorphs of malachite after azurite.

The SG of azurite lies between 3.77 and 3.89 and the principal refractive indices for the crystals are 1.73 and 1.84. The refraction is biaxial and positive in sign and the birefringence is 0.11, large by gem standards but small for a carbonate mineral. The hardness is 3.5–4 on Mohs's scale. Azurite needs little testing for the typical colour and its association with malachite makes distinction obvious. The two are so generally found together that pieces containing both the green and blue materials in bands are cut as ornamental stones to which the name azurmalachite is given.

Azurite effervesces when touched with acid, and further will give a reaction for copper. Thus if a fragment of a suspected specimen is moistened with hydrochloric acid and introduced into the edge of a Bunsen flame, the characteristic blue of the flame of copper chloride will be seen. Malachite behaves in similar manner.

Azurite is found at Chessy in France, Bannat in Romania, Tsumeb in Namibia (partly translucent), and Bisbee and Morenci in Arizona in the United States of America. The mineral is also found in New South Wales and South Australia, and in Siberia. A rock-like mixture of azurite, malachite and cuprite is called burnite.

Owing to the usually friable nature of pure azurite it has not been so extensively worked as an ornamental stone as the closely related malachite, but in 1971 samples recovered from an old abandoned source known as the Copper World Mine were found to be an unusually tough form of the mineral, mixed in some cases with malachite and other copper minerals. This was soon a popular lapidary material and has been christened 'Royal Gem Azurite'. The Copper World Mine has had a long history and is just north of Gambler's Highway between Barstow and Las Vegas.

Barite (Barytes)

The Barium sulphate mineral ($BaSO_4$) barite is also known as heavy spar. The mineral forms orthorhombic crystals which are white in colour and may be transparent to opaque. Crystals coloured yellow, green, red, blue or brown are sometimes found. The massive white material resembles marbles. Barite is rarely cut as a gemstone, except for those who desire anything unusual, for the hardness is only 3 on Mohs's scale, which is too low for durability. There is, however, a stalagmitic variety of brown colour which shows a concentric structure when cut across the stalactite, and such material has been polished as an ornamental stone. Barytes has an SG of 4.3–4.6, and for gemmy material the values are near 4.47; the refractive indices are α 1.636, β 1.637 and γ 1.648, and the refraction is biaxial and positive in sign. The crystals show perfect cleavage in two directions. The mineral sometimes fluoresces and often phosphoresces with a faint blue or light green colour under ultra-violet light. Barytes has a world-wide occurrence: gemmy material comes from Colorado and Sardinia.

Bayldonite

Found in mamillary concretions of fibrous crystals, probably of the monoclinic system, this greenish mineral has been reported as having been fashioned into gemstones. The composition is a complex hydrated lead copper arsenate ($PbCu_3(AsO_4)_2(OH)_2.H_2O$). The hardness is 4.5 on Mohs's scale, the SG is 4.35 and the three refractive indices are 1.95, 1.97 and 1.99, the refraction being biaxial and positive in sign. Bayldonite is found at Tsumeb in Namibia and in Cornwall.

Benitoite

During the autumn of 1906 a prospector, Crouch, while searching for mercury and copper minerals in the area of the headwaters of the San Benito river of California, discovered in a vein of white natrolite some blue crystals. These were subsequently considered to be sapphire, but this notion was questioned by a Californian jeweller on account of the strong dichroism shown by the stones. The crystals were sent to Dr Louderback, of the University of California, who identified them as a new mineral to which the name benitoite was given, after the locality in which they were discovered. That is one account of the finding of benitoite, but Kunz states that the crystals were found in 1907 by Hawkins and Edwin Sanders who were prospecting in the southern part of the Mount Diablo range near the San Benito–Fresno border, and that these crystals were brought to the attention of Dr Louderback by Shreve and Company, a San Francisco firm who had purchased one of the cut stones from a lapidary, and who were later offered some of the rough material as sapphire.

Benitoite, a lovely sapphire-blue stone, is unique in that it crystallises in a class of the hexagonal system which has a trigonal axis of symmetry and a plane of symmetry at right angles to it, a class known as the dihexagonal dipyramidal. It is a form that was mathematically considered possible in nature but not found until the discovery of benitoite which is, so far, the only example in nature. Colourless crystals of benitoite are not uncommon but are not considered worth cutting.

The mineral is a barium titanium silicate with the formula $BaTiSi_3O_9$, and thus it has a chemical similarity to sphene. The SG lies between 3.65 and 3.68, but the latter value is more common. The hardness is about 6.5 on Mohs's scale. The indices are 1.757 for the ordinary ray and 1.804 for the extraordinary ray, the refraction being uniaxial and positive in sign. The birefringence is strong, being 0.047. The pronounced dichroism shows twin colours of blue for the extraordinary ray and colourless for the ordinary ray, so that to obtain the best colour the table facet should be cut parallel to the vertical crystal axis, and as most of the crystals have a tabular habit this precludes the cutting of large stones. Benitoite has exceptionally strong fire: the colour dispersion for the B to G interval is 0.039 for the ordinary ray and 0.046 for the extraordinary ray (as measured by Payne). Thus the fire approximates to that found in diamond but the effect is masked by the body colour of the stone.

The lower density allows distinction from sapphire, but if the stone is set determination of this constant would not be possible and a refractometer reading would be necessary. Care is needed, however, in observing the shadow edges as the edge of the extraordinary ray at its highest is in the region of the shadow edge of the contact liquid (1.81) and may be missed unless its movement is carefully noted. The pronounced dichroism may also give information of value for there is no colourless ray in sapphire. What may be a simpler and more easily performed test is given by the bright blue fluorescent glow seen under short-wave (253.7 nm) ultra-violet light, or under X-rays. This blue glow is not observed under the long-wave (365 nm) radiation. Cavey noticed that, under long-wave ultra-violet light, colourless benitoite showed a dull red glow, and this effect has been confirmed by Mitchell.

Benitoite has been found in only one locality, in the Diablo range of the

Californian mountains in San Benito County, where the flattened triangular-shaped crystals, never of large size, are found in association with another rare titanium mineral – neptunite – in a matrix of white natrolite. A pink benitoite has been reported.

Beryllonite

A rare beryllium mineral – a beryllium-sodium phosphate, $NaBePO_4$ – beryllonite is found at Stoneham, Maine in the United States of America, in the company of phenakite and beryl. The crystals were usually considered to have orthorhombic symmetry, but have now been found to be monoclinic with pseudo-orthorhombic symmetry. As a gemstone this colourless to yellowish mineral has only its rarity to recommend it. The indices of refraction are 1.553 and 1.562 for the principal rays; thus the birefringence is 0.009, the refraction being biaxial and negative in sign. The lustre is vitreous; the hardness is low, 5.5 on Mohs's scale; and the fire is weak, the dispersion being only 0.010 for the B to G interval. The SG varies from 2.80 to 2.85. The mineral is inert under ultra-violet light, but under X-rays there is a dark sky-blue fluorescence with a slight phosphorescence. Other sources are Finland, Zimbabwe and Minas Gerais in Brazil.

Boracite

Some faceted stones of a pale green colour have been cut for collectors from the magnesium chloroborate mineral known as boracite. The chemical formula for the mineral is $Mg_3B_7O_{13}Cl$, and it forms crystals of the cubic system with cubic, tetrahedral or dodecahedral habit. The hardness is 7 on Mohs's scale, the SG is 2.96 and the refractive index is 1.661–1.671. The mineral is pseudo-isometric and may be orthorhombic so that some double refraction of positive sign may be apparent. The lustre is vitreous to adamantine and a very weak greenish fluorescence may be seen. The mineral is found in Germany, but it has been reported from the United States of America, Bolivia and the Hannover district, Germany.

Brazilianite

During the closing months of 1944 some yellowish-green crystals were found in a pegmatitic dyke at a locality near Conselheira Pena in Minas Gerais, Brazil. When first found these crystals were thought to be chrysoberyl, to which they have some resemblance in colour but not in crystal form. Some of these crystals were shown by a dealer to Pough, then in Brazil, and he at once detected the differences in crystal form and that the hardness was lower than for chrysoberyl, but he could not recognise the crystals as being of any mineral that he knew. Later, in conjunction with Henderson, the crystals were found to be those of a completely new mineral to which the name brazilianite was given in honour of the country in which they were found.

Brazilianite is a hydrous sodium aluminium phosphate and has the formula $Al_3Na(PO_4)_2(OH)_4$. Thus it has some degree of chemical affinity to turqoise and to amblygonite. The crystals, generally prismatic in form, are usually of fair size and belong to the monoclinic system of crystallisation. The cleavage is perfect in one direction, which is parallel to one of the pinacoid faces. The material is brittle and shows a conchoidal fracture. The hardness is low, being 5.5 on Mohs's scale, and the SG varies between 2.940 and 2.998. The optical properties show brazilianite to be biaxial positive with indices of refraction of α 1.603, β 1.612 and γ 1.623, giving a double refraction of 0.020. The dispersion is very low, being only 0.014 for the B to G interval. There is no luminescence when the stone is bathed in ultra-violet light and no definite absorption spectrum has been noted. The dichroism is weak, merely a slight change of shade being noted.

Apart from the Brazilian locality already given, some crystals are said to have come from Corrego Frio, north of Sâo Tomé, which is also in the state of Minas Gerais. In 1947 another source of brazilianite was discovered at the Palermo mine, North Groton, in Grafton County, New Hampshire in the United States of America.

Bronzite

Bronzite is a member of the orthopyroxene group which forms a solid solution series with the end members enstatite ($Mg_2Si_2O_6$) and ortho-ferrosilite ($Fe_2Si_2O_6$). Bronzite contains between 5 and 13 per cent iron and crystallises orthorhombic. The hardness is 5–6 on Mohs's scale and a distinct cleavage exists. Cut yellowish-brown bronzite has been reported to come from Sri Lanka. The SG is 3.25 and the refractive indices are α 1.663, β 1.669 and γ 1.677 with a birefringence of 0.014; the optic sign is positive. Brown six-rayed star bronzite also comes from Sri Lanka. The SG is 3.41 and the refractive indices are α 1.680, β 1.689 and γ 1.693 with a birefringence of 0.013. The star effect is caused by scattering of light at oriented hollow tubes.

Brookite

One of the polymorphous forms of titanium dioxide (TiO_2), the others being rutile and anatase, brookite, which crystallises in the orthorhombic system with varied habit, has scant use as a gemstone. The mineral is yellowish-brown to reddish-brown in colour and has a hardness of 5.5–6 on Mohs's scale. The SG varies from 3.87 to 4.08 and the refractive indices are near to 2.583 and 2.705 for the principal rays; the biaxial and optically positive double refraction is about 0.122, but it can reach to 0.157 in certain cases. The lustre of brookite is metallic adamantine. The mineral is found in France, Switzerland, Russia (Urals) and the United States of America.

Bustamite

Transparent pink bustamite ($(Mn,Ca)_3Si_3O_9$) occurs in Australia. The triclinic mineral was named after Bustamente, who had found the mineral first. The hardness is 5.5–6.5 on Mohs's scale, the SG is about 3.3–3.4 and the refractive indices are α 1.683, β 1.698 and γ 1.701 with a birefringence of 0.018. Gem-quality bustamite is also found at Daghazeta in Tanzania. Bustamite can be confused with rhodonite because of the colour and the common occurrence, but the refractive indices are lower.

Cancrinite

A semi-opaque yellow-coloured fibrous variety of cancrinite, a complex mineral with the formula $Na_6Ca_2Al_6Si_6O_{24}(CO_3)_2$, has been cut as beads and as cabochons. The mineral is named after Count Cancrin, Minister of Finance in Imperial Russia where the mineral was originally discovered. The mineral is occasionally found in crystals belonging to the hexagonal system which have a perfect prismatic cleavage, but is more often found massive. The hardness is between 5 and 6 on Mohs's scale and the refractive indices approximate to 1.50, which is all that would be expected to be seen on the ordinary refractometer with the massive gemmy material. The crystals of cancrinite have indices for the ordinary ray of 1.515–1.524 and for the extraordinary ray of 1.491–1.502, the double refraction of 0.022 being uniaxial and optically negative. The SG varies from 2.42 to 2.50 (a specimen of the Canadian gem material gave a value of 2.435). The yellow gem cancrinite does not luminesce under ultra-violet light but an orange-yellow glow has been observed when the mineral is irradiated with X-rays. Cancrinite effervesces with acid. The mineral is found in many places, such as Russia, Transylvania, Norway, and Maine in the United States of America. The material reported as cut for gems comes from Bancroft and French River in Canada.

Carletonite

At Mont Saint Hilaire in Canada, gem-quality pale blue carletonite has been found. Carletonite has the chemical formula $KNa_4Ca_4Si_8O_{18}(CO_3)(OH,F).H_2O$ and crystallises tetragonal. The hardness is 4.5 on Mohs's scale and a perfect cleavage is present. The SG is 2.44 and the refractive indices are 1.517 and 1.521 with a birefringence of -0.004. The mineral was named after Carleton University in Ottawa.

Cassiterite

Cassiterite, tin oxide (SnO_2), is the principal ore of tin. Usually, owing to the presence of iron, the mineral is black and opaque, but occasionally crystals occur which are light reddish-brown in colour and sufficiently transparent to cut as faceted stones; their interest is for collectors only. The mineral crystallises in the tetragonal system as square-section prismatic crystals capped by pyramids, and the crystals are often twinned with the twin plane parallel to one of the pyramid faces producing knee-shaped forms (geniculate twins). The crystals show only an indistinct cleavage.

Cassiterite has a hardness of about 6.5 on Mohs's scale and is characterised by having a high specific gravity of 6.95. The refraction, uniaxial positive, has indices of 2.003 for the ordinary ray and 2.101 for the extraordinary ray; thus the birefringence is 0.098. The dispersion is 0.071 over the B to G interval, and the lustre shown by the mineral is adamantine. Owing probably to the iron content, cassiterite does not show any luminescence and the stones show no distinctive absorption spectrum.

Cassiterite can be distinguished from brown diamond, brown zircon and sphene by the great density of the mineral; from zircon by the absence of any typical absorption lines; from sphene by the absence of (or a much weaker) dichroism; and from diamond by the double refraction.

The mineral is found in many places and particularly in the Malay peninsula. In Cornwall a source has been known since Roman times: in those days it was called the Cassiterides from the occurrence of the tin. Other localities are Mexico, Australia, Bolivia, Tasmania, Saxony, Indonesia, Spain, where clear yellowish-red pieces suitable for cutting have been found, and at the Erongo tin fields, Namibia.

Catapleiite

Transparent colourless catapleiite ($Na_2ZrSi_3O_9.2H_2O$) is found at the famous locality of Mont Saint Hilaire in Canada. The hexagonal crystals possess a perfect cleavage and have a hardness of 6 on Mohs's scale. The SG is 2.72 and the refractive indices are α 1.590, β 1.609 and γ 1.629 with a birefringence of 0.039 and a positive optic sign.

Celestine (Celestite)

The low hardness of 3.5 on Mohs's scale of celestine makes it a most undesirable gemstone. Celestite is a sulphate of strontium ($SrSO_4$) and crystallises in the orthorhombic system with tabular habit. The crystals have at least two directions of cleavage and the rather uninteresting cut stones are fashioned from colourless, yellowish or bluish-green crystals. The SG lies between 3.97 and 4.00 and the refractive indices are given as α 1.619, β 1.623 and γ 1.631 with, therefore, a biaxial birefringence of 0.012 which is positive in sign. The gemmy material may have slightly higher values, for one specimen examined had values of 1.625 and 1.635 for the principal rays, the birefringence being in this case 0.010, and the density was found to be 3.997. A scraping taken from the girdle of a cut celestite and picked up on a platinum wire will, when introduced into a colourless Bunsen flame, colour it the rich red of strontium. A whitish or bluish-white glow is shown by celestite when under ultra-violet light.

Celestite occurs with sandstones or limestone and is often associated with sulphur, gypsum and colemanite at many different localities, particularly in Sicily, Switzerland, Italy and south-western England. Many localities of the United States of America supply the mineral, but Tsumeb in Namibia is the locality from which most of the cut stones may have come. Orange crystals are found in Ontario, Canada. Colourless and blue transparent material comes from Madagascar.

Cerussite

Reported as having been cut for those who want the unusual is cerussite, a lead carbonate whose formula is $PbCO_3$. The mineral is usually white or grey in colour, but black, blue and green colours are known, these two latter owing their colour to copper. The hardness is only 3.5 on Mohs's scale and the SG is near to 6.5 (6.46–6.57). The lustre is adamantine and the refractive indices are α 1.804, β 2.076 and γ 2.078. In common with carbonate minerals the double refraction is large in amount at 0.274, and is biaxial and negative in sign. The luminescence is variable but under the short-wave lamp it usually shows a pale blue or green glow. Some cerussite from Utah is said to show a bright orange under the long-wave lamp. The occurrences of the mineral are world-wide: cuttable-quality material comes from the USA and Tsumeb, Namibia.

Chalcosite

A chalcosite rock from Ambatofinandrahana in Madagascar is used as an ornamental material. The rock is composed of reddish-brown kalifeldspar, green plagioclase feldspar, grey quartz and black mica (biotite).

Chambersite

Pale brownish transparent chambersite ($Mn_3B_7O_{13}Cl$) occurs in Chambers County, Texas, USA. The orthorhombic crystals have a hardness of 7 on Mohs's scale. The SG is 3.50 and the refractive indices are α 1.735, β 1.740 and γ 1.745 with a birefringence of 0.010.

Charoite

A spectacular new ornamental mineral, opaque and streaky purple in colour, was discovered in north-west Alden, USSR, and was first described in October 1976. The name charoite was given to the new mineral after the Charo River, and has been officially accepted. In composition it is essentially a calcium potassium silicate containing hydroxyl and fluorine $K(Ca, Na)_2\ Si_4O_{10}(OH,F).H_2O$. The refractive index is about 1.55 and SG 2.68. It forms part of a rock containing aegerine-augite, microcline feldspar, etc.

The colour and structure of charoite are so distinctive that it can be recognised at sight without the necessity for any test. Some tonnes of the mineral have already been exported, and it has become popular as material for vases and other decorative objects.

Chlorastrolite

Found as rolled pebbles which have weathered out from the basic igneous rocks which border the shores of Lake Superior in North America, chlorastrolite occurs as small spherical aggregates of greenish fibres. The mineral depends for its attractiveness upon its unique markings of white and green, the circular areas being caused by the radial groups of the fibrous crystals, the whole forming an interlocking mass. The material is not completely homogeneous but the main component is pumpellyite, a hydrated calcium aluminium silicate ($6CaO.3Al_2O_3.7SiO_2.4H_2O$), which forms narrow plates or fibrous crystals of the orthorhombic system. The hardness of chlorastrolite is from 5 to 6 on Mohs's scale, the SG is between 3.1 and 3.5, and the mean refractive index, all that would be seen on a refractometer, is about 1.70. No luminescence is shown by the mineral under ultra-violet light. Chlorastrolite is usually cut in the cabochon style in order to bring out the beauty of the markings. The main source of the stones is along the shores of Isle Royale in Lake Superior and the shores of the Keweenaw peninsula on the Michigan side of the lake. Chlorastrolites are sometimes called 'green stones'.

Chondrodite

A member of the humite group of minerals, chondrodite is an unusual mineral cut for the whim of collectors. Of monoclinic symmetry, the mineral is a magnesium silicate with fluorine and hydroxyl, and accords to the formula $(Mg,Fe)_5(SiO_4)_2(F,OH)_2$. The colour of the mineral varies from yellow to garnet-red and brown; the hardness is 6.5 on Mohs's scale and the SG varies from 3.1 to 3.2. The refraction is biaxial and positive in sign, the indices varying from 1.59 to 1.60 and from 1.62 to 1.64 for the principal rays. Some chondrodite shows a weak orange fluorescence under long-wave ultra-violet light and is inert under the short-wave lamp. The mineral (mostly honey-yellow in colour) is found at Pargas and Kafveltorp in Sweden and crystals of garnet-red colour are found in the Tilly Foster mine at Brewster, New York.

Chrysocolla

A cryptocrystalline mineral of mountain-green, bluish-green, sky-blue and turquoise-blue colour, often with an opal or enamal-like texture, chrysocolla is a hydrous copper silicate ($(Cu,Al)_2H_2Si_2O_5(OH)_4.nH_2O$), but the composition is somewhat variable. Indeed, through impurities such as free silica, alumina, black oxide of copper, limonitic oxide of iron and manganese oxide, the colour can vary from those given above to brown and black. Much chrysocolla may be a mineral gel with copper oxide, silica, and water in varying proportions depending upon the conditions of formation. Thus, the constants of the mineral are variable. The mean refractive index is 1.50 (ordinary 1.46 and extraordinary 1.57 have been determined in the case of microscopic acicular crystals from Mackay, Idaho). The hardness varies from 2 to 4 on Mohs's scale, rising to over 6 if much quartz is present, and the SG varies between 2.00 and 2.45.

Chrysocolla is a mineral of secondary origin occurring in the oxidised zones of copper veins at widespread localities, particularly at Nevada, New Mexico and Arizona in the United States of America. Other localities are at Katanga in the Congo, and in Russia, Peru and Chile. Much of the chrysocolla of jewellery consists of very attractive cobochons of green or blue chrysocolla impregnating either rock crystal or opal. Such material will have the hardness (7) and the refractive indices of quartz; the SG may be slightly lower than the 2.65 for rock crystal owing to the slight lowering by the included chrysocolla.

It may be convenient to include in this section the stone called 'Eilat stone' or 'Elath stone', which is found near Eilat at the heart of the Gulf of Aqaba on the Red Sea. It is said to come from the copper mines of King Solomon. The rock, which is usually cut into cabochons or 'tumbled', is a mixture of copper minerals. The constituents vary considerably, but include chrysocolla, turquoise and pseudomalachite, a copper phosphate mineral which accords to the formula $Cu_3P_2O_83Cu(OH)$ and resembles malachite in colour. Other copper minerals may be included, and in one case apatite was determined. The colour, which is variegated, is blue to green. The SG, on specimens determined, varied from 2.8 to 3.2, and like most copper minerals the stone turns yellow when a spot of hydrochloric acid is applied.

Clinohumite

Transparent yellow, yellowish-brown, brownish-orange and brownish-yellow monoclinic clinohumite ($(Mg,Fe)_9(SiO_4)_4(F,OH)_2$) is found in the Pamir Mountains. The hardness is 6 on Mohs's scale. The SG is about 3.18 and the refractive indices are α 1.625–1.632, β 1.636–1.647 and γ 1.659–1.668 with a birefringence of 0.024–0.036; the optic sign is positive. Exposed to short-wave ultra-violet radiation, clinohumite shows an orange-yellow fluorescence.

Coeruleite

Opaque blue turquoise-like coeruleite ($Cu_2Al_7(AsO_4)_4(OH)_{13}.11.5\ H_2O$) is found in the gold mine Emma Luisa near Huanaco in Chile as well as in Boliva. The massive polycrystalline material possesses an SG of about 2.7 and a refractive index of about 1.60. The aggregate has been found to be stabilised by resin similar to turquoise; the SG is 2.58. Coeruleite is associated by a trigonal green mineral with the chemical formula $(H_3O,Ca)Al_3(AsO_4,SO_4)_2(OH)_6$ which was named schlossmacherite after the famous German mineralogist and gemmologist Prof. Dr Karl Schlossmacher.

Colemanite

For the benefit of collectors who desire the curious, the monoclinic mineral colemanite, a hydrous calcium borate ($Ca_2B_6O_{11}.5H_2O$), has been fashioned. Most commonly colourless to milky-white in colour, the mineral has a hardness of 4.5 on Mohs's scale, has an SG of 2.42 and is biaxial with positive sign. The refractive indices are α 1.586, β 1.592 and γ 1.614. Colemanite usually fluoresces whitish or green under ultra-violet light. The mineral is found mostly in the United States of America at Death Valley and at Kern and Riverside Counties, California, and at Clark County, Nevada. It is also found in Turkey.

Creedite

The mineral creedite is rare. It has the chemical formula $Ca_3Al_2(SO_4)(F,OH)_{10}.2H_2O$ and forms monoclinic crystals of prismatic habit, or as radiating masses. The colour is usually white, but may be rarely purple. With a hardness of only 3.5 on Mohs's scale and a perfect cleavage, the material is unsuitable as a gemstone except for collectors of the unusual. Such a stone has been recorded in literature. The refractive indices are α 1.461, β 1.478, γ 1.485 and the SG is given as 2.71. The only locality recorded is Colorado, USA.

Crocoite

Translucent bright red, orange and brown crocoite shows an SG of 6.0. The monoclinic mineral has a hardness of 2.5–3 on Mohs's scale and possesses a weak reddish to brownish fluorescence when exposed to ultra-violet radiation. The bright hyacinth-red monclinic crystals of this lead chromate ($PbCrO_4$) mineral have been cut into cabochon stones at the whim of collectors. The low hardness of 2.5–3 on Mohs's scale, and its distinct cleavage, contra-indicate its use as a gemstone despite its bright colour. The SG of the mineral ranges from 5.9 to 6.1. The refractive indices are well above the range of the refractometer at α 2.31, β 2.37 and γ 2.66, and the refraction is biaxial and positive. The absorption spectrum of crocoite, if in thick pieces, tends to cut off all the colours except the yellow, orange and red, but if in thinner sections a distinct band is seen in the general absorption at about 555 nm. Under ultra-violet light there may be seen a weak reddish or brownish glow which is probably more pronounced with the short-wave lamp. There is no fluorescence shown by the mineral when under X-rays. The mineral occurs in the Ural mountains of Russia, Rézbánya in Romania, Dundas in Tasmania, Ouro Preto in Brazil, and in Arizona in the United States of America.

Cuprite

The red oxide of copper (Cu_2O) forms red crystals of the cubic system and this mineral has been cut for collectors. The hardness of the mineral is 4 on Mohs's scale, and the SG lies between 5.85 and 6.15. The refractive index of cuprite is 2.85 and the mineral has a widespread occurrence. When found the crystals often have the surface altered to the green basic carbonate, malachite. Crystals from Santa Rita, New Mexico, and the Ongarija mine, Namibia, have been cut. Cuprite has widespread occurrence.

Danburite

The calcium borosilicate mineral which accords to the formula $CaB_2(SiO_4)_2$ and which is known as danburite has been fashioned into bright and attractive gemstones. It was first discovered at Danbury, Connecticut, USA, from where the name danburite was derived, but the material from that source does not appear to have been cut. Gem-quality material is found in the Mogok district of Myanmar, from which source large wine-yellow and colourless stones have been produced. Stones of a good yellow, yellowish-brown and brown colour have been cut from material found in Madagascar, and colourless crystals, from which faceted stones have been cut, emanate from Bungo, Japan. A danburite of light pink colour has been found at Charcas, San Luis Potosi, Mexico; colourless danburite has also been found in Mexico.

The crystals of danburite are orthorhombic and approximate in angles and habit to those of topaz. The hardness is 7 on Mohs's scale and the brilliant vitreous lustre enables the production of bright and durable gemstones from the crystals. The refraction is biaxial and the sign, owing to the angle between the optic axes being nearly a right angle, is negative for red to green light and positive for light of shorter wavelengths. The values of the least and greatest refractive indices are 1.630 and 1.636 with a double refraction of 0.006. The fire is small, being only 0.017 for the B to G interval. The absorption spectrum shows, albeit very weakly, the rare earth spectrum of didymium (see section on apatite). The SG approximates to 3.00 and there is little variation from this value. Danburite will float in methylene iodide while the similarly coloured topaz will sink. In a similar manner danburite will sink in bromoform whilst the yellow quartz will float. Danburite fluoresces with a sky-blue glow when irradiated with ultra-violet light, and the mineral is said to phosphoresce with a reddish tint when heated.

Datolite

A calcium borosilicate mineral which accords to the formula $CaBSiO_4(OH)$ and is therefore near danburite in composition is datolite, which forms short prismatic monoclinic crystals of varied habit. Such transparent crystals, colourless or with a pale tinge of yellow or green, are only cut for collectors; there is, however, a massive or granular type of milk-white to orange-brown colour which has been cut as cabochons. The hardness of datolite is near to 5 on Mohs's scale, the SG varies from 2.90 to 3.00 and the principal indices of refraction are 1.625 and 1.669, the birefringence being 0.044, biaxial and negative in sign. The dispersion for the B to G interval is 0.016. The mineral sometimes fluoresces blue under ultra-violet light (said to be activated by europium), and sometimes a yellowish or pinkish-white glow is seen under X-rays. The mineral is found at Habachtal near Salzburg in Austria, and at Springfield, Massachusetts and New Jersey in the USA. The Alps of the Tyrol and the Lizard, Cornwall, England, are other sources of datolite. The massive variety is found, often with included copper, in the Lake Superior copper district and on Micopoten Island of Lake Superior.

Diaspore

The orthorhombic mineral diaspore (AlOOH) had not, until 1977 been found in crystals of sufficient optical quality to be considered as a gem material, though its hardness (6.5–7) might otherwise warrant it. However, an occurrence in

Turkey became known from which transparent pieces of gem quality were recovered, and these showed some interesting characteristics.

Specimens examined by Scarratt in the Gem Testing Laboratory were transparent and showed a distinct colour change from greenish-brown in daylight to pinkish-brown under tungsten light, very similar to that seen in alexandrite of moderate quality. The refractive indices were found to be α 1.702, β 1.722, γ 1.750, the birefringence being 0.048 and positive in sign. The average SG was 3.30–3.35. Three absorption bands were measured in the blue at 471, 463 and 454 nm, very similar in position to those of green sapphire. The strong doubling of the back facet edges under lens examination forms a valuable clue to the nature of the stone.

Diopside

One of the pyroxene group of minerals which crystallises in the monoclinic system with a perfect prismatic cleavage, diopside produces stones which are mostly bottle-green, although colourless, brownish and violet-blue stones are found, and some material is fibrous, producing cat's-eyes when cut cabochon. Diopside is a calcium magnesium silicate ($CaMg(SiO_3)_2$), but some of the magnesium is always replaced by iron which gives the green and brown colours to the stones. The iron may increase in quantity until the stones are so dark a green that they appear almost black and finally reach the calcium iron pyroxene hedenbergite which has the formula $CaFe(SiO_3)_2$. Some diopsides contain chromium and are then a much brighter, and livelier green.

Diopside has a hardness of 5.5 on Mohs's scale, and the SG varies little from 3.29 for the gem material but may reach higher values when the material is rich in iron and so dark as to be virtually hedenbergite. The biaxial double refraction is positive in sign and the refractive indices are 1.675–1.701, but may rise in the case of the material near hedenbergite in composition. The double refraction is 0.026, the lustre vitreous and the fire small in amount. The absorption spectrum of the chrome diopsides consists of two sharp lines at 508 and 505 nm in the green and a band at 490 nm in the blue. There are rather woolly bands at 635, 655 and 670 nm in the orange and red with a strong doublet at 690 nm. The duller green diopsides do not show such a good spectrum but ill-defined bands may be seen at 505, 493 and 446 nm. The luminescence shown by diopsides is somewhat variable. Under long-wave ultra-violet excitation some green stones glow with a green light, do not show any glow under the short-wave lamp and show a dull mustard-yellow glow under X-rays. A lighter green stone showed a mauve, an orange and a yellow glow under the three radiations, while a colourless stone showed a mauve, a strong whitish-blue and a yellowish-lilac under similar radiations.

Beautiful chrome diopsides are found in the blue ground of the Kimberley diamond mines and in the Mogok Stone Tract of Myanmar, the latter stones being chatoyant and producing attractive cat's-eyes. Diopsides of a more sombre green are found in the Ala Valley, Piedmont, Italy, and it is from this locality that the alternative name alalite is derived. The mineral is also found in the Zillertal in the Austrian Tyrol, in the Sri Lankan gem gravels and in the state of Minas Gerais, Brazil. Material of a smoky yellow or brownish colour is found at Laurel and Three Rivers in Quebec, Canada, and small crystals of a bright green colour are found near to Georgetown in Eldorado County, California. Other North American sources are at St Lawrence County, New York and at Crestmore, Riverside County, California. The green stones from Slyudyanka, Baikal, in Russia have been called baikalite, and light-coloured diopside has been called by another alternative name, malacolite. Gem-quality chrome diopside is found in Yakutia, Siberia, in Kwale district, Kenya and in Outukumpu, Finland.

Large crystals of chrome diopside, almost emerald-green in colour, are found associated with rubies in the Hunza Valley in Pakistan. These are known locally as 'Hunzanite'. Some of the specimens are cloudy owing to the presence of fibrous inclusions, and these when cut *en cabochon* show a pronounced cat's-eye effect.

Violane, spelt violan in the United States of America, is a translucent to opaque dark violet-blue variety of diopside, which is usually found massive, but sometimes occurs crystalline. The material, which has a somewhat waxy lustre, takes an attractive polish and is worked into beads, but is mostly used for fancy articles and for inlay. The hardness of violane, which owes its name to its violet-blue colour, is 6 on Mohs's scale. The SG is near to 3.23 and the index refraction, as far as a blurred shadow edge can be read on the refractometer, is 1.69. Violane is found at Saint Marcel, Piedmont, Italy.

About 1964 there came on the stone market a very dark black-green to dark brownish-black star-stone identified as star diopside, in which a certain amount of iron replaced the magnesium in the formula. The star is four rayed with one ray very sharp and the other more diffuse, and the angles between them are 73° and 107°, and therefore not quite at right angles to one another. The SG is 3.33 and the inclusions have been found to be needles of magnetite. It is these which not only produce the star effect but also account for the stones being magnetic in that they are attracted to a magnet. These star diopsides are said to come from Nammakal, in southern India.

Dioptase

The beautiful groups of emerald-green crystals of dioptase are of more importance and are lovelier than the small number of faceted or cabochon-cut stones which have been cut from them. Dioptase is a copper silicate and has a chemical likeness to chrysocolla. It has the formula $CuSiO_2(OH)_2$, and forms crystals of the trigonal system. The crystals have a hardness of 5 on Mohs's scale, which is too soft for effective use as a gemstone; moreover the green is too saturated and the stones are at best translucent only. The SG ranges from 3.28 to 3.35 and the refractive indices are 1.644–1.658 for the ordinary ray and 1.697–1.709 for the extraordinary ray; the refraction is uniaxial and the sign positive. The double refraction approximates to 0.053 and the colour dispersion is 0.036 for the B to G interval, so that the stones have more fire than many gemstones, but this effect is masked by the rich body colour of the stone. The absorption spectrum shows only a broad band in the yellow and green centred at about 550 nm and there is a strong absorption in the blue and violet. There is no luminescence induced in dioptase by ultra-violet light or X-rays. Some of the best crystallised specimens of dioptase are found near Altyn-Tübe in the Kirghiz steppes of Russia; in the basin of the Niari river in the Republic of Congo; from the Shaba district of Zaire; the copper deposits of Atacama in Chile; and in Arizona and other localities in the United States of America.

Dolomite

Clear crystals are occasionally cut as collectors' items from colourless to light-yellow rhombohedral crystals of dolomite, a mineral closely allied to calcite. Dolomite has the formula $CaMg(CO_3)_2$ and has a hardness of 3.5–4; the SG is given as 2.8–2.9, and the refractive indices as 1.502 and 1.681, showing a birefringence of 0.179 and of negative sign. The localities are widespread; indeed, dolomite forms rock masses as in the dolomite district of southern Tyrol, and crystal specimens are found in many places in the world. Beautifully developed, clear and lustrous rhombohedral crystals are found at Erguá, near Pamplona, Spain. A clear, colourless specimen of dolomite, supposedly from Fort Sumpter, New Mexico, was found to have an SG of 2.85. Massive dolomite or 'dolomitic marble' is used for small ornamental objects as the material takes a good polish. It is often banded and in colours of red, brown, yellow, green and white. Such material comes from the United States and Brazil. Some of the North American material has been miscalled 'wonderstone'.

Dumortierite

Dumortierite is a basic aluminium borosilicate, but until recently the formula had not been completely determined. This has now been carried out on a brown stone and will be referred to later. The mineral is normally found in violet and blue masses which when polished make attractive ornamental stones. The mineral crystallises in the orthorhombic system but the crystals are usually fibrous or columnar aggregates producing a massive material without distinct form. With the massive material the refractive index would show as a blurred shadow edge on the refractometer at about 1.68. The SG of the massive dumortierite varies from 3.26 to 3.41, the hardness is 7 on Mohs's scale and the lustre is vitreous. The individual fibres are strongly dichroic but in the mass the effect is not so evident. There is no diagnostic absorption spectrum and the luminescent phenomena are weak and variable.

In 1958 a red-brown faceted stone was reported as dumortierite. This stone, which came from Sri Lanka, had an SG of 3.41 and the refractive indices were α 1.686, β 1.722 and γ 1.723. The biaxial double refraction, negative in sign, was therefore 0.037. The pleochroic colours were black, deep red-brown and brown for the three directions. Careful chemical analysis produced a formula approximating to $(Al,Fe)_7(BO_3)(SiO_4)_3O_3$. Rather surprisingly this stone was found to have a hardness of 8 on Mohs's scale.

Dumortierite is found near Lyons in the French Rhône valley, near Soavina, north of Ambatofinandrahana, Madagascar, and at Tvedestrand, Norway, but most of the gemmy material comes from Oreana, Humboldt County, Nevada (usually violet in colour). Dumoretierite is also found in California, Washington, in Canada and in Brazil.

Much gem dumortierite, particularly from Arizona, is really dumortierite impregnating quartz. Such material will give a refractometer reading for quartz (1.54–1.55) with an SG of about 2.8–2.9, although lower values have been found in specimens of, presumably, dumortierite in quartz which possibly emanated from India.

Durangite

Found as orange-red crystals of monoclinic symmetry, this fluor-arsenate of sodium and aluminium ($NaAl(AsO_4)F$) has been cut for collectors. The mineral has a hardness of 5 on Mohs's scale, and an SG which lies between 3.87 and 4.07; the refractive indices are α 1.662, β 1.695 and γ 1.712. The biaxial negative refraction has a birefringence of 0.050. The stones are strongly trichroic in which two rays are almost colourless and the third is orange-yellow. Durangite is found at Durango, Mexico.

Ekanite

During 1953 a green translucent water-worn stone showing some asterism was found in a gravel pit in Sri Lanka by Ekanayake, who thought it to be a new mineral. Since that time further specimens, some exhibiting a four-rayed star, have come to light. It was not until early in 1961 that these stones were properly identified and found to be a new mineral. Ekanite is a metamict calcium thorium silicate with the chemical formula $ThCa_2Si_8O_{20}$, having a hardness of 6–6.5 on Mohs's scale, a refractive index of 1.5969 and an SG of 3.28. The stones are markedly radioactive.

A crystalline (i.e. non-metamict) variety of ekanite has been recovered from a glacial syenitic boulder in the Tombstone Mountains in Yukon Territory, Canada. Justification for the name 'ekanite' being used for this variety of the mineral was based on identity of its chemical composition with that of type specimens from Sri Lanka and the exact correspondence of its X-ray powder pattern with that given by samples of the metamict material to which crystallinity had been restored by heat treatment. The crystalline mineral is straw-yellow in colour when pure, though sometimes dark red owing to inclusions. The largest crystals are only some 2 or 3 millimetres in length and are tetragonal in symmetry. Refractive indices were measured as 1.568 and 1.580 for the extraordinary and ordinary rays. The measured SG of 3.08 was much lower than the calculated figure of 3.36, owing to impurities and inclusions.

The name given to the mineral was derived from that of its original discoverer in Sri Lanka, and the data given above for the crystallised form of the mineral were taken from a paper by Szymanski *et al.* in the *Canadian Mineralogist* (1982).

Enstatite

A member of the pyroxene group of minerals, enstatite is a magnesium-iron silicate with a formula $(Mg,Fe)SiO_3$, and crystallises in the orthorhombic system. The crystals are usually green or brownish-green in colour and have two prismatic directions of cleavage. Most of the gem material is found as rolled pebbles. Some stones are chatoyant and a peculiar glassy grey variety has been cut cabochon in order to show this effect.

The hardness of enstatite is 5.5 on Mohs's scale and the SG for the gemmy green stones lies between 3.26 and 3.28. The refractive indices for the green gem stones are 1.663 and 1.673 for the principal indices; the biaxial birefringence, which is positive in sign, is 0.010. With the increase of iron the indices rise. The dichroism is weak, the twin colours being green and yellowish-green. Enstatite is characterised by an absorption spectrum which has a sharp clear-cut line at 506 nm. There is no luminescence shown by the mineral.

With the increase of iron enstatite passes into hypersthene, which is a mineral too opaque for faceting but which often encloses minute tabular scales of what may probably be brookite, goethite or hematite, and such material cut as cabochons makes quite attractive stones. The SG of hypersthene lies between 3.4 and 3.5, with the refractive indices ranging from 1.673 to 1.683 and from 1.715 to 1.731; the optical sign is negative. There is an attractive transparent brown intermediate hypersthene-enstatite found in Mysore, India, which has been faceted into gemstones. The refractive indices for these stones vary slightly around 1.669 and 1.680 for the least and greatest values. The optical sign is negative which suggests that the stone is nearer to hypersthene than to enstatite. The SG is fairly constant at 3.3.

A leek-green altered enstatite is known as bastite or schiller spar and is close to serpentine in composition. Bastite has an SG of about 2.6, and a hardness of 3.5–4 on Mohs's scale. This material has been fashioned into cabochons. A six-rayed star enstatite has been reported which has an SG varying from 3.30 to 3.41, and a refractive index about 1.68.

Enstatite of a good green colour is found with diamond in the blue ground of the South African mines, particularly the Kimberley mine, and brownish-green stones are found in the Mogok Stone Tract of Myanmar. The chatoyant greyish stones are said to come from Sri Lanka and bronzite is found at Styria in Austria. The mineral is found in the Fichtelgebirge in Bavaria and in the so-called olivine bombs of the Dreiser Weiher in the Eifel district of the German Rhineland. Enstatite is also found in Norway and California. Bastite comes from Baste near Harzburg in the Harz Mountains in Germany and from Burma. Hypersthene is more universal in its occurrence, but the material mainly comes from Norway, Greenland, Bavaria and the North American continent. Transparent orange-brown, yellowish-brown and green enstatite has been found in Tanzania; Kenya produces yellowish-green stones; and Sri Lanka gives colourless and pale yellow as well as green and brown samples. The colourless enstatite from Sri Lanka shows the lowest refractive indices, α 1.650, β 1.653 and γ 1.659, with a birefringence of 0.009. The SG is 3.22. A dark brown six-rayed star enstatite has been found in south India.

Eosphorite

Allied to childrenite, which is an iron aluminium phosphate mineral, is eosphorite, in which manganese replaces the iron. The prismatic crystals are of the orthorhombic system and the colour is yellow or rose-pink. The formula is

$MnAl(PO_4)(OH_2).H_2O$. The hardness is 4.5 on Mohs's scale and the SG is near 3.1. The refractive indices are given as α 1.63, β 1.65 and γ 1.66. A specimen of yellowish-brown colour from Itinga, Minas Gerais, Brazil, was found to have an SG of 3.08 and refractive indices of α 1.645, γ 1.680, thus giving a birefringence of 0.035. A brownish-pink stone examined by a laboratory had an SG of 3.06 and indices of 1.640 and 1.668. This stone showed an absorption spectrum consisting of a very strong absorption line at 410 nm and a moderate one at 490 nm.

Epidote

The dark brownish-green or pistachio-green colour of epidote is characteristic of the mineral and gives to the mineral its alternative name of pistacite. Closely related to zoisite (which is orthorhombic) epidote is a calcium aluminium silicate with some iron, which accords to the formula $Ca_2(Fe,Al)_3(SiO_4)_3(OH)$. The mineral crystallises in the monoclinic system, usually as deep vertically striated prismatic crystals which seldom have distinct terminations. The crystals show a brilliant lustre and stones cut from them are a peculiar greenish-brown in colour which is darker the greater the percentage of iron they contain. The hardness is 6.5 on Mohs's scale, the SG being about 3.4, and the principal refractive indices are 1.736 and 1.770 with a biaxial double refraction of 0.034 which is negative in sign. With less iron the refractive indices and the amount of double refraction can be lower than the values given above. The stones are strongly pleochroic, the twin colours being green, brown and yellow. The fire is moderate, the dispersion being 0.030, and the lustre is vitreous to metallic. The absorption spectrum shows a very intense band near 455 nm in the α ray, is virtually absent in the γ ray, and in the β ray shows a second but much weaker line at 475 nm. Epidote shows no luminescence.

Clinozoisite is an epidote containing less than 10 per cent of the iron molecule and is usually a much lighter green in colour. The mineral is monoclinic and has an SG near to 3.37; the refractive indices are α 1.724, β 1.729 and γ 1.734, with a birefringence of 0.010, which, however, is positive in sign. The absorption spectrum is similar to that of normal epidote.

When manganese is a replacing metal in the epidote composition the mineral piedmontite is produced. This is a red mineral which does not have a gem significance, but is the cause of the red colour in the red porphyry of Egypt. A chrome epidote or tawmawite is a deep green stone showing strong pleochroism (emerald-green and bright yellow) which is found at Tawmaw in the Kachin Hills of Myanmar, and gem-quality crystals are said to come from the Fungwe area of Zimbabwe.

An epidote rock, or epidote granite as it is sometimes called, is usually sold as tumbled or polished pieces under the name 'unakite'.

Epidote is a fairly common mineral and is found at many places in the alpine system of Austria (Knappenwand), Switzerland and France. It is also found in Norway and there are a number of localities in the North American continent. Clinozoisite comes from Austria, Italy, Switzerland, Bohemia (Czechoslovakia) and Baja California, Mexico. A grey-green clinozoisite is found in Kenya.

Euclase

A species which owes its name to the easy cleavage which makes the cutting of crystals such a hazardous matter and the cut stones so liable to fracture, euclase is a beryllium silicate ($BeAlSiO_4(OH)$), and forms monoclinic crystals characterised by numerous smooth faces. The colour of the material is usually a pale aquamarine colour although stones with a strong greenish-blue colour have been encountered.

Like aquamarine in appearance, euclase may be distinguished by the positive biaxial optical character and the refractive indices are, for the principal rays, 1.652 and 1.672 with a birefringence of 0.020. The SG is fairly constant at 3.10, and the hardness is 7.5 on Moh's scale. The dispersion is 0.016 for the B to G interval, which is too weak for the stones to show much fire. The absorption spectrum is, in the case of the deeper-coloured stones, characterised by two vague bands in the blue at 468 and 455 nm, and also lines in the red, due to chromium, which give a strong doublet at 705 nm. The luminescence, even under X-rays, is too feeble to be of value in distinction. Euclase shows a similarity to green spodumene in both colour and properties; spodumene, however, has less birefringence (0.015) and a slightly higher SG (3.18). The principal localities for euclase are the Ouro Prêto region of the Brazilian state of Minas Gerais. Some crystals come from near the Sanaka river in the Orenburg district of the southern Urals, and from the Morogoro district of Tanzania. Minor sources are Bavaria and Austria in central Europe.

Some years ago, specimens of gem-quality euclase of a dark sapphire blue were recovered from ancient pegmatite sources in the Miami district of Zimbabwe. As examined and described by Gübelin, these fine blue specimens had precisely the same constants as those given above. No absorption bands were visible but a spectrometer trace showed a marked transparency region between 400 and 500 nm. The stones contained 0.12 per cent Fe_2O_3 to which the blue colour must be attributed.

Eudialyte

Transparent to translucent eudialyte $(Na,Ca)_6Zr(Si_3O_9)_2(OH,Cl)_2$ comes from Sweden and Canada near Kippaw. The trigonal mineral has a hardness of 5–6 on Mohs's scale. The SG is 2.88 and the refractive indices are 1.596–1.598 and 1.600–1.602 with a birefringence of +0.004. Eudialyte is readily soluble in acids.

Faustite

Faustite ($(Zn,Cu)Al_6(PO_4)_4(OH)_8.4H_2O$) is a zinc-rich member of the turquoise group and crystallises triclinic. Gem materials of apple-green and yellow-green colour have been described. Light bluish-green massive samples of turquoise-faustite aggregates occur at the turquoise deposit of Neyschabour, Iran. The hardness is about 4.5 on Mohs's scale. The SG is about 2.9 and the refractive index about 1.612. The colour is caused by the copper of the turquoise content.

Fibrolite (Sillimanite)

Sapphire-blue and chatoyant blue-green stones have occasionally been cut from the aluminium silicate mineral fibrolite (Al_2SiO_5) which is polymorphous with andalusite and kyanite, and crystallises in the orthorhombic system. The crystals occur as long slender prisms without distinct terminations and are often in parallel groups. They have one direction of cleavage parallel to one pair of prism faces and are frequently fibrous, hence the name fibrolite. The alternative name is sillimanite (after Silliman, one-time professor at Yale University in the United States of America).

The hardness of fibrolite is, for the crystals, 7.5 on Mohs's scale, but for the compact material, owing to the fibrous nature, the hardness may vary from 6 to 7. The refraction is biaxial and positive in sign and the indices are 1.658 and 1.678, the birefringence being 0.020. The stones have little fire for the dispersion is only 0.015 between the B and G lines of the solar spectrum. The pleochroism is strong, the colours for the three principal optical directions being pale green, dark green and blue. The absorption spectrum is indistinct with bands at 462, 441 and 410 nm. The SG is 3.25. Fibrolite, which shows a very weak red fluorescence, at least in the transparent blue stones, is found in the Mogok Stone Tract of Myanmar, where some lovely violet-blue stones have been found; in the Sri Lankan gem gravels, where a greyish-green chatoyant fibrolite is obtained; and in Kenya, where colourless and bluish species occur. A densely compact form of brownish or greenish colour which resembles jade is known. It has an SG which lies between 3.14 and 3.18. Water-worn pebbles of a massive fibrous variety, usually called sillimanite, which are mostly fashioned as baroque stones by the tumbling process, are found in the valley of the Clearwater river in Idaho, USA.

Fluorspar (Fluorite)

The beautiful cubic crystals of fluorspar, so many fine specimens of which grace our museums, are occasionally cut as gemstones, usually in the trap-cut style and mainly for collectors, for the hardness of fluorspar (fluorspar is the standard 4 on Mohs's scale) is far too low to resist the wear and tear encountered in jewellery. The range of colour shown by fluorspar is equalled by few other gemstones. The crystals may be colourless, yellow, brown, green, blue, violet and pink, but a true red is not known. An emerald-green fluorspar probably from near Otjiwarongo, in Namibia, has been faceted and sold under the misnomer 'South African emerald'.

Blue John or Derbyshire Spar

More important ornamentally than the crystals is the massive crystalline variety known as Blue John or Derbyshire spar, a material which has been used since Roman times for vases and other decorative objects (*Figure 17.1*). Blue John is prettily patterned in curved bands of blue, violet and purple, the latter often so deep in colour as to be almost black, with often a reddish or colourless ground. The material is characterised by having only one source of supply, that

Figure 17.1 An exceptional vase of Blue John in the Geological Survey Museum at South Kensington, London (by courtesy of the Controller of HM Stationery Office)

is at Treak Cliff, an outlier of the Mam Tor range near Castleton in the Kinderscout district of Derbyshire, England, a source which is now said to be exhausted. The Blue John mine was driven for lead ore and consists of a number of workings opening out of a fine range of caverns, where often the beautiful fluorite is not at first seen owing to the complete covering of the rock face by stalagmitic formations. The fluorspar occurs in nodular masses and veins in oölitic limestone (aggregates of little spherical deposits of carbonate of lime which has formed as concentric crusts around nuclei which may have been a grain of sand or a minute organism) and tends to be botryoidal in form with the typical radial and banded structure showing little trace of cubic structure. The amethystine colour of Blue John has been variously said to be due to traces of manganese, to impurities of vegetable origin or crude petroleum or both, and to physical disarrangement of the crystal lattice, possibly by radioactive emanations. The most usual explanation of the colour is that a pulsatory flow of hydrocarbon-rich liquid caused the banded colour while the crystallisation of the fluorite was taking place.

The fashioning of small objects of Blue John is carried out by first rough grinding the piece of spar to the requisite shape by the use of a foot lathe, a method which gives complete control through varying speeds. The roughly shaped piece is then finely surfaced by using a Water of Ayr stone, after which crocus powder (a coarse-grained iron oxide – a coarse rouge) on a revolving felt pad is applied to smooth the surfaces and to put on a semi-polish. The final fine glaze polish is carried out with putty powder (tin oxide) on a power-driven lathe. For larger pieces, owing to the fact that the rock is chiefly composed of an aggregate of friable crustals, it is necessary to bond them after the piece has been cut to a suitable shape by an emery or carborundum powder-charged copper disc. The sawn piece is therefore heated in a natural resin which runs between the cracks of the aggregate of crystals thus effectively binding them. This bonding process needs to be repeated continuously as the process of turning on a lathe is carried out. The piece is cemented to a chuck and cut by the use of high-speed tools for the actual lathe shaping. The piece is then polished to produce the finished article. Care must be taken in the heating process, for overheating tends to lighten the colours, and while this may be desirable with dark-coloured material it is disastrous in other cases.

Other Varieties of Fluorspar

Mention must be made of a massive fluorspar which does not exhibit the beautiful bands of colour shown by Blue John. Such material may be nearly colourless but veined with yellowish-brown markings, and there is a variety of strong violet-blue colour in which the aggregate nature of the crystals forming the piece are clearly seen. There is also the Yellow Ashover spar, in which the colour is a full yellow, obtained from the Ashover quarries in Derbyshire. A massive green fluorspar has a vogue for carved pieces and these may appear similar to massive green beryl. A hardness test on the base or other inconspicuous part will indicate the nature of the piece.

Occurrences

Apart from the localities already mentioned fluorspar is found, often in lovely crystal groups, at Weardale in Durham, Alston and Cleator Moor in Cumberland, in the lead mines of Derbyshire and in Cornwall; indeed it may be said that England provides the finest fluorite crystals. The Swiss source at Chamonix is notable for the pink octahedral crystals and fluorspar is also found at Brienz, Berne. The mineral is obtained from many localities in the United States of America, the more important being in the states of Illinois, New Hampshire and Missouri. There are other sources in Nigeria, in Ontario, Canada, in Saxony, Bavaria and Baden in Germany, in Bohemia, Czechoslovakia and in Silesia, Poland. Italy and Norway also supply fluorspar.

Chemical and Physical Properties

Fluorspar is calcium fluoride (CaF_2) and crystallises in the cubic system, most commonly as cubes and rarely as octahedra and dodecahedra. The cube forms are often bevelled at the edges by a form of a lower crystallographic index, and the cube faces often show very low pyramids (vicinal faces), which produce striations on the surface. Interpenetrant twinning is common and, due to parallel grouping of minute cubes, some crystals, particularly those of octahedral habit, exhibit faces with a drusy character. Many fluorspar crystals are coated with quartz or pyrites crystals, and some apparent fluorspar crystals are quartz or chalcedony pseudomorphs after fluorspar. *Figure 17.2* shows a group of fluorspar.

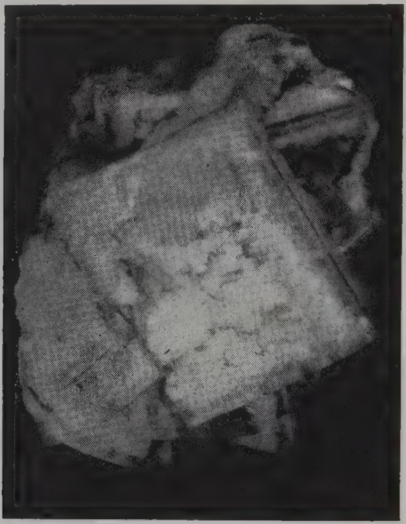


Figure 17.2 Crystals of fluorspar from Matlock in Derbyshire, England

Fluorspar has an easy octahedral cleavage, but the highly characteristic cleavage surfaces are rarely perfect, showing a stepped effect; it is this easy cleavage which makes the cutting of the crystals so difficult. The fracture, which is overshadowed by the easy cleavage, is flat conchoidal but in the compact types may be splintery.

The SG of fluorspar is 3.18 and does not vary much from this figure in the case of crystals, but the massive types, owing to contamination with impurities, may vary between 3.00 and 3.25. The refractive index is 1.434 and the dispersion is very small (0.007 B to G). The absorption spectrum is generally vague and indecisive, but in the green variety weak bands occur at 634, 610, 582 and 445 nm, and there is also a strong broad band at 427 nm which may be seen in sizeable pieces. Most fluorspar when excited by long-wave ultra-violet light exhibits a strong and often vivid sky-blue to violet-blue glow, said to be due to a trace of divalent europium. Some varieties show a green glow and this is ascribed to divalent ytterbium, and some, including the Blue John variety and many of the crystals from Illinois, are inert. A brown luminescence has been recorded for fluorspar and the brown-coloured crystals from Clay Center, Ohio, show a white glow with a perceptible yellow afterglow. This is said to be due to the inclusion of petroleum or bituminous compounds. The fluorescence shown by fluorspar when under short-wave ultra-violet light is similar to that shown under the long-wave lamp, but very much weaker. Under X-radiation the glows induced are again similar, and in some cases glows may be induced even in Blue John. A persistent phosphorescence is generally prominent when fluorspar is bombarded with X-rays. Fluorspar has been made synthetically and some material (generally pink) has been cut and faceted for collectors.

Friedelite

Faceted stones and cabochons of a rose-red to orange-red colour have been cut from the manganese silicate mineral friedelite, which has the formula $Mn_8Si_6O_{15}(OH,Cl)_{10}$, and which forms tabular crystals of the trigonal system. Most of the material is massive. The hardness is from 4 to 5 on Mohs's scale and the SG is given as 3.07 (one specimen was found to have an SG of 3.058). The refraction is uniaxial and negative in sign with indices for the ordinary ray of 1.66 and for the extraordinary ray of 1.63, the birefringence being therefore 0.030. The absorption spectrum shows a broad band centred at 556 nm and a band about 456 nm in the blue which is indistinct as there is a partial absorption in the blue and violet part of the spectrum. This absorption spectrum is not very diagnostic. A specimen of cut friedelite showed a red glow under ultra-violet light of both wavelengths. Dake mentions a bright yellow glow under long-wave ultra-violet light and a bright greenish glow under the short-wave rays for some friedelite. The localities for the mineral are France, Sweden and Franklin Furnace, New Jersey in the United States of America, the last named probably being the source of the gem material.

Gahnite

The zinc-spinel gahnite ($ZnAl_2O_4$) which forms cubic crystals with octahedral habit is usually too dark a colour to cut into gemstones. However, some stones of a tourmaline green colour have been found and cut in Brazil, and some blue species in Nigeria. The hardness of gahnite is from 7.5 to 8 on Mohs's scale, the SG is 4.40 and the refractive index is 1.805. Some variations from these values must be expected owing to isomorphous replacement by other metal ions; for example, a green gahnite has been reported having an SG of 4.64 and a refractive index of 1.798. Gahnite is found in zinc deposits at many different localities. Gahnite has been made synthetically.

Gaspeite

Gaspeite belongs to the calcite group and has the chemical formula $(Ni,Mg,Fe)CO_3$. Translucent green to yellowish-green material of the trigonal mineral occurs at the penninsula of Gaspe, Quebec, Canada. The hardness is 4.75 on Mohs's scale and the SG is 3.21. The refractive indices are 1.61 and 1.83 with a birefringence of -0.22.

Gaylussite

Colourless transparent gaylussite ($Na_2Ca(CO_3)_2.5H_2O$) is known from a locality in Kenya. It is named after the French chemist Gay-Lussac. It crystallises in the monoclinic crystal system and has a hardness of about 2.5 on Mohs's scale. The SG is 1.98 and the refractive indices are α 1.440–1.443, β 1.514–1.517 and γ 1.520–1.523 with a birefringence of 0.080; the optic sign is negative.

Grandidierite

Found as orthorhombic crystals in southern Madagascar (Andrahomana), grandidierite is an iron aluminium magnesium silicate ($(Mg,Fe)Al_3(BO_4)(SiO_4)O$) of bluish-green colour which has turned up as a cut stone. The hardness of the mineral is 7.5 on Mohs's scale and it has an SG of 3.0. The refractive indices are α 1.602, β 1.636 and γ 1.639 and it thus shows a negative birefringence of 0.037. It is strongly pleochroic.

Hambergite

A beryllium borate ($Be_2(OH)BO_3$), hambergite forms colourless prismatic crystals belonging to the orthorhombic system. It was originally found in southern Norway in material of non-gem quality, but a discovery has now been made of large colourless crystals in central Madagascar. The mineral is characterised by its large double refraction which is biaxial and of positive sign, the indices ranging from 1.553 to 1.559 and from 1.625 to 1.631 for the principal rays, the birefringence being 0.072. The lustre is vitreous and the colour dispersion is small (0.015 B to G). In relation to the refractive indices the SG of hambergite is remarkably low, being only 2.35. The hardness is 7.5 on Mohs's scale and no luminescence was shown by the specimens examined. Hambergite was named after Axel Hamberg.

Haüynite (Haüyne)

More important as one of the constituents of lapis lazuli, haüynite, named after the Abbé Haüy, is a complex sodium aluminium silicate with a formula $(Na,Ca)_{4-8}Al_6Si_6(O,S)_{24}(SO_4,Cl)_{1-2}$. Haüynite crystallises in the cubic system and the translucent blue material has been cut as items of curiosity for collectors. The hardness is about 6 on Mohs's scale, the SG is 2.4 and the refractive index is 1.496–1.5. There is usually no luminescence with the mineral but it has been reported that material from the Laacher See, Germany, may glow with an orange-red glow which is best seen under the long-wave lamp. The mineral, which is further discussed with lapis lazuli in Chapter 12, is found at many places, particularly in Italy and the German Rhineland.

Hemimorphite

Transparent colourless hemimorphite ($Zn_4Si_2O_7(OH)_2.H_2O$) is found in a locality in the USA. The orthorhombic mineral has a hardness of about 5 on Mohs's scale and a perfect cleavage. The SG is 3.44 and the refractive indices are 1.612 and 1.633 with a birefringence of 0.021; the optic sign is positive.

Herderite

Some greyish material of the mineral herderite has been fashioned for those who desire something different. A fluophosphate of beryllium and calcium ($CaBe(F,OH)PO_4$), the mineral crystallises in the monoclinic system. The hardness is 5 on Mohs's scale, the SG is 3.00 and the negative biaxial refraction has indices of α 1.594, β 1.613 and γ 1.624, the double refraction being 0.030. The mineral fluoresces a pale greenish glow under both ranges of ultra-violet light and shows a strong orange glow with persistent phosphorescence under X-rays. Herderite is found in Saxony and at several places in the state of Maine, USA.

A green transparent cut specimen of herderite from Brazil, weighing 5.90 carats, was acquired by the US National Gem Collection in 1973. This was investigated by Dunn and Wight in 1976 and found to have the abnormally low refractive indices of α 1.581, β 1.601 and γ 1.610, with birefringence 0.029, optically negative. The lower RI values were thought to be due to the specimen being unusually fluorine-rich. In 1977 Bank and Becker described gem-quality violet and colourless specimens of the mineral from localities in Maine, USA. These gave values for the three indices as follows: α 1.587–1.590, β 1.609–1.610, γ 1.619–1.621. In all cases the SG seems fairly constant at 3.00, a value shared by another rare gem mineral, danburite.

Brown herderite from the Virgem da Lapa mine in Minas Gerais, Brazil posesses the hitherto highest refractive indices α 1.610, β 1.630, γ 1.642; it has a fluor content of 0.2 per cent.

Hodgkinsonite

In Franklin Furnace, New Jersey, USA, transparent hodgkinsonite ($MnZn_2(SiO_4)(OH)_2$) occurs in pink colour. It was named in 1913 after H H Hodgkinson. The monoclinic crystals have a hardness of 4.5–5 on Mohs's scale and possess perfect cleavage. The SG is 3.98 and the refractive indices are α 1.720, β 1.739 and γ 1.743 with a birefringence of 0.023.

Howlite

The massive variety of howlite, which is milk-white in colour and veined with black, has some use as an ornamental stone, despite its low hardness of 3.5 on Mohs's scale. The mineral is an aggregation of monoclinic crystals and is a silicoborate of calcium ($Ca_2B_5SiO_9(OH)_5$). It has an SG of 2.58 and the mean refractive index is 1.59. Howlite fluoresces a brownish-yellow by short-wave ultra-violet light, and some Californian material is said to glow a deep orange with long waves and not to respond to the short-wave lamp. Howlite is found in large amounts in California in the United States of America. It is sometimes dyed blue.

Idocrase

The transparent varieties of idocrase, sometimes known under the name vesuvianite, are not often met in jewellery but more often in collections, despite the yellowish-green, green, yellowish-brown and violet stones having an attractiveness and sufficient hardness (6.5 on Mohs's scale) to be suitable for some types of jewellery. What is more important as gem material is the massive green variety, called californite, which has some resemblance to the jades. Cyprine is a blue variety containing copper, and is so called after Cyprus, which was the ancient source of copper. This variety is seldom met. A transparent yellowish-brown idocrase which is found at Amity, New York, has been called xanthite (after the Greek word for yellow).

Idocrase is a complex calcium aluminium silicate and accords to the formula $Ca_{10}Mg_2Al_4(SiO_4)_5(Si_2O_7)_2(OH)_4$, in which some isomorphous replacement by iron of the aluminium and by magnesium of the calcium occurs. Titanium, fluorine, beryllium and boron may be present. It has been suggested that a tetragonal variation of the garnet-type molecule is present in idocrase. The tetragonal crystals of idocrase form square prisms capped with pyramids and are often terminated with the basal pinacoid; thus they have some similarity to the crystals of zircon, except that zircon rarely shows the basal pinacoid. Idocrase crystals often have the edges of the prisms truncated by the second-order prism producing an eight-sided form.

The SG of idocrase ranges from 3.32 to 3.47: the gold-brown stones from Canada were found to have an SG of 3.38, a green specimen 3.42, but the massive green californite has an SG somewhat lower, between 3.25 and 3.32. The refractive indices show some variation at 1.712–1.716 and 1.700–1.721, the optical sign changing from negative in the case of the lower values of refractive indices to positive for the stones having higher values. Idocrase has a vitreous lustre and shows only weak dichroism and little fire: the dispersion is 0.019 for the B to G interval. The absorption spectrum in idocrase consists of a strong band at 461 nm and a weak band at 528.5 nm. In the golden-brown stones, however, the general absorption of the blue precludes observation of the 461 nm band. Further, these brown stones (particularly those from Canada) sometimes show a rare-earth series of absorption bands, some six in all between 591 and 574.5 nm. The absorption band at 461 nm is strongly seen in the californite variety and allows distinction of this stone from jadeite. This is of particular importance as the densities of these two minerals are near one another. Idocrase shows no luminescence. The stone is often found as an admixture with grossularite.

The localities for idocrase are the Ala valley, Piedmont, Italy, where green and brown crystals are found. Lake Baikal in Siberia, Zillertal in the Tyrol and Zermatt in Switzerland are other localities. The golden-brown stones come from Laurel in the Laurentian mountains of eastern Canada. Californite, as its name implies, is found in Fresno, Butte and Siskiyou Counties of California, USA, while the rare cyprine is found at Telemark in Norway. Some small crystals of a yellowish-green colour characterised by high pyramidal terminations with no basal pinacoid have been found near Quetta in Pakistan. Other occurrences are in Sri Lanka, Tanzania and Russia.

Inderite

Inderite ($MgB_3O_3(OH)_5.5H_2O$) is dimorphic with kurnakovite and crystallises monoclinic. The mineral is named after the locality of Inder Lake in western Kazakhstan. Transparent colourless crystals have been faceted. The hardness is 2.5 on Mohs's scale. The SG is 1.79 and the refractive indices are α 1.488, β 1.491 and γ 1.505 with a birefringence of 0.017; the optic sign is negative.

Iolite

Owing to the sapphire-blue colour of gem-quality iolite, the material was in earlier days miscalled 'water sapphire'. Iolite is a complex silicate of magnesium and aluminium ($Mg_2Al_4Si_5O_{18}$) but replacement of part of the magnesium by ferrous iron and manganese, and the aluminium by ferric iron, often occurs. These replacements make the constants for iolite somewhat variable.

The name iolite is applied to the stone on account of the blue colour of the gem material, the name being derived from the Greek word for violet. Iolite, however, has other names applied to it, such as dichroite, from the strong pleochroism which is such a prominent feature with this species; and cordierite, a name given to the mineral in honour of the French geologist Cordier. The term cordierite is used for the mineral in mineralogy.

Iolite crystallises in the orthorhombic system: the crystals are often found as short pseudo-hexagonal prismatic twins which to some extent resemble quartz. Most of the gem material is found in the gem gravels as water-worn pebbles. The mineral has a hardness of 7–7.5 on Mohs's scale. The SG may vary from 2.57 to 2.66; most gem material is, however, confined to the more restricted range of 2.57–2.61. The indices of refraction may vary within the limits of 1.53–1.54 to 1.54–1.55 and the amount of birefringence varies from 0.008 to 0.012. The sign of refraction is negative, but it has been reported as positive. Iolite has weak dispersion – the value being 0.017 in the B to G interval.

The pleochroism of iolite is particularly strong, the colours for the three principal directions being yellow, light blue, and dark violet-blue. The best blue colour is seen when the crystal is viewed down the length of the prism. The absorption spectrum of iolite resembles to some extent that of blue spinel in that the spectrum is due mainly to ferrous iron. The strong dichroism of iolite precludes any confusion with the singly refracting spinel. The absorption bands shown by iolite are not strong and are at 645, 593, 585, 535, 492, 456, 436 and 426 nm. The absorption spectrum varies with the direction, so that in the direction of the violet-blue colour the 645 and 426 nm bands are masked by the general absorption and appear as cutoffs which shorten the spectrum. Owing probably to the iron content, iolite does not luminesce under ultra-violet light.

The inclusions seen in iolite vary considerably, but one type seen in Sri Lankan stones is worthy of comment, for if profuse they tend to give the stone a red colour. These inclusions are thin hexagonal platelets of either haematite or goethite, which usually show a parallel orientation. Thus, if the stone is viewed when the thin tablets are broadside on the stone appears a good red colour, but if it is viewed so that the thin inclusions are edgewise on the red colour is not so pronounced, this effect giving a pseudo-dichroism. Such stones have been called 'bloodshot iolite' and the inclusions seen in them are shown in *Figure 17.3*.

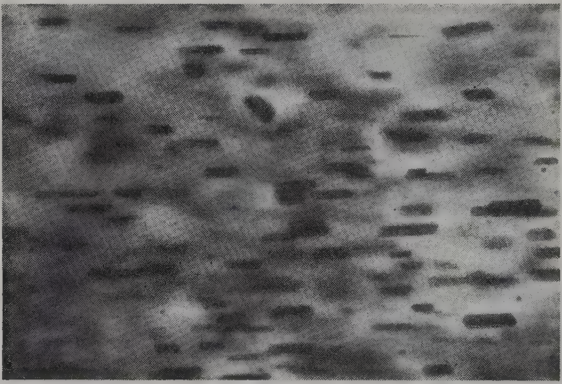


Figure 17.3 Hexagonal platelets of an iron mineral seen in 'bloodshot iolite'

Carved objects, said to be ancient Colombian and which had the appearance of grey jadeite, were found to be massive iolite.

The localities for iolite are the gem gravels of Sri Lanka and the Mogok Stone Tract of Myanmar. Gem material is also found in Madagascar, particularly from Mount Tsilaizina, and iolite is also found in the hills of Vizagapatam and the Trichinopoly and Coimbatore districts of Madras, India. Some iolite is found near the Great Slave Lake in the North-West Territories of Canada. Good iolite is found at Karasburg, Namibia, at Babati in Tanzania, and in southern Norway.

Jeremejevite

In 1973 a 1.51 carat step-cut gemstone resembling aquamarine was identified by X-ray diffraction in the GIA Laboratories as the rare aluminium borate mineral jeremejevite. The SG was 3.30 and the refractive indices were 1.639–1.648. Dana-Ford gives the hardness as 6.5 so it can be claimed as one of the extremely rare gem minerals. The owner, Edward R Swoboda, gave the new locality as Cape Cross near Swakopmund in Namibia, and later provided two clear crystals of the mineral: one blue, the other colourless.

Jeremejevite is orthorhombic but pseudo-hexagonal in habit. The chemical formula is $Al_6B_5O_{15}(F,OH)_3$. A second occurrence is in the Pamir mountains.

Kakortokite

An ornamental rock found on the southern bank of the Kangererdluarssuk fjord, in the Julianehab district of southern Greenland, has been fashioned into souvenir objects, such as small bowls which are actually models of Eskimo grease lamps, and as cabochons. The rock is a nepheline syenite spotted with red crystals of the rare zirconium mineral eudialyte. The white is nepheline and the black is arfvedsonite, a member of the amphibole group. The SG of the rock ranges from 2.7 to 2.8. A geologically younger series of the rock formation is naujaite, after the Eskimo name for seagull, as the material consists of whitish nepheline and feldspar with pastel green grains of sodalite, some dark green aegirine and arfvedsonite, and the red grains of eudialite.

Kämmererite

The chromian clinochlore ($(\mathrm{(Mg,Fe)_5Al(Si_3,Al)O_{10}(OH)_8})$) kämmererite was named after Kämmerer of Leningrad. It crystallises in the monoclinic system and has a hardness of 2.–2.5 on Mohs's scale. The SG is about 2.7 and the refractive indices are 1.585–1.588 and 1.587–1.594 with a birefringence of 0.002–0.006.

Kornerupine

A rare magnesium iron aluminium borosilicate, kornerupine has been faceted as gems, but its interest is mainly for collectors who crave the unusual. The mineral was first found at Fiskernaes in Greenland as material with a radiating columnar habit in translucent to transparent pieces of pale green to sage-green colour. The mineral was reported upon in 1884 by Lorenzen who named it kornerupine in memory of Kornerup, a young Danish scientist. The material from Greenland is scarce and has no gem significance. In 1912 a pale sage-green variety was discovered at Betroka, Madagascar, and in 1922 another deposit of similar coloured material was found at Itrongay on the same island. About 1936 some deep browny-green cut stones from the illam of Sri Lanka were identified as kornerupine and a number of such stones have since been found in parcels of Sri Lanka gravel. In 1952, although a similar but unidentified stone had been known for some time, a lovely green-coloured stone was identified as kornerupine, and there is little doubt that the stone came from the Mogok Stone Tract of Myanmar. It has been credibly reported that a star kornerupine has been found at this locality. Other sources of kornerupine, but not necessarily of gem quality, include Waldheim in Saxony, where the mineral was first known as prismatine; some opaque material has been found at Port Shepstone in Natal; and material of two types, one a dark green and the other a yellow or greenish-yellow, comes from Lac Ste Marie, Gatineau, Quebec, Canada. Kornerupine cat's-eyes have been found in surprisingly large quantity in Sri Lanka in recent years. These are usually small and dark in colour but have shown a very sharp chatoyant ray. Green kornerupine of gem quality has been recovered in Kwala, Kenya. Analysis showed the presence of vanadium, which has been found extensively as a trace element in the East African stone province which extends from Tanzania into Kenya, and can be responsible for fine green colours much in the manner of chromium.

Kornerupine has the formula $Mg_4(Al,Fe)_6(Si,B)_4O_{21}(OH)$, with considerable replacement of the aluminium by iron and boron. The crystallisation is orthorhombic, but the material, particularly that from Sri Lanka, is found as rolled pebbles. The hardness is 6.5 on Mohs's scale and the SG varies from 3.20 to 3.45, the gem material having the more restricted range of 3.28–3.35. The indices of refraction approximate to α 1.665, β and γ 1.678 (Sri Lankan stones α 1.668, β and γ 1.680) with a negative biaxial birefringence of about 0.013. The gem varieties are pseudo-uniaxial. The stone has only moderate fire for the dispersion is 0.018 for the B to G interval; the pleochroism, with colours of green and yellow to reddish-brown, is sufficiently strong as to be apparent to the eye. To obtain the best colour the stones need to be cut with the table facet parallel to the length of the crystal. The absorption spectrum shows several weak bands which are not easily observed, but a band at 503 nm can usually be detected in most kornerupines. No fluorescence has been observed in Sri Lankan stones but the green stones from Myanmar show a yellow glow under both long and short wavelengths of ultra-violet light. Some kornerupines recently found in East Africa show an even stronger yellow glow.

Kurnakovite

The triclinic magnesium borate kurnakovite ($MgB_3O_3(OH)_5.5H_2O$) is found in transparent crystals which are colourless. It was named after Kurnakov, a Russian mineralogist and chemist. It has a hardness of 2.5–3 on Mohs's scale. The SG is about 1.83 and the refractive indices are α 1.490, β 1.510 and γ 1.520 with a birefringence of 0.030; the optic sign is negative.

Kyanite

Characterised by having the same chemical composition as andalusite and fibrolite, that is aluminium silicate (Al_2SiO_5), kyanite forms flattened triclinic crystals with bladed habit, which are unique in having considerable differences in hardness in different directions. The Mohs's scale hardness is 7 across the crystal and 5 along the length. The name kyanite, or cyanite as it is spelt in older literature, indicates that the species is typically of a blue colour, which may be either a light or a dark hue. The blue colour is almost always confined towards the centre of the crystal and tends to colourless towards the edges. The crystals display a marked cleavage parallel to the exceptionally large prism face, and this makes cutting hazardous. Chatoyant (cat's-eye) stones have been met.

The SG of kyanite lies between 3.65 and 3.69, most gem material having the higher values of 3.68; the refractive indices for gem material approximate to α 1.715, β 1.726 and γ 1.732; the biaxial double refraction is 0.017 and is negative in sign. The dispersion over the B to G interval is 0.020. Kyanite shows pronounced pleochroism: the colours for the three principal directions are violet-blue, colourless and cobalt blue. The absorption spectrum shows a line in the deep red and two lines in the deep blue. The fluorescence shown by the mineral is variable: most stones show a dim red under the long-wave ultra-violet lamp, but this glow is more readily seen by the crossed filter method.

Gem-quality kyanite is found in Myanmar, in Kashmir, Patiala and the Punjab in India, and Kenya. The mineral is found in Switzerland and in several states of America, particularly North Carolina. A white variety, found in the Pfitschtal district in Italy, is called rhaetizite but this variety has no gem significance. A green-coloured variety emanates from North Carolina. An alternative name for kyanite is disthene, a name which means double strength and relates to the differential hardness of the mineral.

Lawsonite

A rarity in minerals and the more so as a cut stone is lawsonite, a mineral of which a two carat cut stone has been seen. Lawsonite has the formula $CaAl_2Si_2O_7(OH)_2.H_2O$. The colourless or pale-blue crystals are found as orthorhombic crystals with a hardness of 7–8. The SG is 3.08–3.09 and the refractive indices are α 1.665, β 1.669 and γ 1.684 with a positive birefringence of 0.019. The crystals are found in California, in Italy and in Caledonia.

Lazulite

The mineral lazulite is rarely met as fashioned stones or as ornamental material where the blue colour could be most effective. The mineral is an iron magnesium aluminium phosphate ($MgAl_2(PO_4)_2(OH)_2$) which crystallises in the monoclinic system. The hardness is 5.5 on Mohs's scale, the SG is near to 3.1 and the mean refractive index is 1.62, a value which is near to turquoise and odontolite. Specimens from the Bhandara district of Central Provinces, India, gave an SG of 3.17 and indices of refraction of α 1.615, β 1.635 and γ 1.645, the biaxial refraction being negative in sign. The lustre of lazulite is vitreous and stones show strong pleochroism; the two main colours are colourless and azure blue. The mineral, which is usually found in small pieces, comes from many localities, particularly from Minas Gerais, Brazil, Sweden, Austria, Switzerland, India and North Carolina, USA. Lobito Bay, Angola is another source.

Legrandite

A cut specimen of this rare mineral has been reported in the literature. Legrandite is a hydrated zinc arsenate with the chemical formula $Zn_2,(AsO_4)(OH).H_2O$, and is usually found in bundles of monoclinic crystals. The stone is transparent and of a bright yellow colour. The hardness is about 5 on Mohs's scale and the SG varies from 3.98 to 4.04. The refractive indices are α 1.675, β 1.690, and γ 1.735; thus the mineral has a birefringence of 0.060 and the refraction is positive in sign. The mineral is known only from Mexico.

Lepidolite

The massive fine-grained rose-red granular lepidolite ($K(Li,Al)_3(Si,Al)_4O_{10}(F,OH)_2$), or as it is sometimes called lithia mica, has been polished into slabs for ornamental purposes. The mineral has a hardness of 3.5 on Mohs's scale and the SG lies between 2.8 and 2.9 for the massive material, although higher values up to 3.3 have been mentioned for lepidolite. The mean refractive index is 1.55. There is no distinctive absorption spectrum and no luminescence is shown by the mineral. Massive lepidolite is found in the Ural mountains of Russia, in Madagascar, in the states of Maine, California and Connecticut in the United States of America, in the Karibib district of Namibia, and at Bikita in Zimbabwe. Translucent to transparent lepidolite comes from Brazil.

Leucite

For those who crave the curious, small colourless stones have been cut from the icositetrahedral crystals of leucite, mainly the crystals from the Italian volcanic rocks. Leucite is a potassium aluminium silicate ($KAl(SiO_3)_2$) and crystallises in cubic system. The hardness of the mineral is 5.5–6 on Mohs's scale, the SG varying from 2.45 to 2.50, being generally near to 2.48. The refractive index is 1.51 but, although from its cubic crystallisation the mineral is isotropic, specimens commonly show feeble double refraction between cross Polaroids. Except under X-rays when a dull bluish glow may be seen, cut leucites show little luminescence. Leucite is found in the Alban Hills in Italy, in Germany and at a number of localities in the United States of America.

Ludlamite

Transparent green ludlamite ($(Fe,Mg,Mn)_3(PO_4)_2.4H_2O$) has been found in the USA. The mineral was named after Ludlam of London. It crystallises in the monoclinic system and the hardness is 3–4 on Mohs's scale. The SG is about 3.1 and the refractive indices are α 1.653, β 1.673 and γ 1.693 with a birefringence of 0.040. Ludlamite has a perfect cleavage and is soluble in hydrochloric acid.

Magnesite

Transparent white crystals of magnesite, a magnesium carbonate ($MgCO_3$) mineral which crystallises in the trigonal system, have been cut as specimens for collectors. The hardness, about 4 on Mohs's scale is too low for it to be a satisfactory gemstone. The SG is 3.0–3.12. The uniaxial refraction is optically negative with indices for the ordinary ray of 1.717 and for the extraordinary ray of 1.515; the birefringence is therefore 0.202. Much magnesite fluoresces with a blue, green or white glow, probably best under the short-wave lamp. A greenish phosphorescence is often seen. Magnesite will effervesce with warm acid. The clear gemmy crystals are said to come from Brazil, but the mineral has a world-wide occurrence.

Malachite

The agate-like banding of different shades of green readily distinguishes malachite from any other mineral, except perhaps the much rarer pseudomalachite, or an opaque green aventurine quartz. Essentially a hydrated copper carbonate ($Cu_2(OH)_2CO_3$), malachite is formed through the dissolving of copper ores and the subsequent deposition in rock cavities and veins as botryoidal reniform or stalactitic masses.

The mineral is actually a compact mass of monoclinic crystals, at least so far as the material used for ornamental purposes is concerned. If the material shows crystal form these crystals are slender prisms in divergent arrangement and it is these prisms, as radial fibres closely packed together, which produce the botryoidal forms and the circular banding (*Figure 17.4*). The hardness of malachite is low at about 4 on Mohs's scale, and owing to the nature of its structure the mineral breaks easily, although with care it can be turned on a lathe. The SG of the ornamental material has a mean value of 3.8 but varies somewhat according to the compactness. The mean refractive index, all that may be expected to be seen on a refractometer, is about 1.85, although for the fibres the values are α 1.655, β 1.875 and γ 1.909, the large birefringence being a common factor in carbonate minerals.

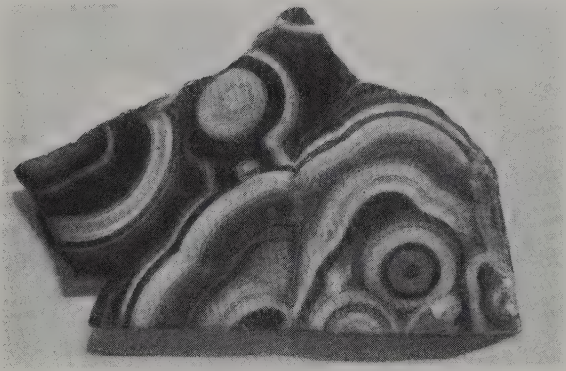


Figure 17.4 The circular banding seen in malachite

Malachite effervesces when touched with a spot of acid, and if the acid is taken up by a platinum wire which is then introduced into a Bunsen flame the flame will be coloured green if the acid used is nitric, blue if hydrochloric. This indicates copper which is an essential part of malachite. The mineral does not show luminescence under ultra-violet light or X-rays.

The use of malachite in ornamentation is mostly in the guise of flat plates for inlay purposes, or as rather flat cabochons, or as beads. Malachite has a world-wide distribution, being a common ore of copper where it is found typically in the oxidation zone of copper deposits. Much of the malachite used for ornamentation in older days was obtained from the copper mines in the Ural mountains in Russia, the major mines being at Nizhne-Tagilsk, Bogoslovsk, and at Gumeshevsk and Mednorudiansk, where the best cutting material is found. Malachite suitable for cutting is obtained from Queensland, New South Wales and South Australia. The copper mines of Africa supply much malachite but little seems to be used for ornamental purposes, and the United States of America produces fine-quality material at the copper mines of Arizona and elsewhere.

Malachite is often found together with the other copper carbonate azurite, and when the pieces are cut and polished a blue and green banded stone is produced to which the name azurmalachite is given. Malachite is also found in association with the copper silicate chrysocolla and they may be fashioned together. The opaque green aventurine quartz which looks so much like malachite may be distinguished from malachite by the red residual colour of the green quartz seen under the colour filter.

Pseudomalachite is a copper phosphate ($Cu_3P_2O_8 3Cu(OH)_2$), the monoclinic crystals of which form botryoidal structures similar in both colour and form to malachite. The hardness is 4.5 on Mohs's scale, the SG is given as 3.6 and the mean refractive index is 1.80. The mineral is less common than malachite and is found at Rheinbreitbach in Germany and Nizhne-Tagilsk in Russia, and has been reported from Zambia and elsewhere.

Manganotantalite

Transparent red manganotantalite ($MnTa_2O_6$) comes from Morrua in Mozambique and from Rio Grande do Sul in Brazil. The orthorhombic crystals have a hardness of 5.5–6 on Mohs's scale and a perfect cleavage. The SG is 7.73–7.97 and the refractive index is about 2.16; in mineralogical literature values of α 2.14–2.19, β 2.15–2.25 and γ 2.22–2.34 with a birefringence of 0.008–0.015 are mentioned. The deep red colour is idiochromatic due to manganese.

Meerschaum (Sepiolite)

Meerschaum, a word derived from the German meaning sea foam, is a hydrated magnesium silicate ($Mg_4Si_6O_{15}(OH)_2.6H_2O$), and is a compact white mineral which is mostly used for the bowls of pipes. Microscopic examination has shown the mineral to be an intermediate mixture of a fine fibrous material and an amorphous substance of the same composition. The hardness is 2 on Mohs's scale, with a refractive index of about 1.53 which is only vaguely visible on the refractometer. The SG is 2 but owing to the porosity of the dry material it will float on water. Meerschaum does not fluoresce. The mineral is found near Eski Shehr in Asia Minor in stratified earthy or alluvial deposits. Other sources are Moravia and near Thebes in Greece, in Spain and in the United States of America. Morocco was an early source of meerschaum, which was used in earlier times in place of soap and was known as 'pierre de savon Maroc'.

Melinophane (Meliphanite)

Purely a collector's stone, melinophane is a fluosilicate of beryllium, calcium and sodium with a formula $(Ca,Na)_2Be(Si,Al)_2(O,F)_7$, which forms yellow crystals of the tetragonal system. The hardness is just over 5 on Mohs's scale, the SG is 3.0 and the uniaxial (sometimes biaxial) refraction of negative sign has indices of 1.612 for the ordinary ray and 1.593 for the extraordinary ray. The mineral is found in the Langesundfjord district of southern Norway.

Mellite

Transparent golden-yellow mellite has been reported to come from Thuringia in Germany. Mellite is an organic aluminium salt with the chemical formula $Al_2[C_6(COO)_6].18H_2O$ and crystallises in the tetragonal crystal system. The hardness is 2 on Mohs's scale. The SG is about 1.6 and the refractive indices are 1.509 and 1.541 with a birefringence of −0.032.

Mesolite

One of the zeolite group of minerals, mesolite is intermediate between natrolite ($Na_2Al_2Si_3O_{10}2H_2O$) and scolecite ($CaAl_2Si_3O_{10}3H_2O$), and the stone has been cut into cabochons which have a silky lustre. The fibrous crystals, white or colourless, are monoclinic in crystallisation and packed closely together in the massive form produce the silky material. The hardness is 5 on Mohs's scale and the SG of mesolite is 2.29, and the indices of refraction are 1.505 and 1.506 with a birefringence of 0.001. The mineral occurs in amygdaloidal basalt and similar rocks and is found in Sicily, Scotland, Ireland, Iceland, Greenland, India, Australia and the United States of America.

Microlite

A mineral rarely cut except for collectors, microlite – a calcium pyrotantalate ($(Ca,Na)_2Ta_2O_6(O,OH,F)$) – is found in crystals of the cubic system which are of a brownish-green, yellowish-brown to hyacinth-red colour. The crystals are small and rarely large enough for cutting. The hardness is 5.5 on Mohs's scale, the SG is 5.5 and the mineral has a refractive index of 1.93. Microlite occurs in Sweden, the island of Elba and at Maine, Virginia, and Massachusetts in the United States of America.

Milarite

Milarite belongs to the osumilite group; also sugilite. Milarite was named after the Val Milar in Switzerland. It crystallises in the hexagonal crystal system and has the chemical formula $K_2Ca_4Al_2Be_4Si_{24}O_{60}.H_2O$. Transparent yellow to yellowish-green material is found at Rössing in Namibia. The hardness is 5.5–6 on Mohs's scale. The SG is about 2.52 and the refractive indices are 1.541 and 1.539 with a birefringence of −0.002.

Millerite

Millerite, a nickel sulphide (NiS) mineral which crystallises in the trigonal system, usually found as brass- or bronze-yellow slender hair-like crystals, and hence sometimes known as capillary pyrites, seems unlikely as a gemstone. However, a stone of cloudy yellowish-green colour has been cut from material found at Rössing in Nimibia. Millerite has a hardness of 3.00 to 3.50 on Mohs's scale and is said to have an SG of 5.30 to 5.65. No refractive indices have been given for this mineral.

Mimetite

Bright orange cabochons have been cut from mimetite found in Mexico. The mineral, which crystallises in the hexagonal system, has a hardness of 3.5 on Mohs's scale and an SG of about 7.1. It is only cut for collectors of the curious. Mimetite is an arsenate of lead with the chemical formula $Pb_5(AsO_4)_3Cl$.

Monazite

Transparent reddish-orange, yellowish-orange and brownish-yellow monazite ($(Ce,La,Nd,Th)PO_4$) is found in Sri Lanka and Montgomery County in North Carolina, USA. The monoclinic mineral possesses measurable radioactivity because of distinct contents of thorium and uranium. Monazite has a hardness of 6 on Mohs's scale and a perfect cleavage. The SG is about 5.2 and the refractive indices are 1.795 and 1.845 with a birefringence of 0.050; the optical sign is positive. A colour-changing monazite has been reported to come from Sri Lanka, being reddish-orange in daylight and pinkish-brown in tungsten light. Exposed to ultra-violet light, the material shows a green fluorescence.

Natrolite

A member of the zeolite family of minerals, natrolite is a sodium aluminium silicate with the formula $Na_2Al_2Si_3O_{10}.2H_2O$. The massive material, white in colour, consists of orthorhombic fibrous crystals and is not very suitable for cutting purposes, but it has been fashioned for those who desire something different. The hardness is 5.5 on Mohs's scale, the SG is from 2.20 to 2.25, and the refractive indices are α 1.480, β 1.482 and γ 1.493, the refraction being biaxial and positive in sign with the birefringence of 0.013. The USA, Norway and Scotland are well-known localities for the mineral.

Nepheline

The inclusion of this sodium aluminium silicate mineral ($(Na,K)AlSiO_4$) is because the massive types of the variety, called elaeolite, have occasionally been used in the arts. The material may be bluish-green, brown or tile-red in colour and usually contains numerous inclusions which give rise to a cat's-eye effect. The mineral is hexagonal in symmetry, has a hardness of 5.5–6 (Mohs's scale), and has an SG varying from 2.55 to 2.65. The refractive index is 1.54 with a birefringence of 0.004. The material gelatinises with hydrochloric acid. The localities are Norway, Russia and the United States of America. It is said that it is the green stones which are cut, the red stones rarely. Translucent reddish-brown nepheline from Norway has refractive indices of 1.531–1.535 and 1.534–1.539, with a birefringence of 0.003–0.004 and an SG of 2.58–2.59.

Nevada Wonderstone

Used for ornamental objects and as baroque stones fashioned by the tumbling process, Nevada wonderstone is a volcanic rock which weathers into alternate strips of red and buff, and which sometimes has grey patches. The material has an SG of about 2.53. Nevada wonderstone is not to be confused with the dark grey pyrophyllite rock which has been called South African wonderstone, to which reference is made in the section on pyrophyllite.

Nunderite

An interesting ornamental material occurs in Australia showing a green colour with brownish spots. The occurrence is located at Nundel in New South Wales and the material is named nunderite. The composition has been determined to be plagioclase feldspar and jadeite.

Nuummite

In 1987 an iridescent orthoamphibole was reported to come from Nuuk, the capital of Greenland, and was named nuummite. Cut and polished the material shows a sparkling iridescence that ranges from green and metallic-blue through yellow to golden, reddish and rarely violet colours. The stones belong to the anthophyllite-gedrite series and have an SG of 3.24. The refractive indices are 1.64 and 1.66 with a birefringence of 0.02. The fluorescence is dark violet when exposed to both long-wave and short-wave ultra-violet radiation.

Odontolite

Variously known as 'bone turquoise' or 'fossil turquoise' but more correctly called odontolite – a word derived from two Greek words meaning tooth and stone – is a material which has a fine blue colour and simulates the true turquoise remarkably well. It is actually the fossilised bones, or more often the teeth, of extinct animals, particularly the mastodon and dinotherium, and perhaps other prehistoric beasts.

Odontolite has, therefore, an organic derivation, and specimens may still show this organic structure. The material has had the organic constituents completely, or in major part, replaced by another mineral; thus the mineral could vary in character between rather wide limits and this is particularly so with regard to SG. Natural ivory (with about 40 per cent of organic material) has an SG of about 1.80, and if the organic material is replaced by apatite (SG 3.2) the SG would be much greater than for natural ivory. It has been found by X-ray powder photography that odontolite gives a typical apatite picture, so that apatite is a major replacing mineral in odontolite. There is, too, a certain amount of replacement by calcium carbonate, indicated by the effervescence shown when a spot of acid is placed on the specimen (a distinction from true turquoise). A further and more important replacement, or impregnation, is by the ferrous phosphate mineral known as vivianite ($Fe_3(PO_4).8H_2O$), to which the colour of odontolite is due. The colour of the material as mined is said to be a dingy greyish-blue and the rich blue of the jewellery stones is said to have been brought out by subsequent heat treatment. The SG of odontolite of a good blue colour is just over 3.00 and the refractive index varies from 1.57 to 1.63. The hardness is about 5 on Mohs's scale.

Odontolite is found at Simmore, near Auch in the *département* of Gers in southern France, a locality which was known before the French Revolution as Languedoc, and for a time these deposits were systematically worked. An imitation odontolite has been made by calcining recent ivory and staining blue by soaking in a solution of copper sulphate. Experiment shows that such material does not differ in density from that of recent ivory, that is 1.8.

Painite

Painite is possibly the rarest of all gem minerals, only three crystals having been recovered from which at the time of writing no cut stone has been fashioned. The original dark red prismatic crystal was purchased by the gemmologist and dealer Pain (then resident in Mogok) from a small-time miner who had recovered it from a locality about a mile to the north of Mogok. Preliminary tests and an experienced eye convinced Pain that this was an unknown mineral and he sent it for testing to the Precious Stone Laboratory of the London Chamber of Commerce in August 1952. Here it was found to be hexagonal, showing the faces (0001) $(10\bar{1}0)$ $(10\bar{1}1)$ $(10\bar{1}2)$ and $(11\bar{2}0)$. The refractive indices measured on a table spectrometer were 1.8159 and 1.7875, uniaxial positive, birefringence 0.0284. The hardness was slightly higher than 8 on Mohs's scale, and the SG was 4.01. The absorption spectrum showed a strong chromium doublet at 709 and 701 nm, with weaker lines at 693, 668 and 660 nm. The pleochroic colours were a pale brownish-orange for the ordinary ray and deep ruby-red for the extraordinary ray. It would take a skilled lapidary to orient the stone in a way which would produce a pleasing gemstone.

The mineral was sent to the British Museum (Natural History) for X-ray crystal analysis and chemical analysis, for which purposes a slice was removed from the base of the crystal, reducing the weight from 1.6897 to 1.4770 grams. The mineral resisted attack by acids and the initial analysis was eventually found to be incorrect in certain details. Moore and Araki in 1976 after X-ray and electron-probe analysis suggested the correct formula to be $CaZrB(Al_9O_{18})$, and that in the octahedral framework of its hexagonal lattice the mineral showed a relationship with jeremejevite and fluoborite.

A second and smaller painite crystal was recovered not long after the first by the same miner and both specimens were donated by Pain to the Mineral Department of the British Museum. No further specimens of the mineral were reported until 1979 when a third crystal was recovered by the GIA from a box of gem spinels from Mogok. The crystal measured 7.5 × 3 millimetres and weighed 1.7 carats. Its identity was proved by chemical analysis and comparison with the type material.

Palygorskite

An opaque pink to pink-white ornamental material called palygorskite ($(Mg,Al)_2Si_4O_{10}(OH).4H_2O$) comes from Peru and Mexico. The hardness is 2–2.5 on Mohs's scale. The SG is about 2.1, and a refractive index of about 1.55 can be determined.

Parisite

Transparent yellow to brown parisite is found in gem quality at the well-known emerald mine of Muzo in Colombia and is named after the then owner Paris. Parisite has the chemical formula $Ca(Ce,Nd,La)_2(CO_3)_3F_2$ and crystallises hexagonal. The hardness is 4.5 on Mohs's scale, the SG is 4.33–4.34 and the refractive indices are 1.671 and 1.772 with a birefringence of $+0.101$. Parisite shows a distinct line spectrum due to the rare-earth elements, which has been observed in Muzo emeralds containing parisite inclusions by Anderson. A six-rayed star parisite has also been found in the Muzo mine.

Pectolite

Found in close aggregations of monoclinic acicular crystals, and of a white or greyish colour, pectolite has been fashioned into cabochons which have a silky lustre. The mineral is a sodium calcium silicate with the formula $NaCa_2Si_3O_8(OH)$. Pectolite has a hardness of 5 on Mohs's scale, an SG which varies from 2.74 to 2.88 and an optically positive biaxial refraction having indices of α 1.595, β 1.606 and γ 1.633, but only a vague reading of about 1.60 would be seen on the refractometer with the massive material. The mineral usually shows a yellow or orange glow under ultra-violet light (probably best under the short-wave lamp), and some phosphorescence, which may be strong, is often seen. The glows are said to be due to traces of manganese. Pectolite is one of the zeolites and is found in cavities in basalts and other volcanic rocks in Italy, Scotland and the United States of America. The massive material, specially that from Alaska, is used as a substitute for jade. In 1977 a massive blue pectolite named larimar was found in the Dominican Republic.

Petalite

Purely as collectors' pieces, colourless petalite, a lithium aluminium silicate ($LiAlSi_4O_{10}$), has been cut as faceted stones, but the gems have little merit owing to their glassy appearance. The mineral crystallises in the monoclinic system but crystals are rare and the mineral is usually found massive. Petalite is cleavable and somewhat brittle and has a hardness of just over 6 on Mohs's scale. The SG ranges from 2.39 to 2.46 and the refractive indices are α 1.504, β 1.510 and γ 1.516. However, a colourless stone of 2.17 carats gave values of α 1.5056, β 1.5122 and γ 1.5199, giving a positive biaxial double refraction of 0.014. The SG was found to be 2.396. This stone showed a very weak and vague absorption spectrum with a band at about 454 nm, and under ultra-violet light showed a weak orange glow. Under X-rays a bright orange light was seen which had persistent phosphorescence. Petalite occurs in Sweden and in Massachusetts and Maine in the United States of America, and at Karabib, Namibia. From near Arassuahy, in Brazil, is obtained transparent petalite, and from this material a fine stone of 206 carats has been cut. A transparent white to pale yellow petalite from Minas Gerais, Brazil, gave an SG of 2.39 and indices of 1.51 and 1.523. Some petalite showing chatoyancy has been reported: these are petalite-analcime cat's-eyes from Zimbabwe.

Phenakite (Phenacite)

A gemstone which has occasionally appeared in jewellery, phenakite resembles colourless quartz in appearance. Indeed, it was so often mistaken for quartz that the name phenakite is derived from the Greek for the word to cheat. Phenakite is a beryllium silicate (Be_2SiO_4) and is found in bright crystals of the trigonal system which may be either tabular or prismatic in habit. These crystals show no distinct cleavage. The refraction is uniaxial and positive in sign, the indices being 1.651–1.654 for the ordinary ray and 1.663–1.670 for the extraordinary ray; thus the double refraction approaches that of tourmaline, being 0.016. The stones have little fire for the dispersion is only 0.015 for the B to G interval, the bright vitreous lustre being their only saving grace. Phenakite is harder than quartz at 7.5–8 on Mohs's scale and the specific gravity varies between 2.92 and 2.97. There is no characteristic absorption spectrum and any luminescence under ultra-violet light is too weak to be of value; it may be pale greenish. Under X-rays the fluorescence is quite distinct and of a blue colour; there is no afterglow. Crystals of a bright wine-yellow and a pale rose-red, the latter said to emanate from Russia, are reported but such hues have not been met with in cut stones. During the early part of 1963 an emerald-cut phenakite of greenish-blue colour was reported. This stone, which had an SG of 3.00 and refractive indices of 1.654 and 1.670, was noticeable for its strong dichroism ranging from a peacock-blue to violet-red. The stone fluoresced in light blue under ultra-violet light.

The usual occurrence of phenakite is most commonly in pegmatites, in granite druses and in mica schists. Crystals are found in the Tokawaja river in the Ural mountains of Russia in association with emerald and chrysoberyl, and the Miask district in the Ilmen mountains are another Russian source. A prominent occurrence of large colourless crystals is at San Miguel di Piracicaba, Minas Gerais in Brazil. Other sources of phenakite are the Usugara district, Tanzania in East Africa, the states of Maine, New Hampshire and Colorado in the United States of America, Switzerland, Austria, and Alsace in France. Crystals of phenakite are found in the Kein Spitzkoppe in Namibia. Probably the largest phenakite found was a rough pebble weighing 1470 carats which was found in Sri Lanka. This was later cut into one large, oval, faceted stone of 569 carats and several smaller stones. The stone is marred by the many needle inclusions it contains.

Phosgenite

Crystallising in the tetragonal system, phosgenite is a chlorocarbonate of lead ($Pb_2(CO_3)Cl_2$). With a hardness of about 3 it is only suitable for a collector's piece and its sole merit is the strong yellow fluorescence shown by the stone when under a beam of ultra-violet light. The SG is about 6.2 and the indices of refraction are 2.114–2.140 with positive sign. The mineral is found in many places, including Sardinia, Namibia, Tasmania and New South Wales.

Phosphophyllite

In the Smithsonian Institution of America there is an emerald-cut specimen of phosphophyllite of bluish-green colour and weighing 5.04 carats. Phosphophyllite is essentially a zinc phosphate ($Zn_2,(Fe,Mn)(PO_4)_2.4H_2O$) and is too low in hardness (3.5 on Mohs's scale) for it to be an effective gemstone. The SG is 3.1 and the refractive indices are 1.595–1.621 and positive in sign, the crystallisation being monoclinic. The mineral shows a violet fluorescence under short-wave ultra-violet light. The source of the mineral is usually said to be in Bavaria, but the cut stone described is probably from Bolivia. There is another specimen in the Geological Museum in South Kensington, in London.

Pollucite

An extremely rare mineral, pollucite is a silicate of aluminium and caesium with the formula $(Cs,Na)_2Al_2Si_4O_{12}.H_2O$, and is unique in containing the rare alkali metal caesium as an essential constituent. The mineral was first found in the granite pegmatites of the island of Elba. Breithaupt, in 1846, found pollucite in association with another rare mineral and he named them pollux and castor after the twin brothers of Helen of Troy in Greek mythology. Subsequently the name was modified to pollucite by attaching the usual mineralogical termination. Castor was proved later to be the mineral petalite.

Pollucite is a colourless or white mineral which has a vitreous lustre and is found in crystals of the cubic system, usually as cubes; it is often found massive. The hardness is 6.5 on Mohs's scale and the mineral has an SG range between 2.85 and 2.94 (a colourless specimen weighing 1.725 carats was determined by Spencer as 2.86). The refractive index varies from about 1.517 to 1.525, the material from Maine having the higher index. The dispersion is low (0.012 for the B to G interval), and the luminescence under ultra-violet light or X-rays is usually orange or pink in colour.

Sources of the gem-quality material (and the stone is only cut as collectors' pieces) are Newry, Oxford County, Maine and Middletown, Connecticut, USA. Massive material has been found in the Black Hills of South Dakota, and a mauve-white massive pollucite has been found at Varuträsk, Västerbotten in Sweden. A cabochon-cut piece of this Swedish material was found to have an index of refraction of 1.518 and an SG of 2.90. Pollucite is also found in Minas Gerais, Brazil, in Zimbabwe and in Namibia.

Porphyries

Porphyries are types of igneous rocks which show comparatively large and well-formed crystals embedded in a groundmass of much finer texture. The porphyritic structure is considered to be due to a two-stage crystallisation, or solidification, of the igneous magma at the time of its intrusion into the surrounding rock or extrusion on to the earth's surface, when the magma contained already formed crystals enclosed in the molten liquid which subsequently solidified as a fine-grained groundmass. Porphyritic structure is common in rocks and it might be expected that a wide range of such a type of rock could well be used as an ornamental stone. This does not seem to be the case and the two porphyries first considered have more historical interest than as ornamental stones of modern application.

The first of these is the green porphyry found in the province of Laconia in Greece, a rock with an olive-green groundmass with light green feldspar crystals sprinkled abundantly through it. The green colour is due to included epidote and chlorite throughout the rock, which was known in classical times as 'marmor lacedaemonium viride'. It was later known as 'perfidio serpentino', but the rock is not a serpentine. The quarries yielding this rock lie between the towns of Sparta and Marathonisi.

The other and perhaps more important porphyry is the famous red porphyry of Egypt, 'porfido rosso antico', which was known in classical times as porphyrites leptosephos'. This rock has a dark red groundmass, the colour being due to included piedmontite, a manganese mineral. In this groundmass is an abundance of small white and light pink feldspar crystals. The rock is quarried from a dyke some 25 m thick on the Jebel Dhokan mountain which lies some 40 km inland from the junction of the Red Sea with the Gulf of Suez and about 80 km eastwards from the Nile. It is doubtful whether the rock was known to the Egyptians but probably it was discovered in the reign of Claudius by the Romans who took it to Rome, where it was called 'lapis porphyrites', and later 'The Stone of Rome'. During the Roman occupation of Egypt thousands of workmen were employed in the quarries and the stone was transported to the Nile *en route* for the imperial city of Rome. A carved head of the Emperor Hadrian in Egyptian porphyry may be seen in the British Museum at Bloomsbury, London. The head is said to have been made in Egypt about AD 130 and the carving was carried out by using copper tools fed with sand and emery.

Llanoite or (llanite) is a reddish porphyry which consists mainly of reddish microcline crystals in a dark brown matrix, but which also contains small patches of quartz (?) which show bluish gleams. This rock is found in Llano County, Texas, in the United States.

Although not strictly a porphyry, the rock called corsite, or sometimes napoleonite, might conveniently be mentioned here. It is a greyish rock containing lighter-coloured oval rings showing some radial structure. The material is an orbicular diorite or hornblende gabbro which occurs in the island of Corsica. There are two fine examples of this material in the form of vases in the Chateau de Malmaison outside Paris.

Prehnite

Prehnite is an orthorhombic mineral, which is rarely found as distinct crystals but forms aggregates with botryoidal habit in cavities in volcanic rocks. It has been cut as cabochons or as carved pieces. The colour is usually an oil-green but an attractive brown material is common, the green material having some similarity to jade. Some translucent pale yellowish-brown prehnite has been cut cabochon and such stones show a cat's-eye effect.

Prehnite is a hydrated calcium aluminium silicate ($Ca_2Al_2Si_3O_{10}(OH)_2$) with a hardness of 6 on Mohs's scale. The SG lies between 2.80 and 2.95, but for the gem material the range is much closer and lies between 2.88 and 2.94. The principal refractive indices are 1.61 and 1.64 with a double refraction of 0.030. On the refractometer, owing to the massed fibrous nature of the material only a vague shadow edge at about 1.63 will be seen. No characteristic absorption spectrum is seen in prehnite and the mineral does not normally exhibit luminescence, although the brownish-yellow chatoyant stones may show a dull brownish-yellow glow under ultra-violet light and X-rays. Under the colour filter a weak reddish residual colour is seen.

Prehnite is found in China, in New Jersey in the United States of America, at Bourg d'Oisans, south-east of Grenoble in France, and in the Cape Colony, from which place it was first brought over by Colonel von Prehn, hence the name. Attractive green and brown botryoidal masses are found at Prospect, near Sydney in New South Wales, Australia. Botryoidal groups of pale green prehnite are found at Renfrew, the Kilpatrick Hills, Dunbarton, the Campsie Hills, Stirling and elsewhere in Scotland. A mixture of chlorite and prehnite, often with inclusions of copper, occurs in the Lake Superior district and is said to produce attractive pink and green stones for which the name patricianite has been proposed.

Prosopite

Although discovered by Scheerer as long ago as 1853, the mineral prosopite had not been considered as a gem material until the similarity in appearance to turquoise of samples of blue prosopite found associated with azurite near Santa Rosa, Zacatecas, Mexico, caused Liddicoat and Fryer to make a brief report on the mineral in 1974. In 1976 Dunn and Fryer added further information in the

Journal of Gemmology (October 1976). The formula for the mineral as given in Dana-Ford's *Textbook of Mineralogy* is $CaF_22Al(F,OH)_2$.

It has been found in monoclinic crystals as well as in granular massive form. The hardness is 4.5 and the SG is fairly constant at 2.88. Refractive indices for crystals are 1.501, 1.503 and 1.510 for the three critical rays, but in the massive state a general reading of 1.50 is seen, which separates it clearly from turquoise which gives readings near 1.62.

A refractometer reading provides the best conventional test in distinguishing prosopite from turquoise as the SG is rather close to that of the best Egyptian and Persian turquoise. The Santa Rosa occurrence of prosopite is in close association with azurite, and the 1.39 per cent of copper found in samples from this locality sufficiently accounts for its handsome blue turquoise-like appearance. The name of the mineral is derived from the Greek word for mask, in allusion to its deceptive appearance: it is unlikely, however, that this name was bestowed with its similarity (in its massive form) to turquoise in mind.

Proustite

The light red silver ore called proustite is famous for the lovely crimson crystals of the trigonal system that it forms. Although the mineral has been cut for collectors it provides a most unsatisfactory gemstone for, not only is the hardness only 2.5 on Mohs's scale, but the glorious red colour rapidly darkens to a dark red to nearly black colour on exposure to light. The composition is silver sulphide ($3Ag_2S.As_2S_3$) and the mineral has an SG varying from 5.57 to 5.64, the purer material having the lower values. The refractive indices, too high to be measured on the refractometer, are 2.7 for the extraordinary ray and 3.0 for the ordinary ray, the uniaxial negative birefringence being 0.3. Proustite is found as a primary silver mineral in silver deposits at Jachymov in Czechoslovakia, Freiberg in Saxony, Atacama in Chile, Alsace in France, at various places in Mexico, in Idaho, Colorado and Nevada in the United States of America and at Cobalt, Ontario in Canada.

Pyrargyrite

Cut pyrargyrite (Ag_3SbS_3) was found in a hematite lot from Brazil. The trigonal mineral has a hardness of 3.5 on Mohs's scale and an SG of 5.85 which is higher than hematite (5.2–5.3). Pyrargyrite is found in several occurrences, especially in Mexico, Chile, Peru, the USA and Spain.

Pyrophyllite

The compact massive variety of pyrophyllite, white, grey or greenish in colour, is in appearance like soapstone, and has, too, some similarity to massive talc in composition. It is an aluminium silicate with the formula $Al_2Si_4O_{10}(OH)_2$ (soapstone has the formula $Mg_3Si_4O_{10}(OH)_2$). The hardness is again similar to talc, that is about 1.5 on Mohs's scale, but the SG is slightly higher at about 2.8.

The refractive indices are 1.55 and 1.60, but these do not help very much with the massive material for only a vague shadow edge can be seen. Like soapstone, pyrophyllite has a greasy lustre and the two materials cannot be distinguished from each other by the eye alone. The higher SG or a determination of the presence of aluminium will indicate which material is being handled. This may be carried out by a method commonly used by mineralogists. A fragment of the mineral is moistened with a solution of cobalt nitrate and then heated. If a blue colour results, aluminium is indicated and the material is probably pyrophyllite. On the other hand, if a pale red colour is produced magnesium is present and the mineral is probably soapstone. The method needs some practice before a positive result can be obtained with surety. In many localities pryophyllite is often found in association with kyanite and andalusite. The material occurs in the Sverdlovsk (Ekaterinburg) district of the Ural mountains of Russia, in Scandinavia, in the region of Ouro Prêto, Minas Gerais, Brazil, and in California, Georgia and Carolina in the United States of America. Much of the agalmatolite of China is pyrophyllite.

South African wonderstone, also known as Ottosdal G stone or Koranna stone, a dark grey slaty-looking rock, which is found near the village of Ottosdal in western Transvaal, has been used for ornamental objects. It is also used as a container for the reaction constituents in the synthesis of industrial diamonds (its melting point rises under high pressure). The stone occurs up to about 60 m in thickness in volcanic formations, the principal outcrop being at Gestoptefontein Hill. The composition is 89 per cent pyrophyllite with 9.5 per cent chloritoid or epidote and 1.5 per cent rutile. A specimen of this rock gave a vague refractive index of 1.58 and an SG near to 2.72.

Pyroxmangite

Transparent red pyroxmangite ($MnSiO_3$) occurs at Broken Hill in Australia. The triclinic mineral has a hardness of 5–6 on Mohs's scale and a perfect cleavage; the SG is 3.77 and the refractive indices are 1.736 and 1.753 with a birefringence of 0.017; the optic sign is negative.

Rhodizite

As the name indicates, the rare potassium (caesium, rubidium) aluminium borate $(K,Cs)Al_4Be_4(B,Be)_{12}O_{28}$ mineral known as rhodizite is usually of a rose-red colour. When found as crystals the mineral forms dodecahedra of the cubic system, but there are grounds for doubt as to whether the crystals truly belong to the cubic system. The hardness of rhodizite is 8 on Mohs's scale, the SG is 3.4 and the refractive index is 1.69. Specimens from Madagascar and the Urals were found to luminesce with a weak yellowish glow under ultra-violet light and to show a strong greenish or yellowish fluorescence, with perceptible phosphorescence, when irradiated with X-rays. Rhodizite was originally found in masses of a rose-red colour in the Ural mountains near Sverdlovsk, and crystals of yellowish and greenish hue have been found at Antandrokomby and Manjaka in Madagascar. Stones of this species are only fashioned for collectors.

Rhodochrosite

Rhodochrosite, found as rhombohedral crystals of the trigonal system, and in granular masses, usually has a paler and more delicate rose-red colour than rhodonite. Rhodochrosite, the manganese carbonate ($MnCO_3$), as used as an ornamental stone, is characterised by the lovely pink shade of colour, which is variegated and in bands of different shades of pink. The material may be likened in its banding, but not in colour, with green malachite. Indeed, like malachite, the banding is due to stalagmitic formation, the prismatic crystals tending to a radial formation. Grey, fawn and brown colours are also found.

Although rhodochrosite is found in many different localities, only a few supply the compact material which is used as an ornamental stone, and its use as such began just before the commencement of World War II, when a quantity of this stalagmitic rose-coloured stone came from San Luis in Argentina. The deposit from which it came was said to have been found in a long-disused mine situated on a mountain fissure at a high altitude, which was reputedly worked by the Incas for silver and copper during the thirteenth century. It was owing to this connection that the names 'Rosinca' or 'Inca rose' were given to the stone. Colorado, Montana and other states of the North American continent are other sources of the mineral. Further localities are Romania, Hungary, the Central Provinces of India and Freiberg in Saxony, but these are unimportant as commercial sources for ornamental material.

An important new source of rhodochrosite in both the massive and the rare clear crystal form was discovered in 1974 in a mine at N'chwaning in the Kalahari Desert region of Cape Province, South Africa. The mineral occurs in a variety of shades in isolated pockets up to 1 m by 0.5 m in size, together with other manganese minerals, braunite and bixbyite. Clear crystals are rare, but stones up to 60 carats in weight have been cut and sold for as much as 50 dollars per carat.

The hardness of rhodochrosite is near to 4 on Mohs's scale and it is more easily scratched than is rhodonite. The SG is rather variable and lies between 3.45 and 3.70, but the ornamental material has the smaller range of 3.5–3.65. The refractive indices are 1.820 for the ordinary ray and 1.600 for the extraordinary ray. The negative uniaxial double refraction of 0.220 is large in amount and characteristic of a carbonate mineral. These refractive indices can only be seen on stones cut from clear, nearly transparent, material (crystals), for in the ornamental rhodochrosite the crystalline aggregate precludes anything more than a diffuse shadow edge being seen on the refractometer. The absorption spectum of the mineral shows a band of 551 nm (and other vaguer lines), but the spectrum scarcely assists identification. A small clear crystal showed a band at 415 nm, which could not be seen in the more opaque ornamental types. Under the stimulation of ultra-violet light a dull red glow was observed in samples of the mineral from Argentina and Colorado. The mineral effervesces with acid, but the test is not conclusive for rhodonite may contain some carbonate. A few small stones have been cut from the clearer crystals.

Rhodonite

Best known as an ornamental stone, translucent to opaque, and of a fine rose-red colour, rhodonite has at times been found sufficiently transparent to have been cut for collectors as faceted stones. Much translucent material is fashioned into beads and cabochons for ornamental articles and as an inlay, like rhodochrosite, to give colour contrast to the white variety of 'onyx marble'.

The mineral is a silicate of manganese ($MnSiO_3$) with some calcium usually present, and in the case of fowlerite from New Jersey, zinc is also present. When in crystals the stones are commonly large and rough and belong to the triclinic system, and according to some authorities the species is referred to the pyroxene group of minerals, but this is not universally agreed. The massive material is the most common and is found in the Urals in large masses resembling marble – a pink marble veined with black where the manganese has oxidised by weathering.

Rhodonite has a distinct cleavage and an uneven fracture and brittle nature; the lustre is vitreous to pearly on fractured surfaces. The mineral takes a good polish. The hardness is about 6 on Mohs's scale and the SG varies between 3.40 and 3.70, but the more restricted range of 3.60–3.70 has been found for the gem-quality material. The refractive index, as far as is given by the vague shadow edge shown when the massive material is placed on the refractometer, is near to 1.73. The dichroism and absorption spectrum are not clearly defined in the massive material and rhodonite shows no luminescence under ultra-violet light or X-rays. An orange-red transparent cut stone, from Australian material, was found to have an SG of 3.707 and refractive indices of 1.733 and 1.747 for the principal rays. The stone showed distinct dichroism with the twin colours orange-red and brownish-red, and the absorption spectrum showed a broad band centred at 548 nm, a strong narrow line at 503 nm and a weaker and more diffuse band at 455 nm.

Rhodonite has a wide occurrence. The major localities are in the Sverdlovsk district of the Urals in Russia (mainly at Sedelnikovo, a village 25 km from Sverdlovsk), the Vermland district of Sweden, a number of localities in the United States of America, Mexico, the Broken Hill district of New South Wales, Australia, southern Africa and in Cornwall, England.

Rutile

Natural rutile is rarely encountered as a gemstone, for the material is very rarely transparent, and even if it were so the colour – red, brown or black – is too dark to produce attractive gems, although the black material has been used for mourning jewellery. Other colours such as yellowish, bluish and violet have been reported, and extremely rarely a grass-green, but most of these are opaque and have not been met as cut stones.

The tetragonal crystals, which have vertically striated prisms capped with pyramids, are commonly twinned in knee-shaped forms (geniculate twins), and may even be so repeatedly twinned as to produce a closed ring. Acicular or hair-like crystals are common and when these are enclosed in rock crystal give rise to rutilated quartz, or as it is sometimes called Venus hair stone.

Rutile is titanium dioxide (TiO_2) and is polymorphous with anatase and brookite. The hardness of the mineral is 6–6.5on Mohs's scale and the SG is near to 4.2. The indices of refraction are 2.62 for the ordinary ray and 2.90 for the extraordinary ray, the positive birefringence being 0.287; thus cut stones show pronounced doubling of the back facets. The mineral is also exceptional in the degree of fire it displays, which is over six times that shown by diamond, but in the natural stones the effect is masked by the dark colour. The lustre of rutile is that known as adamantine metallic and the dichroism is variable but usually strong. Rutile is widely distributed both in the localities where it is found and in the nature of the rocks in which it occurs. Of major gemmological importance is the synthetically produced rutile, which is discussed in the chapter on synthetic materials.

Sapphirine

Transparent facetable sapphirine of purplish-pink, brownish-green and blue colours occurs in Sri Lanka. The mineral is named because of its similar colour to sapphire. Sapphirine has the chemical formula $(Mg,Al)_8(Al,Si)_6O_{20}$, crystallises in the monoclinic crystal system and has a hardness of 7.5 on Mohs's scale. The SG is 3.45–3.51 and the refractive indices are 1.701–1.711 and 1.707–1.718 with a birefringence of 0.006–0.007; the optic sign is negative. The purplish-pink sapphirine shows the lower indices, the blue ones the medium and the brownish-green samples the higher values.

Scapolite

The mineral scapolite is best explained as being part of an isomorphous series whose end members are marialite ($Na_4Cl(Al_3Si_9O_{24})$) and meionite ($Ca_4(SO_4CO_3)(Al_6Si_6O_{24})$), the whole group being the scapolite series; scapolite is therefore a silicate of aluminium with calcium and sodium. The mineral crystallises in the tetragonal system with prismatic habit. The crystals, usually found in metamorphic rocks, are commonly coarse with large uneven faces. The crystals have three directions of easy cleavage parallel to the prism zone.

The gem material was first found in 1913 in the Mogok Stone Tract of Myanamar as white, pink or violet stones, which are distinctly fibrous. When cut in the correct direction as cabochons these stones produce attractive cat's-syes, the chatoyancy being due to the included parallel rod-like cavities. The pink stones of this type have been miscalled 'pink moonstone'. A clear yellow scapolite was found, about 1920, in Madagascar and 10 years later similar yellow material was found in the state of Espírito Santo, Brazil. Some yellow stones of this species have been found with the pink variety in Myanmar, and from Mozambique.

The hardness of scapolite is 6 on Mohs's scale and the SG varies from 2.60 to 2.71. The refraction is uniaxial and negative in sign, with indices which rise from 1.540 for the extraordinary ray and 1.549 for the ordinary ray to 1.555 and 1.577 for the extraordinary and ordinary rays respectively, with increase of the meionite molecule. The pink and white stones have an SG of 2.63; the refractive indices are 1.549 and 1.540, the double refraction being 0.009 (or 0.010 if the fourth place of decimals is taken into account). A violet scapolite cat's-eye reported upon had an SG of 2.634 and refractive indices of 1.560 for the ordinary ray and 1.544 for the extraordinary ray, the birefringence being, therefore, 0.016. The constants of this variety show that it conforms to an intermediate scapolite which has 50–80 per cent of the marialite molecule and 20–50 per cent of the meionite molecule. This intermediate scapolite has been called dipyrite or dipyre, but the name has been applied to common scapolite (which is also known as wernerite) which has 20–60 per cent of marialite and 40–80 per cent of meionite, or for another intermediate member of the family known as mizzontie. Much confusion occurs with these names in mineralogical texts. The clear yellow scapolite has the higher SG of 2.70 and refractive indices of 1.568 and 1.548, the double refraction being 0.020. Yellow scapolite from the pegmatites east of Entre Rios, in Mozambique, gave refractive indices of 1.554–1.556 and 1.540–1.541, giving a birefringence of 0.015; and yellow scapolite from the Umba river in Tanzania gave an average SG of 2.671, with refractive indices of 1.567 and 1.548, while another stone from this locality gave an SG of 2.659 and indices 1.562 and 1.543. The birefringence of 0.019 is given for these stones. The highest values for corresponding data of gem scapolite have been reported for a yellow sample from East Africa (1.594, 1.590).

The lustre of scapolite is vitreous inclining to resinous and the dispersion is weak, being 0.017 for the B to G interval. The dichroism of the pink and violet stones is strong, the twin colours being dark blue and lavender blue; the yellow stones show colourless or pale yellow and a yellow colour. The absorption spectrum of the pink and violet stones is characterised by bands in the red at 663 and 652 nm, with a strong absorption in the yellow; this spectrum is ascribed to chromium. The scapolites from Myanmar show a yellow or orange fluorescence under long-wave ultra-violet light, and the spectrum of this glow, which is sometimes quite strong, exhibits a discrete structure. Under the short-wave lamp the glow is more pinkish. The fluorescence under X-rays is much feebler and of a whitish to lilac colour, and the stones quickly photocolour to a violet hue. The effect is, however, not permanent. The yellow transparent stones, particularly those from Myanmar, show a lilac or mauve fluorescence under ultra-violet light and a strong orange glow under X-rays, and also photocolour to a violet shade.

An opaque massive yellow variety of scapolite found in Quebec and Ontario, Canada, which could be cut into effective cabochons, is characterised by the brilliant yellow fluorescence it emits when under long-wave ultra-violet light. Some material also phosphoresces with the same coloured glow. The spectrum of this glow shows a banded structure resembling the effect seen in minerals owing their fluorescence to uranium. The effect and the fluorescence have, however, now been proved to be due to small quantities of sulphur.

Scapolites of gem quality have been found in recent years in Kenya and the adjoining stone tracts, including colourless and yellow forms of the mineral. One type was of interest in resembling amethyst in colour and moreover sharing the same SG value of 2.65. Confusion should be avoided, however, by a test on the refractometer since readings of 1.536 for the extraordinary and

1.541 for the ordinary ray reveal the difference in the extent and sign of the birefringence.

Scheelite

Yellowish-white to brownish but sometimes almost an orange-yellow in colour, the calcium tungstate mineral scheelite ($CaWO_4$) has, despite its low hardness of 4.5–5 on Mohs's scale, been faceted as a gemstone for collectors. The crystals are of the tetragonal system and usually have a pyramidal habit. The SG varies between 5.9 and 6.1 and the refractive indices are 1.918 and 1.934; the sign is positive and the birefringence is 0.016. The lustre is vitreous inclined to adamantine and the absorption spectrum may show faintly the didymium rare earth spectrum of groups of lines in the yellow and green, the strongest of the yellow group being at 584 nm. The most useful and striking feature of scheelite is the strong bright blue fluorescence shown by the mineral when it is bathed in short-wave ultra-violet light (253.7 nm), in contradistinction to its lack of response to the long-wave ultra-violet lamp, under which it is practically inert. Scheelite is found in Czechoslovakia (in the old Bohemia), Saxony, Italy, Switzerland, Finland, France, England (Cumberland and Cornwall) and Sonora in Mexico. In the United States of America it is found in South Dakota, Connecticut, Arizona and California. Much scheelite is obtained from Australia. Few of these localities produce material clear and transparent enough for cutting into faceted stones. In recent years scheelite of a fine yellow to orange colour has come from Santa Cruz, Sonora, Mexico from which stones over ten carats in weight have been cut. Good cuttable material is found in Arizona and California. The fine yellow-coloured stones may resemble a coloured diamond but are easily differentiated by the strong double refraction of scheelite. Scheelite has been made synthetically.

Scolecite

Transparent colourless scolecite occurs in Poonah, India. The rare zeolite mineral has the chemical formula $CaAl_2Si_3O_{10}.3H_2O$, crystallises in the monoclinic crystal system and has a hardness of 5–5.5 on Mohs's scale. The SG is 2.21 and the refractive indices are α 1.512, β 1.518 and γ 1.523 with a birefringence of 0011; the optic sign is negative.

Scorodite

A mineral which has been reported from a gem-laboratory is a variety of scorodite having an unusual blue colour with reddish overtones. Scorodite ($FeAsO_4.2H_2O$), which crystallises in the orthorhombic system, is a hydrated ferric arsenate. The normal colour of the material is leek-green to liver-brown. The hardness of the mineral is 4 on Mohs's scale and it is soluble in hydrochloric acid; hence it would not in any way produce a durable stone. The SG is 3.30, the refractive indices are 1.785, 1.816 with a birefrigence of 0.027–0.031, and the stone shows pronounced pleochroism. The stone described came from Tsumeb, Namibia.

Scorzalite

Magnesium-rich blue and blue-green scorzalite of gem quality has been found in Brazil. The mineral was named after the Brazilian mineralogist Scorza. Scorzalite forms a series with lazulite, has the chemical formula $(Fe,Mg)Al_2(PO_4)_2(OH)_2$ and crystallises in the monoclinic crystal system. The hardness is 5.5–6 on Mohs's scale; the SG is 3.24 and the refractive indices are α 1.629, β 1.655 and γ 1.660 with a birefringence of 0.037.

Sellaite

The Brumado mine in Bahia, Brazil produces transparent colourless sellaite crystals. The rare mineral was named after the Italian mineralogist Quintino Sella, has the chemical formula MgF_2 and crystallises in the tetragonal crystal system. The hardness is 5–5.5 and the SG is 3.15. The refractive indices are 1.378 and 1.390 with a birefringence of +0.012.

Senarmontite

Grey-white senarmontite has been found in a lot of faceted scheelite from Brazil. Senarmontite was named after the French mineralogist de Senarmont, has the chemical formula $Sb_2O_3$and crystallises cubic. The hardness is 2–2.5 and the SG is 5.4–5.5.

Serandite

Transparent faceted pink-orange serandite comes from the well-known mineral occurrence of Mont Saint Hilaire in Canada. Serandite forms a series with pectolite, has the chemical formula $Na(Mn,Ca)_2Si_3O_8(OH)$ and crystallises triclinic. The hardness is 4.5–5 on Mohs's scale. The SG is 3.52 and the refractive indices are α 1.672, β 1.675 and γ 1.708 with a birefringence of 0.036.

Serpentine

As an ornamental material, serpentine is encountered in two main forms: as a hard massive variety known as bowenite and as the 'serpentine marble', which occurs as rock masses mixed with other minerals. The name serpentine is in some doubt, one version suggesting that the name arose from the ancient view that the mineral was a cure for a serpent's bite, and another, and perhaps better suggestion, that it was because of the resemblance of the dark green mottled variety to the skin of a serpent.

There can be many variations of the mineral and since the nineteenth century mineralogists have divided the serpentines into groups, and again into varieties, to some of which specific names have been applied. Most of these have no place in gemmology. A better division for gem purposes is: precious, or noble, serpentine comprising the purer translucent varieties having an oil-green colour; and the resinous-waxy yellow to yellow-green material called retinalite. The second type is the so-called common serpentine which includes the rock-like types.

From X-ray studies Selfridge divided the serpentines into two groups, serpentine and antigorite, and he suggested the name serpentine for the rock-like forms of serpentine, antigorite or a mixture of both. Whittaker and Zussman have more recently divided the serpentines into three groups: lizardite, antigorite and chrysotile.

Serpentine is a hydrated silicate of magnesium ($H_4Mg_3Si_2O_9$) and crystallises in the monoclinic system, but the mineral is always massive and is never encountered as crystals. A number of different geological processes may produce the mineral by alteration of basic rocks of igneous origin or of metamorphic pyroxenes. Serpentine is soft, about 2.5 on Mohs's scale, except in the variety bowenite, which reaches 5 or more. The rock-like types may also vary in their hardness owing to the admixture of other minerals.

Most of the bowenite variety of serpentine used so much today for carvings and other articles of virtue is a translucent yellowish-green material, which often contains whitish cloudy patches. The SG is 2.58–2.59 and the mean refractive index – all that is likely to be seen on a refractometer – is 1.56. The absorption spectrum shows bands at 497 and 464 nm but they have little diagnostic value. Owing to the iron content which in part gives the green colour to serpentine there is little, if any, luminescence under any excitation by ultra-violet light or X-rays. X-ray patterns have shown that bowenite belongs to the antigorite group of serpentines.

There is a translucent deep green or bluish-green variety of bowenite found in the South Island of New Zealand which was used by the Maoris, but little dark green bowenite is encountered today; nor is the rather coarser dark green bowenite from the Delaware river, Pennsylvania, and at Smithfield, Rhode Island, seemingly used. The SG of a Maori ear-pendant in dark translucent bluish-green bowenite serpentine was found to be 2.617, slightly higher than the usual SG for bowenite.

Much light yellowish-green bowenite in the form of carved figurines has been exported from China to the Western world under the misnomer 'new jade'. It is possible that this mineral has emanated from Tuoyuan in Hunan province. Bowenite, known to the Persians as 'sang-i-yashm', is found in Afghanistan, and this material is utilised at Bhera in the Shahpur district of the Punjab for the manufacture of dagger hilts, knife handles, caskets, amulets and other articles. Afghan bowenite appears to occur in rock masses at the head of one of the mountain gorges that run down from the Safed Koh into the valley of the Kabul river. Bowenite and other serpentines are found in South Africa.

A variety of serpentine called williamsite is a translucent stone of oil-green colour, often with whitish veins of brucite and cloudy patches; it also contains dark cubic or octahedral crystals which may be chromite or magnetite. Williamsite has a refractive index near to 1.57 and specimens were found to have an SG near to 2.61. Under the long-wave ultra-violet lamp this variety of serpentine shows a weak whitish-green glow but is inert under the short-wave lamp and under X-rays. Some williamsite is found in the United States of America.

A deposit of serpentine, usually worked by native craftsmen, is found some 5000 m up in the Karakoram Mountains in Kashmir. The material was found to have a hardness of 2.5 on Mohs's scale, an SG of 2.56 and an index of refraction of about 1.56. X-ray powder patterns showed that the material was lizardite with some brucite.

Two other varieties of serpentine should be mentioned. These are ricolite, which is a fine-grained serpentine occurring in curious coloured bands and is found at Rico in New Mexico; and satelite, a fibrous greyish to greenish-blue material which produces a type of cat's-eye and comes from Maryland and California in the United States. It may be a variety of chrysotile.

The most notable source of the serpentine marble in classical times was the brecciated serpentine quarried at Casambala, a few miles north-east of Larissa in Thessaly, and known as 'verde antico'; it was known to the Romans as 'lapis atracius' for the quarries were near the ancient town of Atrax. It has been reported that the quarries were destroyed by the Germans during World War II. Some authorities class the 'verde antique' with the ophicalcites. Much fine serpentine is found near Genoa and Levanto in Liguria, and near Prato in Tuscany. These Italian serpentines vary from green to brownish-red in colour and often the material is veined with white steatite.

In England the best known serpentine rock is that found on the southern promontory of the Lizard peninsula, Cornwall. The Cornish serpentines (the major quarries are at Kennack Cove, Kynance Cove, Spernic Cove and Carleon Cove) vary considerably in colour and texture and may be green, veined or spotted with red, brown or white, or may be red or purple to nearly black and relieved by coloured veining. The Lizard serpentine is usually fashioned locally into small wares suitable for the tourist. Serpentine marble is found at Rhoscolyn, Holy Island, which is off Anglesey, Wales. It is known locally as Mona marble. Another source of serpentine is at Portsoy, Banffshire, Scotland. Rock-like serpentines are found at St Paul in the French Basses-Alpes, south of Innsbruck in the Austrian Tyrol, and at Hof Gastein in the province of Salzburg. A slightly banded material in two shades of green is found at the Congo Vaal mine near Carolina, Transvaal, South Africa, two pieces of which gave SGs of 2.595 and 2.603. The material has been found to consist of antigorite with the lighter stripes of antigorite and calcite; it has a hardness of about 4.5 on Mohs's scale and therefore can be placed with the bowenites.

The SG of serpentine marble varies somewhat, as might be expected in such an impure rock. The values between 2.5 and 2.7 are those most commonly found and in only a few cases have densities been recorded outside this range. Except for the hardness the other properties agree with those of bowenite. Serpentine has been stained to imitate jade.

Another variation of serpentine, which has been referred to in Chapter 16, is the serpentine mixed with more or less calcite, dolomite or magnesite, producing a rock of clouded white to green which is called ophicalcite or ophicite. The best known of this material is that which comes from Connemara in Eire, and is hence called 'Connemara marble' or 'Irish green marble'. The hardness of this material is about 3 on Mohs's scale and the index of refraction about 1.56. The SG varies considerably and lies between 2.48 and 2.77. There is a strong absorption band at 465 nm.

A variety of aluminous serpentine is pseudophite, or as it is often miscalled 'Styrian jade', a material which has been used to fashion small bowls and ornamental pieces. The material is found at Bernstein, Burgenland, Austria, about 90 km south of Vienna on the borders of Styria and Austria, a place which, before the Versailles Treaty, was in Hungary. Another material of similar appearance is found at Gurtipohl near St Gallenkirche in Montafon Valley, Vorarlberg, a province of Austria which lies between the Tyrol and Leichtenstein. This material is worked as an ornamental stone under the name miskeyite. Pseudophite is soft, with a hardness of 2.5 on Mohs's scale, and the mineral is somewhat similar to the rock known as chlorite schist. The refractive index is about 1.57 and the SG 2.69.

A translucent to transparent greenish-yellow serpentine (antigorite) has been found in Pakistan. The SG is about 2.57 and the refractive indices are 1.559–1.560 and 1.561, with a birefringence of 0.001–0.002.

Shattuckite (now Planchéite)

A hydrated copper silicate ($Cu_5(SiO_3)_4(OH)_2$), shattuckite is a compact granular or fibrous mineral of a blue colour, which may have an appearance like some turquoise or azurite. The fibres are of monoclinic symmetry but the material is massive and when cut is practically opaque. The SG of the mineral is about 3.8 and the refractive indices are 1.752 and 1.815 for the principal directions, but only a vague reading of about 1.75 would be seen on a refractometer. Shattuckite is mainly found at the Shattuck mine, Bisbee, Arizona, where it forms pseudomorphs after malachite. Some material shows green patches, which may be malachite. The mineral has also been reported from Shaba in Zaire. The shattuckite which is fashioned, often by the tumbling process, is shattuckite in quartz or another mineral, and thus has a density which will not agree with shattuckite as a mineral. SGs of 2.84, 2.67 and as low as 2.53 have been recorded for ths mixed material. Shattuckite has now been made synonymous with planchéite, but the old name is kept here as being better known as a gem material.

Siderite (Chalybite)

A cut stone of this iron carbonate mineral has been reported, the specimen having a pistachio-brown colour. Siderite ($FeCO_3$) crystallises in the trigonal system and is really too soft for a cut stone. The hardness is 3.5 to 4 on Mohs's scale; the SG is 3.83 to 3.88; and the refractive indices are 1.873 and 1.633, and thus the birefringence is 0.240 and negative in sign. The cut stone reported is said to have come from Pinasquevia, Portugal.

Simpsonite

An exceedingly rare mineral of bright orange-yellow colour, simpsonite is the hexagonal aluminium tantalate $Al_4(Ta,Nb)_3(O,OH,F)_{14}$. It has a hardness of 7, and an SG near 6.00. The refractive indices are about 2.06 with a birefringence of about 0.100. The mineral is said to occur only at Alto de Gis, Rio Grande do Norte, Brazil.

Sinhalite

For a number of years a stone understood to be brown peridot has been known. The stone has refractive indices and other properties close to those of peridot, but has the somewhat higher SG of 3.48, a discrepancy ascribed to an increase of unessential iron. In 1952 the nature of the stone was questioned and by means of X-ray crystallographic and chemical analysis the stone was found to be a completely new mineral species. It is a magnesium aluminium iron borate with the formula $Mg(Al,Fe)BO_4$, (peridot is $(Mg,Fe)SiO_4$). The colour of sinhalite varies from pale yellow-brown to golden or greenish-brown to black, the depth of colour being in relation to the iron content. The stones have a strong resemblance to brown chrysoberyl or brown zircon.

The crystallisation of sinhalite is orthorhombic, but except for an isolated recovery of a good crystal from the Myanmar gem gravels, the material is found only as rolled pebbles from the gem gravels of Sri Lanka. Indeed, it is from Sinhala, the Sanskrit name for Sri Lanka, that the name of the species is derived. Sinhalite has been found in a contact metamorphic limestone in Warren County, New York, but this has no gem significance.

The hardness of sinhalite is 6.5 on Mohs's scale, the SG lies between 3.47 and 3.49, and the refractive indices are 1.67 and 1.71 for the principal rays, the negative biaxial birefringence being 0.038. The pleochroism is distinct with the colours pale brown, greenish-brown and dark brown. The dispersion is 0.018 over the B and G interval, and the absorption spectrum is similar to that of peridot; the bands are at 493, 475, 463 and 452 nm, and there is a general absorption of the violet. Sinhalite does not luminesce.

Smithsonite

The bluish-green and green massive varieties of smithsonite, the zinc carbonate ($ZnCO_3$) which crystallises in the trigonal system, have been cut as cabochon stones and mounted in jewellery under the name Bonamite, after the French for Goodfriend: Goodfriend Brothers first marketed the stones. The stones have a low hardness, 5 on Mohs's scale, but they are quickly identified by the high SG which approximates to 4.3. The indices of refraction are 1.621 and 1.849, the refraction being uniaxial and negative in sign with double refraction of 0.228. As the material is usually massive these optical constants are not very helpful, as only a vague edge would be seen on the refractometer. Being a carbonate, smithsonite will effervesce when touched with acid and this may be used as a test if any inconspicuous part of the back is tested, for the acid will take away the polish. Apart from the green and the greeny-blue material which is the common type used in jewellery, there is a pink smithsonite due to cobalt, and a yellow variety which owes its colour to cadmium. Smithsonite is found at Laurium in Greece, Tsumeb in Namibia, Sardinia, Santander in Spain, New Mexico and Utah in the USA, and East Africa.

The zinc silicate mineral hemimorphite ($Zn_4(OH)Si_2O_7H_2O$) is usually associated with smithsonite, and massive material of blue or green colour, the colours often being banded, has been fashioned. The crystallisation of the mineral is orthorhombic, the crystals when found doubly terminated show different inclinations of the faces at each end (hemimorphism) and hence the name of the mineral. The hardness is 5 on Mohs's scale; the principal refractive indices are 1.614 and 1.636. The SG varies from 3.4 to 3.5. The localities for hemimorphite are similar to those for smithsonite.

Soapstone

Soapstone is the massive variety of the mineral talc or steatite, an acid metasilicate of magnesium ($Mg_3Si_4O_{10}(OH)_2$), and is used for carved ornaments. The mineral may be white to silvery-white, but because of impurities it may be green, brown, yellow or reddish, and often veined and mottled. The hardness of talc is 1 on Mohs's scale, but owing to the presence of impurities soapstone may be considerably harder, although it may usually be scratched by the fingernail. The mineral is said to harden by the action of heat. Soapstone has a greasy feel and the SG – which for pure talc is between 2.7 and 2.8 – has a much greater variation and may be anything from 2.20 to 2.80. The refractive indices for talc are approximately 1.54 and 1.59 for the principal rays, but only a vague edge at about 1.54 would be seen on the refractometer in the case of the massive soapstone. The material does not luminesce. Soapstone is extensively carved into ornaments by the Chinese and the material had many uses in olden days, for the earliest scarabs of the Egyptians were of steatite and three-sided prism seals found at Knossos were of the same material. Steatite is of world-wide occurrence, and in some places forms extensive beds. The mineral is often associated with serpentine and with chlorite schists, and may be pseudomorphic after quartz. Notable localities are at the Limbue quarries, Lake Nyasa, central Africa, and in quarries at Kundol, Tdar state, Bombay presidency, India. Some varieties of Indian steatite bear the name 'pratima culler' or 'image stone'. Some agalmatolite is steatite. A grey-green soapstone is carved by the Eskimos of northern Canada and a richer green-coloured material by the inhabitants of Zimbabwe.

Sodalite

Best known as one of the components of lapis lazuli, sodalite became of importance as an ornamental mineral on the discovery in Canada of masses of sodalite of a rich blue colour. Sodalite forms cubic crystals, usually of dodecahedral habit, which may be grey, greenish, yellowish, white, light red or blue in colour. It is only the blue-coloured massive variety which is used as an ornamental stone, a stone which in appearance may well be mistaken for lapis lazuli.

In composition sodalite is a sodium aluminium silicate with sodium chloride ($Na_8Al_6Si_6O_{24}Cl_2$) and the hardness of the mineral is 5.5–6 on Mohs's scale. The SG varies from 2.15 to 2.35, but the value for the massive blue variety is near to 2.28. The refractive index is 1.48. Sodalite luminesces with patches of orange-coloured light when under ultra-violet light. The blue mineral has been found in the Langesundfjord district of southern Norway and also at Litchfield and West Gardner, Kennebec, Maine and at Salem, Essex County, Massachusetts in the United States of America. Another source is in the state of Rajputana (Rajasthan), India. The major commercial source is the massive royal blue material, often speckled with small spots of bright red, pink or orange, which may also include feldspar, which is found near Bancroft in the township of Dungannon, Hastings County, Ontario, where it occurs as segregations in a belt of nepheline syenite. Other Canadian localities are in the counties of Peterborough and Haliburton, Ontario, and in the rocks of Mount Royal in the city of Montreal. Sodalite is also found in Bahia, Brazil and at the Ice River, British Columbia. Very beautiful rich blue and more crystalline material comes from near Ohopoho in the northern region of Namibia.

Sodalite is fashioned as cabochons and beads, and is cut and polished into slabs for use as inlays in clock cases and cigarette boxes, when the lovely blue colour blends so admirably with the creamy-white 'onyx marbles'. The mineral was found in Canada at the time of a royal visit and the blue sodalite was thus named 'princess blue'. In recent times the material used for inlay is termed in the trade by the names 'Canadian blue stone' or just 'bluestone'.

Sodalite never reaches the beautiful ultramarine blue of true lapis lazuli, the colour being more of a royal blue. Further, sodalite rarely contains the brassy specks of pyrites as is found in lapis, but it has been reported that pyrites has been seen in sodalite, so proof of lapis is not obtained by mere inspection. The SG will provide a surer test, for the SG of lapis is higher (2.75–2.95).

A transparent pink variety of sodalite called hackmanite is found at Mont Saint Hilaire in Canada. The SG has been determined to be 2.30–2.32 and the refractive index varies between 1.485 and 1.487. The material shows a distinct photochroism: exposed to ultraviolet radiation the mineral has a pink to violet-red colour which fades to yellow in visible light.

Sphene

Sphene, which is either yellow, brown or green in gem-quality material, is a very brilliant transparent stone with a resinous to adamantine lustre. It is named after the wedge-like shape of the monoclinic crystals, which are often twinned. The crystals are found in cavities in gneiss and granite, and also in such metamorphic rocks as schists and certain granular limestones.

Cut sphenes are characterised by having a pronounced fire; hence for the best effect the stones are always faceted in the brilliant-cut or mixed-cut styles and never in the cabochon form. Sphenes are magnificent stones when freshly cut, but the low hardness of 5.5 on Mohs's scale does not make the stones suitable for constant wear.

Sphene is a silicate of titanium and calcium ($CaTiSiO_5$) and it is from the titanium content that the alternative name for the species, titanite, is derived. The latter name, however, is more usually applied to the black or reddish-brown non-gem-quality material. Some iron is always present in sphene and the rare earths cerium and yttrium are commonly present. This trace of rare-earth impurity manifests itself in the absorption spectrum which generally shows, albeit weakly, the typical rare-earth spectrum of didymium.

The refraction of sphene is biaxial and positive in sign, the refractive indices varying from 1.885 and 1.990 to 1.915 to 2.050 for the two major directions. The double refraction likewise varies from 0.105 to 0.135, and thus exceeds in amount many other gemstones, so that the doubling of the back facets will be observed with ease. The stones show strong trichroism, the colours for the principal directions being greenish-yellow, reddish-yellow and nearly colourless, but the exact shades depend on the colour of the stone. The dispersion of sphene is 0.051 for the B to G interval, a fire greater than that of diamond. The SG varies between 3.52 and 3.54 and sphene, probably owing to the presence of iron, does not exhibit luminescence. The stones are brittle and also have a weak cleavage.

The major localities for gem sphene are at Schwarzenstein and Rotenkopf in the Zillerthal of the Austrian Tyrol, in the St Gotthard and the Grisons in Switzerland, in Renfrew County, Ontario, Canada, and in Madagascar. A very fine cut stone of 22.26 carats, which had an SG of 3.542, and was an orange-brown colour, came from the Myanmar Stone Tract. Both brown and green sphenes are found at El Alamo, Pino Solo and San Quintin in Baja California. Brazil is another source. In 1981, the first occurrence of gem-quality specimens of sphene from Sri Lanka was reported.

Spurrite

Opaque to translucent purple spurrite shows refractive indices of α 1.637, β 1.672 and γ 1.676 with a birefringence of 0.039; the optic sign is negative. Spurrite has the chemical formula $Ca_5(SiO_4)_2(CO_3)$ and crystallises monoclinic. The hardness is 5 on Mohs's scale. The mineral possesses a distinct cleavage and is soluble in hydrochloric acid.

Staurolite

Faceted gems of a deep brown colour have been cut from transparent crystals, but most staurolite is prized for the cross-shaped interpenetrant twin crystals which cross one another at nearly 90 degrees or 60 degrees (*Figure 17.5*). These crystals provide one of the so-called 'cross stones' (the other being the chiastolite variety of andalusite) which are used as amulets and baptismal stones in Mediterranean countries. Staurolite is a hydrated aluminium silicate. A suggested formula is $2Al_2SiO_5Fe(OH)_2$, which shows the mineral to have a chemical relationship to kyanite. There may, however, be small-scale isomorphous replacement by magnesium, manganese, cobalt or nickel. The crystals, which belong to the orthorhombic system, have a weak cleavage and show a conchoidal fracture. The hardness of staurolite is 7–7.5 on Mohs's scale; the SG, which varies somewhat from 3.65 to 3.78, is generally just over 3.7. The refractive indices, biaxial and positive in sign, vary from 1.739 to 1.747 for the α

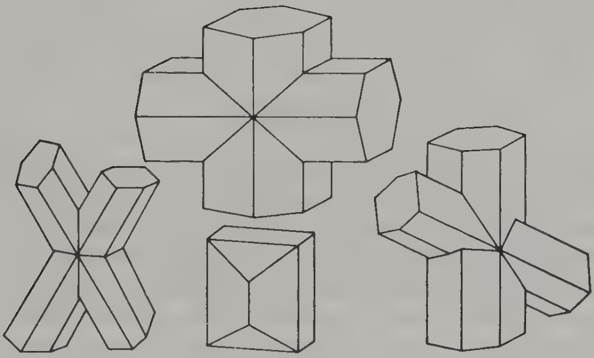


Figure 17.5 Typical crystals of staurolite

ray, 1.744 to 1.754 for the β index, and 1.750 to 1.762 for the γ index; the birefringence varies from 0.011 to 0.015. The pleochroism is distinct but varies somewhat in the colours seen. These are usually colourless and some shade of yellow or red. The dispersion of staurolite is 0.023 for the B to G interval. The absorption spectrum shows a weak band at 578 nm and a strong one at 449, but these are of no diagnostic importance. Staurolite does not show luminescence. The mineral occurs in crystalline schists and gneiss owing to regional metamorphism and the crystals are often associated with garnet, fibrolite, and tourmaline. Staurolite is found in the Ticino and St Gotthard districts of Switzerland, Finisterrre and Morbihan in Brittany, France, Brazil, Russia, Scotland and several of the states of North America.

A zincian staurolite, quite a new variety of this mineral, has been reported. It has a hardness of about 7, an SG of 3.79 and refractive indices 1.721 and 1.731. It is biaxial and trichroic; with colours of green, yellow and red, and the stone is inert under ultra-violet light and X-rays. The colour of the stone is red-brown when seen under incandescent light and yellowish-green under fluorescent light.

Stibiotantalite

The transparent brownish-yellow niobate and tantalate of antimony ($SbO_2(Ta,Nb)_2O_6$), stibiotantalite, has been cut for collectors. To avoid confusion it may be mentioned that the earlier name for niobium (Nb) is columbium (Cb), the latter term being more commonly used in the United States of America for the element. Stibiotantalite crystallises in the orthorhombic system, has an adamantine to resinous lustre and one direction of distinct cleavage. The mineral has a decided resemblance to zinc blende. The hardness is 5.5–6 on Mohs's scale and the refractive indices are 2.46 and 2.39 for the greatest and least values respectively. The biaxial refraction is positive in sign. A specimen of the gemmy material, which comes mainly from Mesa Grande, San Diego County, California in the United States of America, was found to have an SG of 7.46, but lower values for the mineral are given in mineralogical literature.

Stichtite

A few cabochon stones of the rose-red or lilac-coloured mineral stichtite have been seen in collections of gem materials. Stichtite is a rather soft (hardness 2.5 on Mohs's scale) alteration product of serpentine and owes its red colour to the presence of chromium. In composition it is a hydrated carbonate-hydroxide of magnesium and chromium ($Mg_6Cr_2(OH)_{16}CO_3.4H_2O$), but the chromium is often replaced in part by iron. The mineral is opaque and often veined with green and is found massive as a matted aggregate of plates, fibres or micaceous scales which are small trigonal crystals, and which have a strong basal cleavage. By thin-section mineralogical methods stichtite has been found to have uniaxial crystallisation and to have refractive indices of 1.55 for the ordinary ray and 1.52 for the extraordinary ray, with a negative birefringence of 0.027. The fibres are pleochroic in shades of light and dark red, but this is not easily seen in the massive material. Likewise, in the mass only a blurred shadow edge will be seen in the refractometer at about 1.53. The material is rather friable and has a greasy, wax-like or pearly lustre, and the SG has been found to range from 2.15 to 2.22 with South African material and 2.16 in material from Quebec. The absorption spectrum shown by stichtite is typically that of chromium, with three lines in the red at 665.5 and 630 nm and the third line approximately midway between. There are broad absorptions in the yellow-green and in the violet, the 'window' of blue light being centred at 500 nm. No luminescence is shown by stichtite. First identified as a new mineral in 1910 from material found at Dundas in Tasmania, stichtite was also reported from the Black Lake district of Canada in 1918. In the same year the deposit in the Barberton district of Transvaal was mentioned although the material was first found here as early as 1883 but not reported upon. There is another occurrence in Algeria. The mineral was named after Robert Sticht of Tasmania.

Sugilite

The mineral sugilite was first described in 1976 by Murakami and his co-workers in the *Mineralogical Journal of Japan*, and was named in honour of the late Professor Kan-ichi Sugi. As first discovered the mineral consisted of brownish-yellow grains in an aegirine syenite from Iwagi islet, Ehemi prefecture, Japan. The mineral is hexagonal in structure, with hardness 6 on Mohs's scale, SG 2.74 and refractive indices 1.607 for the extraordinary and

1.610 for the ordinary ray. In composition, sugilite is a complex silicate of alkali metals, iron, aluminium, etc. and contains water. In its composition, crystal structure and physical properties it closely resembles another rare mineral sogdianite (first described in 1968) with which it has in fact been confused. Sogdianite, however, contains essential zirconium and has a rather higher SG (2.82–2.90).

The yellow-brown grains of sugilite as originally discovered had nothing to offer as a gem material, but more recently a very different and strikingly handsome manganoan form of the mineral has been recovered from the Wessel Mine, Hotazel, in the north of the Cape Province of South Africa. Here the mineral is found in the form of a purple rock-like material of which 'royal azel' and 'royal lavulite' have proved the most popular. As an aid to the gemmologist in the identification of this manganoan form of sugilite by standard techniques, the presence of three fairly sharp bands in the violet region at 411, 419 and 437 nm, due to manganese, should be mentioned. These bands were first recorded by Dillman, and being at the violet end of the spectrum can only successfully be observed by using a powerful beam of light which has passed through a good blue filter.

Taaffeite

In 1945 Count Taaffe, a Dublin gemmologist, found a pale mauve stone in a jeweller's 'junk box' that resembled spinel in appearance and properties but showed distinct double refraction. The stone, weighing 1.419 carats, was sent to the Precious Stone Laboratory in London for testing and was found to have refractive indices 1.718 and 1.723, uniaxial negative, and SG 3.613, hardness 8. Tests by Claringbull in the Mineral Department of the British Museum established that this was an unknown mineral and Count Taaffe gave permission for a slice to be taken from the culet region to enable chemical and X-ray analysis to be completed. An analysis on only 6.16 mg of material suggested the formula $MgO.BeO.2Al_2O_3$, and the structure to be hexagonal trapezohedral, a very rare class of symmetry. This was the first occasion on which a new mineral had been first encountered as a cut gemstone.

Despite diligent search it was not until 1949 that Payne found a second taaffeite specimen (weight 0.86 carat) in a routine test of 104 mixed stones, mostly from Sri Lanka. The third taaffeite was recovered in 1957 by Robert Crowningshield of the GIA, and the fourth – a 5.30 carat stone of brownish-purple colour – some ten years later. Since that time several more cut specimens of the mineral have been identified. Two of these are of special interest, one being a ruby-red specimen and the other a sapphire blue.

The red stone was sent to Gübelin from Sri Lanka by Amarasinghe and, though having the properties of taaffeite, was found on analysis to have a BeO content of 4.4 per cent compared with the assumed 9.3 per cent in taaffeite. It was thus thought to be yet another new mineral, for which the name 'taprobanite' was proposed (after an ancient name for Sri Lanka).

Re-analysis, however, of the original taaffeite specimen (now in the Geological Museum, South Kensington, on loan from the owner, Mitchell) by Schmetzer revealed that the first analysis was at fault and that taaffeite and 'taprobanite' are both the same mineral, the formula of which can be written as $BeMg_3Al_8O_{16}$.

A colour-change taaffeite has been reported to come from Sri Lanka. The stone is bluish in daylight and reddish in tungsten light.

Thaumasite

The Black Rock Mine in South Africa produces transparent colourless to pale yellow thaumasite crystals worth cutting. Thaumasite has the chemical formula $Ca_6Si_2(CO_3)_2(SO_4)_2(OH)_{12}.24H_2O$ and crystallises in the hexagonal crystal system. The hardness is 3.5 on Mohs's scale. The SG is 1.88–1.91 and the refractive indices are 1.505–1.510 and 1.467–1.480 with a birefringence of −0.030 to −0.038.

Thomsonite

Belonging to the zeolite family of minerals, thomsonite is a hydrated calcium sodium aluminium silicate ($(Ca,Na_2)Al_2Si_2O_8.H_2O$) which crystallises in the orthorhombic system. The gem material is mostly columnar with a radial structure, or as radiated spherical aggregates or concretions, which are translucent and closely resemble agate. They may be milk-white, yellow, reddish, brownish and greenish, the fibres being arranged radially producing eye-like forms.

Thomsonite has a hardness of about 5 on Mohs's scale; the SG varies from 2.3 to 2.4. The refractive indices are also variable and may have limits between 1.52 and 1.54; a vague shadow edge is all that would be seen on a refractometer. The lustre is porcellaneous and the stones take a good polish although they are somewhat brittle. Under ultra-violet light the luminescence seen is patchy with brownish and whitish glows.

The mineral occurs in cavities in lavas and other igneous rocks as a secondary mineral resulting from the alteration of feldspars and nephelite. The gemmy material is found on the shores of Lake Superior, particularly at Thomsonite Beach and the Isle Royale in the lake. A variety with a translucent olive-green colour, and which resembles some jadeite and is remarkably different from the usual 'eyed' thomsonite, is lintonite, which is found along the shores of Stockly Bay, Michigan, and near Grand Marais, Minnesota. A specimen of lintonite gave an SG of 2.364 and refractive index of 1.53. A snow-white variety of thomsonite from Arkansas is called ozarkite.

Tremolite

Tremolite (grammatite) is better known when in a compact mass of felted crystals as mutton-fat jade (nephrite). Two very dissimilar varieties of this monoclinic calcium magnesium silicate mineral need to be mentioned. The first is a greenish chatoyant variety which gives a good cat's-eye effect when cut cabochon and which comes from Ontario, Canada. The second is an attractive transparent lilac-pink variety (hexagonite) found at Fowler, St Lawrence

County, New York. A specimen of the cat's-eye type gave an SG of 2.976 and a crystal of hexagonite a value of 2.980. The hardness of tremolite lies between 5.5 and 6 on Mohs's scale and the refractive indices are 1.60 and 1.62 for the least and the greatest indices. Hexagonite shows an orange fluorescence. An amphibole cat's-eye of tourmaline-green colour has come from Myanmar. Some tremolite shows the 437 nm line which is characteristic of jadeite. An emerald-coloured tremolite from Taiwan was found to have an SG of 2.98 and indices of α1.608, β 1.624 and γ 1.636. The absorption spectrum resembled that of emerald with lines at 684 nm (strong) and at 650 and 628 nm.

Tugtupite

A new mineral of cyclamen-red colour was described in 1960 and has since been used in jewellery. This was named tugtupite after a promontory in Greenland where it was found. Tugtup means reindeer, so the stone could be looked upon as 'reindeer stone'. Most of the material comes from Greenland but small pieces are also found in the Kola peninsula (now named Poluostrov Kolskiu), in the north-west of Russia.

The mineral, which is allied to sodalite, has tetragonal crystallisation, a hardness of about 6.5, and an SG varying according to impurities present between 2.30 and 2.57. The refractive indices are 1.496 and 1.502, with a birefringence of 0.006, the dichroism being marked and bluish-red and orange-red. The massive material is mottled white with lighter and darker reds. The lighter parts when placed in the dark fade to white and only regain their colour when exposed to daylight. The material often contains black needles or yellow spots. Under long-wave ultra-violet light, tugtupite fluoresces an orange colour, but under the short-wave lamp the glow is salmon-red.

Tugtupite has been found sufficiently transparent for faceted stones to be produced. Bank examined these and found the SG to be 2.38 and the refractive indices 1.492 and 1.500, giving a positive birefringence of 0.008.

Ulexite

Strictly not a gemstone, ulexite is included owing to its mention in gem literature for the curious optical effect which can be produced by the mineral. Ulexite is a hydrated borate of calcium and sodium ($NaCaB_5O_9.8H_2O$) and the mineral is made up of fine fibrous crystals of the monoclinic system. The hardness is 1 on Mohs's scale and the SG is 1.75 or slightly higher. Specimens of the massive ulexite examined gave a hardness of 2 and an SG near 1.99, and the mean refractive index was found to be 1.51. The mineral is said to fluoresce blue and green under short-wave ultra-violet light and many specimens show phosphorescence.

The fibrous nature of the mineral allows cabochon stones to give an exceptionally good cat's-eye effect, but the material is far too soft and friable to be so used. The most interesting effect is seen when a slab of the mineral is cut and polished on both faces, so that the polished planes are at right angles to the direction of the fibres. It is seen then that the fibres are so straight and reflective that when newsprint is placed against one polished face it appears as if by magic, even with an inch or more of intervening mineral, on the opposite face. Such cut plates of ulexite have been called 'television stones'. The material emanates from the borax deposits of California, USA.

Unakite

Unakite is a variegated rock in red, pink and green colours used, particularly by amateur lapidaries, in the United States of America. The material is a type of granite containing quartz, pink feldspar and green epidote and the rock owes its name to the source in the Unaka range of North Carolina, where it was first found. Other localities in the United States of America are said to produce the rock. The SG of the material is variable depending upon the relative amounts of the heavier epidote and the lighter quartz and feldspar; values varying from 2.85 to 3.2 have been recorded. The refractive indices vary according to the areas examined, and examination of one specimen showed that the pink areas gave an index of 1.52, the green areas 1.76 and the white parts 1.55. The material is prized simply for its mottled colouring and is usually fashioned in the cabochon form or tumbled baroques. Similar material comes from Zimbabwe and from Galway Bay, Eire. The epidote of various colours found in the vicinity of Keimos, in northern Cape Province, South Africa and sold as an ornamental stone under the name okkolite, may be a similar material.

Variscite

Despite its rich green to greenish-blue colour, variscite has a limited use as a gem material. The mineral is a hydrous aluminium phosphate ($AlPO_4.2H_2O$) but replacement of some of the aluminium by chromium and iron occurs, and to this the colour is due. The gem material is a massive variety composed of a compact mass of fibres of orthorhombic crystallisation, which have biaxial negative birefringence; the principal refractive indices vary from 1.55 to 1.56 and from 1.58 to 1.59. A vague edge at 1.56 is all that would be seen in the case of the gemmy massive material. The hardness is 5 on Mohs's scale and the SG varies from 2.4 to 2.6, but lower values have been recorded. The lustre is vitreous and the absorption spectrum shows a strong line at 688 nm and a weaker line at 650 nm; there is no luminescence shown by the mineral.

Variscite is found at Messbach in Saxon Voightland, sometimes Variscia, and it is from this that the name of the mineral is derived. The most important sources of gemmy material are the nodular masses called utahlite found in Tooele County, Utah. Banded material from Utah is known as sabalite or trainite, after the collector Percy Train of Manhattan. Ely in Nevada is another American source and much of the American material is concretions of variscite in quartz or chalcedony to which the name amatrice is given. A material which has the properties of variscite emanates from the top of a mountain near the town of Dayboro, about 65 km north-west of Brisbane in Queeensland, Australia. This material has been referred to as 'Australian turquoise' or 'Australian jade'. It is also found in Spain.

Väyrynenite

Gem-quality transparent pinkish-red väyrynenite occurs at Chitral in Pakistan. Väyrynenite was named after the Finnish mineralogist Väyrynen, has the chemical formula $MnBe(PO_4)(OH,F)$ and crystallises in the monoclinic crystal system. The hardness is 5 on Mohs's scale. The SG is about 3.2 and the refractive indices are α 1.639, β 1.661 and γ 1.667 with a birefringence of 0.028; the optic sign is negative.

Verdite

A deep green ornamental stone often containing red or yellow spots was found in 1907 on the south bank of the Nord Kaap river, in the Barberton district of Transvaal in South Africa, and from its colour the mineral was named verdite. Essentially a rock, it may be referred to as a massive muscovite rock coloured green by the chromiferous mica fuchsite. The material is rather soft, 3 on Mohs's scale, and the refractive index is about 1.58. The SG varies between 2.80 and 2.99. The absorption spectrum shows three lines in the deep red and a vague line in the blue, a spectrum reminiscent of chromium-coloured minerals. The rock does not exhibit luminescence. Similar material has been reported from the Piggs Peak mines, Swaziland, South Africa, and from the western slopes of the Green mountain range near Shrewsbury in Vermont, USA. This latter material is known as the 'green marble of Shrewsbury'. Somewhat similar material is found at Roeburne, Pilbara district, Western Australia, and probably in Venezuela and in the Panama Canal Zone. There is a report extant that a vase found at Mohenjo-Dara, India, and reputed to be not later than 2750 BC, is fashioned from a green mica rock, and may be nearly pure fuchsite.

Another rock of somewhat similar composition is selwynite. The material has been found to consist of chrome mica (fuchsite) with either diaspore or chlorite, and could be called an impure massive fuchsite. Specimens of this material gave a range of SG of 2.79 to 3.11; the refractive index is about 1.55. Vague chromium lines in the red end of the absorption spectrum could be seen. The rock comes from the Heathercote area of Victoria, Australia.

Villiaumite

Facetable transparent reddish villiaumite has been reported to come from the island of Los in Guinea. Villiaumite was named after the French explorer Villiaume, has the chemical formula NaF and is cubic. The hardness is 2 on Mohs's scale. The SG is 2.79 and the refractive index varies between 1.328 and 1.332.

Vivianite

Cut stones of a green colour fashioned from the hydrous ferrous phosphate mineral vivianite ($Fe_3(PO_4)_2.8H_2O$) are known to exist in the hands of collectors despite their hardness of only about 2 on Mohs's scale. The monoclinic crystals are said to be colourless when unaltered but deepen to a blue or green on exposure to light. The SG is about 2.6 and the indices of refraction are α 1.580, β 1.598 and γ 1.627. Vivianite is the colouring mineral of odontolite ('bone turqoise').

Wardite

Found as bluish-green concretionary incrustations in cavities of nodular variscite at Cedar Valley, Utah, this mineral has some resemblance to turquoise. It is thought to be tetragonal in crystallisation. It has a hardness of 4 on Mohs's scale and an SG of 2.81, and the refractive indices are 1.590 and 1.599. The mineral is a hydrous aluminium phosphate with the formula $Na_4CaAl_{12}(PO_4)_8(OH)_{18}.6H_2O$. Sousmansite from Montebras in Sousmans, Creuse, France, may be identical with wardite.

Whewellite

Clear colourless monoclinic crystals of this calcium oxalate mineral ($CaC_2O_4.H_2O$) have been cut for collectors. With a hardness of only 2.5 on Mohs's scale such stones make unsatisfactory gems. The SG is 2.23 and the biaxial optically positive refraction has indices α 1.490, β 1.555 and γ 1.650; thus the double refraction is large in amount at 0.160. The mineral has been reported from Saxony, Bohemia (Czechoslovakia) and Alsace, France.

Willemite

Willemite, a zinc silicate (Zn_2SiO_4) which is chemically and crystallographically related to phenacite, is most important as an ore of zinc. The mineral is, however, occasionally found in transparent crystals of the trigonal system. It is from these crystals that a few greenish-yellow stones have been cut. The stones do not take a good polish; they have a somewhat resinous lustre, a low hardness (5.5 on Mohs's scale) and a brittle nature with a conchoidal fracture. These preclude the stones from being cut into attractive gems. Some orange stones do, however, take a good polish.

The SG of willemite varies between 3.89 and 4.18 and the refractive indices are 1.69 and 1.72; the uniaxial birefringence is 0.028 and is positive in sign. The dichroism is variable. The absorption spectrum shows several weak bands at 583, 540, 490, 442 and 432 nm, and there is a strong band at 421 nm. The yellow colour of the stone is due to iron, but much willemite contains traces of manganese to which is due the brilliant bright green fluorescence of the mineral when under the rays from an ultra-violet lamp or X-rays. Strong and persistent phosphorescence is often exhibited by willemite. The mineral, which is named after William I of the Netherlands, is found in a number of localities, but the gemmy crystals mainly come from Franklin Furnace, New Jersey, the important zinc mining location of the United States of America.

Witherite

Translucent witherite of an off-white colour has been cut as collectors' pieces. Orthorhombic in crystallisation, the mineral has the composition of barium carbonate ($BaCO_3$), a hardness near to 3.5 on Mohs's scale and an SG which lies betweeen 4.27 and 4.35. The refractive indices are α 1.532, β 1.678 and γ 1.680; the biaxial double refraction, negative in sign, is 0.148, which is large in amount and typical of a carbonate mineral. Witherite will effervesce with acid. The mineral is found in Cumberland and Northumberland in England, in Japan, near Rosiclare, Illinois, USA, and at Thunder Bay, Ontario, Canada.

Wollastonite

A cabochon of white compact wollastonite, a calcium metasilicate ($CaSiO_3$), has been encountered. Wollastonite crystallises in the monoclinic system and has a hardness of 4.5–5 on Mohs's scale. The SG is from 2.8 to 2.9, and the optically negative biaxial refraction has values of 1.61 and 1.63 for the principal indices. The material when massive is identified with difficulty and may need an X-ray powder photograph to determine the mineral correctly. Wollastonite is found in Finland, Romania, Mexico, and in several of the states of North America. A compact variety is found on the Isle Royale in Lake Superior.

Wulfenite

More important for the beautiful crystal specimens which the mineral forms, wulfenite is found in tabular crystals of the tetragonal system which may be orange, yellow, green, grey or white in colour. The mineral is a lead molybdenate ($PbMoO_4$), has a hardness of just below 3 on Mohs's scale, and has an SG varying from 6.7 to 7.0. The uniaxial birefringence is negative in sign, with indices of 2.402 for the ordinary ray and 2.304 for the extraordinary ray. Wulfenite is a secondary mineral found in lead and zinc deposits in Austria, Yugoslavia, Poland, Bohemia, Morocco, the Congo Republic, New South Wales, Mexico and the United States of America. The mineral is far too soft for use as a gemstone and is attractive only for its colour. It has apparently been cut for those who desire the unusual.

Yugawaralite

Transparent colourless yugawaralite of gem quality occurs at Nasik in India. Yugawaralite was named after the Yugawara thermal spring in Japan, has the chemical formula $CaAl_2Si_6O_{16}.4H_2O$ and belongs to the zeolite group. It is monoclinic and has a hardness of 4.5 on Mohs's scale. The SG is about 2.2 and the refractive indices are α 1.490–1.495, β 1.497–1.503 and γ 1.501–1.509 with a birefringence of 0.011–0.014.

Zinc Blende (Sphalerite)

Often better known in its shortened form – blende – the mineral is a common and important ore of zinc. Usually the mineral is nearly black in colour, but occasionally it is found in transparent pieces of a yellowish-brown hue. It is from this latter material that the few faceted stones have been cut to satisfy those who prize the unusual. The low hardness, 3.5–4 on Mohs's scale, coupled with a perfect dodecahedral cleavage (six directions), precludes zinc blende having much value as a gemstone. The SG of the mineral is 4.09 and the refractive index is 2.37. Zinc blende has a large colour dispersion (0.156 for the B to G interval) which is over three times the fire shown by diamond. An absorption spectrum consisting of three bands in the red can sometimes be observed in zinc blende. They are at 690, 667, which is the strongest, and 651 nm. Much zinc blende does not show these lines, which have been attributed to cadmium, but there is a danger that if they are present they may be mistaken for a zircon spectrum.

Blende, a zinc sulphide (ZnS), crystallises in the cubic system, generally in tetrahedra, but often with cube, dodecahedral and trisoctahedral forms. Twins are common. The name zinc blende is derived from the German *blenden* (to deceive), because while resembling galena (lead sulphide) it yields no lead. In North American mineralogy the name sphalerite is used instead of zinc blende, and against this name is derived from the mining world: it means 'treacherous'. Zinc blende has been used for the 'dense-glass' prisms of extended-range refractometers.

The mineral has world-wide occurrence but the major localities for the transparent material are the Chivera mine, Cananea, Sonora, Mexico and Picos de Europa in the Cordillera Cantabrica, near Santander on the northern coast of Spain. An interesting variety, not of gem quality, is a massive granular stone from Tsumeb, north of Otavi in Namibia, which exhibits triboluminescence – that is, when struck or rubbed with the blade of a knife or a wire brush, it emits showers of orange-coloured sparks. Except for this type, which also fluoresces orange under the influence of the ultra-violet lamp, zinc blende does not fluoresce.

Zincite

The red oxide of zinc (ZnO) has occasionally been found as irregular transparent pieces, but rarely as crystals, from which a few stones have been cut. The mineral crystallises in the hexagonal system. It is rather soft (4–4.5 on Mohs's scale) and the SG for gem-quality material is near to 5.66. Owing to the high indices of refraction, 2.013 for the ordinary ray and 2.029 for the extraordinary ray, the lustre is adamantine. The uniaxial birefringence, which is positive in sign, is 0.016. Zincite, which if pure would be white in colour, owes its orange-yellow to deep red hue to traces of manganese oxide (MnO). The mineral does not fluoresce. The gem-quality zincite is found in the famous zinc mines of Franklin Furnace, New Jersey in the United States of America.

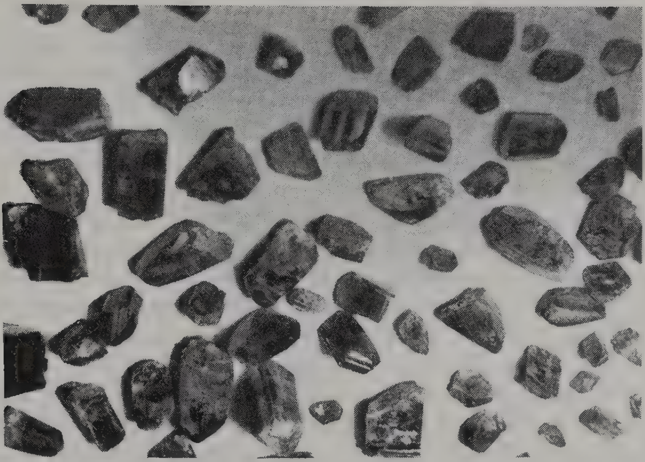


Figure 17.6 *Zoisite crystals from the Meralani Hills, Tanzania*

Zoisite

Before 1967 the only varieties of zoisite which had any pretensions as a gem material were the pink ornamental mineral known as thulite, and the green chrome-rich material with included black amphibole, which acts as the matrix for the large hexagonal crystals of ruby found in Tanzania. However, in 1967 beautiful transparent blue-violet crystals of zoisite were found in the Meralanie Hills, in the Lelatema district of Tanzania, which lies some 100 km south-east of the town of Arusha, and from these crystals amazingly attractive stones have been cut (*Figure 17.6*).

The cut stones, which are now being marketed under the name Tanzanite, are recovered from many deposits in the district. The crystals are found in various colours: blue, green, yellow, pink, brown and a peculiar colour which has been described as 'khaki'. All these shades of colour are said to turn to the favoured blue on careful heat treatment, and this is usually carried out. The heating is said to be carried out at 380 °C; higher temperatures are hazardous as the stones tend to disintegrate. Care too must be taken with zoisite, for the stones have been known to fracture badly when jewellery set with them is cleaned in an ultrasonic cleaner.

Zoisite, which belongs to the epidote group of minerals, forms orthorhombic crystals with the formula $Ca_2(Al.OH)Al_2(SiO_4)_3$. The hardness is just over 6 on Mohs's scale; the SG is 3.35 and the refractive indices are α 1.692, β 1.693 and γ 1.700 with a positive birefringence of 0.0088. There is one perfect cleavage. The stone exhibits pronounced pleochroism; the colours respective to the three vibration directions are sapphire-blue, purple and sage-green. The absorption spectrum shows a broad absorption in the yellow-green near 595 nm with two fainter bands, one in the green at 528 nm and another in the blue at 455 nm. There are several weak lines in the deep red. There is no noticeable luminescence under ultra-violet light. It has been suggested that the blue colour is due to vanadium.

A clear blue zoisite examined was found to have an SG of 3.38 and refractive indices of 1.702 and 1.696 with a birefringence of 0.007. The trichroism was purple-blue and slaty-grey and the stone had the normal absorption spectrum as given above. Zoisite crystals have been found which contain parallel fibres or canals and when these are cut in the cabochon style zoisite cat's-eyes are produced.

Thulite, the massive pink variety, is named after Thule, the ancient name for Norway. The mineral is used as an ornamental stone as it has a pleasing pink colour which is often variegated with areas of white. The hardness is 6 and the SG does not vary greatly from 3.10. The refractive index, at least so far as the vague shadow edge can be seen on the refractometer scale, is about 1.70. There is no typical absorption spectrum, and, except in the type from North Carolina which is said to glow orange-yellow under long-wave ultra-violet light, thulite does not fluoresce although a weak rose-coloured glow may be seen with X-rays. The mineral is found in the parish of Souland in Telemark, in Trondhjem and near Arendal in Norway. Other localities are in the Zillerthal in the Austrian Tyrol and in Mitchell County, North Carolina, and Western Australia.

The green zoisite with rubies from near Longido in Tanzania, mentioned above, has been fashioned complete with the rubies as an ornamental stone for small objects, such as ashtrays, and has been named anyolite from *anyoli*, the Masai name for green. Clinozoisite is a variety which has the chemical composition of zoisite but the crystal form of epidote and has been mentioned under that mineral. A massive greenish-grey variety of zoisite found in Wyoming is used for producing tumbled gems. This variety shows an absorption band at 455 nm which is common to epidote.

18

Synthetic Gemstones

Present thinking and commercial rules restrict the adjective 'synthetic' to materials which, while being manufactured by man, have a natural counterpart, however unornamental this might be. The adjectives 'imitation'and 'simulant' can refer to any substance, natural or man-made, which can be mistaken for another which can itself be natural or artificial. As many man-made gemstones are expensive and many are rare, they have themselves become sought by collectors and there have been instances of a natural stone being offered as a synthetic!

As a natural counterpart must exist, a synthetic stone will have the same chemical and physical properties and in fact there is only a small variation in these over the whole of the gem species. Generally speaking synthetic materials are cheaper, larger, clearer and more spectacular than most natural stones.

Gem-quality crystals may be grown by methods which echo the work of natural processes or which have no natural counterpart. Many of the more expensive gem species are grown from the melt, but some of the cheaper ones are too; others are grown from a solution, fewer by chemical precipitation, and some by growth from the vapour.

Diamond

Both diamond and graphite are polymorphs of carbon, but of the two it is graphite which gives the stable form at ordinary pressures. Diamond becomes stable at high pressures but, as it will not convert to graphite below about 1500 °C, it is safe enough for wear! Diamond can be described as metastable.

The very high mechanical strength and hardness of diamond are due to its bonding. All bonds are covalent and equivalent, with the only direction of weakness in the octahedral plane, which gives rise to diamond's easy cleavage in this direction. For successful diamond synthesis such a structure has to be reproduced, and very high pressures are needed. Even when this problem is solved the grower still has to be able to achieve high temperatures to enable rapid movement of carbon atoms from other carbon polymorphs to diamond. All three problems having been solved, the grower wanting large stones is then faced with further tests of ingenuity. The materials from which suitable diamond synthesis can be achieved need to be very strong, and capable of withstanding extremely high pressures at which most materials will break down, so the resources of high-pressure technology are stretched.

Over the centuries from Tennant's discovery in 1797 that diamond is pure carbon, many attempts, some involving colourful personalities and eccentric techniques, have been made to grow diamond. Quite early on it was realised that pressure would be needed to convert a substance with a specific gravity of 2.25 (graphite) to one with an SG of 3.52 (diamond). One notable experimenter was James Ballantyne Hannay (1855–1931), a Scottish chemist working in Glasgow. By sealing a mixture of lithium metal, bone oil and paraffin into a heavy wrought iron tube and heating the tube to red heat for some hours, he found at the end of three runs (in all the rest the tubes exploded) that diamonds of diameter about 0.25 mm were present. Several investigations have been undertaken into the Hannay product; the strongest probability is that the undoubted diamonds found in the tubes were natural rather than synthetic. Attempts to reproduce Hannay's results by his methods have been unsuccessful.

The experiments by Ferdinand Frédéric Henri Moissan (1852–1907) involved heating iron with sugar charcoal in a carbon crucible in a furnace; temperatures up to 4000 °C were achieved. Carbon dissolves in the iron, and Moissan solidified the molten iron by plunging it into cold water, thus solidifying it from the outside inwards. Excess carbon was subjected by the process to very high pressure. The iron was dissolved by acids and the residue sank in di-iodomethane (SG 3.32). Moissan's claim to have made diamond was both refuted and confirmed by other workers of the time, but today it is thought that his diamonds were natural specimens placed in the apparatus by a co-worker; he could not have achieved high enough pressures at the right temperatures to make diamond.

Of the many other attempts to fabricate diamond the only work of importance is that of the steam turbine inventor Charles Parsons. He tried both Hannay's and Moissan's experiments, adding some ingenious and colourful ideas of his own. One of these involved firing bullets into materials containing carbon and heating carbon rods embedded in a mixture of quartz and calcium oxide under pressure. In fact Parsons realised in the end that his product was colourless synthetic spinel; in 1928 he issued a disclaimer via another worker.

At the close of 1954 there was no real proof that diamond had been synthesised. As early as 1941 Nickle referred to experimental research on diamond synthesis at the Schenectady Laboratories of General Electric. Little more was heard of these experiments until 1955 when the company published information on the synthesis of minute diamonds at Schenectady. One-carat synthetic diamonds are reported to have been made, but of industrial quality only.

Graphite to Diamond

In 1947, Bridgman contributed valuable information on considerations of the thermodynamic equilibrium between graphite and diamond, and carried out considerable work on high pressures and temperatures. Bridgman obtained high pressures in his experiments but found difficulty in obtaining high enough temperatures simultaneously with the pressure, and for a sufficient length of time. The success of the General Electric team (Bundy, Hall, Strong and Wentorf) is due mainly to their overcoming this difficulty of obtaining high pressure and temperature simultaneously. By using a 1000 ton press and special heat and pressure resisting chambers, pressures up to 100 000 atmospheres (1 atmosphere = 101 325 Pascals (Pa) or N/m^2) and temperatures up to 2760 °C were produced. An undisclosed carbonaceous compound was used to supply the carbon. Although the results of their experiments were only the production of minute crystals, these are now made in such quantity that the product is available commercially as diamond powder and as industrial abrasive grits.

The heart of Bridgman's work lies in the use of an 'anvil', in fact two anvil-shaped pieces of cobalt-bonded tungsten carbide; pressure is exerted on the sample which is contained in a catlinite container. This material squeezes out under pressure into a thin gasket adhering to the anvil; it does not thin out any further. The anvil is placed in a hydraulic press and allows pressures up to 6 million psi to be achieved. In present-day apparatus a special Bridgman hydraulic seal, the catlinite gasket, and a special technique (massive support) by which the strength of the anvils is increased greatly, are retained albeit with modifications. Although Bridgman was able to achieve high pressures, the complementary high temperatures required could not be attained; he succeeded only in reaching 3 GPa (3×10^9 Pa) at temperatures in the range 1000–2000 °C.

A group of workers at General Electric began work in 1951 on the high-pressure synthesis of diamond. Hall and Wentorf (physical chemists) and Bundy and Strong (physicists) were joined by the engineers Cheney and Bovenkerk. Nearly 6 GPa were obtained with high temperatures. An innovation by Hall in 1953 gave the project the clue to its final success. This was the belt, which allowed 18 GPa to be attained at a simultaneous temperature of 5000 °C (*Figure 18.1*). Massive support and a non-extruding gasket were used as with the Bridgman apparatus, though catlinite was substituted by pyrophyllite as the container material. As pyrophyllite is an insulator it allows an electric current passing from the upper to the lower anvil to pass only through the graphite sample which is contained in the pyrophyllite tube.

Strongly tapered pistons give a large motion while keeping the gasket relatively thick, and the compressed pyrophyllite in turn enhances the pistons' strength. The largest diamond crystal achieved by these runs, which succeeded in producing diamond in 1954, was about 150 microns across and was octahedral. In reviewing the results it turned out that iron sulphide, the mineral troilite, had been added to the graphite; this echoed the diamond–troilite association found in the Cañon Diablo meteorite. Later, sulphur was found to be superfluous but iron necessary for success. Much later the presence of a catalyst was abandoned with no detriment to diamond growth. In 1955, the results from these experiments enabled Berman and Simon to plot a diamond–graphite equilibrium curve (*Figure 18.2*), indicating the range of temperatures and pressures necessary to convert graphite to diamond.

These accounts so far have produced no gem-quality diamond crystals. The first announcement of this major achievement, again by General Electric, was

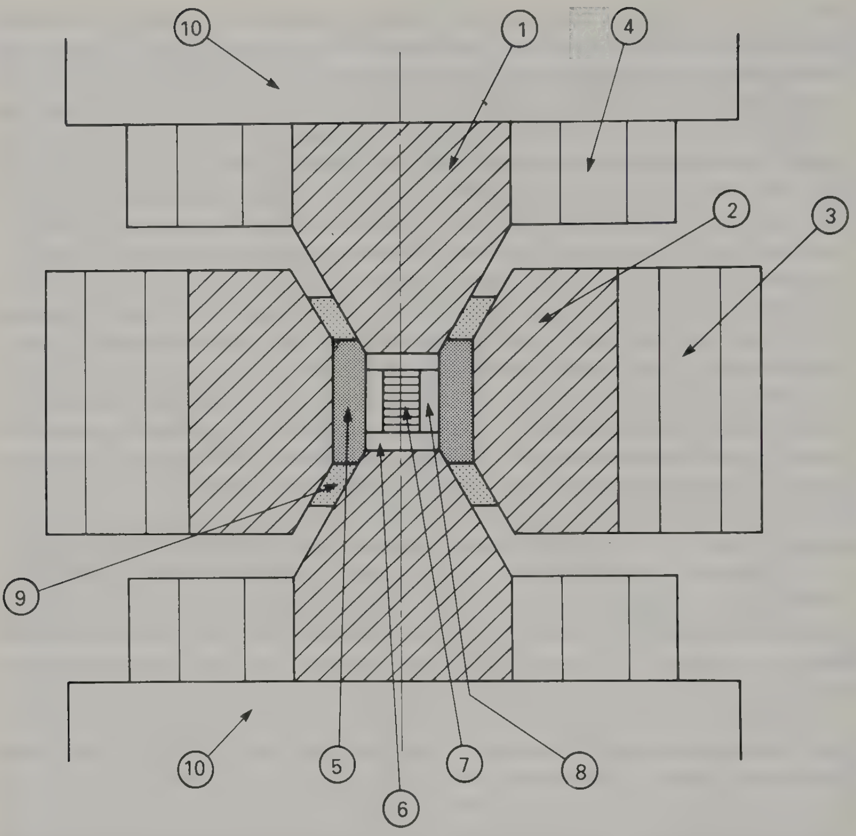


Figure 18.1 Schematic section through a typical belt type apparatus 1, tungsten carbide anvil; 2, tungsten carbide die; 3, steel support rings for the die; 4, steel support rings for the anvil; 5, ceramic tube; 6, electrical contacts; 7, reaction volume; 8, heater sleeve; 9, gaskets; 10, press plattens (Wedlake, 1979)

not made until 1970, with the first descriptive paper published in 1971. Before that time further developments in diamond growth were assisted by processes and apparatus largely the work of Hall. From the belt he developed the tetrahedral press to give the same range of temperatures and pressures as the belt: instead of the belt and two anvils the tetrahedral press has four anvils so shaped that when they impinge upon a pyrophyllite tetrahedron about 25 per cent larger than the final area, some of the pyrophyllite is squeezed out, thus forming a non-extruding gasket. This in turn lets the pressure rise as the pistons continue their inward motion. A graphite tube containing the sample is placed across the pyrophyllite tetrahedron and so positioned to allow passage of an electric current to heat the tube and sample. Further developments of the press and of the belt have taken place over the years. The successful growth of diamond grits by high-pressure methods has continued since the 1950s using hydraulic presses with the belt apparatus; virtually any form of carbon, including peanuts, has been pressed into service!

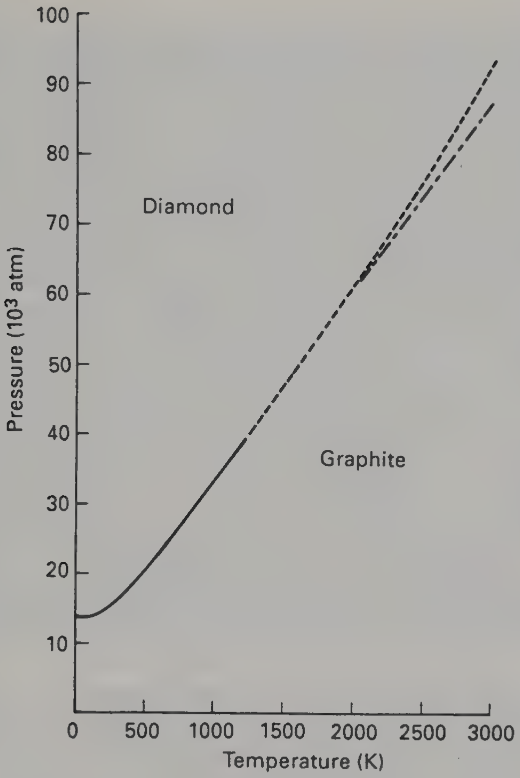


Figure 18.2 Diamond-graphite equilibrium curve (———) calculated from reliable data by Berman and Simon (1955); (----) calculated using later data (Berman 1965); (—-—-) linear extrapolation proposed by Berman and Simon

Crystals of diamond large enough to provide material for faceting need very slow growth under the most rigorously controlled conditions while using the belt or tetrahedral press apparatus. So far the cost would seem to outweigh the benefits of large-scale production, but crystals grown for laser windows or for high-power semiconductor heat sinks can and no doubt have been cut and polished. The best material for conducting heat is type IIa diamond, so these have a market from which there may be some 'stray' faceted stones.

The pyrophyllite tube described above contains seed crystals which may be thin pieces of natural diamond or synthetic diamond. Feed material may be grit or graphite. The ends of the tube are nickel plates; as heating gets under way, part of the nickel melts and dissolves the graphite which crystallises as diamond. The centre of the tube is hottest, so the diamond is more soluble in the molten metal there than at the seeds placed at the ends. Transport from the centre to the ends gives a growth time of approximately one week to give a 5 mm gem-quality 1 carat diamond. The growth method and the arrangement of the pyrophyllite tube are similar to those used for the production of grit in the belt apparatus, but for the use of seeds.

Many years after the event, workers at the Swedish Allemanna Svenska Elektriska Aktiebolaget (ASEA) announced that they had produced synthetic diamonds in 1953. The report, describing apparatus built by von Platen, cited work carried out by Liander and Lundblad. The product was not of gem size or quality.

Diamond crystals grown by both GE and De Beers show cube and octahedron as predominant forms, with the dodecahedron sometimes seen (*Figure 18.3*). Up to 40 faces have been reported on a crystal 5 mm in size. The first production gave colourless, canary-yellow and pale blue colours, and apparently no difference was detected by polishers between these and natural diamond crystals. By excluding nitrogen a good white resulted, and blue arose from the incorporation of boron. Dust-like inclusions with some rounded or plate-like nickel inclusions can be seen under high magnification. Some blue stones show a whitish cross. All except the yellow stones are semiconductors, a property shown only by natural blue stones. No absorption spectra have been reported and all are inert to LW UV. Under SW UV a variable response has been noted.

Of eight stones tested by GIA in 1984, three cut stones and five crystals responded to SW UV in ways with some testing application. The cut stones consisted of one near-colourless, one bright yellow and one greyish-blue. The largest crystal was near-colourless, two were bright yellow and one was greyish-blue. The near-colourless cut stone gave a very strong yellow fluorescence with very strong persistent phosphorescence of the same colour. The yellow cut stone and crystals were inert. The greyish-blue cut stone and crystal showed very strong slightly greenish-yellow fluorescence with very strong persistent phosphorescence of the same colour. The near-colourless crystal gave a strong whitish-yellow with long phosphorescence of the same colour.

Only blue natural diamonds will phosphoresce after exposure to both types of UV. X-ray fluorescence results were identical with those obtained under SW UV. Blue and near-colourless crystals were electrical conductors, as were the similarly coloured cut stones; yellow cut stones and crystals were not. GE stones could all be lifted by a pocket magnet, especially those with metallic inclusions (*Figure 18.4*). GE stones could be distinguished from natural diamonds using a superconducting magnetometer.

Some useful tips for identification suggested by GIA are as follows:

1. near-colourless stones conducting electricity
2. near-colourless stones fluorescing and phosphorescing strongly under SW UV but inert to LW UV*
3. fancy yellow stones with no absorption spectrum and inert to LW UV
4. near-colourless stones with no hint of blue, grey or brown and with no absorption at 415.5 nm
5. stones with strong yellow fluorescence under X-rays and with strong persistent phosphorescence
6. any yellow fluorescence under X-rays.

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*In 1994 Russian-made gem-quality yellow diamonds were reported to fluoresce under LW UV.

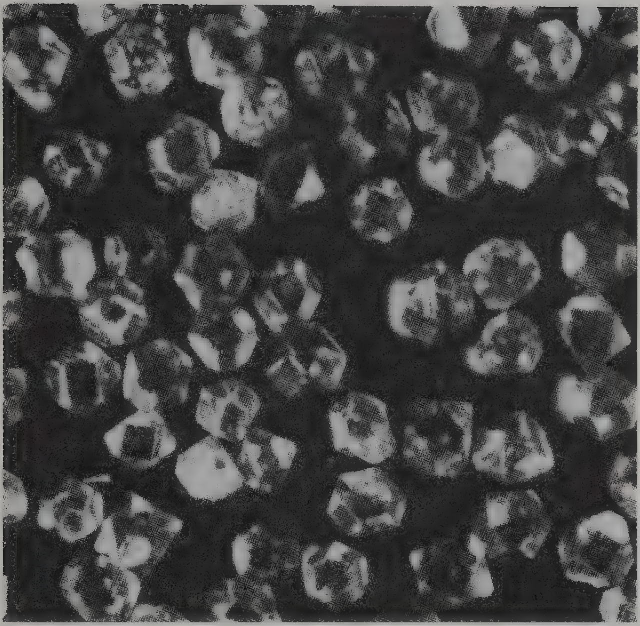


Figure 18.3 Top: Very small blocky crystals of synthetic industrial diamond. The habit of the crystals can be modified by adjustment of process temperature and pressure. Bottom: A production unit containing a group of high-pressure presses used in the De Beers synthetic industrial diamond process. (De Beers)

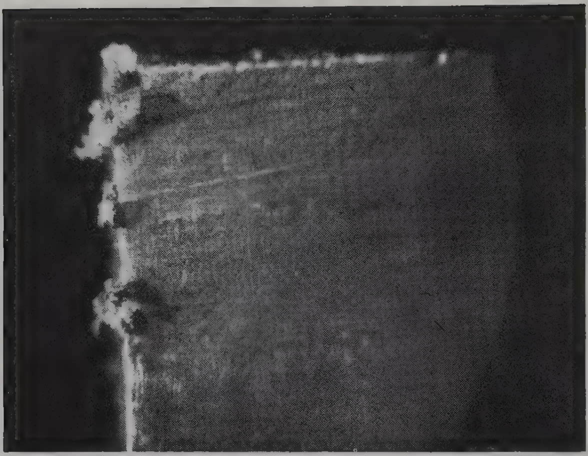


Figure 18.4 American synthetic diamonds adhering to the pole of a small horseshoe magnet. The edge of the magnet pole shown is only 6 mm in length, and this shows the very small size of the synthetic diamonds

The Japanese firm of Sumitomo manufactures yellow diamonds for non-gem purposes, but some crystals have been cut and polished (*Figure 18.5*). The crystals, up to 0.40 carat, grow as distorted octahedra, with modifying cube and dodecahedral faces. They are inert to LW UV but under SW they give a moderate to intense green or greenish-yellow response. There is no phosphorescence, but there is a weak to moderate X-ray fluorescence coloured bluish-white. No absorption bands can be seen. Stones are type Ib, as are GE yellows. They do not conduct electricity and are similar to natural stones in their heat conductivity. Vein-like colourless areas are characteristic, as are opaque black flux inclusions. Graining can be seen on the surface by reflected light, this effect sometimes surviving polishing. The interference pattern is distinctive, resembling a bow tie, with the four arms of the cross-shaped pattern either coinciding with or at 45 ° to the direction of the radiating internal grain lines. Stones faceted from Sumitomo crystals did not show the pattern.

Two Sumitomo gem-quality diamonds examined in 1990 showed how the manufacture of these crystals has developed over the decade. One crystal appeared to have been produced from an originally cube-shaped crystal. It was brownish-yellow with visible areas of brown graining; it had a central brownish-yellow area free from graining, with narrow, very light yellow to colourless to blue zones beneath the corners. Metallic inclusions were present. The second crystal examined was probably cut from an originally octahedron-shaped crystal. In reflected light dendritic patterns were observed on some faces.

Both samples are inert to LW UV, but show a weak orange-yellow response under SW UV. Natural type Ia stones either are inert or fluoresce yellow, blue or green to both kinds of UV, and some variation of luminescence exists among natural yellow type Ib diamonds. Examination of a number of natural type Ib

Figure 18.5 Top: Crystals of gem-quality synthetic diamonds produced by Sumitomo with, in front, examples of heat sinks cut from them. Bottom: Crystals of gem-quality synthetic diamonds produced by De Beers

and mixed type Ib and IaA stones showed that there is some overlap between the luminescence of the synthetic product and some natural type Ib stones. However, all synthetic diamonds so far tested were inert to LW and fluoresced under SW UV. In one of the samples the colourless centre is inert to SW UV while the yellow outer areas fluoresce weak yellow in planes paralleling octahedral faces. A stronger yellow fluorescence under the corners appears to be banded parallel to dodecahedral faces. Fluorescent areas phosphoresce a weak yellowish-white lasting about 10–15 sec. This uneven distribution of fluorescent areas shows the presence of both cubic and octahedral internal growth sectors. Growth zoning appeared to be typical of this product in 1990.

Gem-quality synthetic diamonds weighing up to 11 carats have been grown by the De Beers Diamond Research Laboratory since the 1970s (*Figure 18.5*). Stones, not so far placed on the market, are brownish-yellow, yellow and greenish-yellow with metallic inclusions, uneven colour distribution and geometrical patterns of graining. Stones are inert to LW UV but brownish-yellow specimens give a moderate to strong yellow or greenish-yellow, and greenish-yellow stones fluoresce weak yellow. Only the latter show phosphorescence. Both this effect and the fluorescence are pronounced in the outer portions of the greenish-yellow crystals. A zoned pattern seen when stones are exposed to an electron beam indicates growth sectors, and this feature of cathodoluminescence is useful rather than diagnostic when testing De Beers diamonds. It is possible that the more apparent properties of all synthetic gem diamonds so far examined (colour zoning in particular) correlate with an observed higher nitrogen content.

Cathodoluminescence (CL) tests show up a number of features in the synthetic diamond made by De Beers. Internal features show up well, and those stones which luminesce display distinct growth sectors. Greenish-yellow CL of high intensity is emitted from cubic and octahedral growth sectors, the spectra giving peak wavelengths between 534 and 526 nm. The predominating CL colour of natural yellow diamonds was blue, but their spectrum differs from that shown by blue-luminescing synthetic diamonds. Some of the De Beers stones (3 out of 10 tested) contained inclusions which showed orange-red under electron bombardment. The inclusions showed a distinct band in the near IR at 820 nm.

Corundum

The first synthetic ruby was announced in 1902 but in the preceding years, at least since the 1850s, work had continued on the synthesis of corundum. The name of Verneuil is lastingly associated with ruby synthesis but others also worked towards the final successful production.

General Description of Early Synthesis Work

The factor which gives gem-quality and gem-sized corundum is the correct choice of feed powder: the alpha form of Al_2O_3, with Cr_2O_3 added to give the ruby colour and other dopants added to give sapphires of various colours. Around 2.5 per cent of chromic oxide is needed to give a satisfactory ruby colour. One problem is that any other substance which may get into the growing crystal may discolour it; this is particularly true of iron, which gives a brownish tinge. Another problem is the mechanical stability of the grown crystal or 'boule'; this may crack if some impurities are present. Verneuil used ammonium alum to begin the preparation of his feed powder: $(NH_4)Al(SO_4)_2.12H_2O$ is dissolved in distilled hot water with subsequent filtering to remove solid matter. On cooling, crystals of alum form from the solution and any impurities are left in it. After this process has been repeated several times the purity is high enough to allow the powder to be used in the crystal growth process. Chromium alum $(NH_4)Cr(SO_4)_2.12H_2O$ is purified in the same way to give the dopant for ruby. The two alums are mixed and fired at a temperature of about 1000–1200 °C to give the final feed powder. Other components are vaporised at the high temperature. The powder needs to flow freely and is sieved before use. The method of preparing the feed powder is the same today.

The feed powder is melted to give a characteristic boule which is a single crystal. The smooth flow of feed powder is ensured by tapping the powder container with a hammer, and the heating is achieved by a very hot flame, produced from an oxygen stream and a stream of coal gas which was available in Verneuil's time. The powder drops down through the flame. The flame touches a ceramic pedestal upon which the powder builds up a sintered cone whose tip melts and enlarges. The pedestal is lowered to give a start to the formation of the boule; the gas flow is maintained while the oxygen flow is monitored to control growth. On shutting down the flame the boules tend to crack through thermal shock; the longitudinal splitting can be done by nipping with pliers to provide boule sections for the lapidary. The boule of the early period would have yielded several cut stones up to 2 carats; most were cut in sizes of 0.5 to 1.5 carats.

Identification of early Verneuil rubies was by curved growth striations and by gas bubbles. Verneuil himself stated that the flame needed to be rich in hydrogen and carbon as this stopped the formation of bubbles in the melt; transparency is achieved by allowing slow growth in layers from the bottom of the boule. To prevent the formation of many crystals, and to stop cracking of the contact area of the sintered cone, the boule has to be kept small.

Though the name of Verneuil is inseparable from the story of corundum growth, other workers were active in the nineteenth century, some of them with similar ideas to Verneuil. In 1817 Gay-Lussac reported that pure aluminium oxide could be obtained by heating ammonium alum. This allowed progress towards the final successful corundum growth, although a hare was started by the transient belief that silicon oxide was present in corundum. This rumour was soon laid, however, and Gaudin published his first report on ruby synthesis in 1837. By 1870, the date of his last report on the topic, gem-quality ruby had still not been grown. By using a downward-pointing flame, Gaudin obtained hexagonal platelets of corundum which were modified into ruby with the addition of a chromium salt. His product contained profuse bubbles which lowered the specific gravity. Other workers found that the high melting point (2050 °C) made growth difficult. One idea was to dissolve Al_2O_3 with Cr_2O_3 in a high-melting solvent to give a saturated solution. This was heated, allowing the solvent to evaporate and permitting the ruby to crystallise from the solution. By using borax as a solvent, hexagonal platelets of ruby were obtained. This solvent was later termed a flux and became the basis of the important flux-melt method used today for high-quality ruby and emerald.

The work of Edmond Frémy is important because he was the first to produce clear red, though small, rubies. Verneuil became Frémy's laboratory assistant and worked with him for about 16 years on ruby synthesis. Frémy's previous personal assistant, Feil, died in 1876 but he had been junior author of a paper with Frémy on ruby growth. This was published in 1877. By using large fireclay crucibles with 20 kg batches held at red heat for 20 days, thin ruby crystals were obtained. Lead oxide Pb_3O_4 reacted to form lead aluminate, which then reacted slowly with silica to form lead silicate with aluminium oxide crystallising as sapphire plates. Potassium dichromate up to 3 per cent gave the ruby colour.

Frémy and Verneuil worked together for 16 years after Feil's death. Frémy's book *Synthèse du rubis*, published in 1891, is the best account of their work; it is now a very rare and valuable item, containing quaint-coloured plates. Their final effort produced very clear rhombohedral crystals ranging from colourless to red, violet or blue with some giving red at one end and blue at the other. They were about 3 mm in diameter and up to one-third of a carat in weight. The process turned on the recrystallisation of alumina with some potassium dichromate by using potassium hydroxide and barium fluoride. Temperatures of 1500 °C were achieved in a ceramic crucible. Nassau (in *Gems Made by Man*, 1980) considers that alumina reacts with the barium fluoride to give gaseous aluminium fluoride which then reacts with moist air to re-form alumina at a constant temperature. Vapour-phase nucleation and growth then take place in small cavities scattered in the porous mass which fills the crucible. This is possible because the reactions take place in a multi-phase medium. Thus the process gives multiple nucleation with only a small amount of growth on each nucleus. It is not strictly flux growth as the phrase is understood today. Many of the crystals were used as watch bearings, though some unfaceted crystals were used in jewellery. The retirement of Frémy in 1902 signalled the end of this particular line of work until the 1950s.

The 'Geneva rubies' produced in 1885 were first thought to be made from fragments of natural rubies fused together. With properties the same as natural rubies but with profuse round gas bubbles, the stones were ruled artificial by the French Syndicate of Diamonds and Precious Stones. Many stories circulated about the stones, as in the following example from a trade paper of 1890:

> A Berlin jeweller has just been the victim of a curious hoax. He recently received a circular from a Zurich firm offering rubies at remarkably cheap rates, and therefore entered into negotiation for the purchase of some. He bought rubies for which he paid 4500 marks (£225), receiving a guarantee from the firm that the stones were genuine. Shortly after, the jeweller heard that false rubies were being manufactured so cleverly as to deceive the connoisseur, and, becoming alarmed, sent those he had purchased to Paris to be examined by the Syndicate of Dealers in Precious Stones, who are considered unimpeachable authorities. They reported that the stones were not imitation, but were real rubies, which were small and consequently of little value, fastened together so cleverly as to render detection difficult. The jeweller then wrote to Zurich requesting the firm to take back the stones. This they refused to do on the ground that their guarantee only ensured the genuineness of the gems and contained no mention of their size.

Examination by Nassau showed that the Geneva ruby is made in three distinct growth stages. This was deduced partly by the high Cr and Fe content of the 'skin' of the boule forming when the gas supply ceases and the melt solidifies. With this observation as a background it was deduced that a tiny boule was first grown on a sintered cone, broken off and grown further in a different direction. The bulk of the final boule was then grown by the use of two torches on a rotating support. The stones sold until the Verneuil process out-performed the Geneva process. The term 'reconstructed' or 'reco' was used loosely in the trade for synthetic rubies for many years. A final blow to the 'reconstruction' legend was Nassau's discovery of the notably low Fe content of the Geneva material and the highly purified aluminium oxide used. This would not be the case if natural ruby was the starting material. An attempt to fuse ground natural rubies in a Verneuil torch produced an orange-brown opaque material with a high iron content.

Rubies were grown in 1903–4 in Hoquiam, Washington, USA, the technical expertise being provided by one of Verneuil's assistants from Paris. They appear to have been grown by the early type of Verneuil apparatus and contain profuse gas bubbles; boules are unevenly coloured and small. Highly purified feed powder was used; the source of the gases needed is uncertain, but Nassau suggests that they may have come from the electrolysis of water into hydrogen and oxygen. Geography and cost led to the ultimate failure of the venture.

The Verneuil Furnace

In 1891 Verneuil deposited with the Paris Academy of Sciences a sealed account of a new and revolutionary process of ruby synthesis – a process which he freely published to the world in November 1902. In this paper he told of the construction of an inverted oxyhydrogen blowpipe – his famous *chalumeau* – which in its essentials is still used today for the production of many types of synthetic stones.

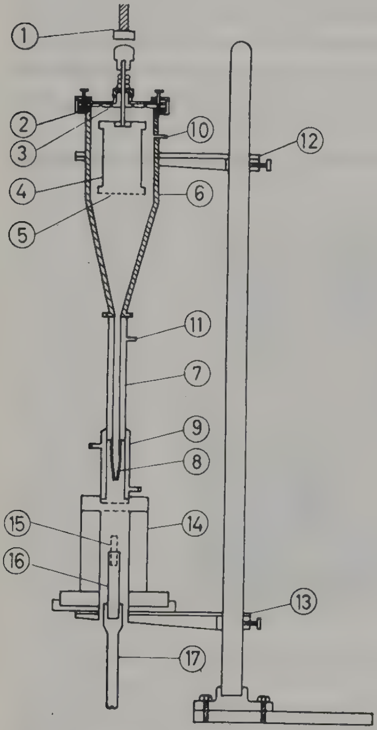


Figure 18.6 The Verneuil furnace: (1) hammer, (2) rubber gasket, (3) corrugated metal diaphragm, (4) powder hopper, (5) sieve, (6) main body of the furnace forming the expanded top of the inner tube, (7) outer annular tube carrying the hydrogen, (8) removable nozzle to inner tube, (9) water jacket, (10) oxygen inlet, (11) hydrogen inlet, (12) and (13) brackets for securing furnace to upright, (14) divided fireclay chamber, (15) window in fireclay chamber, (16) candle upon which the boule grows, (17) candle support connected to centring and raising and lowering adjustments (not shown)

The Verneuil inverted furnace (*Figure 18.6*) consists of two iron tubes (6) and (7). Tube (6) is widened into a circular chamber at the top, the lower and thinner end passing down the centre of the tube (7) into which it is tightly screwed so as to form a gas-tight joint. Both tubes are constricted to nozzles at the lower ends, that of (6) being situated close to but inside and above that of (7). Pure oxygen under pressure is admitted to the tube (6) through the pipe (10). Within the upper chamber of (6) is placed a small hopper (4) with a fine wire-mesh bottom (5) which is rigidly fixed to a metal rod which passes upwards through a block of resilient rubber (or a metal diaphragm) (3). At the top of this rod is an anvil head which is periodically struck by the hammer (1). This hammer, which is operated by an electromagnet or by a cam rotating on a shaft (not shown in the diagram), may be regulated so as to give a regular series of gentle taps. Hydrogen under pressure is admitted to the tube (7) by means of the pipe (11) This hydrogen meets and mixes with the oxygen at the orifice, where it is ignited.

Owing to the intense heat generated, some 2000 °C, it is necessary to protect the pipes against fusion, and this is done by placing round them, just above the nozzles, a water jacket (9) with cold water continually running through it (with modern metals and construction this water jacket is sometimes omitted). Below the orifice is placed a fireclay support (16) (usually known as the 'candle') which is carried on an iron rod (16) connected to a screw adjustment, whereby the candle may be centred below the orifice of the furnace; it may also be raised or lowered into or out of the flame as the boule grows. 'Boule' is the name given to the pear-shaped single crystal which forms on the candle (*Figure 18.7*): the name is derived from the French world for ball, for the small specimens first made by Verneuil were ball-shaped. To protect the growing boule from cold draughts and to maintain a regular temperature around it, a divided fireclay chamber (14) is provided. This has a 'window' in front of which is supported a coloured glass screen so that the growth of the boule can be watched without damage to the eyes.

Figure 18.7 Early experimental and Verneuil boules

Manufacture of Stones by the Verneuil Process

In the manufacture of synthetic stones by the Verneuil process, or as it is sometimes called the flame-fusion process, the gases and chemicals used must be of exceptional purity and have certain physical attributes. Today most factories manufacture their own gases and the chemical powders. To make the corundum gems – ruby, and colourless, blue and fancy-coloured sapphires – it is necessary to first prepare a fine powder of alumina as the feed powder. This is done by calcining crystals of ammonium alum in silica trays in a muffle furnace at 1100 °C for 2 hours. If ruby is required, about 8 per cent chromic oxide is added to the ammonium alum before calcining. During decomposition, the noxious gases generated are carried off by high chimneys. The charge swells up spectacularly to a meringue-like cake: this is anhydrous (water-free) alumina. These cakes are then ground down to a fine powder by a tumbling process.

This snow-white powder (pale green if chromic oxide has been added) is placed in the hopper (4) at the top of the blowpipe. The bottom of this basket has a sieve with a 40–80 mesh through which the powder is shaken. The hydrogen gas is turned on and lit at the nozzle, and the oxygen is then admitted, which with the already ignited hydrogen forms the intensely hot oxyhydrogen flame. The hammer (1) is then started, at about 80 taps per minute, causing the release of a sprinkling of the alumina powder at each tap. This powder travels down the oxygen stream and fuses as it passes through the hottest part of the flame.

The molten powder is caught on the top of the ceramic candle (15), which is about 20–25 mm in diameter and is situated in the cooler part of the furnace. This fused alumina solidifies on the candle in the form of a small cone consisting of a number of small crystals of corundum. The tip of this cone is in the hotter part of the flame and remains molten. By manipulation of the speed of tapping down of the powder, and the amount of powder delivered at each tap, which can be controlled by altering the distance of the head of the peg from the hammer, and with control of the gas supply, a single central crystal grows upwards in stalagmitic fashion and opens out to mushroom shape, after which the speed of tapping is reduced in order to keep the boule diameter to about 20 mm. The rate of tapping, for ruby, is about 20 times per minute.

When the boule reaches a suitable size, about 65 mm in length for ruby, and weighs from 150 to 200 carats, the gas supply is cut off and the boule is allowed to cool on the furnace. When cool it is removed from the furnace and broken away from the candle and from the fritted cone of crystal aggregates. The stem of the boule is nipped with a pair of pliers or given a slight tap with a hammer, which causes it to split into two nearly equal pieces, the faces of which are essentially plane.

Manufacturers employ slight differences in technique, but the essentials are the same, and little difference is to be noticed between the original blowpipe apparatus used by Verneuil and that used today, and even the arrangement of the banks of furnaces differs little. Quite recently, for a special purpose, an ingenious slow-motion drive to lower the growing boule (usually operated periodically by a hand wheel) and reduce the rate of tapping, both of which are controlled by a photoelectric cell and an electronic circuit, has been constructed.

Frémy's crystals had shown a violet colour in some instances. Although a different valence state of Cr was suspected at first, a report of 1908 by Verneuil's former student Paris stated that blue sapphire crystals had been grown, coloured blue by cobalt and with magnesium oxide added to the feed powder.

Verneuil grew a number of experimental crystals with various compositions and found that Frémy's violet crystals contained iron and other elements with the chromium and that cobalt gave an uneven blue. Paris's crystals were spinel rather than corundum. When Verneuil grew corundum with added titanium and iron, blue sapphire was obtained. Intervalence charge transfer between $Fe^{2+}Ti^{4+}$ and $Fe^{3+}Ti^{3+}$ is the cause of the blue colour.

During World War II the United States government encouraged the Linde Air Products Company to grow Verneuil ruby and sapphire in anticipation of the loss of European supplies. After the war European production was once more available; the crystals were cheaper owing to lower labour costs, and the Linde operation was no longer viable. Star corundum was made by Linde from 1947 and later the demand for laser rods helped to keep production going. Work on Verneuil corundum ceased in the USA in 1974.

Colours of Transparent Synthetic Corundum

Table 18.1 gives a fairly complete list of the colours most commonly made in transparent synthetic corundum, complete with the manufacturers' trade names. In addition, some synthetic corundums have been made in America which are parti-coloured, such as blue sapphire one end and ruby the other.

Table 18.1
Colours of transparent synthetic corundum

Colour	*Manufacturers' trade name*
Colourless	White Sapphire
Red	Ruby
Dark red	Garnet Colour
Deep pink	Rosaline
Pink	Pink Sapphire
Lilac-pink	Rose de France
Orange	Padparadscha
Deep yellow	Danburite
Yellow	Topaz
Yellow-brown	Madeira Topaz
Brown	Palmeira Topaz
Green	Green Sapphire
Pale green	Amaryl
Blue	Burma Sapphire
Purple	Amethyst
Purple/green	Alexandrite

To get the red of ruby about 1–3 per cent Cr_2O_3 will be added to the feed powder; a variety of reds and pinks is made to suit commercial demand for colour and size. A slaty/purple variety is made by adding about 3 per cent vanadium; this is offered as 'Alexandrite' and causes more confusion than any other synthetic stone.

Star rubies and blue sapphires are made by adding 0.1–0.3 per cent TiO_2 to the feed powder. The boule is grown in the normal way and then reheated to about 1300 °C. This causes the previously disseminated rutile to take up needle-like forms in six (sometimes twelve) rays at right angles to the vertical axis of the boule. Stones are cut with the cabochon top coinciding with the top of the boule. Stars in synthetic corundum are notably perfect with bright, even rays reaching the edge of the stone, and the backs are flat and smooth. Early stars were imperfect with uneven rays and areas of transparency caused by the migration of titanium to the edge of the boule. The trouble was cured by varying the oxygen flow to the flame at even intervals. This allowed each deposited layer to solidify on the growing boule before the next was deposited, thus holding the rutile in place. Diffusion of a slurry into the stone which is heated for 24 hours at 1800 °C can also give a star which is about 0.1 mm inside it. The slurry is made from two parts of alumina to one of rutile.

Physical and Optical Properties

Inclusions

The physical and optical characteristics of synthetic corundums are those of natural stones. However, owing to their mode of formation being so different, inclusions differ enough to identify them.

Synthetic rubies and sapphires, owing to the shape of the top of the boule and to the discontinuous feed of the powder, show curved structure lines when examined in the correct direction under a microscope. In the case of ruby these lines have been aptly likened to the grooves seen on a gramophone record (*Figure 18.8*). With blue sapphire the bands are wider and more diffuse (*Figure 18.9*) and these are often better seen if the stone is placed in a highly refractive oil in a white cell and the stone viewed in different directions, as under the microscope the bands may be so wide and diffuse that they may not be seen at all clearly.

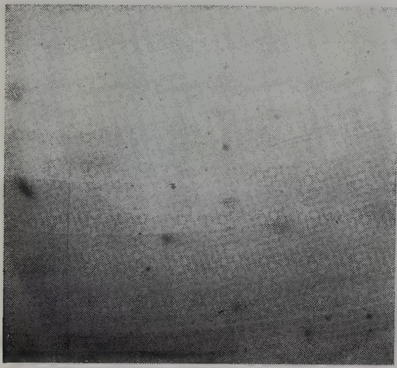


Figure 18.8 Curved lines and gas bubbles in a synthetic ruby

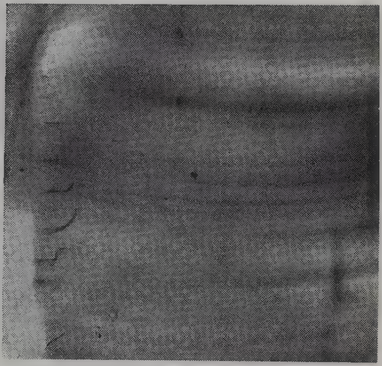


Figure 18.9 Curved bands and fire marks in a synthetic blue sapphire

Included gas bubbles, which may be round or take characteristic 'flask' or 'tadpole' shapes (*Figure 18.10*), are common and give positive evidence that the stone is synthetic. Clouds of very small bubbles, looking like black dots, are often seen and these sometimes tend to follow the direction of the curved bands of colour (*Figure 18.11*).

In natural rubies and sapphires the inclusions are largely mineral and characteristic liquid formations. Sometimes the inclusions in synthetic stones may be most deceptive, for undissolved alumina can produce natural-looking inclusions (*Figure 18.12*) and in some cases triangular cavities containing a gas bubble (*Figure 18.13*). Careful observation will generally reveal that these

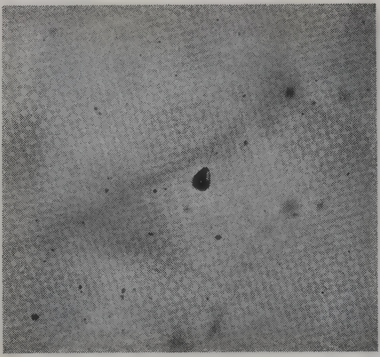


Figure 18.10 Tadpole-shaped gas bubble and curved lines in a synthetic ruby

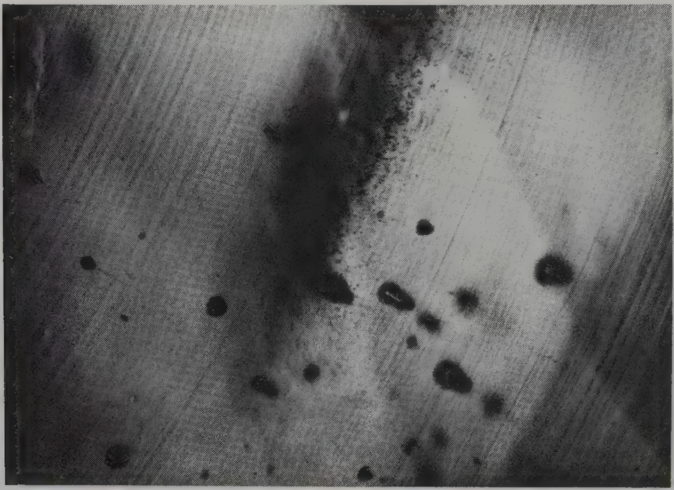


Figure 18.11 Flask-shaped bubbles and a bubble cloud in a synthetic sapphire

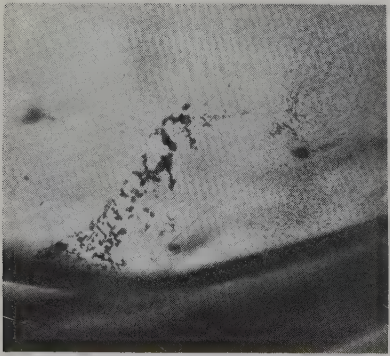


Figure 18.12 Bubble cloud and deceptive solid inclusions (probably undissolved alumina) in a synthetic ruby

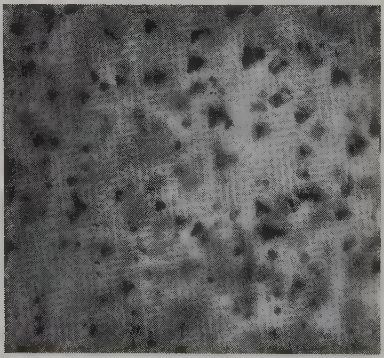


Figure 18.13 Two-phase inclusions in a German synthetic star ruby

deceptive inclusions are in conjunction with tell-tale normal gas bubbles and curved colour lines. Twinning lines in parallel planes usually indicate a natural stone, but these too have been seen, although rarely, in synthetic corundums. Plato has reported that under certain conditions some synthetic corundums show faint zonal lines with angles of 60° and 120°, but these lines are difficult to see and differ from the zonal lines observed in natural stones. To do this the stone should be immersed in di-iodomethane; find the optic axis and, using a magnification of 20 to 30 times, examine the stone in directions parallel to the optic axis. These lines, said to resemble repeated twinning lines, are thought to be specific for synthetic corundum as they are not normally seen in natural corundum.

Absorption Spectrum

The absorption bands seen in synthetic ruby are the same as may be observed in natural ruby. In natural blue sapphire the iron lines, three bands at 450, 460 and 471 nm, are usually visible in the absorption spectrum. Sometimes only a fine but sharp line may be seen in fine blue sapphires at 450 nm, while with the greenish-blue and green stones the three bands are strong. In synthetic blue sapphire the line at 450 nm does not normally show, and although a weak smudgy line may sometimes be seen about this position, it is nothing like the sharp line of the natural stone.

The synthetic sapphire made to imitate alexandrite provides a case where the absorption spectrum is so markedly different that identification of the synthetic stone is easily accomplished by the spectroscope alone. There is an absorption line in the blue at 475 nm and there are no fine lines in the red as seen in the spectrum of the true alexandrite. This 475 nm line, which is ascribed to the element vanadium, is only rarely seen in a natural corundum, and then the colour of the stone is different. The 475 nm line has, however, been observed in a synthetic corundum of green colour. Some synthetic green sapphires show an absorption line at 688 nm which may be due to nickel.

Colour Filter

The Chelsea filter gives little help in the identification of synthetic from natural rubies and sapphires, for the effects seen through the filter are similar. There is one exception to this; that is in the synthetic green sapphire which shows reddish through the filter whereas the natural green sapphire shows dark.

Ultra-violet Light

The luminescent effects shown by corundum in ultra-violet light are occasionally helpful as a means of identification. Synthetic rubies mixed in a parcel, or set with real rubies, can sometimes be spotted by their stronger glow. The short-wave lamp is probably the more helpful in this case. With synthetic blue sapphires the short-wave lamp very often induces a bluish-green glow and, with care and turning the stone, the curved bands may be seen as bands of different intensity of light in some cases where the bands have not been observed under lens or microscope examination. A low-power lens is useful when looking for the coloured fluorescent bands.

It has been found that synthetic corundum transmits ultra-violet light much more freely than does natural corundum, and proof of this effect may provide an ancillary method of identifying synthetic stones. The natural corundums usually absorb ultra-violet light below about 290 nm, while the synthetic stones of this species generally transmit quite freely down to 220 nm. With the aid of a spectrograph the absorption edge can be measured, but an easier and more practical method for identification purposes is to use a short-wave ultra-violet lamp which has its main emission at 253.7 nm, which is between the absorption edges of the natural and the synthetic corundums, in conjunction with photographic paper. The suspected stone is placed, with other known stones as controls, on the bare surface of a slow photographic printing paper, which is then developed. As the ultra-violet rays will be transmitted through the synthetic corundums and not through the natural, the paper will be darkened to some extent under where the synthetic stones have rested but not so under the natural stones. As the short-wave lamp emits some long-wave ultra-violet rays the exposure time is critical and must be gauged by the use of control stones. Particular care is needed with blue sapphires in which the method is not always certain. *Figure 18.14* shows the effects seen with different stones of the corundum species.

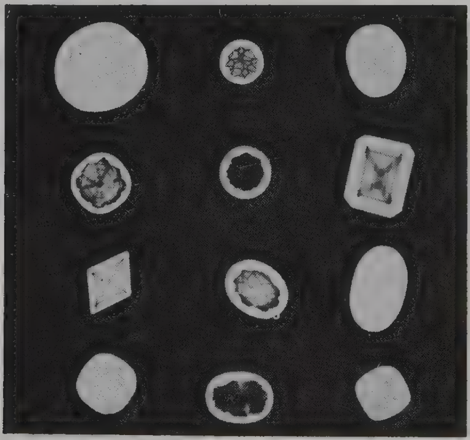


Figure 18.14 The differential transparency to short-wave ultra-violet light of various colours of corundum. The synthetic stones show a darkening of the film below them, illustrating that they have a greater transparency to ultra-violet rays than the natural stones

Identification and Detection of Difficult Corundums

The most difficult synthetic corundums to detect by the aid of the microscope, for they are usually very clean, are the pink, yellow, orange and brown stones.

When irradiated by X-rays such stones, except the brown, in common with rubies, exhibit a pronounced phosphorescence. Natural corundums do not show this afterglow, probably because they contain a trace of iron. Synthetic pink sapphires may be distinguished from natural pink sapphires in that the former glow violet under short-wave ultra-violet light and the latter crimson.

Another method which sometimes yields results in difficult cases is to immerse the stone in di-iodomethane (refractive index 1.74, which is near to that of sapphire, 1.76–1.77) in a glass cell and place this cell with liquid and stone on piece of fine-grain photographic film. From a nearly parallel light source held at some distance above (an enlarger with the lens stopped down makes an ideal source) a short exposure, about 15 s, is given. On development of the film, curved lines may be visible, curved lines which do not reveal themselves by ordinary microscopic examination. This method may not always work, and further, it may be necessary to take the picture with the stone in different positions, for one cannot tell the direction of the curved lines, but if results are obtained they are positive.

Some ruby has been grown hydrothermally (details of the process are given in the section on quartz later in this chapter) but although this growth method parallels natural growth it has not been found economic to continue it on a commercial scale. Vessels are lined with silver or platinum to avoid a green colour from introduced iron. Most experimental crystals are small and heavily included. NaOH is added as a mineraliser and sodium bichromate gives the colour.

Ruby and some sapphire have also been grown from the vapour phase but the slow growth makes the process uneconomic. A compound such as aluminium trichloride is reacted with an oxygen-containing gas in one such process.

Both these growth methods produce stones with a strong phosphorescence under X-rays: a liquid veiling of tiny particles may show in the hydrothermal product, to some extent resembling the wisps and lacy feathers of some flux-grown rubies. There are no mineral inclusions and separation from natural stones is not difficult. Some hydrothermal stones were grown on seeds of Verneuil corundum.

Ruby and sapphire have been pulled from the melt by the Czochralski process in which the desired substance is melted in an iridium crucible. Platinum cannot be used as it melts at 1774 °C (corundum melts at 2050 °C). A corundum seed is lowered to the melt surface and, if the temperature is right, growth on the seed will take place when the seed is vertically withdrawn (rotating at about 30 revolutions per minute). A rod-like crystal is formed. Heating of the crucible is by water-cooled RF. Pulling rates range from 6 to 25 mm per hour and quite large crystals can be grown. They are virtually inclusion-free though some may contain elongated bubbles.

Flux-Grown Synthetic Rubies

Flux-grown synthetic rubies (*Figure 18.15*) produced in a fundamentally similar manner to that employed by Frémy have been grown for scientific and commercial purposes since the 1960s (*Figure 18.16*). The procedure followed in the Bell Telephone Laboratories in employing this method has been described

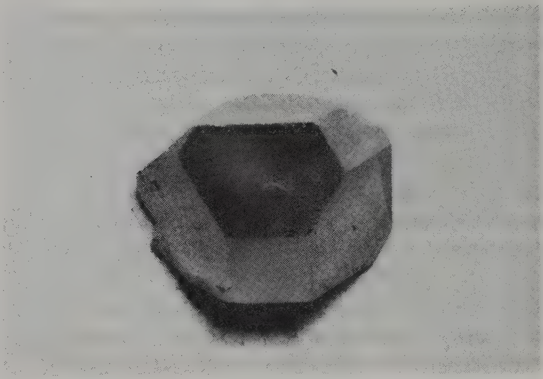


Figure 18.15 Synthetic flux-grown ruby crystal

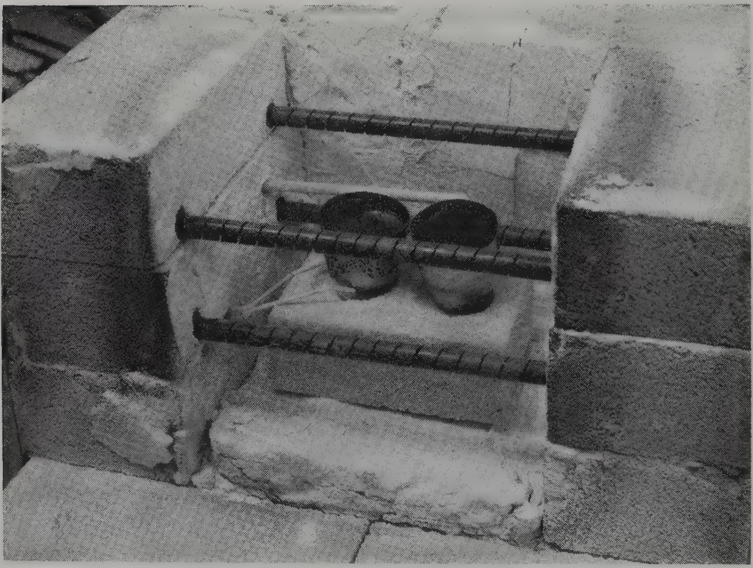


Figure 18.16 A flux-melt furnace used for the experimental production of synthetic stones (by courtesy of General Electric)

in detail by Nassau in his book *Gems Made by Man*. The flux most often used was lead fluoride, and some 20 kg of the compound were contained in a large platinum crucible, together with 3.6 kg of aluminium oxide and several grams of chromic oxide, according to the depth of colour desired in the resulting rubies. The crucible is covered with a lid and placed on a large ceramic pedestal which can be raised into the centre of a special furnace, and the contents are melted. The problem of thoroughly mixing the fused contents is solved by rotating the plinth on which the crucible rests, reversing the direction of rotation at intervals. After a long period of slow cooling during which perhaps 1.8 kg of ruby crystals may have been formed at the base of the vessel, another problem to be solved is to find a successful way of obtaining these free from the remaining flux. One drastic-sounding method is to punch a hole in the base of the crucible allowing the fluid contents to drain down a central hole in the supporting pedestal. The exceedingly expensive platinum crucible can later be repaired by welding, ready for use in a further experiment.

Similar methods have been used in growing ruby crystals by Carroll F Chatham in San Francisco and by F Truehart Brown of Ardon Associates Inc in Dallas, Texas. The latter products have been extensively marketed as Kashan rubies and owing to their high quality have achieved a considerable reputation. The price asked is far higher than that of Verneuil synthetics, but this is understandable in view of the costly nature of the process used. Uncut crystals have been occasionally available for amateur or professional lapidaries who wish to carry out their own faceting. The manufacturers of the Kashan stones at one time took the unusual step of issuing identification aids in the form of samples of their products with suggestions for recognising their origin, and with photomicrographs of their inclusions in colour. The most typical inclusions in Kashan stones consist of flattened 'footprints' or 'paint-splashes' in small groups which contain solid flux. There are also fine pinpoint inclusions in lines sometimes described as 'rain'. Twin lamellae are frequently seen but are also common in natural stones. The fluorescence under short-wave ultra-violet light tends to be brighter in Kashans than in Myanmar or Sri Lankan stones, and certainly more than in Siam rubies.

In a paper on the differentiation between natural and synthetic rubies of all kinds, Bosshart (*Z Dt Gemmol Ges.*, December 1981) measured the ultra-violet absorption characteristics of 94 rubies using a Pye Unicam SP 8-100 UV-VIS spectrophotometer. The specimens used included rubies chiefly from Myanmar, Sri Lanka, Kenya, Tanzania and Thailand, plus a few from Pakistan, Cambodia, Brazil and Australia, as opposed to 11 Verneuil stones, 14 Kashan, 16 Chatham and 4 Knischka synthetics. These tests were found to give a clear separation between the natural and man-made rubies. Absorption bands due to titanium and ferric iron affect the position, depth, and width of the UV absorption minimum.

A report in 1985 classed Kashan inclusions into four types, all consisting of melt residues. They are feathers, fingerprints, strings of pearl-like bodies, and comet or hairpin shapes.

In 1983 the Ramaura ruby was placed on the market by Overland Gems Inc. of Los Angeles. The product is grown by Judith Osmer and the growth method is a high-temperature flux process with spontaneous nucleation. Crystals show a near-equidimensional rhombohedral form and this form predominates in the majority of the other crystals. Some thin platy crystals show a predominating basal form. Growth without a seed makes for notably clear crystals as there is no need for forcing. The RI is 1.762 and 1.770 for the extraordinary and ordinary rays respectively, with a DR of 0.008. The SG is 3.96–4.00. Orange-yellow and white flux fingerprints are reported, with colour zoning, comet-tail inclusions and fracturing. A chalky-yellow and bluish-white zoning can be seen under LW and SW UV with a chalky-red to orange fluorescence. Although an early statement by the grower stated that a dopant (europium oxide) had been added to give a characteristic shift in fluorescence towards the orange-yellow, but this appears difficult to detect in the faceted product.

Rubies grown by Professor Paul Otto Knischka of the University of Steyr, Austria are a very fine red with crystals showing many faces. Some crystals show a pseudo-cubic habit. The growth is thought to be via a technique involving a temperature gradient with supercooling and supersaturation. Cloudy veils and healing fissures have been seen as inclusions; some early products also show metallic platelets of platinum or silver. Later specimens appear to be devoid of these crucible residues. Gas bubbles have also been noted. The SG averages 3.976. The RI is 1.760–1.761 and 1.768–1.769 for the extraordinary and ordinary rays respectively, with a DR of 0.008. There is a strong carmine-red fluorescence with no trace of chalkiness. A weak phosphorescence can be seen after subjection to X-rays. Although growth details are not released, the flux used for the first production at least is thought to be Li_2O-Na_2O-K_2O-WO_3-PbF_2 and/or PbO. Knischka ruby crystals over 50 mm in length have been produced, and material is being marketed as faceted stones in sizes ranging to over 11 carats, as preforms which may exceed 25 carats, and as rough macro-clusters, plates and micro-clusters. These qualities are distinguished by their relative freedom from inclusions.

In 1985 *Gems and Gemology* reported cut Lechleitner ruby and blue sapphire. Stones showed both Verneuil-type growth features and inclusions characteristic of flux growth, suggesting that a Verneuil-grown crystal was encased by flux-grown corundum, or that a small Verneuil seed crystal was placed in the crucible used for flux growth, either to initiate growth or to influence its size and direction. The inclusions serve to distinguish these products from natural corundum.

Contact twinning on the prism faces $r(10\bar{1}0)$ or $r(11\bar{2}0)$ is frequently found in Chatham synthetic rubies. In Ramaura crystals there is penetration twinning about the *c*-axis, while Kashan stones show repetitive twinning of intercalated lamellae on $r(10\bar{1}1)$. There is also seen in Chatham rubies. Natural rubies often show repetitive twinning on $r(10\bar{1}1)$.

A star ruby manufactured by the Kyocera American Corporation and marketed under the trade name Inamori shows sharp, intense white six-rayed stars with some wavy or broken lines giving them a more natural appearance. Properties overlap those of natural star rubies and testing must rely upon observation of internal characteristics: these include smoke-like bluish-white swirls running at random between the rays of the star, and round and distorted gas bubbles. The stones are probably grown from a high-temperature melt since the absence of curved striae would seem to rule out Verneuil production.

Some fluxes used by different manufacturers of synthetic ruby are as follows (Schmetzer, 1986):

Li_2O-MoO_3-PbX, where $X = F_2$ or O_2	Chatham, Gilson, Lechleitner
Na_3AlF_6	Kashan
Li_2O-WO_3-PbX	Knischka
Bi_2O_3-La_2O_3-PbX	Ramaura

Note that natural-looking fingerprint inclusions can be induced into Verneuil stones by flux healing. Also note that natural-looking needle-like inclusions identified as the edges of twinning planes may be confusing in Verneuil stones.

Ruby with induced fingerprint-type inclusions and polysynthetic twin lamellae has been reported.

Synthetic Corundums of Other Colours

Corundum of colours other than ruby has been grown by several manufacturers using flux-growth techniques. Chatham produces orange and blue sapphires as single crystals or as crystal groups, the groups being held together by a ceramic glaze which contains gas bubbles and which lowers the SG to around 3.70. Individual crystals in the groups are bladed and too thin for faceting. Orange groups show strong reddish to yellowish-orange fluorescence under LW UV; most natural orange corundum is inert. Flux and platinum inclusions are characteristic of both blue and orange Chatham products as well as of similar specimens produced by Japanese growers.

Lechleitner has produced ruby and blue sapphire as well as orange, colourless and pink corundum. An alexandrite imitation is also reported. The ruby and blue sapphire both show strongly saturated colours and, though showing some haziness, are relatively inclusion-free. Flux inclusions are responsible for the haziness. In the ruby the optic axis is nearly parallel to the table while in the blue sapphire the optic axis lies about 20–30° away from the table plane. The ruby has an SG near 4.00 and an RI of 1.760–1.768 with a DR of 0.008. While the ruby shows no phosphorescence under any circumstances there is reddish fluorescence under both types of UV. Pleochroism is strong purplish-red parallel to the *c*-axis and pale orange-pink at right angles to this direction. Wispy veils can be seen varying from transparent to opaque. Some may be colourless and some white. Some curved striae have been observed. The blue sapphire has an RI of 1.760–1.768 with a DR of 0.008 and an SG of 4.00. Similar inclusions to the ruby are reported. Neither in the ruby nor in the blue sapphire does the absorption spectrum help in identification. Growth could involve a Verneuil-grown seed.

Curved colour banding in yellow and orange synthetic sapphires may be seen if a translucent medium blue plastic filter (just over 3 mm thick) is placed over dark-field or transmitted light, the stone being positioned over the diffused illumination thus provided.

Flame-fusion-grown blue sapphire showed needle-like inclusions as well as curved growth lines. They are in fact strings of tiny gas bubbles.

Synthetic rubies with glass fillings have been reported.

Brown star corundum has been synthesised by the Linde Company in the 1960s. The stones show no absorption in the visible and are inert to both LW and SW UV. Widely spaced colour bands have been observed as well as minute gas bubbles.

Czockralski-pulled pink sapphire, recently on the market, is titanium-doped and gives a strong orange-red through the Chelsea filter. It fluoresces moderately orange under LW UV and a very strong bluish-violet under SW. There is no distinctive absorption spectrum.

Blue and green sapphires have been grown by Czochralski pulling, the stones having a slightly violetish-blue colour in the case of the blue sapphire. Rod fragments showed concentric colour zoning from core to rim.

Spinel

It was not until the 1930s that spinel became commercially significant. Natural spinel, except for the red variety, has no great use in jewellery and a simple simulation of the spinel would have had no especial value. The synthetic spinel is therefore made to imitate stones of important but different species, such as aquamarine, blue zircon, green tourmaline, pale green Brazilian emerald, and a greenish-yellow shade which may imitate the chrysoberyl. An attractive rose colour and a royal-blue shade are also made, as is a completely colourless stone which rivals the synthetic white sapphire in brilliance. When these colourless or white spinels, as they are called, were first marketed they were the subject of a silly scare when retailed by a jeweller and antique dealer with considerable press ballyhoo as 'Jourado diamonds'. After many fruitless experiments a red synthetic spinel is now produced but this stone has properties slightly different from the usual run of the synthetic spinels of other colours. It will be mentioned later.

Physical and Optical Properties

Very rarely do the boules of synthetic corundum exhibit any crystal faces, but the spinel boules commonly show flat four-sided forms which indicate the cubic nature of the mineral, and unlike natural spinel synthetic spinel boules often show cubic cleavage cracks.

Normal natural spinel has the formula $MgO.Al_2O_3$ which implies equimolecular proportions of magnesia and alumina. It was found that equimolecular amounts of the two ingredients did not produce good boules, and the synthetic spinel as now made is usually in the proportion of 1MgO to $2\frac{1}{2}Al_2O_3$, the alumina remaining in the cubic gamma form. This extra alumina does slightly alter the physical and optical properties of the spinel. The specific gravity varies from the value 3.60 of the normal natural spinel to 3.63 for the synthetic, and the refractive index is higher, from 1.72 (usually 1.718) for the natural to 1.73 (1.728) for the synthetic. The excess alumina in the synthetic spinel strains the crystal lattice and this is apparent when stones are viewed between crossed polarising filters, for a typical anomalous double refraction is seen, the stone extinguishing in stripes (*Figure 18.17*). Further, many spinels show pseudo-interference figures when rotated between polarising filters (*Figure 18.18*), and peculiar 'strain knots' may be observed (*Figure 18.19*). Also seen in synthetic spinels are worm-like gaseous tubes (*Figure 18.20*).

Colours of Synthetic Spinels

The blue colours of synthetic spinel are due to the addition of cobalt oxide sometimes modified with other metallic oxides. The yellow and yellowish-green colours are due to a trace of manganese, and the dark green stones are coloured by chromium oxide, which in corundum gives a red colour, for at the temperature of the oxyhydrogen furnace the stable coloration of the gamma alumina and magnesia boules is green. A chromium-coloured red spinel is now marketed, but, owing to the fracturing of the boules, only in small sizes. However, red spinels of large size have been grown in the United States of

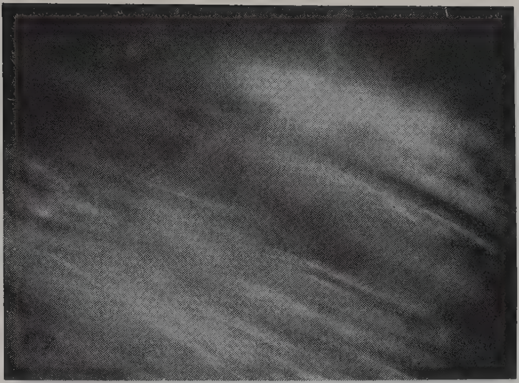


Figure 18.17 Anomalous double refraction (tabby extinction) in a synthetic spinel

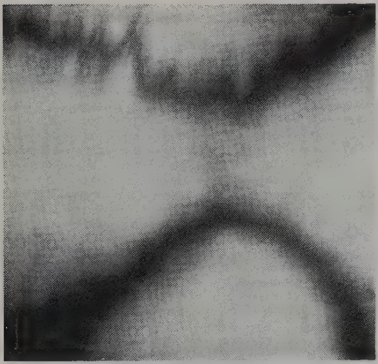


Figure 18.18 Pseudo-interference figure shown by a synthetic spinel between polarising filters

Figure 18.19 Strain knots in a synthetic spinel

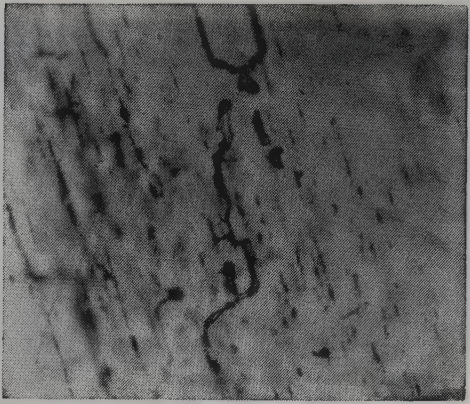


Figure 18.20 *Worm-like distorted gaseous tubes in a synthetic spinel (by courtesy of E Gübelin)*

America using the flame-fusion method. Unlike the general run of synthetic spinels, these stones are made with equimolecular amounts of magnesia and alumina as in the case of natural spinels. Their SG approximates to 3.60 and their refractive index from 1.722 to 1.725, the higher values, compared with those of the natural stones, being due to excess chromium.

Such red synthetic spinels vary somewhat in their internal structure, but as a rule show many gas bubbles and very pronounced curved colour lines (*Figure 18.21*). Sometimes, too, they may show straight lines rather like twin lines seen

Figure 18.21 *Curved bands (Venetian blinds) in a synthetic red spinel*

in some red and blue corundum of natural origin. The fluorescence spectrum differs from the 'organ-pipe' pattern as seen in the natural red spinel, for one fluorescent line near 685 nm predominates markedly over the others.

The lovely pink-coloured synthetic spinels which have been marketed for some years owe their colour to a trace of iron. A type with a colour change (being made to imitate the alexandrite) is, although rarely met, a better simulation than the much more common similarly coloured synthetic corundum.

A list of the usual colours of synthetic spinels and the trade names sometimes applied to them is given in *Table 18.2*.

Table 18.2
Colours of synthetic spinels

Colour	*Manufacturers' trade name*
Colourless	Synthetic White Spinel
Blue	Hope Sapphire
Blue (bright)	Azurite
Green-blue	Blue Zircon
Pale blue	Aquamarine
Yellowish-green	Brazilian Emerald
Dark green	Tourmaline Green
Yellow-green	Peridot
Pink	Synthetic Pink Spinel
Red	Synthetic Red Spinel
Green/red	Alexandrite

In about 1957 a spinel was made to imitate moonstone, the schillerisation probably being induced by some form of heat treatment of the synthetic white spinel. The bright blue-white fluorescence shown by these stones under short-wave ultra-violet light indicates their nature, for neither the 'heated quartz' imitation of moonstone nor the true feldspar shows this type of luminescence. A blue schillerised synthetic spinel is known.

Synthetic spinels rarely show curved colour bands or the structure lines seen in synthetic corundum. If bubbles are present they are sparse and may have a typical whorled or turned appearance with the end tending to show crystal form; they are termed 'profilated bubbles' (*Figure 18.22*). A disturbing kind of inclusion sometimes seen in synthetic spinel is solid crystals of alumina (*Figure 18.23*). The synthetic spinels may be distinguished by the unusual colour (for spinel), the refractive index and SG, although there are certain zinc-rich spinels from Sri Lanka which have a higher refractive index than usual. They do not have the colour of the synthetic spinel, being mostly pale mauve to dark inky blue.

Absorption Spectrum

The blue colours of synthetic spinel show a distinctive absorption spectrum of three broad bands in the orange-red, yellow and green, the bands being centred

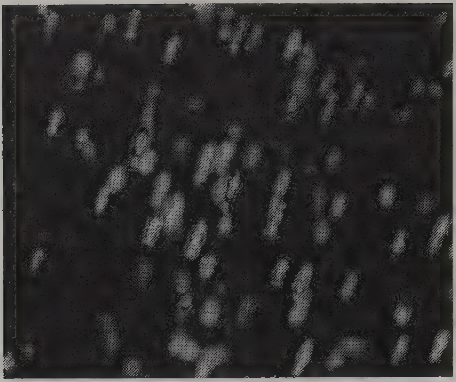


Figure 18.22 Profilated bubbles in a synthetic spinel (by courtesy of E Gübelin)

Figure 18.23 Solid crystals of alumina brought into being by exsolution. These are a disturbing kind of inclusion sometimes seen in synthetic spinel (by courtesy of E Gübelin)

at 635, 580 and 540 nm, the latter being only about half the width of the first two. A blue glass coloured by cobalt exhibits a similar spectrum but in this case the bands are slightly wider apart and, further, it is the central band which is the narrowest. Such cobalt-coloured blue stones show a red or orange residual colour when viewed through the Chelsea colour filter, unlike sapphire, aquamarine and blue zircon which show a bluish-green through the filter. The synthetic spinel made to imitate the alexandrite also shows a cobalt absorption spectrum.

The yellow and greenish-yellow synthetic spinels show an absorption spectrum of two bands in the blue-violet at 445 and 422 nm due to manganese. In certain shades of pale blue, the cobalt spectrum may be in association with the two bands due to manganese, and it sometimes occurs that the cobalt bands complete a spectrum which shows the bright fluorescence line of chromium.

Luminescence and Fluorescence

The luminescence of synthetic spinels has some diagnostic value. The synthetic white spinel shows only a faint misty glow under the long-wave lamp but under short-wave rays the glow is usually a bright bluish-white, although only a weak but distinct blue light may be seen in some white synthetic spinels. As the synthetic white sapphire shows a dull deep blue glow under short-wave excitation, this provides a distinction between the two white synthetics. Synthetic white spinels emit an apple-green light with similar phosphorescence when excited with X-rays. A few specimens have been found to give out a blue or greenish-blue light under X-rays. Synthetic white spinels quickly turn to a brown colour on irradiation with X-rays, but they may be decolorised by heating to about 250 °C.

Most blue spinels show a red glow when under the long-wave ultra-violet lamp. Under the short-wave rays the glow seen may be either red, orange or bluish-white. The yellow, yellowish-blue and yellowish-green stones, those which show the manganese absorption spectrum, emit an apple-green glow with all radiations. The 'tourmaline-green' colour of synthetic spinel shows a red glow under the long-wave lamp a milky greenish-white glow under the short-wave lamp, and usually a red colour under X-rays. The pink-coloured synthetic spinels are inert under any of the three radiations.

Flux-Fusion and Other Synthetic Spinels

Spinel is also grown by flux fusion. Crystals grow as octahedra or groups of octahedra, the latter having the greater gem significance as these groups have been used in the modern concept of jewellery design where uncut crystals form the central motif. Such spinel groups are grown in many colours by doping with trace elements, such as red by chromium and blue by cobalt, and there are seen groups with a yellow colour, the doping agent being nickel.

Specimens of these synthetic spinel groups, all of English manufacture, included two stones of red colour having SGs of 3.592 and 3.598, both showing a fluorescence spectrum with a single strong line at 685.5 nm and traces of others. This fluorescence spectrum is similar to that shown by the Verneuil flame-fusion synthetic red spinels. Under ultra-violet light of both types the glow was crimson, and under X-rays the fluorescence was more of a purplish-red with a persistent phosphorescence.

The blue-coloured group had an SG of 3.60 and showed the typical cobalt absorption spectrum. Under the Chelsea filter the group showed a bright red, but the group did not show the differential response to ultra-violet light as seen in the Verneuil-type blue synthetic spinels which show red under the long-wave ultra-violet lamp and a greenish- or bluish-white under the short-wave ultra-violet lamp. Indeed in the group examined there was very little luminescence under ultra-violet light or X-rays, except for a possible dull red glow when irradiated with the short-wave lamp. It is always problematical whether such a glow is not reflected from the light passed by the lamp.

The yellow-coloured specimen was found to have an SG of 3.609, showed no distinctive absorption spectrum, but exhibited a green fluorescence under long-wave ultra-violet light. It was practically inert or with a slight dull yellow glow under the short-wave lamp, but under X-rays the glow was a vivid green, there being no phosphorescence. The pale green specimens, having SGs of 3.601 and 3.589, again showed no characteristic absorption spectrum and only slight luminescent response of indeterminate colour under ultra-violet light, but a dull green glow under X-rays.

Two unusual specimens of similar habit and of a pale bluish-green colour were found to have unusual characters, for the SG was about 5.7, and the absorption spectrum showed a fine line in the red and indeterminate lines in the yellow, which may be traces of the didymium series. The luminescence under ultra-violet light and X-rays was a strong yellow.

The flux-grown lithium-iron spinel has an SG of 4.58 and is strongly magnetic.

Fine-quality flux-grown spinel is reported from the USSR. One red octahedron weighing 17.19 carats has been seen, and the writer's collection includes a similar crystal and also a blue octahedron coloured by cobalt and showing a bright red through the Chelsea filter.

Said to have been devised by a German dentist, a lapis-coloured synthetic spinel has been marketed since 1954. This is a coarse powder of synthetic spinel heavily charged with cobalt oxide which is sintered together in an electric furnace. Some specimens have bright specks of 'pyrites' so common in true lapis lazuli, but in the case of sintered spinel the specks are gold. These synthetics show a brilliant red residual colour through the Chelsea colour filter and have a refractive index of 1.725, but the reading is never as sharp as in transparent synthetic spinels of normal type. Sintered spinels have a hardness of 8 and an SG of 3.52. The absorption spectrum may be observed quite clearly by light reflected from the surface of the specimen. It is a typical cobalt spectrum, although the distribution and strength of the bands are not quite the same as those shown by the blue spinels made by the Verneuil process. The three bands in this spinel are at 650 nm (broad and strong), 580 nm (weak) and 480 nm (strong).

A Verneuil red spinel came on to the market in 1987. It has an SG of 3.59 and an RI of 1.72, with minimal strain birefringence and no fine line absorption in the red part of the spectrum. A red fluorescing band is centred around 685 nm under LW/UV. Broad curved colour banding is seen with a wide variety of bubbles oriented at right angles to the bands.

A synthetic spinel crystal grown in Russia was a transparent purplish-red. The RI was measured from a flat face at 1.719 and the SG was 3.58. Neither these figures nor the absorption spectrum sufficed to distinguish the synthetic material from a natural red spinel.

Under magnification the stone (represented as a hydrothermally grown product) showed what appeared to be primary flux inclusions coloured a deep orange-brown with an angular to jagged profile. Some brightly reflective and iridescent air-filled fractures had signs of strain associated with them seen under polarised light. No signs of the presence of water were found, so the material cannot have been a hydrothermal product. Should stones be faceted from this material, considerable care in examination will be needed.

Rutile

The birefringent dark red or brown mineral rutile TiO_2 is made by a modification of the Verneuil process to give a soft but highly dispersive diamond simulant. Some experiments with a flux growth of rutile were made in the nineteenth century, but the Verneuil torch has proved to be a more effective means of production. To offset the oxygen loss a third outer tube is added to give a tricone burner with a sequence oxygen–hydrogen–oxygen. Up to three volumes of hydrogen to one of oxygen may be used, this giving a strongly reducing flame in the conventional Verneuil burner, but the tricone apparatus needs only $1\frac{1}{2}$H to 1O. The oxygen deficiency results in a black crystal, this being altered by annealing at about 1000 °C to a gunmetal blue, then a paler blue and finally a pale yellow. Colourless crystals cannot be obtained owing to a strong absorption of the deep violet. Following original production by the National Lead Company in the USA, one or two other companies grew rutile for a time, production being around 150 kg annually in peak years. Today only a little is grown and specimens are becoming rare.

Rutile has a hardness of just over 6, an SG of 4.25 and an RI of 2.8 on average. The high DR of 0.287 shows very clear doubling of back facet edges and the dispersion of about 0.33 is so high compared with diamond's 0.044 that rutile shows an opal-like play of colour. Blue rutile is strongly electroconductive.

The addition of about 0.5 per cent magnesium oxide to the feed powder with annealing of the finished boule gives a star effect when cabochons are cut. A thin layer of corundum deposited on the rutile surface may harden it and this has been tried, though with little commercial importance. The feed powder is made from highly purified titanium tetrachloride $TiCl_4$, and reaction with ammonium sulphate gives a basic titanyl double salt which is recrystallised and washed to remove the chloride. It decomposes at 900 °C to give TiO_2. Rutile melts at about 1860 °C.

Strontium Titanate

In nature the mineral tausonite, with no ornamental importance, Verneuil-grown strontium titanate is a highly dispersive isotropic though soft diamond simulant. Other titanates have also been grown but with less commercial success. Early work was carried out by the US National Lead Company using a three-tube burner as strontium titanate suffers from an oxygen deficiency. The grown boules are rendered colourless by annealing for 12 hours at 1000 °C. In some cases two anneals were performed, the first at 1700 °C to eliminate strain and the second at 500 °C to improve the colour. The feed powder is made by reacting highly purified titanium tetrachloride $TiCl_4$ with strontium chloride $SrCl_2$ and oxalic acid to give the basic titanyl double oxalate salt $SrTiO(C_2O_4)_2.2H_2O$. The chloride traces are removed by washing, and on heating to over 1000 °C a free-flowing granular powder is obtained. The melting point of strontium titanate is near 2080 °C.

Strontium titanate, which had the trade name Fabulite (among others), has a hardness of 6, an SG of 5.13 and an RI of 2.41. The dispersion is 0.19, giving a very notable play of colour. When it is used as mêlée, or in the base of composites, the jeweller or gemmologist can be deceived: the surface can be marked by the point of a needle, and there is no absorption in the visible and no luminescence. It is opaque to X-rays and somewhat brittle, so ultrasonic cleaners should not be used.

Quartz

The search for a non-twinned single-crystal quartz for electronic purposes during the Second World War led to developments of a hydrothermal growth technique to which Spezia had given the greatest development impetus during 1898–1908. He used a quartz crystal as a seed which was supported by a silver wire in a steel pressure vessel with a silver lining. A solution of hot water with sodium silicate and crushed natural quartz was placed under pressure, giving up to 15 mm of growth on the seed over a period of about 200 days. Ignoring the advantages of thermal convection, Spezia placed the hotter region at the top and the cooler below; present-day runs are much quicker because these positions are reversed. Work by Nacken of flux emerald fame and by Bell Laboratories, Sawyer Research Products Inc. and others have led to the development of processes which can produce crystals several metres in length as well as amethyst, citrine, smoky and colourless gem-quality quartz.

The pressure vessel or autoclave which is sealed (and appropriately known as a bomb) is about 460 mm in diameter externally and 3.7 m long (*Figure 18.24*). Internally it is 150 mm in diameter and 3 m long; the volume is about 2 litres. The bottom feed temperature is about 390 °C, the top crystallisation temperature 330 °C. An 80 per cent fill with a 4 per cent NaOH solution will give a pressure of about 1700 bars. A baffle is placed between the quartz source

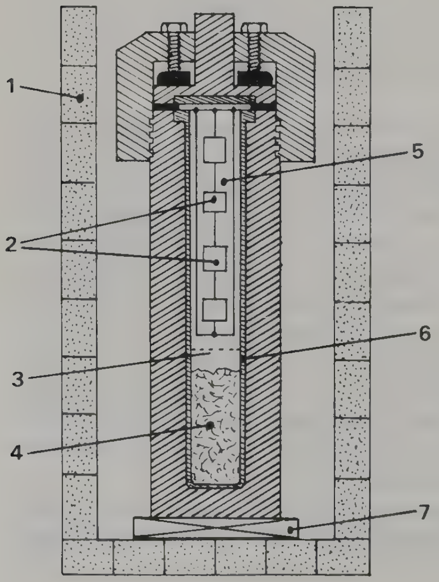


Figure 18.24 *Simplified sketch of a silver-lined autoclave for the production of hydrothermally grown quartz: 1, thermal insulation; 2, seed plates; 3, baffle; 4, source material; 5, silica-rich aqueous solution; 6, silver liner; 7, electrical heater*

material and the seeds and has a 5 per cent opening. The purpose of the baffle is to control the convection currents to ensure an even deposit on all the seed crystals. About 32 kg of quartz feed will be exhausted in a growth period of 20 days and will grow on to 40 seed plates which begin at 4 cm × 15 cm × 1 mm. The final crystals will be almost 50 mm thick and weigh about 700 g. The sodium hydroxide is used as a mineraliser and increases solubility by an order of magnitude. Heat dissolves the crushed quartz at the bottom of the vessel. The saturated liquid rises by convection to the upper part of the vessel where it deposits on the seed plates. Crystals grown by this method show characteristic cobbled faces, the effect arising from small disc-like structures (*Figure 18.25*).

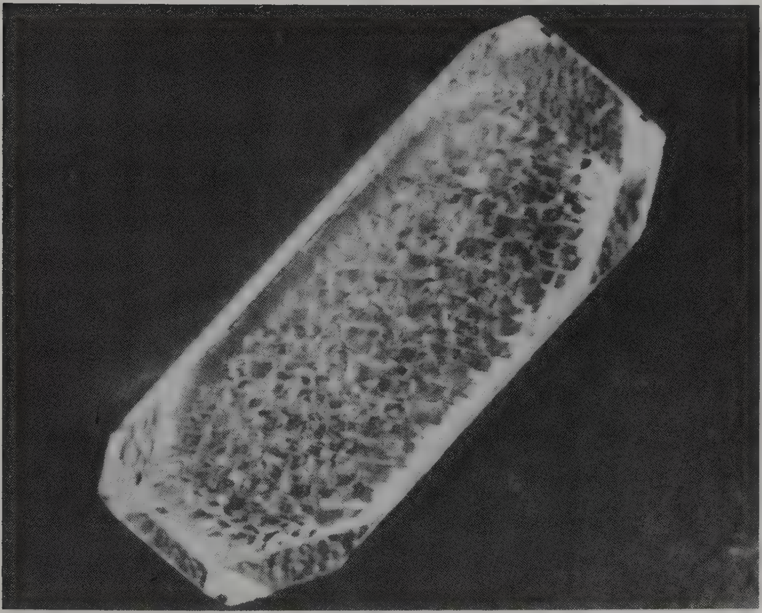


Figure 18.25 A synthetic quartz crystal showing the 'cobbled' surface of the large basal face

These faces are basal ones and do not exactly correspond with faces on natural quartz crystals.

This is an efficient method of crystal growth for certain substances but it is not without problems. Apart from the possibility of a vessel failure it is necessary to achieve a reaction (melting the feed) and its reverse (recrystallisation). The mineraliser which reacts with the quartz to give a more stable compound must not make it too stable or the reverse reaction will not take place. Growth of 1 mm per day would be an acceptable rate to give clear crystals.

In an earlier work the twinning-free Brazilian quartz known as lasca was used as feed material. However, a Brazilian government ban on the export of all but small quantities in 1974 forced growers to look elsewhere. Fortunately adequate supplies of material do exist in other countries, including the USA.

The coloured varieties of quartz are also grown hydrothermally. A smoky colour is obtained when a trace of aluminium is present and the specimen is irradiated by X-rays or gamma rays. Some smoky quartz will give a greenish-yellow on heating. Yellow citrine occurs when Fe^{3+} is present, and irradiation can give an amethyst colour from the citrine provided that the iron is in the appropriate site. Natural citrine has iron in a different site and cannot usually be irradiated to give amethyst, though heating will often accomplish this. A green colour may be obtained by heating some amethyst.

Synthetic smoky quartz is grown as colourless and later irradiated by gamma rays to give the smoky colour. Aluminium has to be present replacing some of the silicon. A greenish-yellow quartz can be obtained by heating smoky quartz; depending on the degree of heating a range of colours, including lemon and honey, brown and greenish-brown can be obtained in this way.

Adding iron oxide or hydroxide to the growth solution will give the required Fe^{3+} for citrine. Oxidising conditions are necessary and $LiNO_3$ or $LiNO_2$ may be added to give yellow. About 0.01 per cent Fe_2O_3 will give a medium yellow. The steel of the autoclave might contribute iron which would be undesirable when colourless quartz is to be grown, but the use of a sodium-containing mineraliser will lead to the formation of an insoluble silicate on vessel walls and stop migration of iron into the growing crystal. When iron is required the use of sodium compounds is ruled out and salts of potassium or ammonium are used instead.

When amethyst is to be produced, the crystals as grown are near-colourless and are later irradiated by gamma rays. Iron must be present in the crystals for the colour change to operate. Aluminium must be eliminated as a smoky purple colour will result. The use of lithium salts such as $LiNO_2$ will prevent the aluminium entering the quartz in large amounts since they will cause $LiAlSiO_4$ (eucryptite) to form as an insoluble compound.

A green quartz will result from the presence of iron and the absence of oxygen during growth. The green colour results from Fe^{2+}. Blue quartz can be obtained by adding Co^{2+}. If there is Al in the crystal, the blue will deepen the more Al there is. Colours such as ruby red and emerald green are not possible in quartz since the structure will not accommodate the appropriate ions. Further details of the synthesis of quartz will be found exhaustively treated in Nassau's *Gems Made by Man*.

Identification of synthetic quartz is difficult since the physical and optical properties accord with natural quartz, and there are usually few if any significant inclusions. A Japanese synthetic amethyst was found to contain feather-like inclusions made up of liquid-filled and two-phase structures and sharp growth zoning parallel to one rhombohedral face. Twinning structures seen in the same stone differ from those seen in natural amethyst.

A technique involving the examination of amethyst using a horizontal microscope with the optic axis parallel to the path of light through the microscope shows Brazil twinning by its interference colours in natural specimens, while in synthetic stones a succession of broad colour bands is seen. Some Japanese amethysts have shown arrowhead or small flame-like structures.

Some stones showing combined amethyst and citrine colours ('ametrine') may be synthetic and could perhaps be identified by this method.

The presence of Brazil-law twinning in an otherwise flawless amethyst virtually proves natural origin, while an acutely angled flame-like pattern seen while the specimen is immersed between crossed polars confirms artificial origin. Angular or straight zoning with juxtaposition of colourless or violet-blue zones next to purple areas indicates a natural stone, while the presence of light and dark purple zones, or the absence of zoning, indicates a synthetic amethyst.

Colourless synthetic quartz has been grown over seed plates of natural amethyst, both portions showing Brazil-law twinning. This may make previous work on distinguishing natural from synthetic quartz more difficult. In a report of 1989, GIA found such a composite to show the twinning clearly between crossed polars together with tiny fluid inclusions and breadcrumb-like particles. Earlier assertions that a flame-like appearance between crossed polars would serve to distinguish natural from synthetic quartz are disputed in the 1989 paper which holds that the flame-like appearance is a form of Brazil-law twinning.

Two crystals with 2 mm thick amethyst seed plates were used as seeds in a hydrothermal growth experiment. The seeds were Brazil twinned and differently oriented from each other. The resulting crystals were of differing morphologies, one being tabular (with the seed oriented nearly parallel to the *c*-axis) and the other more characteristic of a natural quartz crystal and providing sufficient material for two faceted stones. The seed in this case was oriented nearly perpendicular to the *c*-axis. In both cases the seed turned yellow during the growth process; in polarised light Brazil-law twinning was visible as a phantom between the interface of seed plate and overgrowth. Further examination in polarised light with the stones immersed in benzyl benzoate showed that the colourless quartz overgrowth was Brazil-law twinned. The GIA paper shows that synthetic amethyst twinned according to the Brazil law can be grown.

Emerald

Growth Methods

The early attempts to synthesise emerald go back to the middle of the nineteenth century. In 1848 Ebelmen reported that he had obtained emerald crystals by heating powdered natural material with molten boric acid as a flux. The emerald dissolved in the H_3BO_3 and recrystallised as hexagonal crystals of small size. In 1888 and 1900 Hautefeuille and Perrey found that by using Li_2O with MoO_3 or with V_2O_5 as solvents (fluxes) emerald crystals could be obtained. Their crystals were 1 mm across after a growth period of 14 days at 800 °C. At higher temperatures phenakite resulted. Chromium was added to give the emerald colour.

In 1911 the firm which was later to become IG-Farbenindustrie began research on emerald growth, and in 1924 Espig began the work which led to the growth of larger crystals. The ingredients needed for emerald growth reacted in the flux to give emerald in the growth region only, rather than allowing

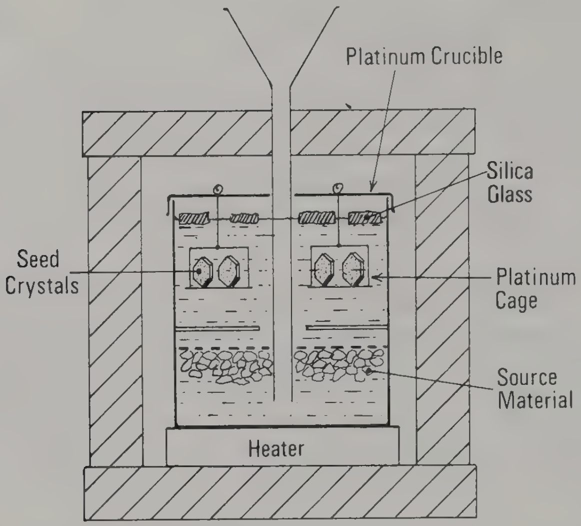


Figure 18.26 The flux-melt apparatus used to grow synthetic emerald crystals by the I.G. Farbenindustrie process

spontaneous nucleation to give tiny crystals all over as had happened with earlier work. A flux of lithium molybdate with extra MoO_3, and with silica glass to give the SiO_2, allowed emerald crystals to grow, but they grew on the quartz, giving rise to unacceptable inclusions and cracking.

A platinum apparatus (*Figure 18.26*) was later used with a flux SG of 2.9; the silica glass was permitted to float while the growing emeralds were confined by a platinum screen so that they could not settle on the quartz. BeO and Al_2O_3, with $LiCrO_4$ to give the colour, could be added via a bottom tube and extra SiO_2 could be added at the top. This topping-up is not possible with the sealed-vessel hydrothermal process. Growth by diffusion (SiO_2 dissolving near the top and diffusing downward, the other materials dissolving near the bottom and diffusing upward) allows emerald to form in solution in the middle where the growth materials react. Espig obtained emerald crystals up to 20 mm long in a growth period of one year. Later, commercially successful growers such as Chatham and Gilson used the same or a similar process, though the colour of their product is better than that obtained by Espig (he found that chromium did not give a satisfactory emerald colour by itself; vanadium when added improved the colour greatly). Crystal groups made by Espig and his co-workers were shown at the Paris Exhibition of 1937. Though the name Igmerald was used no crystals were ever put on the market; some were sent in attractive presentation cases to noted gemmologists of the time.

Professor Richard Nacken, a pioneer in the hydrothermal growth of quartz, also grew emerald crystals which were frequently cited as hydrothermal in gemmological literature. The absence of water (proved by an examination of the infra-red absorption spectrum) showed that this could not be so, and the crystals are in fact grown from a flux. Both natural and hydrothermal emeralds contain water. The colour of Nacken's product was better than that achieved by Espig and this is probably due to the use of a flux containing vanadium oxide (this is used in modern emerald production). Inclusions of flux resembling wreaths of smoke and nailhead-type inclusions, characteristic of later flux products, are seen clearly in Nacken crystals which are now very rare.

Modern emerald production using a flux accounts for by far the greater amount of synthetic emerald on the market, though some hydrothermal emeralds are still made. The work of Carroll F Chatham of San Francisco (now carried on by his son Thomas) who produced the high-quality Chatham Created Emerald and of Pierre Gilson of France (his process has now been sold to Japan), leads the field in emerald production. No water is present but there are traces of Li, Mo and V, so it is assumed that a lithium molybdate-vanadate flux is used. The work of Chatham, Gilson and others probably parallels Nacken's work fairly closely, although details are unavailable owing to commercial secrecy. In turn Nacken's growth method must have been very similar to that of Espig as described above. While Chatham appears to use a flux reaction method, Pierre Gilson, after encountering trouble with spontaneous nucleation, uses a natural colourless beryl seed on which emerald forms on both sides (*Figure 18.27*). The emerald layers are then used as seeds for commercial growth. The growth rate is about 1 mm per month.

The addition of iron to eliminate the normally characteristic red fluorescence under UV shown by synthetic emerald was experimentally tried for a few runs; an absorption line at 427 nm indicates this product. Both Chatham and Gilson have made and sold clusters of emerald crystals unlike any combination of natural crystals. Gilson has made crystals yielding faceted stones as large as 18 carats, and at its highest the quality is superb in any size. Stones are or were sold on a graded basis of quality as well as size.

Gilson appears to use or to have used a flux transport system in which the source material dissolves in one section of the vessel and grows on seeds on the other side which is cooler. The growth rate is slow and the formation of phenakite has to be avoided by careful temperature control. Also to be avoided is spontaneous nucleation of emerald. A detailed account with the history of emerald growth processes can be found in Nassau's *Gems Made by Man*.

Hydrothermal growth of emerald of commercial size and quality was not achieved until the 1960s. Johann Lechleitner of Innsbruck, Austria, grew emerald hydrothermally on to faceted natural beryl seeds. The emerald layer was thin and stones show a characteristic cracking. The lower facets were often left unpolished. The trade names Emerita and Symerald were used. It is probable that earlier work may have been hindered too greatly by the use of an alkali medium which could not produce crystals of useful size.

A beryl with vanadium only as a colouring element (though with emerald colour) was grown by A M Taylor in the 1960s, but examples are very few.

The Linde Division of Union Carbide produced hydrothermal emerald from 1965 to 1970. As always in emerald growth, any silicon in the growth material must be separated from the other elements in the feed to prevent spontaneous nucleation and allow growth to take place only on seeds. Growth is by diffusion reaction with convection. Water boils in the sealed vessel, building up pressure and filling the vessel as a single fluid. Pressure increases, dissolving feed quartz at the top and the rest of the feed at the bottom. Emerald in solution forms in the

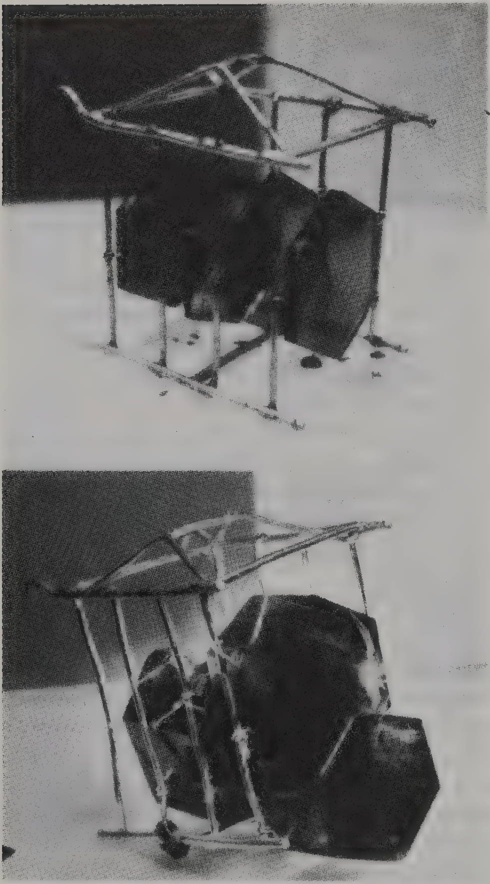


Figure 18.27 Top: Platinum cage containing Gilson synthetic seed plates after 2 months overgrowth. Bottom: Gilson synthetic emerald crystals after 10 months growth. (Laboratoire Gilson)

vessel centre and crystallises on the seeds. Too much mixing will produce phenakite. Pressures are around 700–1400 bars at temperatures of 500–600 °C. Aluminium is obtained by using gibbsite $Al(OH)_3$, beryllium from $Be(OH)_2$, silicon from crushed quartz and chromium from $CrCl_3.6H_2O$.

A variation in the original process initiates growth on a natural beryl seed. The new growth is removed to serve as a seed in its turn and can be seen as a colourless layer in the finished stone. No topping-up can take place as the vessel is sealed, so that grown crystals have to be coated up to three times in successive runs.

The Linde product was set in the company's own jewellery (Quintessa) and the process was sold to Vacuum Ventures Inc. of New Jersey who are manufacturing by the hydrothermal process at the time of writing.

Other methods of beryl growth have been tried experimentally. However, since many beryllium compounds are toxic to a dangerous degree (the toxic ones are those which are soluble in water or biological fluids) there is not much latitude in choice of growth method.

The Igmerald was copied closely for a few years by the firm of Walter Zerfass of Idar-Oberstein. One of Espig's IG-Farben colleagues in the Zerfass firm used the same flux process and a flux of Li_2O-MoO_3 with V_2O_5. Stones are notably included and are very rare. Very occasionally a small hexagonal crystal may be seen, sometimes with small crystals growing from the prism faces. Such crystals are prized collectors' items.

Characterisation

Synthetic emerald shows inclusions which are characteristic in themselves, but are remarkably like inclusions in natural stones. These inclusions are liquid-filled feathers, usually two-phase, which assume veil-like formations and may be likened to curtains waving in a draught, or they may be in a series of parallel bands (*Figure 18.28*). Zoning is quite common and these zonal lines may be straight or angular in conformity to the hexagonal prism (*Figure 18.29*). Quite large crystals of phenakite may also be an inclusion.

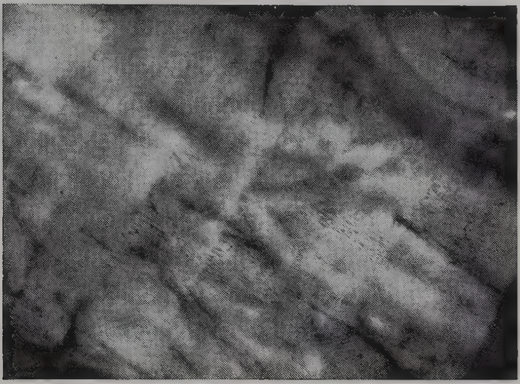


Figure 18.28 Parallel arrangement of feathers in an American synthetic emerald

The specific gravity of synthetic emerald at 2.65 is perceptibly lower than that of natural emeralds. Thus, in a bromoform/monobromonaphthalene mixture in which quartz just floats, a synthetic emerald will either remain freely suspended or just float. Natural emeralds will sink decisively in such a liquid. The refractive indices also differ perceptibly from those of natural emerald. Again they are lower and are usually 1.563 for the ordinary ray and 1.560 for the extraordinary ray, the birefringence being approximately 0.003.

When viewed through the Chelsea colour filter the synthetic emeralds show a strong red residual colour which, while indicative, must not be taken as conclusive; some natural emeralds, particularly those from the El Chivor mine in Colombia, also exhibit this strong red colour through the filter. This warning also applies to the fluorescent red glow shown by synthetic emeralds when in ultra-violet light, of which the radiations from the long-wave fluorescent ultra-violet lamp are the more useful. Tests carried out in the London Gem Testing Laboratory in 1953 revealed that Chatham synthetic emeralds showed a far greater transparency to short-wave ultra-violet light than natural emeralds

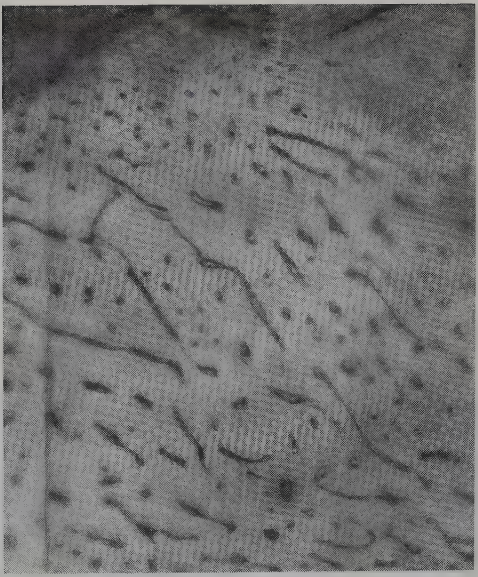


Figure 18.29 Liquid-filled feather and zoning in an American synthetic emerald

or indeed any natural beryl. This was shown by taking photographs of the spectrum of a copper arc as transmitted by the stones tested. No natural emerald was found to transmit light of shorter wavelength than 295 nm, while Chatham stones transmitted freely to 230 nm or even beyond. A more convenient way of employing this as a test was found to be to expose any doubtful stone, resting on slow photographic film (preferably immersed in water) to light from a short-wave UV lamp in a dark-room, using known natural and synthetic emeralds for comparison on the same film to ensure that the exposure has been of the right duration. The developed film should show a marked difference between natural and synthetic emeralds (*Figure 18.30*).

Carroll Chatham maintained that the synthetic crystals are free from impurities and strain so that they can be raised to an incipient white heat

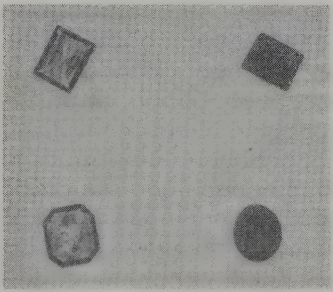


Figure 18.30 Differential transparency to SW ultraviolet light of synthetic and natural emeralds

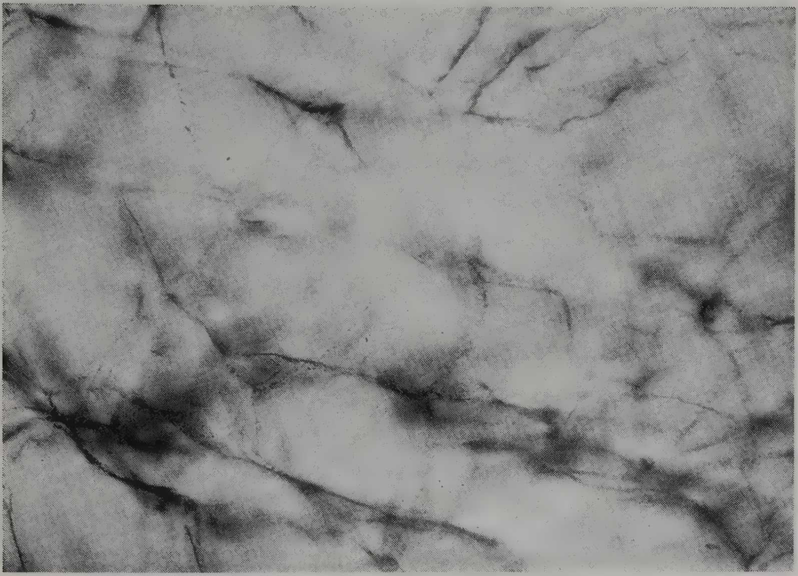


Figure 18.31 Feathers in a flux grown synthetic emerald

without damage, while the natural stone is destroyed far below the visible temperature range.

Emeralds produced by Pierre Gilson of France have ranges of SG and refractive indices similar to those of Chatham's stones. The veil-like feathers are also similar (*Figures 18.31, 18.32, 18.33*). The Gilson stones do have one character different in that under the ultra-violet lamp they glow orange and not red, but recent products show red.

Linde synthetic emeralds have refractive indices of 1.572 and 1.567, with a birefringence of 0.005, and the SG of the stones is near 2.67 or even higher. The inclusions in Linde stones are the veil-like structures so commonly seen in other synthetic emeralds, and also nail-like cavities with the head of the nail formed by a single, or a group of, phenakite crystals. However, the most striking observations made on this type of synthetic material are the strong red light shown by the stone when it is bathed in a fairly intense beam of white light, and also the strong red fluorescence shown by the stone when viewed through a Chelsea colour filter or crossed filters or under ultra-violet light.

Some Linde hydrothermal emeralds examined recently by workers in the United States of America have refractive indices of 1.578 and 1.571, with a birefringence of 0.007. The SG was found to be 2.678. These stones showed much less fluorescence under ultra-violet light, although the red appearance when the stones were in a beam of white light was still a characteristic feature, and so were the nail-like cavities capped by phenakite crystals (*Figures 18.34* and *18.35*), as well as the veil-like feathers which are so common in synthetic emeralds.

Some characteristics of Nacken, Igmerald and Symerald synthetic stones are shown in *Figures 18.36, 1837* and *18.38* respectively.

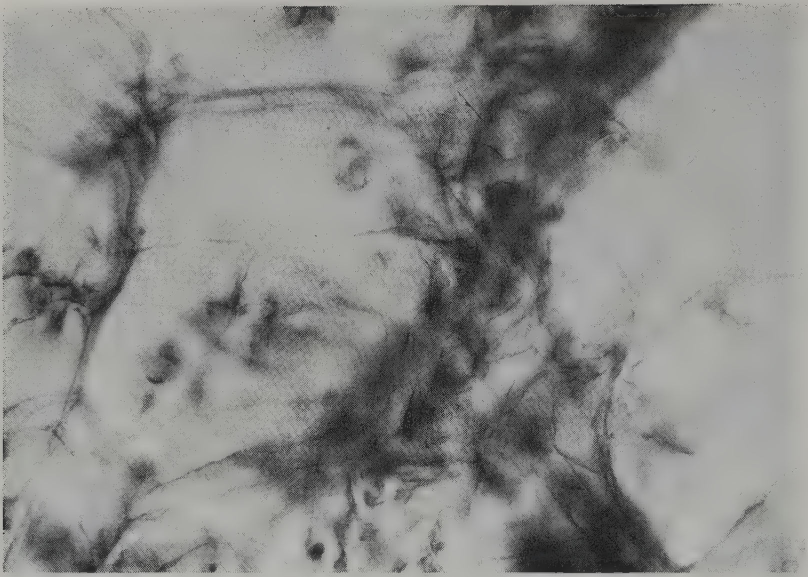


Figure 18.32 Feathers in a Gilson synthetic emerald

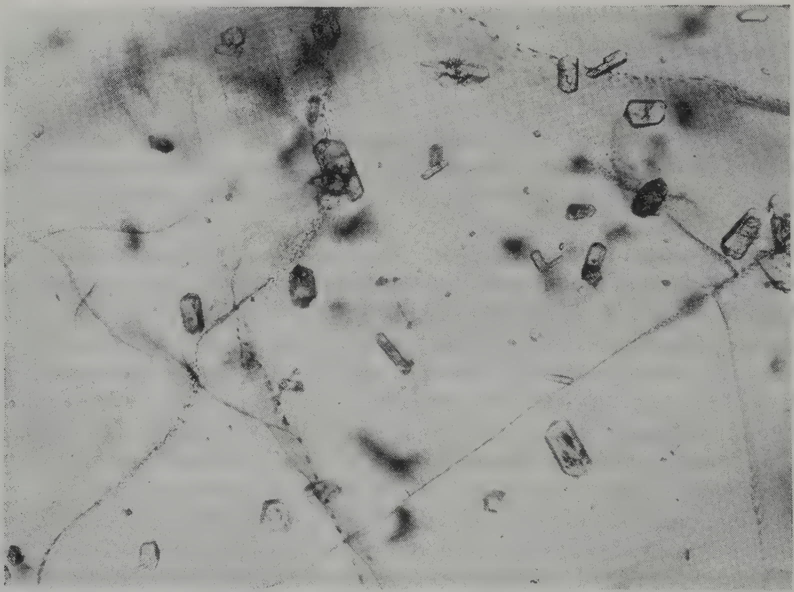


Figure 18.33 Phenakite crystals in a Gilson synthetic emerald

The Lennix synthetic emerald is a flux-grown product with low RI at 1.556–1.562 and 1.558–1.566, with DR 0.003. These figures are for the light green areas; those for darker areas are a little higher. The SG is in the range 2.65–2.66. Fluorescence is not clearly diagnostic, with stones showing bright

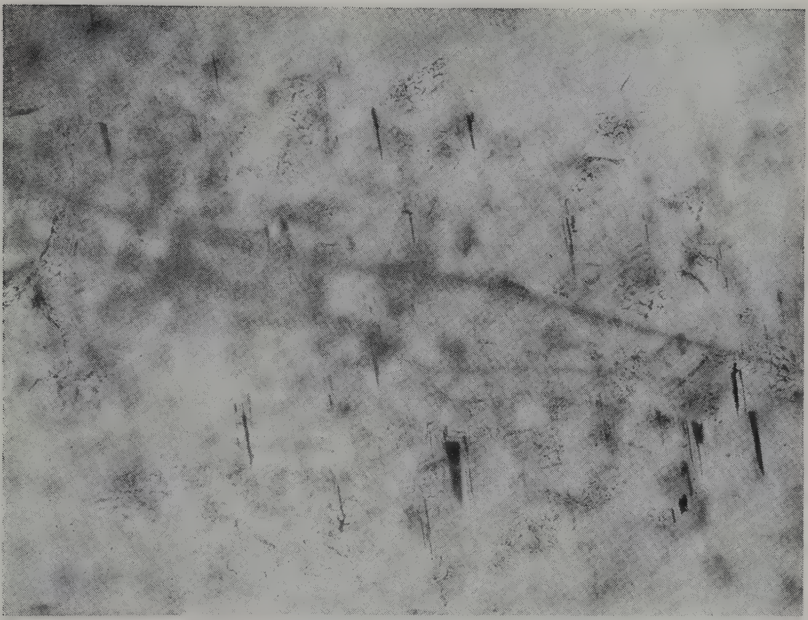


Figure 18.34 Feathers and needles in a Linde synthetic emerald

Figure 18.35 Conical cavities capped with phenakite crystals in a Linde synthetic emerald

red under LW UV and dim orange-red with transparency under SW UV. Lennix emeralds show fairly high FeO and MgO contents compared with many other synthetic emeralds, but the levels are lower than the average for most natural stones. A purple or bright violet-blue cathodoluminescence has been observed

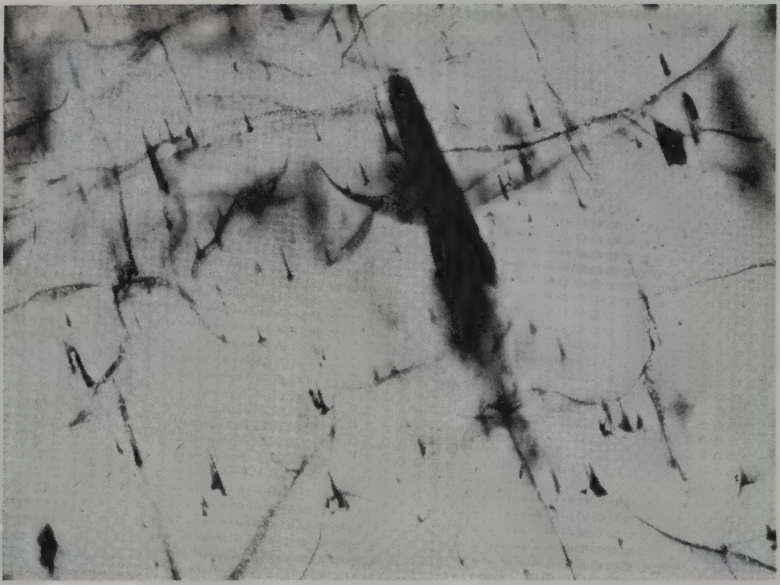


Figure 18.36 Inclusions in a Nacken synthetic emerald (circa 1926)

Figure 18.37 Feathers in an Igmerald (1935) (photo B W Anderson)

and appears to be peculiar to this product. With the microscope, a variety of inclusions has been observed: opaque tube-like structures preferentially aligned to the c-axis; clusters of inclusions along the borders of sequential growth zones paralleling the edges of the basal pinacoid; slender crystals of phenakite and

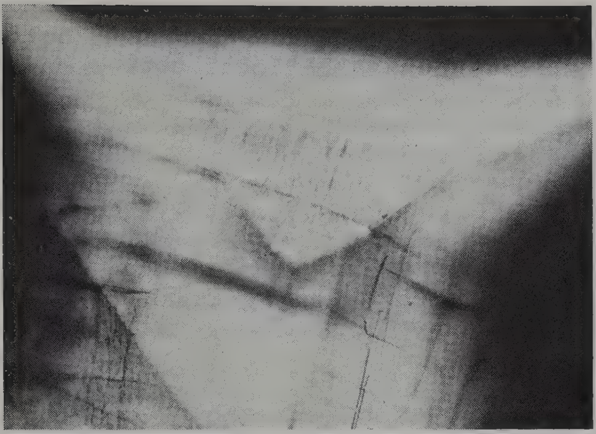


Figure 18.38 Synthetic emerald-coated beryl (Symerald) showing the reticulation of crack-like markings and one unpolished facet

beryl; secondary flux-lined healed fractures resembling veils at low magnification; and two-phase inclusions along the edges of the basal pinacoid and sometimes parallel to the *c*-axis. Lennix emeralds have been found with no iron but with vanadium. Some contain three-phase inclusions similar to those seen in natural Colombian stones.

The Biron hydrothermal emerald contains both chromium and vanadium as well as chlorine. It was first produced in Western Australia early in the 1980s. In about 1988 the Emerald Pool Mining Company (Pty) of Perth, Australia, claimed that the source of their product was natural emerald and that a secret and unique process was used to convert low-grade material from their mine into high-grade emerald. Examination proved that Pool material was Biron-type synthetic emerald. The stones show considerable clarity but contain characteristic inclusions of gold in various forms, phenakite crystals, large two-phase inclusions, nail-head spicules with gas and liquid phases, comet-like white particles, parallel needle-like structures, veils of flux and dark metallic inclusions. The SG is 2.68–2.70, the RIs are 1.570–1.571 and 1.577–1.578, and the DR is 0.007–0.008. Chlorine is present in the Biron stones but not in natural emeralds.

Full Lechleitner hydrothermal emeralds have shown the presence of layers and sublayers parallel to the table with colour zoning between subsequent layers and sublayers. Schmetzer (*Journal of Gemmology*, 1990) summarises the Lechleitner product types as follows:

A Flux growth of emerald on seed plates of natural beryl. Only a few samples ever made 1956–58.
B Pre-shaped natural beryl seeds overgrown hydrothermally. Seeds were colourless or slightly greenish. Made and marketed between 1959 and 1972.
C Natural beryl seeds cut at oblique and variable angles to the *c*-axis.

Hydrothermal emerald overgrowth. Grown in 1962 and 1963; samples sent to laboratories only.

D Fully synthetic hydrothermal first made in 1964; several autoclave runs needed, hence the presence of layers and sublayers.

E Very few grown for study in 1961 or 1962. Flux-grown seed plates with hydrothermal overgrowth.

F Growth began in about 1972 and ran up to the 1980s. May be an improvement of type A process. Presumably flux grown since no water present; basal plates of natural or synthetic beryl used as seeds.

Russian hydrothermally grown emerald is made in steel autoclaves without precious metal inserts using seed plates of colourless beryl. Distinct amounts of chromium, iron, nickel and copper are incorporated and characteristic microstructures are found. The RI range is 1.580–1.586 to 1.573–1.579, with a DR of 0.006–0.007; the SG is 2.68–2.70. Step-like growth lines and colour zoning are characteristic.

Gilson has tried out an emerald containing chromium and nickel (flux grown) which gives a yellowish-green colour. The Gilson operation was acquired in the 1980s by Nakazumi Earth Crystals Corporation. The Gilson emerald had RIs of 1.563 and 1.559, with an SG of 2.65. Chromium and nickel were the dominant colour-causing elements with smaller amounts of V, Fe and Cu. Absorption bands are due to the presence of Cr^{3+}, Ni^{3+} and Ni^{2+}, differentiating this product from Russian chromium- and nickel-bearing hydrothermal emerald. The Gilson stone was yellowish-green.

A quick, non-destructive separation of natural from synthetic emerald can be carried out by infra-red spectroscopy using a Fourier transform instrument to give rapid analysis of results. The spectra vary according to the orientation of the sample with respect to the incident IR beam, giving very weak to strong response with direction, owing to beryl's birefringence. It is not difficult to separate natural and hydrothermal beryl, which contain water, from flux-grown material from which water is absent. Hydrothermal emeralds show absorption features at 4375, 4052, 3490, 2995, 2830 and 2745 cm^{-1} in the far infra-red, while natural stones do not.

An epitaxial flux growth of emerald on to opaque white beryl has been sold under the trade name Emeraldolite. The material has been made in France, and so far specimens have been opaque. In contrast to the method of growth of such products as the Lennix emerald, where the Al_2O_3 and SiO_2 are dissolved from the crucible itself with a typical flux of lithium molybdate and a boron salt, Emeraldolite is made using a chemical rather than a physical reaction involving fluorine as a transport agent, giving faster growth.

The SG is estimated at 2.66 and the RI at 1.56, both characteristic of flux-grown emerald; the hardness is approximately 8 and the material is notably tough. Under the Chelsea filter surfaces appear intense brownish-red. A mosaic of tiny parallel crystal faces covers the overgrowth layer, and in some specimens the overgrowth had chipped to reveal the white beryl substrate. Characteristic signs of flux growth can be seen in the overgrowth.

Emeralds grown by accelerated crucible-rotation flux techniques in Novosibirsk were reported to reach 100 mm in length and 60 mm in diameter, yielding cut stones adequately sized for jewellery. The SG and RI are in the characteristically low range for flux-grown material, but stones are more satisfactorily identified by the presence of flux inclusions which occur as secondary healed fractures and as primary void fillings.

Aquamarine of gem quality has been synthesised by hydrothermal growth in Siberia. The main constants overlap with the natural material but some specimens at least show distinct amounts of Ni and a high Fe content. Spectra in the visible and UV areas indicate the presence of Fe and Ni, and IR spectra confirm the presence of water and Li in channel sites, thus proving hydrothermal growth. Under magnification a distinct boundary can be seen between the near-colourless seed and the light blue beryl; small groups of birefringent crystals have been noted as well as opaque hexagonal platelets, perhaps of hematite. Cavities with multiphase fillings and of irregular shape, feather-like structures, virtually planar and with liquid and two-phase fillings, and residues of the growth solution trapped as twisted veils are also found.

A Biron hydrothermally grown pink beryl is stated to have Ti^{3+} as the main colouring element. This can be detected by an absorption pattern characteristic of Ti^{3+} in octahedral co-ordination. Orange to blue light is absorbed by a band with two apparent maxima at 550 and 494 nm. Stones show a very strong pale pink to strong purplish-pink dichroism. The IR spectrum shows absorption characteristic of hydrothermally grown beryl.

The thermal conductance of synthetic emerald can be distinguished from that of natural emerald by the use of the Alpha test meter. The greatest difference is seen with flux-grown emeralds but hydrothermally grown stones can also be distinguished.

Alexandrite

Synthesis of the alexandrite variety of chrysoberyl was attempted in the middle nineteenth century using borate fluxes. Modern production uses lithium molybdate and combinations of lead oxide, lead fluoride and boron oxide. In 1973 Creative Crystals Inc. of San Ramon, California produced a flux-grown alexandrite with some Fe as well as Cr to give a satisfactory effect. Kyocera of Japan produces Crescent Vert Alexandrite (marketed as Inamori Created Alexandrite in the USA). Alexandrite rods have been used in lasers, but colours are too pale for the rods to be used ornamentally as only about 0.05 per cent Cr is incorporated.

In all cases so far reported the physical and optical constants are within the range for the natural material. The inclusions, typically wisps and twisted veils of flux material, give the best guide to a man-made origin, though a startling colour change is suspicious!

Czochralski-grown alexandrite shows very strong bright red fluorescence under both LW and SW UV. Most natural alexandrites show only a weak to moderate response to both types. There are no apparent inclusions characteristic of Czochralski-grown stones.

A synthetic alexandrite has been marketed under the name Nicholas Created Alexandrite. Made by J O Crystals (Judith Osmer), it has had the chromium content adjusted to give a better change of colour. The centre part of the Czochralski rod has myriads of oriented gaps or negative crystals which may resemble bubbles. Faceted stones are cut from the periphery and cabochons from the centre of the rods.

A Czochralski-grown alexandrite is being marketed under the trade name Allexite. The manufacturer is The House of Diamonair, a subsidiary of Litton Airtron. From 7 to 10 days are needed to grow a large crystal. While properties accord with other synthetic and natural alexandrite, this product shows distinct curved striae. In both colours displayed (i.e. reddish-purple and bluish-green) there is a noticeably strong red transmission.

The first synthetic cat's-eye alexandrite was reported by *Gems and Gemology* in 1987. It is manufactured by Inamori; the growth process is by pulling, as the parent firm Kyocera states in a patent assigned to them in 1986. Stones show a dark purplish-red in incandescent light and a dark greyish-green in fluorescent light. Although the fluorescence under LW UV overlaps the response of some natural material, the synthetic gives a weak, opaque chalky-yellow fluorescence under SW, with the effect seeming to be confined to surface areas; there is an underlying weak red-orange fluorescence. Unevenly spaced parallel growth features with associated colour zoning and whitish particles oriented in parallel planes serve to distinguish the Inamori stones from natural alexandrite.

Infra-red spectroscopy has helped to distinguish natural from synthetic alexandrite. Fourier transform instrumentation provides a quick evaluation of results. Observation of specimens over the range 4200–2000 cm^{-1} in the far infra-red (2300–5000 nm) has shown that natural alexandrites invariably have absorption features centred approximately at 4150, 4045, 2403 and 2160 cm^{-1} and that these are not found in synthetic stones, which give features only in the range 3300–2800 cm^{-1}, with some specimens absorbing in the range 2700–2500 cm^{-1} and others with absorption between 3700 and 3300 cm^{-1}. Absorption features between 3300 and 2800 cm^{-1} are always stronger in natural stones. This may be attributed to the absence of water in the synthetics.

Cavities in an alexandrite were shown to contain a variety of substances using qualitative energy-dispersive analyses with the help of a scanning electron microscope. Fissures surrounding inclusions were found to contain tin, copper, nickel and lead (this may have come from the polishing process). The presence of potassium-rich aluminium silicates, however, proved the natural origin of the stone.

Jadeite

In 1987 General Electric announced the synthesis of jadeite in a variety of colours. As the main properties do not serve to distinguish it from natural jadeite, when and if the synthetic comes on to the market gemmologists will need to look for broken edges on some of the thin layers from which it is made. Colours tend to be mottled and rather more intense than natural jadeite. A belt-type apparatus is used for the synthesis.

Malachite

A synthetic malachite made in Russia exhibits three distinct types with banded, silky and bud-like structures. The malachite is synthesised from aqueous solutions and can only be distinguished from the natural mineral by differential thermal analysis, a destructive testing method.

Synthetic Garnets

These hard, highly refractive materials are not garnets in the chemical sense since they are not silicates, but they possess the same structure as natural garnets and have the general formula $A_3B_2C_3O_{12}$, or $A_3B_5O_{12}$ if the elements corresponding to B and C are the same. Substitution can also take place as in the natural garnets. The structures will accommodate a range of dopants, the rare earths being frequently used, and their high dispersion makes the colourless varieties reasonably acceptable diamond substitutes. Work on these groups began comparatively recently, in the 1960s, when $A_3B_5O_{12}$ compounds were grown by the flux method for work on magnetic and insulating properties. The crystals grown from the flux were too small to be developed for ornamental use and it would have not been worth while scaling up the process on grounds of expense. Instead the method of crystal pulling was used. This technique, involving lowering a seed crystal to the melt surface and then slowly drawing it upwards, is also used for ruby and sapphire growth. High-quality crystals are required for laser use, and for this reason the work on crystal characterisation was hastened, giving a consequent impetus to allied but less important gemstone development.

One of the earliest of the synthetic garnets was YAG (yttrium aluminium garnet) with an SG of 4.55, an RI of 1.83 and a dispersion of 0.028 (compared with diamond's RI of 2.42 and dispersion of 0.044). Some difficulty in eliminating iron was found in early work on colourless YAG but colours were easily obtained from dopants: yttrium giving green, terbium pale yellow, dysprosium yellow-green, holmium golden yellow, erbium pink, thulium pale green, ytterbium pale yellow and lutecium pale yellow. In practice few rare-earth dopants were used for gem material. Chromium has been used to give a green which in the early days of the product was mistaken for demantoid garnet; manganese gives a darkish red, cobalt blue and titanium yellow. Neodymium, often used, will give a characteristic lilac colour with distinct colour change when the type of illumination is changed; praseodymium gives a pale green. Many of these elements give an absorption spectrum with many lines and bands; no natural mineral shows a comparable spectrum. Mechanically YAG and its analogues are hard at about 8.25. Since they are isotropic, no doubling of back facet edges can be seen. Some green YAG shows red through the colour filter; some colourless stones have been reported to show yellowish under UV and mauve under X-rays. The fluorescence spectrum has been found to show a discrete band in the yellow in some cases. No really characteristic inclusions have been reported, though some specimens show angular flux particles when they have been grown from the flux rather than by pulling.

The analogous substance $Gd_3Ga_5O_{12}$ (GGG or three Gs) has also been used as a diamond simulant, though one can hardly imagine very seriously as the SG is 7.02. This material has a hardness of 7 and is isotropic; the RI is 1.97 and the dispersion 0.045. Trace elements may result in originally colourless stones turning brown; the UV component in sunlight may be enough for this, but the effect is usually reversible when the stone is removed from UV. Some GGG shows a fluorescence spectrum under both types of UV and under X-rays. This is accompanied by a pale straw fluorescence under LW and a peach colour under SW. Under X-rays the stones may fluoresce lilac. GGG, like YAG, can be doped with trivalent ions such as Cr (green), Pr (yellow) and Nd (lilac with colour change). Elements with divalent ions need a coupled substitution with a four-valent ion such as silicon. Examples are blue from the replacement of $2Al^{3+}$ with $Co^{2+} + Si^{4+}$. Manganese coupled with silicon gives a pink to red. In general, coloured GGG is rare; the growing number of collectors of synthetic gemstones will pay surprisingly high prices for them today.

Cubic Zirconia

The most successful diamond simulant so far is cubic zirconia (CZ), a hard, highly dispersive isotropic version of the ornamentally insignificant monoclinic ZrO_2 baddeleyite. To obtain a cubic form stable at room temperatures, either yttrium or calcium needs to be added: these are incorporated as the oxides CaO or Y_2O_3. Though ZrO_2 has been grown by the flux method, the high melting point of 2750 °C makes that method unsuitable for the growth of large transparent crystals; most flux-grown crystals are monoclinic in any case. As no container can withstand the temperatures required, a method which has come to be called skull melting (from the shape of the apparatus) is used (*Figure 18.39*).

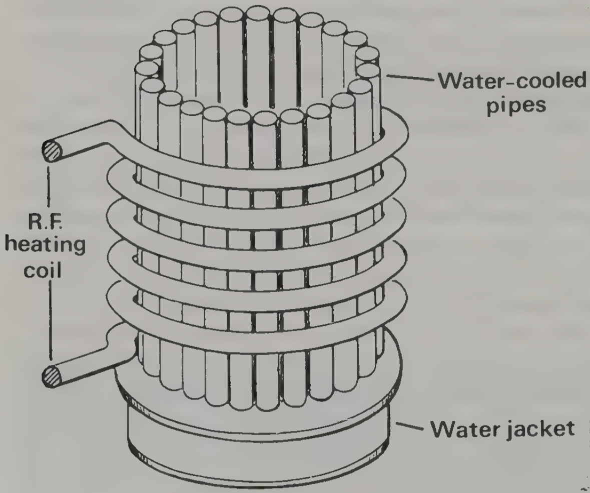


Figure 18.39 Sketch of a skull-crucible apparatus showing the vertical water-cooled pipes and the radio-frequency induction coil

Scientists of the former USSR devised the cold crucible (an alternative name to skull melting, and more descriptive). A block of zirconia powder incorporating some zirconium metal is placed inside a cup (skull) with an open top, surrounded by copper tubes (fingers) containing cooling water. Radio-frequency heating (4 MHz, up to 100 kW) melts the powder inside the block. The heating is helped by the incorporation of some zirconium metal which heats up first. Then the zirconia powder close to the heated metal also begins to conduct electricity and to melt, the oxygen surrounding the open apparatus contributing to further zirconia formation. The powder can be topped up, but a 1 mm skin closest to the cooling water remains unmelted. The skin reduces the possibility of unwanted elements entering the melt from the apparatus materials. Crystals nucleate at the bottom of the skull, growing to form columnar crystals (*Figure 18.40*).

Figure 18.40 *A single crystal of cubic zirconium oxide (weighing around 600 carats) as broken out of the mass of crystals in the skull crucible*

Grown crystals are annealed in air for about 12 hours to eliminate any strain, and can then be faceted. A charge of 1 kg will give a maximum of 500 g of facetable material.

Yttrium-stabilised zirconia has hardness 8.25, SG 5.95, RI 2.171 and dispersion 0.059, with some greenish-yellow or reddish fluorescence. There may be parallel rows of small semi-transparent isometric crystal-like cavities extending into hazy stripes of tiny particles. Faceted stones may have rounded facet edges, small chips or percussion marks. Calcium-stabilised zirconia has hardness 8.5, SG 5.65, RI 2.177 and dispersion 0.065, with some distinct yellow fluorescence. The form is virtually inclusion-free, with faceted stones showing similar features to the yttrium-stabilised stones. Both types of CZ have a far lower thermal conductivity than diamond, and the polished surface will break an ink drop into beads, contrasting with the coherent drop seen on diamond.

CZ is doped to give a variety of colours. Nassau lists the following:

CeO_2,Ce_2O_3 to give yellow, orange, red
CuO,Fe_2O_3,NiO,Pr_2O_3,TiO_2 for yellow, amber, brown
Er_2O_3,Eu_2O_3,Ho_2O_3 for pink
Cr_2O_3,Tm_2O_3,V_2O_3 for olive green
Co_2O_3,MnO_2,Nd_2O_3 for lilac, violet.

CZ is opaque to X-rays and is thus easily distinguishable from diamond. For everyday testing the thermal conductance probe is probably the most convenient instrument, followed by the reflectance meter. Some manufacturers have incorporated both methods of testing in the one instrument (see Chapter 32).

Emerald-green and good-quality sapphire-blue colours were achieved in cubic zirconia in the 1980s, although production of CZ in general took off early in that decade. To produce the emerald and sapphire colours, much more stabiliser is added than usual. The original Russian manufacturer called this product C-Ox.

White, pink and black non-transparent CZ has also been produced in Russia. The material is sold as cabochons or as beads. The white material is a uniform milky white and the pink is a uniform medium pink. Using strong transmitted light the cabochons show banded or striated colour distribution. Some of the black pieces appear dark brownish-red with strong transmitted light. The lustre of all samples is high.

A dark yellowish-green CZ appeared green through the Chelsea filter and gave absorption bands at 607,583,483,472 and 450–443 nm. The product resembled good-quality tourmaline.

Opal

Once the cause of the play of colour in opal had been established in the 1950s, the way was clear for scientists to attempt the manufacture of an artificial opal-like material. Three stages are necessary for successful synthesis: the production of uniformly sized spheres (of whatever material); the settlement of the spheres in an orderly close-packed array; and the consolidation of the structure, filling the voids between the spheres with a substance that will produce a hard material that can be fashioned.

If the sphere material is silica the product can be called synthetic opal; if other substances are used, opal simulant or imitation is a preferable term.

Silica spheres may be prepared by dispersing an organic silicon compound in fine droplets in an alcohol-water mixture. Tetraethyl orthosilicate $(C_2H_5O)_4Si$ has been used. When ammonia or similar mild alkali is added to the mixture, which is carefully stirred, silica spheres containing some water are formed by the reaction

$$(C_2H_5O)_4Si + 2H_2O \rightarrow SiO_2 + 4C_2H_5OH$$

(The spheres must all be the same size.) It may take one year to settle the array, which will then be sintered and subjected to a small degree of pressure before fashioning. Gilson began producing opal in various types in 1974: black, white,

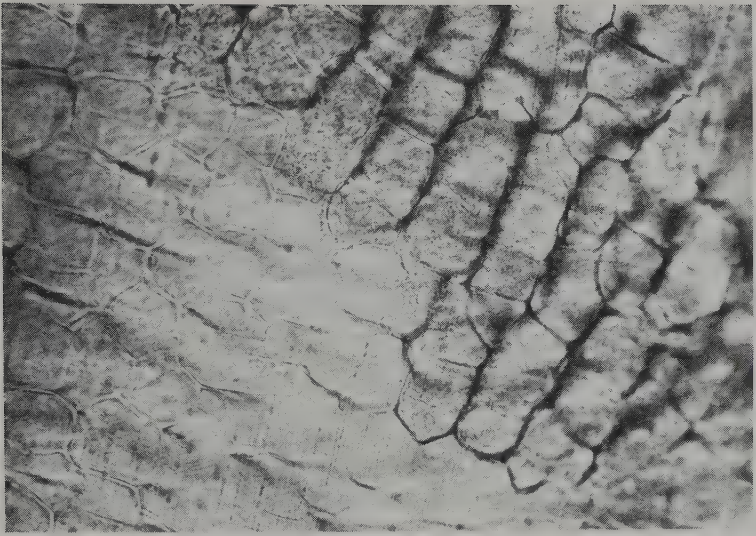


Figure 18.41 Gilson synthetic white opal, showing lizard-skin shrinkage cracks: × 118 (photo W F Eppler)

water and fire opals are on the market, the quality often being very high. A diagnostic lizard-skin effect (*Figure 18.41*) can be seen within the patches of colour; stones may also show a chalky-blue fluorescence with a similar but stronger surface glow, with some phosphorescence. These effects will not be seen in all Gilson opal products, but the glow where seen is stronger under LW UV. Gilson opal uses silica spheres, but the composition does vary: some yellowish-brown stones contain a variety of organic compounds, and another sample has been reported to contain about 0.5 per cent crystalline ZrO_2.

Where silica spheres are not used, a variety of substances has taken their place. Latex, for example, gives a stone with a very low SG, only just above 1.0. The stones are hardened by impregnating with another plastic with a different RI. Another product has been shown by IR spectroscopy to consist of a co-polymer of styrene and methyl methacrylate. This stone had an SG of 1.17 and an RI of 1.48.

Gilson has produced a hydrophane opal which improves in appearance after being placed in water. The play of colour in the stone examined was predominantly orange and appeared in small angular patches. Transformation on immersion took approximately 35 minutes to reach its full effect. On removal from the water the stone appeared slightly more transparent than before.

A sugar-treated opal coated with plastic has been reported, with spot RI readings on the dome of 1.45 and on the base from 1.56 to 1.57. Under LW UV the dome fluoresced a very strong yellow-green, while the base gave a very strong chalky blue-white. SW UV gave similar but weaker reactions. The surface could be indented by the point of a pin.

Examination of Kyocera products showing a play of colour (opal imitations with dark or light background) shows that they consist of amorphous silica glass with no admixture of water; thus they fall outside the compositional range of natural opal. They should be designated as opal simulants.

Less Common Synthetic Products

Materials described in this section are known to have occurred as fashioned stones and all are likely to turn up from time to time. This could be said of almost any man-made substance, but only those which are persistently though sporadically reported are included here. Some have natural counterparts, others not. All materials listed are transparent.

Bismuth germanate ($Bi_{12}GeO_{20}$ or $Bi_4Ge_3O_{12}$) These can give a fine orange with hardness 4.5, SG 7.12, RI 2.07. Isotropic.
Bismuth silicate ($Bi_{12}SiO_{20}$) Also gives brown to orange; colourless crystals may be obtained by annealing. Isotropic with RI near 2.0.
Bromellite (BeO) Very hard (hardness 9) hexagonal material with SG 3.01 and RI 1.720–1.735. Rarely cut owing to the toxicity of beryllium dust. Usually colourless.
Fluorite (CaF_2) A wide range of dopants has been used to produce coloured fluorites with the same properties as the natural mineral. Spectacular examples include a colourless crystal with a brilliant green fluorescence with exceptionally long phosphorescence under X-rays and red crystals, unknown in nature.
Germanates With similar properties to silicon, germanium has been used in a number of compounds, some of which have been transparent. As well as the bismuth germanates cited above, a lead germanate ($Pb_5Ge_3O_{11}$) of a fine yellow is known.
Periclase A colourless though sometimes doped isotropic material with hardness near 5, SG 3.55–3.60 and RI 1.73. The trade name Lavernite has been used; some stones fluoresce whitish in UV.
Phenakite (Be_2SiO_4) A vanadium-doped crystal is known with a most attractive light blue colour, and colourless crystals could easily be produced. Properties as for the natural material.
Scheelite ($CaWO_4$) Various dopants are added to colour this material, which is a possible diamond simulant when colourless. The strong sky-blue fluorescence under SW UV is the most spectacular feature of the colourless variety.
Silicon carbide (SiC) Very hard (hardness 9.5) anisotropic greenish material whose dispersion (twice that of diamond) may cause confusion until the DR (0.043) is spotted. SG 3.20, RI 2.648–2.691.
Yttrium compounds other than YAG Include: (1) $YAlO_3$ with hardness 8+, SG near 5.35, RI 1.938. Isotropic; may be colourless diamond simulant or be coloured by rare-earth dopants. (2) $Y_3(Al,Ga)_5O_{12}$ with a strong red fluorescence under LW UV; has SG 5.05–5.08, RI 1.88–1.90; a possible imitation of green grossular but with observable flux inclusions. (3) Y_2O_3 with trade name, Yttralox is a ceramic product with a high dispersion, SG 4.84, RI 1.92 and hardness 7.5–8. It is isotropic.
Zincite ($(Zn,Mn^{2+})O$) Has been doped to give a variety of colours. Hardness about 4.5, SG near 5.5 and RI 2.0; hexagonal.

Zircon Zircon and some analogous substances including $ThGeO_4$,Mg_2SiO_4 and $ZnSiO_4$ have been grown. Hydrothermal zircon doped with vanadium gives a fine purple. As zircon is soluble in most convenient fluxes, the hydrothermal method is used for growth. Rare-earth dopants colour the analogues.

The materials described above are all capable of being grown to reasonably large sizes. Various other materials have been synthesised. Greenockite (CdS) is orange-yellow, with hardness near 3.5, RI 2.5 and SG 4.9. Powellite ($CaMoO_4$) with SG 4.34, RI 1.92–1.98 has been produced in a light blue faceted form (see also below). Lead tungstate, highly dispersive, soft and yellow, is $PbWO_4$ (the natural mineral is stolzite) and is tetragonal. Berlinite is $AlPO_4$ and structurally isomorphous with quartz, showing left- and right-handed forms; it shares a similar interference figure with quartz, and a possible fashioned bead could be mistaken for quartz if this test were used. The hafnium analogue of zirconia, HfO_2, has been grown in a colourless form but is far more expensive to manufacture than zirconia owing to the cost of hafnium feed material. Cut stones of lithium tantalate, the monoclinic zinc tungstate sanmartinite, Nd-doped YVO_4, the lead molybdate wulfenite (highly dispersive) and the magnificent red proustite (Ag_3AsS_3) are also known.

The trigonal material lithium niobate has a dispersion in excess of that of diamond (0.130 against 0.044) but its high DR of 0.090 gives it away via the doubling of back facet edges. Grown by the Verneuil process, it has a hardness of just over 5, SG 4.65 and RI 2.2–2.3. Coloured versions from doping are occasionally seen. An early trade name was Linobate.

During January 1972 there was a report of the examination of a cut powellite, a calcium molybdate-tungstate, $Ca(Mo,W)O_4$, a mineral allied to scheelite. Powellite has a hardness of 3.5 on Mohs's scale; the refractive indices are given as 1.974 and 1.984, and the SG is 4.34. The stone was pink in colour owing probably to doping with holmium. The fluorescence under short-wave ultra-violet light was said to be green, and unlike scheelite, which glows blue under the short-wave lamp and is inert under the long-wave lamp, this specimen of powellite was said to glow green under the long-wave lamp as well as under the short-wave lamp. Natural powellite glows yellow to golden-yellow under the short-wave lamp only, so this may give a clue to the synthetic nature of the stone.

Oolongolite, with RI 1.93–2.00, dispersion 0.030, SG 6.7–7.0 and hardness 7.5–8, and singly refractive, is being manufactured in Switzerland. Colours seen include dark and medium blue, medium and dark bluish-green, lilac and colourless. The material is reported to have a garnet-type structure.

Sodalite has been synthesised in China. Crystals are heavily included and the blue colour arises from irradiation.

Imitation Gemstones

We have already seen that a synthetic gemstone must have a natural counterpart, but any gemstone can imitate another; to the collector of synthetic stones the natural version can imitate the synthetic as well as the other way round! The chief gemstone imitation is of course glass, but some substances described as 'synthetic' are more accurately classed as imitations; they include Gilson lapis lazuli and coral, which are described in Chapter 19.

19

Gemstone Simulants

Faience

The simulation of precious objects by substances of much less value reaches back to pre-history. An artificial blue frit composed of quartz, malachite, calcium carbonate and sodium carbonate had been carved into small objects as early as the 6th dynasty (3503–3335 BC). It is, however, faience, a glazed siliceous ware made in Egypt as long ago as pre-dynastic times (before 4777 BC), which is the more important as an early imitation gemstone.

Faience, which was used for beads, necklet pendants and rings, consisted of an inner core of gritty material, probably powdered quartz, and an outer coating of coloured vitreous glaze. Occasionally a thin middle layer was present between the core and the glaze which was apparently incorporated in order to enhance the glaze. Although glaze was used in Egypt so early, glass itself was not used before the 18th dynasty (1587–1328 BC).

Glass

The glassy state arises when a melt becomes so viscous when it cools that the crystalline state cannot form and only short-range atomic order is found. During the passage of time some of the constituents of the glass may crystallise, a process known as devitrification; this is positively encouraged when glass ceramics are made. The glassy or vitreous state can be described as metastable, and glass is one of the few amorphous substances known.

Silica (SiO_2) forms the basis of most glasses as it is always prone to form glassy substances on cooling. Most non-ornamental glass such as window glass is Na-Ca glass. The addition of boron or aluminium oxides gives greater resistance to heat and to chemical attack. Lead oxide increases dispersion and improves optical performance. Lead (flint) glasses are used for cut glass ('crystal') ornaments and for the glass in refractometers; a high lead content may tarnish the glass which will be very soft and brittle with a high SG. When a very high dispersion is needed, thallium may be added. Colour can be given by the addition of a wide variety of agents such as selenium, copper or gold to give red, uranium compounds to give a yellow-green, and cobalt oxide to give blue. Final colour also depends upon oxidising or reducing conditions during manufacture and upon annealing after the glass is cooled. Translucent or opaque glass may need the addition of an opacifier.

Very cheap glass gemstones will be pressed in moulds, only the more expensive varieties being faceted. Moulded glass can be identified by its rounded facet edges. The names paste, strass, rhinestone and others once had specific meanings but are now used so loosely that their history is no longer relevant to modern commercial production.

Most glass used as gemstone simulants has a hardness of 5.5–6.0 and will contain large, well-shaped gas bubbles which are often elongated (*Figure 19.1*). A distinctive swirliness (*Figure 19.2*) from incomplete mixing of the constituents also helps to identify a glass which, as a poor heat conductor, feels warm to the tongue compared with crystalline substances. Any stone which is isotropic (especially when showing anomalous double refraction) and has an RI between 1.50 and 1.70 is more likely to be glass than anything else.

Some interesting glasses include beryl glass (fused emerald, scientific

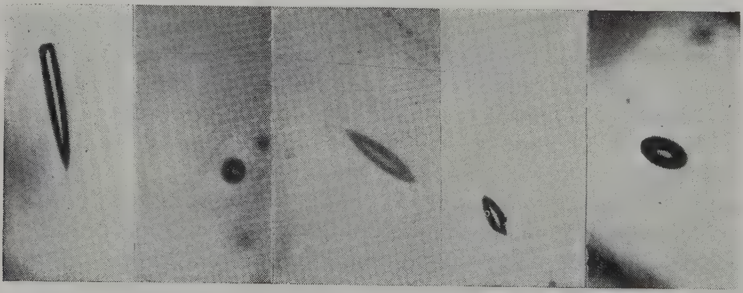


Figure 19.1 Typical bubbles in glass

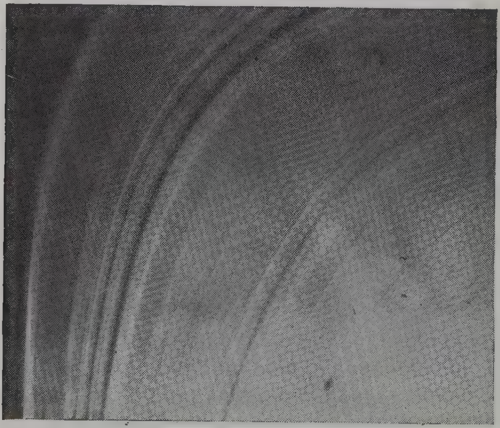


Figure 19.2 Swirl striae in a paste

emerald) with the emerald composition but made by melting the constituents and then cooling the melt. This is softer than emerald and has an RI near 1.52 and an SG varying from 2.39 to 2.49, usually 2.42. Other beryl colours are obtained by adding cobalt (mass aqua) or didymium (pink). A very convincing cat's-eye imitation (Cathay stone, Catseyte) is made with thin glass optical fibres in fused mosaics, the fibres being of several distinct glasses (fibre optic faceplates). Stacked in cubic or hexagonal arrays, they give a fine sharp eye as there can be about 150 000 fibres per cm^2 (over a kilometre of fibre in a small cabochon).

Fluorides and phosphates may be added to glass to give an imitation of moonstone or even pearl. The glass must contain lime so that the calcium compounds can precipitate to give the translucency desired.

A star-stone can be made by pressing a white opaque glass in a mould so that ridges in star ray formation are impressed into it. The cabochon is then coated with a deep blue glaze which is thinly applied, causing the star to appear below the surface. A less effective star is made by scratching star rays on the back of a glass cabochon or cementing rayed foil to the back. An opal imitation has been made by foiling with tinsel.

An interesting partly crystallised glass was made in the 1970s with the aim of simulating jade. Under the names Meta-jade, Victoria stone or Kinga-stone, glass of varying degrees of devitrification and of different colours was offered. A chatoyant effect can be obtained by incorporating fibrous inclusions in parallel bands. Iimori stone, from the same source, Iimori Laboratory of Tokyo, was a clear or translucent jade imitation, also with a variety of colours.

Goldstone is a glass simulant of sunstone (*Figure 19.3*), the glass being filled with cuprous oxide which reduces to metallic copper during later annealing. If the glass host is blue, an effect resembling lapis lazuli is obtained.

Glass with a near-metallic lustre and black body colour showed an indistinct red/green blink to the RIs of 1.59 and a (very low) 1.35. The SG was 3.21 and

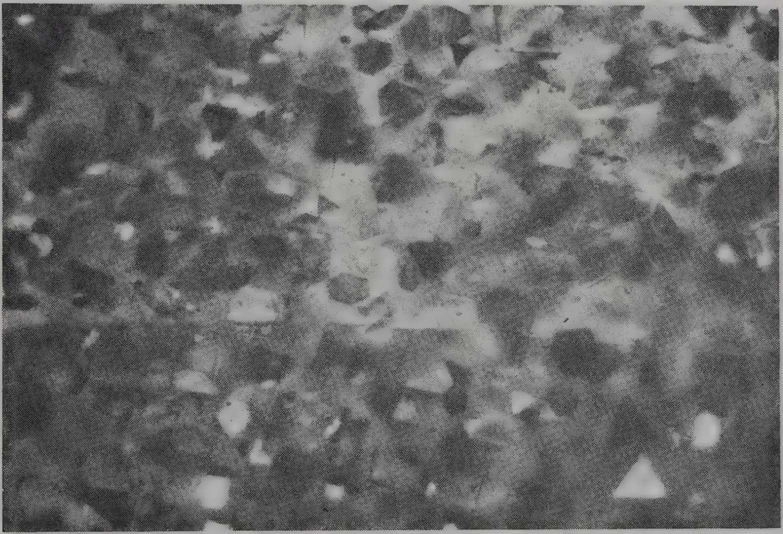


Figure 19.3 Goldstone, a simulate of sunstone, showing the copper crystals

the hardness 4–5. It was not possible to go from the high to the low RI reading by rotating the stone. It is possible that some at least of the optical anomalies result from the addition of an opacifier to the glass and from tarnishing.

Radioactive glass with a fine emerald colour gave an RI of 1.635 and SGs of 3.754 and 3.767. Chalky orange and chalky green fluorescence could be seen under LW UV and SW UV respectively. Strong absorption extended from 700 to 600 and from 440 to 400 nm with a set of two lines centred at 470 and 460 nm. Radioactivity was measured at 12 × background levels.

Metal Imitations

Hematite is the mineral most imitated by metals. One imitation is a steel-grey titanium dioxide with a yellow-brown streak (hematite has a red streak). The hardness is about 5.5 and the SG near 4. Another imitation appears to be made from powdered lead sulphide with some added silver. The hardness is 2.5–3 and the SG 6.5–7. It is a brittle and easily fusible substance. Hemetine is the name given to a sintered material with several constituents, including lead sulphide (galena). It has a black streak and an SG of 7. Natural hematite is non-magnetic but some of the simulants will be attracted by a magnet.

A hematite imitation made from silicon produced from a refined melt by the pulling process has SG 2.33 and hardness 7.

Opal Simulants

The material 'opal essence', formerly Slocum Stone (manufactured by John S Slocum of Rochester, Michigan), where not too gaudy is a good imitation of opal. It is a glass made by a controlled precipitation process, with SG 2.4–2.5 and RI 1.49–1.50. The play of colour seems to come from included tinsel-like laminated material which diffracts light from the spacing between the laminations, approximately 0.3 μm. Typical gas bubbles and swirl marks indicate a glass. It is possible that some of the colour flakes arise from the disrupted remains of what were probably continuous sheets produced by a sedimentation process.

In some plastic opal imitations the lizard-skin effect cannot be seen. Another type, in which the colour domains were scattered rather than compact, transmitted wavelengths at about 430 nm, as does natural opal which it closely resembles. This opal is made from colourless polystyrene in the main, but some structural features in both types give an absorption region at 590–565 nm. The RI is 1.485 and the SG 1.18. A strong bluish-white fluorescence with no phosphorescence can be seen under LW UV.

Some synthetic opals give a blush (not necessarily of pink or red) which sweeps over the surface as the stone is turned. An early Gilson opal had colour bands rather than patches; they followed the long direction of the oval cut stone.

Colour-enhanced opals are made from poor-quality yellowish to greyish Brazilian opals, plastic impregnated by *n*-butyl methacrylate, probably in a vacuum chamber. The RI is 1.41 to 1.46 and the SG is 1.85. Excess polymer can be scraped from the surface.

A plastic imitation opal with the trade name Opalite was reported in 1989. Sold as polished cabochons, the stones show a true play of colour with both pinfire and flash effects in various colours. Under incandescent light, the stones are a milky bluish-white and translucent; using transmitted light they appear a pinkish-orange. Stones are probably assembled, as a layer of a different plastic substance overlies part of the base. The outer layer may be an acrylic resin coated over the polystyrene imitation opal to protect it. The RI is 1.50–1.51 (natural opals are in the range 1.37–1.47); the SG is approximately 1.20 (natural opal is in the range 1.99–2.25). The colour patches show characteristic lizard-skin patterning, confirming artificial origin. The hardness of the Opalite was found to be 2.5, against 5.5–6.5 for natural opal. Opalite is hydrophobic and is warmer to the touch than natural or synthetic opals. It will indent with the point of a pin and can be diagnosed by IR spectroscopy.

Plastic imitation opal seen in Thailand had a vague spot RI of 1.57, with a strong chalky bluish-white fluorescence under LW UV and a weaker yellowish-green reaction under SW. Fine absorption lines extending from 700 to about 430 nm could be seen, with a typical plastic reaction to the hot point.

Colourless glass with fragments of synthetic opal embedded in it has been marketed under the name Gemulet. The RI of the glass is 1.47, close to that of the opal at 1.45, so giving the latter a low relief. The play of colour thus appears to be coming from the larger stone.

Chips of white opal, boulder opal and rock matrix with a transparent colourless binder have been offered in Australia as natural opalised shell. Various tests show that the binder is a plastic.

Porcelain

Porcelain has occasionally been used for the production of some semi-opaque gemstone simulants. Porcelain, or pottery, is simply a baked uniformly fine clay and the frits and faiences mentioned at the beginning of the chapter are a type of porcelain. The material is not as a rule cut and polished, but is moulded and then glazed with a glassy coating; thus the refractive index will be of little assistance in its identification. On the other hand the specific gravity is fairly constant at 2.3 and this will give an indication of the nature of such material, for, with the exception of a few minerals like sodalite and thomsonite, this value is not common to ornamental gem materials.

Ceramics

Finely ground inorganic powders which are heated, fired or sintered and sometimes compressed will produce a polycrystalline solid known as a ceramic. A binding agent with a low melting point can be used to help the particles adhere to one another. The surface, as in porcelain, is often glazed. Natural substances like turquoise, jade and lapis lazuli have similar compositions.

A lapis lazuli simulant made by Gilson is sold either with or without pyrite inclusions. More porous than natural lapis, the Gilson product has a lower SG at near 2.46 (natural lapis is 2.81). The hardness is 4.5 compared with the 5.5 of the natural stone, and the RI is a vague edge at 1.50. Some quartz and iron has been detected by X-ray analysis. It has been considered that the product consists of ultramarine and hydrous zinc phosphates with the added pyrite.

A possible ceramic imitation of lapis lazuli seen as a rectangular bar-cut cabochon of 4 carats had RI 1.55 and SG 2.85. There was a strong chalky greenish-yellow under SW UV but weak red under LW. No evidence of dye was found. EDXRF chemical analysis revealed patterns from the coloured areas consistent with phlogopite mica. The colouring agent is not so far identified.

Gilson has also manufactured a turquoise simulant which probably approaches a ceramic substance, though full details of manufacture have never been released. A medium blue is marketed as Cleopatra and a darker blue as Farah. Thought to be made by precipitation, grinding and pressing with no trace of the iron normally found in natural turquoise (suggesting the use of pure starting materials rather than ground natural pieces), Gilson turquoise comes with or without matrix; it is only slightly porous and the colour is stable. When the surface is examined with a magnification of 30–40 × , a mass of angular dark blue particles against a whitish groundmass is seen. The SG is near 2.74 and the average RI is 1.60. The absorption band at 432 nm is faint, leaving the microscope as the only simple test available.

An imitation turquoise made by Syntho Gem Company of Reseda, California, a so-called reconstituted turquoise made by Adco Products of Bueno Park, California, and Turquite made by Turquite Minerals of Deming, New Mexico, were examined together. The Adco and Syntho materials were similar to Gilson stones, while Turquite had little aluminium but a larger amount of sulphur, silicon and calcium. Though containing less iron, the Gilson product approached most closely to the composition of the natural stone. Structurally the Gilson turquoise was the only one to have the same crystal structure as natural turquoise.

Imitation turquoise has been made with pyrite inclusions and apparent veins of matrix. The stones are plastic-coated gibbsite, a clay-like aluminium hydroxide. Hot point tests inside the drill hole produce a characteristic plastic odour. No absorption line could be seen at 432 nm; the RI was 1.55. Stones had a sugary, speckled appearance.

Dyed magnesite has been used as a turquoise simulant. It has RI readings of near 1.51 and 1.70, the high birefringence of 0.19 suggesting a carbonate. The SG was close to 3.0. Magnesite will effervesce with warm HCl.

Blocks of azurite-malachite formed by compressing and impregnating chalky porous azur-malachite nodules have been offered as cabochon material. The material is tough, shows good colour and polishes well. A hydraulic ram compresses the nodules into a dense block which is then stabilised by a pore-filling technique similar to that used in stabilising turquoise.

Gilson makes a coral imitation in various shades of reddish-pink. The chief constituent is calcite from a French source, but some ingredients not found in natural coral are present. The SG is 2.44 against the natural 2.6–2.7. Both imitation and natural have a hardness of about 3.5 and both will effervesce with acids. The RI of the imitation is about 1.55 against 1.49–1.65 for natural coral. Gilson coral shows a brecciated structure while natural coral shows a wood-like graining. Gilson coral gives a reddish-brown streak; natural coral gives only a whitish mark.

Coral has been imitated by barium sulphate with a plastic binder. A 21.26

carat orange-red sawn slab gave an RI of near 1.58 with an SG of approximately 2.33. The hardness was estimated at 2.5–3. Whitish-pink veining could be seen under magnification.

Dyed marble has been offered as a coral imitation, the deception easily yielding to a drop of hydrochloric acid. A spot RI showed high birefringence. Instead of the usual coral structure a sugary, granular texture was observed.

Ceramic alumina has been used in the manufacture of cameos. The hardness of a white on blue piece was over 8 and the blue colour could have been due to cobalt. The RI was vague, between 1.75 and 1.76. Later the blue was indeed proved to be due to cobalt.

Plastics

Many of the commoner plastics have been used as gemstone simulants and most have a hardness of 1.5–3, an SG of 1.05–1.55 and an RI of 1.5–1.6. Most are made by the injection moulding process and most are sectile. Touched with the hot point, plastics usually give off sharp, unpleasant but characteristic odours.

Celluloid, one of the early plastics, is a mixture of the lower nitrates of cellulose and camphor heated under pressure to 110 °C. Acetic acid removes the risk of high flammability possessed by early celluloid. Old celluloid has an SG of 1.35, rising to 1.80 when fillers are added; it has an RI in the range 1.495–1.520, and a hardness of 2. 'Safety celluloid' (cellulose acetate) has an SG of 1.29 and a hardness of 2. It gives off a vinegary smell when touched with the hot point.

The plastic casein is manufactured from the protein part of milk, made hard when formaldehyde is added. It has an SG in the range 1.32–1.39, commonly 1.33. The RI is 1.55. It will turn yellow when touched with a drop of concentrated nitric acid, and when touched with the hot point gives off a smell of burnt milk.

The phenolic resin Bakelite yellows with age and is less tough than some of the other plastics. It shows a good range of colours and has an SG of 1.25–1.30 and an RI of 1.61–1.66. Chips of bakelite can be placed in a small test-tube and covered with distilled water which is then boiled. After boiling, a pinch of 2.6 dibromoquinonechlorimide is added. On cooling of the liquid a drop of a very dilute alkali solution is added. If a blue colour forms it indicates the presence of phenol and the specimen must be bakelite.

A bakelite modification, the amino plastic, is transparent and will take dye to give a range of colours. The hardness is close to 2, the SG is near 1.50 and the RI is 1.55–1.62.

Perspex is an acrylic resin with a low SG of 1.18 and an RI of 1.50. It is clear and resembles glass. Used for the manufacture of cheap beads and for the cores of imitation pearls, it is quite serviceable as a gemstone simulant. Polystyrene resins may be moulded to look like faceted stones, and have an SG of 1.05 and an RI of 1.59. They are easily dissolved by many organic liquids, including di-iodomethane.

Descriptions of other gemstone imitations, including diamond simulants, are included in the appropriate chapters.

20

Composite Gemstones

A composite, or assembled, stone is no new device, for they were known since the days of the Roman Empire; the Roman lapidaries constructed their *jaspis terebinthizusa* by cementing together three different coloured stones with Venice turpentine. Many different types of doublets were mentioned by Camillus Leonardus as early as 1502. King refers to Italian glass intaglios of the eighteenth and nineteenth centuries which could not be distinguished from the real except by the use of a file, and to baffle this mode of detection the dealers used the ingenious contrivance of backing the paste with a slice of real stone of the same colour. Presumably any test would be made on the base rather than on the incised front. King also refers to the fact that the same method is used for forging all coloured stones, a paste of proper colour being backed by a suitably faceted rock crystal.

Composite stones are generally described as *doublets* when the stone consists of two main pieces, and *triplets* when three pieces are used. Internationally there are some slight differences in the nomenclature, for in North America the modern soudé-type stones are known as triplets while in Europe these stones are called doublets.

The fundamental reason for the manufacture of these composite stones is in many cases to obtain a larger stone from a given natural material, or to produce a stone of much better colour and appearance. Other considerations are the provision of a harder wearing and more lustrous surface to a glass imitation, which is probably the reason underlying the making of the garnet-topped doublets, although it has been suggested that the use of garnet here is to overcome the testing by a file. Further, doublets may be made for the purpose of supplying a rigid support for gem material which can often be found only as thin and easily damaged slices. This is the most logical reason for the production of opal doublets.

True Doublets

The true doublet or genuine doublet consists of two parts constructed by cementing together two suitably fashioned pieces, one for the crown of the stone and the other for the pavilion, both pieces being cut from similarly coloured material of the same species (*Figure 20.1a*). Thus true doublets can be made of two pieces of diamond, or of ruby, sapphire, emerald or other species of stone. Except in the case of opal on opal doublets, true doublets are rarely encountered. However, there has been a report of a jadeite doublet in which both sides were jadeite: the top was a thin layer of green jadeite and the bottom a thicker layer of white jadeite in the form of a tablet, 20 × 6 × 2.5 mm.

Semi-Genuine Doublets

When a piece of genuine material of the stone simulated forms the crown of the composite stone and this is cemented to a pavilion cut from a less valued stone, or even glass, the stone is known as a semi-genuine doublet. The most important stone of this type is the diamond doublet (*Figure 20.1b*), a composite stone where the crown consists of a piece of real diamond and the pavilion is any suitable colourless stone, such as rock crystal, white topaz, synthetic white sapphire or spinel, or even glass.

When unset such diamond doublets may easily be detected, not only by the join at the girdle which may be seen when the stone is inspected with a hand lens, but convincingly when the stone is immersed in di-iodomethane or monobromonaphthalene, when the difference in relief of the diamond top and the material of inferior refraction forming the base is readily seen. It must be pointed out that there is always a danger in immersing such doublets in these liquids as they may have a deleterious effect on the cement and cause pseudo-flaws or even cause the two parts to separate.

Most often diamond doublets are set with rubbed-over settings, which in England are often called gypsy settings, and such a setting effectively covers the join of the two pieces. Diamond doublets may be readily detected if the jewel is held so that the table facet of the stone is slightly tilted away from the observer, when a dark border to the opposite edge of the table facet will be seen (*Figure 20.2*). This is due to reflection of the facet edge on the cement layer. There may also be seen prismatic colours due to air films which have penetrated along areas of deterioration of the cement layer. A word of warning: the so-called *lasque diamonds*, large thin parallel-sided plates, often with the top edges faceted as seen in Indian jewellery, may also show the dark shadow of the table facet edge reflected from the lower surface of the stone, which may lead to an incorrect diagnosis.

Except for diamond doublets and opal doublets, semi-genuine doublets are uncommon. However, Weinstein mentions pale-coloured emeralds backed with green glass, and an American journal has reported a semi-genuine doublet made of a crown of flawed aquamarine and a base of green glass, and another in which the top was a very transparent chrysoberyl cat's-eye on a darker base, the nature of which was not recorded. Recently two new types of semi-genuine doublet have made their appearance on the market. In both cases the crown of

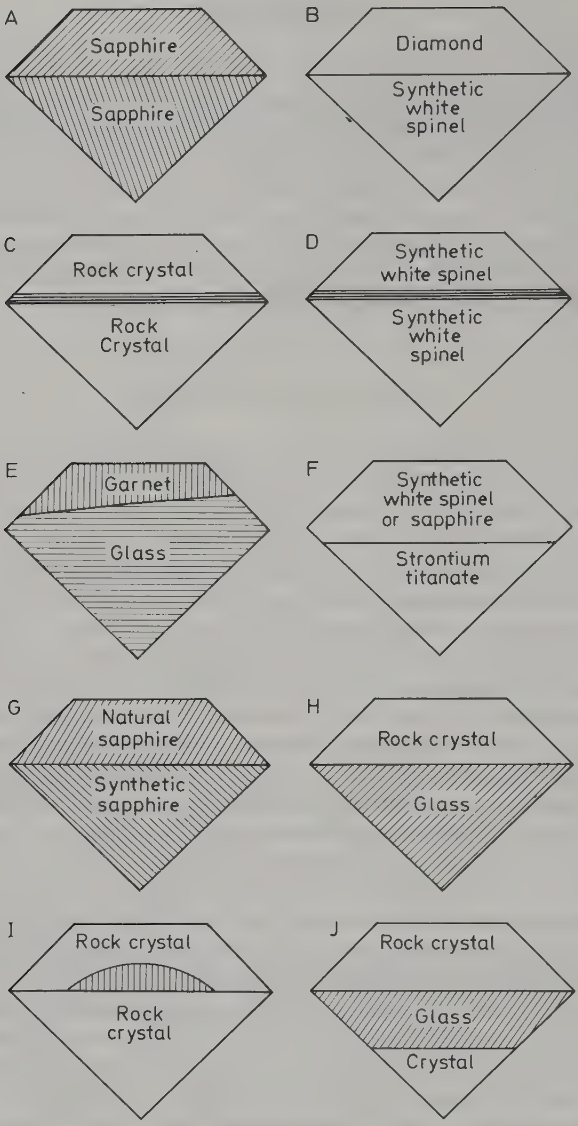


Figure 20.1 Types of composite stones. (a) True doublet with top and base of genuine stone of the species simulated. (b) Diamond doublet; real diamond top and any colourless inferior stone for the base. (c) Quartz doublet; the so-called soudé emerald. (d) Synthetic spinel doublet (soudée sur spinel). (e) Garnet-topped doublet. (f) Doublet of two synthetic stones, usually made to simulate diamond. (g) Doublet with natural sapphire top and synthetic sapphire (can be synthetic ruby) base. (h) Quartz on glass doublet. (i) Liquid-filled hollow capped doublet. (j) A triplet

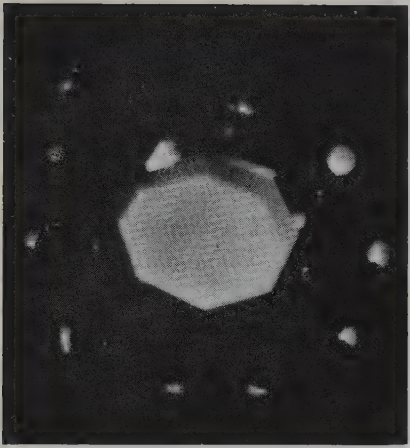


Figure 20.2 The reflection of the edge of the table facet on the cement layer, and Newton's rings where the cement has deteriorated, seen in a diamond doublet (by courtesy of the Journal of Gemmology)

the stone is made of natural greenish-yellow sapphire and the pavilion either of synthetic blue sapphire or of synthetic ruby (*Figure 20.1g*). Again, when unset the distinction is easy, but when set and of sapphire colour the natural zoning and silk of the top portion, and the fact that the stone shows the 450 nm absorption band, tend to prove the stone genuine. The base, if one thinks that far, will show the curved bands and gas bubbles of synthetic sapphire, or the use of a short-wave ultra-violet lamp will show the greenish glow of the synthetic sapphire base. The same applies to the red variety, for the base will show the curved fine lines and gas bubbles, and the long-wave ultra-violet lamp will show the base to glow crimson and the top to be inert. There is also a report of a jadeite doublet whereby the quartz top is glued with a green jelly-like cement and attached to a green-dyed base.

False Doublets

The so-called false doublets are composite stones where the crown consists of rock crystal or other colourless stone which is cemented to a suitably coloured glass (*Figure 20.1h*). Three specimens of such doublets, one of sapphire blue colour, another a purple and the third a yellow colour, gave in all cases a refractive index reading for quartz from the crown, but an isotropic reading of 1.51 for the glass base. The SGs were 2.61, 2.56 and 2.55 respectively. The blue stone exhibited the absorption spectrum of cobalt; the purple stone showed a faint cobalt spectrum with a fainter band in the blue. The danger with this stone lies in the fact that if a refractive index measurement is taken only from the table the stone could be mistaken for a true amethyst. The yellow-coloured stone resembled the yellow synthetic spinel, and like it showed a strong yellow-green fluorescent glow under ultra-violet light from the glass base. This glow, examined with a spectroscope, unlike the glow from the synthetic spinel showed a discrete spectrum, indicating that the glass was coloured by uranium. Except for the yellow stone where the strong glow masked the effect, irradiation with ultra-violet light showed the cement layer as a bright line around the girdle of the stone.

Doublets have been seen where the crown is glass and the pavilion is quartz, the reason for such a type being hard to determine. A most unusual example of a doublet was one which consisted of practically all of the stone being white topaz with just the tip of the pavilion made of a piece of natural blue sapphire. Presumably the idea was that the blue base would suffuse colour through the stone rather in the same way that native lapidaries leave colour at the base of their sapphires. It did not seem to work in the case of this doublet which may have been an experimental try-out.

Hollow Doublets

Max Bauer mentions hollow doublets. They are said to consist of a crown of rock crystal or glass which is hollowed out below, the walls of the hollow being highly polished. This cavity is filled with a coloured liquid and the whole closed in with a pavilion of the same material as the crown (*Figure 20.1i*). Such composite stones, which are extremely rare, are said to be readily spotted for the cavity of coloured liquid is visible when the stone is observed from the side.

Imitation Doublets

This term is usually applied to doublets which consists of two pieces of colourless glass cemented together with a coloured cement. Two such red-coloured specimens were found to have a glass with a refractive index of 1.52, and the SGs were found to be respectively 2.478 and 2.488. The only point of interest was that the red colouring matter gave an absorption spectrum reminiscent of that of almandine garnet.

Triplets

True triplets are constructed of three pieces, the crown being some real stone such as quartz, and the tip of the pavilion being of similar material, the central portion being, usually, coloured glass (*Figure 20.1j*). The idea behind this type appears to be that not only will the crown resist a file but the lower part of the pavilion also. Such triplets are not common.

Garnet-Topped Doublets

These are the more important types of doublets but are now slowly going out of circulation. They are made by fusing a thin slice of almandine garnet to a blob of coloured glass and are produced in many different colours to imitate many different stones, particularly ruby, sapphire, emerald, amethyst, peridot, topaz and even colourless stones (*Figure 20.1e*). It is the colour of the glass which controls the colour of the finished stone, the thin layer of garnet having little or no influence on the resulting colour.

When garnet-topped doublets were first made provides an intriguing problem. No specific mention was made of these doublets in the long series of editions of Herbert Smith's *Gemstones* until the 1940 edition, but Michel gives a very good account in his book published in Leipzig in 1926. A much earlier reference to the fusing of two parts of a doublet together is given in the Viennese book written by Schrauf in 1869. A little-known book *L'Industrie lapidaire* by Burdet attributes the invention of the doublet, as we know it, to Cartier, lapidary of the Comte de Mijoux, in 1845. Frank E Goldie, who spent his early days as an apprentice in the Jura Mountains just after World War I, tells how these stones were made

> After the day's work and our evening meal, a small pile of doublet moulds were put on the kitchen table, together with a packet or two of thin slices of garnet, and also a mound of glass squares. Everyone sat down to their respective job, even neighbours who called in to pass the time with us. Some put in the garnet, others would place a piece of glass on top. The moulds were made of baked clay, measuring about 16 in by 10 in with a number of indentations depending upon the size of doublet required. Actually it was a very pleasant way of passing an evening, refreshments were *ad lib* and the conversation always interesting and amusing.
>
> Friday was an important day, the kiln was stacked with prepared moulds, the fire lit and heated to the correct temperature. Next morning the moulds having cooled were removed. The rough doublets were then sorted into their different colours and sizes ready to be given to the local craftsmen who cut them in their homes.

Garnet is the only stone which will easily fuse to glass, and the objects removed from the firing moulds are each composed of a thin slice of garnet which has fused to a ball-like piece of glass. When these are cut no great care is taken to get the plane of joining in the plane of the girdle. Hence, the join may be perhaps half-way up the side facets of the crown, and may not even be at a regular distance from the girdle of the stone. Examination with a hand lens will show this join and, what is just as important, will show the difference in lustre of the garnet top and the glass base (*Figure 20.3*). If the stone is loose and laid table facet down on a sheet of white paper, a red ring will be seen round the stone. This is obvious with all such doublets except those of red colour, which masks the effect.

Examined by a low-power microscope, garnet-topped doublets may show crystals or reticulation of needles in the garnet top, and, owing to the fusing of the glass, a layer of bubbles in the plane of joining of the two pieces (*Figure 20.4*). The garnet used for the top of these doublets has a refractive index of about 1.78, and the glass base usually between 1.62 and 1.69, although a glass with an index as low as 1.51 has been met in these doublets. Thus, if such stones be immersed in oil and viewed sideways the difference in relief of the top and base will be strikingly revealed. The SG has little significance but is generally above 3.34 (di-iodomethane). Short-wave ultra-violet light usually induces a whitish or greenish glow in glass and this may show up the two parts of such a doublet as the garnet part is inert under such radiations.

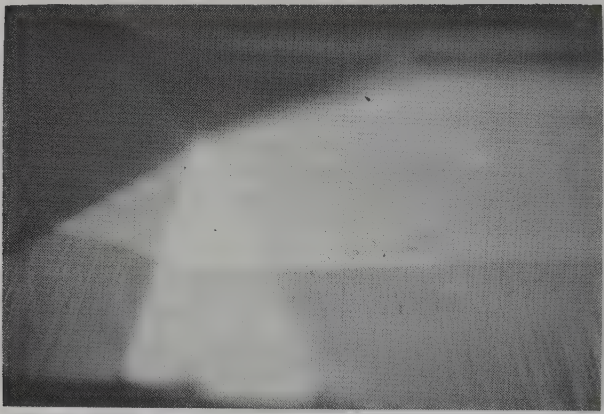


Figure 20.3 *A garnet-topped doublet showing the difference in relief between the garnet top and the glass base*

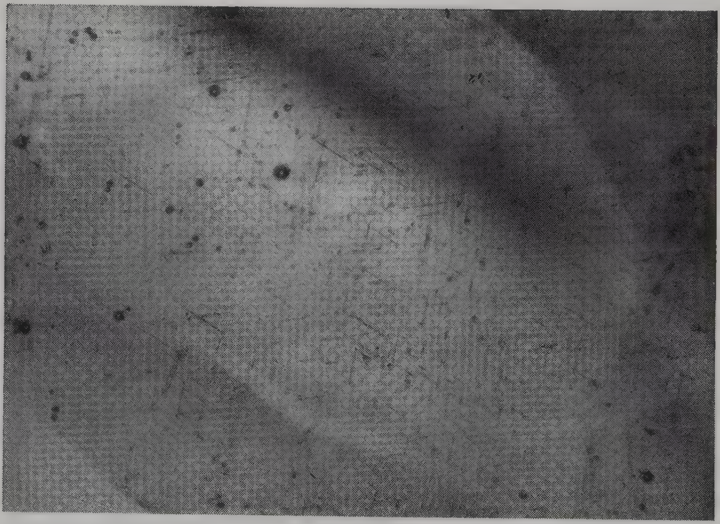


Figure 20.4 *Needle inclusions in the top and a layer of bubbles in one plane seen in a garnet-topped doublet. The difference in relief of the garnet top can also be seen*

Soudé-Type Stones

Early Soudé Emeralds (Quartz Doublets)

These stones consisted of two pieces of rock crystal forming the crown and pavilion of the stone cemented together by a green-coloured gelatine. These stones were first made to imitate the emerald and were called soudé emeralds from the French *émeraude soudé* (soldered emerald); under present legislation 'quartz doublets' may be the better term. Other colours are known, such as a sapphire blue and an 'alexandrite' colour resembling the colour of the alexandrite-type fancy-coloured synthetic sapphire. Both these stones showed the three-band cobalt spectrum with the 'alexandrite' one showing an extra band in the blue violet. The green-coloured stones of the early make showed a red residual colour when viewed through the Chelsea colour filter, and a further disadvantage of the green stones is that the colour tends to deteriorate and turn to a yellow colour, thus producing a 'citrine'. The refractive indices of 1.544 and 1.553 will, of course, indicate the nature of the stone, and between crossed polars the orientation of the two pieces of quartz are seen to be different. In all colours of these stones there was a significant lowering of SG, despite the thin layer of the gelatine. The value was found to be fairly constant at 2.62. Under ultra-violet light the cement layer will tend to glow and is most prominent at the girdle, indicating that the stones are doublets.

Modern Quartz-Type Soudé (Modern Quartz Doublets)

Believed to have entered the market during the early 1920s these composite stones are similar in construction to the earlier type, with the exception that the unstable gelatine is replaced by a layer of coloured and sintered glass – or at least that is what it is thought to be. The colour is probably due to a metallic oxide and not an organic dyestuff. In these stones the refractive index is that for quartz but the SG is higher at about 2.8; this high value has been ascribed to the heavy lead glass of the coloured layer, but this has not been proved. In North America these composite stones, which show green and not red through the Chelsea colour filter, are known as triplets. The colour layer of this type does not glow under ultra-violet light and it is said that colours other than green have been produced.

Synthetic Spinel Doublets

During 1951 Jos Roland of Sannois, France, produced a type of soudé stone in which the crown and pavilion were made of colourless synthetic spinel instead of quartz. These were known as *soudée sur spinelles*, but in English nomenclature are better termed 'synthetic spinel doublets'. These stones are made in all colours and the coloured layer may also be a sintered heavy lead glass, for again there is a rise in SG to 3.66–3.70, with one exception, a black-coloured stone, which had an SG of 3.63. The refractive index of this type of composite stone is 1.73.

When the quartz types of these doublets are immersed in water and viewed sideways the clear colourless parts of the crown and pavilion with the dark line of colour in the plane of the girdle are clearly seen. With the synthetic spinels this is not so evident if water is used, but with oils of higher refraction the effect is well seen (*Figure 20.5*). All synthetic colourless spinel fluoresces with a strong bluish-white glow under short-wave ultra-violet light and this is useful for, as reported by Richard Liddicoat, the cement layer does not glow and shows up as a dark line indicating the composite nature of the stone. No characteristic absorption was seen whatever the colour of the stone, and under the Chelsea colour filter the green stones showed a green residual colour; the blue zircon and aquamarine coloured material showed green and *not* orange as in the same

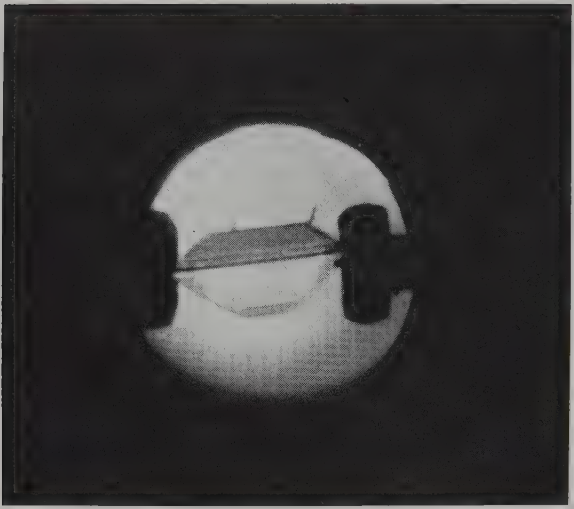


Figure 20.5 A spinel soudé emerald immersed in di-iodomethane and viewed through the side clearly shows the colourless top and bottom and the line of green colour

colours in synthetic spinels. The amethyst and sapphire blue coloured stone did show an orange colour when examined through the filter.

Beryl Doublets

In 1931 Kraus and Holden illustrated a triplet consisting of a crown and pavilion of pale emerald or beryl separated by a thickish layer of green glass. It would be fair to assume that in some cases the slice of glass could be replaced by a green-coloured cement layer, and indeed such types of emerald doublets were apparently encountered in early days, but they were scarce.

During 1966 the firm of Kämmerling of Idar-Oberstein, West Germany, produced a doublet comprising two pieces of colourless beryl, pale aquamarine or poor-quality emerald for the crown pavilion of the stone, the two pieces being cemented together with an emerald-coloured Duroplastic cement. These were marketed under the trade name Smaryll. When two pieces of aquamarine are used, negative crystals or canals ('rain') indicate the nature of the object, and, further, the stones show green under the Chelsea colour filter and the spectroscope shows the typical dyestuff lines in the red. When unset, examination in water will usually show the division made by the dark colour line.

More recently the crown and pavilion have been made of two parts of real emerald. These stones provide a greater difficulty in identification, specially if they are in a setting. They may show a refractive index for emerald and the spectroscope may show a trace of the chromium spectrum of emerald, usually and happily with the saving grace of the dyestuff spectrum. The emerald-type inclusions and the possibility of a reddish residual colour through the Chelsea colour filter help to make things difficult. Ultra-violet light does not seem to greatly assist in this case.

Synthetic Doublets

Apart from the sapphire/synthetic-sapphire and sapphire/synthetic-ruby doublets mentioned in the section on semi-genuine doublets which came out at about the same time, a new type of doublet appeared on the market during 1971. This new composite stone consists of a crown of synthetic colourless spinel or sapphire and a pavilion of colourless strontium titanate (Fabulite) (*Figure 20.1f*). The probable notion behind the manufacture of such stones is to give a better wearing face to the rather soft strontium titanate, and perhaps to reduce the exceptional fire of that stone. These composite stones are usually joined below the girdle so as to prevent the edges chipping. They are not difficult to identify for the refractive index taken from the table will be 1.72, that of synthetic spinel, while the fire of the stone is too great for spinel. Further, the short-wave ultra-violet lamp will reveal the synthetic spinel top by its strong whitish glow. There has also been a report of a doublet made with a synthetic sapphire crown and pavilion. The object of making such a doublet seems obscure.

Opal Doublets

Opal, which shows a fine play of colour, is often found in too thin a vein to cut any solid gemstone from it. Such pieces are then backed by other common opal (potch opal, which shows little or no play of colour), by black onyx, or by a black glass called ‘opalite’ which is obtained from Belgium. Such a device supports the thin piece of colourful opal and allows the stone to be set into jewellery. Opal doublets on black glass or black onyx are fairly easy to detect, but opal on opal doublets are much more difficult, and when in a setting it may be impossible to be sure. The reason for this is that many natural opals are cut with the natural backing of the original seam wall, and when this is fairly straight the stone can resemble to a great extent a doublet. Careful examination with a lens may assist in determining whether the stone is a doublet or not but in most cases it is necessary to remove the stone from its setting in order to be quite sure. When looked through from the back most opal doublets appear dark but some transmit light; and then by lens or microscope observation, through either the front or the back, there may be seen flattened bubbles which will indicate a doublet.

Another version is the *opal triplet*, called by the trade name Triplex Opal. This composite stone is a simple opal doublet, usually with a common opal backing, to which is cemented over the top part of the opal a suitably fashioned cabochon of rock crystal. Similar triplets of opal made with caps of synthetic colourless spinel and synthetic colourless sapphire have been reported. The idea seems to be to present a better-wearing face to the opal and to give the opal more brilliancy, as to some extent the quartz cover acts as a lens. The overall effect is a little unreal.

An imitation opal, which in fact could be termed a false doublet, consists of a cabochon of rock crystal or glass to the back of which is cemented a slice of iridescent mother-of-pearl, either from the pearl oyster or from the colourful paua shell (*Haliotis*), or the abalone as it is called in America.

A variation is the Schnapperskin triplet in which the layer consists of fish skin with red or blue dye. They are detected by the false hue of the colours and the fact that the skin shows grey at the girdle. Another type is a hollow-backed cabochon of rock crystal which is filled with clear plastic and opal chips.

Another interesting variation is an example of assembled ironstone opal. The opal, in this case, was cemented to the brown matrix of typical ironstone opal. The cement was of the same colour as the matrix, thus effectively masking the unevenness of the opal to the matrix. The glue was checked with a thermal reaction tester and it melted when it was touched.

Jadeite Triplets

During 1958 there came on the market a jadeite triplet which has the colour of Imperial jade. These stones were made up of three pieces, the components being: a hollow cabochon of very fine translucent white jadeite about 0.5 mm thick, a cabochon of smaller size made of the same white jadeite cut to fit into the hollow cabochon, and a flattish oval piece fashioned so as to close in the back. The central cabochon is coloured with a jelly-like dystuff of Imperial green colour. The dyed centre piece is inserted into the hollow cabochon and the bottom piece cemented on and repolished to make a perfect fit. When unset the nature of the stone is readily seen from the join of the outer pieces; it is when the stones are set with the edge concealed that they are so deceptive. They can, however, be detected by the characteristic dyestuff absorption band or bands in the red part of the spectrum.

Star-Stone Doublets

A number of attempts have been made, with some success, to produce a star-stone doublet. In one case a star doublet was made using a black star sapphire as a base with the cabochon top of synthetic padparadscha sapphire, and a similar doublet was constructed of a cabochon of medium blue synthetic spinel cemented to a flat base of a natural star sapphire. Another composite stone consisted of two pieces of synthetic blue spinel with a very thin foil engraved with intersecting lines at 120° cemented between the top part of the cabochon and the base part.

Some few years ago there was produced the so-called star rose quartz doublet which was constructed by preparing a cabochon cut from a correctly oriented piece of pale star rose quartz, to the back of which was cemented a blue-coloured mirror, maybe by a sputtering technique, and in some cases this was backed by a base plate of some other stone. Although rose quartz does sometimes show asterism by reflected light (epiasterism), the best effect is found by transmitted light (diasterism), and this is the reason for the mirror at the back. Unlike the star corundums and other natural star-stones, it is found that when the star in a star rose quartz doublet is viewed under an electric lamp, an image of the lamp bulb is seen at the crossing of the rays of the star. The nearer the stone is brought to the lamp the larger the image becomes. The colour of these star doublets is not quite like that of a natural star sapphire, probably owing to the transparency of the rose quartz being greater than that of most natural star sapphires, and, of course, the lustre of rose quartz is less than that of sapphire.

Cameo and Intaglio Doublets

Cameo doublets, where the raised portion is separate and is only cemented on to the base, are only occasionally met, except perhaps in some cameos made of porcelain. Intaglio doublets are more common and date back to Roman times, if not before. Similar objects of more modern vintage are encountered today. They are usually two pieces of glass, the upper piece either engraved or, more commonly, moulded to produce the intaglio. This top piece is then cemented to a base plate, usually with a reddish-brown cement in order to imitate cornelian. The pigment used is usually not very stable and it is common for the colour to deteriorate and the cement to craze. A more stable and convincing doublet has the back made of a piece of real cornelian.

Moss Agate Doublets

These doublets are produced by placing some chemical, such as manganese dioxide, with gelatine on a glass plate and allowing a ‘tree’ to form on the gel, after which the glass plate is gently heated so as to drive off the excess water. Another clean glass plate is then cemented on to the top and the whole is then ground to a suitable form, either as a flat plate or as a cabochon. When the stones are unset the join between the glass plates readily reveals the fake, and even when set the greater transparency of the piece compared with true moss agate would indicate that something was wrong.

Turquoise Doublets

Unimportant, but mentioned for the sake of completeness, is the turquoise doublet constructed by cementing a base of blue-stained chalcedony, or other suitable material, to a cabochon of turquoise-coloured opacified glass. Very few of these objects have been seen.

Mosaic Doublet (Triplet)

An experimental doublet was produced in 1972 by Dr Suzuki of Australia and is unique in that between two pieces of colourless stone, usually crown and pavilion of synthetic white spinel, is sandwiched a transparent filter in which there is a mosaic of three basic colours. This mosaic is made by first producing a larger original by painting squares, rectangles or triangles of the three basic colours with the addition of areas of white in random position, presumably on a white card or even glass. This is then photographed on reversal colour film to a suitable size of pattern and this film is used for cementing between the crown and pavilion of the stone.

21

The Fashioning of Gemstones

Although the origins of gem cutting are unknown, it is thought that as early as 4800 BC people used reeds such as bamboo, or conch-like shells, to fashion ancient seals. Later, by crudely rubbing stones against each other, they learned not only to fashion tools and weapons but also to transform brightly coloured pebbles into gems that could be worn for personal adornment. As the years progressed, they developed techniques that led to the arrival of the cabochon cut and intricate engravings using both transparent and opaque materials. Later, during the tenth and eleventh centuries, Europeans engaged in the art of faceting gemstones which eventually led to the establishment of the first gem cutters guild in Paris in 1290. A century later, diamond cutting and polishing was established in Nuremburg, Germany.

During the fifteenth century, great advancements were made in diamond cutting by a Belgian named Louis de Berquem who announced that he had discovered a method of cutting diamonds. This made possible the eventual development of the round brilliant cut, which was originally credited to a Venetian cutter named Vicenzio Peruzzi during the latter part of the seventeenth century. Over the years, this underwent a gradual transformation until 1914 when Marcel Tolkowsky published his treatise on the use of certain angles and proportions to maximise brilliance.

Without question, the greatest advancements, in both diamond and coloured gemstone cutting, have occurred in the latter part of the twentieth century. Modern equipment has permitted the development of new techniques which have, in turn, led to the advent of new and exciting cutting styles. Today, owing to the establishment of numerous organisations and trade journals, there is a tremendous interest in gemstone cutting, not only from a commercial aspect but also from an amateur standpoint.

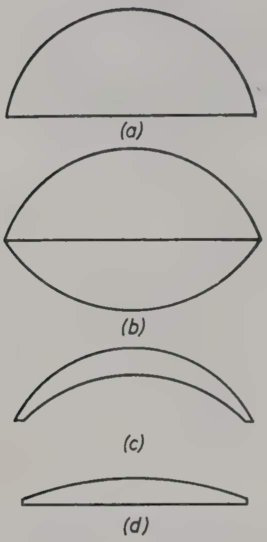


Figure 21.1 The cabochon cuts: (a) simple cabochon, (b) double cabochon, (c) hollow cabochon, (d) tallow-topped cabochon

Styles of Cutting

Cabochon Cut

The earliest form of cutting simply gave a curved surface to the stone, and, was known as the cabochon cut. There are four styles used today (*Figure 21.1*): the simple cabochon which has a convex (dome-shaped) upper surface and flat base; the double cabochon in which the base is also convex, but less steep than the top; the hollow cabochon in which the underside is hollowed out to form a concave depression; making a concavo-convex form and a low-domed simple cabochon known as a tallow top owing to its resemblance to a drop of candle grease.

In stones cut *en cabochon,* as the French term it, the outline of the setting edge may be circular, oval, polygonal or of a fancy shape; a common fancy outline is a heart shape. The cut is used for those stones which are translucent or opaque, such as turquoise and jade, and for stones showing optical effects such as asterism and chatoyancy, which must be cut so as to bring out to the full the star and cat's-eye effects. The play of colour in opal and the adularescence of moonstone are best shown by this style of cutting. Deep colour almandines are often cut as hollow cabochons in order that the depth of colour may be lightened, and in some cases the hollowed back is foiled to make the stone appear more brilliant. Such hollow cabochons of almandine garnet are called carbuncles, a name used since ancient times for cabochon-cut red stones, but now usually restricted to the almandine garnet.

Very often, heavily included commercial-grade sapphires are cut in the double cabochon style, and such stones are sometimes set with the flatter side uppermost as this gives a better colour and lustre. Star corundums and chrysoberyl cat's-eyes are set with the steeper dome to the front while the

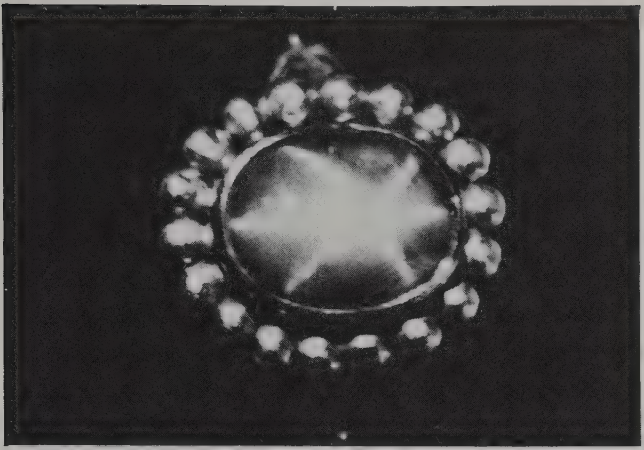


Figure 21.2 A large star sapphire cut in the cabochon style

curved back of the stone is usually left unpolished. *Figure 21.2* shows a star sapphire cut in the cabochon style.

Rose Cut

One of the first styles of cutting to employ flat facets was the rose cut or rosette, a name derived from a fanciful resemblance in the arrangement of the facets to the petals of an opening rosebud. The origin of the style is not known with any surety but it was developed sometime before the sixteenth century. The rose cut consists of an upper portion only, the underside being just a single large flat base. The upper portion takes the form of a pyramid with three-sided facets meeting at the apex at a more or less steep angle. The rose cut is mostly used for diamonds owing to its economy in material, allowing small cleavage fragments and macles to be used up. In Victorian jewellery the then popular bright blood-red pyrope garnets from Bohemia were also cut in this style.

The most common form of rose cut is the round rose. In its most usual form the facets are arranged in multiples of six and in two groups, the upper six facets constituting the crown or star while the lower facets are the cross facets or, as they are often known, the teeth or dentelle (*Figure 21.3*). (The facet names of a later development towards the brilliant cut stone are shown in *Figure 21.4*.)

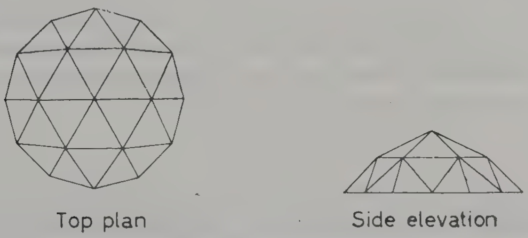


Figure 21.3 The round rose style of cutting

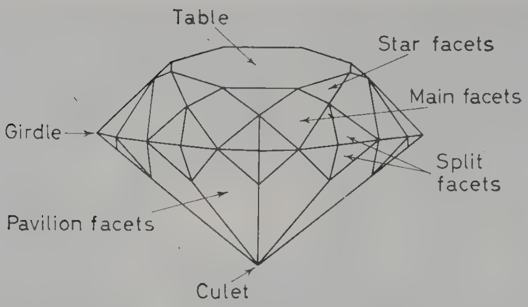


Figure 21.4 *The facet names of the brilliant-cut type stone*

In the Dutch or crowned rose the height of the pyramid from the base is usually equal to half the diameter of the stone, and the distance from the base to the crown is three-fifths of the total height; the diameter of the crown is three-quarters that of the base, which may be round or oval. The Brabant or Antwerp rose is similar to the Dutch rose except that the pyramid is more flattened. The distribution of the facets is the same in each of these three types. The cross rose and the rose recoupée are modifications of the facets and are shown in *Figure 21.5* and *21.6*.

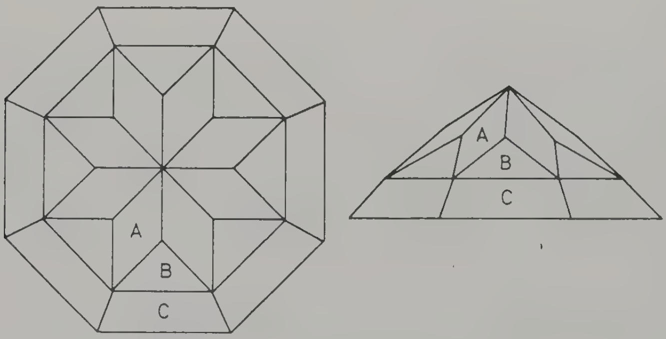


Figure 21.5 *The cross rose style of cutting*

The rosette has a crown of the normal six triangular facets, but the dentelle of the round rose is replaced by six rectangular facets; it is a simpler form. The double rose may be described as two roses joined together base to base, but in certain cases the heights of each may not be equal, and if the top half of the double rose is excessively elongated a drop-shaped form, termed a briolette (*Figure 21.7*), is produced, but such a stone can be faceted with rectangular facets in place of the triangular facets.

Table Cut

What was probably the first advance from the mere polishing of the diamond octahedron – termed 'point stones' – was the table cut (*Figure 21.8*). This cut was

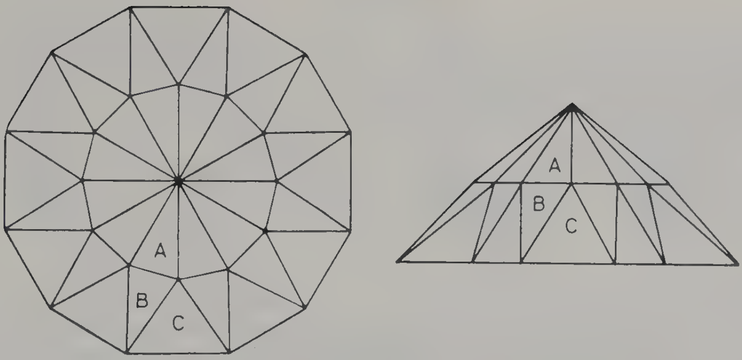


Figure 21.6 The rose recoupée style of cutting

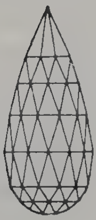


Figure 21.7 The briolette

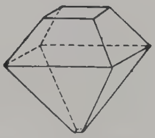


Figure 21.8 The table cut

produced by truncating one of the corners of a diamond octahedron until a face about equal to half the width of the stone was secured. The opposite corner was then removed in the same way leaving a face about a quarter the width of the stone. The whole of the faces were then polished. The table cut, a style extensively used by the ancient Indian cutters, may have many variations both in the depth of the stone and in the outline of the setting edge. Such table-cut diamonds are usually encountered only in old Indian jewellery, but a similar cut was used by the Nuremberg diamond polishers in 1373. One modification of this cut is made very thin and acts as a window or coverglass for small miniatures set in rings. Such stones are usually known as portrait stones.

Trap Cut

The table cut may well be said to have been the forerunner of the trap cut which is so popularly used at the present time for important diamonds and coloured gems. This cut, sometimes called the step cut, has the large table facet surrounded by a series of strip-like rectangular facets which increase in steepness towards the setting edge (the girdle); the lower half of the stone (the pavilion) has similarly arranged rectangular facets decreasing in steepness towards the basal facet at the point (*Figure 21.9*).

The outline of such stone can take many forms. They may be square, rectangular, triangular, kite-shaped, keystone-shaped and lozenge-shaped, and

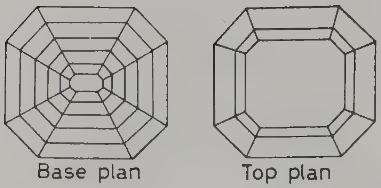


Figure 21.9 *The trap or step cut*

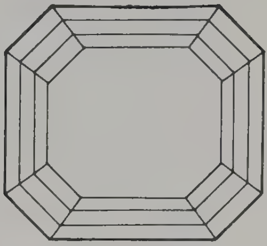


Figure 21.10 *The emerald cut*

other polygonal forms. The rectangular form with the corners truncated, producing an eight-sided outline, is often called the emerald cut on account of its extensive use in cutting emerald (*Figure 21.10*). Small trap-cut stones of a long rectangular shape are known as baguettes and are extensively used today as accent stones especially in pieces of designer jewellery. The term *calibré* is applied to small trap-cut stones, usually of square outline, which are cut to special sizes to fit channelled settings; in fact they are tailored to fit, and that is literally the meaning of the name. Some of these small calibré stones, although trap cut, do sometimes deviate from the true definition in that the outline may be curved, forcing curvature on some of the facets, but these facets are still strip-like. A common modification of the trap cut is the cross cut, or scissors cut as it is sometimes called. Here the side facets consist of four triangular facets corresponding to each of the rectangular facets of the regular trap cut (*Figure 21.11*). The double scissors cut as a double set of these triangular facets on each side facet. A square trap-cut stone is called a *carré*.

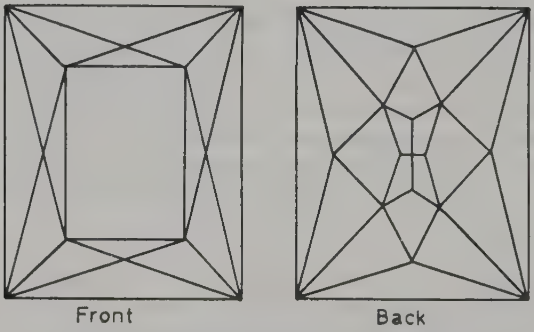


Figure 21.11 *The scissors cut or cross cut*

Brilliant Cut for Diamonds

The most common cut for diamond is the brilliant cut. When correctly cut it not only produces the greatest amount of fire and brilliancy, but also enables the best use to be made of the octahedral form of the diamond crystals. The style

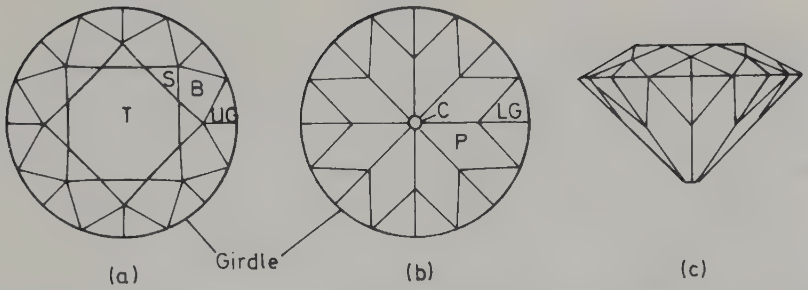


Figure 21.12 *The standard brilliant cut consists of (a) the crown of the stone, comprising an octagonal table facet T, surrounded by 8 triangular star facets S, 8 quadrilateral bezel or kite facets B, and 16 triangular upper girdle facets UG, making 33 facets in all; and (b) the base or pavilion of the stone, consisting of a very small octagonal culet C, surrounded by 8 five-sided pavilion facets P, and 16 triangular lower girdle facets LG, making 25 pavilion facets and a total of 58 facets for the complete brilliant. It should be noted that many of these facets have alternative names, but those given represent modern practice*

has become so universally used for diamond that the name 'brilliant' is now synonymous for diamond.

The standard brilliant cut (*Figure 21.12*) consists of 58 facets, 33 on the top or crown of the stone, and 25 on the base or pavilion. The crown has a large eight-sided central facet called the table which is surrounded by 8 triangular star facets. These in turn are surrounded by 8 quadrilateral facets called bezels, of which 4 are called quoins and the other 4 templets; the significance of these latter names will be more apparent when the methods of cutting diamonds are discussed. Surrounding the bezels and meeting the edge of the girdle, or setting edge of the stone, are 16 triangular facets which are known as upper girdle facets.

The back portion of the stone, or pavilion as it is called, has 8 long five-sided facets called the pavilions which are symmetrical with the 8 bezels on the crown of the stone. Corresponding to those on the front of the stone there are 16 lower girdle facets which join up with the pavilions. At the point of the stone where the pavilions meet at the bottom there is usually ground on a small facet parallel to the table facet of the crown. This culet as it is called, put on to prevent splintering, is sometimes omitted in small stones.

In order to ensure maximum brilliance in a diamond (which has a critical angle of 24° 26′), the back facets need to be at an angle of approximately 41° to the plane of the girdle, and the angle between the side facets of the crown and the plane of the girdle needs to be between 35° and 37°. As the angle of the octahedron is 54° 44′ a considerable wastage of material – some 50–60 per cent – occurs in cutting such a stone from a diamond crystal; even when the crystals are sawn the loss is great (*Figure 21.13*).

Modifications of the Brilliant Cut

There are many modifications of the brilliant cut, both in outline and in the number of facets. Marquise (*Figure 21.14*) is the name used when the outline is

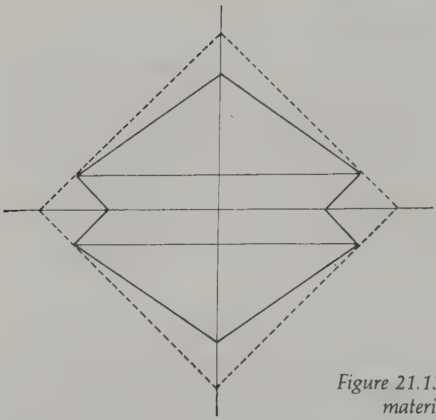


Figure 21.13 Even with a sawn diamond crystal the loss of material when cut into the brilliant style is great

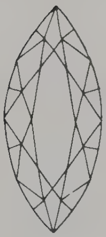


Figure 21.14 The marquise or navette

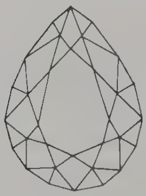


Figure 21.15 The pendeloque

boat-shaped, although navette is used in a similar connection. A pear-shaped outline is called a pendeloque (*Figure 21.15*), and an outline which tends to be squarish with rounded corners is termed cushion-shaped (*Figure 21.16*). Many of the old Brazilian diamonds were cut in this fashion to retain weight even though it resulted in a reduction in overall brilliance. For small diamonds the single cut or eight cut is often used, and consists of 8 facets surrounding the table and 8 pavilion facets below the girdle (*Figure 21.17a*). The Swiss cut has 17 facets on the crown (including the table) and a further 17 facets on the pavilion (if there is a culet) for a total of 34 facets (*Figure 21.17b*). The zircon cut (used extensively for zircon) is characterised by a second set of facets surrounding the culet (*Figure 21.18*).

For large stones a greater number of facets than the 58 of a standard brilliant

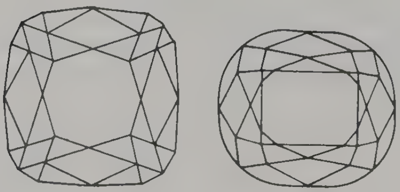


Figure 21.16 The cushion-shaped brilliant

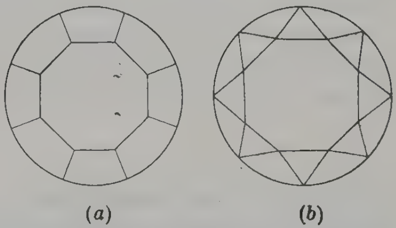


Figure 21.17 (a) The eight cut, (b) the Swiss cut

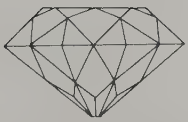


Figure 21.18 The zircon cut

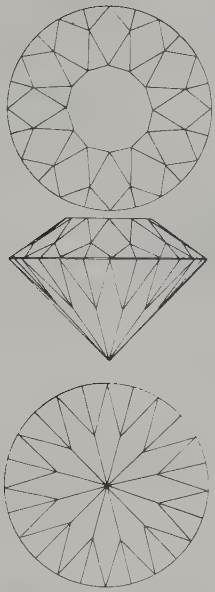


Figure 21.19 The king cut

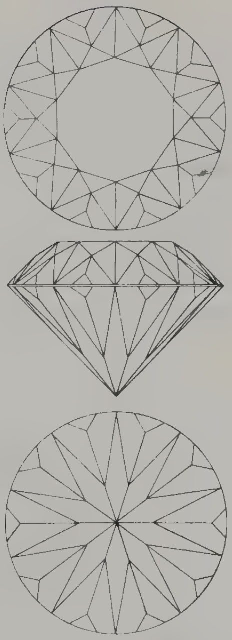


Figure 21.20 The magna cut

may be put on, but they will still conform to the general symmetry. More elaborate modifications of the brilliant cut are the king cut which has a twelve-sided table with 48 surrounding facets to form the crown of the stone, and 37 facets including the culet on the pavilion, for a total of 86 facets in all (*Figure 21.19*). The magna cut has a ten-sided table facet surrounded by 60 facets on the crown and 41 facets on the pavilion, making 102 facets in all (*Figure 21.20*).

New Diamond Cuts

During the 24th World Diamond Congress in Singapore (August 1989), Nicholas Openheimer, chairman of the Central Selling Organization, presented five new diamond cuts (Zinnia, Sunflower, Dahlia, Marigold and Fire Rose) (*Figure 21.21*). Created by Gabi Tolkowsky, after preliminary studies by the CSO, these new designs were developed to better utilise rough that was either irregularly shaped, heavily included, small or strongly coloured. Adaptable to sizes ranging from mêlée to several carats, the new cuts not only improved yield but also, in many cases, enhanced either brilliance, clarity or colour. Compared with the more conventional cuts, the new designs represent a radical departure in terms of their angles and proportions (*Table 21.1*). As can be seen in the table, variants can still exist within each cut depending on the shape of the rough.

In addition to these new cuts, several other cuts have been developed over

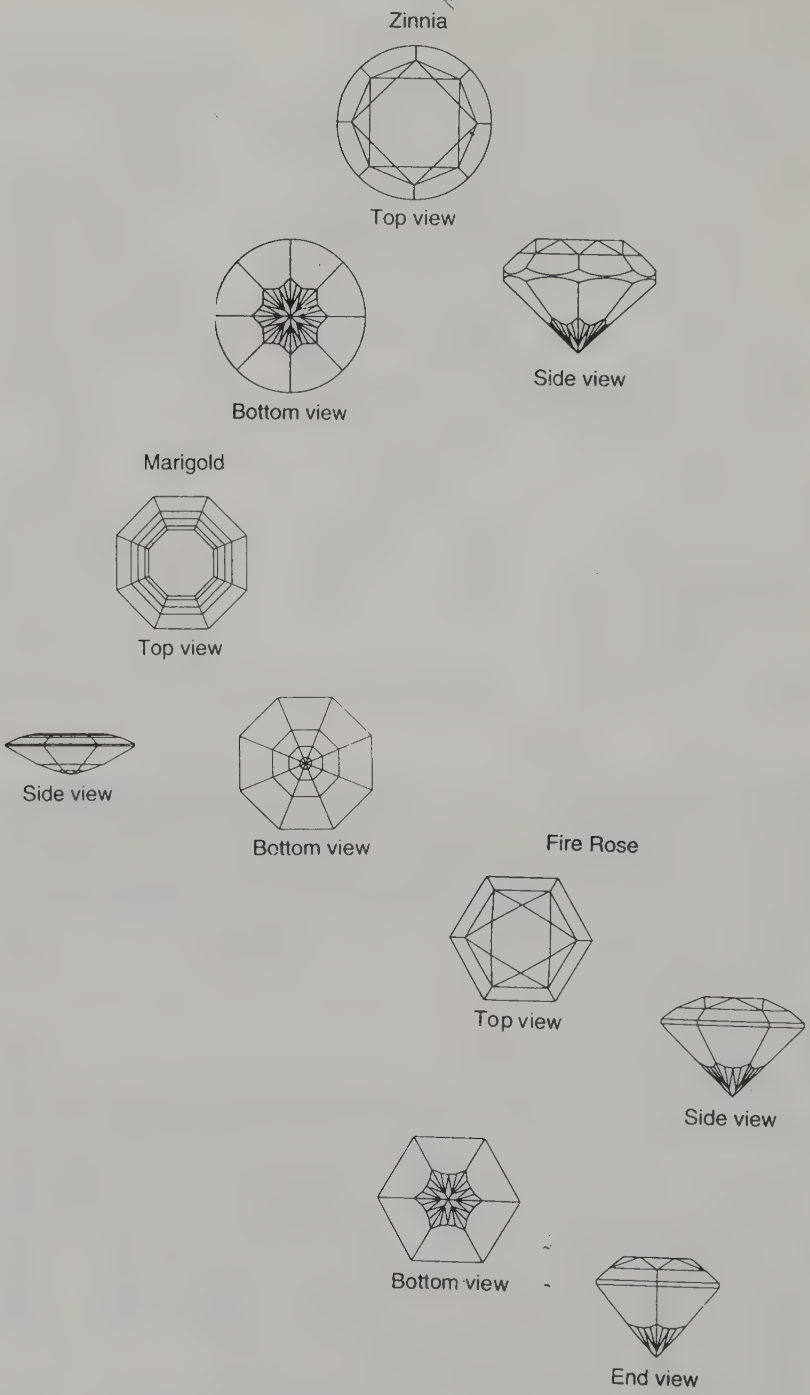
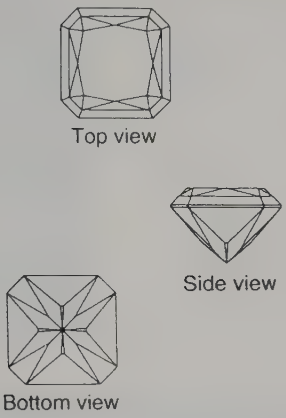


Figure 21.21 The Tolkowsky Flower Cuts (courtesy of De Beers)

Sunflower



Dahlia

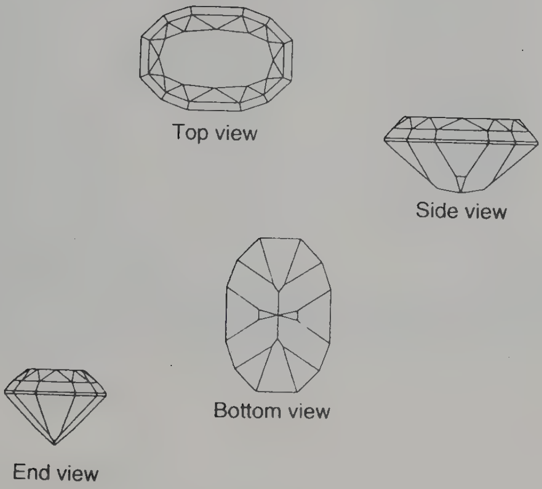


Figure 21.21 (cont)

Table 21.1
Proportion comparison chart for new diamond cuts

Shape	*Table (%)*	*Crown height (%)*	*Girdle thickness*	*Pavilion depth (%)*
Round Brilliant	57.5	14.6	Medium	43.1
Zinnia	52	16	Thick to very thick	46
Sunflower	53 to 58	17.5 to 24	Thin to thick	42.5 to 51.5
Dahlia	56	15	Medium to thick	49
Marigold	51	12.5	Very thick	35
Fire Rose	47 to 62	15 to 20	Thin	45 to 51

Based on an analysis conducted by GIA personnel: other specimens may vary.

the last 25 years. The Radiant Cut (designed and patented by Henry Grossbard) consists of 70 facets and combines a step-cut crown with a brilliant-cut pavilion for added brilliance. The Trillion Cut (designed by Leon Finker and patented by LF Industries) is triangular in shape and consists of 50 facets. The Trilliant Radiant Cut resembles the Trillion but is usually cut with more rounded sides for additional weight retention. The Quadrillion Cut (patented and trademarked by Ambar Diamonds) is square-shaped and consists of 49 facets. The Princess Cut is similar in appearance to the Quadrillion but is usually cut with steeper crowns, thicker girdles or deeper pavilions to provide greater yield from the rough.

Perfection in cutting, which is sometimes called the 'make' of the stone, is much more important in the case of diamonds than in other stones, for faults and imperfections adversely affect the value of the diamond. Such deficiencies can include (1) unsymmetrical outlines or large culets, (2) spread tables, (3) overthick or irregular girdles, (4) naturals or extra facets, (5) polishing marks, and (6) bearding, which is often caused during the bruting process and resembles a series of fine lines extending in from the girdle.

Other Cuts

In addition to the cuts already discussed, there are a multitude of other cuts used for coloured gemstones. Today, it would seem that there is no limit to the variety of cuts available. Each new issue of a trade journal brings new and exciting cutting styles that are sometimes merely variations on an existing theme. One of the newest cuts to emerge in the marketplace is the fantasy cut, which is used extensively for amethyst, citrine and blue topaz. Characterised by its irregular form, it is favoured particularly by designers who wish to create unique one-of-a-kind pieces of jewellery. Other favoured cuts include the mixed cut, which consists of a brilliant-cut crown and a step-cut pavilion; the Barion cut (developed by Basil Watermeyer), which was designed to improve the brilliance of square and rectangular stones and consists of 62 facets; the Portuguese cut, which can have up to 177 facets; and the cushion cut, which is a cross between an oval and a rectangle.

Figure 21.22 *Intaglio carved in an amethyst*

Figure 21.23 *Shell cameo*

Figure 21.24 *A fine stone cameo (white on a greyish-brown background), being a carved copy by R Hahn of Idar-Oberstein of the Tazza Farnese (actual size about 200 mm)*

Intaglios and Cameos

Gemstones are also carved. Heavily included, translucent and opaque gemstones may be carved in the shape of leaves, flowers or stylised designs. Intaglios (*Figure 21.22*) are incised carvings used mainly for seals, while cameos (*Figures 21.23* and *21.24*) have the carving raised above the surface. In both cameos and intaglios a layered material having two distinct colours is often used, in particular banded agates and shells of the giant conch and the helmet shell.

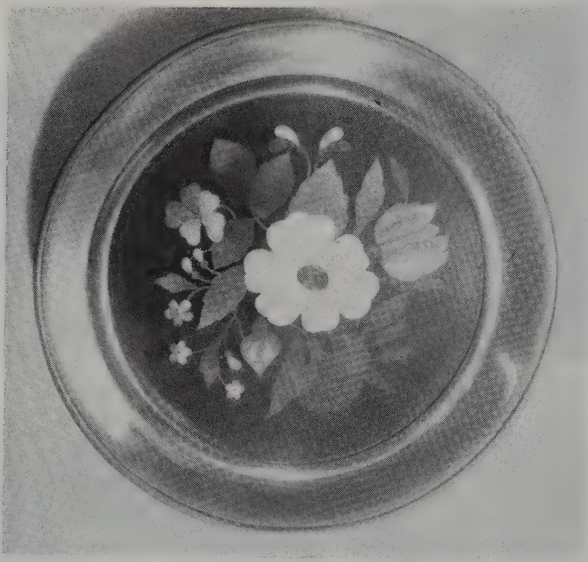


Figure 21.25 *A Florentine (intarsia or pietra dura) mosaic*

Mosaics

The fitting together of small pieces of coloured ornamental stones to form a pattern or picture is called a mosaic or inlay and may be either of two types. The first of these is the Florentine mosaic, which is sometimes known under the names *intasia* or *pietra dura* (*Figure 21.25*). The pattern is made up of suitably shaped pieces of coloured stone – marbles, coral, malachite, opal, lapis lazuli and turquoise are often used – cemented into a recess cut into, usually, a black marble slab which forms the background. Parquetry is somewhat similar except that the pieces of stone are cut in geometrical shapes and then set in a metal mount. Some Scotch agate brooches are built on this style. The second type, the Roman or Byzantine mosaic (*Figures 21.26* and *21.27*), is made not of natural minerals but of small pieces of coloured glass rods of uniform length cemented in an upright position to a recess in, usually, a glass frame. The patterns depicted are often those of ancient ruins.

Gemstone Cutting

Cutting Considerations

Before any cutting can commence, a thorough examination of the rough must take place, since it is the decisions made during this inspection that will ultimately determine the value of the finished stone. Although the objectives of the cutter will vary according to the gemstone being cut, there are some fundamental points that need to be considered.

Figure 21.27 Roman mosaic

Weight Retention

The most important factor is the amount of weight that will be lost during the cutting process. If this exceeds the acceptable level (50 to 60 per cent in diamonds and up to 75 per cent in coloured gemstones), this will result in either (1) a per carat price which is too high, or (2) a reduction in profits in order to remain competitive.

Factors that influence the amount of weight loss include the following.

Shape

The shape that the cutter chooses (which is largely dependent on the original outline of the rough) will ultimately dictate how much weight is lost or recovered. When all other factors are considered, the shape chosen must result in the greatest amount of weight retention in order to maximise profit potential.

Calibration

Since manufacturers tend to produce mounts with settings that are designed to accommodate calibrated stones (i.e. 5 mm × 3 mm, 6 mm × 4 mm, 8 mm × 6 mm), most cutters will normally choose to sacrifice weight in order to produce finished goods that will fit into these ready-made settings.

Rather than penalise the cutter, it is generally accepted that calibrated stones will sell for a higher price per carat to compensate for the additional weight loss.

Brilliance

In order to achieve maximum brilliance, a cutter must adhere to certain angles (*Table 21.2*) to ensure that the majority of incoming rays (entering through the crown) strike the pavilion facets at an angle greater than the critical angle. The critical angle is given by the following formula

Table 21.2
Gem facet angles (degrees)

Gemstone	*Bezel*	*Star*	*Upper girdle*	*Pavilion main*	*Lower girdle*
Andalusite	43	28	47–49	39	41
Apatite	43	28	47–49	39	41
Beryl	42	27	46–48	43	45
Chrysoberyl	37	22	41–43	42	44
Corundum	37	22	41–43	42	44
Diamond	35	20	39–41	41	43
Feldspar	42	27	46–48	43	45
Garnet (demantoid)	43	28	45–49	40	42
Garnet	37	22	41–43	42	44
Iolite	42	27	46–48	43	45
Opal	41	26	45–47	45	47
Peridot	43	28	47–49	39	41
Quartz (coloured)	42	27	46–49	43	45
Quartz (colourless)	45	30	47–49	41	43
Spinel	37	22	41–43	42	44
Spodumene	43	28	47–49	39	41
Topaz	43	28	47–49	39	41
Tourmaline	43	28	47–49	39	41
Zircon (high)	35	20	39–41	41	43
Zircon (low)	37	22	41–43	42	44

Source: Edward J Soukup, *Facet Cutter's Handbook*

$$\sin(\text{critical angle}) = \frac{\text{RI surrounding medium}}{\text{RI gemstone}}$$

As the surrounding medium is normally air with an RI of 1,

$$\sin(\text{critical angle}) = \frac{1}{\text{RI gemstone}}$$

It is equally important that the rays reflected back from the pavilion facets meet the crown facets at an angle less than the critical angle, otherwise they will not be returned to the eye. Failure to achieve this will result in a higher yield at the expense of overall brilliance. To encourage cutters to prioritise brilliance, well-cut stones usually sell at a premium. Generally speaking, the more expensive the rough, the less likely the cutter is to follow these guidelines. In this case, a compromise is normally sought between brilliance and weight retention. In diamonds and lighter-coloured gemstones, cut is far more important since it can make a stone more appealing and saleable. In darker-coloured gemstones (where colour is more of a factor), adjustments (such as shallower pavilions) are sometimes made to ensure that the stone does not appear overly dark.

Position of Inclusions

In some cases, the position of certain inclusions may dictate that a different shape be chosen. In certain gemstones (aquamarine, blue topaz, kunzite and tanzanite) the presence of inclusions has a detrimental effect on their value, whereas in others (ruby, sapphire, emerald and pink tourmaline) there is a greater tolerance. Therefore a cutter may opt to cut a smaller aquamarine that is free of inclusions rather than a larger, more included stone when considering overall value. Similarly, a piece of rough that is well suited for an emerald cut may be fashioned as a pear shape in order to remove an inclusion that could present problems from a durability standpoint.

Optical Phenomena

Stones that possess optical phenomena (such as asterism, chatoyancy or labradorescence) must be oriented correctly otherwise the finished stone will not display its optical properties to maximum effect, and this can result in a reduction in value.

Cleavage Planes

Since it is difficult to produce a good polish parallel to a cleavage plane, a cutter must orient the stone so that this is avoided. At the same time, care must be taken during the cutting process to avoid undue pressure on stones possessing cleavage planes since this can cause a stone to break.

Colour

Since colour accounts for 50 to 60 per cent of the overall value in a coloured gemstone, every effort must be made to orient the stone so that the most desirable colour is seen in a face-up position (through the table). In some cases, however, the presence of two or more colours (pleochroism) seen at the same time (e.g. in andalusite) is highly desirable, and this must be accomplished even if it compromises some of the other value factors.

Diamonds

Methods of Separation

In the case of large rough diamonds, and in any diamond containing inclusions, advantage is taken of the perfect octahedral cleavage of diamond to separate the stone into smaller pieces. This is done so that pieces of a more workable size may be obtained, and to remove included parts, so that the maximum yield and purity is assured.

The separation of diamonds by the use of the cleavage direction is the job of the cleaver who, with the aid of a sharp-edged piece of diamond set in a holder, cuts a small groove or 'kerf' in the cleavage direction (*Figure 21.28*). For this operation the stone to be cleaved is set into a holder, and when the groove has been cut to a sufficient depth, this holder with the stone mounted on it is placed in a lead support attached to the bench. A blunt steel knife is then inserted into the groove with the blade parallel to the cleavage direction. A sharp steady blow is then struck on the back of the blade, when the stone, if correctly grooved and the blade set right, will split into two pieces (*Figure 21.29*).

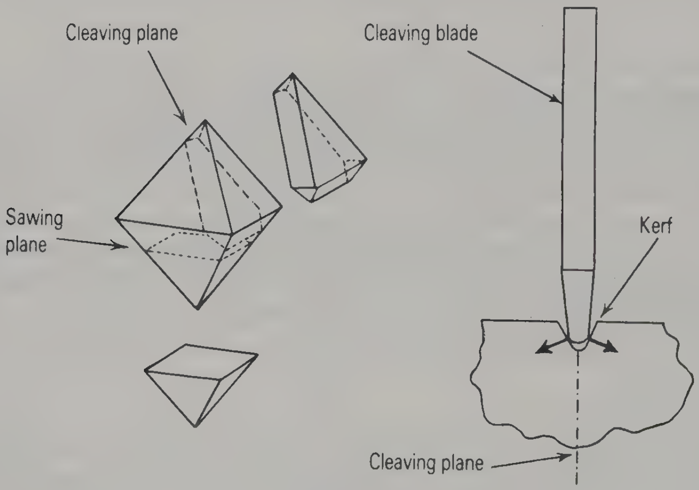


Figure 21.28

A more modern method (invented in 1905) for separating diamonds into two pieces is by sawing the stones. Well-formed octahedral crystals are commonly sawn in two (*Figure 21.28*). The sawing is carried out by the use of a rapidly revolving diamond-charged phosphor-bronze disc, and the stone to be sawn is first marked out in Indian ink to show the direction in which it is to be sawn. The

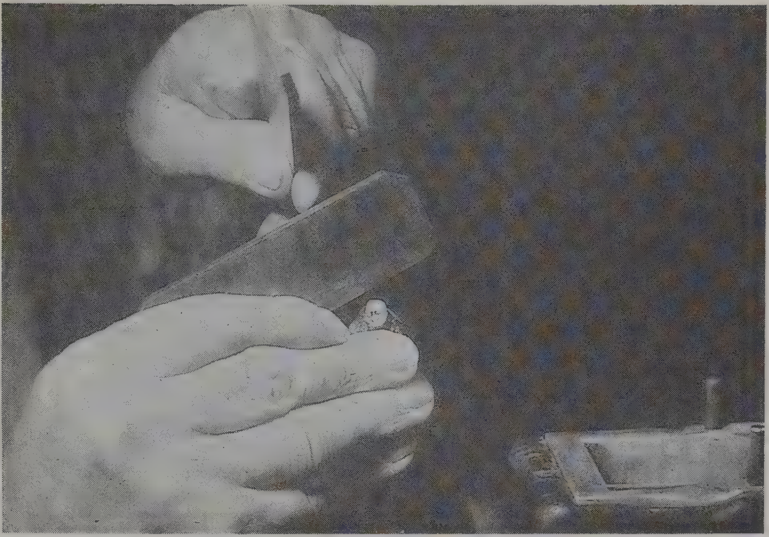


Figure 21.29 *The cleaving blade in position ready for the blow which will cause the diamond to split in two (courtesy of De Beers)*

stone is then set between two metal 'dops', which are fixed to a counterpoised movable arm on the sawing machine. The diamond is suspended above the diamond saw, and by manipulating adjusting screws it can be moved laterally for centring over the saw. The phosphor-bronze disc is about 75 mm in diameter and has a thickness of 0.06 mm, and is run at a speed of approximately 6000 rpm. The edge of the saw is impregnated with diamond powder mixed with olive oil by a hand roller, which not only forces the diamond powder into the edge of the disc but also spreads this edge to give a 'set' so that the saw will not bind in the cut (*Figure 21.30*).

The diamond is then gently lowered on to the edge of the revolving saw, starting the cut at a corner of the crystal (*Figure 21.31*). It is also necessary to ensure that the sawing will be across the 'grain', that is across the traces of the cleavage edges. While the cutting process is proceeding the saw needs constant replenishment with the diamond powder and olive oil, for if the disc runs dry it is likely to tear and cause the stone to break. One operator, the sawyer, deals with this and may look after a battery of as many as 40 saws (*Figure 21.32*). It takes up to 8 hours to cut a crystal weighing 1 carat. The cut, in the case of well-formed octahedral crystals, is made through the thickest part so as to produce two equal halves.

Grinding

The next process is to grind the stone into a truncated double cone (*Figure 21.33*). Previously carried out by a laborious method of hand grinding by working two diamonds one against the other, grinding is now done mechanically. This grinding, termed 'bruting' or 'girdling', is carried out by mounting one stone on the headstock of a special lathe. Another diamond,

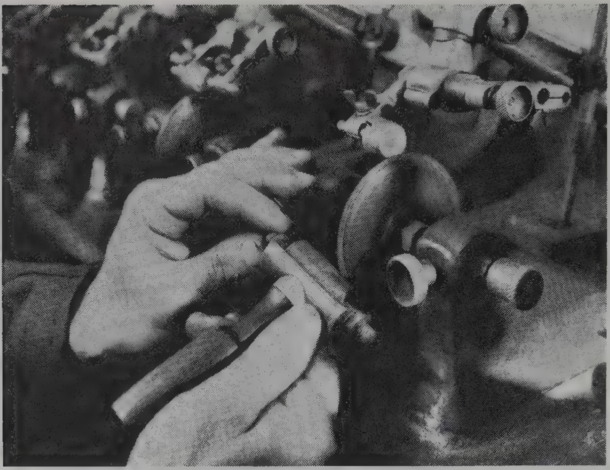


Figure 21.30 Charging the sawing disc with diamond powder (by courtesy of Shell Petroleum Company Limited)

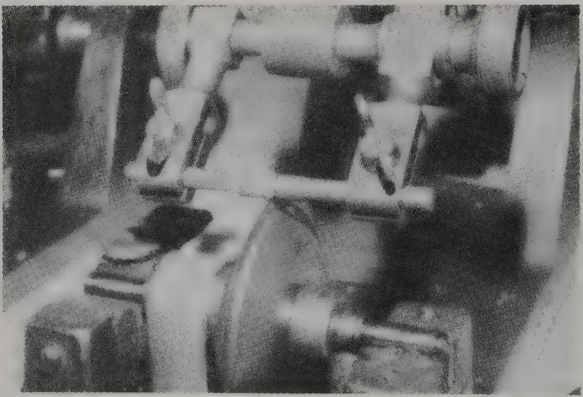


Figure 21.31 A diamond crystal, cemented in a double-sided dop, is lowered under pressure on to the phosphor-bronze saw blade (courtesy of Monnikendam)

selected for its sharp edges, is mounted at the end of a long holder which the bruter or grinder holds firmly under his arm. He grinds one stone against the other until both are the required shape, a double cone with one end, where the table facet will be placed, flatter than the other. The roughly rounded edge, called the rondist, will become the girdle in the case of brilliant-cut stones, for bruting is not done in the case of emerald-cut stones and rarely for baguette shapes.

From the bruter the stone goes to the polishers who grind on the facets to complete the finished product. As a stone cannot be polished except across a grain it is necessary for these directions to be known (*Figures 21.34* and *21.35*). A certain nomenclature is used in describing the grain. Stones which have been

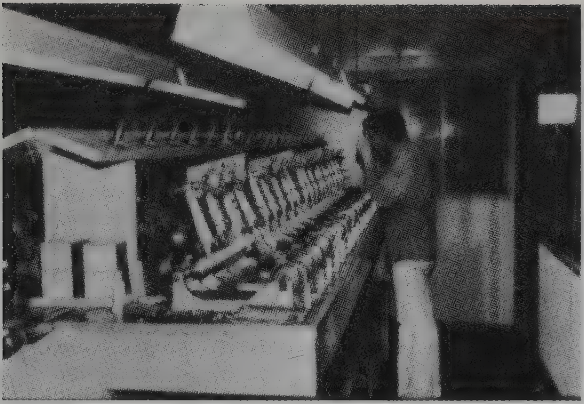


Figure 21.32 *A double bank of machines attended by the diamond sawyer (courtesy of Monnikendam)*

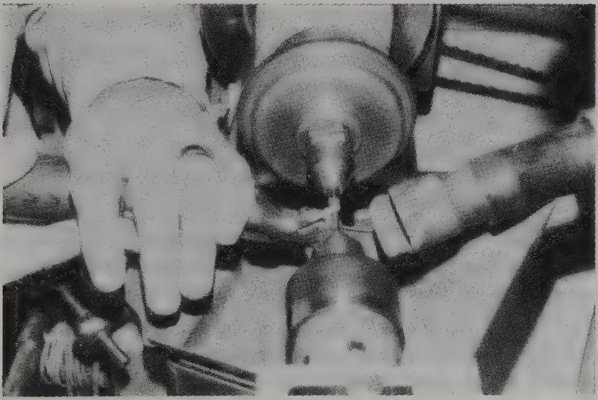


Figure 21.33 *The bruter rondisting a sawn octahedral diamond. A corner of the other section of the sawn stone is clamped in a dop stick and used as the cutting tool (courtesy of Monnikendam)*

sawn are said to be 'four-point', for the table facet will be parallel to a cube face – a face of fourfold symmetry – and will have two directions of cleavage traces. 'Three-point' stones are those which have the table facet parallel to an octahedral face, a face of trigonal symmetry. Along this direction the stone can only be cleaved and cannot be sawn; further, polishing such a surface is difficult and slow. Only cleavages and spinel twins, the so-called macles, are in this category. Macles are disliked by the diamond polisher owing to the twin plane, or naat, which gives the stone a cross grain. 'Two-point' stones have the table facet parallel to a dodecahedral face and give two directions for polishing.

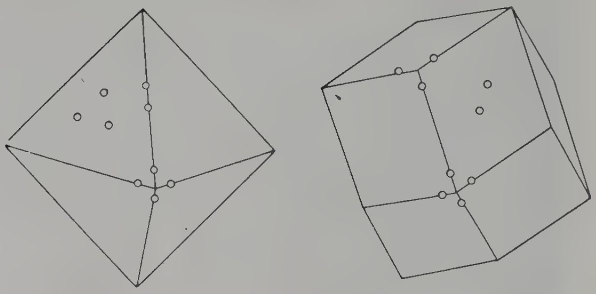


Figure 21.34 Situations of the 'point' on (left) a diamond octahedron and (right) a rhombic dodecahedron

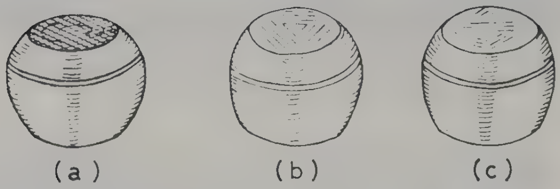


Figure 21.35 The grinding directions on the tables of bruted stones: (a) four point, (b) three point, (c) two point

Technique of Faceting and Polishing

Polishing operations are usually divided into two groups and it is usual for the craftsmen to specialise on one group. These are the cross cutter (kruisworker) who cuts the table facet and four main side facets, and the corresponding four back facets and the culet. Care must be taken at this stage to ensure the correctness of the angle of these facets from the girdle, a gauge being used to check them. From the cross cutter the stone goes to the brillianteerer who puts on all the remaining facets.

The cutting of the facets and the polishing are carried out in one operation. This is performed on a revolving horizontal 'lap' or 'scaife', a cast iron lap about 12 to 18 mm in thickness and having a diameter of about 300 mm. The scaife is most carefully balanced so as to run perfectly true on the spindle, and the scaife, after the scouring of the surface with sandstone blocks, is charged with diamond powder and olive oil. The speed of rotation used is between 2400 and 3000 rpm.

The diamond to be polished is mounted in a 'dop' which consists of a brass cup with a soft copper tail. The dop is filled with soft solder into which the diamond to be polished is mounted whilst the solder is still pasty. In modern practice a mechanical dop, which came out between the two world wars, is extensively used (*Figure 21.36*), but for some cuts the older solder dop is still the best. The copper tail of the dop is gripped in a movable bench clamp called a

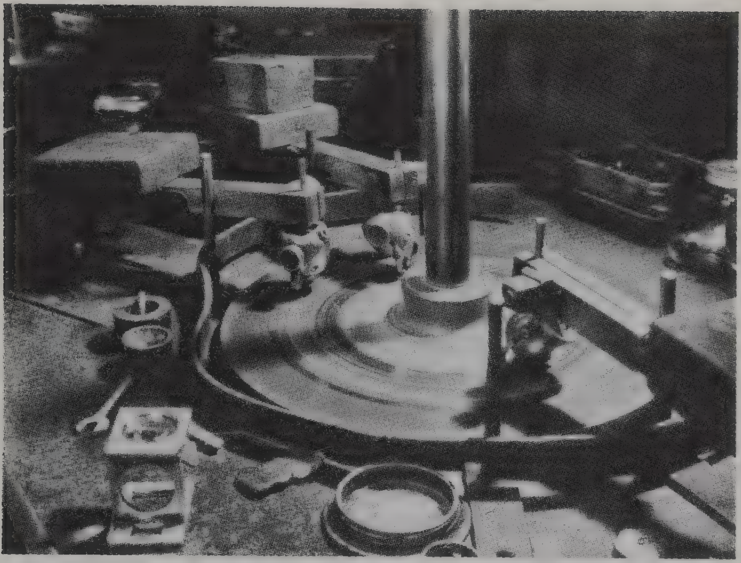


Figure 21.36 *Mechanical clamp-type dops holding diamonds on a scaife. The dops are mounted in the end of tangs, which are weighted to achieve the necessary polishing pressure (courtesy of De Beers)*

'tang' which, with its two feet on the bench and the dop set with the diamond resting on the scaife, forms a tripod.

One or two stops fixed to the bench, which is called the mill, prevent the tang being carried round by the motion of the lap, and, in order to give added pressure, lead weights are loaded on to the arm of the tang. The operator can feel whether he is polishing the stone in the correct direction for the grain. Moving the angle of the tang in relation to the scaife will enable the best polishing position to be found. By bending the copper stalk of the dop most of the side facets can be polished on, and the stone may only need resetting when the rear facets are to be polished. Constant inspection is made as the work of polishing proceeds, as all facets must be symmetrical and of uniform size for the group. On completion the stone is cleaned in acid and methylated spirits, after which it is passed to the sorting rooms for grading into size and quality.

Coloured Gemstones

The methods used by the lapidary for the cutting of stones other than diamond, although similar in many respects, differ in that there are two distinct processes: a definite cutting where the facets are ground on leaving a finish like ground glass, and a final polishing of these facets.

Cabochons

Once the pattern or shape has been decided, a template is used to scribe the desired outline on to the rough. In order to save time, a diamond-charged trim saw is often used to remove any unwanted material. The preformed stone is then secured on to a dopping stick (usually made of wooden dowelling measuring anywhere from 6.35 mm to 22.25 mm in diameter) using special dopping wax. The dopping process is very important because unless the stone is centred and secured properly, problems can occur during the grinding process which will affect the eventual symmetry of the finished stone. After the stone is gently heated, the wax (usually in stick form) is melted over an alcohol lamp and dabbed on to the end of the dopping stick until a sufficient amount of wax has been collected. The heated stone is then carefully placed on to the wax (with the template markings still visible), centred and secured by moulding the wax around the base of the stone. Once the wax has cooled, the corners of the stone are rounded using a 100 to 120 grit wheel. Since additional material will be removed during subsequent polishing, care must be taken not to grind too closely to the template outline otherwise the finished stone will be smaller than originally planned. Using 200 to 230 grit wheels, wheel marks and deep scratches can then be removed by either dry or wet sanding. Generally speaking, there is a preference to wet sanding, especially when dealing with heat-sensitive stones since it reduces friction. Final sanding is carried out using a finer grit (320 to 400) until the stone acquires a semi-gloss or satiny finish. For stones of greater hardness (8 or more) a finer grit (600) is used. The final polish is achieved by using a variety of polishing compounds including tin oxide, cerium oxide, chrome oxide, Linde A and levigated alumina. Once all grinding and polishing has been completed, the stone is then removed from the dopping stick (by gently heating the wax) and cleaned using denatured alcohol. At the discretion of the cutter, the back of the stone will then be either sanded or polished.

Faceted Stones

Once the cutter has made his preliminary examination, the rough is normally trimmed to remove any unwanted material or inclusions that could cause problems during the cutting process. Once this has been accomplished, the trimmed rough is secured to a dopping stick (which is generally two-thirds the size of the stone) using a special faceting wax. During the faceting of a gemstone, this procedure will be performed twice, once for the crown and once for the pavilion. As with cabochons, correctly dopping the rough is very important since it will not only ensure that the finished stone is symmetrical but also help to avoid problems in trying to realign facets should the stone become loose during the grinding and/or polishing process.

Once the stone has been properly secured, the cutter can begin to cut the stone into the desired shape. Prior to the 1960s, the jamp-peg method (described in earlier editions) was preferred. During the last 30 years, however, a variety of electrically powered faceting machines (*Figure 21.37*) have emerged in the marketplace which allow today's lapidaries to achieve a higher level of precision and accuracy.

Today's faceting machines consist of a faceting head (*Figure 21.38*) and a master lap (*Figure 21.39*). The faceting head consists of a central rod (which is normally secured by a rack-and-pinion assembly), a sleeve assembly and a dop arm. The dop arm is regulated by an index gear and gear trigger which is

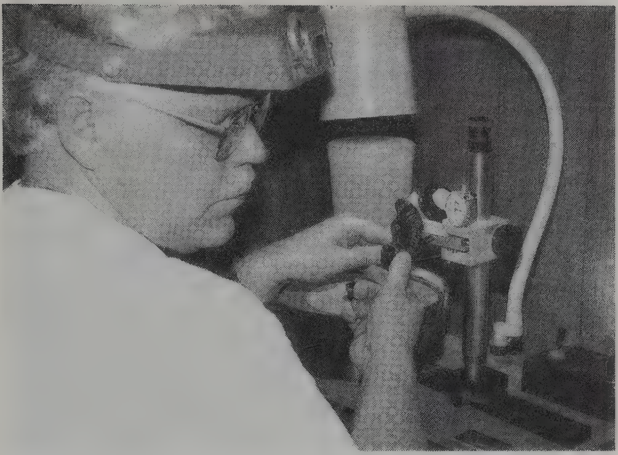


Figure 21.37 *An Alpha-Taurus electrically powered faceting machine (courtesy Victor Sawatzky)*

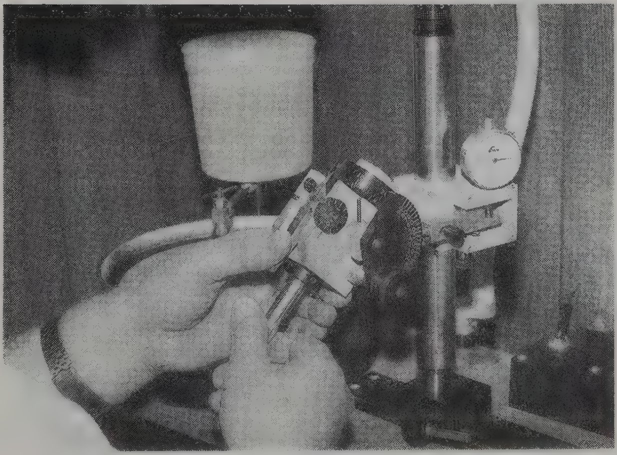


Figure 21.38 *The Alpha-Taurus faceting head showing index gear and protractor (courtesy Victor Sawatzky)*

located at the right end of the arm. A pointer, located towards the centre of the arm, is used to measure the angle of elevation which can be ascertained by using the protractor attached to the sleeve assembly. A slot, which is cut into the base of the machine, allows the operator to adjust the lateral movement of the faceting head. The master lap (which remains on at all times) is usually made of machined iron or aluminium. In order to achieve the best results, it is imperative that the master lap be absolutely level otherwise it will be virtually impossible to cut a gemstone correctly. Surrounding the master lap is a drip pan which can be removed for easy cleaning.

Figure 21.39 *The Alpha-Taurus faceting head and master lap (courtesy Victor Sawatzky)*

Since it is important that none of the cutting and polishing laps become contaminated, many cutters will use a series of laps (invariably pre-charged) tailored to meet their own specific needs. Preforming and faceting are carried out on a cutting lap which is made of either copper, solid steel or aluminium in a variety of grit sizes ranging from 180 up to 3000. Final polishing is performed (using a variety of polishing compounds as noted above) on a polishing lap made of either plastic, tin, tin-typemetal, typemetal, finely charged diamond tin, wax or even ceramic.

Although no standard procedure is used in the faceting of gemstones, many cutters agree that it is wise to keep detailed records of the index readings used so that if a stone has to be recut, the task can be accomplished more easily.

Gemstone Carving

The carving and engraving of gemstones (*Figure 21.40*) is carried out by the use of fine burrs like dentists' drills. These may be made of carborundum or more commonly of hardened steel, and are charged with diamond dust in olive oil. The worker has before him a number of these burrs of different shapes and sizes. Such tools are driven from a fixed headstock by electric motor, a suitable burr being screwed into the chuck for the work in hand. The art of gem carving embraces not only the cutting of cameos and intaglios but quite large carvings in hardstone. The hollows of agate cups and ashtrays are cut by a similar headstock fitting with a larger burr called a cupping tool.

Tumbled Gemstones

Tumbled gemstones can be produced by using either a rotary tumbler (*Figure 21.41*) or a new vibrating tumbler. By using firstly an abrasive agent and then a

Figure 21.40   A magnificent carving in rock crystal by the German carver Martin Seitz

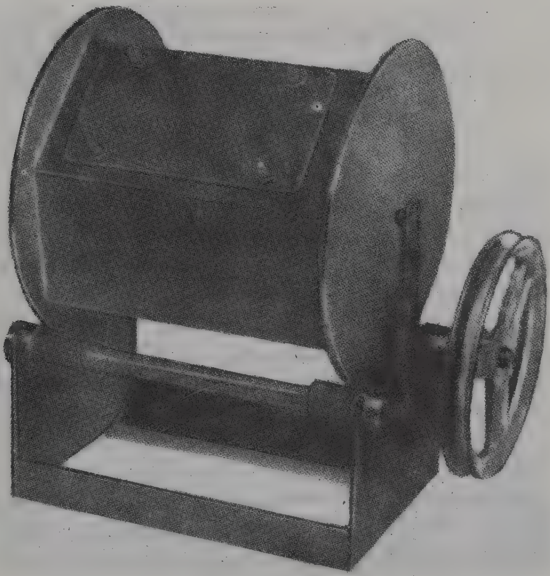


Figure 21.41   Machine for tumbling gems

polishing compound, it is possible to process large quantities of baroque-shaped gems at the same time. Although the procedure takes considerable time, it does provide an economical means of processing polished gemstones. Again, it is important to thoroughly clean the machines between stages to ensure that they do not become contaminated.

Today, tumblers come in a variety of shapes and sizes and are geared to both the hobbyist and the commercial operator. When operating a tumbler, it is wise (1) to thoroughly clean the material prior to placing it in the machine, (2) to operate the tumbler in a cool place, and (3) to check the contents daily in order to avoid a potentially dangerous gas buildup which many believe is caused by the chemical breakdown of the silicon carbide in the grit when combined with water.

A Word about Polishing

The older conception of the polish of a material was that it was simply one of superfine grinding so that the hills and the dales of the uneven surface were ground finer until any scratches thereon were too small to be visible. The work of Beilby during the early part of the twentieth century showed that this was not so, except in a small number of cases. Beilby found evidence that in polishing there is an actual flow of the solid surface with the formation of a liquid-like layer. This layer, termed the Beilby layer, lies like a coat of varnish over the underlying scratches. That the scratches are only varnished over by the layer may be demonstrated by etching with acid when they are revealed again.

In 1937 Finch experimented with the new technique of electron diffraction, which reveals the structure of the surface layer of a solid. He substantiated and extended Beilby's findings. Briefly put, Finch found that there are four different types of polish layer in minerals. They are as follows:

1 No Beilby layer as the melting point of the material is too high for the necessary local fusion. In this case, therefore, the polishing is just a fine abrasion. Such is the polish surface of diamond.
2 A Beilby layer forms but immediately recrystallises in conformity with the underlying structure. This is what occurs when corundum and quartz are polished.
3 The Beilby layer forms but remains amorphous except parallel to important crystal planes, or on long heating. Calcite and kyanite are examples.
4 In this case the Beilby layer remains amorphous on all surfaces. This occurs with zircon and spinel.

More recently, Huddlestone discovered more evidence of the existence of the Beilby layer by the use of Nomarski interference contrast techniques.

Beilby's contention that in general polishing involved surface flow of the polished material has often been attacked, but the account of his meticulous experiments given in his book *Aggregation and Flow of Solids* (London, 1921) and the later confirmation of his theory by modern methods by Finch (*Science Progress*, April 1937) are convincing and worthy of mention here despite continuing controversy.

The Carat Weight

The price of a finished gemstone depends upon the quality, the perfection of cutting, and the weight. The unit of weight used almost exclusively for gemstones is the metric carat of 200 mg (0.2 g), a unit which is of comparatively recent derivation.

A carat weight has been used for the weighing of gold and gemstones since ancient times, but the derivation of the weight is obscure. Seeds which have a fairly constant weight were used as 'weights'. Indeed the English grain (gr) was derived from the use of a seed of wheat taken from a well-ripened ear, and the carat weight was said to have been derived from the weight of a seed of the carob or locust tree, whose seeds are remarkably constant in weight whether taken from the centre or the ends of the pod. The seeds of the carob tree (*Ceratonia siliqua*) are chocolate brown and are of a flattened pear-shaped form. According to Spencer the seeds have an average weight of 0.197 g. The same author refers to the Greek weight ceratium, and also the Roman siliqua, as being equivalent to $\frac{1}{144}$ oz, or $3\frac{1}{3}$ gr, which is only slightly more than the $3\frac{1}{6}$ gr of the old English carat.

Also claimed as the origin of the carat weight are the orange kidney-shaped seeds with a black spot at one end obtained from the coral tree (*Erythrina corallodendron*). These have an average weight of 0.197 g, but are not so consistent as the seeds of the carob tree. Kuara, the African name for one species of the coral tree, has been suggested as the origin of the name carat, but the most likely origin of the carat, in both name and weight, is the *Ceratonia siliqua*.

The carat weight varied considerably in different parts of the world. At one time this difference was from 0.1885 g to 0.2135 g. The value of 0.204304 g was defined for the carat by the UK Standards Department of the Board of Trade and reported in the proceedings of the Weights and Measures Acts of 1878, 1888 and 1889, but the old English carat was never a legal weight.

The international aspect of trading in gemstones called for an international standard. In 1871 an attempt was made by Paris gem merchants to standardise the carat at 0.205 g and this was approved in 1877, but contrary to their hopes it did not gain international recognition. In 1907 Paris again took the lead in a second attempt to obtain world standardisation. The Comité International des Poids et Mesures proposed a metric carat of 200 mg, a weight approximately 2.5 per cent less than the old English carat weight. This proposal was accepted by the Quatrième Conférence Générale des Poids et Mesures in Paris, and it approached through diplomatic channels those other countries who would be interested. Eventually practically all countries legalised the position and the metric carat is now universally standard.

In England, the inclusion of the metric carat, as a unit of weight, was put through by an Order of Council on 1 April 1914. The metric carat can also be described in terms of points (100 to a carat) or grains (4 to a carat).

The only true way of determining carat weight is by using a precision scale (encased in a glass case to avoid draughts) and accurate to three decimal places, since a gemstone can only be sold as a carat when the third decimal place is a 9 (i.e. 0.999 carat). When estimating the weight of a mounted stone, use is made of either a stencil gauge with circular or cushion-shaped holes having diameters corresponding to the girdle diameters of correctly proportioned diamonds, or a

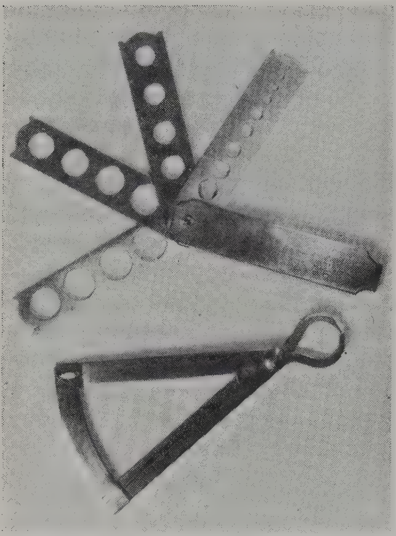


Figure 21.42 Diamond gauges: top, stencil gauge; bottom, caliper gauge

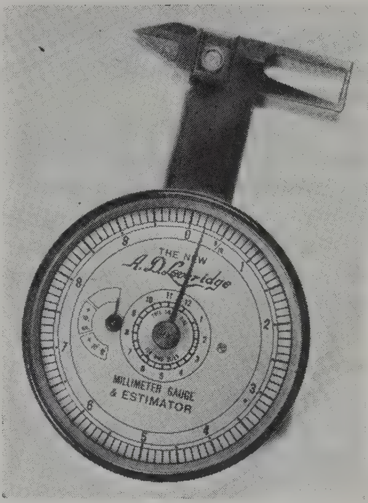


Figure 21.43 Leveridge's caliper gauge

more expensive caliper gauge such as the Moe (*Figure 21.42*) or Leveridge gauge (*Figure 21.43*). Such instruments measure the girdle diameter and the depth of the stone from table to culet, usually in millimetres. By using accompanying tables or weight estimation formulas (*Table 21.3*), a close approximation, often less than 5 per cent in error, may be obtained. In order to compensate for proportional deficiencies, weight correction factors must be used to ensure reasonable accuracy.

A modern electronic balance is shown in *Figure 21.44*.

Less expensive stones (including flame-fusion synthetics and imitations) are normally sold either by the gram or by the piece (based on measurements).

Handling Stones

For the handling of gemstones, a variety of tweezers are now available. These include spring-loaded, retractable prong and locking types in a full range of shapes, sizes and prices (*Figure 21.45*). Since the springiness and the width of the tweezers can vary greatly, it is important to select a pair that is most suitable for everyday use.

Miniature scoops or shovels are also popular, especially when dealing with groups of small stones. Stone papers, with liners to prevent stones piercing through, are a popular way of storing or transporting gemstones. Very often, especially when handling expensive or brittle stones, a fold of lint or cotton wool is used to prevent stones from rubbing against each other and causing damage. When this occurs, the effect is called 'paper wear' and can result, in extreme cases, in the stones having to be recut.

Table 21.3
Weight estimation formulae

Diamonds

Round brilliant: average diameter × average diameter × depth × 0.0061 × weight correction factor
Oval brilliant: average diameter × average diameter × depth × 0.0062 × weight correction factor
Heart-shaped brilliant: length × width × depth × 0.0059 × weight correction factor
Triangular brilliant: length × width × depth × 0.0057 × weight correction factor
Baguette: length × width × depth × 0.00915
Tapered baguette: length × width × depth × 0.00915
(width is the average of the two parallel sides)

Emerald cut: length × width × depth × adjustment factor × weight correction factor

Length to width ratio	*Adjustment factor*
1.00:1.00	0.0080
1.50:1.00	0.0092
2.00:1.00	0.0100
2.50:1.00	0.0106

Marquise brilliant: length × width × depth × adjustment factor × weight correction factor

Length to width ratio	*Adjustment factor*
1.50:1.00	0.00565
2.00:1.00	0.00580
2.50:1.00	0.00585
3.00:1.00	0.00595

Pear-shaped brilliant: length × width × depth × adjustment factor × weight correction factor

Length to width ratio	*Adjustment factor*
1.25:1.00	0.00615
1.50:1.00	0.00600
1.66:1.00	0.00590
2.00:1.00	0.00575

Weight correction factor varies from 1 to 12 per cent and is dependent on diameter and girdle thickness

Coloured gemstones

Faceted
Add 2 to 6 per cent depending on bulge factor

Round brilliant: diameter × diameter × depth × SG × 0.0018
Oval faceted: diameter × diameter × depth × SG × 0.0020 (diameter = length + width × 0.50)
Emerald cut: length × width × depth × SG × 0.0025
Rectangular: length × width × depth × SG × 0.0026
Square: length × width × depth × SG × 0.0023
Marquise: length × width × depth × SG × 0.0016
Pear shape: length × width × depth × SG × 0.00175

Cabochons
General: length × width × depth × SG × 0.0026

Sources: GIA Diamond Grading Lab Manual; The Guide Pricelist and Reference Manual

Figure 21.44 An electronic balance for weighing gemstones

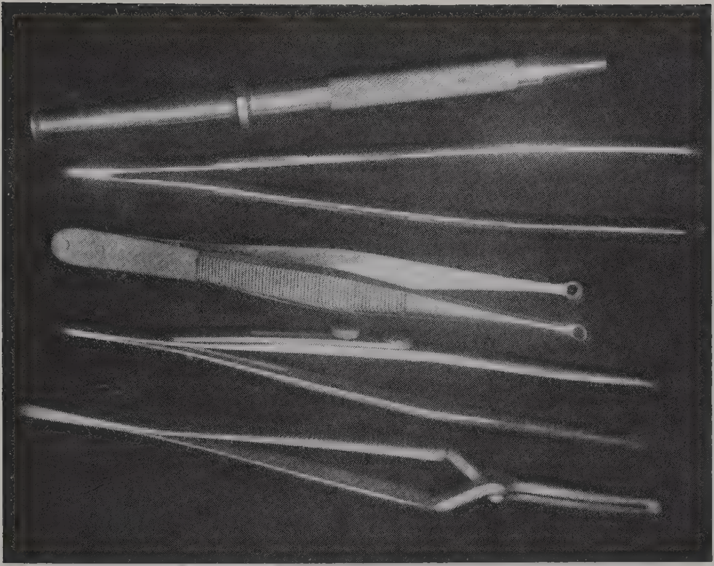


Figure 21.45 Various types of tweezer

22

Pearls: Natural, Cultured and Imitation

The gem materials which have been described in the preceding chapters have consisted of inorganic minerals derived from the earth's rocky crust, or of similar man-made materials produced by specialised laboratories. There are, however, a number of gem materials which are formed by biological processes, chief among which is the lovely pearl, and the story of these gems will be told in the following pages.

Natural Pearl

There are few lovelier gems than fine pearls, and throughout history they have been allotted a high and special place in the hierarchy of precious stones. The discoverer of the decorative beauty of pearls is lost in the mists of pre-history; it may well be that pearls were the earliest gems known to mankind, gems which need no treatment by lapidary or artist to enhance their native beauty.

That pearls are obtained from oysters is a general conception, and, indeed, the shell of the pearl oyster resembles strongly that of the true oyster, but the oyster which produces the pearl so prized in jewellery has more affinity zoologically to the scallop than to the true edible oyster. The pearl oyster belongs to a group of molluscs popularly known as bivalves (animals with a double shell), and the scientific name for the class of these animals is Lamellibranchia.

Nature and Formation

Any shelled mollusc can produce a pearl of sorts, but only those animals which have a shell with a pearl (nacreous) lining can form lustrous pearls worthy of use in ornamentation. The formation of a pearl is an abnormal case of the normal biological processes which build up the shell forming the protective covering of the animal. To understand the nature and formation of pearls some knowledge of the anatomy of the animal and the structure of the shell is necessary.

Anatomy of the Bivalve

One of the more rudimentary forms of animal life, the mollusc consists of a soft visceral mass enclosed between two valves of shell which are hinged together. The animal has a heart, a mouth and an alimentary system, but has no head. There are two large adductor muscles attached to the two parts of the shells (the valves); these muscles serve to pull the shells together so as to close the animal in. On the ventral side of the adductor muscles are two plate-like gills, rather like curtains. Near the mouth, which is adjacent to the hinge line of the shells, is the foot, and from a gland in a small pit near the base of the foot is secreted a substance which forms into a number of fibres, called the byssus, which serves to attach the animal to the rocks and debris of the sea floor.

The most important part of the animal, in regard to pearl formation, is the fold of epithelial tissue which covers the animal loosely beneath and above, the two halves being joined to one another along the hinge line of the shells. This double flap of skin is termed the mantle and is responsible for the formation of the shell.

The adductor muscles, by relaxing, allow the shells to open by virtue of a black inanimate elastic ligament near the hinge which is compressed when the valves are closed. This opening of the valves, termed gaping, allows sea-water to enter, and this flow of water carries with it the microscopic animal life from which the mollusc obtains its sustenance, these minute organisms being driven by hair-like processes, or cilia, on the gills, their wave-like motion wafting the food-laden water towards the mouth. It is this circulating water which supplies the life-giving oxygen.

The mantle is bounded on its outermost faces by a layer of secretory cells – the ectoderm – and from these cells is secreted the shell-forming substance. The shell is composed of three layers, although a fourth layer occurs at places where the abductor muscles are attached. The first layer is a dark horny outside layer composed of the organic substance conchiolin ($C_{32}H_{48}O_{11}$), a scleroprotein of keratin type; this layer is called the periostracum. The second layer is shelly and is made up of prismatic columns of crystalline calcium carbonate, usually in the form of calcite. The prisms of this layer are arranged at right angles to the surface of the shell and are held together by a 'mortar' of conchiolin; this layer is aptly termed the prismatic layer. These two layers are secreted by the cells at the edge of the mantle and once formed cannot increase in thickness. The third, or inner, layer forms the internal surface of the shell and this is normally secreted by the entire surface of the mantle and increases in thickness during the whole of the animal's life. It is this layer which provides the commercially important mother-of-pearl, and is known as the nacreous layer. This nacre is built up of overlapping platelets of crystalline calcium carbonate in the form of aragonite, and the principal crystal axes of these platy crystals are for practical purposes at right angles to the shell surface. Where the adductor muscle is attached to the shell another layer similar to the prismatic layer is formed, a layer which is known as the hypostracum, but this has little importance in our study.

Blister Pearls

The shell is a natural arrangement to protect the animal, and the nacreous inner surface of the shell provides a smooth cover for the soft mantle to bear against. Should, therefore, a sharp piece of grit, such as a grain of sand, a piece of broken shell, or even a shell-boring animal, get between the shell and the mantle, irritation would be set up and this the animal would attempt to ease. This it does by secreting nacre over the irritant and cementing it to the shell. This smooth bulge, or blister as it is called, can occasionally be removed from the shell and used as a jewel, such objects being termed blister pearls. They may be almost regular hemispheres or of a very irregular shape, and the non-nacreous base where it has been cut from the shell – a part usually concealed by the setting if the blister is mounted – clearly shows that it has been removed from the shell and is not a true pearl. Blister pearls are sometimes called chicot pearls.

Encystation

The highly prized whole pearls which are so important in jewellery are formed by another method, that of encystation, and such pearls are often termed 'cyst' pearls. The irritant in the case of these pearls is usually a minute parasite, which may be a trematode or a cestode worm. These minute wriggling intruders do not allow the oyster to cement them down on to the shell to form a blister, so another type of action is taken. The mollusc immobilises such a lively irritant by first forming a depression in the mantle into which the worm is trapped. By successive stages this depression deepens until a sac-like pouch is formed. This eventually joins at the neck producing a hollow sac of invaginated mantle tissue completely inside the connective tissues of the body of the oyster and quite separate from the mantle of which it was a part. The wound in the mantle coalesces (*Figure 22.1*). This sac containing the irritant, now most probably dead, is called the pearl sac, and is essential for the formation of a pearl. The nacre-secreting cells of the pearl sac are now on the inside surface; they are still living cells and go on secreting nacre over the irritant, building up a usually spherical mass of nacre which is a pearl. There are other theories to account for the formation of the pearl sac but the outline given above is the most generally accepted, although in a minor way and in other molluscs it is considered that different causes promote the occurrence.

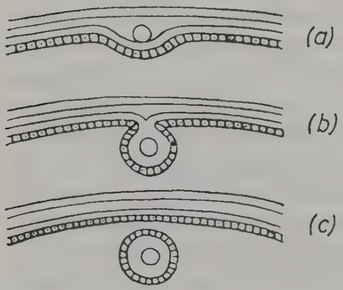


Figure 22.1 *Diagrammatic picture of the formation of a cyst pearl: (a) the irritant forms a dent in the mantle; (b) the mantle forms a pouch which contains the irritant; (c) the pouch separates from the mantle forming a cyst in the body of the animal. This pouch is the pearl sac and contains the irritant*

Figure 22.2 A thin section of a natural pearl photographed in polarised light. This clearly shows the concentric structure

The deposition of the pearly substance around the irritant in the pearl sac is arranged in layers, thus giving to the pearl a concentric structure. These layers are built up, like the nacre of the shell, of minute platy crystals of calcium carbonate in a network of the organic substance conchiolin, the crystals being so arranged that their principal axes are at right angles to the surface of the layers, thus giving a radial structure to the pearl (*Figure 22.2*). The fact that pearls have this concentric and radial structure has an importance in their testing. The calcium carbonate in gem pearls is practically always in the form of aragonite, and only in some freshwater pearls are the prismatic layers of calcite prisms found at all. The layers are seasonal growth and may be likened to the growth rings of trees, but unlike trees the age of the pearl cannot be assessed from the rings because, for various reasons, the deposition is often irregular and varies also in thickness.

Nomenclature

These 'free pearls', free because they are not attached to the shell, are termed 'cyst' or 'mantle' pearls when found in the connective tissue. Near the margins of the mantle 'hem pearls' of a rather dark colour may be found. Pearls found in the neighbourhood of the adductor muscle are termed 'muscle pearls' and are usually of fairly good colour, and near the ligament at the hinge of the valves are found dark brown conchiolin-rich pearls called 'ligament pearls'.

Chemical Properties

The chemical composition of pearl is about 82–86 per cent calcium carbonate (as aragonite), 10–14 per cent conchiolin, and 2–4 per cent water. The SG of aragonite is 2.93; therefore pearls would have an SG lower than this value owing to the other light constituents, conchiolin having an SG of 1.34 and water 1. The SG of pearls ranges from 2.60 to 2.78 (the non-nacreous pearls

Table 22.1
Pearl specific gravity

Locality	*Mollusc*	*Colour of pearl*	*Range of specific gravity*
Sea-water pearls			
Persian Gulf	*Pinctada radiata*	Creamy-white	2.68–2.74
Gulf of Manaar	*Pinctada radiata*	Pale cream-white	2.68–2.74
North coast of Australia	*Pinctada margaritifera*	Silver-white	2.68–2.78
North-west coast of Australia	*Pinctada maxima*	Silver-white	2.67–2.78
Shark Bay, W. Australia	*Pinctada carcharium*	Yellow	
Venezeula	*Pinctada radiata*	White	2.65–2.75
Japan (natural)	*Pinctada martensi*	White, with greenish tinge	2.66–2.76
Florida, and Gulf of California	*Strombus gigas* (the great conch)	Pink	2.85
	Haliotis (the abalone)	Greens, yellows, blues, etc.	
Gulf of California		Black	2.61–2.69
Freshwater pearls			
North America	*Unio*	White	2.66 to over 2.78
Europe	*Unio margaritifera*	White	
Cultured pearls			
Japan	*Pinctada martensi*	White	2.72–2.78
Non-nucleated cultured pearls			
Japan	*Hyriopsis schlegeli*	White	2.67–2.70
Australia	*Pinctada margaritifera* or *maxima*	White	about 2.70

from the giant conch and the giant clam are over 2.8) and to some extent the pearls from different sources conform to narrower ranges. *Table 22.1* gives a general idea of the value of SG for the most important pearl types.

The beautiful lustre of pearls is known as the orient of pearl and is due to a combination of two optical effects. These are the breaking up of light into minute spectra by diffraction caused by the irregular edges of the overlapping crystal plates of aragonite (*Figure 22.3*), and by the interference of light at thin films given by these same platelets. It is the edges of these overlapping platelets which cause the pearl to feel rough when the surface is drawn over the teeth; this is a useful test for pearl against imitation pearls, which are smooth to the teeth. It is no test for cultured pearls which have a true nacreous outer skin and feel rough like real pearls. The cause of the delicate shades of colour, such as that prized pinkish tone termed rosée, is unknown. These colour nuances are so minute and subtle as to be distinguished only by experienced persons. Likewise the cause of the colour of nacreous pearls showing pronounced colour, such as golden-yellow, yellow, pink, blue, grey, gunmetal, bronze and black, is not

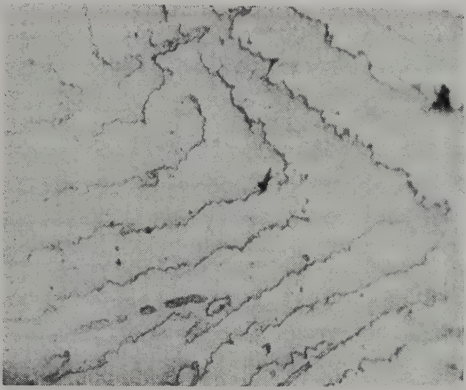


Figure 22.3 *A magnified photograph of the ridges of the overlapping plates as seen on the surface of the pearl (× 180, reduced by half in reproduction) (by courtesy of V G Hinton)*

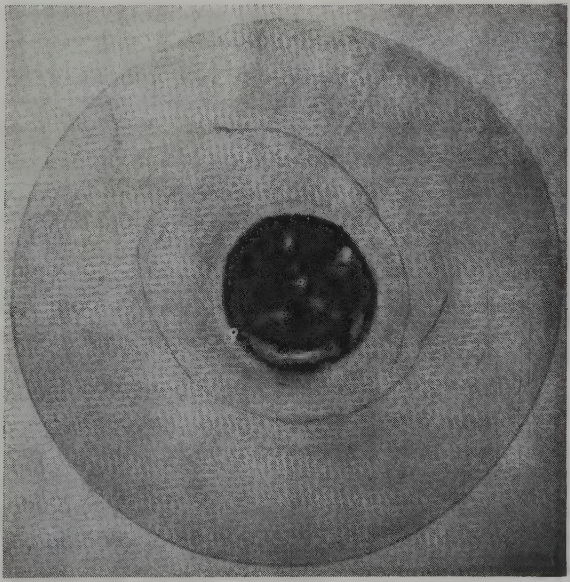


Figure 22.4 *A photograph of a thin section of a natural pearl with a conchiolin-rich centre*

clearly known, but it often has some affinity with the colour of the shell, and, to some extent, with the position of the pearl in the oyster. The nature of the water which the animal inhabits has been proposed as a reason for some of the colours.

The so-called 'blue pearls', pearls of a leaden-grey colour, possess a broad conchiolin layer lying near the surface, or have a 'mud centre', that is a central core rich in conchiolin (*Figure 22.4*). It is this dark-coloured organic substance showing through the translucent layers of aragonite crystals which give such pearls the dark appearance.

Pearl-Producing Animals

The animals which produce the pearls so prized in jewellery belong to the second order (Filibranchia) of the class known as Lamellibranchia. The generic name is *Pinctada*, although in previous years the name employed was either *Margaritifera* or *Pteria*, and earlier still the term *Meleagrina* was used. Various species of *Pinctada* produce pearls and to some extent these species live in well-defined localities. This being so, the different species will be mentioned when the various fisheries are discussed. All *Pinctada* are sea-water animals: there are other sea-water shellfish which also produce pearls and which have been found useful in decorative jewellery. Such animals include the giant conch and the giant clam, and the *Haliotis* with its highly coloured nacreous shell. Other pearls are found in freshwater molluscs, particularly the mussels (*Unio*). Such animals and their pearl production will be discussed later.

Life History of Pearl Oyster

The life history of the pearl oyster begins with the shedding of the ova or spermatoza into the sea according to the sex of the animal. In the pearl oyster the sexes are separate although cases of sex reversal are not unknown. Oysters are gregarious animals and therefore the ova and spermatozoa are ejected in localised waters, making the chances of fertilisation great. After about 24 hours the fertilised egg commences to develop a tiny bivalve shell but remains a free-floating animal carried about at the whim of the ocean currents. After about a week the animal, if not carried out to parts where the sea bed is unsuitable, or if not a victim to larger predatory animals, attaches itself by the thread-like byssus to hard objects or seaweed fronds on the sea bottom. These youngsters are at this stage about 0.1 mm in diameter and are termed spat.

It is clear then that the nature of the sea bed has much to do with the formation of colonies of oysters, and suitable conditions of depth and temperature of the water are necessary factors. The dead coral, rocks and shells on the sea bed to which the oysters attach themselves are collectively known as culch, and artificial culching of the sea bed is sometimes carried out.

The oyster grows rapidly for the first two years of its life and for the first five years has to battle with its enemies – the starfish, skates and rays, filefishes, the boring molluscs and sponges. The size of the full-grown oyster depends upon its species and upon the conditions in which it lives.

Natural Pearl Fisheries

The finest pearls are those which the jewellery trade terms oriental, and these are confined to the fisheries in the Persian Gulf, which extend from Kuwait in the north to the United Arab Emirates in the south: those off the islands of Bahrain are the best known. The other fishery is in the Gulf of Manaar which separates Sri Lanka from India. Perhaps the somewhat unimportant fishery in the Red Sea may also be included as supplying oriental pearls.

Persian Gulf

The beautiful pearls fished in the Persian Gulf, a fishery which has been known since 300 BC, are never very large, usually being under one grain in size: pearls over 12 grains are rare (1 grain = 0.25 carats). The pearl oyster which lives in these waters is the *Pinctada vulgaris*, which has now been reclassified as *Pinctada radiata*, a small oyster with a shell about 60 mm in diameter and which is fished solely for the pearls which may be found in it, for the shell is too small to have any commercial value itself.

The diving season in the Persian Gulf lasts from about the middle of May until the end of September, and it is during this period that the teakwood sailing dhows, which are sometimes equipped with auxiliary motors, sail out to the limestone reefs where the pearl oysters abound. During the inter-war years as many as 600 dhows, some so large that they carried 100 men, left for the fishing grounds, but since World War II the scale of the fisheries has decreased till now only a small number of boats operate the fishery. The finding, refining and export of oil in Bahrain and on the mainland has materially altered the status of the labour market, with the subsequent trend for the worker to take employment with the oil firms rather than to engage in the more precarious pearl fishing. Unfortunately the residues from the refineries and leakage from the tankers may eventually have a deleterious effect on the life of the pearl oyster.

The manner of diving employed by the Arabs in the Persian Gulf fisheries has scarcely altered since the time of the Arab historian Ibn Battutah in the fourteenth century, and indeed perhaps has not changed for the past two thousand years.

When the fishing grounds are reached the crews of the dhows extend their square-bladed oars out from the side of the vessels in order to steady the craft and to provide a place of attachment for the descending ropes. Two ropes are employed, one of which is fixed to a stone of about 25 kg upon which the diver stands when he is ready to descend. The diver is naked except for a loin cloth, for modern diving dresses with their attendant pumps are not used. On his fingers and big toes he wears protective sheaths, and either carried in his hand or slung round his neck is a string bag to which is attached the second rope. This rope is used to haul him to the surface on completion of his dive.

When ready to submerge the diver takes a deep breath and fixes on his nose a leather clip, rather like a clothes peg. He then pulls free the slip-knot of the rope holding the stone, the weight of which rapidly takes him to the bottom. Reaching the sea bed the diver steps off the stone and plucks as many oysters as he can from the immediate vicinity, placing them in the string bag. The divers, thin and wiry individuals whose age may be anything from 20 to 70 years, make about thirty dives of approximately one and a half minutes' duration each day, going to a depth which varies from 10 to 30 m, although depths much above 15 m are not common. When ready to ascend the diver jerks on the rope attached to the basket. This is the signal to the crewmen to haul him up, but meanwhile he may start climbing hand over hand up the rope in order to reach the surface and fresh air all the quicker.

Each diver and crewmen receive a share of the profits. The men who work the ropes and do not dive get only half the amount of that received by the diver, as their work is less arduous. The men are given two advances of pay during the year, one at the beginning of the season and another half-way through the off-season, these being intended to maintain the diver's family whilst he is away at sea and during the time he is not working. It is these advances of pay which had, prior to 1923, been the cause of much abuse. In that year Shaikh Hamad bin Isa al Khalifah, the then deputy ruler, instituted reforms which have made the lot of the divers much better.

Gulf of Manaar

The celebrated fisheries located in the Gulf of Manaar, an arm of the Indian Ocean which, with Palk Strait, separates Sri Lanka from the southern tip of India, have been known for some 2500 years. In this fishery the conditions needed for the well-being and growth of the pearl osyters are only found on the patches of rock, termed *paars*, which lie within 1 to 30 km from the shore and at a depth of not more than 30 m. Either through becoming exhausted, or through being covered by shifting sand, the fishing is now only of sporadic occurrence.

The oyster found in these fisheries is the same species as that fished in the Persian Gulf – the small mollusc *Pinctada radiata* – and the method of fishing is also by naked diving.

In recent years motor boats and dredges have been used, which, to some extent, have replaced the old practice of diving for oysters. The method is, however, said to have its disadvantages.

Before the formation of India and Sri Lanka as separate countries the working of the Gulf of Manaar fisheries was carried out by state control from Sri Lanka, and the fishing boats operated from the temporary hutted town of Marichchikkaddi on the north-east coast of the island, Indian people being permitted to join the camp only through certain indicated routes. The only fishery operated since the partition of the two countries from direct British rule was that of 1955, and this was from Tuticorin on the Indian side of the Gulf.

At the commencement of the fisheries an inspection of the fishing grounds is made and the fishing areas are marked out by flagged buoys (*Figure 22.5*). Divers are sent down to take samples of the oysters from the various *paars* within the buoyed areas, and from the data so obtained by this survey a plan is made for the guidance of the pearl fishers, and to ensure that the areas are not overfished.

After this preliminary governmental survey has been made an advertisement is published in various languages in a number of local and world newspapers. This advertisement gives the date the fishery is to be commenced, the location of the *paars* to be fished and the estimate of the likely production, and finally the method of payment, for the government puts up the oysters in lots as deemed expedient. It is this advertisement which attracts the divers, gem buyers and small merchants, with many Indian and Sinhalese coolies, to the fisheries.

The divers or the ship masters (*tindals*) provide the sailing vessels and the gear necessary for the actual fishing, while the government sees to the shore buildings and much of the shore labour. The buildings, comprising those for administration and social services, and sites are leased out for the period of the fishery to dealers and merchants who usually sit on a mat before open-fronted stalls.

Figure 22.5 Pearl fishing in the Gulf of Manaar. The pennant is on one of the marker buoys

Figure 22.6 Gulf of Manaar pearl fishery. Auctioning the oysters

After the day's fishing the anchors are weighed and the ruddy-hued sails hoisted for the run home. On the arrival at Marichikkaddi the catch is unloaded and separated into three piles; two are selected for the government and the third is divided among the divers and crew who may sell them as they will.

The oysters selected by the government are counted and auctioned in lots of 1000 or in multiples of that number (*Figure 22.6*). The balance unsold at the end of the day is disposed of privately on the following day.

The recovery of the pearls from the oysters is carried out by simply leaving them to rot, assisted by the maggots from the blowflies which infest the area. The rotten mass is subsequently searched through by hand for the larger pearls. The smaller ones are recovered by washing in *ballams*, which are simply dug-out canoes. The mass of decomposed oyster and shells is placed in these dug-outs and covered by water, the floating scum being skimmed off, and one by one the shells are removed and examined for any pearls and blister pearls. By constant changing of the water the bulk of the filth remaining is washed over the edge of the *ballam*. Finally the remaining debris, known as *sarraku*, is carefully searched, usually by women, for any remaining small pearls.

The pearls recovered are then sold to the numerous buyers who congregate at the fisheries. The pearls usually go to Bombay for drilling.

Red Sea

The Red Sea fisheries, which flourished at the time of the Ptolemies, is not now of great importance, but some fishing takes place on the banks along the Arabian shore between Jiddah, which was once the pearl centre, and the Farasan Islands; and also along the opposite African shore near Massawa. The oysters fished are the small *Pinctada radiata* of the Persian Gulf and Sri Lanka fisheries, but the pearls found are said to be whiter than those from the other oriental sources. They were previously marketed through Alexandria and have, from this connection, been known as 'Egyptians'. The somewhat larger oyster *Pinctada margaritifera* has also been fished from the Red Sea locality, but for the value of the shell only.

Minor Fisheries

A minor fishery is in the Arabian Sea off the coast of Bombay around the mouths of the Indus, south of Karachi.

There are oyster beds off the Mergui archipelago, a group of islands in the Andaman Sea which lie just off the west coast of lower Myanmar (Burma). These beds, indeed, stretch southwards to the Malacca Strait and may be said to be the northern section of the fisheries of the Malay archipelago and northern Australia. Here the oyster is the *Pinctada margaritifera* (the black-lipped oyster) and the shell has considerable commercial value, any pearls found being rather in the nature of a bonus.

Australia

The pearl fisheries of Australia extend from Shark Bay on the west coast (*Figure 22.7*), right round the north-west and northern coasts, through the Torres Strait which separates the tip of Cape York peninsula of northern Queensland from Papua, and thence to the fishing area of the Coral Sea. Adjacent to, and one may say part of, the Australian fisheries are the Aru Islands in the Arafura Sea south of Indonesia. Here Dobo is the pearling centre, and pearls from this locality are sometimes called 'Dobo pearls'. The Sulu Sea and the littorals of the Philippine Islands are also fishing grounds.

Thursday Island is the main centre of fishing but the luggers are mostly based on Broome on the north-west coast of Australia. In these waters naked diving

Figure 22.7 An early photograph of the Shark Bay pearl fishery

has practically disappeared, except for some goggle diving in shallow waters of the tropical islands. The modern armoured diving suit is now used in fishing for the large oyster *Pinctada maxima*, the gold-lipped or silver-lipped oyster (*Figure 22.8*), which may measure up to 300 mm in diameter, the pair of valves weighing as much as 5.5 kg. The fishing in these tropical waters is mainly for the shell, which forms a more commercially important industry, than for the, often large, white Australian pearls which may be found in the oysters. The pearls are recovered by a similar method as used in the Sri Lanka fisheries, that is by allowing putrification in 'poogie' tubs.

The small fishery at Shark Bay produces from the *Pinctada cacharium*, a small oyster some 75–100 mm in diameter, pearls of a yellowish or straw colour, often with an attractive golden tinge, and often up to 20 grains in weight.

South Sea Fisheries

The fisheries, mainly run by native fishers, in the numerous islands of Micronesia and Polynesia produce from the *Pinctada maxima* pearls similar to those found in Australian waters. These pearls are often large and of good shape – round, drop and button-shaped – and may sometimes weigh to over 100 grains. The most important centre of the South Sea fisheries is Tahiti in the Society Islands, but most of the pearls are fished from the Tuamoto archipelago. The more northern fisheries in Micronesia are allied to the Australian fisheries.

Figure 22.8 *Gold-lip shell* (Pinctada maxima) *with blister pearls from the Thursday Island fishery*

Note may be made of the fisheries around the Sulu Sea, where the oysters are often dredged by the use of rakes having curved prongs which are slowly drawn along by boats. The waters around the Palau Islands just north of Papua were, when under Japanese control, used for the cultivation of pearls from the large oysters *Pinctada margaritifera* and *Pinctada maxima*.

Japan

The fisheries in Japanese waters, where the oyster is the small *Pinctada martensi*, are now unimportant owing to the cultivation of cultured pearls in the east coast inlets. Any natural pearls found in Japanese waters would be suspect.

New World Fisheries

Turning to the seas of the New World, the first to consider are the fisheries of the coastal waters of Venezuela. These fisheries were known to the inhabitants long before Columbus visited the South American continent in the sixteenth century. Under the Spaniards the fisheries flourished, but the enterprise failed at the turn of that century owing to the acts of cruelty and oppression which caused the inhabitants to turn against the settlers. The fisheries were abandoned and not restarted until the nineteenth century.

The Venezuelan fisheries are centred mainly around the islands of Margarita and Ciagua. The oyster found in these waters is the small mollusc *Pinctada radiata*, an animal similar in size to the Sri Lanka pearl oyster. The pearls from these oysters are never of large size and vary in colour from white to bronze or even black, and the white pearls from Venezuelan waters are often so extremely translucent as to be almost glassy.

The Gulf of Mexico is often mentioned as an area for pearl fishery, and admittedly there is an unimportant fishery off the Marquesas which lie off the

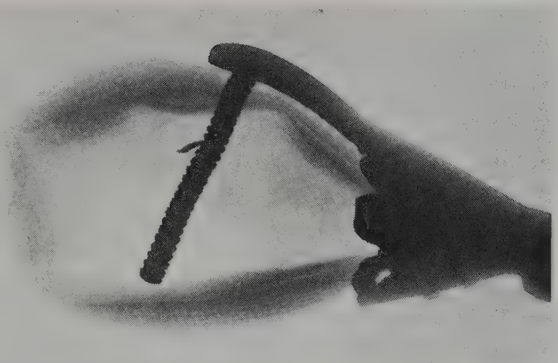


Figure 22.9 X-radiograph of a Haliotis pearl showing the hollow centre of such a pearl

western tip of Florida Keys. The important Mexican fisheries are situated on the western coastline of the country. These fisheries have been known to the Old World since the conquests by Cortés in the sixteenth century. The fishing waters extend from the apex of the Gulf of California, all round the littorals of Baja California, and along the Pacific coast of Mexico proper. The oyster fished is a greenish-edged variety of *Pinctada margaritifera* (*mazatlanica*), and the fishing was originally carried out by nude diving, but in more recent years armoured diving suits have been used. The chief trading centre for the Mexican fisheries is at La Paz. The Gulf of California is the locality which supplies many of the black and gunmetal-coloured pearls.

In the Gulf of Panama along the northern shores of Colombia light yellowish and silvery-grey pearls are found in the thin-shelled oyster *Pinctada squamulosa*, but this fishery has little importance.

Other Pearl-Producing Molluscs

Salt Water

Other members of the Mollusca which live in salt water also produce pearls, and in this connection three of these animals need to be mentioned. The first of these is the abalone of American water (the *Haliotis*), which in New Zealand is the paua shell prized for its highly iridescent mother-of-pearl. The Japanese called the abalone *awabi*. Such shellfish are univalves (single-shelled creatures) and may produce rather baroque pearls which are, like the shell, highly coloured and iridescent. Such pearls are often hollow inside (*Figure 22.9*) but their highly coloured iridscence serves to prevent confusion with any other pearl. An abalone pearl of reddish colour is found in the *Haliotis rufrescens*. The ormer shells (*Haliotis tuberculata*) which abound in the shallow waters off the Channel Islands produce pearls of sorts, but rarely have they been worthy of use in ornamentation.

The second and much more commercially important type of fancy pearl is that produced by the giant conch (*Strombus gigas*), the shell of which is used for

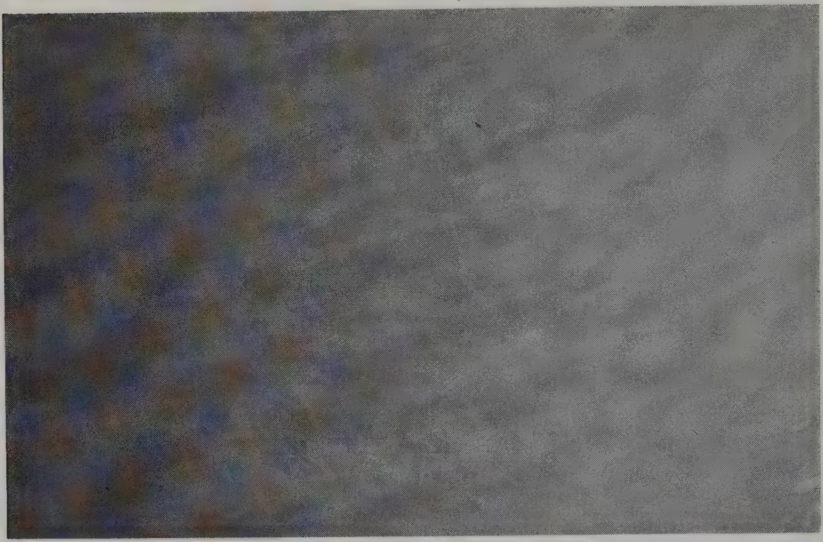


Figure 22.10 *Flame markings seen on the surface of conch pearls (photo courtesy of K Scarratt)*

the making of cameos. The pink or white pearls from this animal, the so-called conch pearls, are non-nacreous and have a porcelain-like surface with a peculiar appearance and a sheen like watered silk; the markings have been likened to 'flames' (*Figure 22.10*). It is by this surface structure that the pearls are distinguished from coral. The SG of these conch pearls is higher than for the nacreous pearls from the pearl oyster and ranges from 2.81 to 2.87. The giant clam (*Tridacna gigas*), another large mollusc, also produces a similar type of pearl, white in colour, having similar characteristics to those of the conch pearl. Orange pearls with an appearance similar to the conch pearl have been found in Malaysian, Mynamarian and Vietnamese waters. Similar orange pearls have been associated with the Baber.

Other members of the Mollusca which occasionally give pearls, but have little commercial importance, are the *Pinna*, the *Placenta*, the *Mytilus*, the *Cassis*, the *Venus*, which gives the porcellaneous black and dark purple clam pearls, the *Trochus*, the *Xancus*, and the *Turbo marmoratus*, the central column of the last shell often being turned into beads for necklets. The *Malleus*, found on the Pacific coast of America, produces a brass-coloured or black pearl having no iridescence. The SG of black clam pearls has been found to lie between 2.21 and 2.66.

Fresh Water

The pearl-producing Mollusca so far discussed have been those which live in salt water, but a number of freshwater shellfish produce nacreous pearls of varying degrees of beauty. The best of these river pearls are found in the mussel (*Unio*), which inhabits the rivers of Europe and America. The pearls from this mollusc have a nacreous lustre and, although never having the lovely orient of the pearls from the pearl oyster, can at times be of exquisite beauty. Such pearls are found, as they have been for some 2000 years, in the rivers of Scotland, when they are known as 'Scotch pearls', and in north Wales and Ireland. Scotch pearls are found in the Tay, Earn and Teith in Tayside and many rivers in Grampian and Highland. The Doon and Nith of southern Scotland are other rivers where the pearl-producing mussel is found.

The method of fishing in Scotland is for the fisherman to wade into the river and search the bottom with a glass-bottomed bucket through which he is able to peer below the surface of the water (*Figure 22.11*). He uses a cleft stick to bring up the mussels and these he puts into a sacking bag after which he returns to the banks and opens the mussels, searching the soft flesh for any pearls they may contain.

The river Conwy in north Wales and many streams of Ireland are fished in a similar manner.

The historical fishery of the Vologne river of the French department of the Vosges seems not now to be fished, and the same may be said of other French rivers which are inhabited by the pearl mussel. The German and Austrian rivers, particularly the Bavarian streams, are haunts of the *Unio*, and the Bavarian river Ilz produces pearls which are fished and marketed today. The others, including the streams on Luneberg Heath, are now unimportant, and the same may be said of the Russian rivers, although Scandinavian rivers seem to be gaining in importance.

River pearls have long been known from the North American continent, particularly in the streams of the Mississippi valley. Such pearls are often coloured, are rarely spherical and often assume various baroque forms in the shape of wings, dog's teeth, petals and other bizarre forms, shapes which lend themselves to the production of 'flowers' in jewellery. Although pearls are found in the freshwater mussel (*Unio*) in American rivers, many of the pearls are obtained from the niggerhead (*Quadrula ebena*), the three-ridge (*Quadrula undulata* or *Quadrula plicata*), the bullhead (*Pleurobema oesopus*), the buckhorn (*Tritogonia verrucosa*), and a number of other genera of shellfish.

Freshwater pearls are found in the rivers of the Amazon basin and in the rivers of Canada, where in the Nova Scotia district they are obtained from a bivalve named *Alasmodon margaritifera*. The *Cristaria plicata* of Chinese rivers are of more interest in the production of cultured blister pearls and for the nacre covering of metal images than for the few pearls they may contain. Rather attractive freshwater pearls of pinkish colour have been obtained from the rivers of Bangladesh, although there are now severe production problems.

The freshwater pearls rarely have as fine an orient as the oriental pearls, but they do have a soft pleasing appearance. The better-quality freshwater pearls are, like their salt-water sisters, mainly aragonite, although those from the *Alasmodon* are generally made up of the calcite prismatic structure. Freshwater pearls usually fluoresce strongly when bathed in a beam of X-rays, probably owing to a trace of manganese, while natural sea-pearls do not; this may hinder the fluorescence test for cultured pearls.

Grading and Shape

Pearls are graded according to colour and shape. The colour grading in the best

(a)

Figure 22.11 (a) Fishing for pearls in a Scottish river and (b) equipment used (photo courtesy of K Scarratt)

pearls depends upon delicate tinges of colour, which may be apparent only to the most experienced eye. Such nuances are termed rosée when showing a delicate shade of pink; silvery and white are other classifications. There is a subtle yellow tinge in pearls, a colour nuance which is more appreciated by people of Latin countries. Fancy-coloured pearls are those which have a decided colour and can be yellow, bronze, gunmetal black, rose-pink, green and blue.

The shapes of pearls vary greatly, the perfectly spherical pearls mostly being used for necklets. Pear-shaped or the so-called drop pearls are used for ear-rings

Figure 22.11 (*continued*)

and pendants, while those with a button shape (with one side somewhat flattened), sometimes called boutons, are suitable for ear-studs, dress studs and rings. Irregularly shaped pearls are called baroque pearls (barroks), and very small pearls are seed pearls.

Drilling

The drilling of pearls, generally carried out in Bombay in the case of oriental pearls, is done by using a bow drill with a needle bit which has the end flattened to a spade point. The pearl is drilled from each end, calipers being used to ensure the centring, and the freshly drilled pearl has a very straight hole 0.3–0.4 mm in diameter. This is, of course, for pearls selected for necklets, for the drop and button pearls are only partly drilled so as to be cemented on to a metal peg. Sometimes, in the case of these partly drilled pearls, a groove is cut in the side of the hole, and at the end the hole is enlarged by the aid of a 'dog-leg' cutter; the metal peg of the mount is then made with a key-shaped end and this is slid down the groove and rotated at the bottom so that it cannot be pulled out. The peg in all cases is cemented with the aid of a pearl cement; the best is a special cement rather like white sealing wax, and slight heat is necessary in order to soften it.

The oriental pearls which are drilled completely through so as to be used for necklets are usually sorted into quality and size at Bombay. These are prepared for marketing by stringing each size on silk; a number of sizes suitable for a necklet are then held together and finished off by tassels of silver wire and blue silk. Such a bunch of pearls is known as a 'Bombay bunch' and is usually provided with a pearl statement on an attached label (*Figure 22.12*). Sometimes drop and button pearls are drilled across the top of the drop or across the low back of the button pearl so that they may be sewn on to material. Such pearls are known as 'Chinese drilled'; they have less value than pearls drilled normally.

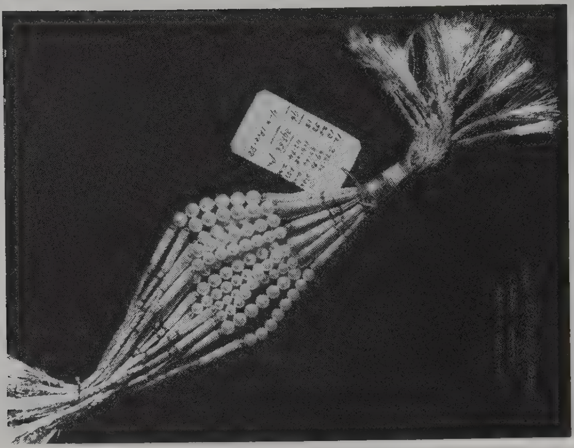


Figure 22.12 A Bombay bunch

Price Calculation for Natural Pearls

In calculating the value of any of the more precious stones such as diamond, ruby, sapphire or emerald, the rate per carat for stones of equal quality rises quite sharply with the size of the stone, at least in the range of sizes most used in jewellery, this being a reflection of the greater rarity of the larger specimens. Only in the case of pearls, however, is this steep rise in price not only tacitly acknowledged but made precise and systematic.

It is interesting to read in *A Treatise on Diamonds and Pearls* by an eighteenth century jeweller, Richard Jeffries, that the value of diamonds at that time was in fact regulated by the square of the weight in carats, and that precisely the same process was laid down in the case of pearls, which, according to jeweller Jeffries 'are next in importance to diamond, as they constitute the next greatest share of wealth'. For pearls, in the jewellery centres of London and Paris at least, what is known as the 'base' system of pearl valuation has for long been traditional, and rests essentially on the square of the weight of a pearl or of the average weight of a group of pearls of similar size reckoned in pearl grains. The pearl grain, like the diamond grain, represents a weight of a quarter of a metric carat and bears no correspondence other than in name with the grains of the ancient systems of Avoirdupois and Troy.

In the case of a single pearl the matter is simple: to arrive at the value, the square of its weight in grains (known in the trade as 'once the weight') is multiplied by its 'base' value, which can only be judged by an experienced dealer familiar with the current market in pearls. In the case of a graduated necklace of pearls, to which the base system is particularly applied, the matter is rather more complicated. The first task is to divide up the necklace into groups known as 'sizes'. The centre pearl is normally considerably the largest and always constitutes the first 'size': its 'once the weight' is simply the square of its weight in grains, as indicated above. The two pearls, one on either side of the centre, should be almost equal in weight and are often taken as the next 'size', or, if the graduation is not steep, it may be that the next four or even six are chosen. In this case 'once the weight' for the size is determined by multiplying the average weight by the combined weight of the group. For the remaining sizes larger groups are chosen as the effect of size on the value of the pearls is less critical in the case of smaller pearls. The 'once the weight' figures for all the sizes are then added together. The valuer will then decide what multiple of 'once the weight' is suitable. As the system was originally used before decimalisation of the currency, in the following examples the original shilling base (20 shillings to £1) will be used but with the current decimal figures added for the final calculation of the value of the necklace. In 1982 the trade price for poor-quality pearls might be 5 shillings (£.025) while for very fine quality it would be 60 shillings (£3.00) to 70 shillings (£3.50).

An actual example of a typical necklace should make the process more understandable. A graduated necklace of 121 pearls was sized and the 'once the weight' calculated as follows:

Pearls	*Total Weight* (grains)	*Once the Weight*	*Shilling Base*
1	7.3	7.32 × 7.32	53.58
2	12.24	12.24 × 6.12	74.90
8	30.84	30.84 × 3.85	118.73
36	54.32	54.32 × 1.50	81.48
74	46.24	46.24 × 0.62	28.66
121	150.96		357.35

If the valuer considered a 50 shilling £2.50 base to be appropriate (speaking in trade terms) the final sum is seen to be 357.35 × 2.50 = £893.37.

For ungraduated pearls of the smaller sizes the base system does not operate, the pearls being sold at so much per carat as in the case of precious stones.

Treatment

The 'doctoring' of pearls by 'skinning' has often been mentioned. The notion is that by removing a bad-coloured or blemished outer layer, a more attractive, although smaller, pearl could be obtained. The layer is removed by careful filing of the surface, or by the use of abrasive emery paper. There are, however, very few people who are experienced in this exacting work, and in any case the result is problematical.

Cracks in the surface of pearls are sometimes 'cured' by soaking them in warm olive oil, but such improving methods, called decraqueler, are fraught with danger, for at quite a low temperature – about 150 °C – the pearls tend to turn to a brown colour and then lose their value.

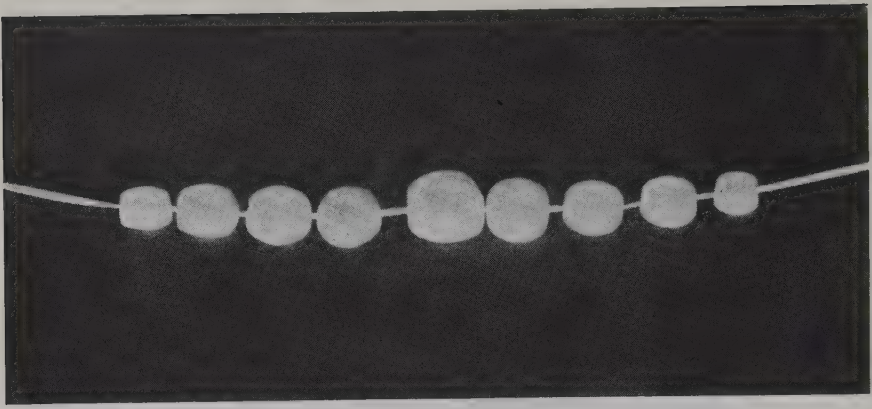


Figure 22.13 A pearl necklet showing many of the pearls to have worn barrel-shaped

Protection

Pearls will last for centuries provided normal care is used in protecting them. The loss of lustre and the cracking of pearls are due to one of two things: (1) the drying out of the organic constituent – the conchiolin – so that too dry an atmosphere is detrimental to pearls: (2) the facility of the mineral part – calcium carbonate – to be dissolved away by weak acids. This is manifest in the formation of a barrel shape assumed by well-worn old pearls in necklets (*Figure 22.13*). This effect is particularly evident in the pearls near the snap end where the necklet lies close to the neck and where the pearls are close to the skin, the erosion being due to the acid nature of exudations from the skin. Keeping pearls in cotton wool may also be detrimental for much cotton wool is not acid free.

Modern cosmetics which seep into the string canal may penetrate into the layers of the pearl and cause deterioration; they may also rot the string causing it to break. Thus, pearls should be cleaned periodically, and this is best done when the necklets are restrung. Such restringing and cleaning should be carried out at intervals of not longer than six months, and should be carried out only by a competent pearl stringer who will know the correct way to clean the pearls and the correct silk to use for the stringing. The best necklets should be strung so that there is a knot between each pearl; then should the necklet be accidentally broken only one pearl at most would be lost.

Staining

The staining of pearls is sometimes carried out. This may be to induce the delicate rosée tint, but such a staining is not very successful. Methods to induce a black colour are quite often employed with dark-coloured pearls which are not acceptable for jewellery. The most common method is to soak the pearls in a weak solution of silver nitrate and then expose them to sunlight or ultra-violet rays. This treatment causes the silver to be reduced (by action of the organic constituent) to a finely divided condition: this powder is black in colour, and gives that hue to the pearl, which is 'buffed up' to give a lustrous finish.

Such 'treated' pearls are not commercially acceptable, but the identification of such artificial coloration is not easy. X-rays may give an answer owing to the 'reduced silver' being congregated in the conchiolin-rich layers. This causes an opacity to the rays instead of a transparency. On the film, therefore, such organically rich areas will show light and not dark as in untreated pearls. It has been found that naturally coloured black pearls show a dim reddish glow when examined by light passed through a copper sulphate solution and a red fiter. Pearls stained black artificially do not show this dim red glow.

Cultured Pearls

With the popularity of pearls it is not surprising that experiments have been made to stimulate the pearl-forming shellfish to produce objects of this nature. Indeed, such experiments are centuries old, for the covering with nacre of objects inserted between the shell and the mantle of pearl-producing molluscs is attributed by the Chinese to a native of Hou-Tcheon-Fou who lived in the thirteenth century. For centuries the Chinese have inserted objects, particularly metal figures of Buddha, between the shell and the mantle of the Chinese freshwater mussel (*Cristaria plicata*) (*Figure 22.14*).

History of Early Experiments

The Swedish naturalist Carl V Linne tried experiments for the making of pearls using a freshwater mussel. This was during the eighteenth century. The method Linne empoyed was to bore a small hole through the shell of the mollusc and insert in the hole a fine silver wire bearing on its end a rough fragment of limestone. This artificial nucleus was placed near the ends of the shell to avoid too much irritation of the animal's body. The wire kept the nucleus away from the shell to prevent the formation of a blister pearl. The results were not encouraging and had no commercial significance.

A recent examination of the Linne pearls cultured in 1761, along with the shells, revealed that he also developed another and potentially more successful method, although again it was not commercialised. A part-drilled mother-of-pearl bead was adhered to one end of a T-shaped metal holder and the whole, along with several others, was placed inside the mussel (*Cristaria plicata*). The beads were kept separate by means of a thread. The resulting cultured pearls and holders were amost entirely coated with nacre.

During the last decade of the nineteenth century the Japanese Kokichi Mikimoto, an itinerant pedlar of noodles who became interested in pearls, commenced experimental production of the cultured semi-spherical or blister pearl (*Figure 22.15*). In 1896 he patented the process used and such objects were commercially produced.

The method used was to force open the valves of a pearl oyster and cement to the nacreous internal surface of the shell a spherical bead of mother-of-pearl. The jaws were released and the animal returned to the water, when after a few years the oyster was found to have coated the bead with nacre, which seems to have been deposited with greater rapidity than for the deposition in the case of

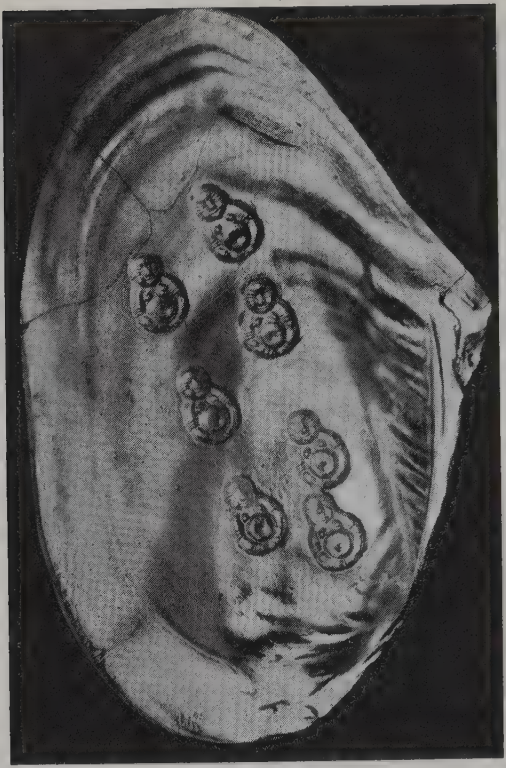


Figure 22.14 Pearl-covered Buddhas on Chinese fresh-water mussel (Cristaria plicata)

oysters forming a blister pearl naturally. As nacre cannot be deposited on the cemented side of the bead this needs to be ground off and is usually replaced by a piece of mother-of-pearl which is ground symmetrically to shape. This non-nacreous base is covered by a closed-back setting when mounted in jewellery. There appear to be variations of this type of cultured pearl in that the mother-of-pearl base may be pegged into the bead nucleus, or may be just cemented on to the flat surface of the bead. Most commonly the original bead nucleus is removed and after the inside of the shell of nacre has been polished, and may be tinted, the empty recess is refilled by a new bead and backing which is cemented in by the use of a white cement. Such an object makes a striking picture when photographed by X-rays. Such pearls are called 'mabe' pearls. A cultured blister pearl, probably of mabe type, in which the bead was made of half a nut, probably an areca nut, has been met.

It is said that Mikimoto first marketed the fully spherical cultured pearls during 1913, but it was 1921 before the whole cultured pearl came upon the general market to any extent. This was the outcome of many years of experiment, and contrary to general belief was not the brain-child of Mikimoto, who, however, had much to do with the subsequent commercial marketing of these cultured pearls. There is still some doubt as to who first produced a whole

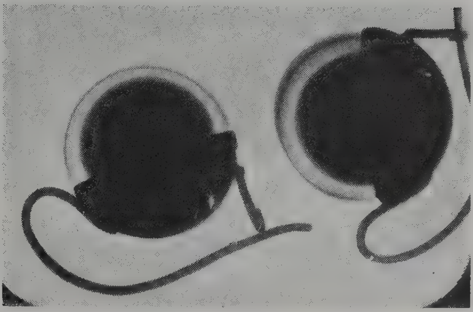


Figure 22.15 *X-ray picture of a pair of ear-rings set with cultured blister pearls (mabe pearls)*

cultured pearl, but the most successful experiments were essentially those of Japanese workers. The history is vague, but investigation has shown that it was in all probability Tatsuhei Mise, a carpenter who became interested in pearls because of his stepfather who had been on an oyster prospecting trip to Australia. He had no scientific training, but working on an idea of his own he produced at his home in Watakano-shima in Matoya-wan (*wan* means bay) a whole cultured pearl. The pearl was developed in the Japanese pearl oyster (*Pinctada martensi*) by a tissue graft around a tiny lead nucleus. The exact date is unknown but it was prior to 1904. In 1907 Mise applied for a patent on his process but was refused such protection on the ground of Mikimoto's early patent and another patent by one Nishikawa, which in point of fact was five months late. Mise was, however, granted a patent on the needle he used in his method, and this was the first patent issued in respect of whole cultured pearls. Mise left no published record of his work.

The first person to produce whole cultured pearls from planned scientific experiments was Tokichi Nishikawa, who until 1905 was a technologist in the Japanese Bureau of Fisheries. In this year he resigned to take up research on pearls. The method used by Nishikawa was in essentials similar to that of Mise except that tiny gold and silver nuclei were used. Nishikawa applied for a patent on 23 October 1907, five months after Mise's application, and, the patent office accepting the claim made by Nishikawa that he had completed his invention as early as 1899, granted him protection, but even so this was not until 1916, and when Mise's earlier application had been ruled out as an infringement. In 1908, however, Nishikawa and Mise signed an agreement of joint ownership of the Mise/Nishikawa method: this seemed to indicate the priority of Mise's discovery. Nishikawa died in 1909.

In 1914 Mikimoto again came on the scene when he applied for a patent for his own method of spherical pearl culture, and this was granted in 1916, 50 days before the Nishikawa patent was granted, a patent applied for seven years earlier than Mikimoto's. Mikimoto did not invent the method he patented, the inventor being Otokichi Kuwabara, a great friend of Mikimoto, whose previous profession was that of a dentist. This Kuwabara/Mikimoto method is the so-called 'all-lapped' system, by which a bead nucleus was wrapped and tied with fine silk thread in a sac made from the mantle of an oyster, this being inserted into the body of another oyster where it was attached 'by pressing'. Today it is the Mise/Nishikawa method which is extensively used, as the Mikimoto method was found to be too delicate and wasteful. Subsequent intermarriage of the principal families gave rise to some sort of unified organisation presided over by Kokichi Mikimoto until his death in 1955 at the age of 96.

Australian and Other South Sea Cultivation Farms

The modern production of cultured pearls has been brought to a fine art in Japan, and also in certain islands of the equatorial Pacific Ocean, such as the Palau group, which were under Japanese mandate during the years between World Wars I and II. Except for an abortive attempt to cultivate pearls in Australian waters during 1907, Japan has been the only source of cultured pearls. However, after 35 years' embargo on the cultivation of pearls by the government of Western Australia, the state, during 1956, granted a licence for 3 years for an Australian company to grow cultured pearls in a prescribed area in Brecknock Harbour which lies between Augustus Island and the mainland of Western Australia. In a bay here, now called Kuri Bay, cultivation has been carried out by the company using Japanese technicians, with the large oyster *Pinctada maxima*. Cultured blister pearls of large size have been successfully produced which, after removal from the shell, are sent to Japan to have the nucleus removed, the inside of the blister polished and if required tinted, and the empty recess refilled with a fresh mother-of-pearl bead and a backing which is cemented in by a special white cement. Whole cultured pearls are also produced in Australian waters and these pearls are of large size, some being over 100 grains in weight. These cultured blister and cultured whole pearls were seen on the European market during the autumn of 1958, which indicates a faster rate of growth when the large oyster is used. Some experiments with the production of non-nucleated pearls have also been carried out in these waters but the pearls formed were usually baroque. Large whole and blister cultivated pearls are also produced in certain Pacific islands and off the coasts of Myanmar and Thailand. Naturally coloured black cultured pearls are produced off Tahiti. An Australian firm has started banks of oysters at Port Moresby in New Guinea and at Friday, Banks and Thursday Islands in the Torres Straits.

Japanese Cultivation Farms

The pearl-producing mollusc which lives in Japanese waters is the small oyster *Pinctada martensi* (*Figure 22.16*), which at maturity is not more than about 80 mm in length. The centre of the pearl culture carried out in Japanese waters is in Ago-wan, a bay which is situated near the Shima Hanto (*hanto* means peninsula) which itself forms the greater part of the Ise-shima National Park at the south-eastern end of Mie prefecture. Other nearby bays – Gokasho-wan, Matoya-wan, Kagaimura-wan and Nie-wan, all of which, like Ago-wan, lie on the eastern coastline of the main Japanese island of Honshu – are also used for oyster farms. There have been attempts to develop the industry in other parts

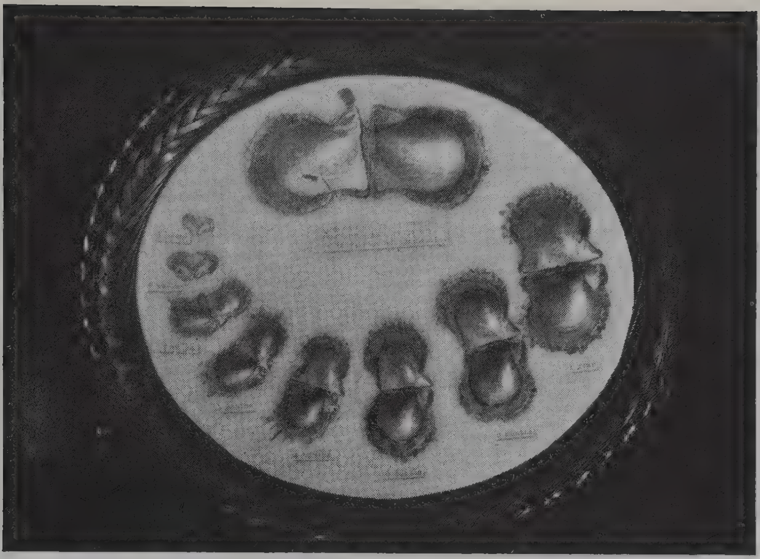


Figure 22.16 The Japanese pearl oyster Pinctada martensi, *showing the size at various stages of growth from three weeks*

of Japan, such as the Omura-wan in Kyushu, and the Tsushima islands and Tos-wan in Shikoku. Recently a new strain of *Pinctada martensi* has been bred which grows to double the size of the same species grown in Ago Bay. These larger oysters allow pearls of up to 12 mm diameter to be produced as against the maximum of 10 mm obtainable with the Ago Bay strain.

The geographic and climatic conditions in the Ago-wan area are perfect for the production and growth of pearl oysters which demand water of a uniform shallow depth never falling below 10 °C. These small bays along the peninsula provide protected water in which peramanent oyster beds may be safely laid.

The pearl fisheries (farms) start with the collection of naturally grown oysters common to the area or, more usually now, oysters raised from cultivated 'spat'. Motor launches, or fishing skiffs, with a crew of four or five, two or three being divers, go out to collect these oysters.

Diving Techniques

The divers are mostly women, for it is said that these Japanese women have more endurance and can hold their breath longer than men whilst under water. These sturdy, picturesque divers, known as *amas*, in former days dived practically nude, but today they are clothed in short white sarongs and long-sleeved white shirts which cover them from throat to knees. They bind their hair and cover their heads with white cotton kerchiefs, and their faces are protected with wide glass-fronted face masks which cover all except the mouth and chin.

When the floor of the bay is less than 5 m deep the only kit taken is a small hand-net about 250 mm in diameter, a 30 mm mesh cotton netting bag some

Figure 22.17 *Girls diving for oysters (by courtesy of the Cultured Pearl Company Ltd)*

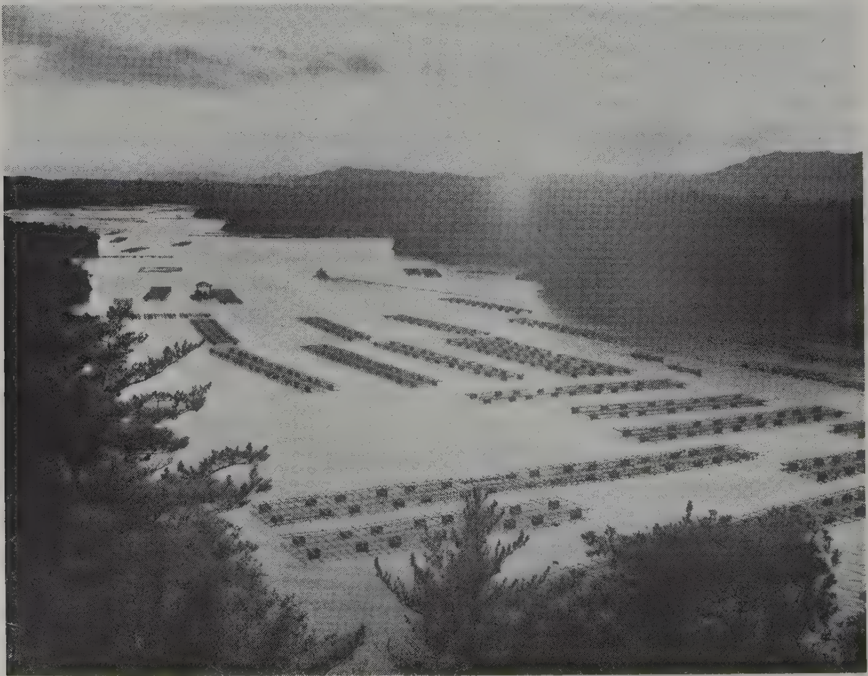


Figure 22.18 *General view of rafts in pearl cultivating area (by courtesy of the Cultured Pearl Company Ltd)*

half a metre in depth, and a large wooden bucket about 500 mm deep and 600 mm in diameter which is attached to the diver's waist by a stout cord (*Figure 22.17*). The *ama* gives a powerful kick as she dives below the surface, then gropes along the dark sea floor. On each dive she collects, according to the skill of the diver, from 1 to 10 oysters, which she puts into her hand-net and transfers to the wooden tub on surfacing. Each dive lasts for about 25–40 seconds; the constant holding of the breath causes the *amas* to breathe with a peculiar whistling sound when they come from a dive.

In deeper water, up to 8 m, the *amas* operate directly from the sides of the boat, using a heavy stone or weight on a rope which passes over a davit on the boat's gunwale, just aft of amidships. Taking a deep breath the diver, with another rope round her waist, grasps the rope with the weight, and on release of this rope, sinks quickly to the bottom. On the diver's signal the crew in the tender pass the lifeline over the davit and haul the girl up to the boat, in which she empties her net containing the oysters she has gathered. She rests on the deck for about two mintues while the weight on its rope is raised. The divers work for two $2\frac{1}{2}$-hour periods each day, and during the non-working period rest on the shore before open fires. The active figures of these industrious women add colour to the enchanting scenery of the Shima peninsula (*Figure 22.18*) and attract thousands of sightseers every year.

Sorting of Collected Oysters

The oysters collected by the divers are taken to the sorting tables at the shore base. Here the unsatisfactory shells are discarded, and the 2-year-old oysters are separated by their size from the 3–4-year-old individuals. The catch is weighed in order to credit the diver who receives a rate of pay per *kan* (about 3.75 kg), representing about 100 oysters. The 3–4-year-old oysters are taken to the 'farms' and distributed over previously cleaned moderately rocky bottoms of shallow water. These remain undisturbed until the next April or May, when divers again collect the oysters for them to be taken to the laboratory for nucleus insertion.

Cultivation of the Spat

The principle of the cultivation of spat had long been understood and methods had been devised for such cultivation in the case of edible oysters. The earliest method employed consisted in the collection of spat by allowing them to settle on submerged stones, or pieces of bamboo, and then removing them to more sheltered waters where their growth could more easily be observed. It was later discovered that the free-swimming spat develops, just before settling, a marked aversion to light, and to avoid this special cages were developed by Mikimoto. These cages, some 840 × 540 × 200mm, are formed by covering a heavy galvanised wire frame of 20 mm wire mesh, and having seven horizontal wire mesh shelves and provided with a door at the foot of the cage. Black painted boards are fastened to the sides and bottom which provide a darkened area attractive to the spat. The cages are, before attachment of the boards, dropped into hot tar and then into a sand and cement mixture to provide an excellent base upon which the larvae can settle. Some 50 cages are suspended at a depth of 6 m from large frame rafts supported by empty oil drums or barrels. In 1947 a simplified and inexpensive spat collector was designed. It consists of a bamboo raft frame from which is suspended a series of 40 straw ropes strung with discarded shells of the oyster, abalone or *Turbo*.

These rafts are set out in July, the oyster spawning season being from July to September, and are anchored in suitable waters in a series of 5 or 10 lashed together end to end. The cages remain in place until late November, by which time the young oysters are 15 mm long. They are then transferred to rearing cages which resemble in many details the collecting cages, except that the size of the covering mesh is smaller at 10 mm, or cotton mesh may be used, and the internal divisions are slightly different. The cages, however, do not protect the oysters from the damage caused by the so-called 'red tides', a poisonous form of plankton which chokes the oysters. The young oysters are allowed to remain undisturbed until they are a year old and some 25 mm in diameter. These oysters are then sown in shallow water, 3–5 m deep, which has a rough rocky bottom, and here the oysters are allowed to remain undisturbed for about 2 years.

From June to August the oysters, now 3 years old, are collected by women divers and brought to cleaning barges – large fully decked pontoon-like structures with a simple sloping roof – which have been towed to the collecting site by motor launches. The shells are then cleaned from adhering incrustation and seaweed by scraping with a blunt knife. Distorted and old shells are discarded and undersized shells returned to the growing beds for another year. The cleaned shells are then placed in culture cages in shallow water for 10 days for acclimatisation to their new environment and to recover from the shock of cleaning.

After the period of acclimatisation the oysters are taken up from the cages and prepared for the operation of nucleus insertion. One of three methods is used to induce the partial opening of the valves (shells). The oysters may be placed in shallow trays with the hinge of the shell downwards and then covered with sea-water, when in a minute or two the valves 'gape'. They are then forced about 10 mm apart by the use of opening forceps, called the 'shell speculum', inserted between the shells at the antero-ventral region sufficient to allow a bamboo wedge, or 'key', to be inserted at the postero-ventral region and at about 45 degrees to the hinge line (*Figure 22.19*).

An alternative to this 'stagnant water method' is the 'running water technique', and this differs solely by the fact that the trays are supplied with constant running water. In a third method, the 'dry method', the host oysters are brought in baskets to the station wharf about 24 hours before the nucleus insertion. The baskets meanwhile are hung from nearby rafts, and some 30 minutes before the technicians are ready to carry out the operation the oysters are dumped on to the wharf, and shortly after about 25 per cent of the oysters begin to gape. These are selected for immediate operation and the bamboo wedge is inserted; this must not be kept in for more than 2 hours before the operation for the insertion of the nucleus is performed.

The oysters which do not gape within the time are returned to the water for

Figure 22.19 Opening the oysters and inserting pegs

another 4 hours and again taken to the wharf for testing. The gaping of the valves indicates that the oyster is healthy and vigorous enough to withstand the operation, which is best carried out only 20 minutes after the keying of the oyster. This keying itself needs care, for should the edge of the shell be broken, the animal first repairs this damage to the detriment of the formation of the pearl sac and the quality of the resultant pearl.

While the pegging or keying of the oysters is carried out the technicians who do the actual operation prepare their desks and apparatus, and also a supply of mother-of-pearl beads used for the nucleus.

Nucleus Operation

Preparation of Nuclei

The best material for the nucleus is a substance which is not foreign to the oyster; a spherical bead of mother-of-pearl is eminently suitable and is consistently used. As these nuclei range in diameter to more than 6 mm for *Pinctada martensi* to as much as 13 mm from pearls cultured in *Pinctada maxima*, a solid heavy shell from which they are to be cut must be obtained. Before China's embargo on trade, the shell for the beads of cultured pearls was obtained from the *Gamanose* clam shell from the Yangtze river. Since then shell from the pig-toe mussel found in the Mississippi valley is used, although in recent years with the opening up of China the Yangtze mother-of-pearl is again being used, particularly in Myanmar. In some cases sea-water *Trochus* shell has been used.

The American shells are shipped to Japan for processing. This is carried out by cutting the shells into small cubes of the required general size. They are then placed between iron sheets, the upper one being revolved, and by the general rubbing of the cubes between these plates they attain a roughly spherical shape. The beads are then placed in cotton bags and subjected to a further grinding treatment. This may be followed by placing powdered talc or jeweller's rouge in the bag to impart a polish to the surface, although a polished surface is not essential.

The finished beads are then graded to size: for *Pinctada martensi* they are from 1.2 mm to 6.6 mm in diameter, each group being 0.3 mm larger with individual variation within the groups of less than 0.05 mm. Larger nuclei up to 13.2 mm are prepared for *Pinctada maxima*, and beads between 6.3 and 6.6 mm are used for *Pinctada margaritifera*. Experiments with plastic beads as a substitute for the nucleus showed the material to be generally unsatisfactory, but these are used for mabe production in the pearl farms of Thailand. Marble mechanically prefabricated into spherical beads has been used experimentally. This marble has been obtained from Shikoku and Gifu prefectures; but from experiments on cultured pearls which have been found to have an unusual nucleus it is uncertain whether the material is a marble or a banded talc.

Preparation of Graft Tissue from Oyster

The technicians first prepare the graft tissue from the frilled mantle edge of a living oyster. A selected oyster is carefully opened by inserting the blade of a knife between the valves and the adductor muscle is then cut from its attachment to one shell. With the blunt edge of a scalpel all extraneous matter is scraped out and then a strip of living tissue, about 7 mm wide and 70 mm long, is cut from the mantle edge. This is smoothed out on a wet graft trimming block – a soft wooden disc some 20 mm thick and 80 mm in diameter made from the crape myrtle or magnolia – and the adhering slime wiped off with a viscose sponge. The piece is first cut into strips 2–3 mm in width, and then transversely into tiny squares, the size of which is determined by the size of the nucleus employed. It must be of such a size as to cover one-third of the nucleus. The whole block, with the cut tissue adhering, is then dipped in a beaker of sea water, the tissue remaining alive for about 2 hours if kept wet and at a temperature of 17–22 °C. There is a report that to obtain a better rate of production and higher quality of pearls, both the pearls and the instruments used are dipped into a solution of an antibiotic such as aureomycin.

Insertion of Nucleus

With the nuclei and the grafts prepared all is ready to perform the operation of nucleus insertion. Taking one of the partly opened 'pegged' oysters, the technicians – these are usually women – place it in the desk clamp. This is a specially designed brass spring clamp for holding the oyster in position without lateral movement and without damaging the shell. The clamp is mounted on a telescopic column which has an adjustable tilting head, the whole being mounted on a heavy wooden base.

With the aid of a spatula the operator smooths back the mantle folds exposing the body and foot of the animal, holding the latter down and slightly extending it with an instrument called the retractor hook. This is to prevent muscular action. With a flat probe a small cut is made in the epithelium of the foot, and this is enlarged into a slender channel into the main mass of the tissue. Along this channel is passed a piece of the graft tissue to the site selected for the nucleus. A mother-of-pearl nucleus is then picked up with the moistened end of the nucleus lifted using a special probe with a cup-shaped end, and with this instrument is inserted down the channel into the body of the oyster so that it is just above the previously introduced graft tissue. The channel is carefully closed by gently smoothing back the foot mass (*Figure 22.20*).

Culturing of the Pearls

Unless a second, or possibly a third, nucleus is to be inserted, the foot is released from the retractor and the plug removed from between the valves, whereupon the oyster closes. The oysters are then returned to the holding tray and subsequently to the culture cages in sheltered waters for a period of 4–6 weeks in order that they may convalesce. After this time they are inspected, dead shells removed and the remainder transferred to permanent culture rafts by motor boats or barges. In restricted waters a newer method is employed. As the rafts take considerable space a modern innovation, the 'straw code' or 'bamboo pole' method, is used. These entail the fastening of the oysters round pieces of straw code or bamboo poles which are then hung vertically in the water. This uses a greater depth of water but less area than the cages.

Some 60 cages, holding over 3000 oysters, are suspended at a depth of 2–3 m from the permanent culture rafts. They are periodically inspected, usually three times a year, and the oysters cleaned from encrusting growths. Dead oysters are removed, and a few live oysters are opened in order to determine the growth rate of the pearls. There is a report that the pearls are examined by weak X-rays to detect whether the oyster has ejected the bead nucleus, as a large percentage of the larger beads are aborted (spat out) within the first year. For good-quality cultured pearls, after a period of from 3 to 6 years (usually $3\frac{1}{2}$ years) the oysters are recovered and taken to the laboratory where the shells are opened and the cultured pearls removed – and also any accidental pearls which may have formed. An unfortunate modern practice is to remove the pearls after

Figure 22.20 Inserting the dice of mantle in culturing pearls

only 12–18 months, resulting in a much thinner nacre coating. The pearls are then washed free from slime and carefully dried (*Figure 22.21*). Cultured pearls of dark colour, and most of them show a greenish tinge, are 'bleached' by placing them in a warm weak solution of hydrogen peroxide which lightens the dark conchiolin causing the unattractive shade of colour.

Grading

The pearls are then graded into size by the use of sieves with different size holes: it is at this time that all deformed pearls are removed. The next operation is to count the pearls and this is done by sliding into the container of pearls a paddle-like plastic plate having ten rows of ten holes. On withdrawing the paddle and seeing that all the holes are occupied a quick count of 100 pearls is made.

After counting, the pearls are graded for quality. There are three main grades:

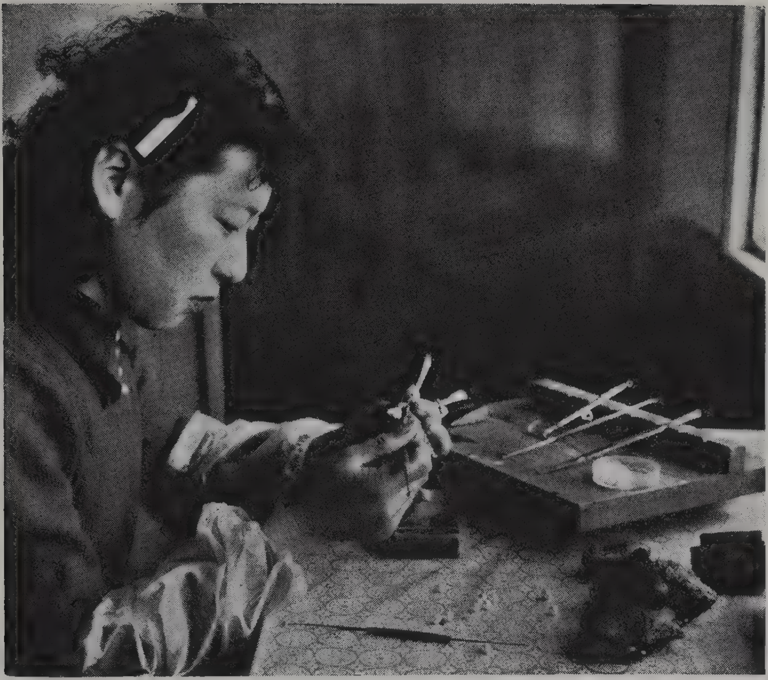


Figure 22.21 Removing the cultured pearls

A good, B medium and C poor. These gradings are then divided into three subdivisions, taking into consideration the form, colour, lustre and perfection of surface. This work is carried out by valuers who subsequently place the market price on the necklets, pairs or single pearls as is considered most suitable.

Drilling

The drilling of pearls for necklets, and their stringing, is carried out at the fishery estate. Any blemish on the pearl to be drilled is marked with an ink spot and the drilling commenced at this point. The drilling itself is carried out by using a mild steel wire 0.75 mm in diameter with its end ground to a triangular point. This is held in a small chuck directly driven by a low-power motor. In line with the chuck is a movable tailstock with a small brass chuck into which the pearl to be drilled is fixed. This tailstock is capable of being moved along the drill bed and when this is moved forward to the pearl the motor is automatically started and the pearl drilled more than half-way through. The pearl is then removed and a sliver of bamboo is passed into a centring hole in the back of the tailstock chuck. The drill is restarted and the hole drilled from the opposite side. A vertical drill is sometimes used, in which case the pearl is held by two side chucks. Some modern drills are double and simultaneously drill from each end to the centre. Some are so arranged that when one drill reaches a certain distance it 'backs off' to allow the opposite drill to carry through without touching the first. In theory this method should produce a straight canal, but X-ray pictures show that the two drillings are rarely joined straight. This is considered to be due to the straight layers in the mother-of-pearl bead causing the drill to run in line with the layers and to go off course. X-ray pictures have revealed extra drill holes which are at an angle and travel nearly to the outside of the pearl. It is suggested that these are made to allow the weak dye used for tinting to be directed to the discontinuation layer of conchiolin surrounding the bead nucleus.

Weight of Cultured Pearls

The pearls are then graduated into necklets, a grooved tray being used for the purpose, as is used for genuine pearls. After graduation they are strung on silk, the ends being tied with enough silk left over for the snap to be attached. The rows are passed for inspection, weighed and recorded. Finally 100 necklets are tied together and the total weight found.

The unit of weight for cultured pearls from Japan is the *momme*, which equals 3.75 g or 18.75 carats. The base method is not used for cultured pearls, a parcel of a number of necklets being sold as 'so much' per *momme*.

Composition of Whole Cultured Pearl

A whole cultured pearl consists of a large bead nucleus of mother-of-pearl surrounded by a thin layer of true nacre usually between half a millimetre and one millimetre in thickness, which has been secreted around the nucleus by the oyster. As the nucleus consists of a bead cut from a shell, the layers conform to the surface of the shell, and are in general parallel and straight, never concentric. Hence the bead shows directional properties of which advantage is taken in the testing of cultured pearls (*Figure 22.22*).

Non-Nucleated Pearl Production

Attempts were first made to produce a cultured pearl without a nucleus and some success was attained by workers using the freshwater mussel *Hyriopsis schlegeli* (*Figure 22.23*), which abounds in the freshwater Biwa-ko (*ko* means lake) in Shiga province in Honshu. This mussel, locally called *ike-chogai*, is a large bivalve with a greenish-black periostracum and an internal nacre of fine colour and lustre. It is a slow-growing mollusc, which takes some 7 years to attain operable age for culture, and does not reach maturity until it is 10–13 years old. This animal has an internal anatomy complicated by a long twisting intestine leaving little space in the connective tissue useful for nucleus insertion, and experiments using nuclei of any size either caused a high mortality rate or produced bad-coloured pearls.

To overcome this a system of grafting by pieces of epithelial tissue is employed. The pieces are cut from the mantle of a mussel in a similar manner as for normal pearl culture. This graft tissue is inserted alone into the body of the mussel, no bead nucleus being used. From 6 to 10 grafts used to be inserted into the gonads (sex organs) by means of a special type of forceps which simply intrudes the graft into place without any incision being made.

The pearls produced were baroque in shape and poorly coloured. Later, it

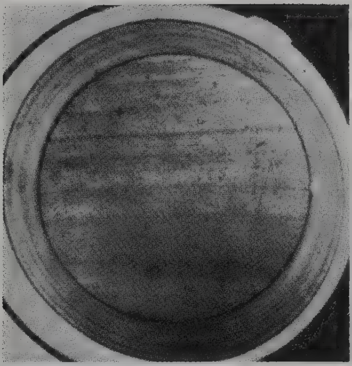


Figure 22.22 Section of cultured pearl showing parallel-banded mother-of-pearl nucleus with concentric outer layers

was found that if the dice of mantle be inserted into incisions made in the edge of the mantle, pearls of better shape and quality could be produced.

Hyriopsis schlegeli are not, so far, propagated artificially in Biwa-ko, as sufficient natural clams are available in the lake to satisfy present needs. The clams spawn in June and July and the eggs attach themselves to fish, but they later fall to the lake bed. The clams, which are three-quarters buried in the mud of the lake, are recovered by local fishermen, who drag a trawl net fitted with rakes, the prongs of which are spaced so that only mature clams are caught. They are then kept in pens until needed for the operation.

The operating procedure consists of the removal of the clams from the retaining pens to a building where women peg the shells open and expose the mantle. Ten incisions are made in each half of the mantle and into each is pressed a piece cut from the mantle of another clam. After the operation the clams are placed in plastic baskets which are then suspended about three feet below the lake surface for three years. They are then removed and any pearls carefully removed with tweezers.

The recovery rate of the Biwa pearls has been good as about 60 per cent of the mussels operated on produce pearls, and nearly 100 per cent of these bear the full twenty pearls. At full growth the clam reaches 225 mm and the animal lives for about thirteen years. If the animal is returned to the water after the removal of the crop of pearls, a second crop of pearls may adventitiously form. The Biwa lake non-nucleated cultured pearls, sometimes called tissue-graft cultured pearls, are a bright white in colour and are usually bun shaped and run to about 7.5 mm in diameter.

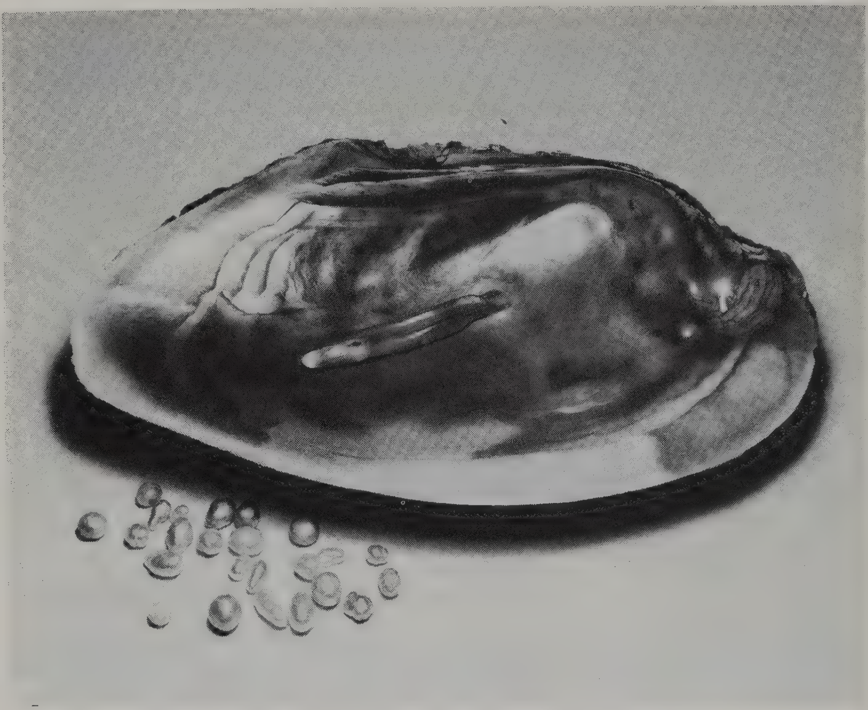


Figure 22.23 Shell of the Hyriopsis schlegeli

The cultivation of non-nucleated pearls has been accomplished in Australian waters using the large oyster *Pinctada maxima.*

In recent years pollution has reduced the productivity from Biwa-ko. However, the same period has seen the enormous growth of the non-nucleated cultured pearl industry in China. Here small man-made pens are grouped together in a manner similar to those seen in trout farms elsewhere. The Chinese raise their mussels from spat until they are large enough to allow for up to 40 tissue grafts. With each shell producing up to 40 pearls, production has been very high and resulted in the lowering of prices for certain types. The appearance of the better-quality Chinese pearls is similar to those from Biwa-ko but with more variations in colour. The lower qualities are often termed 'rice krispy' pearls.

It is interesting to note that on a lake in Hanoi, Vietnam, beaded freshwater cultured pearls are now being produced in a variety of colours.

Treatment

Preservation

It will be realised that cultured pearls consist of some 80 per cent non-pearly material, that is the large mother-of-pearl bead, and the comparatively thin outer layer of true nacre. Such pearls cannot in any way be described as natural pearls, and moreover, although they are serviceable and beautiful they are never quite comparable to the pearls formed by natural processes throughout. Cultured pearls often show a greenish tinge and subcutaneous markings, rather like varicose veins, and, if the skin is thin, the sheen of the mother-of-pearl bead may show as a gleam when the pearls are rotated. Just as much care, perhaps even more, should be taken with cultured pearls, particularly when strung into necklets, for grease from the skin and cosmetics tends to enter the discontinuation layer between the bead nucleus and the outer nacreous layer. This grease is usually dirty, for it picks up dirt remarkably quickly, and shows through the thin pearly outer layer and gives the pearls an unhealthy appearance. Cultured pearl necklets should therefore be cleaned just as frequently as the real pearl necklets. The formation of a barrel shape to the pearls at the back of the necklet is just as likely with cultured pearls as it is for real pearls, but the effect is even more serious for the periphery of the pearl may have the nacre completely worn away leaving two 'caps' of nacre at either end.

Some cultured pearls have been found unaccountably to darken, and this has been attributed to the action of sulphur on a trace metal in the pearl causing the formation of a dark sulphide which gives to the pearl a blackish colour. Soaking in hydrogen peroxide (normal 10 or 20 volumes solution) for a few days may clear this and give a great improvement in colour. The use of hydrogen peroxide is not advised except in such cases, for indiscriminate use may cause pearls, real or cultured, to assume a chalky appearance. Lacquer has been applied to thin-skinned cultured pearls.

Staining

Cultured pearls may be stained rosée by first bleaching in hydrogen peroxide for several hours and then immersing in a dye made up of vegetable oil, or alcohol, and eosin and letting the pearl soak for 1–24 hours according to the depth of colour required. A black colour is induced in cultured pearls by the use of silver nitrate, as described for the blackening of real pearls. Pearls have been turned to a black colour by exposing them to 100 000 roentgens of gamma rays from cobalt 60 for approximately 16 hours. This treatment has been carried out in Japan on cultured pearls. Benson investigated the staining of cultured pearls and found that there were two other types, one of which had the bead nucleus coloured before nucleation and the other surface dyed. Surface-dyed pearls, either natural or cultured, could be identified by swabbing with a minute pad of cotton wool moistened with a very weak solution of hydrochloric acid, which removes some of the dye giving a brown stain on the cotton.

The Detection of Cultured Pearls

When the whole cultured pearl first came on the European market during 1921 it was quickly seen that some means of detection was imperative if the value of real pearls was not to suffer. These early cultured pearls, seen in necklets, studs, pins, rings and brooches, were of good quality, a quality better than many of the cultured pearls marketed today. With no previous experience to rely upon the jeweller was mostly at a loss over these pearls.

Many ideas and suggestions for the detection of these new pearls were considered and tested with experimental apparatus. The story of these endeavours, which have led to the present methods allowing undeniable proof as to whether a pearl is cultured or real, needs to be told, for this history shows how the scientist and the gemmologist have solved one of their most difficult problems.

X-Ray and Ultra-Violet Tests

It should be clear from what has been told before that the layered nature of the bead nucleus of a cultured pearl, as against the concentric structure of the real pearl, would provide distinction if some satisfactory method could be evolved to show this difference, or if any other test would conclusively prove that there was a bead inside the pearl. Initial experiments by Herbert Smith and Hopkins were by the use of fluorescence under long-wave ultra-violet light, and these workers considered, at the time, that the greenish-yellow glow shown by the cultured pearl was so markedly different from the sky-blue effect exhibited by oriental pearls that they could be distinguished by that means, apart from the peculiar greenish tinge and other surface markings as seen in ordinary light. It was later found that this green fluorescence was common to some natural pearls, particularly those from adjacent waters, and also was not so pronounced in some pearls as in others: this method did not provide the clear-cut answer required.

About the same time the employment of X-rays was mooted as a possibility that the rays might reveal the presence of the bead, as the bones are revealed in the flesh. The ordinary radiographic techniques as known in those days proved unsuccessful as a means of spotting the bead core. Nor could the genuineness of the real pearl be proved by X-rays. As will be seen later, differences in technique now allow this method to be used with some degree of success.

Specific Gravity Tests

As early as 1922 it was suggested that the slightly greater SG of cultured pearls could be used as a test by employing in suitable immersion fluid. Later Kerr in the USA described experiments which gave hopeful but inconclusive results. In the London Pearl Testing Laboratory facilities existed for SG determinations on large numbers of natural and cultured pearls, which were carried out as a matter of scientific interest. In summary, it can be said that if a bromoform solution is prepared, diluted with benzene to a point where Iceland spar (calcite: SG 2.71) remains suspended, and pearls from an entire necklace of average quality are poured into the liquid, then if the pearls are natural some 70 per cent will float, whereas if the pearls are cultured less than 10 per cent will do so. It can be seen from these typical figures that this simple test gives a very strong indication of the nature of a doubtful pearl necklace.

The reason for the higher SG of cultured pearls can be easily explained. The mother-of-pearl beads used by the Japanese as the nucleus for their cultured pearls, and which form by far the larger part of the entire pearl, are taken from Mississippi freshwater mussels, and the nacre from these happens to have an unusually high SG, averaging 2.82. The choice is made because the unwanted 'sheen' characteristic of mother-of-pearl is in this variety unusually subdued and thus hardly noticeable through the skin of the finished pearl. Incidentally, should the test be made (by a beginner) on beads from an *imitation* pearl necklace, there should be no danger of confusion, and again the test would show its usefulness. Imitation 'pearls' formed from filled hollow glass beads have an SG very much lower than natural or cultured pearls, while those based on solid glass beads have a very much higher SG.

The Lucidoscope

In 1925, Szillard designed an apparatus which he named the lucidoscope, which depended upon the transparency of the layers of the mother-of-pearl bead nucleus of a cultured pearl when they are oriented parallel to a beam of strong light. The apparatus consisted of a powerful light source, in the base of the instrument, directed upwards through a system of condensing lenses on to the glass base of a receptacle which contained the pearl to be tested. The pearl rested on a centrally perforated and concave diaphragm placed in the receptacle which was filled with a liquid having an index of refraction near to that of the pearl (*Figure 22.24*). Above was a low-power microscope to observe the effect,

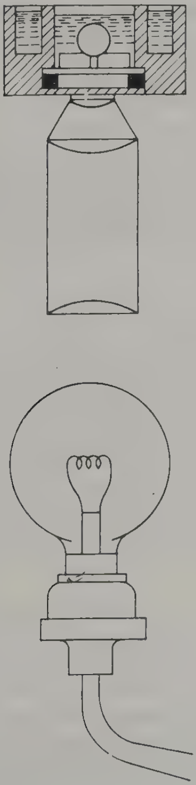


Figure 22.24 Principle of the lucidoscope

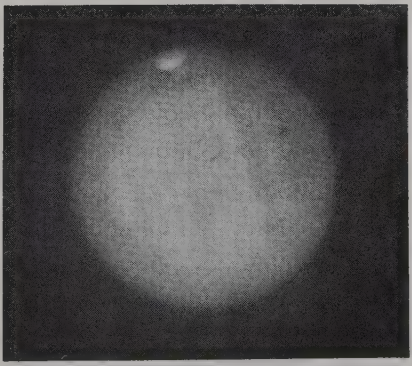


Figure 22.25 The layered structure seen in a cultured pearl on examination with a lucidoscope

and this could be changed to a camera in order to record the result photographically. In some cases the microscope was dispensed with and the observation made with a binocular head loupe. On switching on the light and turning the pearl round in the liquid with the aid of a pair of eyed tongs the layered structure, if the pearl is cultured, usually shows up as light and dark stripes when the layers are parallel to the light beam (*Figure 22.25*). The method, which is suitable for undrilled and part-drilled pearls as well as for drilled pearls, is specific for cultured pearls as long as the stripes can be seen. The effect can fail with thick-skinned cultured pearls and by this method pearls cannot be proved to be real.

Quick proof of thin-skinned cultured pearls may be carried out in the lucidoscopic way by employing the microscope with a powerful light source and immersing the pearl in a highly refractive liquid in a glass cell, a diaphragm being used upon which to rest the pearl and to limit the light to the central portion of the cell. Strung necklets of thin-skinned cultured pearls can be examined dry in the beam of a strong light, such as the beam emerging from the socket of an endoscope (described later) when the needle is not in position. Each pearl in turn is held in the beam of light and rotated to see if the tell-tale stripes are present. Such a method is termed 'candling' in the United States of America. Experiments by Leroux, Raub and Frohlich showed that if a beam of long-wave ultra-violet light is passed through a correctly oriented cultured pearl resting on a piece of bare film the 'stripy' pattern will be seen on development.

Pearl Compass

An interesting piece of apparatus devised by Professor Nacken for the detection of cultured from real pearls is the pearl compass. The principle of the instrument is that a crystalline substance will take a certain position according to its

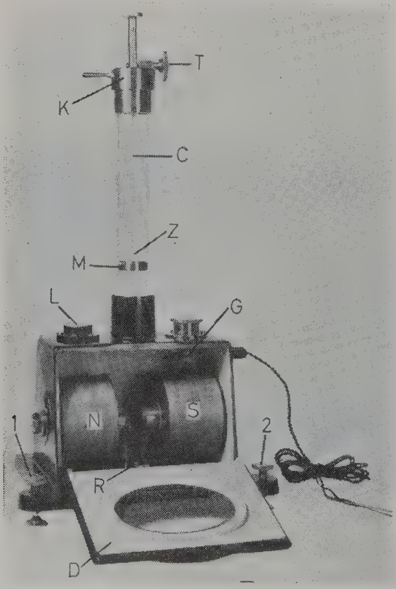


Figure 22.26 The pearl compass: (C) quartz torsion fibre; (D) front cover; (G) lamp for internal lighting; (K) rotable head; (L) spirit level; (M) graduated indicating ring; (N) and (S) magnet coils; (R) steadying platform; (T) height adjusting screw; (Z) indicating fly; (1, 2) levelling screws

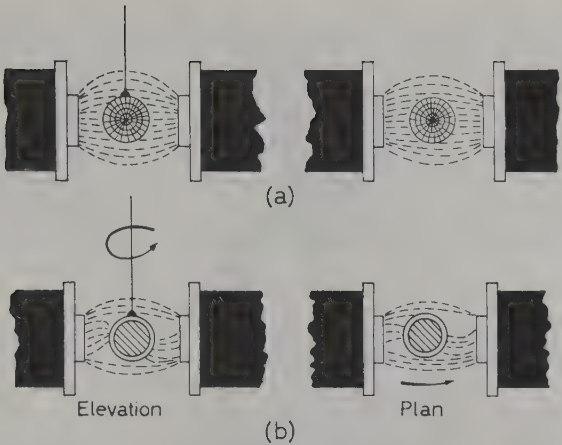


Figure 22.27 Schematic diagram of the action of the pearl compass. (a) The magnetic field has no turning action on a natural pearl; (b) the straight layers of the bead in a cultured pearl tend to orient themselves in line with the magnetic field and the pearl moves

crystallographic structure when brought into a magnetic field. The apparatus (*Figure 22.26*) consists of a powerful electromagnet, between the poles of which is set the pearl to be tested. The pearl is cemented centrally to the end of a glass rod which is suspended by a silk or quartz thread from the adjustable head of the upright glass tube. When the pearl is correctly oriented between the pole pieces the current is switched on and any movement of an indicating bristle or vane observed. The mother-of-pearl core of a cultured pearl causes the pearl to turn, except if the layers of the core are already parallel to the lines of force of the magnetic field. If they are not parallel then they are pulled round under the influence of the magnetic force to such a position (*Figure 22.27b*). The radial and concentric structure of a real pearl causes no turning movement and the pearl remains stationary (*Figure 22.27a*). It is clear that as there is one position where a cultured pearl will not turn under the magnetic influence it is necessary to take two observations when the pearl does not turn; this is done by rotating the pearl through 90 degrees by the use of the adjusting head. The reliability of the method is weak, and it is only recommended for perfectly round pearls. Unsymmetrical mounting, metal in the drill hole and odd-shaped pearls will give spurious results.

Pearl Microscope

Examination of the walls of the string canal in drilled pearls by the use of a microscope with a special mounting for the pearl opens up another profitable line of inquiry. The 'pearlometer' (*Figure 22.28*) devised by Michel and Riedl is such an instrument that will illustrate the method and the apparatus. The microscope itself is a normal instrument, either monocular or binocular, which contains a built-in light source below the stage, and a subsidiary adjustable lamp which throws a strong beam of light illuminating the pearl from the front or

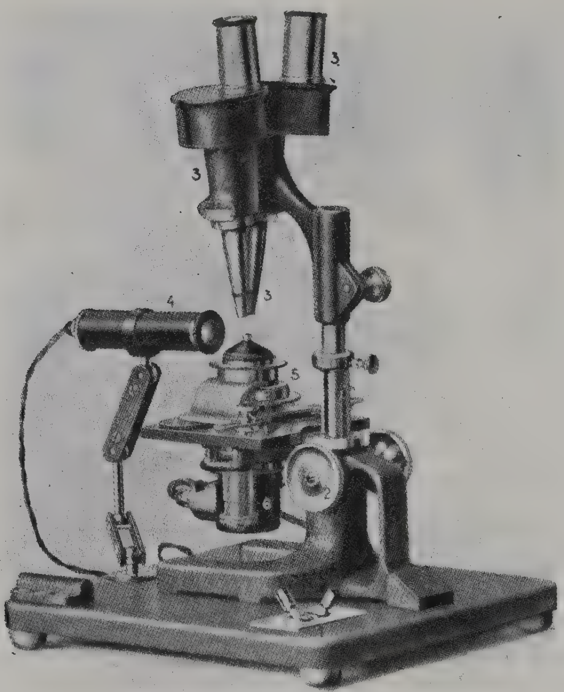


Figure 22.28 The pearl microscope: (1) light switches, (2) microscope focusing adjustment, (3) binocular microscope, (4) lamp for side lighting, (5) the cardiometer, (6) sub-stage lighting

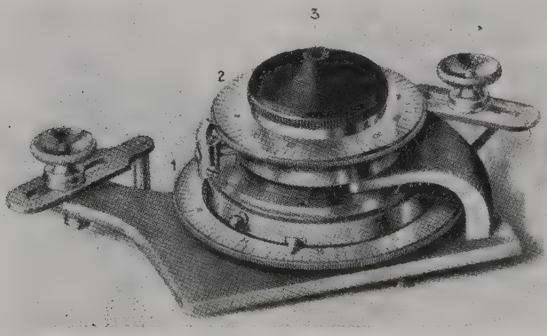


Figure 22.29 The cardiometer: (1), (2) calibrated adjustments for the rise and fall of the mirror/needle, (3) aperture for the needle

sides. The essential accessory for the pearl-testing microscope is the so-called cardiometer (*Figure 22.29*). This is a special stage-support for the pearl and has a very thin needle, with the end polished at 45° to its length to a mirror finish, and which is inserted into the string hole of the pearl.

The mirror end of the needle when in the string canal of the pearl is examined by the microscope and, by reflection, shows the nature of the canal walls. The needle can be raised and lowered by adjustment of the graduated ring of the cardiometer and measurements of one-thousandth of a millimetre may be made of the rise or fall of the needle in the drill hole of the pearl. Thus, the thickness of the layers of a real pearl, or the thickness of the nacreous skin of a cultured pearl, may be measured. Therefore, by observing the reflection of the canal wall in the mirror of the needle whilst it is raised or lowered in the string hole, it may be seen whether the pearl has a concentric structure throughout, or has a bead nucleus of a cultured pearl.

A similar idea was employed in the apparatus designed by Galibourg and Ryziger who, instead of employing a fine needle with a polished end, arranged for the pearl to be mounted on a holder which allowed a thread of mercury to be squeezed up, from a container below, into the string canal. By varying the pressure on the container by a screw and pressure plate the thread of mercury may be allowed to ascend or descend in the drill hole. The brilliant reflecting surface of the meniscus of the mercury provided a convex mirror reflecting surface of the canal walls. A simplified arrangement devised by Wild and Biegel is said to be more convenient in use. More successful than some other methods which have been suggested, the examination of the canal walls by the microscope and reflecting needle method does suffer, however, from the time-consuming setting-up.

The Endoscope

During 1926, Chilowski and Perrin designed the endoscope for the examination of drilled pearls, it being modified a year later by René and Simon Bloch. The endoscope was for many years recognised as being the most satisfactory instrument for the positive identification of both genuine and cultured drilled pearls.

The endoscope (*Figure 22.30*) consists of a powerful source of light in a suitable housing, the source being either an arc lamp or a Pointolite lamp. The beam of this light is passed through a system of condensing lenses and then through a fine hollow needle which has at its end two polished mirrors at 45 degrees in opposite senses. The first, or interior, mirror causes the beam of light to reflect upwards and out of a small aperture cut in the top of the tube: the exterior mirror forms the end of the tube. The surface of this end-mirror is viewed by a small low-powered microscope which is capable of being directed vertically and horizontally small distances and of being focused on to the needle end. Above the optical system is arranged a low-powered biconvex lens which allows the operator, while seated before the instrument, to see the surface of the pearl whilst it is on the needle.

When the needle, of which there are three sizes (0.3, 0.4 and 0.5 mm in outer diameter), is placed on the instrument and the arc lit, a fine beam of bright light is seen directed up through the aperture in the top of the needle. If, however, a natural pearl is first placed on the needle, this upward beam of light will enter one of the concentric layers and travel round it by a process of total reflection. This totally reflected beam will be 'lost' (*Figure 22.31a*) except when the needle

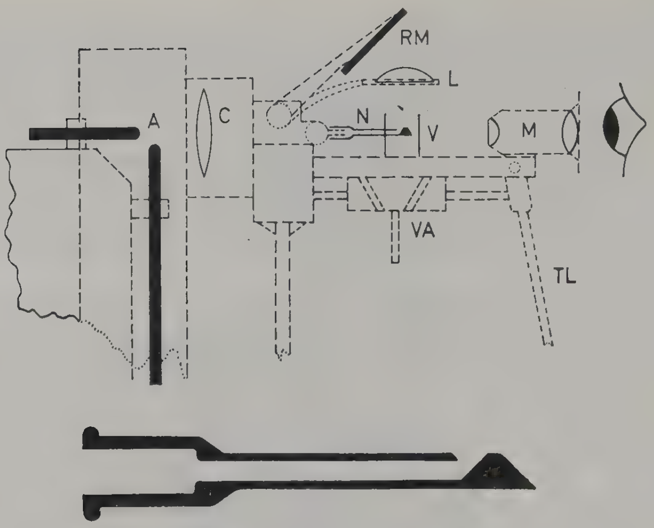


Figure 22.30 *Schematic diagram of the endoscope: A, arc light; C, condenser; RM, reflecting mirror to show surface of pearl; L, lens to enlarge surface of pearl; N, needle; V, vice to hold pearl; M, microscope to view end of needle; VA, vice adjustment; TL, traversing lever to move pearl along needle. Below: enlarged section of needle*

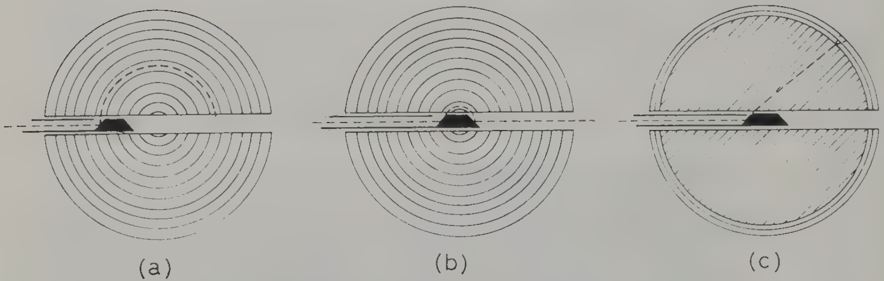


Figure 22.31 *Paths of light rays from an endoscope needle when a natural or cultured pearl is mounted on it: (a) a natural pearl not central on the needle showing the light 'lost'; (b) a natural pearl when central on the needle showing the ray reflected from the end-mirror out through the drill hole; (c) a cultured pearl, which has straight layers in the core, cannot return the light ray to the end-mirror but directs the light up through the layers to the outside of the pearl*

is at the centre of the pearl, when the reflected beam will strike the end-mirror of the needle and be reflected out through the drill hole where it will be seen as a brilliant reflection through the microscope eyepiece (*Figure 22.31b*). In practice the pearl is passed back and forth along the needle while the end-mirror is observed through the microscope. When the centre of the pearl passes across the mirrors of the needle a flash of light is seen which proves without doubt that the pearl is concentric throughout and therefore natural.

A cultured pearl with its layered structure cannot return the light reflected from the first mirror of the needle to the end-mirror; hence no 'flash' will be seen when the pearl is drawn back and forth along the needle. In this case the beam of light entering the pearl travels along the straight layers of the mother-of-pearl core and will be seen as a cat's-eye streak on the outside of the pearl (*Figure 22.31c*). Should the layers of the bead nucleus be parallel to the needle and horizontal to the base of the instrument no streak will be seen on the outside of the pearl; rotation of the pearl on the needle will bring the layers vertical and show the streak from front to rear over the top of the pearl. In practice it is usual always to rotate the pearl so that the streak moves, as it is more apparent in certain positions.

Some natural pearls have a conchiolin-rich core and this may preclude the reflection of the light, and hence give no flash. In such cases the characteristic cutoff of the general illumination shown by the pearl as seen from the top lens as the needle passes into the dark core is indicative. Examination by a hand lens of the structure seen down the drill canal will show the dark centre and the reason for the lack of result.

The vice which holds the pearl on the endoscope is connected to the traversing lever which moves the pearl along the needle, and the end of this traversing lever travels over a scale marked with a zero when the lever is vertical and therefore the mirrors of the needle are central in the pearl. The divisions, marked one to five, on each side of the zero mark are centimetres and are divided into millimetres. As the lever is so designed to move the pearl one-tenth the distance of the sweep of the lever over the scale, the movement of the arm of the lever over 1 cm of the scale indicates 1 mm movement of the pearl; thus, as the scale is marked in millimetres, one-tenth of a millimetre may be measured. This enables the reflections from the concentric layer edges of a natural pearl to be measured, and also the thickness of the nacreous outerlayer of a cultured pearl.

Despite the layered structure of the bead of mother-of-pearl which forms the nucleus of cultured pearls, this structure does not show as lines on the wall of the string canal, and the surface, as seen in the endoscope needle, is uniform. With part-drilled natural pearls the endoscope will be of little use, but a cultured pearl may show the 'streak' when the needle is able to penetrate the pearl only a short distance. With experience and constant practice, and when the pearls are clean and 'easy', some 200 pearls an hour can be tested on the endoscope, which in competent hands gives infallible results (*Figure 22.32*).

Lauegrams

Methods involving examination of the structure of the walls of the string canal cannot, of course, be utilised when the pearl is undrilled; there is also difficulty when the pearl is only partly drilled. In 1924 the Frenchman Dauvillier, and later in collaboration with Shaxby, considered the effect of taking lauegrams by X-rays of natural and cultured pearls which, according to known experiments, should give a different pattern in one direction with cultured pearls, whereas with the radial structure of the crystallites of real pearls a similar pattern should be obtained from whatever direction the narrow beam of X-rays passed through

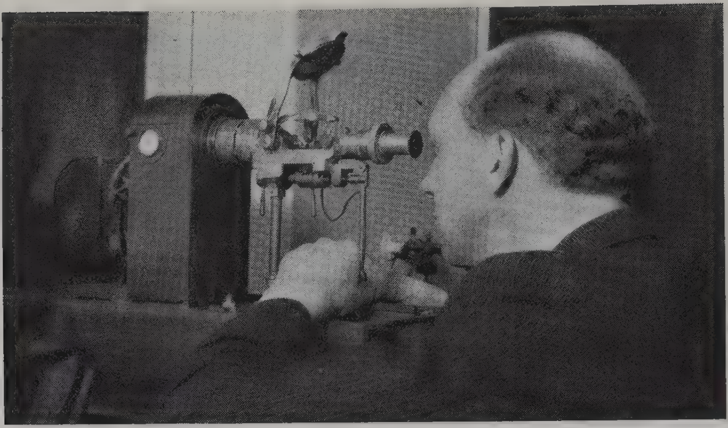


Figure 22.32 The endoscope in use

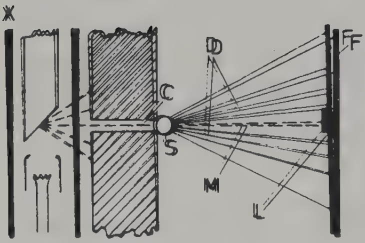


Figure 22.33 Schematic diagram of the lauegram method: X, X-ray tube; C, collimator or diaphragm; S, pearl; M, main trace of the X-ray beam; D, diffracted rays; L, lead disc to cut out heavy spot of main trace (not usually employed in pearl testing); F, film

the centre of the pearl. This method was put on a firm basis by Galibourg and Ryziger in 1926.

The production of lauegrams will be referred to in Chapter 37 on X-rays in gem testing, but for completeness may be briefly described here. A narrow beam of X-rays passed along the symmetry axis of a crystal will produce on a suitably placed photographic plate a pattern of spots indicative of that symmetry (*Figure 22.33*). This method provides the most conclusive identification of undrilled or partly drilled pearls.

This is due to the fact that the aragonite crystallites which, common to a number of minerals which crystallise in the rhombic system, form 'cyclic twins' having a pseudo-hexagonal symmetry, are radially arranged in natural pearl and are not so arranged in cultured pearl. Thus in a natural pearl a narrow beam of X-rays passed through the centre of the pearl must travel along the vertical axes of the aragonite crystallites whatever the orientation of the pearl, and this will produce a lauegram having a pseudo-hexagonal system of spots.

In the case of cultured pearls the picture varies with the orientation of the bead nucleus, from that of the natural picture (*Figure 22.34*) to a picture showing a rectangular system of four spots, sometimes termed the Maltese Cross pattern (*Figure 22.35*). This occurs because the bead nucleus is made from mother-of-pearl having straight layers to which the aragonite crystallites are arranged

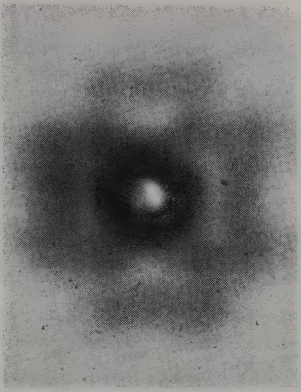


Figure 22.34 Lauegram of natural pearl

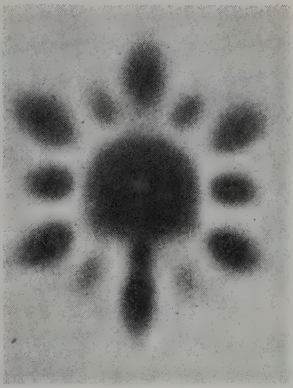


Figure 22.35 Lauegram of cultured pearl

perpendicularly. Thus, a narrow beam of X-rays passing through the pearl at right angles to the layers (*Figure 22.36b*) will be travelling along the vertical axes of the crystallites and will give a hexagonal spot pattern as in a natural pearl. At right angles to this direction the X-ray beam is travelling across the prisms of the crystallites and this is a direction of fourfold symmetry, and the characteristic four-spot pattern is produced.

Experiment has shown that the hexagonal pattern will persist even if the pearl is up to 30 degrees from the vertical to the plane of the layers. Beyond this the picture becomes distorted and a kite-shaped pattern occurs, and then the four-spot pattern becomes increasingly evident. It will be seen, therefore, that the hexagonal picture by itself does not give a true indication of the nature of the pearl. If a hexagonal picture is first obtained nothing is proved, but on turning the pearl through an angle of 90 degrees and taking another picture, then, if this is also a hexagon, the pearl is natural, for proof has been made that the pearl structure is radial. If the first picture shows a Maltese Cross pattern then the pearl is cultured and no further test need be made.

It may be of interest to mention that button-shaped pearls when taken with the X-ray beam traversing the short axis will not give a hexagon but will show a circular ring, usually termed the halo pattern. Even the hexagonal spot pattern can vary considerably in its appearance, from a pattern where the spots are developed into spokes, the spoke pattern, to one where the spots are joined together to produce a closed hexagon.

Exposure Time for Lauegrams

All lauegram work needs lengthy exposure times and therefore the X-ray tubes used must have some cooling arrangement: water cooling is commonly used. Absence of cooling need not preclude lauegrammatic work, for lengthy exposures can be carried out with intermittent exposures of short duration, but this is time-consuming. For satisfactory work and for readable spot pictures the collimator which narrows the X-ray beam needs to be no more than 1.5 mm in

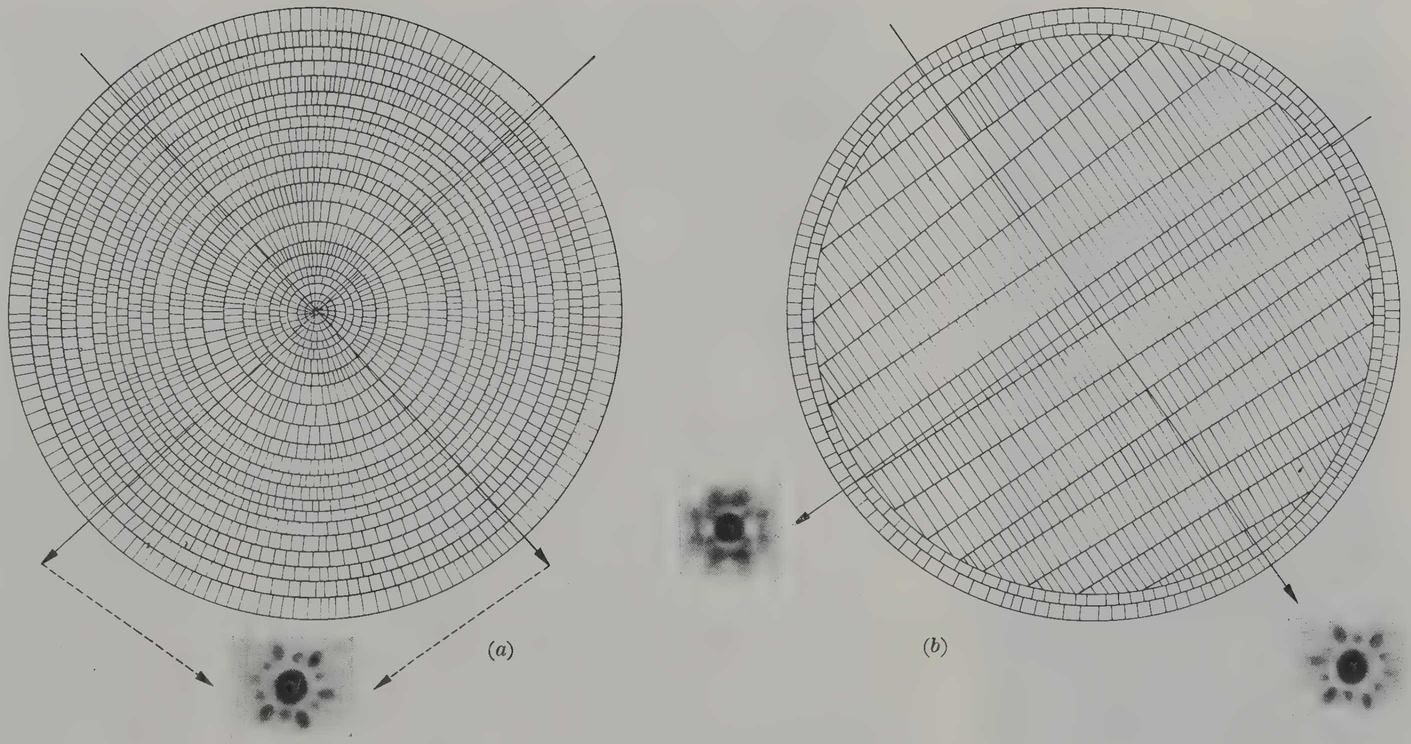


Figure 22.36 *Schematic diagram of the lauegram method for identifying pearls by X-rays*

diameter, and the distance from the pearl to the film cassette about 75 mm, for with this size of collimating tube and subject/film distance the heavy 'main trace' of the undeviated X-ray beam seen in the centre of the spot picture will not mask the outer spot pattern, and shielding off the central main beam is unnecessary. A fast double-coated film is used and placed in cassettes fitted with intensifying screens in order to give a strong picture and lessen the exposure time.

X-Radiography (Shadowgraph or Skiagram)

The X-radiography method, also known as the shadowgraph, direct or skiagram method, which was such a failure during the initial early experiments, has now been found by a difference in technique to be of definite value and is being used in laboratories throughout the world for the rapid testing of pearls. The comparative ease with which necklets of pearls may be examined makes the method seem more attractive than is actually the case. Taking the picture presents few problems providing certain factors are taken into consideration, but interpretation of the picture may need considerable skill and can only be confidently carried out by workers who have had much experience.

The method depends upon the differences in X-ray transparency of the conchiolin from that of the calcium carbonate which makes up the composition of the pearl. The conchiolin in natural pearls may fill the centre of the pearl, as in the case of the so-called 'blue pearls', or it may fill fine layers between the concentric layers of the aragonite crystals, and if these show up on the X-ray picture as circles or arcs near the centre of the pearl then that pearl can be assumed natural (*Figure 22.37*).

Figure 22.37 Direct X-ray picture of a natural pearl necklet (negative image of positive print)

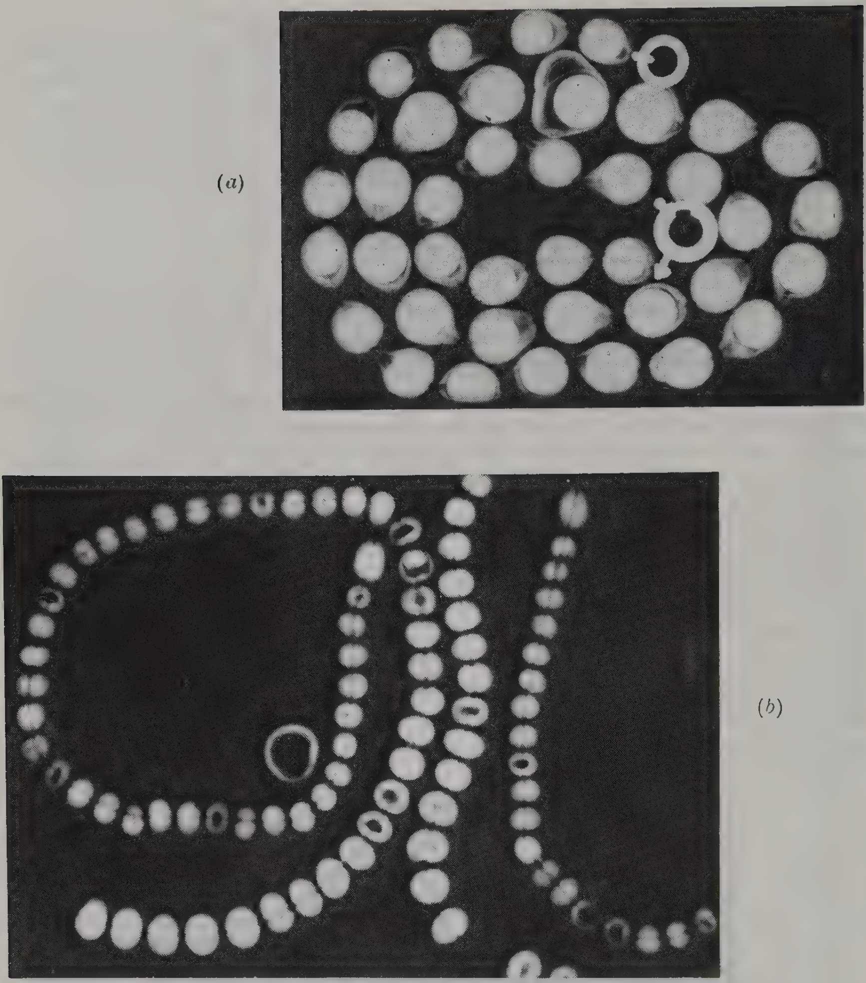


Figure 22.38 *Direct X-ray of (a) nucleated and (b) non-nucleated cultured pearl necklet (negative image of positive print)*

In the case of cultured pearls the effect is that normally the oyster does not like the job of coating with nacre the large bead nucleus placed in its body and first coats the bead with a layer of conchiolin, which is in some cases irregularly deposited. The transradiancy of this layer of conchiolin produces in an X-radiograph an outline of the bead nucleus, which itself is usually somewhat more opaque to the rays than the outer rim of nacre (*Figure 22.38*). Further, if the cultured pearl happens to be so oriented that the straight bands of the mother-of-pearl nucleus are perpendicular to the surface of the film, that is parallel to the X-ray beam, they may show on the picture as weak stripes across the bead due to the slightly different radiability of the layers. This is a similar effect to that seen in one of the oldest methods of pearl testing, that is by the lucidoscope. The detection of the non-nucleated cultured pearls by X-ray shadowgraph method is less easy for there is no bead nucleus to show up. What is seen is either a large cavity or a fine vermiform patch, which may not even be at the centre of the pearl. However, this, with the strong fluorescence shown by Biwa pearls under X-rays, is conclusive evidence of this form of culturing.

Exposure Times

The structures seen in an X-radiograph of pearls are as a rule very fine and the photographic technique therefore needs the use of a very fine-grain film. Such fine-grain films are slow and need long exposures; the best type of film to use and the exposure times needed can only be worked out by experience.

Pearls, being spherical bodies, necessitate the X-rays having different thicknesses to travel: a large distance at the centre of the pearl and grading to relatively nothing at the edges. Hence the edges tend to be overexposed and may mask the structure, such as the division between the bead and outer layer in thin-skinned cultured pearls. Alexander devised a method to get over this differential exposure by placing the pearls to be tested in a plastic dish which rests upon the paper-covered film. Into this dish is poured carbon tetrachloride, which has a similar radiability to pearl, until the pearls are immersed up to their greatest diameter; this to some extent equalises the pearls' thickness and also helps to absorb the scattered X-rays secondarily produced when the primary beam strikes solid bodies, in this case the pearls (*Figure 22.39*).

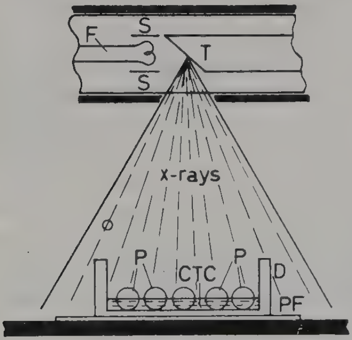


Figure 22.39 Schematic diagram of the method of taking direct X-ray pictures with pearls immersed in carbon tetrachloride: T, target of X-ray tube; F, filament of X-ray tube; S, Shields to focus cathode rays; P, pearls; D, plastic dish containing carbon tetrachloride; PF, photographic film; CTC, carbon tetrachloride

Carbon tetrachloride is no longer used and has now been replaced by various other fluids. However, some laboratories prefer to use the less messy dry technique. In this case, single pearls are surrounded by a thin lead shield which is a most effective device for absorbing any scattering. Necklaces are placed in direct contact with the 'wallet' containing the film, and kept steady by means of double-sided adhesive tape. The question of overexposure at the edges of the pearls is dealt with by including several pieces of film in the wallet and under- and overdeveloping accordingly.

Processing of Film

The processing of the film is a normal photographic job, and there may be some advantage in overexposure and underdevelopment. The interpretation of the picture is always made from the negative, which is translucent and will always show more of the tones and detail than can be seen on a positive print. The negative is best viewed, if a proper viewing box is not available, by holding the film up to a 40 or 60 watt pearl or opal bulb electric lamp. With all precautions taken it is rare that a 100 per cent result can be obtained with pearl necklets by the direct X-ray method or with cultured pearl necklets which are normally easier to interpret. Care must be taken not to misinterpret a picture when the bead nucleus is not spherical. Drop and oval-shaped nuclei have been encountered in cultured pearls, but they are rare as it is said that mortality of the oysters is greater when nuclei of other than spherical shape are used.

Fluorescence

The fluorescent glows shown by pearls under ultra-violet light are not discriminative, and this applies whether the radiations are long-wave (365 nm) or short-wave (253.7 nm). Under the influence of X-rays, however, genuine pearls rarely show any glow, but cultured pearls glow with a greenish-yellow light. This is much weaker in intensity than the bluish-white glow shown by all pearls under ultra-violet light. Thus this glow under X-rays, which needs to be viewed in total darkness, may give some indication as to whether the pearl is cultured. The glow in cultured pearls is derived from the bead core of mother-of-pearl which contains a trace of manganese. The test is not conclusive, for all freshwater pearls and some sea-water pearls from Australian waters show a similar fluorescence. Wild has suggested a variation of the method which is carried out by examining the fluorescence of the bead induced by X-rays through the drill canal using a low-powered microscope for the observation. A further method suggested by this worker is to mount the pearl on a micrometer stand and gradually raise the pearl into a narrow beam of X-rays limited by a lead conduit 1 mm wide. This beam strikes a suitably placed fluorescent screen and when the edge of the pearl reaches the beam a shadow in the form of an arc is shown on the screen. When the pearl is raised further, if it is cultured, a sudden flash of light is seen when the X-rays strike the bead core. Genuine pearls do not show this effect. Non-nucleated cultured pearls from Biwa Lake, Japan, show a strong greenish-yellow glow under X-rays, but the non-nucleated pearls cultured in salt water areas, such as Australia, do not show this glow.

Core Scraping Test

Alexander has suggested that scrapings from the core of a pearl by the aid of a suitable wire, when examined microscopically, show a typical block-like pattern if the pearl is cultured. Further, if the scrapings are tested for manganese and a positive result is obtained the pearl must be cultured. These tests are far too delicate for general testing.

The appearance of cultured pearls may reveal their nature. Many medium- and low-quality cultured pearls have a significant greenish or yellowish tinge of colour, owing to the layer of conchiolin surrounding the bead showing through the nacreous skin. It might be thought that the thicker the nacre the better would be the colour of the pearl, but this is not necessarily the case. If the conchiolin layer is thick and dark coloured the pearl will appear dark, while if the layer is thin and light coloured the resulting pearl is of good colour. Subcutaneous markings, rather like 'varicose veins', are often seen on cultured pearls and are indicative of the nature of such pearls. However, the small dimples called 'piqué marks', which usually indicate that the pearl is natural, are not conclusive, for such 'pits' have been seen on a few cultured pearls. If a presumably cultured pearl necklet is extended horizontally just below a good light (desk lamp) and the beads are rotated, some of the pearls will, if not too thick skinned, show the tell-tale sheen of the mother-of-pearl bead.

Imitation Pearls

Fish-Scale Essence

The popularity of pearls for adornment led to their imitation, and today the manufacture of imitation pearls has become a world-wide industry. In 1656 a French rosary maker, Jaquin (Jacquin or Jonquin), produced imitation pearls at Passy on the outskirts of Paris. Jaquin had noticed that water in which small fish had been washed contained a highly lustrous substance, which when concentrated and applied to small beads produced a remarkably good imitation of pearls. Jaquin's pearls were small hollow spheres made from an opalescent and easily fusible glass, the inside of which was lined with parchment size which 'fixed' the fish-scale essence giving the pearly appearance. The interior of the bead was finally filled with wax in order to increase the solidity of the bead (*Figure 22.40*). The beads, often known as 'Roman pearls', are not commonly encountered today as they have been superseded by a type using a solid glass bead upon the outside of which is applied the pearly coating. Thus imitation pearls have at least two parts – a material producing the pearly coating and the rigid base.

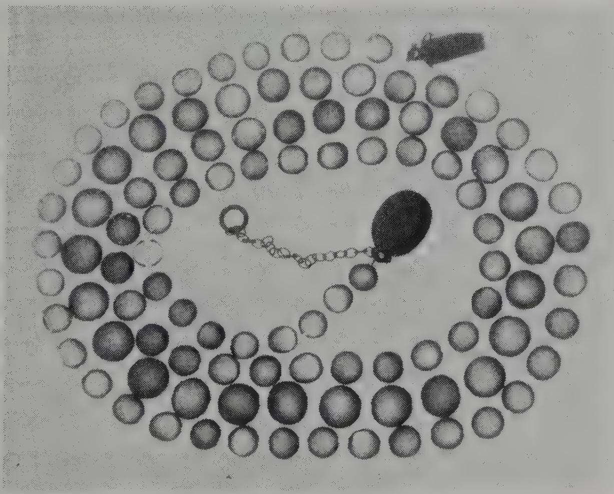


Figure 22.40 An X-ray picture of an early (wax-filled) imitation pearl necklace (positive print)

Quite early it was discovered that the iridescent lustre of fish scales was not part of the scales themselves, but was created by tiny crystals embedded in the skin attached to them, and it is suspensions of these minute crystals in a suitable vehicle which produce the *essence d'orient,* a term which may have been derived from the possibility that the Chinese knew of the material long before Jaquin's discovery. Others at the time, a period before the art of chemical analysis was commonplace, believed the crystallites to be silver and called the material 'fish silver'. When careful purification and analysis became possible the crystallites were found to be the organic chemical compound guanine.

Guanine ($C_5H_5ON_5$) is a derivative of purin and belongs to the group known as the purin base, and is a decomposition product of the nucleins. Guanine is actually a waste material secreted by the fish and is closely allied to uric acid. The guanine has an SG of 1.6 and forms colourless needles or lath-shaped crystals which are not decomposed by heat under 360 °C, are insoluble in neutral solvents, are non-toxic, non-corrosive and chemically inert.

Until 1919 the manufacture of *essence d'orient* was principally a French industry, the scales of the bleak (*Alburnus lucidus*) being used for the purpose. These small fish are found in the Seine and other European rivers; at one period when the French manufacture was at its height a million francs' worth of bleak scales were exported annually from the Thames. In 1919 it was discovered that the sardine herring caught in Norwegian waters produced a superior quality of pearl essence. A French company exploited the discovery, erected a factory in Norway, employed trained chemists, and constantly strove to improve the purity and quality of their pearl essence. Until the outbreak of World War II the company prospered, but in 1939 the business ceased and the process was taken to America. About 1943 experiments were made with the herring from British Columbian waters, but this was not commercially successful. Since the end of the war the Norwegian herring industry has returned to the manufacture of fish-scale essence, and South Africa is producing its own essence from the scales of fish caught off the coasts of South Africa and Namibia. In 1949 some experiments on similar lines were carried out by the Scottish herring industry, but little has since been heard of this endeavour.

The best fish scales are obtained from the herring fisheries of the Bay of Fundy, an inlet which practically divides Nova Scotia from New Brunswick in North America. Here the tides range from 10 to 20 m and figuratively boil up the ocean floor, liberating a steady supply of fish food which attracts countless schools of herring. The fish are trapped in weirs, caught in seine nets, and loaded into crates on the scale boats or dorys, which have slatted false bottoms. As the fish flop round in the crates they lose their scales which drop through the slats in the crate, and through the false floor to the bottom of the boat. The scales are then scooped into baskets and hurried to the factory, which is situated at Maine on the American side of the bay, where, because of the numbing cold of Fundy region, the scales arrive perfectly preserved.

As soon as the scales are brought to the factory they are put into mixers or churns with a suitable cleansing mixture. The movement of the churns causes the scales to rub together releasing the tiny and delicate guanine crystals which are embedded in the rough fatty tissue attached to the fish scales. These crystalloids, as they are termed, are strained away from the scales which are discarded. The final purification and suspension of the crystals is then made in a special solvent, which may be an ether/amyl-acetate solution. This aggregate of guanine crystals in viscous liquid is then added as required to the vehicle, usually a nitrocellulose lacquer, which forms the final 'paint' employed for covering the modern imitation (mock) pearls. A dyestuff is incorporated in the lacquer if coloured finishes are needed.

Modern technology has produced a number of synthetic pearl essences which are used either alone or as undercoats to fish-scale essence. These inorganic essences are usually of two types. In one of these the small needle-shaped or platy crystallites, which are only about 30 micrometres (microns) in length, consist of basic lead carbonate; and in the other minute crystals of mica are coated on each side with layers of titanium dioxide in the form of anatase. The crystallites are disseminated in pyroxylin (nitrated cellulose) so that they have some degree of parallel orientation. This produces a Bragg lattice which causes the iridescence, although interference of light at thin films may be a partial explanation of the effect.

Glass and Plastic Beads

The beads of the modern imitation pearls or, as they are sometimes called, simulated pearls, usually consist of glass beads formed on an iron or copper wire in a blow-torch flame (*Figure 22.41*). Subsequent treatment in acid dissolves away the wire and leaves a cavity forming the string canal, but this method is

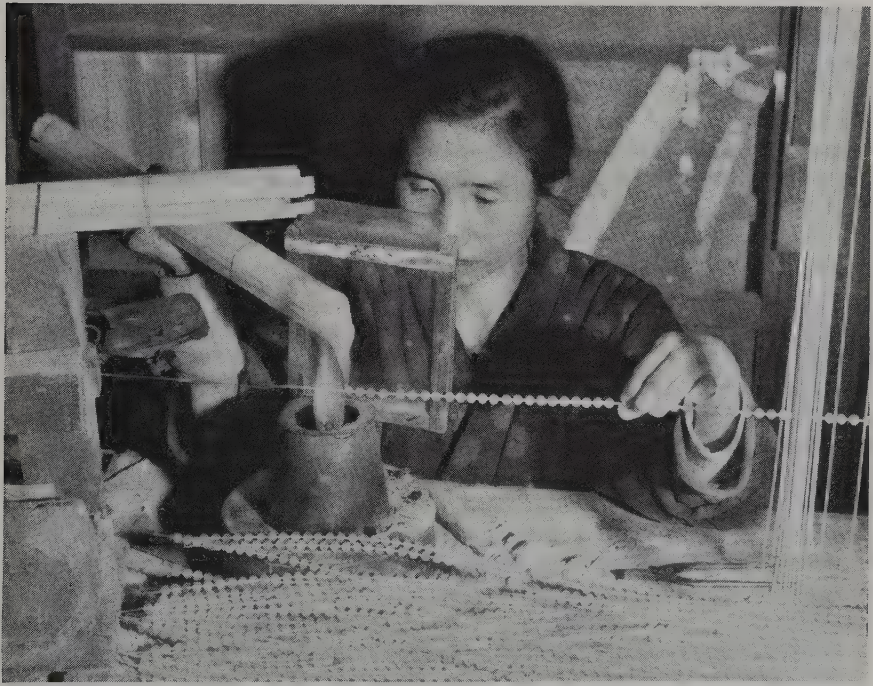


Figure 22.41 Forming the glass beads from easily fusible glass in Japan

now obsolete and the present method is to coat the wire with a clay 'slurry' which allows the beads to be drawn off the wire. The glass used is a special opalescent type termed 'alabaster' (not to be confused with the massive variety of gypsum). Moulded plastics, such as Perspex or polystyrene, are often used for the cheap types of imitation pearls, but they are too light in weight to hang well when strung into necklets. Further, these plastic beads often show a ridge where the 'flash' escapes from the junction of the two halves of the mould, for these plastic beads are moulded. Vegetable ivory beads have been used as the core for imitation pearls but they are too opaque to give the finished pearl the desired lustre. During 1922 some imitation pearls consisting of a mother-of-pearl bead coated with pearl essence were the subject of a celebrated court case. Such imitation pearls did not seem to appear again until about 1950 when a few were seen. Today several firms make and market such pearls, but with a three-layer plastic coating whose centre has a peculiar iridescent effect. They have been variously called 'imitation cultured pearls' or 'shell-based imitation pearls'.

The beads are coated with the pearl essence. The cheaper grades of pearl necklets are usually coated by 'string dipping'. The method is only suitable for necklet pearls and these are threaded widely spaced on a linen thread, often in the order of graduation of the finished necklet. These strings of pearls are then mounted across a suitable frame which is then dipped into a vat of essence. This dipping may be carried out several times and on each successive 'dip' the frame is reversed so as to avoid the formation of 'tears'. For better-quality 'pin dipping' is carried out by mounting some 500 beads on special dipping boards. These boards bristle with 'toothpicks' upon which the pearls are threaded: they are mounted in pairs and with the beads on the underside are gently lowered into the pearling solution until all the beads are submerged. After removal the boards are mounted in a machine which rotates them slowly so as to ensure an even coat while drying (*Figure 22.42*). The drying room needs to be air-conditioned and dust free, each dip taking from 1 to $2\frac{1}{2}$ hours to dry. Successive coats up to ten may be put on, but usually not less than five are given so as to build up the bead to a lustrous 'pearl'. The finished pearls are graded, matched and threaded on nylon or double cotton. Imitation pearls used for ear-rings, brooches or pendants may have only a half hole, or none at all. Such pearls are usually cemented into the settings.

Identification

Imitation pearls are easily identified by examination of the surface with a hand lens. The surface, looking like blotting paper, does not have the fine serrated structure of a natural or cultured pearl, and at the string canal the surface of the pearl essence usually shows a wearing away from attrition with the adjacent bead. Most imitation pearls feel smooth when rubbed against the teeth, unlike the effect with natural or cultured pearls which feel chalky or gritty. It has been noted, however, that some recent imitation pearls have been found to give this gritty feeling. A pin pressed into the surface of a coated pearl will scratch or indent it, whereas it will not do so with a nacreous pearl with the hollow glass bead type of imitation. These earlier types of imitation pearls – with a hollow glass envelope – will reveal their nature by lens examination which shows a jagged edge to the string canal and bubbles in the glass envelope; and if a spot

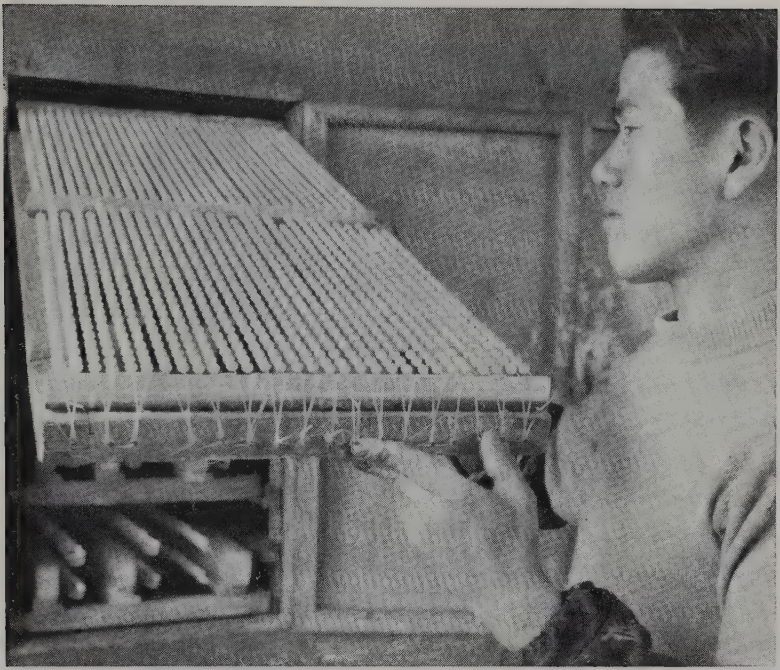


Figure 22.42 *Drying the coated beads producing imitation pearls*

of ink is placed upon the surface it will appear doubled owing to the reflection from the internal surface of the glass shell.

Owing to their opacity to X-rays the glass beads of the modern imitation pearl show up white on the negative (or solid black on a positive print made from it). In the X-ray picture in *Figure 22.43* the nine pearls on each end of the necklet of otherwise cultured pearls, and the one 'intruder' in the body of the necklet, stand out vividly.

Specific Gravity

The SG of imitation pearls varies with the type and with the material from which the core is made. The earlier hollow glass bead type has an SG usually below 1.55. With the solid bead type of coated glass the SG is usually higher than for the natural or cultured pearl, being between 2.85 and 3.18, the higher values, over 3, being the most common. Just after World War II some of the glass bead imitation pearls were found to have SGs of 2.3 and about 2.56. The use of these low-density glasses was considered to be due to the difficulty of obtaining the correct type of glass at this time.

Although articles of only moderate value, care should be taken of simulated pearls. The coatings are soft and will scratch fairly easily so that jewellery set with imitation pearls should be put back into their cases, or wrapped in soft paper, before being put away with other jewellery. Cosmetics, especially some scents, can have a detrimental effect on the surface coatings of imitation pearls. It seems to be the liquid scent, and not the vapour, which does the damage; thus

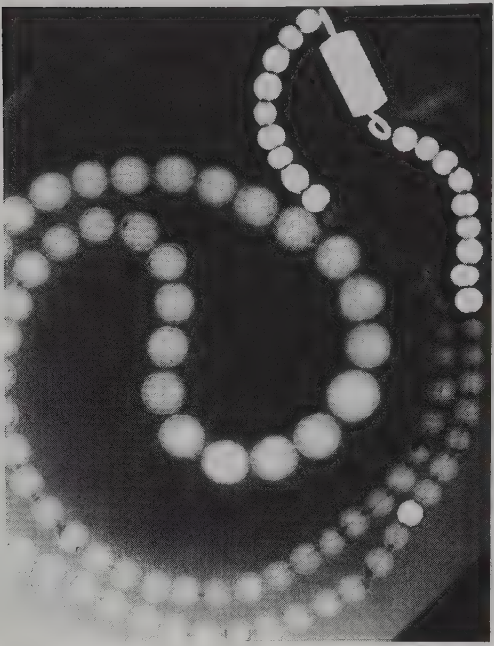


Figure 22.43 X-ray picture showing imitation pearls appearing black in a necklet of otherwise cultured pearls (negative image of positive print)

use of a scent spray may cause 'pitting' of the surface coating of imitation pearls. It is always well to put on jewellery of any kind after, and not before, using cosmetics. The use of hair sprays while wearing jewellery, and especially imitation pearls, will give them a coat of lacquer which later tends to flake off to the consternation of the wearer. The use of a chamois leather will adequately clean any flakes still adhering to the pearls.

Simulation

An unusual type of 'blister pearl' has been encountered which was constructed by covering a bead of mother-of-pearl with an envelope, so thick as to be loose and not adhering to the base, and completing the 'pearl' with an outer skin of glass. Black pearls have been imitated by polished spheres of hematite. Such fakes can easily be identified by the much greater SG of hematite, just over 5, and by the red streak shown by the mineral when it is rubbed across a piece of white unglazed porcelain. The pink conch pearl is simulated by coral, among other substances, but the typical 'flame' markings on the surface shown by the pink conch pearl serve to identify the true from the false. A 'pink pearl' made of suitably coloured glass, which even had imitation flame markings, has been met. Examination of this piece, however, showed bubbles in the glass. The pink conch pearl may also be imitated by beads cut from the conch shell. As the flame markings are also characteristic of the shell, they will be seen on this imitation. However, further examination will reveal the banded nature of the shell, in contrast to the pearl.

23

Coral, Shell and Operculum

Coral

The name coral brings to mind the atolls of the South Seas, those narrow reefs surrounding the beautiful transparent waters of the central lagoon. Lovely as they are these atolls do not supply the precious coral so well known in the jewellery of many ages, for there are many corals and the one which supplies the lovely red and pink coral so prized for ornamentation is not a reef builder.

There is much misconception concerning the formation of coral, particularly that of the noble coral used in jewels, a coral scientifically known as *Corallium nobile* or *Corallium rubrum.* Generally expressed as being the axial skeleton of the coral polyp, which gives the impression of being an internal skeleton, similar to the bones of our bodies, coral is better described as being a scaffolding upon the surface of which the boneless animals live as a colony.

The Coral Polyp

The coral polyp, a primitive type of plant-like animal called a zoophyte, is a small whitish creature about 1.5 mm in diameter. It has a tube-like body from the upper rim of which project eight tentacles surrounding the 'mouth', this top portion being known as the oral zone. Thus the animal tends to resemble a sea anemone in miniature.

At the base of the tube-like body is the basal disc, which in the case of colonies is connected by a layer of communicating canals of living tissue, called the hydrorhizae, to the enteron, or stomach, of each individual member of the colony. The hydrorhizae are embedded in a gelatinous mass, termed the coenosarc, and which itself is covered by a skin-like membrane called the perisarc. Thus the whole colony forms a single entity, and it is from the lower surface of the coenosarc, and from the base of the polyp, that the coral is formed.

Reproduction may be sexually from ova and sperm, or by budding. In the colonies themselves there is always rigorous segregation of the sexes. Usually a colony consists of individuals of one sex only, and if a colony is bisexual it is found that the sexes occupy separate branches. The male individual discharges his fertilising cells into the water, some of which find their way into the body of a female and penetrate the eggs already prepared for fertilisation.

The fertilised eggs of microscopic size are ejected into the water by the female and they subsequently develop into free-swimming medusal forms. The surviving medusal forms, for mortality is high, sink and attach themselves by their convex surfaces to a stone, rock, crab, bottle, but never bare metal. Once the swimming form has attached itself securely to its new home, a knob appears on its free end which quickly enlarges and it soon becomes a fully developed polyp. Calcium carbonate is secreted around the point of attachment forming the nucleus of the coral structure, and of a new colony. The coenosarc grows over the calcareous deposit and the second stage of reproduction commences. This is by a species of budding or self-germination of the polyp itself within the coenosarc – a knob-like protuberance forming and then developing into a polyp. Thus the newly formed colony is gradually populated. As the colony continues to grow the coenosarc spreads to accommodate the new inhabitants, and in order to provide living room for them is continually separating calcium carbonate from the sea-water, and redepositing the mineral in the form of spicules of calcite as coral.

At first this deposition of lime is confined to the point of attachment of the original polyp and then the skeleton commences to extend into a column upon which a number of secondary polyps form. Some of these lateral polyps also start to shoot out sideways and this produces a branch-like form to the whole colony. The branches spread out as widely as possible and are haphazardly arranged, but no two branches spring from the same point of incidence. These branches may be more or less straight or may twist and turn about in an irregular manner; they may also produce secondary branches and so on. Each branch becomes smaller than its parent and terminates with a rounded blunt point covered by a very sensitive layer of coenosarc which projects beyond the end of the branch itself (*Figure 23.1*).

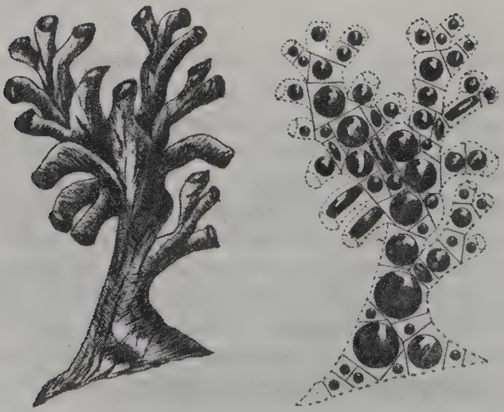


Figure 23.1 Growth of coral and showing the way beads are cut from the 'tree'

Geographical Locations of Coral

The polyps of *Corallium rubrum* are very sensitive to changes of temperature, preferring waters between 13 °C and 16 °C, and which are comparatively still and clear; muddy water is fatal to the growth of the coral colonies. Coral production has been affected in recent years by widespread pollution, and in some areas coral fishing has been banned. Coral's growth requirements limit the geographical distribution to certain well-defined areas, which may be said to stretch from southern Ireland through the Bay of Biscay to Madeira, the Canaries and the Cape Verde islands; thence through the Mediterranean, the Red Sea, Mauritius, the Malay archipelago and Japanese waters. The actual fisheries are those of the Malay and Japanese waters, and most important of all, the waters of the Mediterranean. The best red coral is fished off Algiers and Tunis on the African side, while on the European side the waters off the coasts of Sicily, Calabria, Naples, Sardinia, Corsica, and parts of the French and Spanish seaboard provide good material.

The coral from the Ryukyu islands, south of Japan proper, has now entered the market. The precious coral found there is red (the blood-red variety being called Moro coral), pink and white. The coral is fished in the area between Okinawa and Miyako at depths of 300–400 m.

Methods of Dredging

The actual 'fishing', carried out mostly by Italian fishers for some 6 months of the year, is usually performed by dredging. Divers have been employed but are not so satisfactory as the dredging method. A special net called *ingegno* is employed for securing the coral. It consists of a heavy wooden cross or beam weighted in order to make it sink. To this are attached some 20–30 coarse rope nets, weighted tassels or tufts of horse hair and about a similar number of smaller bags made of ordinary fishing net. The whole contraption is dragged across the bed of the sea by a rope from a fairly large sailing vessel and the coarse nets become entangled with the coral growths and tear them from their seatings, the coral being collected when the dredge is drawn to the surface. Ryukyu coral is similarly fished.

Fashioning

Most of the fashioning of Mediterranean coral is an Italian industry, being carried out at Torre del Greco near Naples. The coral is first sorted into various grades of colour to which typical Italian names are applied (*Table 23.1*).

After sorting the coral is passed on to the workers, the majority of whom are women. Only primitive tools are used, even beads being roughly shaped with a knife and finally ground to shape on a grindstone. Sometimes a form of lathe is used and the drilling is done by a bow or mechanical drill. Coral is mostly fashioned into beads, small carved objects and cameos. The plain polished pieces of coral in natural shape and about 12–20 mm long, bored crossways through the centre, are known as 'Arabian beads'. Much of the worked coral from Italy is sent to the Orient, the peoples of India and China favouring the material for ornamental and ritual purposes. Coral contrasts well with turquoise

Table 23.1
Coral names and colour

Name	*Colour*
Bianco	Pure white
Pelle d'angelo	Pale flesh pink (angel's skin)
Rose pallido	Pale rose
Rosa vivo	Bright rose
Secondo coloro	Salmon colour (second colour)
Rosso	red
Rosso scuro	Dark red
Arciscuro or carbonetto	Very dark red (ox-blood red)

and the Arabians and North Africans use the two gems in combination for the ornamentation of camel trappings and other articles.

Chemical and Physical Properties

The composition of coral is almost wholly calcium carbonate ($CaCO_3$) with about 3 per cent of magnesium carbonate ($MgCO_3$), and possibly a trace of iron oxide and some 1.5–4 per cent of organic matter of indeterminate composition. Walton, working with thin sections of coral, found dark red radii passing from the centre to the outside surface, and these radial colour bands are seen on a longitudinal section as lines of pigment running parallel to the length of the section. Indeed, these colour bands are clearly visible on the surface of much coral by the eye alone, when the effect is reminiscent of the structure seen on polished longitudinal faces of ivory.

The hardness of coral is about 3.5 on Mohs's scale and the material is easily broken, producing a hackly type of fracture. Coral has an SG of between 2.6 and 2.7. Although the refractive indices have little value in the testing of coral it is interesting to record that Walton obtained on specially polished specimens indices of 1.65 and 1.49, which are those of calcite. Therefore the calcium carbonate in coral is in the form of calcite. A spot of acid placed on the surface of coral will cause effervescence owing to the rapid formation of carbon dioxide – a useful test for coral against certain of its imitations.

The cause of the colour of red and pink coral is not fully understood. Iron has been suggested but another theory is that the colour is mainly dependent on the organic part. Pearl has said that oil of turpentine removes the red colour of coral, and this, if true, would tend to indicate an organic cause of coloration, but there is always the fear that the piece or pieces worked upon have been intensified in colour by artificial means and it is this colour that has been removed by the organic solvent.

There may be seen in a thin section of red coral an absorption band in the blue-green at about 494 nm, but this has little value in testing. Under ultra-violet light coral is only weakly responsive, and any glow seen is a pale violet or a dull purplish-red. While this has little value for identification it should be noted that some glass imitations of coral are made of uranium glass and show the characteristic strong green fluorescence, and some plastic imitations show an orange-red glow.

Besides the white to red coral of *Corallium rubrum*, a white coral, *Oculinacea vaseuclosa*, has been fashioned for ornamentation. A black coral, known as 'Akabar' or 'King's coral' (*Antipathes spiralis*), and a blue coral known as 'Akori' coral (*Allopara subirolcea*), have been fished from off the Cameroon coast. Both these types are horny in nature. A specimen of black coral was found to have an SG of 1.34, and a vague refractive index of 1.56. This indicates that the material is organic and may be conchiolin. Unlike true precious coral this type does not effervesce with acid. This black coral appears to have first been found in 1958 off the island of Maui of the Hawaiian group, and later, during 1966, off the coast of Queensland, Australia. There is a golden coral fished in Hawaii and Tasmania; it has a speckled golden sheen when polished, and its appearance is quite characteristic. A coral with a bamboo-like structure is fished in the waters off the island of Tasmania, and is now marketed in Australia under the name of bamboo coral. There is a current ban on the export of coral products from Australian waters. All these corals have been fashioned and used in jewellery.

Simulation

Coral is extensively imitated and by many materials. What is probably the most attractive counterfeit of coral is a suitably stained vegetable ivory, but this may be identified by the dot-like cell structure seen when the surface is examined by a lens. Mixtures of rubber and gypsum, powdered marble mixed with isinglass and coloured red with cinnabar or red lead, stained calcined bone, coral dust suitably bonded together, or even plain sealing wax have all been used in the simulation of precious coral. Today the most common substitutes are glass, porcelain, and the various plastics.

Coral is sometimes stained, often to a deeper red, or in pink patches so as to resemble 'angel's-skin coral'. This can be detected by the dye coming off on to a swab charged with nail-polish remover (amyl acetate). It may be fair to point out that any repairs to, or cleaning of, coral need care. Any acid preparations should not be used, for even such a 'bland' acid as vinegar has been known to attack some coral; and some of the cleaning detergents will be detrimental to the surface of coral.

Gilson Created Coral

Coral consists of the remains of the external skeletons of millions of tiny coral polyps which thrive in large colonies in warm clear seas. Although tales of the coral reefs surrounding South Seas atolls and of the Great Barrier Reef off the NE coast of Australia, which extends for 2000 km, might suggest that there is an unlimited supply of this material available for ornament, the types of coral favoured for jewellery are obtained only in certain areas which suit their rather exacting requirements for growth, and the readily accessible supplies, especially those in the Mediterranean, are now said to be scarce.

This fact, and the continuing popularity of coral, probably decided Pierre Gilson to embark on the difficult attempt to produce a close replica of coral in his laboratories. According to Gilson, the basic material for this coral replica is a pure form of calcite obtained from a new mine in France, a small amount of pigmenting material being incorporated in the crushed mineral. The process of amalgamating the powdered calcite into a solid requires high pressures and some heating. The 'coral' is produced in blocks up to 700 grams in weight, and there is a wide range of colours available from pale salmon pink to deep ox-blood red.

In colour, lustre, and general appearance the Gilson material makes an excellent substitute for the natural product, but it may be distinguished from this without great difficulty by careful inspection and a few simple tests. Examined with a lens the Gilson coral appears quite homogeneous, in contrast to true coral which is well known for its 'wood-grain' structure. The SG of the Gilson product was found by Kurt Nassau to be 2.44 in a chosen sample, increasing to 2.50 after soaking for 24 hours in water owing to its porosity. These figures are decidedly lower than those claimed by the maker and well below the values 2.65–2.70 normally found in true coral. In a more sophisticated test, Nassau found more than a trace of silica in the Gilson samples, whereas silica is entirely absent in genuine coral. It must be generally agreed, therefore, that though Gilson Created Coral provides an attractive substitute for the real thing it cannot be classed as a true synthetic.

Shell

The calcareous armour of many of the shellfish which inhabit the shores of tropical seas have a use in personal decoration. This is particularly so in the case of those shells which have an iridescent lustre, and the most prized of these are the large pearl oysters (*Pinctada maxima* and *Pinctada margaritifera*) from the waters of northern Australia and the Torres Strait, and these form an important and major export in the economy of the region.

Methods of Fishing

The discovery of pearl shell in north-western Australian waters was made in 1861, at Nickol Bay, and later the fisheries extended from Exmouth Gulf, south of Onslow, to the Torres Strait and out to the Great Barrier Reef. In the early days of the pearl shell fisheries, skin divers (naked divers) searched for the shells, but quite soon the influence of the European brought the introduction of the armoured diving dress which is now used almost exclusively. The large shells are fished from sailing luggers, one- or two-masted craft of about 8–10 tonnes, and sailed by a crew of 6 or 7 including the diver. With the era of the pearling fleets came the birth of the township of Broome which is the centre of the pearling industry in these waters.

The luggers sail out with a store of provisions to last for a six-week trip, and on reaching a likely spot, reef the sails and drop anchor. The diver dresses in his suit and when ready goes over the side. He may go down for about an hour, filling his basket or bag with the shells, and on a signal to the boat crew given on his life-line is hauled up to the surface and climbs back into the lugger.

The shells which have been brought up are opened by the use of a broad flat-bladed knife and the fleshy oyster, the meat as it is termed, is removed and

Figure 23.2 Opening Australian pearl shell

searched for any pearls that may be present (*Figure 23.2*). The edges of the shells are trimmed and they are then stacked in boxes which have stretcher-like carrying handles to enable them to be taken through the surf to the shore station. There the shell is sorted into qualities and boxed for transit to Europe and the United States of America, the latter being the chief consumer of pearl shell. Manila shell is the name given to the pearl shell obtained from the Philippines and Burmese shell to that from the waters around the Mergui archipelago, Myanmar.

Ornamental Use

The shell is used for making mother-of-pearl buttons, knife handles, inlay and other ornaments. Some dark-coloured shell from the black-lip pearl oyster, suitably cut, produces a cat's-eye effect and these are used as buttons and even mounted in jewellery. Mother-of-pearl carving has been a staple industry of Bethlehem, Israel since the middle of the eighteenth century. Carved mother-of-pearl in leaf and other designs are used in jewellery, and necklets made of the lustrous small topshells which have had their dark outer periostracum removed are also produced.

These shells with brightly coloured blue and green nacre, termed paua shells (*Figure 23.3*) in New Zealand and abalones in American waters, are fished for their beautiful mother-of-pearl. These shells belong to the genus *Haliotis*, and are larger brothers to the earshells of the Channel Islands. These big colourful shells, which sometimes produce pearls, are found along the Great Barrier Reef off the eastern shore of Queensland, the waters of New Zealand and the coasts of California and Florida.

The larger members of the *Trochus*, the topshells are also fished for the value of their shell, and sometimes the thick column of the shell is turned into beads and strung as necklets.

Two of the largest and most beautiful shells in the world are used for the carving of cameos, which often rely on the different colour shown by the

Figure 23.3 The paua shell or abalone (Haliotis)

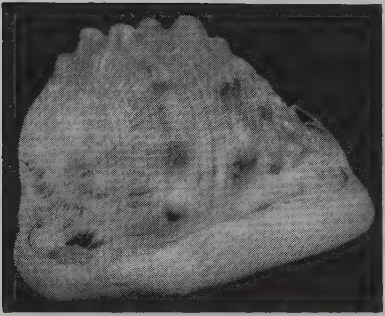


Figure 23.4 The helmet shell found in the warm waters of the West Indies

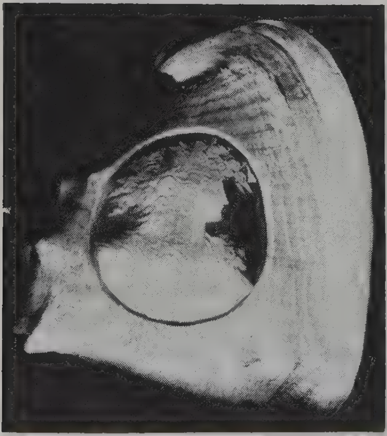


Figure 23.5 Cameo cut in a helmet shell

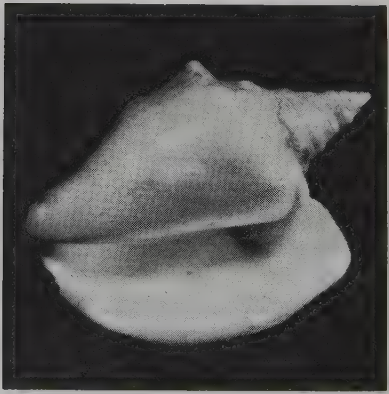


Figure 23.6 The giant or queen conch shell

material when cut to different depths. The shell most commonly used for cameo cutting is the helmet shell (*Cassis madagascariensis*) (*Figure 23.4*), which is found in the warm waters of the West Indies. Cameos cut from this shell stand out in white bas-relief against a brown background (*Figure 23.5*), the shells from

Madagascar being sent to Italy for carving. The giant or queen conch (*Figure 23.6*) (*Strombus gigas*), which produces the pink conch pearls, is another inhabitant of the West Indies and Florida coast, and is used for cameo carving. With this shell the carving is white on a rose-coloured background, or vice versa. The pink colour unfortunately tends to fade on too great exposure to light.

A type of pearl sometimes used in jewellery is cut from suitable pieces of the shell of the sea-snail (*Turbo*). Such a pearl is distinguished by the pearly top surface and the yellowish non-nacreous back. These objects are known as Antilles pearls or oil pearls. The so-called *coque de perle* is cut from the central whorl of the nautilus shell and resembles to some extent a blister pearl. It has, however, a thinner skin and is much more hollow inside and is usually filled in with wax or cement. The inner septa (*Figure 23.7*), which divide the nautilus shell up into chambers, are used for inlay work.

Figure 23.7 An X-ray picture of a nautilus shell showing the septa and the siphuncle, a tube connecting each chamber

Treatments

Mother-of-pearl is often stained various colours. This is achieved by soaking in organic dyes to produce a series of relatively unstable colours. The soaking of pearl shell in silver nitrate will produce a brown coloration which will darken to black on exposure to light. Freshwater mother-of-pearl shell readily darkens on exposure to X-rays, and all mother-of-pearl darkens to black on exposure to gamma radiation.

Operculum

Occasionally the gemmologist meets with unusual objects mounted in jewellery, and one such object is the operculum. These have no optical effect, although they are sometimes called cat's-eyes, solely because of their eye-like markings and circular form. They are the lid, or door, which shuts in certain types of shellfish when they retire into their shell: hence the name operculum, which is derived from the Latin and means a lid or cover.

An operculum is common to many of the univalve shellfish, and may be well explained by considering the better-known and analogous member of the Mollusca, the edible winkle (periwinkle, *Littorina littorea*); the horny plate found attached to the animal is its trap-door or operculum. The trap-door of another mollusc, the gastropod *Turbo petholatus*, supplies the calcareous operculum employed in jewellery.

The animal *Turbo petholatus*, of the order Aspidobranchia, is like a large snail in appearance. Its shell also resembles the shell carried by the periwinkle, but is larger and has more rounded whorls and a taller spire (*Figure 23.8*). Beyond this the resemblance ceases, for the shell is nacreous within and the procelain-like periostracum is prettily coloured a medium to light brown with a cream or white mottling.

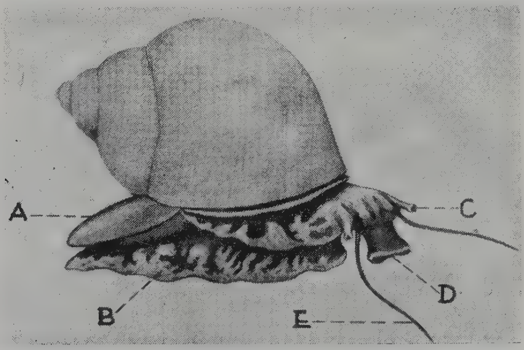


Figure 23.8 *Turbo petholatus: A, operculum; B, foot; C, eye; D, proboscis; E, tentacles*

These animals haunt the tangled masses of seaweed on the shores of the tropic seas of Oceania, Melanesia and Polynesia, specimens having been obtained from Darwin, north Australia, Papua New Guinea, Vietnam, the Moluccas, Fiji Islands, Tahiti and Samoa. They were extensively collected for their opercula by the fighting forces engaged against the Japanese in World War II.

The operculum, generally round or slightly oval, varies from 6 to 75 mm in diameter but is generally between 12 and 25 mm. Its convex upper surface has the appearance of porcelain with the apex of the dome coloured green and verging to yellow and white on one side, and through reddish-brown to dark brown on the other. The reverse or base is flat and shows spiral lines of growth and a deep dextral spiral cut comforming to the direction of growth from the original point of beginning or nucleus, which is rather eccentric to the true centre of the piece. The base, which is the side of attachment to the animal, is covered with a brownish skin of conchiolin.

The operculum is a cuticular development of calcareous and organic substances secreted from a group of cells situated on the dorsal side of the foot of the animal. It is so placed that it acts as a door to the aperture of the shell when the animal retires within, and rests on the animal's back behind the shell when the animal is crawling.

The composition of these pieces is mainly calcareous, with some horny organic matter and water. The SG lies between the limits 2.70 and 2.76 and the hardness is about 3.5.

In New Ireland, on the Bismarck archipelago, these pieces have been used as the 'eyes' for the grotesque and gaudily painted images or idols found in the temples. In the beautiful Stewart Islands, opercula have been used for money.

A similarly calcareous operculum from another mollusc is coloured white with a central eye of red colour, and in some cases the surface is covered with raised 'pimples'. These types have also been encountered in jewellery.

The use of fossil ammonites in jewellery may briefly be mentioned. These fossil ammonites, molluscs resembling in many ways the nautilus, flourished in the Mesozoic era about 150 million years ago. They have a coiled shell and consist of a series of chambers which are often indicated on the outside by a convoluted line. The fossils are actually mineralised, often being calcite casts of the interior of the ammonite shell, although some have the shell replaced by iron pyrites and the inside filled with greenish calcite (*Figure 23.9*).

Figure 23.9 Ammonites from the Oxford clay

Vast numbers of these fossils are found in the Lias of Dorset, England, and some of these, particularly the small ammonite *Promicroceras*, have been mounted in gold and silver. It was quite in industry before 1914 but very little mounting is now carried out and only older pieces are available.

A number of ammonites found in the western states of America, and elsewhere, have the septa filled with crystals and the smaller specimens of these are sawn in two and the cut surfaces polished to produce articles of jewellery.

A beautiful iridescent fossil ammonite shell is found in various localities. It is stabilised by plastic impregnation and is sold under the name of Korite. This is a variety of *Lumachella* or 'fire marble'.

24

Amber and Jet

Amber

Chemical and Physical Properties

Amber is a time-hardened resin which exuded from certain pine trees, particularly *Pinus succinifera,* which flourished in Oligocene times just before the great Ice Age, that is more than 30 million years ago. It is in composition a complex mixture of several resins, acids and a volatile oil. It accords to the general expression $C_{10}H_{16}O$, but also contains a certain amount of hydrogen sulphide (H_2S).

Amber is transparent to translucent and has a greasy lustre. The colour is normally yellow or brown, but may be reddish or whitish; it is often clouded and sometimes fluorescent. The hardness is slightly above 2 on Mohs's scale, and the fractured surface usually shows a conchoidal type of break. The material begins to soften at 150 °C and finally melts at 250–300 °C. The refractive index is 1.54 and the specific gravity approximates to 1.08.

Most amber shows a bluish-white fluorescence, which is brighter on freshly broken surfaces, when exposed to radiations from the long-wave ultra-violet lamp. Under stimulation from the short-wave ultra-violet lamp the fluorescence is a mustard-green colour, although some Myanmar (Burmese) amber shows a blue glow under such excitation. Under bombardment by X-rays amber is inert.

Occurrences

The principal source of amber is in the Baltic Sea along the shores of Lithuania near Königsberg. There are two sources of amber in the district: the sea amber, which has been washed up on the shore by wave action; and the pit amber obtained by open-pit mining for the amber drops (block amber) in the Oligocene deposits of glauconite sand. This sand consists of grains of the hydrous potassium-iron silicate mineral called glauconite, and owing to its greeny-blue colour is known as the 'blue earth'. The sea amber, which has been washed out from the sea bed, is, owing to the low density of the material, carried by tides and currents for considerable distances. Such amber may therefore be found on all the shores of the Baltic Sea, and may even be found on the shores of Norway and Denmark. It has even drifted on to the shores of the English east coast and as far south as the Isle of Thanet.

Treatment of Baltic Amber

This pit amber, the main pit being at Palmnicken, is obtained by digging out the blue earth with steam shovels and dredges, after a sufficient area of overburden has been cleared. The blue earth is then taken to the washing plant where, by means of powerful streams of water, the amber is separated from the sand, washed and sized, and finally graded. The amber may be clear and transparent, when it is known as clear; or it may be slightly turbid owing to a number of contained gas bubbles and then resembling goose fat, and hence termed fatty, or in German *flohmig*. A variety containing a vast number of bubbles making the material quite cloudy is called bastard, while bony or osseous amber has the appearance of dried bone. The foamy or frothy type is chalky in appearance. The small pieces not of gem quality are treated by heat in large retorts in order to produce succinic acid, amber oil and colophony, the latter being used for the preparation of varnish.

Small pieces which are clear enough for gem use are pressed together under gentle heat in order to produce pieces of a size suitable for working – a true reconstruction. This pressed amber, or ambroid as it is called, was made by a process first carried out in Vienna; the small pieces of amber (which softens at about 180 °C) are welded together under a pressure said to be 120 000 pounds per square inch. Such pressed material may be identified by the margins of different clarity and by the elongation of the bubbles due to the flow under pressure. Cloudy material may be clarified to some extent by careful heating in rape seed oil (colza oil), which penetrates and enters the air spaces causing the cloudiness. This clarified amber, unless great care is taken in the operation, will often exhibit crack-like marks which resemble nasturtium leaves. These are known to the amber workers as 'sun spangles' and are possibly due to stresses set up in the amber, or release of such stresses (*Figure 24.1*). A number of amber ornaments have been marketed which show rather large nasturtium leaves and which appear to have been artificially induced and coloured. Staining, too, is carried out, sometimes to redden the yellowish-brown colour in order to simulate the so-called 'aged' colour of amber, or to produce other colours, particularly green. Amber is frequently heated to darken its colour by increasing the speed of surface oxidation.

Examples of pressed amber tested by Anderson were nearly transparent and homogeneous in appearance and no signs of flow were apparent in ordinary light. Under long-wave ultra-violet light, however, the samples showed a strong whitish fluorescence, and the shapes of what had previously been individual fragmented pieces could be seen. Further tests carried out by flotation in a suitable brine solution showed the pressed amber to be slightly but appreciably lower in density than a number of natural pieces. Their SG, when determined later by hydrostatic weighing, was 1.06 against the 1.08 figure which is normal for block amber.

Figure 24.1 Pendant of 'sun spangled' (stress figured) amber

Inclusions

Inclusions in amber have a special appeal – who has not heard of the 'fly in the amber' (*Figure 24.2*)? These occur through the resin exuding from pine trees catching up insects, pieces of moss, lichens and pine needles. A clear piece of amber enclosing a perfect insect is a most prized possession, not only to the layman, but to the zoologist and geologist, to whom such pieces are as an open book showing the flora and insect life of those bygone days. Not all inclusions of amber are organic for, amongst other inorganic inclusions, perfectly formed crystals of pyrites have been observed.

There are many insectivorous inclusions found naturally in amber, although these can be artificially introduced into pressed material during its treatment and processing. Entomologists can usually determine whether the insect is of ancient or modern origin. In the case of natural insect inclusions the majority of these occurred when the insect was enveloped alive, and it is wise to examine specimens for signs of movement and strain around the insects in question

Figure 24.2 Fly in amber

under polarised light, for artificially introduced insects are normally already dead upon entombment and so signs of strain or struggle will be seen.

Nomenclature

The Germans call amber by the name *Bernstein*, a name of comparatively ancient date, for in the early Middle Ages powdered amber was much prized in Germany as an aromatic incense. The name *Bernstein* is derived from the Low German *bernen* (to burn), for amber burns quite readily with a sweet smell. The Greek name for amber was *elektron*. When amber is rubbed it has a property of attracting light articles, for the rubbing process produces a charge of negative electricity on the amber. Electricity was subsequently named after this property.

Other Occurrences of Amber

Although a quantity of commercial amber comes from the Baltic deposits, there are other sources of material though often of a slightly different chemical composition. One of these is the Myanmar (Burmese) variety. This amber is very much redder in colour than the Baltic variety; it is found near Myitkyina in the valley of the Hukong, a tributary of the Chindwin river, and not far from the jadeite mines. This amber differs from the Baltic variety in being harder and denser and is often found to contain included calcite. The Myanmar amber is obtained from a clayey soil and is mined by the Maingthas, the peoples of the Bhamo district, during the season from March to May. Several shafts are sunk close together to a depth of about 15 m, three men working each pit, one below and two above; the *twinlon* method of basket, hooked bamboo pole and bamboo shear legs (similar to the method used in ruby mining) is used to bring up the soil, from which the amber pieces are washed out. The cleaned pieces are sent to Mandalay for disposal, most of the material going to China.

Along the Simeto river, near Catania in Sicily, is found an amber of a reddish-brown colour and fluorescent (green) in appearance. At several places in Romania is found an amber which is said to contain less succinic acid and more hydrogen sulphide. The occurrences are somewhat widespread in the country, the most important localities being in the province of Muntenia near Buzau. This amber has an SG between 1.05 and 1.12 and a hardness of 2–2.5 on Mohs's scale, varies in colour between yellow, brownish-green, brown, green and blue, and shows a striking fluorescence. Other places in this state where amber is found are Ramnicul-Serat and Prahova. In the province of Dobrogea, along the shores of the Black Sea, near Valzea in the province of Oltenia and at Bacau, Neamt, Putna and Sucava in Moldavia are deposits of amber, but, particularly in the last-named locality, the amber is often of a dark to blackish-green colour, or may be bluish. Amber varying between brown-yellow and wax to honey yellow is found near Sibuh and Alba in Transylvania in the central part of the country.

Amber has been found in considerable quantities in the Dominican Republic, and this is currently one of the world's principal amber sources. Prior to 1979 it had been exported to Germany and mixed with Baltic material and sold with it, without any mention being made of its origin. There are a number of localities which produce amber, and the material varies in age depending upon its original source. Care has to be exercised with this material as some localities produce more recent resins, which have to be regarded merely as varieties of copal. Many pieces of Dominican amber are full of organic debris, including a wide range of insects and plants; these can substantially affect the external colour of the material. Strong daylight fluorescence is often seen in this material, and a bluish hue is the most common, followed by greenish and purplish. All these effects diminish as the surface of the material oxidises, and only with the removal of this outer skin and subsequent repolishing will the full fluorescence return.

Amber of a very similar appearance to Dominican material has been known from the Chiapas state of Mexico since the beginning of the century. The material is often carved into Aztec and Mayan designs, and the new carvings frequently show a dramatic surface fluorescence. A deep red variety is found in small pieces and is very similar to the red amber from Myanmar. The majority of Mexican amber is usually clear and has few inclusions.

Mention may be made of other deposits in the north American continent. A variety called chemawinite is found around the south-western margin of Cedar Lake, Manitoba, Canada; and there is a small deposit recorded from the Eocene beds on the north-east side of the Simi Valley in Ventura County, California. Amber has also been found in Pitt County, North Carolina; Coffee Bluff on Tennessee river in northern Hardin County; near Gifford, Hot Springs County, Arkansas; Wando river, South Carolina; and at several places in Maryland, New Jersey, New York, Massachusetts, Mississippi, Wyoming and Colorado.

Synthesis and Simulation

Copal

Amber is simulated by many substances, both natural and artificially produced. Copal resin, a recent fossil resin, is the most important of the natural amber imitations. It is the exudation from various trees, and may come from many parts of the world, particularly from the West Indian locust tree from South America, from trees in West, Central and East Africa, and from New Zealand. The most important are those pieces which have been buried for some considerable time in the earth. This is particularly so with the New Zealand variety, a copal from the kauri pine (*Agathis australis*), hence termed 'kauri gum'. The physical and optical properties of these copal resins do not differ very much from those of true amber, but, owing to the more recent hardening of the copal resins, they are more susceptible to attack by solvents than is the case with amber. A spot of ether (methylated ether obtainable from any chemist will be suitable) placed on the surface of copal will often produce a sticky patch, whereas in true amber there is no action. Under ultra-violet light, particularly the short-wave lamp, copals show a whiter fluorescence than does amber. Rubbing copal vigorously with a cloth will normally produce a sickly resinous odour.

Plastics

Bakelite, a phenol formaldehyde resin, is probably the most important imitation of amber. This material has a greater SG than amber, averaging 1.26, so that such imitations will sink in a solution of salt in water which will float amber (see p. 576 under 'Tests for Amber'). The refractive index is also higher, averaging 1.66. Bakelite imitations of amber are, in general, inert under ultra-violet rays or X-rays; if there is any glow at all it is usually a brown fluorescence quite unlike that given by true amber.

Celluloid can also be used as an amber imitation. This material has a refractive index of 1.50 and an SG about 1.38. Celluloid shows a yellowish-white fluorescence under ultra-violet rays and X-rays.

Casein, the hardened milk plastic, does not appear to be used very much as an amber imitation despite the fact that material of clear amber colour can be produced. The material seems to be met with in the cruder 'filled' form as cheap beads. Casein may be identified by the SG and refractive index, 1.33 and 1.55 respectively. Under both long-wave and short-wave ultra-violet light the material fluoresces with a white glow, but, unlike celluloid, casein is inert under X-rays. If a drop of nitric acid is placed on an inconspicuous surface a bright yellow spot is left. This is conclusive, but the effect may be masked by the body colour.

Urea-formaldehyde resin, the amino-plastic, can make a passable imitation of amber, but as yet does not appear to be used. The SG of this plastic is about 1.50 and the refractive index is usually greater than 1.55, generally near to 1.60.

Perspex, the polymethylmethacrylate resin, is another plastic which has great possibilities as an amber imitation. It is easily recognised by its rather characteristic SG of 1.18.

Polystyrene is used as a medium for the production of fancy costume jewellery owing to its ready flow in injection moulding techniques. The SG of this material is 1.05, just lower than for most amber. The refractive index is about 1.50. There is a vast number of polymerised organic compounds now made for the plastics industry, many of which, suitably coloured, could supply an amber imitation, but those mentioned are the most likely.

Two recent amber imitations of German origin are 'polybern', which consists of small pieces of real amber in a coloured polyester resin; and 'bernat', a plastic which has a similar refractive index to amber but the higher SG of about 1.23. This latter imitation is sometimes sold with pieces of plants and insects embedded in it.

Rhinoceros hide (skin) is very thick (20–30 mm) and when polished can be very amber-like in appearance. It can be turbid and milky, and is sometimes almost completely transparent. It is easily distinguished by its elastic nature and the vein canals.

Flies in Amber

It was thought in some circles that a fly in amber was a sure proof that the piece was amber. This is not true today for 'amber' with flies, beetles, and even moths and butterflies has been produced and mounted in jewellery. These are usually obvious as the plastic 'tomb' is too clear and the animal or insect is too big, and shows no signs of having been embedded alive. True amber, as it trickles down from the pine tree, engulfs the small insects, which struggle in their death throes producing swirls in the then viscous resin. There is a record of a fly in amber doublet; a piece of real amber formed the base upon which was placed an insert which was enclosed by a 'lid' of a material which was possibly copal resin. It is understandable that insects can be caught up by copal resin and one case is known where a small scorpion was entombed in kauri gum, although it can be safely assumed that the majority of large insects (over 20 mm), small reptiles or amphibians are highly suspect and are unlikely to be of natural origin.

Glass

Glass imitations of amber have a much higher SG and are cold to the touch, whereas amber feels warm. The hardness of glass is greater. Quite a number of yellow glasses are coloured by uranium oxide and hence show a brilliant yellow-green fluorescence under the ultra-violet lamp. Other glasses not containing uranium may contain manganese and this gives a dull greenish glow which is entirely different from the glows shown by amber under the ultra-violet lamps.

Tests for Amber

A common salt solution can be made up by the gemmologist simply by slowly adding table salt to water using a known piece of amber as an indicator. When the amber floats in the solution it is ready for use. Most plastics and Bakelite will sink when immersed. Care should be exercised, however, as copal will float, as will plastic beads containing large gas or air bubbles.

A most useful test for amber, providing that care is used in its application, is to apply the blade of a knife to an inconspicuous spot and test for the sectility. Amber, pressed amber and the copal resins break away in powdery splinters or chips. Glass is not touched unless a great deal of pressure be applied. Bakelite is resistant to the blade but will tend to peel off in rather large chips, while the other plastics peel easily. Except for glass, which does not peel anyway, such

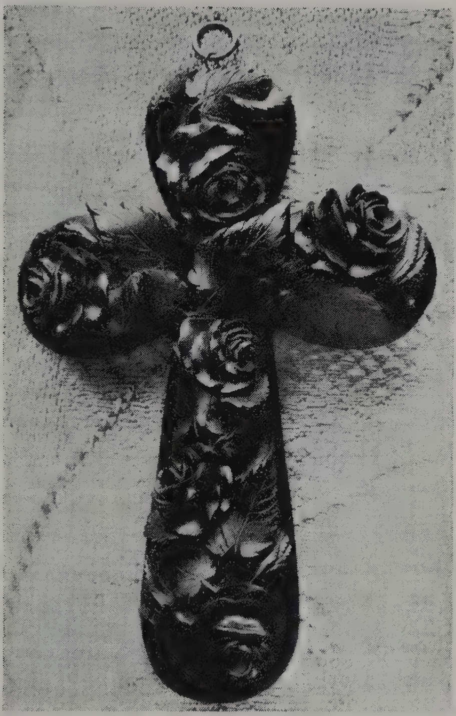


Figure 24.3 A cross in carved jet

peelings, resting on the knife blade and introduced into a flame, will give characteristic reactions. Amber and copal will burn with an aromatic smell: Bakelite and casein will only char, the first tending to give off a carbolic smell and the second that of burnt milk. Celluloid will burn readily, while the safety celluloid (cellulose acetate resin) will burn less readily and give off a vinegary smell.

Jet

A gem popular in Victorian times, jet, with its intense black colour and capacity for taking a high polish, was pre-eminent for certain types of jewellery, particularly those of an ecclesiastical nature (*Figure 24.3*) and mourning jewellery. Indeed, 'Whitby jet' is known far and wide, and Whitby – an ancient seaport town of Yorkshire, England – derived its chief fame from its jet industry, which flourished from Roman times, reached its peak during the middle of the nineteenth century and lasted until the beginning of the twentieth century, when the wheel of fashion turned and jet became more the symbol of Victorianism and less desired.

Jet was known in England before the advent of the Romans and even before recorded history, for jet beads, pendants and charms have been found in early burial mounds in widely scattered parts of the British Isles. True, it is questioned whether all this material came from the Whitby area, but undoubtedly a great deal did. There is evidence that jet was mined as early as 1500–1400 BC. During the Roman occupation of Britain the jet mines were opened up and jet was shipped to Rome. Written records have traced down through the ages Yorkshire jet and the Whitby jet workers.

The name jet has been derived from the old French *jyet* or *jaiet*, which was itself derived from the Latin *gagates*, either directly or through the German *gagat*. The word was apparently first obtained from the Greeks and derived from Gagee or Gagas, a place on the Mediterranean coast of Asia Minor, from where the Romans obtained their jet.

Chemical and Physical Properties

Jet is a fossil wood allied to brown coal, and is derived from driftwood which has been subjected to chemical action in stagnant water and subsequently flattened by great pressures. The material is soft, about 2.5 on Mohs's scale, but may reach as high as 4 in some cases. It breaks with a lustrous conchoidal fracture. The SG approximates to 1.33 (1.30–1.35) and when a flat surface is tested on the refractometer a vague blurred edge at about 1.66 is seen. Jet shows no luminescence under ultra-violet light or X-rays.

The material burns like coal, of which it is really a variety, and when rubbed is said to give off a strong odour, an effect remarked upon by the Roman writer Pliny. Friction is said to develop electricity in jet just as it does in amber, but different pieces of jet may vary considerably in their power to induce frictional electricity, some being quite inert in this respect. It is owing to this effect that jet has been called 'black amber'.

Occurrences

Jet is found in the Upper Lias of the Yorkshire coast, in the neighbouring dales of Rosedale and Bilsdale and at Great Ayton and Oakham Wood near Hawsker, which is one of the earliest known workings. One of the richest deposits is at Robin Hood's Bay, 6 km south-east of Whitby town. The jet rock is a Lias shale, dark blue to black in colour, dense in texture, and smelling strongly of oil when freshly broken. The 'jet rock' which gives the best 'hard' jet is extracted from the lower bed of the Upper Lias – the *Ammonites serpentinus* zone.

The jet, which is found in horizontal seams 25–150 mm thick, and usually of a wedge shape, is mined by tunnelling into the sea cliffs, or the Cleveland hills. The material is also found amongst the debris from the cliff falls along the shore; such pieces are water-worn and are very useful to carve and work.

Jet is found in a number of other parts of the world, particularly at Villaviciosa in the province of Asturias in Spain. Such material is worked at Oviedo, but during the heyday of the Whitby jet industry much Spanish jet was imported and worked at Whitby. Another source of jet is in the department of Aude, France, where the material, like that of Spain, is found in irregular veins in the lower marls or Greensands of the Cretaceous series corresponding to the Sussex Gault. Other deposits are in the United States of America, particularly from the Henry mountains of Utah, at Würtemberg in Germany and in Russia. None of these appear to be systematically worked.

Simulation

Scotch cannel, and similar material from the coal measures at Newcastle, England, have been used as a substitute for jet, but they are more brittle. In the same way Pennsylvanian anthracite has been so used.

Imitations of jet are furnished by vulcanite (the hard vulcanised rubber), by glass, by obsidian and by black stained chalcedony – the so-called 'black onyx'. The plastics, too, may now be said to provide an imitation of jet. 'Paris jet' is a black glass. A black form of faceted synthetic cubic zirconia is now on the market and these cut gems could be mistaken for highly polished jet.

If a heated needle is pressed into a suspected piece of jet it will melt and give off the typical fumes of burning coal should the specimen be jet or cannel coal, but if vulcanite the smell will be of burning rubber. Such treatment will show up glass, obsidian, stained agate or synthetic cubic zirconia, for the needle will have no effect on these materials. With Bakelite any fumes would smell of phenol (carbolic acid), with celluloid the piece would probably take fire, with casein there will be a smell of burnt milk and with Perspex or polystyrene typical aromatic or fetid odours will be produced.

Jet-like in appearance and a material which has been used for carvings is albertite, a mixture of hydrocarbons, which is a mineral asphalt with a glistening black pitch-like lustre. Unlike most mineral asphalts, albertite is moderately insoluble in organic solvents; the SG is fairly constant at about 1.097, the hardness is near to 2.5 on Mohs's scale, and on the refractometer an edge is seen at about 1.55.

25

Ivory and Tortoise-Shell

Ivory

The soft mellow beauty of ivory has been used as a medium of artistic expression from the dawn of history; indeed, pre-history, for some of the earliest examples of man's experiments in art, or picture writing, are the crude carvings on mammoth ivory found in the caves in Périgord, France, and on similar pieces from the Swiss lake dwellings. Throughout all great civilisations, Egyptian, Assyrian, Mycenaean, Greek, Etruscan and Roman, the fine texture and rich creamy colour of ivory have inspired those ancient masters of the glyptic art.

The rudely scratched pieces from the Dordogne caves, the small carved head made from mammoth ivory which was found at Vestonie and estimated to be 30 000 years old, the gold-encrusted Snake Goddess of Knossos, or the ivory treasures of Tutankhamun's tomb, are ivory pieces which form the pages of history before the written word was known. From Classical times through the early Christian era and the medieval period until the present day, ivory has for millennia been an important medium for the artist craftsman.

The thirteenth century saw the zenith of ivory carving in Europe, and that same century also saw the formation, during the Yuan dynasty, of a department of ivory workers in the Palace of Peking. At first the Chinese produced only pieces having a purely domestic or utilitarian object, such as the vase-like brush holders called *pei-tung*, for which the hollow portion of the ivory tusks was so suitable. During the later Ming period the Chinese produced work of a more ornamental nature which, in the seventeenth century, reached the elaboration of the 'two-stage' and 'three-stage' work. This work shows two or three distinct layers of carvings cut one behind the other in the thickness of the ivory (*Figure 25.1*), and is so well finished that the backs of the small figures are carved with the same care as is used for their fronts. During the nineteenth century the art of ivory carving in China became more commercialised and repetition for export became a large well-organised trade.

Figure 25.1 *A fossil ivory vase with 'stage' work*

In Japan, ivory is regarded as a precious material and, as in China, tradition demands that, however odd the original shape of the piece of ivory, the carved piece must conform to that shape (*Figure 25.2*). Utilising Japanese legends and stories, the carvers produced in fine sculpture scenes from folklore, birds, flowers, animals and children, besides mythological creatures of wild imagination. The curious *netsukes*, so commonly seen in ivory, are typically Japanese. The word means 'a root to suspend something on'. Primitive Japanese hunters suspended their tools and belongings from their belt by means of a lump of

Figure 25.2 Female immortal carved in a single piece of ivory (it is nearly one metre high)

material, and it is easily understood how such a lump would be roughly cut or carved till, with the development of artistic feeling, the elaborate carved *netsuke* came into being.

In the present century ivory has been used less for the glyptic artist than as a decorative material for small articles of utility and personal adornment. Ivory has been used for handles in fine cutlery, and the exquisite softness and the excellent polish exhibited by the material have resulted in its use as a backing for hair brushes, mirrors and their accessories. The almost perfect elasticity of ivory made this material an ideal medium, for billiard balls and for fine-toothed combs, and at one time it was invaluable in the production of precision scales and rulers.

Types of Ivory

What is ivory? Ivory, or more correctly dentine, is a substance common to the teeth of all mammals, and provided the teeth, or teeth modifications such as tusks, are sufficiently large to supply material suitable for fashioning these may be the source of the ivory of commerce. They comprise the tusks of the elephant, both recent and fossil, the teeth of the hippopotamus, the tusks of the walrus and the narwhal, and to a lesser extent the tusks of the boar and the teeth of the sperm whale.

Elephant

The elephant is still the principal source of ivory. The tusks are the upper incisor teeth of the animal, and, unlike human teeth, continue to grow through life. The teeth or tusks not being subjected to habitual attrition from an opposed tooth grow to an extraordinary length, following a curve originally impressed upon them by the form of the socket. The tusk gradually widens from the projecting apex to that part which is embedded in the bone sockets of the skull, and is hollow, in a conical form, for about a third of its length. This cavity, or 'nerve' as it is sometimes called, continues as a narrow canal towards the point of the tusk, which consists of ivory only, with just a small patch of enamel on the tip of young teeth.

The African elephant (*Elephas africanus*), a giant which roams the forests of central Africa, supplies most of the commercial ivory. The tusks average about 7 kg in weight, although in exceptional cases tusks of around 30 kg are obtained. Very heavy tusks, over 90 kg in weight, have been found but are extremely rare. The best African ivory has a warm transparent mellow tint with little grain or mottling. Since 1991 there has been a world export ban on the trade in ivory. Poaching still continues and the African elephant is in danger of extinction in many parts of the continent despite the fact that new ivory objects are not being manufactured in the West. The gemmologist will still encounter many ivory objects made during this and previous centuries which were produced prior to the current threat to the elephant populations.

The Asiatic elephant (*Elephas maximus*) inhabits Myanmar, Thailand, Vietnam and India, and is often called the Indian elephant. These animals have smaller tusks than their African cousins; indeed the elephants from Sri Lanka have no tusks at all, while, unlike the African elephant, the female or cow Indian elephant is also tuskless. Asiatic ivory is a denser white, more open in texture and softer to work, and it yellows more easily. Ivory from Thailand is usually soft. It may approach an intermediate type termed 'bastard', but on the whole is considered the best type for working and appearance. It has been suggested that much Indian ivory is in reality African which has reached India by way of Zanzibar and Mozambique.

Concentric layers of dentine are sometimes deposited on and around some foreign body which has entered the pulp cavity of an elephant's tusk, forming a more or less spherical bead of pearl-like appearance. These curious objects have a concentric structure (similar to oyster pearls) and are sometimes referred to in Sri Lanka as elephant pearls (*Figure 25.3*).

Fossil ivory

The so-called fossil, or mammoth, ivory is in general obtained from the remains of an ancient elephant, the woolly mammoth (*Elephas primigenius*), which roamed the northern hemisphere during the geological period known as the Pleistocene, some 200 000 years ago. Many of these great beasts with their inordinately long, spirally curved and divergent tusks were overwhelmed by ice during the great Ice Ages which devastated much of northern Europe, Asia and America in that geological epoch.

This fossil ivory is not a true fossil, for the tusks have not been altered by mineralisation; it is a true ivory, sometimes showing little loss of beauty, despite the countless years the tusks have been preserved in ice below the Arctic ground. It is in Siberia that most of these refrigerated tusks are found, and they are particularly abundant in the neighbourhood of the Lena river, and other

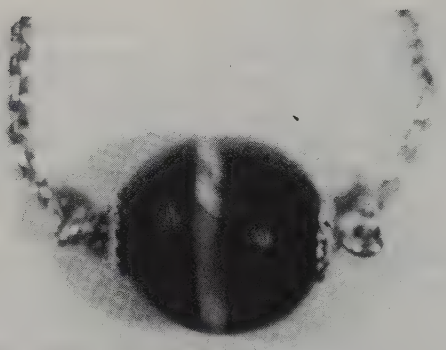


Figure 25.3 An elephant pearl weighing 27 carats (by courtesy of S Suraweesa)

rivers which discharge into the Arctic Ocean. An earlier elephant, the mastodon of Miocene times, is sometimes found in the icy ground of Alaska around the Yukon river. Much of this material is darkly stained and unusable, but at least one carver works in the small amount of mastodon ivory still sound and of a sufficiently good colour to cut into brooches and pendants.

Hippopotamus

Both the incisor and canine teeth of the hippopotamus (*Hippopotamus amphibius*), a genus of pachydermatous (thick-skinned) quadrupeds which inhabit the rivers of central Africa, supply an ivory which is denser and of finer grain than the ivory of the elephant. These teeth weigh from 0.5 kg to over 3 kg and are characterised by their thick layer of enamel. They are either round or triangular in cross-section depending upon the type of tooth, and its location in the animal's jaw.

Walrus

The walrus (*Odobaenus rosmarus*) is an amphibious mammal of the seal family which has an enormous development of the canine teeth of the upper jaw, and a tumid appearance of the muzzle caused by the magnitude of their sockets and by the thickness of the upper lip. These great canines, often a metre in length and of a flattened trefoil section, form two tusks directed downwards. The lower jaw which possesses no canines becomes narrow in front so as to pass between them.

Walrus ivory is less dense and rather coarser than either of the ivories from the elephant and hippopotamus. The exterior possesses a much finer texture and grain than the core which is granular or bubbly in appearance. The teeth grow throughout the life of the animal and are fed with new material through the bubbly central core. The walrus, whose name is derived from the

Scandinavian *val-ros* (whale-horse), inhabits the Arctic seas and the colder parts of the north temperate zone.

Narwhal

A species of whale inhabiting the Arctic seas, the narwhal is seldom seen south of the Shetland Islands, or roughly south of latitude 65°. The 'horn' of the animal is really an incisor tooth, but it projects straight out from the front of the head, normally on the left side, for the narwhal possesses two teeth only; the right one is normally rudimentary and projects only a few centimetres. The female of the species has only rudimentary teeth and they are concealed in the bone like the right tooth of the male. In some rare cases the male has been found with two long tusks, both of which are spirally twisted in the same direction. The tusks have a central hollow nerve cavity. They may reach to about 3 m in length and produce a rather coarse ivory which in earlier years was sold as 'the horn of the unicorn'.

Hog and Sperm Whale

The strong curved teeth of the hogs, particularly the boar and the wart-hog, and other members of the swine family (Suidea), supply a coarse-grained ivory suitable only for small articles. It is used similarly, but to a lesser extent, to the recurved conical teeth of the sperm whale, which is abundant in southern and northern waters, and which swims in schools between the Arctic and Antarctic Circles. The ivory from both these animals is coarse-grained, and both forms have thick enamelled outer surfaces, although the enamel is only present on three sides of the (squarish in cross-section) boar tusk.

Elephant Teeth and Rhinoceros Horn

An unusual ivory is that which is cut from the molar teeth of the elephant. Any cross-section of these teeth shows a characteristic mottled or banded appearance made up by fawn, brown and cream tints. This characteristic structure is due to the teeth being composed of vertical plates of dentine separately enveloped with enamel and cemented together by the cement. As the surface of the tooth is worn down by mastication, the harder enamel is exposed in elevated ridges, thus forming a grinding mill, which crushes and grinds the vegetable food, the sole source of nutrient of the elephant. This molar ivory often shows cracks along the division of the enamel and the cement which produce a weakness in the material. There are definite differences in the arrangement of the enamel between Asiatic elephant molars and those of the African beast; the patterns are elongated ovals and lozenge-shaped areas respectively and this allows distinction to be made. Such ivory is sometimes used for the production of knife handles and often forms the base plate of small models of elephants carved in ivory. The horn of the rhinoceros has been carved in China, and consists of a closely packed mass of hairs or horny fibres growing from the skin of the animal. These horns may be up to a metre in length. The material has a low hardness (about 2 on Mohs's scale, but this varies with direction) and an SG of 1.29.

Chemical and Physical Properties

In all teeth the ivory or dentine forms the main mass of the tooth. On the wearing face this is covered by a layer of enamel which is the hardest substance of the body structures of all mammals. The 'fang' or root end – that part of the tooth which fits into the bony socket of the skull or jaw – is covered by a layer of cement, the crusta petrosa as it is called. The centre of the tooth is in general hollow, the pulp cavity, which in life contains the tooth pulp which forms the new dentine. Neither the enamel, which is generally absent altogether in elephant tusks, nor the cement, has any importance as an ivory.

The ivory from elephants – the Proboscidea – shows, in transverse sections, striae of different shades of cream proceeding in the arc of a circle and forming by their decussations minute curvilinear lozenge-shaped spaces which appear like an engine-turning (*Figure 25.4*). These lines are only seen in elephant ivory, and are not apparent in ivory from the other animals. Much ivory shows a grained appearance along directions parallel to the length of the tusk; but such a striation may be well reproduced in the celluloid imitations of ivory. The engine-turning is not seen in the imitations and provides a certain check on the piece being ivory. The engine-turning lines are due to the dentine being permeated with fine thread-like canals filled with a brownish gelatinous substance, which in life conducts the delicate nerve fibrils. These fine canals extend outward from the pulp cavity of the tusk in flattened spirals of opposite hands, and it is these dense pores with their gelatinous contents which give to ivory its beautiful polish and exceptional elasticity.

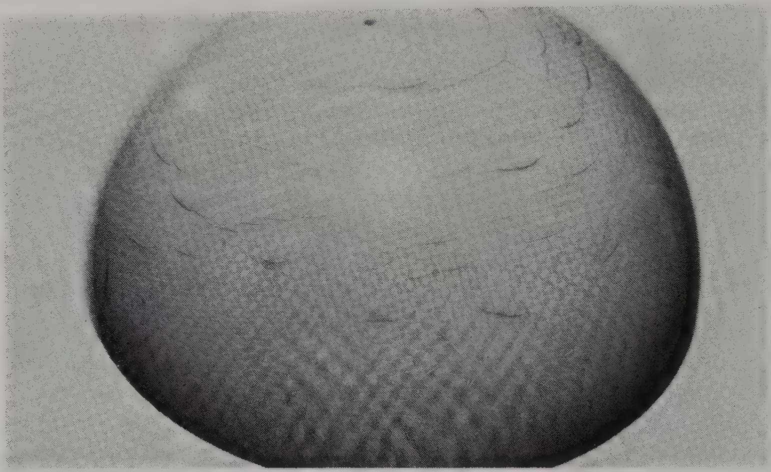


Figure 25.4 The engine-turning lines seen on elephant ivory

Examination of a thin peeling of ivory by a low-powered microscope, preferably with the peeling immersed in an oil of similar refractive index – such as clove oil ($n = 1.54$) – reveals fine fibrils undulating across the field, with, if

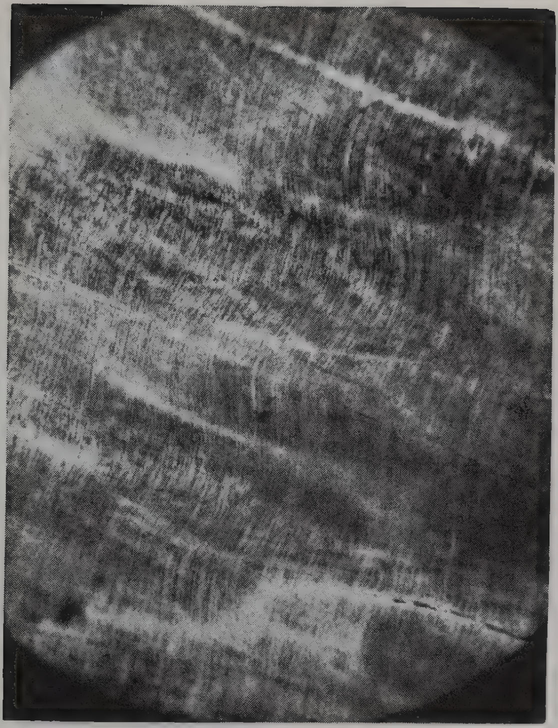


Figure 25.5 Undulating fibrils seen in a magnified thin section of ivory

the peeling is at all thick, darker grain lines crossing at right angles to the 'wave-like' canals (*Figure 25.5*). There is one direction in which the canals can be viewed end-on, and they will then appear as dots; even in this position, however, there will still be seen a wave-like formation made up of the dots. In hippopotamus ivory the undulating pattern is much finer, while in walrus and narwhal ivory it is much coarser with more ramification of the canals. In boar and whale teeth the canals appear straighter and are somewhat radial from the centrum of the tooth.

The chemical composition of ivory is mainly calcium phosphate, and is near to hydroxyl apatite which has the formula $(Ca_3OH)_2(PO_4)_6Ca_4$, with some organic matter, mainly collagen with a trace of elastin. The percentages of mineral matter to organic matter vary considerably; in elephant ivory they are about 65 per cent and 35 per cent respectively. The SG of elephant ivory varies between 1.70 and 1.90, the lower values being for the soft ivory and the higher values for the hard type. Hippopotamus ivory is usually denser, at a little over 1.90, and walrus and narwhal ivory is somewhat denser still, being over 1.95. Unless the ivory has a 'bony' structure the value rarely reaches 2. The refractive index is 1.54 and the hardness varies between 2.25 and 2.75 on Mohs's scale.

Ivory is not resistant to chemical action; nitric acid and phosphoric acid soften it, the latter chemical being used to soften ivory which has been spirally peeled off as sheets from the tusk, a technique employed for obtaining large sheets for paintings. Should the ivory be damaged in any way during life the repair is effected by natural processes, but the repair material is a bony type of ivory termed oestodentine. When irradiated with ultra-violet light ivories fluoresce with a bluish light varying from a whitish-blue to a deep violet-blue, the deeper shades being given by the more coarse ivories of the boar. Irradiation by X-rays does not induce a luminescent glow in ivory, an effect common with many inorganic substances.

Fashioning and Preservation

Ivory, unlike bone, requires no preparation before fashioning, the shaping being carried out by the use of band saws or circular saws, drilling machines and lathe turning operations. Carving is done by the use of ordinary carving chisels as used for wood carving. The fashioned ivory articles are finished by polishing and burnishing, the work being carried out by the use of rotating wheels dressed with hippopotamus skin using tripoli or pumice as a polishing medium, the final polish being given with fine pumice and oil. The scrap pieces, and ivory dust, are sold to manufacturers of pigments who burn it to produce ivory black.

The tendency for ivory to turn yellow has been ascribed to atmospheric action under certain conditions. In the case of ivory articles subject to handling, the absorbent nature of ivory will cause it to take up the fatty acids and oil from the skin once the high polish and finish have worn off. Ivory may be bleached to some extent by exposing to sunlight, preferably under a glass shade to prevent cracking by the heat of the sun's rays; likewise, ivory should never be dried before a fire or radiator. To preserve the tint of ivory, the surface may be wiped from time to time with a cloth damped with methylated spirits and ordinary whiting, which not only maintains the polish but cleans the surface of acids which in the course of time cause a discoloration of the surface. The stains of perfume, or other toilet preparations, are more difficult to remove.

Simulation

Bone

There are many imitations of ivory, both natural and artificial. Bone, which has a composition very similar to that of ivory, may be distinguished by its different structure, and to some extent by its slightly higher SG of approximately 2.00, at least for the compact type used in the arts. This material is usually obtained from the long-bones of the ox, although many fine carved pieces have been produced from the hard bone of the mandible of the large whales. Containing rather more organic content, particularly of a fatty nature, than ivory, bone requires certain preparation, termed degreasing, before use. This entails steeping in brine for some days and subsequently simmering in hot water for about 6 hours in order to remove the fatty matter.

Bone has a hardness of about 2.5 on Mohs's scale and a refractive index near to 1.54. When a peeling is microscopically examined the structure is seen to be dissimilar to that of ivory, and, moreover, shows a marked difference when the sections are transverse and when they are parallel to the length of the bone. The material is characterised by the presence of canals which permeate the bone in a longitudinal direction, canals which in life pipe the vital fluids. When a transverse section of bone is examined with low magnification the field is seen to be pierced with oval or circular cavities surrounded with small dot-like or seed-like spaces, called lacunae, in concentric arrangement. These are known as the Haversian systems. The remainder of the field is made up of less distinctly oriented lacunae and fine canals, called canaliculi, which link up the main Haversian canals (*Figure 25.6*). When a longitudinal section of bone is examined it is seen that the pipes will be cut so as to produce long cavities depending upon how nearly to parallel the run of the tubes is to that of the section. Dot-like lacunae and canaliculi complete the remainder of the field (*Figure 25.7*).

Figure 25.6 Photomicrograph of a transverse thin section of bone

The surface of any piece of worked bone when examined with a lens will show short dark lines or dots. These are the cut Haversian canals into which dirt has infiltrated. It is thus evident that bone can be stained to any colour and perhaps more easily than ivory; staining is often carried out. The fluorescence of bone under ultra-violet light is markedly similar to that shown by ivory, and although it is possibly a whiter blue than the usual fluorescence of ivory, this is insufficient to provide a clear diagnosis. Like ivory, bone does not fluoresce under X-rays.

Deer-Horn

A substance near to bone which has been used for small carvings, and particularly for inlays, is that from the antler of the deer (*Cervus*). This horn is a deciduous bony structure crowning the head of stags. It is a type of bone characterised by extreme rapidity of growth and is derived from the distal point

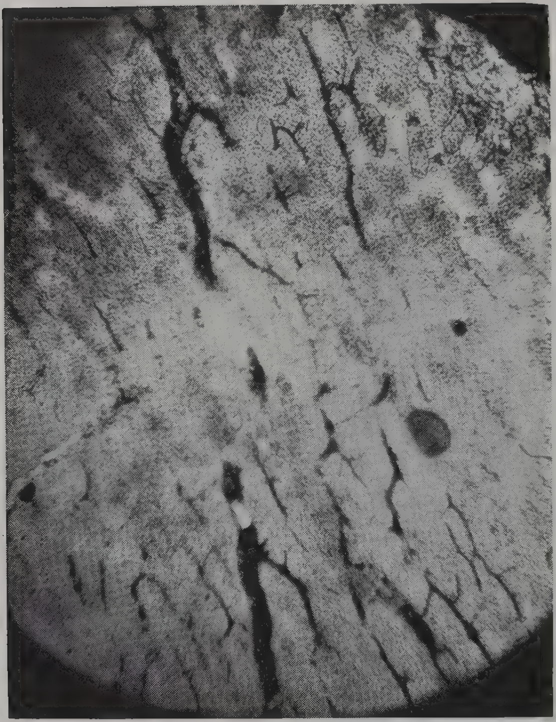


Figure 25.7 Photomicrograph of a longitudinal section of bone

of a pedicle of bone projecting from the frontal bones of the skull. Deer-horn, or stag-horn as it is more commonly called, shows a good resemblance to bone, but is usually more brown in tint. The hardness is 2.5 on Mohs's scale, the SG lies between 1.70 and 1.85 and the index of refraction is approximately 1.56. A thin peeling when microscopically examined shows a structure similar to that of bone, but the Haversian canals are less prominent. In Germany stag-horn has been much used for inlay and there are many fine specimens of sixteenth and seventeenth century firearms so decorated. The material has been used in Japan for small carvings and *netsukes*, and many fine pieces of Sheffield cutlery are handled with horn from the axis deer (*Cervus axis*) from Asia.

Vegetable Ivory

Used as an imitation of ivory are the hard seeds, or nuts, of certain palm trees. The most important of these is the *ivory palm* (*Phytelephas macrocarpa*), a native of the Andean plains of Peru, where it is known as *homero* or *pullipunta*. It is also found along the Coast of Darien (known there as *anti*), and along the Magdalena river in Colombia where the name *tagua* is applied. This tree is one of the most beautiful of the palm family. It grows in damp localities and is characterised by a short and procumbent stem. Proceeding from its crown is a magnificent tuft of light green pinnated leaves of extraordinary size and beauty rising to 12 m in height. The flowers are on a crowded spadix and have neither calyx nor corolla. The fruit, weighing 9–12 kg, which is as large as a man's head, consists of six or seven 4-celled drupes aggregated together, and contains from six to nine nuts of somewhat triangular form and reminiscent of a fattened kernel of a Brazil nut, each nut being about as large as a hen's egg. They are commercially known as corozo nuts (*Figure 25.8*).

Figure 25.8 *Ivory palm nuts (corozo nuts)*

These seeds, in the very young state, contain a clear insipid fluid which travellers can drink. As the nuts become older the fluid becomes milky and of a sweet taste. It gradually continues to change until it becomes exceedingly hard and so white as to resemble ivory so completely that few names have ever been better applied than that of 'vegetable ivory'.

The composition of vegetable ivory is nearly pure cellulose, a resistant carbohydrate ($C_6H_{10}O_5$), which is the fundamental constituent of the cell walls of plants, and therefore forms the framework of vegetable tissues. The hardness is about 2.5 on Mohs's scale and the refractive index about 1.54, a value so commonly found in organic substances. The specific gravity varies from about 1.40 to 1.43, and the fluorescence effect seen under ultra-violet light is similar, but weaker, than the glow shown by ivory, with which it agrees in being inert under X-rays.

A thin peeling (vegetable ivory is very slightly more sectile than true ivory) shows under magnification a pattern quite dissimilar to that shown by either ivory or bone, in that it consists of a great number of torpedo-shaped cells running in roughly parallel lines (*Figure 25.9*). If higher magnification is used these long cells are seen to have sideshoots which terminate in clubbed ends, the complete cell appearing like some grotesque insect of the centipede class. The appearance of these cells will naturally differ, being long-shaped if the section be cut parallel to them, oval if cut obliquely, and dot-like if the cells are cut transversely, a position rarely obtained with a random cut.

There is another type of palm nut which may have a value as an ivory imitation. This is the *doom palm* (doum palm) nut of the Borasseae tribe of palms. This doom palm tree (*Hyphaene thebaica*) is remarkable as the single instance of branching in the palm family (*Figure 25.10*), and grows in north and central Africa, where, with its fan-shaped leaves, it is in some instances most plentiful and sometimes grows amidst the very sands of the desert.

The fruit of the doom palm is irregular, not unlike a quince, and has a reddish-brown outer skin which may be compared to that of a pomegranate.

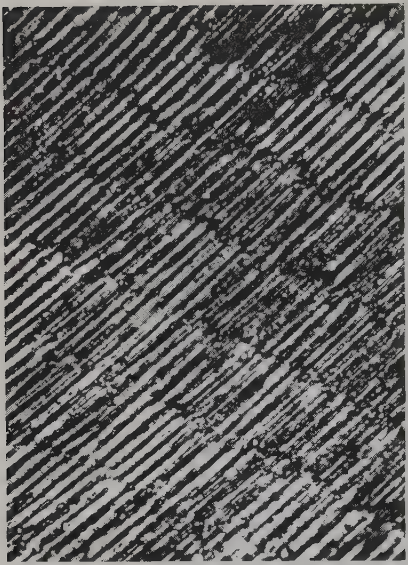


Figure 25.9 *Photomicrograph of a thin section of vegetable ivory*

Figure 25.10 *Doom palm*

When the skin is peeled off, a considerable thickness of spongy dry substance is found within it which has an insipid sweetness and a remarkable resemblance to gingerbread. Indeed, this 'fruit' is used as an article of food, and an infusion of it as a beverage; hence the palm is often called the 'gingerbread palm'.

In the centre of the fruit is the one seed or nut which supplies the vegetable ivory material. The shape of the nut is rather like that of a fig and when cut open the hard white and translucent kernel is seen to have a large central cavity conforming to the outside of the nut (*Figure 25.11*).

The SG of the doom palm vegetable ivory is between 1.38 and 1.40, just below that of the corozo nuts; the hardness is also slightly lower. The refractive index at 1.54 and the whitish-blue fluorescence under ultra-violet light and absence of any glow under X-rays are again similar to corozo nut ivory.

Examined microscopically a thin peeling of doom palm ivory shows structural similarity to that of the ivory nut palm, with, occasionally, an end-on

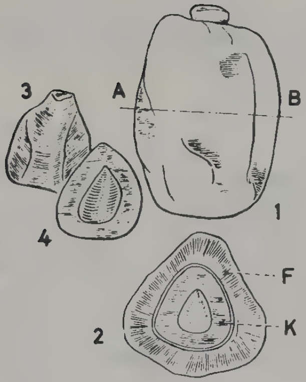


Figure 25.11 *Doom palm nuts: 1, fruit; 2, section across AB; F, fleshy part; K, kernel (nut); 3, nut removed from fleshy part; 4, section through nut*

view showing a polygonal outline to the cells which resembles greatly the structure seen in a leaf.

Vegetable ivory, which like true ivory needs no pretreatment before fashioning, will take stain well, and when a red or pink tint is induced on rounded beads, may be mistaken for and has been sold as coral. However, these vegetable ivory imitations do not effervesce with acid as do the true corals.

Tests

From the foregoing it will be seen that the most effective test for these different ivories is to examine their structures. A small peeling can usually be removed from an inconspicuous part of the object, and identification can be achieved by microscopically observing the structure. A drop of oil placed on the peeling after it has been pressed flat by a knife blade on to the glass microscope slip will facilitate viewing the interior.

Plastic and Fictile Ivory

Regarding manufacturing material, the most usual and effective ivory imitation is celluloid, which is 'filled' to give the desired opacity, and sometimes to give the correct SG. By pressure bonding a number of sheets of the plastic together a grained effect is produced. The tests previously mentioned for the detection of celluloid will supply the necessary proof of the material, which, when a peeling (and the material is very sectile) is examined microscopically, shows a fine-grained structure. Other types of plastics do not make such a convincing ivory imitation as celluloid, but they may be met.

The so-called 'fictile ivories', usually copies or reproductions of artistic ivories, are simply castings made of fine plaster of Paris tinted with yellow ochre, with the surface subsequently treated with a mixture of wax, spermaceti or stearine. These are obvious from mere inspection.

A hard plastic outer surfaced imitation has been on the market for the last ten years. It is cast and the hollow interior is filled with a granular material, which increases its overall SG and provides a more deceptive overall weight. Casting flaws and small air bubble holes can usually be seen on close examination with a

10 × lens or microscope. Touching the suspect carving with a hot needle in an inconspicuous area will normally produce a distinctive burnt plastic smell.

Tortoise-Shell

Tortoise-shell, with its beautiful mottled colour and semi-transparency, is not, as its name would lead one to believe, obtained from the tortoise. The material is obtained from the carapace or shield of a sea turtle, the hawksbill turtle (*Chelone imbricata*) which is found in most tropical and subtropical seas, particularly the Malay archipelago, the West Indies and Brazil. The most highly prized shell, with a rich brown mottling on a warm translucent yellow background, is obtained from the turtles which inhabit the Moluccas and the island of Celebes, now Sulawesi, in Indonesia.

Tortoise-shell is so called because formerly the order of animals to which it belongs was little known, and all were confused under the general name of tortoises. The name hawksbill is derived from the horny beak-like covering of the upper jaw, and the specific name *imbricata* from the remarkable peculiarity in this species of the arrangement of the 13 plates forming the carapace, which, instead of being joined together by their edges so as to make one piece, are thinned off at their edges and overlap each other like the tiles of a roof.

The 13 plates, or blades as they are called, which form the main part of the carapace, are collectively known as the heart, and names are given to the respective plates (*Figure 25.12*); while the 24 small marginal plates, variously called hoofs, claws, feet or noses, have little or no value as tortoise-shell. The carapace, usually about 600–750 mm in length, weighs from 2 to 4 kg. The separate blades, usually measuring about 200 × 150 mm, although they may reach 325 × 200 mm, are about 3 mm thick, and weigh up to 250 g for the larger sizes.

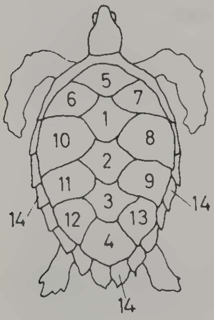


Figure 25.12 The hawksbill turtle showing the blades of tortoise-shell: 1, 2, 3, 4, cross-backs; 5, 6, 7, shoulder plates; 8, 9, 10, 11, main plates; 12, 13, tail plates; 14, hoof

The plates are separated from the bony skeleton of the animal by heat. At one time the shell was obtained by cruelly suspending the living creatures over a fire until the dorsal shields separated from the bone. Today the turtles are killed first. Care is needed in all the operations needing heat, for if it is excessive the colour of the shell tends to darken.

Ivory and tortoise-shell are usually a trade combination, the ivory worker also working in tortoise-shell, a combination all the more romantic because in one of the oldest Indian legends the unstable nature of the world is symbolised by the elephant standing on the back of the humble, patient tortoise.

Fashioning

When received by the tortoise-shell worker the plates are curved and ridged and their first process is to flatten them by the application of low heat and pressure and the removal of the ridges by scraping and rasping. The tortoise-shell is then trimmed and shaped by the same fine saws that are used to work ivory. The extreme thermoplasticity of tortoise-shell, which softens in boiling water, is taken advantage of in the production of larger sheets. In this case the two edges to be joined are bevelled, scraped clean, and after being placed closely together are put in a press which is then immersed in boiling water. Sometimes common salt is added to prevent change of colour, but this tends to make the tortoise-shell somewhat brittle. Likewise thicker pieces may be similarly built up by pressing together several sheets whilst heated to a temperature of boiling water; small boxes are produced by moulding a sheet under such conditions. The shell being fairly expensive, chips, and even dust, of tortoise-shell are softened and moulded together in a manner analogous to the production of pressed amber. The resulting material, often artificially coloured at the same time, is darker and has little of the pleasing coloration of the true material.

Tortoise-shell is polished by first smoothing the surface by the use of charcoal dust, whiting or rottenstone with water and finally finishing with a soft leather and oil, or by the use of a mechanically operated 'dolly' wheel. Broken pieces of tortoise-shell may be repaired by joining the fractured ends by the use of solid Canada balsam applied to the broken edges and the pieces tightly wired together and left for about 24 hours, the excess Canada balsam being removed with a knife. The inlaying of gold, silver or mother-of-pearl into tortoise-shell is carried out by arranging the pieces on the shell and pressing them in by the aid of hot water, after which the piece is quickly submerged into cold water with the further application of pressure.

Blond shell is a plain orangy-yellow coloured shell and has no mottling. It is material obtained from the plastron, or belly shield, of the hawksbill turtle. In the trade it is called yellow belly. This material can easily be mistaken for amber, particularly when it is fashioned as beads.

Chemical and Physical Properties

Tortoise-shell is similar to those other horny tissues which make up horns, claws and nails, and consists of a protein (keratin) of very complex composition, but approximates to 55 per cent carbon, 20 per cent oxygen, 16 per cent nitrogen, 6 per cent hydrogen and 2 per cent sulphur. The hardness is about 2.5 on Mohs's scale and the specific gravity is fairly constant at 1.29. The refractive index is 1.55 and the material is readily sectile. If examined microscopically, the mottling of tortoise-shell is seen to be made up of spherical spots of colour: the closer together the spots the deeper the colour, rather like the effect seen in screen printing (*Figure 25.13*). In the case of imitations of tortoise-shell – the

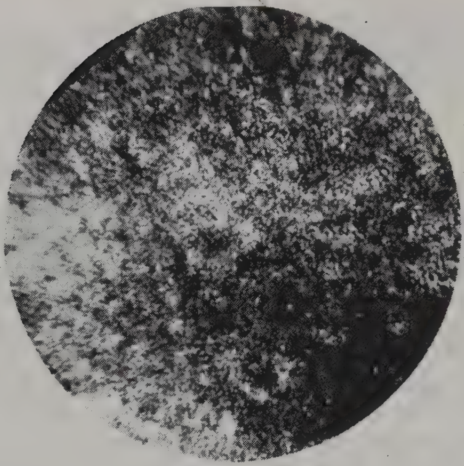


Figure 25.13 *The colour in tortoise-shell is made up of small dot-like patches as shown by this photomicrograph*

Figure 25.14 *The colour in plastic of tortoise-shell is in swathes*

plastics celluloid, casein, Bakelite and some others make excellent imitations – the colour is shown to be in patches or swathes and there is no dot-like or disc-like structure seen when microscopically examined (*Figure 25.14*). An imitation sometimes met with consists of a thin veneer of real tortoise-shell cemented to a base of suitable plastic.

Under the ultra-violet lamp the clearer and yellower portions fluoresce with a bluish-white colour, as does the blond shell. Both are inert under X-rays in common with most organic substances. The imitations of tortoise-shell behave variously under the rays from an ultra-violet lamp, but in a number of cases the glow seen is yellow.

Use of Preservatives

From Roman times tortoise-shell has been used as an inlay for furniture, and the material was increasingly used by Boulle, the cabinet maker to Louis XIV of France, who employed dark-coloured shell inlaid with brass in his so-called 'Buhl' furniture. There are tortoise-shell objects inlaid with small pin-head dots of silver, and this is called piqué work.

A tortoise-shell article needs very little care to preserve its beauty, but such articles should be kept away from heat and damp. The high polish can be maintained by periodic application of a drop of olive oil to which a little rouge may be mixed, on a soft cloth. Tortoise-shell-backed brushes should be washed in luke-warm water, for hot water tends to bring the shell up in fine ridges, and they should be dried naturally. Tortoise-shell articles which have suffered damage should be returned to the makers, who will repolish the surface by scraping it flat and repolishing by the use of a mechanical mop. Broken articles can be repaired by them using the well-known thermoplastic properties of the material.

Other Animal Materials

The so-called 'hornbill ivory' is a horny material obtained from the beak of the hornbill bird, in particular the helmeted hornbill from Indonesia. The material has a hardness of about 2.5 on Mohs's scale, a SG of 1.28 or 1.29 and a refractive index of about 1.55. Under the ultra-violet lamp this horn glows with a greenish- or bluish-white light; it does not react with acid, and when a hot needle is applied to it there is emitted a smell of burning feathers.

In the Eskimo village of Kivalina, on the eastern coast of Alaska, the natives started a home industry by making jewellery from the hooves of the caribou. The material takes a high polish and to some extent resembles tortoise-shell. Although pieces have not been examined, the constants of SG and refractive index should be near that of tortoise-shell.

Bull's horn, water buffalo horn, and various other animal horns are commonly encountered in ethnic jewellery. Their structures vary with the animal of origin, unless the material has been heated and pressed to make boxes, handles etc. All these animal horns are made of compressed hair (so are claws and fingernails) and all give off the smell of burning hair when touched by a hot point. Red-stained bull's-horn beads are being marketed as 'red amber' in various parts of Africa.

Part 2

How Gemstones Are Identified

26

Methods and Techniques

The identification of gem materials depends to some extent on whether they are in the rough state or whether they are cut and polished, and even on the manner in which they are fashioned. Further, if the stone is set in jewellery certain tests cannot be used and reliance must then be placed on other methods. Indeed, ingenuity is quite often needed in order to find the best method of approach and the best tests to apply in order to determine the nature of the stone.

Many gem minerals are found as crystals and from a knowledge of their crystal habits, or more elaborately by the measurement of the angles between their natural faces, they may often be clearly identified. Certain physical properties, particularly the optical characters of a mineral, will aid such an identification just as they will in cut stones. X-ray spectroscopy and electron microprobe analysis will give a positive result, but such a method is outside the scope of the ordinary gemmologist or jeweller. Simply applied chemical tests may well assist in the identification of rough material, and in either cut or rough material the behaviour under ultra-violet light may help.

Only occasionally is the jeweller confronted with natural crystals and rough minerals. When he is, the specimens are generally found to be nothing more than quartz crystals or pebbles of topaz. Every jeweller should aim at a general knowledge of the natural appearance and crystal forms met with in minerals from the lowly quartz to the valuable 'gem' stones, including diamond, for they are now often mounted in the rough state.

Commercially more important is the identification of cut gemstones. With so many minerals now cut and polished, and with the vast numbers of synthetically produced gems and the modern artificial products which simulate precious stones, the jeweller is forced to call scientific methods to his aid. The rough and ready method of hardness testing by the use of a file, so common a test at the turn of the century, has now little value and great risk when applied to many of the gem minerals which are encountered today.

It is true that the intrinsic colour of a stone will often tell the experienced jeweller what a stone is. The lustre and fire of diamond, the characteristic colour of an emerald, a sapphire or a ruby, tell him much, and in earlier days he was rarely wrong. Today, however, with all the new stones, synthetics and other simulants, it is less easy to be sure and the only accurate identification is that made by more scientific methods.

Instruments

In the following pages the methods used in such scientific identification and the instruments which are employed in this work will be described. However, like all such studies, much basic elementary knowledge is necessary for the understanding of the working of the instruments themselves and how they may be used to produce the evidence required in order to identify a stone. Thus, as the behaviour of light in a crystal varies with the type of crystal, it is necessary to understand something of the various crystal types. Chapter 27 entitled 'Crystals' will give sufficient ground work in a subject called crystallography for a general idea to be obtained of gem crystals and their forms.

Except for the determination of specific gravity (i.e. the relation of the weight to the volume) most of the instruments used in gem testing function by light rays. This is true whether the instrument is a microscope, a refractometer, or a spectroscope. The last has been found over the past few years to be a potent weapon in the armoury of the gemmologist. It is therefore necessary to discuss in an elementary way something of the physics of light, without which any observation would be meaningless.

Mention must also be made of the computer as an aid to gem identification. A suitable computer program containing a data bank of gemstone constants was proposed by Peter Read (*Journal of Gemmology*, October 1980; and *Gems and Gemmology*, fall 1983). In this, test readings for refractive index, specific gravity and other parameters are keyed in, and the program searches through its data and displays those gems nearest to the input values. In such a program, further diagnostic data such as inclusions, spectrum, fluorescence and dichroism can also be displayed. A commercial program, GEMDATA, was later developed by Read and made available through the Gemmological Association and Gem Testing Laboratory of Great Britain.

The study of the features of a stone by such a simple piece of apparatus as a hand lens, or a colour filter – which can be carried in the pocket – can often tell the worker the nature of the stone, provided that he knows what to look for, or in other words sensibly applies the methods described in the following pages.

Some problems which arise today, such as the identification of figurines and other carved pieces which may consist of minerals in massive form or rocks made up of several minerals, may need a different approach, for they may not be adequately identified by normal gemmological testing methods. Here more sophisticated techniques using expensive apparatus may be demanded and in such cases the facilities of well-equipped laboratories may be called upon. As a guide to the reader something will be told of these advanced techniques and the instruments used, such as the electron microscope, the infra-red spectrophotometer, the X-ray 'fluorescence' technique and the electron microprobe.

27

Crystals

The descriptions of gem materials in Part 1 will have shown that they may occur as crystals, homogeneous bodies which have plane and often lustrous faces and which show a regularity in their arrangement. Such forms are an outward expression of an inner orderly arrangement of the atoms which make up the material. However, most gem materials occur in irregular pieces which, by optical means or with X-rays, can be shown to be crystalline in structure; while others, such as the natural glasses, do not have this regularity of internal structure even if the chemical composition is similar to that of a crystalline material (*Figure 27.1*). The artificial glasses and certain plastics are similarly non-crystalline materials, but most synthetic gemstones are truly crystalline.

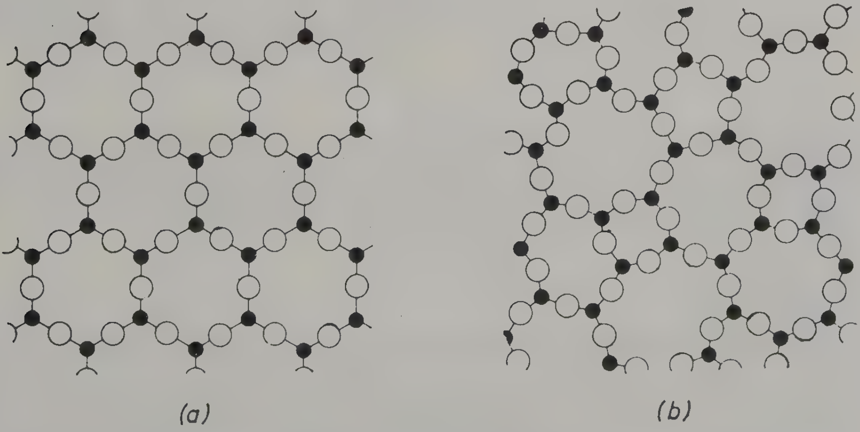


Figure 27.1 (a) A two-dimensional representation of the internal structure of a crystal, showing the high degree of geometric order, (b) a glass of the same composition, with its less orderly arrangement of atoms (after W H Zachariasen)

Internal Structure

The Atom

To obtain an understanding of the structure of crystals it is necessary to know something of the atom itself. An atom may be said to be the smallest part of a chemical element. However, each atom is a complex system consisting of planetary particles, each with unit negative electrical charge and which are called electrons, surrounding a heavy nucleus containing a number of positively charged particles called protons. There is an equal number of protons to electrons so producing, by balancing the positive and negative charges, an electrically neutral atom. Except for the hydrogen atom all the nuclei of atoms also contain a number of uncharged particles called neutrons.

Thus an atom contains three elementary particles, two of which, the proton and the neutron, have approximately equal mass, while the electron has a mass much smaller, only $\frac{1}{1836}$ that of a proton. The structure of atoms is shown in simplified form in *Figure 27.2.* An atom may be considered as consisting of the nucleus – small and compact – surrounded by a cloud of orbiting electrons. It is the electrons which are involved in the joining together of atoms to make up all kinds of materials, including gemstones. *Crystalline* materials are those whose atoms are joined up (bonded) in a particularly orderly way.

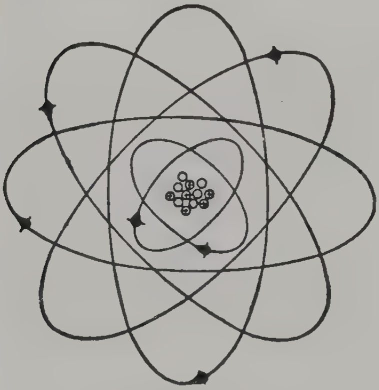


Figure 27.2 Stylised diagram of the structure of an atom. In the core or nucleus the circles with a plus sign represent the protons and the plain circles are the neutrons. The black spots represent the positions of the tiny electrons

Atomic Mass

Each of the chemical elements is made of like atoms, atoms which have the same nuclear charge or, as it is better known, atomic number; that is, they have the same number of protons. Commencing with hydrogen (atomic number 1) which has one proton and one planetary electron, each succeeding atom contains one more proton and electron. Thus helium has two protons and two electrons and has atomic number two, while uranium, one of the most massive atoms, has 92 protons and the same number of electrons.

However, this does not complete the picture, since, except for hydrogen, all the nuclei in atoms of the chemical elements contain neutrons, varying from two in the helium atom to 146 in the uranium atom. The atomic mass (less correctly 'atomic weight') of an element is the total mass of the protons and neutrons which form the nucleus of the atom; the electrons have negligible mass.

While the number of protons determines the chemical nature of an atom, not all the atoms of a given chemical element possess the same number of neutrons; therefore such atoms will differ in their atomic mass. Each atom which has the nuclear charge (number of protons) of a given element but which has a different number of neutrons, and hence a different atomic mass, is termed an isotope. An element, as described above, usually consists of a mixture of isotopes and this explains why published atomic mass values for the elements are not whole numbers. It may conveniently be mentioned here that hydrogen has an isotope with one neutron and one proton. It will be clear that the inclusion of a neutron in the nucleus of a hydrogen atom, while not affecting the electrical neutrality, will double the weight of the atom; this heavy isotope of hydrogen has been given the name of deuterium and the symbol D. Further comments on this isotope will be made later.

Electronic Configuration of Atoms

The configuration of the planetary electrons around the nucleus is important, for the chemical properties of an element and the formation of chemical compounds and crystals depend a great deal upon the disposition of the electrons. In each atom, the cloud of orbiting electrons is disposed in a system of 'orbitals' which represent the most likely positions of each electron in the cloud. Orbitals of electrons are grouped in various energy levels, each of which can be pictured simply as an 'energy shell' of electrons around the nucleus. Each shell contains only a given number of electrons, there being a maximum of 2 in the innermost shell, 8 each in the second and third shells, 18 each in the next two shells and 32 in the next full shell, above which is an unfinished shell starting with the element having atomic mass 87 (francium). Atoms with the same number of electrons in their outer shell have similar chemical properties (*Figure 27.3*). When the outer shell is completely filled the atom has the electronic configuration of one of the 'inert gases' which are chemically almost completely unreactive (*Figure 27.4*).

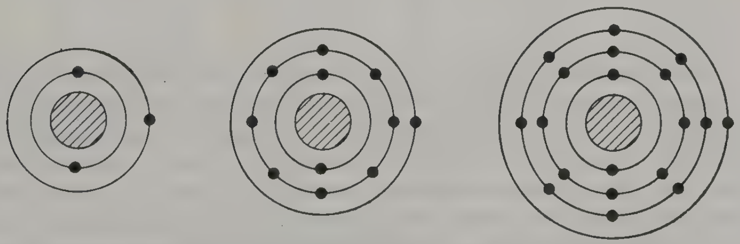


Figure 27.3 Electronic configuration of atoms having similar chemical characters

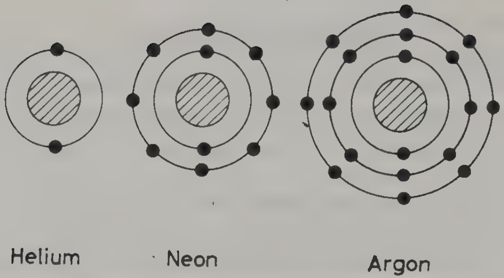


Figure 27.4 *Electronic configuration of atoms of the inert gases*

If the atom gains or loses one or more electrons it ceases to be electrically neutral and becomes what is known as an ion. Gain of electrons produces negatively charged ions called anions, and loss must produce positive ions called cations. It will be seen that if the hydrogen atom is ionised by removal of its sole electron the resulting ion is the proton. Likewise the removal of the two electrons from the helium atom will leave the nucleus consisting of two protons and two neutrons. This is the alpha particle. Removal of the one electron from the hydrogen isotope deuterium will leave the nucleus of one proton and one neutron, producing the deuteron. These are mentioned here because all of these particles have been used in the artificial coloration of diamond.

The characteristic orderly arrangement of the constituent atoms in a crystal is determined by means of X-rays. This, however, is the work of the crystallographer and has little part in normal gem identification. Some further remarks on the subject will be given in Chapter 37 on X-rays in gem testing.

Atomic Bonding

The electronic bonding of atoms producing a solid crystalline substance is essentially a linked pattern which is repeated at regular intervals in all three dimensions. The bonding is achieved in different ways. The strongest forms are ionic bonding, covalent bonding and metallic bonding.

Ionic Bond

In ionic bonding the atoms are in the ionised state and the forces holding the structure together are due to electrical attraction between the ions. This may be illustrated by the structure of common salt (NaCl) where the sodium atom has one electron in its outer shell while the chlorine atom has one electron deficient from the full number needed to complete a shell of eight electrons. By transference of the outer electron of the sodium atom to the chlorine atom, each forms a stable structure comparable with that of the inert gases. However, the two atoms now exist as charged ions and produce a strong electrostatic attraction; the two may then become ionically bonded to form sodium chloride (*Figure 27.5*).

The description given above tends to imply that only two ions are electrically connected, whereas all the ions in a solid ionic structure suffer electronic attraction, normally producing an orderly crystalline structure. This

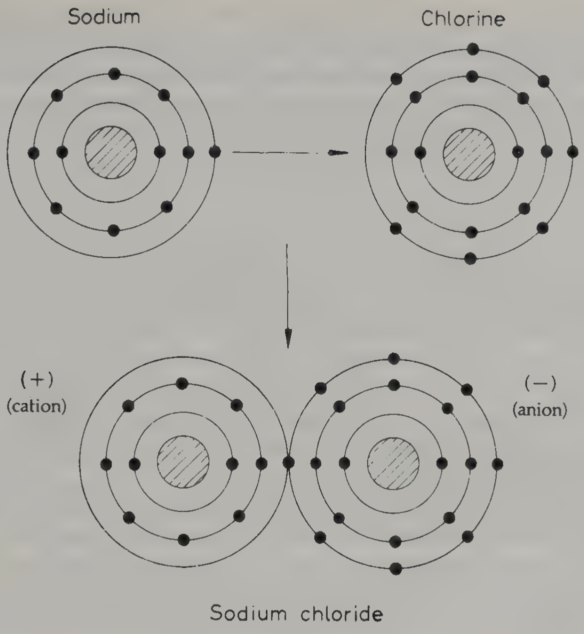


Figure 27.5 *Ionic bonding*

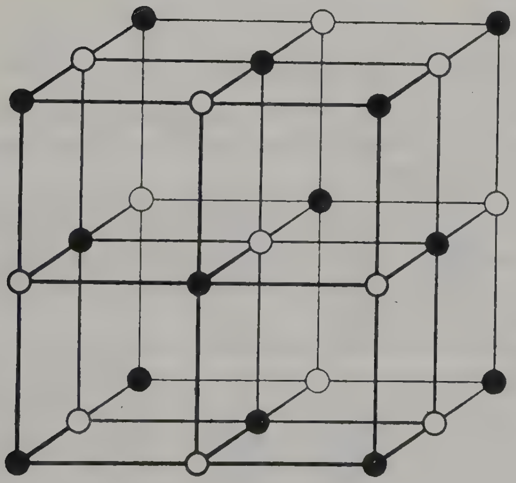


Figure 27.6 *The unit cell of the sodium chloride crystal structure, the mineral halite (the spheres represent the positions of ion centres, not their sizes)*

may be illustrated by considering the distribution of ions in the unit cell, the smallest conveniently depicted structural unit of bonded atoms in a crystal, in the case of a crystal of sodium chloride (the mineral halite) (*Figure 27.6*).

Ionic bonding may not be confined to ions with one electric charge, for two or three interchanges of electrons can occur. Thus, for example, atoms with three electrons in the outer shell (having a valency of +3) can combine with three atoms requiring one electron each (having a valency of −1) to form the inert gas structure. This chemical valency may be illustrated by lithium fluoride (LiF), lithia (Li_2O) and lithium nitride (Li_3N), where fluorine is monovalent, oxygen is divalent and nitrogen is trivalent.

Covalent Bond

Another type of strong bonding is the covalent bond, in which atoms share electrons to form an electron pair; each atom shares its electron with the other and so achieves a structure comparable with that of the inert gases. Thus, two hydrogen atoms may share their single electrons producing a molecule of hydrogen. A molecule is the smallest discrete unit of a substance which will have the chemical character of that substance. Covalent bonds are most important in the case of carbon and silicon atoms; they are therefore important in the diamond and silicate structures.

Covalent bonding therefore involves sharing of bonding electrons whereas ionic bonding involves donation of electrons. These two types of bonding, ionic and covalent, are not mutually exclusive. For example, the silicon–oxygen bond in silicates is about half-and-half ionic and covalent, whereas the sodium chloride bond is highly ionic and the carbon–carbon bond in diamond is highly covalent.

Metallic, van der Waals and Hydrogen Bonds

The metallic bond may be regarded as an aggregate of positive ions immersed in a 'gas' or cloud of loosely tethered electrons. These electrons promote electrical conduction in metals.

Van der Waals bonding, or residual bonding, involves very weak residual forces holding atoms together when all direct bonds between the atoms are satisfied. These are present to some extent in nearly all crystals, and notably in graphite where residual forces hold sheets of strongly bonded carbon atoms together in weakly bonded layers.

Hydrogen bonds are weak residual bonds to hydrogen atoms. These bonds form when the hydrogen's positive nucleus is somewhat 'exposed' and its single negative electron is pulled one way in bonding to another atom. The residual positive attraction is then exploited in further bonding. Ice crystals are held together by hydrogen bonds.

Crystal Lattice and Crystal Structure

The array of points in space at which the pattern of atoms and bonds repeats itself is called the crystal lattice, of which there are only 14 variations possible. However, the positions of all atoms and bonds constitute the crystal structure of which there are thousands of examples. All these structures can be thought of as natural designs, based on the 14 representative three-dimensional lattice patterns.

Isomorphism

When two ions are brought together there is a distance where a force of repulsion abruptly sets in and resists any closer approach. With this in mind it is convenient to consider the ions as spheres in contact, and the distance between their centres is taken as the sum of the radii of the two ions. The relative sizes of certain ions are shown in *Figure 27.7.* It will be seen that the anions, such as the oxygen ion, have large ionic radii, while the cations have radii which are much smaller. The common cations which enter the structure of minerals are those metal ions which have similar sized radii and hence can replace each other in the crystal structure without unduly straining it. This accounts for the phenomenon

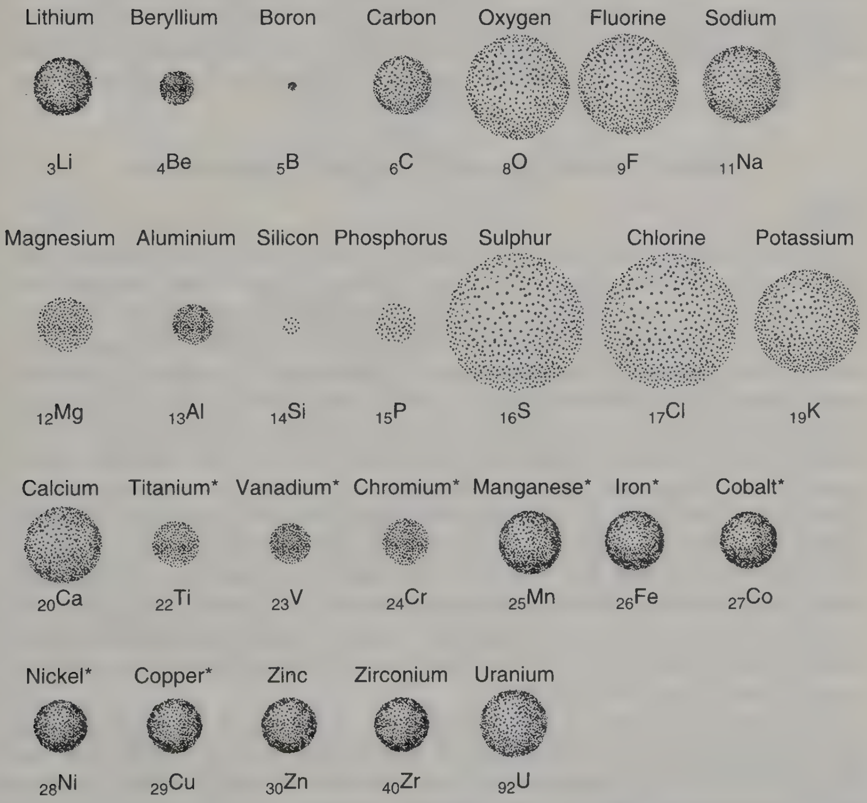


*Figure 27.7 Some of the atom and ion sizes of chemical elements which are important in gem materials; shown 50 million times actual size. The name of each element is shown, with its atomic number and chemical symbol; * indicates transition elements. The relative sizes of electron clouds are shown here for just one valence state or type of bonding for each element. However, the size depends upon the degree of ionisation and type of bonding. The surroundings within a crystal structure also influence (and are influenced by) the shape of the electron cloud for certain elements, notably the transition elements and carbon: rather than the spherical shapes shown here, these will have lobes of electron density where orbital directions are exploited in crystal structure bonding arrangements*

of isomorphism, or isomorphous replacement, which is so common in many gem minerals, such as the garnets, the feldspars and tourmaline.

Polymorphism

When a material has a chemical composition the same as another material but crystallises in a different system or class, the effect is termed dimorphism, or collectively polymorphism. For example diamond and graphite are both carbon but crystallise in the cubic and hexagonal system respectively, and the trigonal calcite has the same chemical make-up as the orthorhombic aragonite.

A material will solidify or crystallise (or recrystallise) with a bonding structure which depends partly on the conditions under which it forms. Many substances can each exist in any of two or more alternative structural arrangements, depending on the particular conditions of growth or recrystallisation. For two polymorphs to coexist, at least one would be in an unstable state; however, the energy required by the crystal structure to revert to a stable state in the new environment may be very great (for example diamond at room temperature).

Internal Structure and External Appearance

Faces

Crystal faces are natural, flat surfaces which reveal where layers of atoms and bonds in crystal structures have stopped growing. Crystal faces are relatively rare in crystalline materials because most crystals have grown together, leaving no chance for faces to develop. Faces on most gem materials are likewise rare: normally they are cut and polished away in fashioning. The regularly repeating arrangement of the atoms and bonds which make up any crystal is the inward reason for the arrangement of any exterior natural crystal face. It is now necessary to consider crystals from the aspect of their exterior forms, remembering meanwhile that the inner structure exerts its control not only of these forms but also of the optical behaviour of crystalline materials. Structurally controlled optical behaviour may be detected in, and used in the testing of, cut and polished crystalline materials which possess no crystal form as external evidence. The fundamental importance of crystal structure in gem testing manifests itself in, for instance, double refraction and birefringence measurement, polarisation of light, pleochroism, optical extinction, interference figures, cleavage and twinning.

The internal structure of any crystalline substance is constant and the outward shape of a crystal must have a definite relationship to this structure. Thus, such external evidence as may occur can be of use in the identification of rough gem material. Many crystals show a symmetrical arrangement of crystal faces. Crystals may be made up of similar symmetrically related faces to give a single 'form'.

A cube and an octahedron (*Figure 27.8*) are examples of single forms, while a crystal which consists of two or more forms is termed a combination of forms (*Figures 27.9* and *27.10*). If a crystal is made up entirely of one form, that form is termed a 'closed' form (*Figure 27.11*). Forms which do not enclose space are called 'open' forms. Thus the hexagonal prismatic crystal of emerald can have

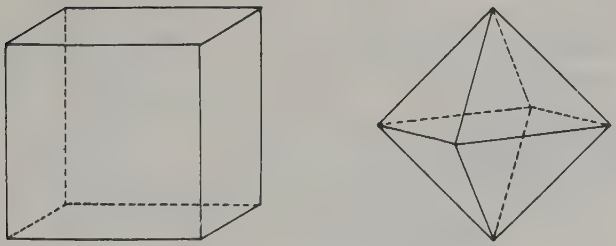


Figure 27.8 The cube and the octahedron

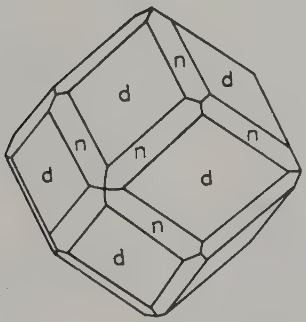


Figure 27.9 Combination of two closed forms. The faces of the dodecahedron have their edges truncated by the faces of the icositetrahedron, a 24-faced form. Such a combination of forms is common in garnet

just two open forms, that of the six parallel faces of the hexagonal prism form, which is closed by the two parallel faces of the pinacoid form at each end of the crystal (*Figure 27.12*). The intersection of any two adjacent faces is called the edge. Crystals showing good faces are said to be euhedral, and those which do not are anhedral.

Symmetry

The regular inner structures of crystals are arranged according to certain laws of symmetry which form the basis of a classification into 32 mathematically possible classes and, conveniently, into seven crystal systems. There are three kinds of symmetry which need concern the reader. They are a plane of symmetry, an axis of symmetry and a centre of symmetry. A plane of symmetry is an imaginary plane which divides a crystal structure into two parts, one of which is the mirror image of the other. The faces may sometimes conform to the symmetry of the crystal structure within, and at least some of the symmetry of the crystal might be discerned from the symmetry of the faces present. Thus in an orthorhombic crystal shaped like a brick, which has three pairs of faces

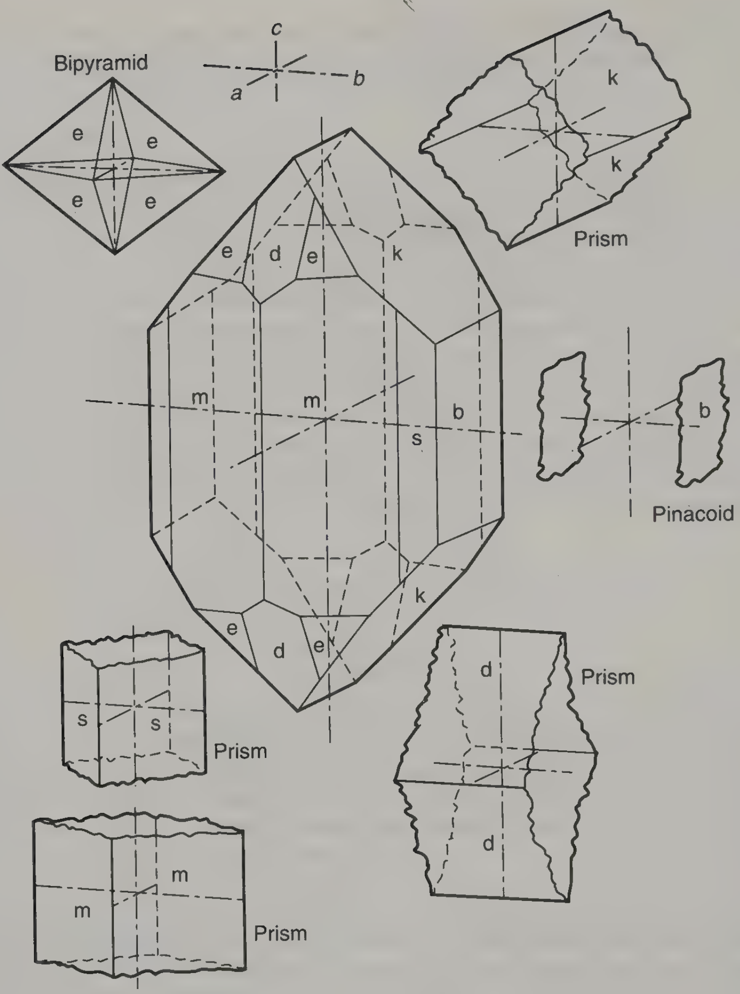


Figure 27.10 A crystal of peridot showing six combined crystal forms: two vertical orthorhombic prisms m and s, a side pinacoid b, two lateral orthorhombic prisms (domes) d and k parallel to the two lateral crystallographic axes, and one orthorhombic bipyramid e

(pinacoid forms), three planes of symmetry can be operated (*Figure 27.13*); and in a cube there are nine planes of symmetry.

The orthorhombic symmetry shown in *Figure 27.13* reflects an underlying crystal structure which has lattice pattern repeats that are different in three directions at right angles. By contrast, cube forms conform to greater symmetry, as a consequence of underlying structures which all have lattice pattern repeats which are equal in three directions at right angles.

The second kind of symmetry is the symmetry axis, an axis about which a crystal structure, when rotating, comes to occupy the same configuration in space more than once during a complete revolution of 360 degrees. Because of

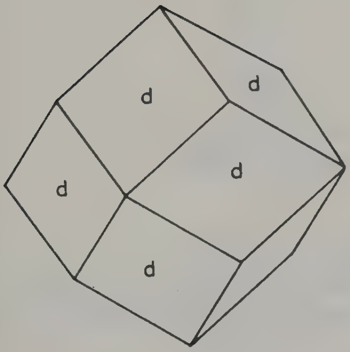


Figure 27.11 The dodecahedron with twelve four-sided faces is a closed form. This is a common form in which garnet crystallises

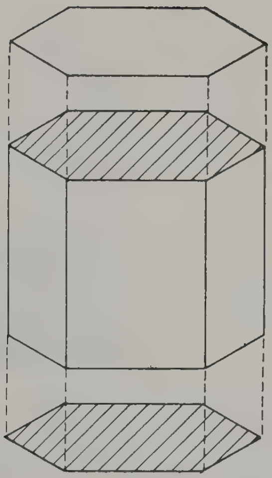


Figure 27.12 Two types of faces are needed to enclose space in the hexagonal emerald crystal. They are the six faces which are all parallel to one direction (hexagonal prism), and the two parallel faces (pinacoid) which close the top and bottom. Both of these are open forms

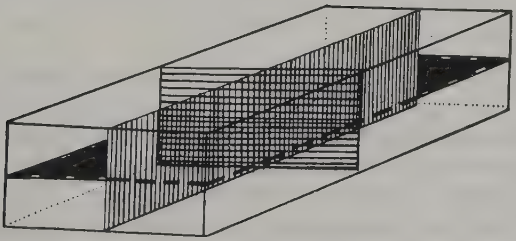


Figure 27.13 The three planes of symmetry in a brick, which represents a basic shape in the orthorhombic system, made up from three pinacoid forms (each a distinct pair of parallel faces) at mutual right angles

this, the crystal faces of any one form will all be parallel to the same angular configuration more than once in a revolution. This will happen regardless of the shape or size of each face in a single form. Depending upon the symmetry a crystal structure may occupy the same configuration twice (twofold, diad or digonal axis), three times (threefold, triad or trigonal axis), four times (fourfold, tetrad or tetragonal axis) or six times (sixfold, hexad or hexagonal axis) during a complete rotation about a symmetry axis. Axes of symmetry of a cube are shown in *Figure 27.14*. The centre of symmetry, the third type of symmetry, is only possible when like structural features, including faces and edges, occupy corresponding configurations on reflection to opposite sides of a point within

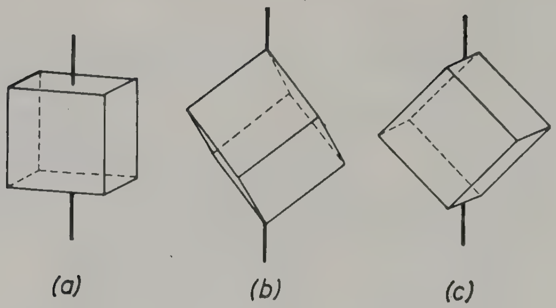


Figure 27.14 Axes of symmetry in a cube: (a) one of three fourfold axes, (b) one of four threefold axes, (c) one of six twofold axes

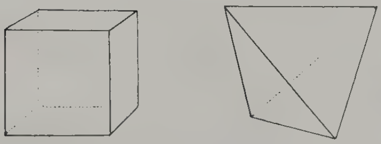


Figure 27.15 The crystal illustrated on the left has a centre of symmetry, but the tetrahedron on the right cannot have one

the structure. A brick or cube has such a centre but a tetrahedron, a form in the cubic system with four triangular faces, cannot have a centre (*Figure 27.15*); it results from a cubic crystal structure with lower symmetry than that of most cubic crystals.

Crystal Systems

Crystals are further divided into seven systems based on the essential symmetry of their inner structures. In describing crystals it is convenient and necessary to assume certain lines passing through the crystal to indicate specific directions of reference. These imaginary directions, called crystallographic axes, are depicted as lines intersecting within the crystal at a point called the origin. The relative lengths of axes indicate the relative repeat distances of the crystal structure in those directions. For many crystal structures these axes are parallel to symmetry axes or normal to symmetry planes. Every face of a given crystal form has similar or related intercepts with the crystallographic axes; for example, each face of an octahedron intercepts each of the three crystallographic axes at an equal distance from the origin. The seven systems with their axes and maximum symmetry (each system has several 'classes' with differing degrees of symmetry) are as follows. Note that the crystallographic axes must not be confused with the symmetry axes.

Cubic System

Crystal structures of the cubic (or isometric) system are referred to three crystallographic axes, all of which are of equal length and at right angles to one another. These lengths represent the relative lattice repeat amounts for all cubic crystal structures: these are equal in the three directions regardless of their actual amount. There is a maximum of nine planes of symmetry and thirteen

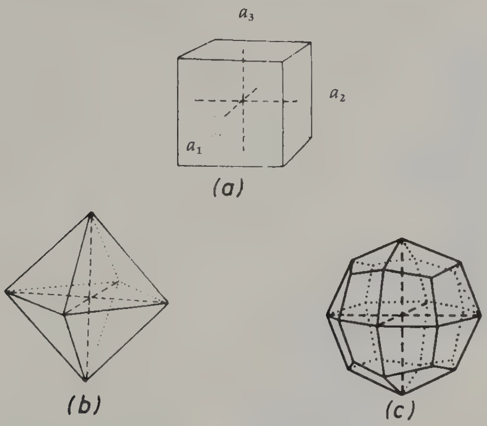


Figure 27.16 The crystallographic axes of the cubic system and examples of cubic crystals: (a) cube (pyrite, fluorspar), (b) octahedron (diamond, spinel) and (c) icositetrahedron (garnet)

axes (three fourfold, four threefold and six twofold) and there is a centre of symmetry. The crystallographic axes in a cube and examples of crystals of the cubic system are shown in *Figure 27.16*. Diamond, garnet, spinel, fluorspar, zinc blende (sphalerite) and pyrite crystallise in the cubic system, but the two minerals mentioned last do not have the full symmetry of the system. The four threefold symmetry axes are essential to all structures of the cubic system regardless of the degree of overall symmetry.

Tetragonal System

Crystal structures of the tetragonal system are referred to three crystallographic axes, all of which are at right angles to one another. The two horizontal axes (the lateral axes) are of equal length, but the vertical or principal axis is either longer or shorter than the lateral axes. There are five planes of symmetry, and five axes of symmetry (one fourfold and four twofold) and there is a centre of symmetry. The crystallographic axes in a tetragonal prism and examples of crystals belonging to this system are shown in *Figure 27.17*. Zircon, idocrase, rutile and cassiterite form crystals having the full symmetry of this system, while the gem scapolite belongs to this system but has less than the full symmetry. The single fourfold axis is essential to all tetragonal crystals.

Orthorhombic System

Crystal structures of the orthorhombic system have three crystallographic axes which are all at right angles to one another but which all have different lengths. There are three planes of symmetry, three twofold axes of symmetry (parallel to the crystallographic axes and perpendicular to each symmetry plane) and a centre of symmetry. *Figure 27.18a* shows the axes in an orthorhombic crystal with three pinacoid forms, giving six faces in parallel pairs. Topaz, chrysoberyl, peridot (*Figure 27.10*), staurolite, tanzanite (zoisite), iolite, andalusite, danburite,

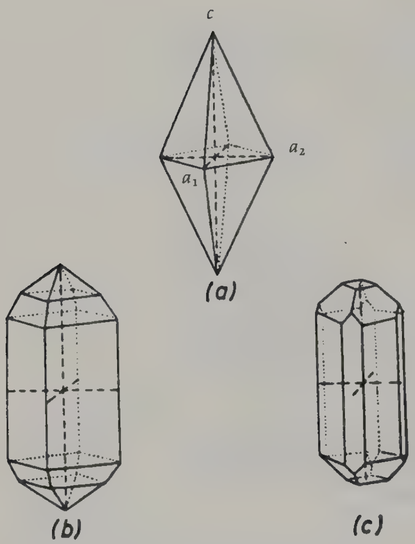


Figure 27.17 The crystallographic axes of the tetragonal system and examples of crystals of the system: (a) bipyramid, (b) prism and two bipyramids (zircon) and (c) two prisms, a bipyramid and a pinacoid (idocrase)

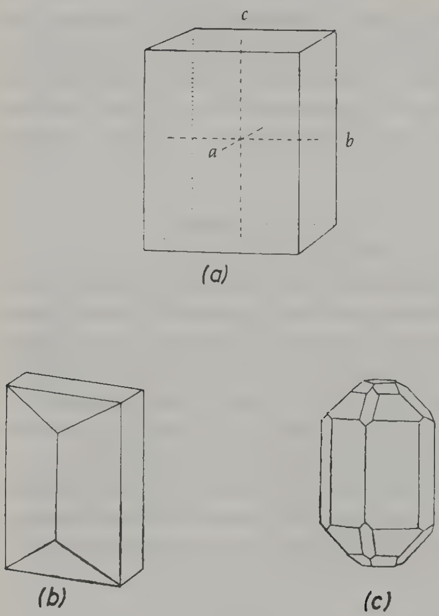


Figure 27.18 The crystallographic axes of the orthorhombic system and examples of crystals of this system: (a) three pinacoids with axes, (b) two prisms and two pinacoids (staurolite) and (c) four prisms, one pinacoid and two bipyramids (topaz)

kornerupine and enstatite are some of the minerals which crystallise in the orthorhombic system.

Monoclinic System

Crystal structures of the monoclinic system have three axes of unequal length. Two (*a* and *c*) are inclined to each other (at an angle other than 90°), and the

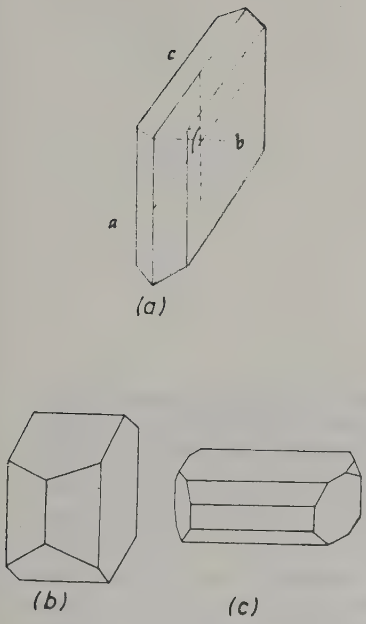


Figure 27.19 *The crystallographic axes and examples of crystals of the monoclinic system: (a) one pinacoid and two prisms, with axes (gypsum, variety selenite), (b) three pinacoids and one prism (orthoclase feldspar) and (c) four pinacoids and two prisms (epidote)*

third (lateral) axis is at a right angle to the plane which contains the other two. The lateral axis is designated the *b*-axis. Such crystal structures have one twofold axis of symmetry (which is parallel to the *b*-axis) perpendicular to one plane of symmetry (which contains the *a*- and *c*-axes), and a centre of symmetry. *Figure 27.19* illustrates the crystallographic axes and examples of crystals of the system. Important gemstones which crystallise in the monoclinic system are kunzite, sphene, jadeite, nephrite, malachite, spodumene, serpentine, orthoclase feldspar, epidote, diopside, brazilianite and datolite.

Triclinic System

Crystal structures of the triclinic system have three crystallographic axes which are all of unequal length and which are all inclined to each other. There is a centre of symmetry but no symmetry planes or axes. *Figure 27.20* shows crystals of this system. Rhodonite, kyanite, the plagioclase feldspars, turquoise and axinite crystallise in the triclinic system, the last having lower symmetry.

Hexagonal System

Crystal structures of the hexagonal system have four crystallographic axes. Three are lateral axes of equal length which intersect at 120 degrees to each other, while the fourth, the vertical axis, is either longer or shorter than the lateral axes and is at right angles to the plane containing them. There are seven planes of symmetry and seven axes of symmetry (one sixfold and six twofold) and there is a centre of symmetry. *Figure 27.21* shows the axes of the hexagonal

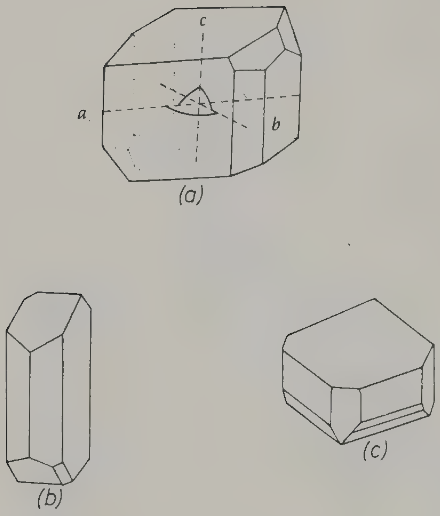


Figure 27.20 *The crystallographic axes and examples of crystals of the triclinic system: (a) twelve pedions (single-faced forms) (axinite), (b) six pinacoids (albite) and (c) eight pinacoids (rhodonite)*

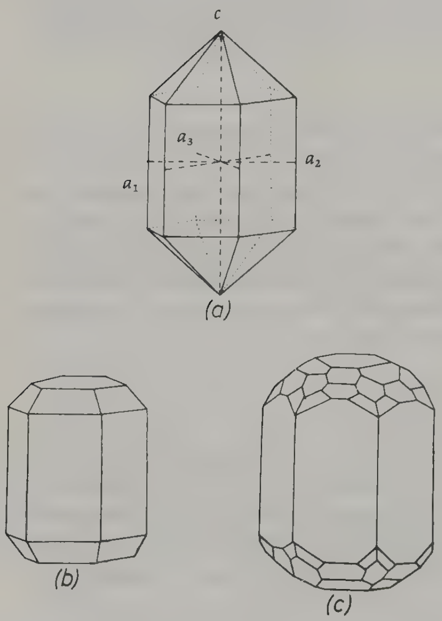


Figure 27.21 *The crystallographic axes and examples of crystals of the hexagonal system: (a) one bipyramid and one prism, with axes, (b) one bipyramid, one prism and one pinacoid (apatite) and (c) one prism, one pinacoid and four bipyramids (beryl)*

system and shows crystals of emerald and apatite which crystallise in the system, the latter having lower symmetry.

Trigonal System

Crystal structures of the trigonal system have the same crystallographic axial arrangement as that of the hexagonal system; indeed, many crystallographers

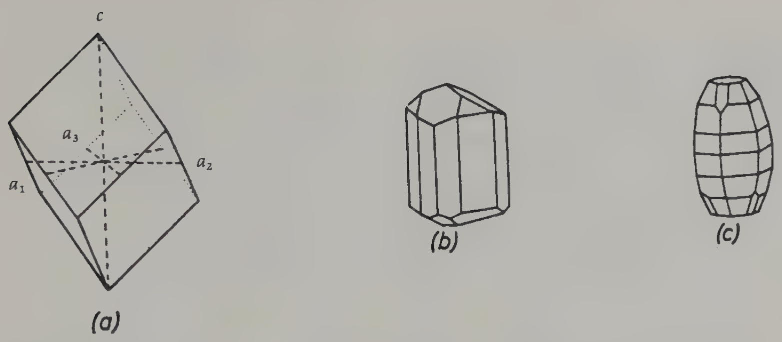


Figure 27.22 The crystallographic axes and examples of crystals of the trigonal system: (a) rhombohedron with axes, (b) two prisms, four pyramids (tourmaline) and (c) one rhombohedron, one pinacoid and three bipyramids (corundum)

incorporate the trigonal as a subdivision of the hexagonal system. The trigonal system has a maximum of only three planes of symmetry and four axes of symmetry (one threefold and three twofold axes). In this system the vertical crystallographic axis is paralleled by the axis of threefold symmetry and not sixfold as in the hexagonal system. There is a centre of symmetry. *Figure 27.22* shows the crystallographic axes and examples of crystals of the trigonal system. The important gems ruby, sapphire, quartz and tourmaline, as well as dioptase, hematite, calcite and phenakite, crystallise in the trigonal system.

Face Angles

Because the disposition of crystal faces is controlled by the underlying organisation of regular crystal structure, the angle formed by the inclination of two corresponding faces on different crystals of the same substance and structure is constant. This fact may provide means of identifying crystals, even if the crystals are of widely different shapes and sizes, or are of uneven growth so common in natural crystals. In crystallography the interfacial angles are by convention the angles between the normals (perpendiculars) to the two faces and not the outside angle formed by them (*Figure 27.23*). A visual appreciation of sets of symmetrically related angles and faces may allow recognition of forms present on crystals, of their crystal system and even of the identity of the material.

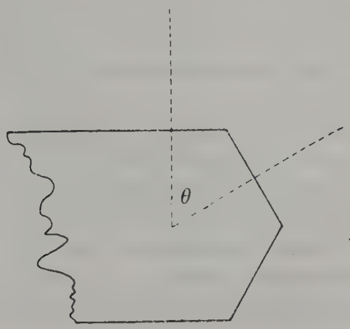


Figure 27.23 Interfacial angles are measured from the perpendiculars of the two faces and not the angle made by the two faces. The interfacial angle is θ

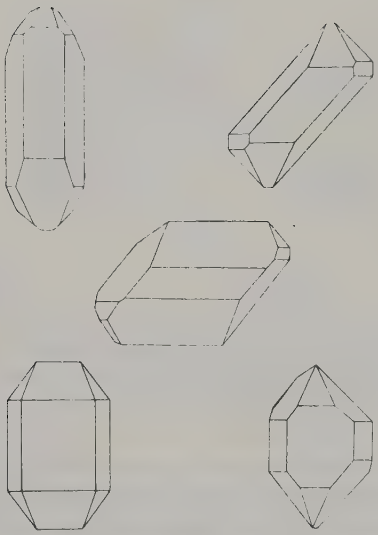


Figure 27.24 'Distorted' quartz crystals

Most crystals which exhibit faces have grown with some departure from 'perfect' form owing to some faces having grown at the expense of others. Their aspect appears very different from the perfect crystal and can appear to have the symmetry of another crystal system. *Figure 27.24* illustrates how quartz crystals can show such imperfect growth. It must be stressed, however, that the crystal structure within each of these crystals is the same regardless of the imperfection of the face shapes and sizes. Because of this the angles between like faces remain constant for all crystals of the same substance and structure. The atomic design and the bonding angles within always conform to the same pattern, so there can be no gross variation in face angle, only in face size and shape. These crystals are therefore not truly distorted; the growth of the inner crystal structure was merely faster in some directions than in others.

Habit

The characteristic shape of a crystal is known as its habit (*Figure 27.25*). While the interfacial angles are always the same for crystals of the same mineral, the relative development of different crystal forms can differ greatly. In gem minerals it has been noticed that a different habit can occur in crystals of the same mineral which come from different localities, or are of a different colour. This is because different forms are favoured by different conditions of growth. Sapphire crystals from Sri Lanka take the habit of a bipyramid while others from Montana are short prismatic in habit. Aquamarine is usually found as long prismatic crystals, while pink beryl (morganite) usually forms crystals which are short and tabular. Other types of habit are octahedral (diamond and spinel), dodecahedral (garnet), bladed as in kyanite and acicular, in slender needle-like crystals such as are found in rutilated quartz. Synthetic crystals may grow with habits which differ from those of their natural counterparts.

A crystal having the full symmetry of the system is termed a holohedral, or

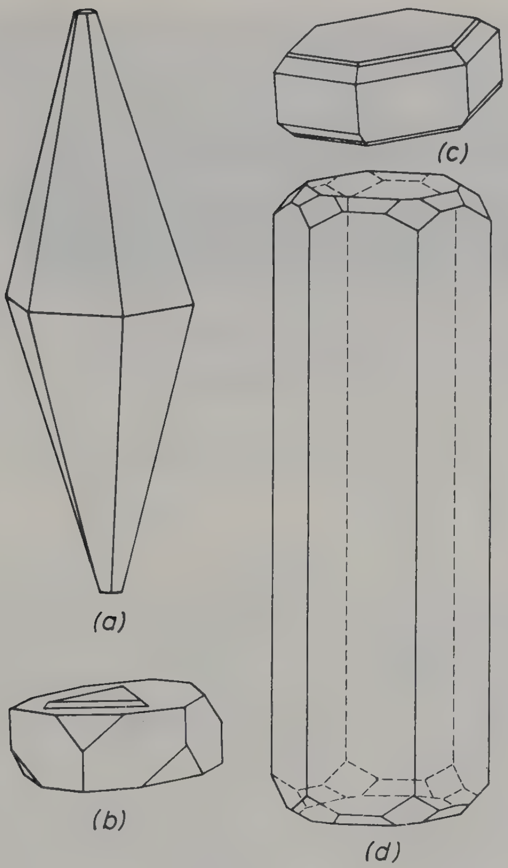


Figure 27.25 Habit in crystals: (a) Sri Lanka sapphire, (b) Montana sapphire, (c) pink beryl, (d) aquamarine

holosymmetric crystal. Some crystals, however, possess less than full symmetry and some of their forms have a restricted number of faces, or may have forms which are not repeated across the crystal. Crystals which exhibit different forms at either end of the crystal are termed hemimorphic or polar crystals.

Crystals may occur in groups which are commonly irregularly related to one another, but sometimes the faces and edges of the crystals are in parallel arrangement with other crystals in the group and usually joined to them. Such crystals are said to show parallel growth (*Figure 27.26*).

Twinned Crystals

Many crystals are twinned, that is they are composed of two or more individual parts such that one part of the structure is distinct from another and not related by the normal symmetry of the crystal, yet both are in structural continuity. Twinning is, in effect, a flip-over of crystal structure. In many types of twin there is an identifiable plane dividing the twinned parts of the crystal, called the

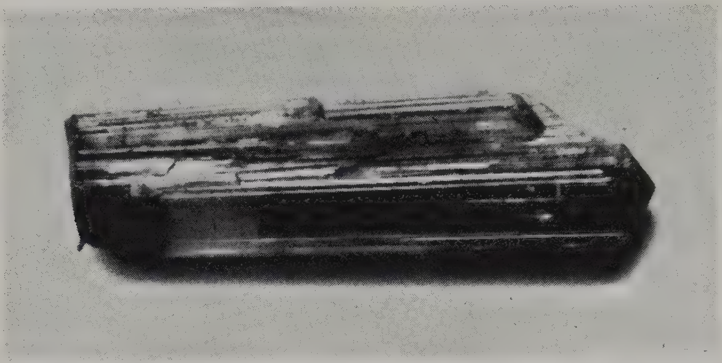


Figure 27.26 A tourmaline crystal showing parallel growth

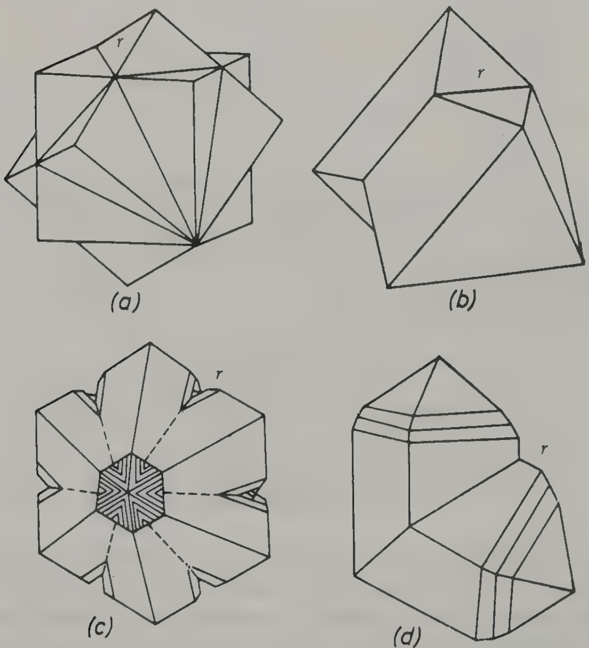


Figure 27.27 Some examples of twin crystals: (a) interpenetrant twin of fluorite, (b) contact twin of spinel, (c) pseudo-hexagonal trilling of alexandrite, (d) geniculate twin of zircon

twin plane, and an axis about which an imaginary rotation would produce an untwinned crystal. This is termed the twin axis and is frequently perpendicular to the twin plane.

Many twin crystals have been twinned from the commencement of growth and physical movement of two parts has not occurred. Others have twinned during changes in physical conditions. Quartz and calcite often have twinned structures caused by temperature and stress changes respectively.

There are various types of twin crystals, such as the simple or contact twin, the most important of which is the spinel twin where one half of the octahedron is in reverse position producing the flattened star-shaped or triangular crystals which are called macles in diamond nomenclature. Some types of twinning, particularly in the tetragonal system, show geniculate (knee-shaped) forms. In interpenetrant twins the crystals are so interrelated that they cannot be divided into separate parts; such a twinning is common in fluorspar. Repeated twinning may occur: when the twins repeat three times they may be called 'trillings'. Such types of repeated twinning often cause the crystal to appear to have a higher symmetry than it actually has. An example is the trilling of alexandrite. Repeated twinning of thin lamellar crystals often shows as parallel striations on a face or cleavage. This polysynthetic or lamellar twinning is well shown by the plagioclase feldspars and is illustrated in *Figure 9.5.* Some twin crystals with faces are characterised by their having re-entrant angles. *Figure 27.27* illustrates some types of twin crystals. Twinning may often be revealed within a crystal or cut gem by observation of materials between crossed polarisers.

Pits and Growth Marks

Many crystals exhibit small pits (etch marks) (*Figure 27.28*), growth marks, or striations on their faces and such marks are useful in showing whether the faces belong to the same crystal form. They may also give an indication of the symmetry: an equilateral triangular pit, for instance, indicates a threefold symmetry at right angles to the face on which it occurs. Striations are due to an oscillation between forms: thus the horizontal striations on the prism faces of a quartz crystal are the result of oscillation between the prism form and the rhombohedral form. Likewise the striations in alternate directions on the faces of a pyrite cube, which reveal its lower symmetry, are due to similar oscillations between the cube form and the edges of the pentagonal dodecahedron form (*Figure 27.29*).

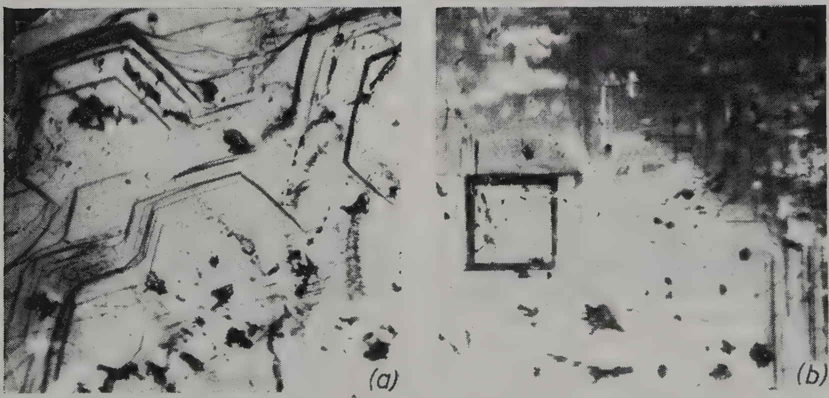


Figure 27.28 Etch marks on the faces of a beryl crystal: (a) hexagonal markings on the basal pinacoid, (b) rectangular markings on the prism face (by courtesy of B W Anderson)

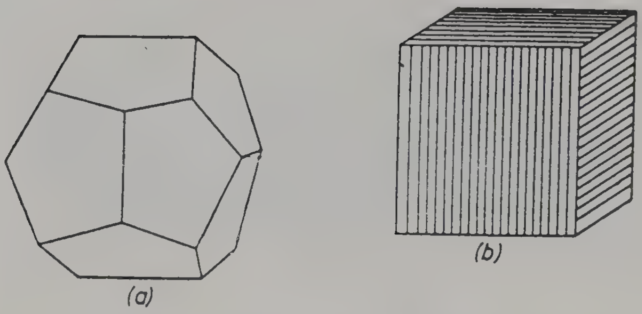


Figure 27.29 The pentagonal dodecahedron (pyritohedron) and the cube are two common forms in which pyrite crystallises. The striations in alternate directions on adjacent faces of the cube are the traces of the edges of the faces of the pentagonal dodecahedron

28

Hardness, Cleavage and Fracture

Hardness

Bound up with the atomic bonding of a substance are the properties of hardness, cleavage and fracture. A high degree of hardness in a precious stone is necessary for only hard substances can take and retain a good polish. Though it may seem absurd to say that a stone 'looks hard' it is in fact true that an experienced eye can judge to some extent the hardness of a cut stone by the quality of the polish on its facets, as hardness and refractive index are the two factors which govern the lustre of a stone.

Although the general meaning of hardness is well enough understood it is less easy to define the term, since there are at least two types of hardness; that measured by the metallurgist, who presses some kind of indenter on to the surface, and the mineralogist's hardness, which is assessed by the resistance of a mineral to scratching or abrasion. What is probably the best definition is that given by Osmond: 'Hardness is that property possessed by solid bodies in varying degree to defend the integrity of their form against causes of permanent deformation and the integrity of their surface against causes of division.' This still gets no nearer, however, to expressing hardness in numerical terms.

Mohs's Scale

Probably the first to describe and use a method of measuring hardness was Réaumur who, in 1722, investigated the results of pressing together the edges of two right-angled prisms made of the substances to be compared. A far more practical means of assessing hardness was proposed by the German mineralogist Friedrich Mohs who, in 1822, after extensive experiments, chose ten well-known and easily obtainable minerals and arranged them in order of their 'scratch hardness' to serve as standards of comparison. Although the numbers of Mohs's list have no quantitative meaning, it is commonly known as Mohs's scale, and still forms the universally accepted standard of hardness amongst mineralogists and gemmologists. Mohs's scale is as follows:

10. Diamond
9. Sapphire
8. Topaz
7. Quartz
6. Orthoclase feldspar
5. Apatite
4. Fluorspar
3. Calcite
2. Gypsum
1. Talc

The numbers on Mohs's list are not quantities, they represent an order only. Diamond is enormously harder than any other mineral, and the gap between 10 and 9 on the list is far greater than that between any other of the numbers. The only substances with hardness between 9 and 10 are the artificially prepared abrasives carborundum (silicon carbide) and boron carbide, to which must now be added borazon (boron nitride) which has a hardness near to that of diamond.

The number 7 on Mohs's scale is an important one, as any gemstone must be at least as hard as this if it is to withstand the action of grit in the air or on clothes, since this grit consists largely of particles of sand, that is, quartz. Stones such as peridot, the resplendent sphene, and the beautiful green demantoid garnet which do not reach this standard of hardness are thus only suitable for occasional wear in brooches, pendants and the like. Worn every day (in a ring, for instance) they would soon lose their lustre. Opal, and still more, pearl, coral and amber, are also relatively soft, and yet much worn in jewellery. Here, however, the case is somewhat different, for such stones are fashioned with curved surfaces and faint scratches are less of a blemish than where highly polished facets are concerned.

Brittleness

A hard stone is not necessarily a tough stone: despite its tremendous hardness, even diamond is rather brittle, and would certainly not withstand a heavy blow on the anvil as legend would suggest. Zircon is notoriously brittle, at least so far as the surface is concerned, for the facet edges chip badly. Unmounted zircons should always be kept apart so there is no danger of the stones touching one another, or if in the same packet each stone should be separately wrapped in a screw of tissue paper to avoid what is termed 'paper wear'.

By special techniques, metals can be grown as single crystals, and a piece of metal of this kind is found to be so weak that it can easily be torn asunder in the fingers. However, if the test piece is gently worked to and fro, it is found to become rapidly harder and tougher and stronger, as the result of the formation of a polycrystalline mass in place of the single crystal with its planes of weakness at the mercy of any sudden stress. Another analogy that can be used to illustrate the same point is plywood, which in quite thin sheets is remarkably strong and resistant to any attempt to split it, whereas the individual sheets of which it is composed are flexible and easily broken.

Thus it is that substances such as the jade minerals and agate are among the toughest minerals known, while the black microcrystalline form of diamond known as carbonado combines the hardness of diamond with the toughness that single crystals of diamond cannot attain, and is thus very highly valued for industrial purposes.

Scratch Hardness Tests

For the gemmologist, scratch hardness, based on the standard minerals in Mohs's list, is a destructive method of identification which can, for all its crudities, occasionally be very useful. The most popular way of applying hardness tests on minerals, apart from the indiscriminate use of a file, has been by means of hardness 'points' or 'pencils'. In these, suitable sharp fragments of the standard minerals on Mohs's scale are mounted in wooden or metal holders. Such implements are certainly convenient, and allow good control when applying the point to the mineral to be tested. With rough gemstones indeed, unless they are fine crystal specimens, there is nothing to be said against their use. The hardness point should be applied firmly but not forcibly to some inconspicuous part of the stone to be tested. The 'feel' of the point as it is drawn a short way along the specimen will at once reveal to an experienced worker whether the stone tested is harder or softer than the point – that is, whether it grips or 'skids'. The whole thing should be done on quite a small scale; a large scratch is a sign of careless work. Any mark produced should be rubbed with the moistened finger and examined with a lens to ensure that it is a true scratch and not powder from the point itself ground off by the harder specimen.

Lacking these special hardness points a small, hard, triangular file, hardness about 6.5, can be used. A good penknife or needle has a hardness about 6, while window glass may be reckoned as 5–5.5, and a fingernail as 2.5 on Mohs's scale.

If it really seems necessary to apply a hardness point or file to a faceted stone, never scratch the table or culet, as any mark here will be immediately visible. Even a paste has some beauty and value, and should not be spoiled in the testing. Work therefore as near to the girdle as possible, or on the girdle itself if the stone is unmounted. When testing faceted stones, however, it is far better to work the other way round, that is, to let the specimen to be tested act as the 'hardness point' against polished plates of standard substances, such as synthetic corundum, topaz (or synthetic spinel), and quartz. Pieces of these can be obtained from a lapidary, and should cost very little, as they need not be of gem quality. Failing this source of supply, the smoother parts of a sapphire boule, a cleavage surface of white or yellow topaz, and the smooth face on a quartz crystal will serve perfectly well, and window glass, of course, is universally available.

Sclerometer

One of the earliest attempts to measure hardness in terms of relative numerical values was by means of an instrument termed a sclerometer. In one form of this, the surface to be tested was fixed horizontally on a small carriage, which could be moved by means of a string passing over a pulley. A steel or diamond point attached to a lever was allowed to rest upon the surface of the specimen. A hardness value was obtained either by determining the load which must be applied to the point in order to produce a visible scratch when the carriage was moved, or by finding what load must be added to the string passing over the pulley in order to move the carriage and produce a scratch when the point was subjected to a standard load. This method produces fairly consistent results with minerals of no great hardness, and serves to demonstrate very clearly the way in which scratch hardness varies according to the direction on the crystal in which the scratch was made. This can best be done by carrying out the tests on a well-developed crystal face, and turning the carriage into a number of different orientations. If now a drawing is made of the face in question and from the central point a number of lines are drawn of lengths corresponding to the hardness found in each direction, a perimeter drawn round the ends of the lines will show a pattern related to the symmetry of the face in question.

Variations in Hardness

Structure

Testing cut gemstones by such a method as the above would be quite impracticable, but it is mentioned here in order to show one way in which the variations in hardness in a crystal can be demonstrated under controlled conditions, and to drive home the point that the symmetry of crystals is a fundamental thing and not merely a matter of geometry. When it is said that the six faces of a cube are identical, this may be manifestly untrue so far as size goes in an actual specimen owing to accidents of growth, since crystals are seldom formed under 'ideal' conditions. However, the properties of the faces are identical, so that not only is the hardness curve described above the same on each, but curves showing heat conduction, elasticity and so on will also be the same, as will be their reaction to chemical solvents, in which pittings and markings again revealing the underlying symmetry will be produced.

Though variations in hardness with crystal direction do exist, such differences are usually not very great, and would not be noticeable when carrying out the ordinary scratch tests used in practical testing. One mineral, kyanite, an aluminium silicate, occurs in pale blue bladed crystals which are occasionally cut as a gem. Parallel to the length of the blades, on the prominently developed pinacoid faces, it will be found that the crystal is easily scratched by the point of a knife blade, whereas at right angles to this the knife blade will make no impression. In terms of Mohs's scale the hardness may be said to vary from 4.5 to 7.

Diamond is a mineral in which the variations in true hardness can be as great as 100: 1, and are of practical importance. It has already been stressed that diamond is harder than any other substance. To grind and polish diamond, therefore, the only possible abrasive is diamond itself; and it is only because one can abrade diamond along its softer directions by the action of its harder surfaces that cutting and polishing of the stone becomes commercially feasible. It has been found by X-ray study and in practice by diamond cutters that directions parallel to the crystal axes are those of least hardness. On a cube face there are thus two optimum polishing directions; on a rhombic dodecahedron there is one (parallel to the short diagonal), while the faces of the octahedron are inclined equally to all three axes, and are thus the hardest and most intractable for working.

Locality and Colour

Variations in hardness due to crystal structure are to be expected, and can readily be explained. More difficult to understand are the variations according to locality and according to colour in the same species. Colour differences do, it is true, indicate slight differences in composition, enough perhaps to affect the hardness of the stone to some degree. Lapidaries maintain that ruby is 'softer on the wheel' than sapphire, and Eppler found that, in grinding, ruby was about 25 per cent softer than colourless sapphire. In sawing or drilling, ruby has proved itself at least as hard as sapphire, which shows how complex a property, or mixture of properties, 'hardness' is and how difficult to classify and measure.

The difference in the hardness of diamond according to its provenance is almost certainly not a true hardness difference, but a variation in what might be termed 'cuttability' owing to stones from certain localities, such as Australia and Borneo, having irregularities in their texture. In grinding and polishing diamond it is essential for the craftsman to know and feel the direction of the cutting 'grain'. Where the rough crystal is twinned or several crystals have grown in together the cutter encounters resistant patches, which he terms a 'naat'; the result is as disconcerting to him as a knot in the even grain of a piece of wood is to the carpenter. Where a locality abounds in such stones they naturally gain an evil reputation among diamond manufacturers and are said to be too hard to cut. That there are no fundamental differences in the hardness of diamond (other than the hardness according to crystal direction already discussed) has been proved by quantitative tests with diamond powder derived from crystals from different localities, in which the powder from reputedly 'soft' diamonds such as those from the Congo has proved itself as efficient an abrasive as that derived from crystals from other districts.

Indenter Tests

When a reliable measurement of hardness is needed, as, for example, on a new or unknown gem mineral, perhaps the best method available today is a micro-indentation test of the 'Knoop' type, or the double-cone indenter developed by Grodzinski. The marks made in these tests are so small as to be invisible except under the microscope, and the long narrow shape of the indenter ensures that there is little risk of shattering the surface. The procedure in these tests is, however, too elaborate to be quickly undertaken, and the stone needs to be unmounted.

Cleavage

One of the peculiarities of crystals is the tendency to break or split parallel to certain definite directions. This property of cleavage, as it is called, is one of the many consequences of that regular arrangement of the atoms which distinguishes crystals from amorphous solids. Some atomic layers, usually those representing an important face in the crystal, are strongly coherent, but are attached to the neighbouring layers above and below by relatively weak forces. Where such a condition exists there will naturally be a direction of weakness parallel to these layers which would constitute at least potential cleavage planes. In confirmation of this simplified version of the underlying causes of cleavage, it is in fact found that cleavage planes in any mineral are always parallel to a possible crystal face in that mineral. The word 'possible' is used to

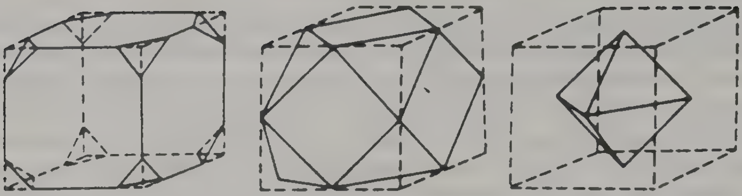


Figure 28.1 The cleavage directions of fluorspar, showing how an octahedral form can be cleaved out of a cube crystal

indicate that the crystal face to which the cleavage is parallel is not necessarily actually present in each specimen, but is one which, by the laws of crystal symmetry, might properly be formed in that mineral. For example, fluorspar is almost always found crystallised in the form of simple cubes, whereas the cleavage planes are parallel to the octahedral faces (*Figure 28.1*).

Types of Cleavage Surface

Cleavage surfaces can be highly *perfect*, as in mica, topaz, or calcite, or *imperfect* as in fluorspar. Again, in some minerals the cleavage is readily developed (calcite) in which case the term *easy* cleavage can be applied, or much less readily – *difficult* – as in peridot. By the use of these four adjectives an adequate description of any cleavage can be given. Thus fluorspar can be said to have an easy but imperfect octahedral cleavage, while the octahedral cleavage of diamond could be termed perfect but rather difficult. Calcite's rhombohedral cleavage is an example of 'easy and perfect' and the rather obscure basal cleavage of beryl fulfils the conditions for 'difficult and imperfect'. The popular term 'strong' cleavage might well be avoided as it is a most inappropriate adjective for a plane of weakness.

Cleavage surfaces are seldom entirely on the same level; there are usually some minutely 'stepped' places when underlying layers are exposed. The surface will often show a slightly pearly lustre due to its laminated nature and perhaps some iridescent colours where a thin film of air has penetrated some underlying layers of incipient cleavage. There is no pattern or structure to be seen in reflected light, unless it be the stepped effect already referred to, but modern interferometry has shown that even if a cleavage surface is quite perfect to the eye, steps of molecular dimensions occur at intervals. On crystal faces, however, no matter how perfect they may seem, there are always some faint signs, in lines of growth, striations, etchings or other marks, which distinguish them from either cleavage planes or polished flats. Such polished surfaces are seldom truly flat, which gives them an insipid look, and parallel and slightly curved polishing marks, due to the action of the polishing wheel, may often be detected.

Obviously, too easy a cleavage is not a desirable quality in a precious stone. It is a nuisance to the lapidary, since under the stresses, vibrations, and sudden changes of temperature inseparable from the grinding and polishing processes, flaws due to incipient cleavage are very likely to develop, or the stone may actually part along a cleavage plane. A further drawback in cutting stones with pronounced cleavage is the fact that a mineral cannot properly be polished along a cleavage plane owing to sections of the surface breaking up, which adds a further complication to the cutting process. On the other hand, diamond cutters make good use of the octahedral cleavage of diamond in the preliminary dividing or trimming of stones of awkward shape before the grinding process begins, with great saving of time and labour.

Of the well-known gemstones, topaz has perhaps the most easy and perfect cleavage – parallel in this case to the basal plane of the crystal. A sudden shock, such as a fall on to the glass top of a dressing table, may well cause a topaz to snap in two, especially if it is in an elongated form, such as a drop-shaped ear pendant. The beautiful lilac-coloured kunzite is another gem with a notoriously easy cleavage, making cutting difficult; while the very name of the rare mineral euclase refers to its extreme readiness to part along the cleavage planes.

Parting

There is another effect akin to cleavage, but due to a different cause – in this case a tendency to split parallel to planes of weakness owing to lamellar twinning. This phenomenon is known as parting, and the separation here can only occur at intervals dictated by the thickness of the twin layers instead of between any adjacent atomic planes parallel to the cleavage direction. Corundum is usually cited as a mineral which has well-developed parting parallel to the basal plane, and a less pronounced effect parallel to the rhombohedral faces. These are undoubtedly planes of weakness in the mineral but whether they are parting planes or true cleavages seems to be a moot point. The planes left by the parting are sometimes extremely perfect, and may be found in synthetic stones where there is no sign of lamellar twinning visible under the polarising microscope. However, the point is chiefly one of academic interest, since the effects of parting and cleavage are very much the same.

Cleavage as Test for Gemstones

One can hardly say that cleavage forms a useful 'test' for certain gemstones, but a knowledge of cleavage can sometimes assist in arriving at a conclusion as to the nature of a gemstone. For example an 'aquamarine' showing two cleavage cracks at right angles to one another can be condemned at once as a synthetic spinel (which has octahedral cleavage); and careful scrutiny of the girdle of a diamond under a lens or microscope will often reveal small chips of which the sides are composed of two of the four directions of the cleavage.

Direction of Cleavage

Where a mineral possesses a very easy cleavage, particularly if this is parallel to three or more directions so that the solid shapes bounded by cleavage planes can be induced, it may be quite difficult to break the stone in any other directions. If a crystal or cleavage rhomb of calcite is struck with a hammer or even pounded in a mortar, and the fragments studied, practically every thin piece will be seen to be bounded by cleavage planes forming little rhombohedral blocks in which the interfacial angles are identical. Again, in the

Table 28.1
Minerals showing pronounced cleavage

Mineral	*No. of directions*	*Parallel to*
Topaz	1	Basal pinacoid
Apophyllite	1	Basal pinacoid
Orthoclase	2	Basal and clino pinacoids
Euclase	1	Clinopinacoid
Fibrolite	1	Clinopinacoid
Epidote	1	Basal pinacoid
Kyanite	1	Macropinacoid
Spodumene	2	Prism
Diamond	4	Octahedron
Fluorspar	4	Octahedron
Calcite	3	Rhombohedron
Dioptase	3	Rhombohedron
Synthetic spinel	3	Cube
Blende	6	Dodecahedron

case of diamond powder, the grains when examined under the microscope will be found to be angular and bounded by cleavage surfaces, and it is these sharply angled fragments that make this material so efficient as an abrasive, in addition, of course, to its superlative hardness.

Quartz, spinel (natural) and garnet are amongst the gemstones which show practically no sign of cleavage.

Table 28.1 indicates minerals showing pronounced cleavage.

Fracture

Even in minerals which have easy cleavage, more random breakage can occur, and in minerals like quartz which have no pronounced cleavage such fractures, as they called, are the rule rather than the exception. Many different terms have been used to describe the various types of fracture found in different minerals, but only two are sufficiently distinctive and frequent to be worth describing. The first of these, the shell-like conchoidal fracture, will be familiar as it is well shown by chipped glass (*Figure 28.2*). This is the natural type of fracture to be

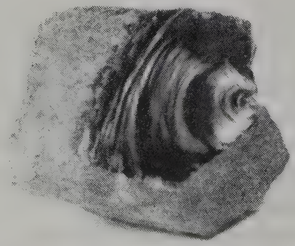


Figure 28.2 *Conchoidal fracture in the natural glass obsidian*

expected when an amorphous substance (or indeed any substance with no pronounced plane of weakness) is struck a sharp blow at some definite point. A series of shock waves travel from the point of impact in the form of a cone, with this point as the apex. Under ideal conditions a form like a limpet (bulb of percussion) is produced, and this can be demonstrated by tapping sharply with a small hammer on a flat surface of flint. Conchoidal fracture is very typical in glass; where it is developed on a large scale in a gemstone it should certainly give rise to suspicion. However, it must be remembered that quartz, beryl, corundum or in fact any mineral, can on occasion show this type of fracture. The other type of fracture which should be mentioned is the hackly or splintery fracture found in tough, fibrous minerals such as nephrite jade.

29

Specific Gravity

Historical Aspects

The differing degrees of 'heaviness' found in solids must have been recognised even by primitive man in handling implements of wood and stone, and later of metal. In comparing the density of substances it is the weight of equal volumes, of course, that must be considered. The contrast between a bucketful of feathers, for instance, and a bucketful of lead would indeed be pretty striking: the one easily portable by a child and the other weighing perhaps 100 kg.

Equal volumes of liquids are easy to obtain for comparison, but how can one measure the volume of an irregular solid? Aristotle, as early as the fourth century BC, saw that the answer could lie in measuring the amount of water it displaces when immersed, but it was the great mathematician Archimedes, in the following century, who first used displacement methods in practice, and we still speak of 'Archimedes' principle' in this connection. Another curious method of comparing densities used by the ancients was to make a copy of the object in wax and compare the actual weight with that of the wax model – a most time-consuming business.

The first actual density figures that have come down to us are due to an Arabian scientist, al Biruni, who lived about AD1000, who actually evolved a crude form of 'specific gravity bottle' (see later). Some of al Biruni's results were very good. In more recent times, the most complete series of specific gravity figures ever compiled by one man from his determinations is that given by Brisson in his book *Pésanteur spécifique des corps* published in 1787, two years before the French Revolution. Brisson had access to the King's cabinet of minerals and gemstones, and the measurements, weight and specific gravity of such famous stones as the 'Pitt' or 'Regent' diamond are given in the work. Working with two accurate balances, weighing his specimens in air and either distilled water or pure rainwater at a temperature of 14° Réaumur – that is 17.5 °C – Brisson achieved results which, when very large, pure specimens were available, were very good indeed.

Nomenclature

Before considering the various methods by which the SG of gemstones can best be measured, it will be as well to give the definitions of the terms used. The *specific gravity* (or *relative density*) of a substance is its weight compared with that of an equal volume of pure water at a temperature of 4 °C. The *density* of a substance is its weight per unit volume, and its numerical value will of course depend upon the system of measures used. Since the gram is fixed as being the weight of one cubic centimetre of pure water at 4 °C, the density of a body has the same numerical value in these units as the specific gravity. The temperature of 4 °C is chosen because this is the critical point at which water is at its most dense. In practice water at this temperature is never used. For very accurate work, a temperature correction can be applied from tables, but since only the third place of decimals is usually affected no temperature correction at all is needed for determinative purposes.

The abbreviation SG is commonly used for specific gravity, while in scientific publications *d* is used for density, often with an indication of the temperature of the experiment and the temperature of the water to which the comparison is referred. Thus d^{18}_{4} would mean the density of the mineral at 18 °C referred to water at 4 °C. The coefficient of expansion of solids is in general far lower than for liquids, so that the density hardly varies measurably within the range of room temperatures.

One condition, unfortunately, is essential before the specific gravity of a stone can be measured: that is, it must be free from its setting. This is perhaps the main reason why this important determinative method has been so disregarded by jewellers. There are two main methods, although there are many modifications of each; they are known as the hydrostatic method and the heavy liquid method. The hydrostatic method is probably the best means for getting accurate results on fairly large individual specimens, but it needs a sensitive balance, some calculation, and 15 minutes or more for each determination. Heavy liquids, on the other hand, are rapid in action where only an approximate result is needed (for instance, to find out whether a cat's-eye is a chrysoberyl or a quartz). They need no calculation, no balance, and give just as good results with tiny specimens as with large ones. Flotation methods also hold the advantage where fine comparisons between stones of very similar SG are concerned (for example between natural and many synthetic emeralds), and for the rapid sorting of whole parcels of stones according to their SGs. Heavy liquids will be discussed first.

Safety Precautions

Care should be taken when using 1,2-dibromoethane (ethylene dibromide), a suspect carcinogenic liquid sometimes used for SG determinations and in hydrostatic weighing, or any other heavy liquids used in gemmology, to avoid skin contact or inhalation of vapour. On no account should any of the liquids used by gemmologists for gem testing be swallowed. In case of contact with the skin, liquids should be washed off; if in the eyes, they should be well flushed out with running water; if swallowed, vomiting should be attempted and medical assistance obtained.

As with certain other volatile liquids (in particular carbon tetrachloride, CCl_4), it is advisable to avoid smoking when using the liquids. Gemmological liquids should only be used in well-ventilated conditions.

Heavy Liquid Method of Measuring Specific Gravity

If a stone is placed in a liquid of lower SG than itself it will naturally sink: but if it is placed in a liquid of greater SG than itself it will float at the surface. In a liquid of the same SG it will remain suspended in any position, neither rising nor falling. All that is needed then to assess the SG of an unknown stone is to slip it into a series of tubes containing liquids of known SG, and observe whether it rises or falls. In theory the method is simplicity itself and in practice too it is undoubtedly the most useful of all methods, though there are snags. One of these is the difficulty of finding liquids dense enough to float the stones of high specific gravity.

Types of Liquids

A large number of liquids have been recommended from time to time, but three are all that are needed to cover the range from 1.0 to 4.15; intermediate values are obtainable as required by dilution. The three liquids are bromoform, di-iodomethane, (methylene iodide), and an aqueous solution of thallium salts, conveniently known as Clerici solution. To these may be added acetylene tetrabromide as a possible alternative to bromoform, and another lighter liquid would be needed to dilute these if lower SGs are needed. A detailed account of the properties of these liquids is given below.

Bromoform

Bromoform ($CHBr_3$) has a composition analogous to the well-known anaesthetic chloroform ($CHCl_3$), and has a rather similar ethereal smell and sweetish taste. Bromoform when pure is a colourless, mobile fluid, having an SG of 2.90 at 15 °C, and with a refractive index of 1.598 at 19 °C. The freezing and boiling points are 6 °C and 149 °C respectively. This liquid should be protected from the action of light, as also should di-iodomethane and in fact all organic compounds where a halogen replaces the hydrogen in the molecule. Keeping a piece of copper foil or a few copper turnings in the liquid will to some extent avoid this darkening and may after a time clear darkened liquid. The liquids are best kept in dark bottles in a dark cupboard. The SG of bromoform as supplied is apt to vary somewhat between 2.85 and 2.90, but this slight difference is not very important so far as gemstones are concerned. In ordering bromoform from any supplier it is wise to stipulate pure bromoform with an SG of 2.90, as there is a pharmaceutical product containing alcohol which has too low an SG to be useful.

Acetylene Tetrabromide

Acetylene tetrabromide, or sym-tetrabromoethane as the chemist may prefer to call it, has the formula $CHBr_2 . CHBr_2$. It is a nearly colourless liquid when fresh, and has an SG of 2.96 and a refractive index of 1.638 at room temperature. Though it has a slightly higher SG than bromoform it does not form such clear and stable solutions, and is thus less in favour.

Di-iodomethane (Methylene Iodide)

Di-iodomethane (CH_2I_2) is undoubtedly the most useful of all liquids to the gemmologist. Not only does it have a higher SG than most other pure liquids (between 3.32 and 3.33 at room temperature) but it also has a very high refractive index (1.745 at 18 °C) which gives it great value in both these important fields. When fresh, it is a pale yellowish-brown fluid, freezing at 5–6 °C, and boiling at 180 °C. It is volatile, and has a distinctive smell. It has a marked tendency to turn brown or black if exposed to light, owing to decomposition with release of free iodine. This can readily be checked by keeping pieces of copper strip in the bottle containing the fluid, and a badly affected sample can be cleaned by degrees in similar manner, though shaking with mercury is quicker.

It will be seen from the formulae of these compounds that they are essentially substituted hydrocarbons which are compounds of carbon and hydrogen only and as such are not generally miscible with water. Fortunately, however, for the gemmologist's purpose they are miscible over a wide range with many hydrocarbons such as benzene, toluene, and so on, all of which are of much lower specific gravity, rendering the production of liquids of special SG easily accomplished. Care must be taken to see that no water, water-wet stones or tongs come into contact with them, as the result will be a messy emulsion.

Clerici Solution

Just the reverse is true of the next heavy liquid to be mentioned – the Clerici solution. This is now considered to be too hazardous for general use. It is a concentrated solution in water of two very soluble thallium salts – the formate and malonate – in equimolecular proportions. It is named after the Italian chemist who first proposed its use in 1907. Being an aqueous solution, it must be diluted with distilled water only, and any tongs or specimens placed in the solution should be cleaned carefully so as to be free from traces of organic fluids adhering from previous tests. The actual SG of Clerici solution will of course vary with its saturation, and the amount of salts in the solution at saturation point will in turn vary with the temperature to a considerable degree. At room temperatures in warm weather a stable liquid of SG about 4.2 can be obtained, but with a liquid of this strength some of the salts will crystallise out in cold weather.

While it is convenient to have some concentrated Clerici solution in stock for rapidly 'gingering up' a sample which has become too dilute for the purpose in hand, in practice Clerici solution slightly diluted to an SG of 4.0 is the highest SG liquid likely to be needed, and this, in a tightly closed bottle, should hold its

SG indefinitely. Clerici solution is practically colourless when fresh, becoming a little yellowish in time. It is far more viscous than the other liquids, is poisonous, and attacks the skin in a rather unpleasant manner. It is very slow to filter and is rather a messy substance to handle. It is also rather expensive. Much, however, can be forgiven a liquid that can float corundum at room temperatures; and being an aqueous solution it has the advantage that it may be reconcentrated by simple evaporation without loss of the essential thallium salts, while to recovery the other 'organic' heavy liquids in a pure stable state usually means a distillation process.

Lower SG Liquids

A few other liquids, useful in the lower SG ranges, may conveniently be mentioned here.

1,2-dibromoethane (ethylene dibromide) ($C_2H_4Br_2$) is a volatile colourless liquid with an ethereal odour, which has an SG of 2.18–2.19 at room temperatures. It is a useful liquid for testing opals. Its chief use is in hydrostatic weighing as described later.

Carbon tetrachloride (CCl_4) is a very volatile liquid, boiling at 76 °C. It has a peculiar smell and a low surface tension, and is non-flammable. It is a powerful solvent for fats and is extensively used as a dry cleaner for clothes. It has a low refractive index (1.44) and a rather high SG (1.59), and on occasion has been used as a medium for hydrostatic weighing. Its heavy vapour, however, copiously given off even at room temperatures, is apt to vitiate the true swing of the balance and is therefore not recommended.

Monobromonaphthalene exists in two forms, according to the position of the bromine in the molecule. It is the liquid alpha form, a rather oily fluid, smelling somewhat like its parent naphthalene, which is variously used as an immersion medium, as a refractometer contact liquid, and as a diluent for heavy liquids. Its formula is $C_{10}H_7Br$ and it boils at 279 °C. The refractive index is 1.66 and the SG is 1.49. It is not very volatile, and is not easily removed from glass dishes, stones or hands.

Benzyl benzoate, another organic liquid, has an SG of near 1.17 at 20 °C and will separate amber from most plastic imitations.

Benzene and Toluene

To complete the list of useful liquids are the two common aromatic hydrocarbons benzene (C_6H_6), which has a boiling point of 80 °C, an SG of 0.88 and a refractive index of 1.50; and toluene ($C_6H_5 . CH_3$), which boils at 111 °C, has an SG of 0.87, and a refractive index of 1.49. Benzene is highly flammable and is chiefly useful as a cleaning agent and as a temporary diluent for heavy liquids. Toluene (often known as toluol) is not quite so volatile or odorous. It is a good medium for hydrostatic weighing.

Sodium Polytungstate

Sodium polytungstate ($3Na_2WO_4 . 9WO_4 . H_2O$) has been proposed as a safer alternative to some of the organic heavy liquids by Hanneman. In its dry state this is a white crystalline powder. When made up as a saturated solution using distilled, deionised or softened water (note: the presence of calcium ions will produce a white precipitate) it has a specific gravity of about 3.10. This can be diluted with water to 3.05 to test for tourmaline, or to 2.65 for quartz.

Because its specific gravity is linearly related to its refractive index, if a solution of sodium polytungstate is made up to suspend a gem specimen, the specific gravity of that specimen can be determined by measuring the refractive index of the liquid on a refractometer, and then applying the formula:

$$\text{specific gravity} = 2.80 + 8.43\ (\text{refractive index} - 1.555)$$

Note: for refractive indices less than 1.555, the multiplying factor within the bracket is minus, and when multiplied by 8.43 the product is also minus.

Liquid Containers

Having enumerated the most important liquids, it remains to describe how best they may be used. This must depend very largely, of course, on the stones most frequently tested by the user, how often the tests are needed and how accurately he wishes to assess the SG of his stones. The nature and size of the containers will be contingent on these factors and also on the dimensions of the stones likely to be tested. As the liquids are all somewhat costly, economy is essential; therefore the containers should be as small as possible consistent with their having wide enough mouths to allow the free entry of tongs for introducing and recovering the specimens, and a sufficient depth to give a column of liquid in which the rate of rise or fall of the specimens tested can be fairly judged.

The small wide-mouthed bottles with Bakelite screw caps, mainly used for solid chemicals, are well suited for the job, and are inexpensive, although Bakelite is rendered brittle by the vapour of many of these liquids. Weighing bottles with ground-glass stoppers are more attractive, have a better depth in proportion to their width, and enable the behaviour of the specimens to be observed more easily, but they are more expensive and rather fragile. Corked specimen tubes about 65 mm deep by 20 mm wide are quite effective; they are cheap and have a flat base, so will stand upright on a plane surface. It is a wise plan when using weighing bottles or specimen tubes to house them up to about three-quarters of their depth in holes bored in a heavy block of wood, in which the tubes fit snugly when not actually in use, secure from damage and shielded from the light. Each tube should have a label near the top showing clearly its approximate SG, and the cork or stopper should preferably be labelled also. Stock bottles of the pure liquids should be kept in reserve in a dark cupboard.

SG Range

So much for the housing of the heavy liquids: now as to their SG range. An imposing array of tubes containing liquids with closely graded SG values have little value for general work. It is better to limit the stock of ready-mixed liquids to two or three preferred values – using pure liquids where possible, as these have SGs which are invariable apart from temperature fluctuations – and to mix a special liquid to solve any particular problem which may require measurement

Figure 29.1 *A set of heavy liquids: the smaller bottle contains a salt solution for checking amber (see Chapter 24)*

of an SG not very close to any of the standard set. An advantage of using pure bromoform or di-iodomethane (apart from knowing their SG to be reliable) is that one can pour them out when a test is needed into a container suitable for the occasion, and need not be too stingy with the quantity. After the test is finished, the liquid can be filtered back into the stock bottle, thus keeping it in a clean state.

A suitable range of SG liquids which time has found to be most convenient are as follows (see *Figures 29.1* and *29.2*):

1. Bromoform, diluted with toluene or monobromonaphthalene to match quartz: SG 2.65.
2. Pure bromoform: SG 2.90 (usually 2.89).
3. Di-iodomethane, diluted with toluene, bromoform or monobromonaphthalene to match pink tourmaline: SG 3.05.
4. Pure di-iodomethane: SG 3.32.

A practical method by which to keep a check on the SG of the mixed solutions is to use two stones of established SG to act as 'indicators'. Thus a bromoform solution might have as indicators quartz (floating) and aquamarine (sinking to the bottom), serving to show the SG of the liquid to lie between the values of 2.65 and 2.70.

With practice a close approximation to the SG of a stone can be obtained by watching its speed of rise and fall in a known liquid, provided that this has an SG not too far removed from that of the stone – say ±0.10. Even a very rapid rise or fall will give a clue. It is unwise to test porous stones in heavy liquids, as their colour may be affected; turquoise is the chief stone to be careful about in this connection.

So far, heavy liquids have been considered in their most usual function of providing an approximate SG value for gemstones, but it must always be

Figure 29.2 A set of five heavy liquids with two small bottles of adjusting fluids (Krüss/GIA)

remembered that these liquids, within their range, provide perhaps the most accurate of all methods for obtaining the exact SG of an immersed solid, for by careful dilution of the heavier liquid a point can be reached where the stone remains exactly suspended in the fluid, neither rising nor falling wherever it is placed. This matching process, adding the diluent drop by drop, and stirring thoroughly after each addition to ensure a homogeneous fluid, requires a good deal of patience; there is a tendency to overshoot the mark in a desire to speed up the experiment.

Methods of Finding the SG of Liquids

There are a number of ways of finding the SG of the liquid, and these will now be outlined.

Pycnometer Method

A pycnometer or 'specific gravity bottle' (*Figure 29.3*) in its simplest form is just a nicely made little bottle with an accurately ground-in glass stopper pierced with a capillary opening. The weight of water contained in the bottle when

Figure 29.3 The pycnometer or specific gravity bottle

completely filled at a stated temperature is engraved on the vessel, and may be 5, 10, 25, or 50 g. Although usually very accurately made, it is wise to check this figure by weighing the bottle empty and dry and then when filled completely with distilled water at a known temperature. The pycnometer is filled and the stopper is then carefully slid into position and gently pressed home. This will cause an overflow of water through the capillary opening. The bottle should then be wiped dry with a clean cloth or duster, taking care that the heat of the hands does not affect it. The bottle should also be examined to make sure that no air bubbles have become entrapped when the stopper was introduced. The dry weight of the bottle subtracted from the weight when filled with water will then give the weight of the enclosed water at the temperature of the experiment. If this temperature is not indicated by the maker, a comparison can still be made by reference to tables giving the SG water at all room temperatures.

The pycnometer having been calibrated (preferably on some earlier occasion, since it is essential that it be now quite dry), the 'unknown' heavy liquid should now be run in through a small funnel as quickly as possible, filling it to the brim, inserting the stopper, and wiping away the slopover as in the case of water. To avoid mess, this operation should be done on a saucer or some form of dish. As soon as the flask has been dried, it should be weighed. The weight of the fluid contained compared with that of the water gives an accurate measure of its SG. The process is not a very difficult one where mixtures of bromoform or of di-iodomethane are concerned. With Clerici solution it is far less easy and pleasant, owing to the difficulty of removing the overflowed liquid, which cannot just be wiped off, but needs to be rinsed off by means of a jet from a wash-bottle. Since one does not want to use more liquid than necessary, the smaller sizes of pycnometer (5 or 10 ml) are the best, though they are less easy to obtain.

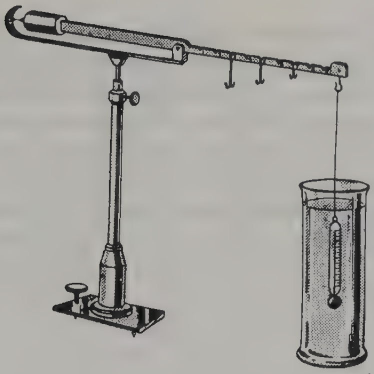


Figure 29.4 The Westphal balance

Modification of Pycnometer Method

What amounts to a rapid variation of the above is to withdraw 5 ml of the solution by means of a pipette (which is a tube with a small bubble in the middle and a tapered outlet, marked in its upper part with a ring up to which the liquid must be sucked) and to discharge the contents of the pipette into a weighed beaker, which is then immediately reweighed and the increase noted.

The Westphal Balance

This is an efficient though simple balance, with one long arm marked at equal distances from the pivot with nine notches and with a hook on the end. The other arm is simply a short counterpoise. A standard plunger, which is also a thermometer, is suspended from the hook and is exactly balanced by the counterpoise (*Figure 29.4*). If the plunger is immersed in a narrow cylinder of water, a wire rider of unit value must be added to the hook to restore the balance. In order for this to happen, the makers have chosen as their unit a rider having a weight that is exactly equal to that of the water displaced by the standard plunger. If a liquid of SG 2.0 were substituted for the water, two such weights would be needed to produce an even balance. With pure bromoform of SG 2.9, a third weight of the same value would have to be placed on the ninth notch in addition to the two unit weights at the end. With a sample of di-iodomethane which has an SG of 3.324, three unit weights would be needed from the end hook, one unit weight on the third notch, one tenth-unit weight on the second notch, and one hundredth-unit weight on the fourth notch. From this it can be seen how by immersing the plunger to standard depth in a liquid of unknown SG, this SG can be determined quite quickly and without calculation by finding the number, denomination and position on the balance arm of the weights needed to bring the apparatus to an even balance. The appropriate rider-type weights representing the various decimal values are provided with the balance. The chief fault of the balance is that a considerable quantity of liquid is required.

By substituting a pan and clip, in which specimens can be held, in place of the normal plunger, the Westphal balance can be adapted to determine the SG of solids if these are not large. With the pan suspended from the hook at the end of the graduated arm, and the clip below it immersed in water, it will be found necessary to add rider weights to the arm to achieve a counterpoise. Let the reading of these (using the decimal notation as outlined above according to their positions on the arm) be A. Clear these weights, place the stone to be tested in the pan, and again add weights to obtain a counterpoise. Let these weights total B. Finally, the process is repeated with the stone held in the clip, immersed in water below the pan. If the weights added on this occasion total C, the specific gravity of the specimen is given by $(A - B)/(C - B)$. This is, of course, only one form of hydrostatic weighing, which will be discussed later in this chapter.

The Hydrometer Method

A hydrometer is a convenient instrument for measuring quickly the SG of a liquid. It usually consists of a glass bulb loaded with shot or mercury, with a narrow stem above it marked with an SG scale (*Figure 29.5*). The instrument is so calibrated that, when immersed in a fluid, it takes up a level such that the correct SG is read off from the stem at the surface of the liquid. With a long stem and widely spaced scale, such an instrument can give an accurate reading to three places of decimals in a matter of seconds, but it would require an inordinately great amount of liquid to float it. A convenient compromise is to have several quite small hydrometers, each of which covers a limited range of SGs. Such instruments, covering the ranges 2.5–3.0, 3.0–3.5 and 3.5–4.0, would fulfil most practical needs. Such instruments are not obtainable from stock but they could be made at no great cost by hydrometer manufacturers.

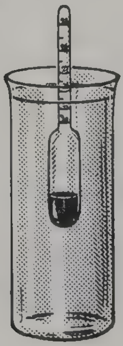


Figure 29.5 The hydrometer

Refractive Index Method

The liquid SG can also be found by taking the refractive index of the solution. The fact that Clerici solution is rather viscous, poisonous and expensive, and can be used only in small quantities, makes the above four methods not very suitable for this liquid. With the method about to be described, however, the reverse is true, since Clerici solution is well adapted for measurement by this technique (also see under 'Sodium Polytungstate' on p. 658).

Where two liquids are completely miscible, and one liquid has a higher refractive index and SG than the other, both the refractive index and the SG of any mixture of the two will depend upon the proportion in which they are mixed, and there is a direct connection between the SG and the refractive index of such mixtures. In the case of Clerici solution, the addition of water, which has a refractive index of only 1.334, to the concentrated solution, which has an index over 1.67, has the effect of lowering both the SG and refractive index very drastically. By carefully diluting a sample of Clerici solution so that three indicators of different known SGs are in turn caused to suspend in a solution, and checking the refractive index at each stage on a refractometer, a graph showing the relation between the refractive index and the SG of the sample of Clerici solution for any intermediate point can be prepared, for the 'plot' of the three indicators should lie in a straight line. Samples of Clerici solution do not vary greatly in this matter and the graph (*Figure 29.6*) will serve fairly well. In any case the slope of the line will be the same for every sample of Clerici solution, so that if, in the case of any particular specimen, the result obtained from the use of the graph is known to be, say, 0.03 too high, the same correction should apply to a specimen of any other SG. The method is extremely rapid once a graph is available, and has the advantage that small quantities of liquid are needed. If great accuracy is aimed at, a very careful matching of specimen and liquid is necessary, and the refractive index must then be taken quickly and accurately, using sodium light, and estimating as closely as possible to three decimal places.

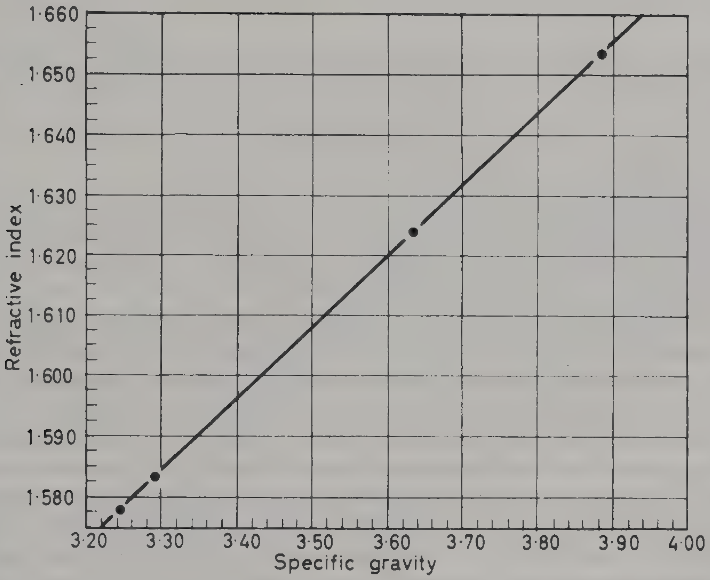


Figure 29.6 Graph of SG versus refractive index of Clerici solution (after Payne, Franklin and Anderson)

Mixtures of bromoform and di-iodomethane, between which there is a good range of both SG and refractive index, can also be utilised effectively by this general method. Where only an occasional experiment of this kind is carried out, there is no need to go to the trouble of making a graph, since the SG can be calculated by simple proportion. For example, pure di-iodomethane with an SG of 3.324 and a refractive index of 1.745 was carefully diluted with bromoform – SG 2.895 and refractive index 1.598 – until the yellow stone under test remained suspended in the stirred mixture. The refractive index of the mixture was found to be 1.697. In using these two liquids an SG difference of $(3.324 - 2.895) = 0.429$ corresponded with a refractive index difference of $(1.745 - 1.598) = 0.147$. The critical mixture showed a lowering of refractive index from that of pure di-iodomethane of $(1.745 - 1.697) = 0.048$. If the corresponding drop in SG is denoted by x, the formula should read

$$\frac{0.429}{0.147} = \frac{x}{0.048}$$

Therefore x equals $(0.048 \times 0.429)/0.147$, which works out at 0.140. The SG of the mixture (and of the specimen) will thus be $(3.324 - 0.140) = 3.184$.

Indicator Method

If a complete range of indicators, differing in SG in steps of only 0.01 or 0.02, were available for the required range, this would provide a rapid and sure means of obtaining an estimate, sufficiently close for all practical purposes, of the SG of any heavy liquid. Such a comprehensive set of indicators could be made from glasses but would be expensive. An indicator set, far less comprehensive but nonetheless useful, was once marketed by the Gemmological Association. The indicators were made of optical glass and the SG value was engraved on each. Aside from this, there is a good range of minerals which can act as indicators, and by intelligent use, if necessary by including pieces of non-gem minerals, it is usually possible to make a close estimate of the SG of an unknown stone suspended in a specially made heavy liquid mixture. Clear pieces of orthoclase (2.56), quartz (2.65), calcite (2.71), fluorspar (3.18), green periodot (3.34), white topaz (3.56), chrysoberyl (3.27) and natural or synthetic sapphire (3.99) are easily obtainable and can be relied upon to have SGs of the values stated.

One other very accurate method of measuring the SG of a liquid will be described a little later, when discussing the use of 1,2-dibromoethane in hydrostatic weighing.

Hydrostatic Weighing

Water

Despite its slowness and certain other disadvantages, hydrostatic weighing remains the most practical method for accurate SG determinations, provided the specimen tested is not too small. The chief requirements are a good balance, a metal or wooden bridge to straddle the left-hand pan of the balance, a beaker of about a 100 ml size, and some fine and coarse wire for suspending the stone in the liquid. A glass thermometer reading to 50 °C or 100 °C is also needed for accurate work.

Either a chemical or a diamond balance can be used. The former will probably be the more sensitive, the latter the more stable and rapid in use. For laboratory work, one of the new types of aperiodic balance is ideal, since it combines accuracy with speed of weighing, and obviates the use of small weights.

First weigh the stone as accurately as possible. It does not matter whether the weights used are carats or grams, since both are based on the metric system, which makes calculation easy. Estimate to 0.005 carat or to 1 mg, according to the weights used. Place the bridge over the left-hand pan in such a way as not to impede the free swing of the balance. Fill the beaker three-quarters full of distilled or boiled water and place it on the bridge. Avoid using water direct from the tap, not because of the impurities it contains, which will not appreciably affect the density, but because it contains a lot of air, and tenacious air-bubbles will form on the stone and wire cage and falsify the results unless prevented or removed.

A spiral wire cage, formed from fairly thick copper or brass wire and capable of holding a strone of from 1 to 50 carats, should have been previously prepared, and provided with the finest possible suspending wire consistent with strength. The suspending wire should end in a generous loop which can slip over the lower hook at the left-hand end of the balance arm. The wire should be made of such a length that when in position the cage is immersed completely, but does not touch the bottom of the beaker. Some balance manufacturers provide accessories for hydrostatic determination of specific gravity (*Figure 29.7*).

The cage should now be suspended from the balance arm, with the spiral immersed in the beaker of water. Any bubbles seen should be removed with a camel's-hair brush (previously well wetted) and the empty cage then carefully weighed. Since this weight will vary only very slightly in subsequent experiments (owing to different temperatures, different amount of water in the beaker, and so on) it will save time to have a note of it in the weight box or some other handy place, though for work of any accuracy its exact weight must be checked on each occasion. An alternative method is to counterpoise the empty cage with a piece of wire cut to the appropriate weight, which can be hung from the hook of the opposite balance arm. If this is successfully done, no allowance for the weight of the cage need of course be made. To get an exact counterpoise for each occasion is, however, a tricky business, and on the whole to substract the weight of the cage each time is more to be recommended.

At this stage, it is usually best to grip the beaker with the left hand and the suspending wire with the right, and remove them both clear of the balance. The specimen to be tested can now be safely placed in the cage and freed from any bubbles before replacing the whole contraption and proceeding to weigh the stone in water.

This done, the necessary figures are to hand: it now remains to apply the formula. The calculation is simple, but it is surprising how often errors are made at this stage. First, subtract the weight of the empty cage from that of the stone and cage weighed together. This will give the weight of the stone alone in water W. Subtract this from the weight in air A, and divide the result into the weight in air. Thus $\mathrm{SG} = A/(A - W)$. For example:

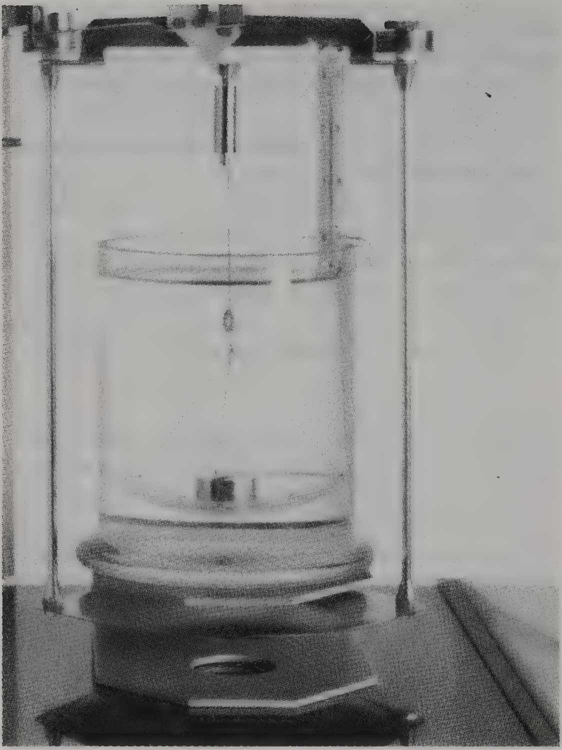


Figure 29.7 A set of hydrostatic weighing accessories for a single-pan balance. The beaker standing on the metal bridge contains a thermometer and an immersed perforated stone holder pan (Salter)

Weight of stone in air	8.405 carats
Weight of spiral in water	15.760 carats
Weight of spiral and stone in water	22.145 carats

Thus the weight of stone in water is (22.145 — 15.760) = 6.385 carats. Therefore

$$SG = \frac{8.405}{8.405 - 6.385} = 4.161$$

Other things being equal, the accuracy of the method depends upon how large the stone is. One says 'large' advisedly, because it is not the weight but the volume that matters, since upon this depends the amount of water displaced, that is the 'loss in weight'. When this figure is large, a small error in weighing, say 0.01 carat, makes very little difference to the final answer, but with small stones, the error becomes serious and the results unreliable. With a ruby weighing 2 carats an error of 0.01 carat in the water weighing will lead to an error of eight in the second decimal place of the SG, which is quite serious. Even with an accurate balance, the method of hydrostatic weighing is hardly worth using with stones of a carat or under, and heavy liquids have to be pressed into service. Modern pocket calculators make the calculations involved a simple matter.

Other Liquids

Greater accuracy with small stones can be obtained by using certain other liquids in place of water, since this has the grave disadvantage of a high surface tension. At the surface of all liquids there is a sort of 'skin' effect, owing to the attraction of the molecules below the surface, and this is called surface tension, and is measured in terms of force per unit length of the surface film (units 10^3 N/m). In water this figure is 73, whereas in ethyl alcohol it is only 23 and in toluene it is 28. Thus, if one of these organic fluids is used – or carbon tetrachloride or 1,2-dibromoethane, which are denser but also have a low surface tension – a much freer swing of the balance will be obtained when the wire is dipping into the liquid. Also the 'wetting' properties of the liquid give less tendency to bubble formation than when using water.

Water has an SG practically equal to unity at room temperatures, so that by simply dividing the weight of the stone by its loss in weight in water the SG can be obtained. When liquids other than water are used, correction must be made for the difference in SG from that of water. All that is required however is to multiply the result obtained by the simple formula given above by the SG of the liquid used at the temperature at the time of the experiment, L. The formula then becomes $[A/(A - W)] \times L$.

The SGs of the commercial samples of these low surface tension liquids can hardly be relied upon beyond the second place of decimals, and moreover the change of SG of each with temperature is too large to be ignored if one is bent on accurate work. A good stock of a chosen liquid (say 500 g, which should be kept in a well-stoppered bottle) should be obtained and calibrated at a known temperature, and the *variation* with temperature of each liquid can be taken without question from the literature. To calibrate a sample a careful hydrostatic determination on two or more pieces of pure quartz (rock crystal) weighing 50 carats or more is carried out. The SG of the liquid is then given by the equation:

$$\text{SG} = \frac{2.6508 \times \text{loss of weight in liquid}}{\text{weight of stone}}$$

Since the known and very constant SG of quartz is 2.6508, if similar results are obtained with several experiments, it can confidently be taken that the value obtained is correct. The temperature of the liquid must be taken carefully during or immediately after the experiment in each case (a thermometer which will read to 0.1 °C is needed). Having now established the SG of the sample for a particular temperature, the SGs of the sample for all temperatures likely to be encountered, say from 10 °C to 25 °C, can be calculated and kept on record. Tables of the SGs for toluene and 1,2-dibromoethane at different temperatures are often given in books, but in practice all that is necessary is to determine the SG of one's sample of liquid by the method described above, using a large specimen of pure quartz as a standard at a carefully noted temperature and for experiments made thereafter at different temperatures to make the necessary correction, given the following data. In the case of toluene (the usual SG of which is 0.8677 at 16 °C) there is a fall in SG of 0.0010 for each rise of 1 °C, while for 1,2-dibromoethane (ethylene dibromide) which has a usual SG of 2.1878 at 16 °C, there is a fall of 0.0020 in SG for a rise in temperature of 1 °C. In the case of water, since the fall in SG is only 0.0002 for each rise of 1 °C it can be seen that a temperature correction is hardly justified since other factors are far more likely to give rise to error. The most serious problem here is the high surface tension of water which causes a 'drag' on the suspending thread or wire. This can largely be nullified by adding a drop of liquid detergent to the surface of the water in the beaker used for the experiment. Care should also be taken to see that the stone is clean and free from grease before the test is made. It is unwise to use water direct from the mains, as this contains air which will form as tenacious bubbles on the specimen. A stock of distilled water or water which has been thoroughly boiled and cooled should be kept on hand for these experiments. Should bubbles form they can be removed by means of a small water-colour paint brush.

In recording SG figures it is seldom desirable to quote more than two decimal places, for, except with very large stones and most careful work, this is the best accuracy that can be attained. It is scientifically a misdemeanour to give a whole string of decimal figures which have no meaning. Significant figures are all that matter; therefore some knowledge of the third decimal place is chiefly useful in acting as a guide to which second figure is the true one. For example, an andalusite giving on calculation an SG of 3.147 would be quoted as 3.15, while one calculated as 3.142 would be given as 3.14.

Weighing Large Specimens

It is often required to obtain the specific gravity of large pieces of material, the size of which is beyond the capacity of the ordinary balance.

An ordinary spring balance, such as that used for weighing silver, may, in an emergency, be used for determining the SG of large carvings and so forth. The specimen is suspended by a wire from the hook of the balance and the weight noted. Then the specimen is immersed in water (dangled in a bucket of water whilst suspended from the balance: a camera tripod makes a useful support for the spring balance) and the new weight is noted. Then, as for normal hydrostatic weighing, the weight in air divided by the loss of weight will give the SG. While not particularly accurate such a determination may be all that is needed to identify a specimen and distinguish between jadeite and nephrite.

The Hanneman Balance

A beam balance of more delicate construction has been designed by Hanneman which is capable of providing a rapid determination of the SG of any unmounted gemstone of reasonable size without the need for any calculation. In this the specimen is suspended by a fine wire or thread from a notch on the left-hand limb of the beam and weights are added to a counterpoise suspended from the zero position on the opposite side of the fulcrum until an exact balance has been achieved. No set weights are needed for this purpose: small pieces of wire, for instance, will serve. The stone is then immersed in a small beaker of distilled or boiled water to which a drop of liquid detergent has been added to lessen the surface tension and prevent the formation of air bubbles, and the counterpoise is then moved along the right-hand beam until the position is reached where an exact balance is again achieved. The specific gravity can then

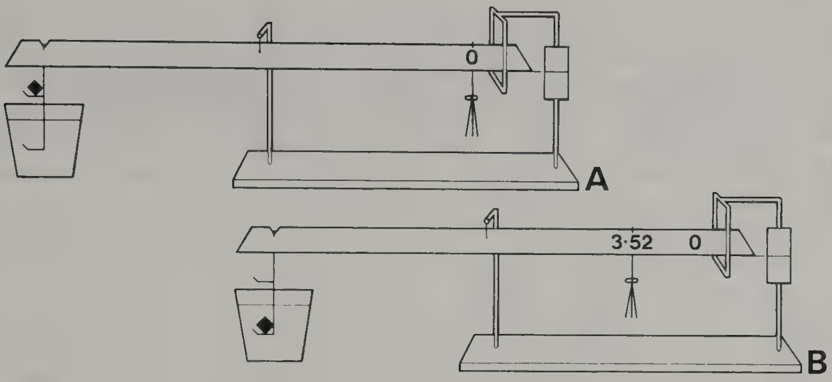


Figure 29.8 *The Hanneman balance*

be read off directly from the scale marked on the beam, which has been carefully calibrated by the makers to give correct results. The very explicit diagram in *Figure 29.8* should serve to make the process quite clear.

Even without actual measurement, the SG of a stone may help in its identification. What the Americans call the 'heft' of a stone, that is the feeling of weightiness or lightness when balanced in the hand, can often serve as a valuable guide, and the faculty of judging SG by this method can be developed considerably by practice.

The jeweller must take notice of the SG of stones when he is asked to estimate for the replacement of stones of another species, i.e. stones which must be of the same size in order to fit the setting. A striking example of this is given where the replacement of a diamond by a strontium titanate (Fabulite) is requested. If the diamond (SG = 3.53) weighs 2.00 carats, then the Fabulite (SG = 5.13) will weigh nearly half as much again – actually 2.91 carats. If this effect is not taken into account there may be considerable error in estimating the cost of the alteration. The difference in weight of two stones of the same size but of different species may be ascertained by using the following formula:

$$\frac{\text{SG of the stone required} \times \text{weight of the original stone}}{\text{SG of the original stone}}$$

A table of specific gravities is given in the identification tables at the end of the book.

Temperature Scales

In the SI system, thermodynamic temperature is expressed in kelvins (K). Scale temperature is given in degrees Celsius (formerly degrees centigrade). On this scale, the freezing point of water is 0 °C and the boiling point is 100 °C. These values correspond to 273.15 K and 373.15 K. The corresponding values on the Fahrenheit scale are 32 °F and 212 °F.

30

Light and Optical Effects

Early Investigations into Laws of Light

It is only natural that speculations as to the nature and investigation into the laws of light should have begun very early. The most reasonable of the early theories was that of Pythagoras (about 550 BC), who considered the sensation of sight to be caused by particles continuously shot out from luminous surfaces and entering the pupil of the eye. The school of Plato maintained that the sensation of sight was caused by the union of three ocular beams. The first was a stream of 'divine fire' emanating from the eye itself, the second something emanating from the object seen, and the third that of the light of the sun, but the whole idea was extremely nebulous. However, the Platonists knew two very fundamental laws of light: (1) that light travelled in straight lines when it travelled in a homogeneous medium, (2) that even when a ray of light was reflected at any surface the angle between the incident ray and the surface was equal to the angle made by the reflected ray.

The Egyptian astronomer Ptolemy, about AD 150, made an investigation of the bending of the light when it passed into glass and into water, but although he measured and tabulated the angles the incident ray makes with the surface, and the angles the refracted ray in the second medium makes with the surface, he did not succeed in seeing what laws connected them. In 1621, W Snell, a professor of mathematics at Leiden, discovered the laws of refraction which Ptolemy failed to deduce from his experiments. Snell died in 1626 without publishing his results, and René Descartes, who had perused Snell's papers, published them as his own discovery a few years later.

The seventeenth century produced many advances and discoveries in the theories of light. Grimaldi, in 1665, gave an interesting account of experiments on 'diffraction', which is the name he gave to the small spreading out of light in every direction upon its admission into a darkened room through a small aperture: an experiment that showed that light bends round corners in the same way as sound does, but to a very much smaller extent. A year later Sir Isaac

Newton discovered that light could be separated into its component colours when it was passed through a prism of glass, and he developed the idea that light consists of exceedingly minute particles shot out from a luminous body which caused the sensation of sight when they impinged upon the retina. This emission or corpuscular theory was indeed similar to that proposed by Pythagoras some 2000 years earlier. Newton's masterly handling of the theory and his authority in the world of science combined to retard for nearly 200 years the development of the wave theory expounded by the Dutch physicist Christian Huygens in 1678.

Erasmus Bartholinus, in 1669, discovered double refraction and polarisation, but the phenomena were not explained until the work of Fresnel some 150 years later. In 1676 Olaus Römer, the Danish astronomer, by observing apparent irregularities in the time of rotation of Jupiter's satellites, demonstrated that light travels with a definite speed through space, and he estimated the speed of light to be about 3×10^8 m/s. Two years later Huygens formulated the first clear statement of the wave theory, which supposes light to consist of waves of some sort emanating from a luminous surface, and he showed how reflection and refraction follow normally from such a theory, but he was unable to show why light bends round corners so little.

It was about 130 years later that Thomas Young discovered the principle of interference and showed how a beam of light may be divided into two portions, which under certain conditions will produce darkness when both portions illuminate the same point. This follows quite naturally from any wave theory but would not be possible with a corpuscular theory such as that postulated by Newton. Young had in mind longitudinal waves such as may be demonstrated by the transmission of compression along a spiral spring, and it was left to Fresnel in 1814, by introducing a happy guess made by Robert Hooke in 1672, to propose that the waves were transverse, that is the individual particles in the path of the wave vibrate perpendicularly to the direction in which the wave is travelling, in the manner of the waves produced on the surface when a stone falls vertically into calm water.

Fresnel, by assuming the transverse character of the waves, was further able to explain the polarisation of light.

Wave Theory of Light

The wave theory of light postulates that it must travel in some sort of medium, a medium which fills all space, and to account for this there was assumed the existence of a hypothetical medium, elastic and weightless, which was termed the ether, and which pervades all space and all material bodies. The theory supposes that wave motion is propagated by successive parts of the ether setting each other in motion by mutually attractive forces.

In 1873 the wave conception was modified by the introduction of the electromagnetic theory of James Clerk Maxwell who, following Michael Faraday's work on electromagnetism, suggested that the vibrations were due to periodic alterations in the electrical and magnetic condition of the ether. Maxwell showed mathematically that the ether which was required for the conveyance of light was the same as was required for the transmission of

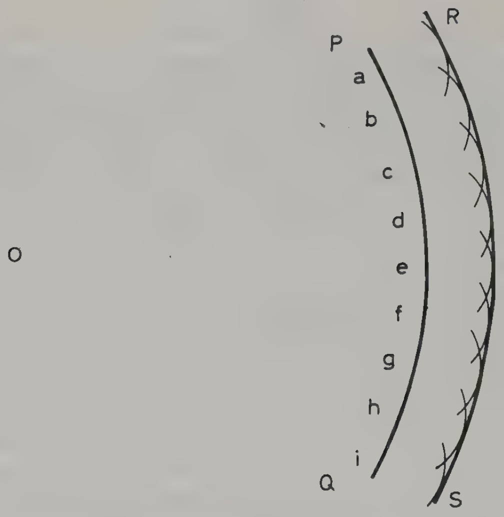


Figure 30.1 *The formation of a wave-front and a secondary wave-front*

electric and magnetic actions, and the known laws governing these would lead to electromagnetic waves which have all the characteristics of light. Twenty years later H Hertz proved experimentally the existence of electric waves, confirming Maxwell's theoretical reasoning.

The electromagnetic wave theory shows light to be a form of radiant energy, which, as it has particles which have mass as well as wave form, is of dual nature. Whilst most of the characters of light may be explained by the wave theory, in the detailed explanation of the emission and absorption of light, and of fluorescence, it has been found necessary to use another theory, the quantum theory of Max Planck. This theory states that light energy can only be emitted or absorbed in small 'packets' of definite size, called quanta or photons. Modern physicists use both theories and the two have not been completely unified. As the work of the gemmologist mainly concerns the behaviour of the light rays through crystals and optical instruments, his prime interest lies in the wave theory.

Formation of the Wave-Front

According to the wave theory of Huygens, each point in a luminous surface is vibrating and sending out spherical waves into the ether. Each vibrating point in the wave-front is the source of a secondary wavelet, and at any instant the surface which touches all the secondary wavelets is the new wave-front. In *Figure 30.1*, O is a luminous point and PQ a portion of the spherical wave-front. The neighbouring points a–i will all be vibrating in unison and each of these may be considered as the centre of a new disturbance sending out its own spherical wavelet. At a certain instant these wavelets are represented by the arcs of circles which have a–i as their centres, and it is evident that the position RS of another sphere with O as its centre envelops the secondary wavelets and forms the new wave-front. If the point O is a great distance away PQ becomes a straight line and the wave-front becomes a plane wave-front and the secondary wave-front is also plane (*Figure 30.2*).

The Wave Form

The generalised idea of a wave form is shown in *Figure 30.3.* The length of the nearest distance measured between two particles on the wave surface in identically the same position and travelling in the same direction is the wavelength and is usually designated by the Greek lower-case lambda (λ). The intensity of the energy (light) is determined by the amplitude which is shown by the distance of the top of the wave curve from the mean level. The intensity of the light is proportional to the square of the amplitude, and inversely proportional to the square of the distance from the source. The path travelled by the wave between one wavelength constitutes one cycle and the number of these cycles completed each second is the frequency, which may be expressed as the speed of light in air (strictly, a vacuum) divided by the wavelength. The frequency remains constant regardless of the medium through which it passes. However, the distance travelled or the speed of travel does not remain constant

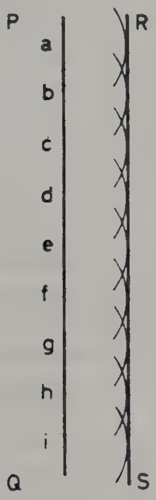


Figure 30.2 The formation of a plane wave-front and a secondary plane wave-front

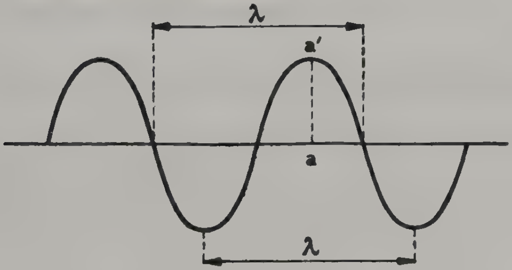


Figure 30.3 Wave form. λ indicates wavelength and a–a′ the amplitude

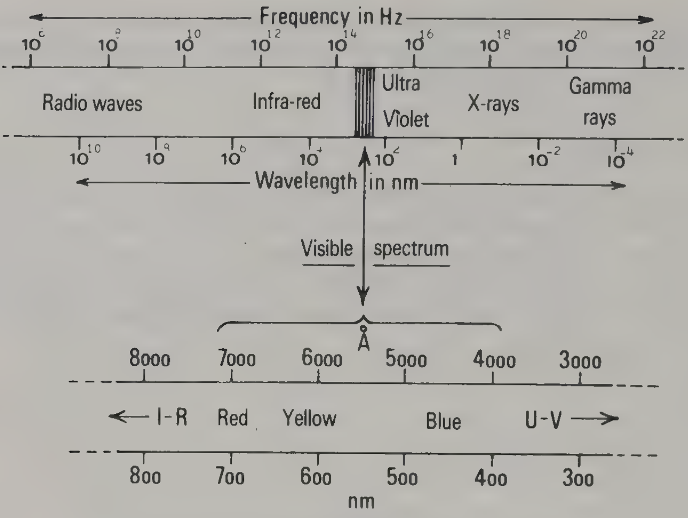


Figure 30.4 The electromagnetic spectrum

from one medium to another, for on entering an optically denser medium there is a resistance to the transmission and the wavelength for the given form of energy changes. On emerging from the dense medium the wave assumes its original shape and speed.

Electromagnetic Spectrum

Visible light forms only a small part of the electromagnetic spectrum known to science which stretches from the high-frequency (short-wavelength) gamma rays to the long radio waves, and beyond (*Figure 30.4*). Besides the visible spectrum other ranges of the long electromagnetic spectrum, such as X-rays, gamma rays, and ultra-violet light, and maybe infra-red rays, have an importance in the study of gemmology. The convention used in *Figure 30.4* is that most commonly adopted by gemmologists, with the longer wavelengths on the left and decreasing length of wave to the right. In the discussion in Chapter 33 of the absorption spectra of gemstones it will be seen that this is continued and the long wavelengths are on the left. From the beginning of the use of the absorption spectra as an aid to gem testing it has been the convention to have 'red on the left' in Europe, although in the USA red is on the right.

Measurement and Speed of Light

There are various units of measurements used for the shorter wavelengths, one being the ångström (10^{-10} m), suggested by the Swedish physicist A J Ångström in 1868. This unit is indicated by the letter Å. The standard today is the nanometre (nm) (10^{-6} mm or 10^{-9} m). The micron or micrometre (μm)

(10^{-3} mm or 10^{-6} m) is also used. Thus the mean wavelength of sodium light is 5893 Å, 589.3 nm, or 0.5893 μm, according to the unit it is expressed in. The range which constitutes visible light is usually given as between 400 nm and 700 nm, but much depends upon the acuity of the eye, which varies between different people, some being able to see farther into the 'invisible' ultra-violet and infra-red than can others. Note that the term micron is so firmly entrenched that it will be some time before it is finally superseded by micrometre, especially as a measure of the grain sizes of diamond powders.

Any electromagnetic radiation can be defined by either its wavelength (λ) or its frequency (ν). The units of wavelength have been discussed above, but a more direct measurement of the energy of radiation is the frequency. However, frequency values for a given range of wavelengths often result in the use of inconveniently high numbers, and to overcome this the reciprocal, called the wave number, is used: this is the number of waves per unit length. Physicists often use another unit, the electron volt. This is the energy acquired by an electron when it falls through a potential of one volt.

During the nineteenth and twentieth centuries a number of determinations of the velocity of light in air or vacuum were made, and the speed, for practical purposes, was found to be 300 000 km/s (186 000 mi/s). The results of all recent experiments are consistent with giving a velocity of light *in vacuo*, usually denoted by the symbol c, as $2.997\,925 \times 10^8$ m/s.

Light Transmission

Transparency

The ability of a material such as a gemstone to transmit light is termed transparency, and a rough classification into degrees of transparency made be made as follows:

1. Transparent – when an object viewed through the material appears clear and distinct.
2. Semi-transparent – considerable light penetrates the material but the object seen through would appear blurred.
3. Translucent – some light passes through but no object can be seen.
4. Semi-translucent – slight transmission of light through thin edges of the material.
5. Opaque – no light passes through the material.

These descriptions are considered to refer to specimens of ordinary thickness, for in thin section most 'opaque' substances transmit some light.

Reflection

More important considerations are the behaviour of light when it is returned from the surface or is transmitted through a substance. When light falls on any surface separating two media (the term medium is used to express any substance through which light passes and may refer to either solids, liquids or gases) part of its is always reflected back into the first medium and part refracted into the second.

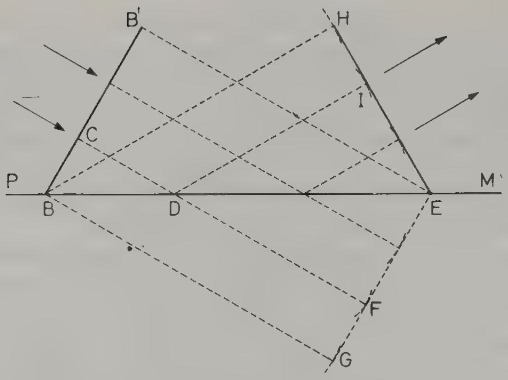


Figure 30.5 *Reflection of a wave-front*

A wave-front impinging on a plane surface is returned at a similar but opposite angle (*Figure 30.5*). PM is the reflecting surface and BB′ a wave-front. As soon as the wave-front strikes the surface a secondary wave is sent out from B, and each point on the wave-front, such as C, gives rise to a secondary wave when it reaches the surface, as at D, and at the instant at which reflection is complete a secondary wave is about to start from E. If reflection had not occurred the point D on the wave-front would have reached F; instead a secondary wave of radius DI equal to DF has developed and similarly the reflected wave at B gives rise to a secondary wave of radius BH equal to BG. The straight line joining the apices of these radii with E forms the new wave-front.

A simpler manner of expressing the laws of reflection is by indicating the wave by a straight line (*Figure 30.6*), where the incident ray IO falling on a

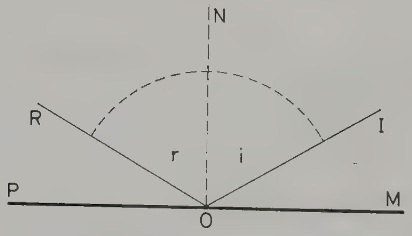


Figure 30.6 *A simple illustration of the laws of reflection*

reflecting surface PM at O (called the point of incidence) is returned along OR. NO is termed the normal at the point of incidence, the normal being an imaginary line at right angles to the surface separating the two media at the point of incidence. The angle ION is the angle of incidence (*i*) and the angle NOR is the angle of reflection (*r*). The laws of reflection are therefore: (1) the angle of incidence (*i*) is equal to the angle of reflection (*r*); (2) the incident ray, the normal and the reflected ray are all in the same plane.

Refraction

When light enters the second medium refraction occurs and the light is bent away from the original direction of travel. If the ray is travelling from an optically rarer medium to an optically denser medium the ray is slowed up and is sent towards the normal. Should, however, the ray be travelling from an optically denser to an optically rarer medium the ray is bent away from the normal. Refraction may be illustrated by the analogy of a column of soldiers being slowed up and deviated when marching from open ground into a dense wheatfield and out again into open ground (*Figure 30.7*).

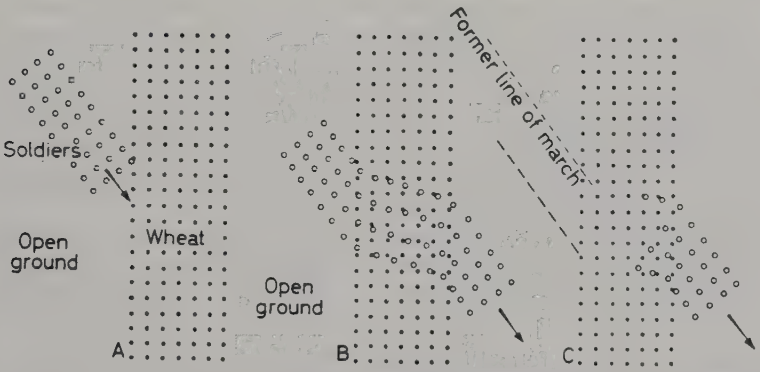


Figure 30.7 *A column of soldiers deviated when passing through a dense wheatfield*

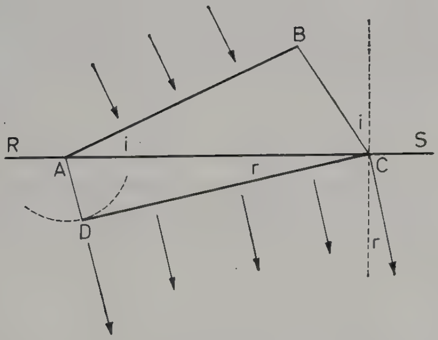


Figure 30.8 *Refraction of a wave-front*

The refraction of a wave-front when it meets the surface separating a rarer and a denser medium is shown geometrically in *Figure 30.8*. In this diagram RS is the surface separating the two media and AB the advancing wave-front. Assuming the denser medium to be twice as optically dense as the first medium the light advancing from A will be slowed up to half the speed it had whilst travelling through the first medium; hence the wave will only travel half the distance as the ray travelling along AB. Therefore, if there is described in the denser medium an arc of a circle with centre A and radius half BC, a tangent drawn from this arc to C will be the new wave-front.

Refractive Index

For any two media in optical contact Snell found the following laws of refraction to be true:

1. The sine of the angle of incidence bears to the sine of the angle of refraction a definite ratio which depends only upon the two media in contact and the nature (colour) of the light: that is (sine *i*)/(sine *r*) is a constant.
2. The incident ray, the normal at the point of incidence and the refracted ray are all in the same plane.

When the optically rarer medium is used as a standard, and air (strictly, a vacuum) is universally so used, the ratio (sine *i*)/(sine *r*), when light passes into the second medium, is known as its refractive index. However, as the refractive index of a medium differs for different-coloured light rays, that is for different wavelengths, it is usual to use the yellow light of sodium vapour which is a nearly monochromatic light having a mean wavelength of 589.3 nm. Reference to *Figure 30.8* shows the angle BAC equals *i*, and the angle ACD equals *r*. Thus (sine *i*)/(sine *r*) = (BC/CA)/(AD/CA) = 2.00, providing that the sine rule and the velocity relationship are equivalent.

A simpler geometrical exposition of the refractive index is by indicating the light rays as straight lines (*Figure 30.9*). The incident ray IO strikes the surface of the two media at the point of incidence O and is refracted along OR. The normal is shown as NM. The angle of incidence (*i*) ION is clearly seen to be greater than the angle of refraction (*r*) ROM. Any increase or decrease in the angle of incidence will cause an increase or decrease in the angle of refraction, and this will be in some definite proportion relating to the sine law. If a circle (*Figure 30.9*) is described with its centre at O and with any radius which cuts in the incident and refracted rays at (a) and (b) respectively, and perpendiculars (ca) and (bd) are dropped on to the normal, there are produced two right-angled triangles whose hypotenuses are the incident and refracted rays enclosed by the circle. In a right-angled triangle the sine of an angle is the ratio between the side

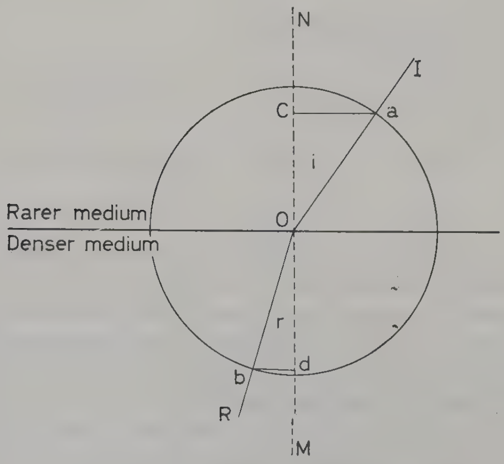


Figure 30.9 *The geometry of refractive index*

opposite the angle and the hypotenuse (the hypotenuse is the side opposite the right angle). As the hypotenuses in both triangles have the same length, being the radii of the same circle, the refraction could be measured by the ratio of the lengths of (ac) and (bd), and if the upper medium is air this ratio will be the refractive index. It will be shown later, when the measurement of refractive index is discussed, that this geometrical method may be used to obtain a rough idea of the paths of rays when the refractive indices of the two media are known. In practice, the trigonometrical ratios of the sine of the angles as given by Snell's law is used, for the angles of light rays can by suitable instruments be measured accurately.

Critical Angle and Total Internal Reflection

Light is reversible, and hence a ray can pass from a denser to a rarer medium, in which case, as already mentioned, the refracted ray bends away from the normal; that is the incident ray (now in the denser medium) makes a smaller angle with the normal than does the refracted ray. Therefore, when the angle of incidence is progressively increased there must be an incident ray which refracts out of the first and into the second medium so that the refracted ray makes an angle with the normal of 90 degrees, that is the ray just grazes the surface of the two media in contact. Any further increase of the angle of incidence will require the ray to turn back into the first (denser) medium where it obeys the laws of reflection and not the laws of refraction. The angle of incidence which gives an angle of refraction of 90 degrees is termed the critical angle, and the effect where the ray is turned back into the first medium is termed the total internal reflection of light. The connection between refractive index and critical angle is expressed by the formula sine $i = 1/n$, where i is the critical angle and n the index of refraction. Hence, it follows, if air is the rarer medium, that the higher the refractive index of the denser medium the smaller will be the critical angle.

The critical angle and the total internal reflection of light are illustrated by *Figure 30.10*, where IO2 is the angle of incidence which gives a refracted ray, OR2, of 90 degrees, that is the critical angle, and IO3, a ray which is greater than the critical angle, is totally reflected along OR3. Total internal reflection is an important property of which advantage is taken in the construction of many optical instruments, including the refractometer, and to it the brilliancy of diamond and other stones of high refraction is in part due.

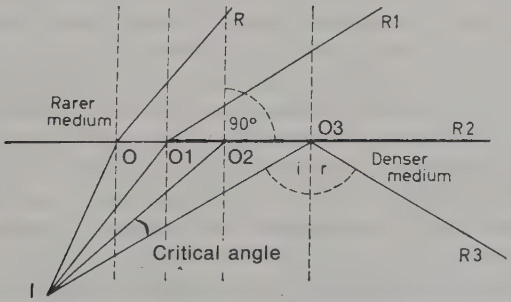


Figure 30.10 *Total internal reflection of light and the critical angle I,O2,R2*

Colour Dispersion

In the descriptions of light rays just given a single wavelength (colour) of light has been assumed, but white light, as Newton found, is composite. A medium has a different refractive index for each wavelength (colour of light): hence a beam of white light which is incident at an angle and then passes through the transparent medium with parallel sides emerges laterally displaced but parallel to the incident rays (*Figure 30.11*). The emergent rays are uncoloured, for the difference in the angles of refraction of the various coloured rays refracted into the parallel plate are countered by the similar, but opposite, angles of refraction on their emergence into the air again, and are thus recombined into white light.

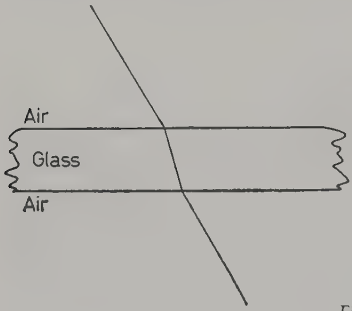


Figure 30.11 Paths of rays through a parallel-sided plate

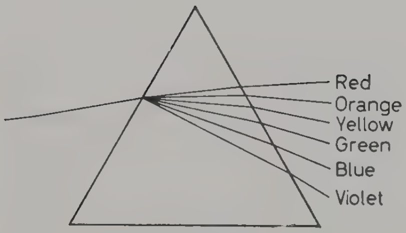


Figure 30.12 Colour dispersion of white light on passing through a prism

If a beam of white light passes through a transparent medium with two inclined faces, such as a glass prism, the rays fan out into the familiar colours of the rainbow, as each colour is deviated still farther on emergence and cannot recombine. The longer waves (red light) are bent or deviated least, and the shorter waves (violet light) are bent more, or are said to be more refrangible (*Figure 30.12*). This 'analysis' of white light is termed colour dispersion and is the cause of the chromatic effect seen in gemstones which is called fire.

Colour dispersion, usually shortened to 'dispersion', is strong in diamond, synthetic rutile, white zircon and the synthetic strontium titanate, while in such coloured stones as demantoid garnet and sphene the dispersion though also strong is in these cases masked by the colour. Dispersion is measured by the difference between the refractive index of the medium for the red ray and for

Table 30.1
Refractive index and wavelength values of diamond

Fraunhofer line	*Colour*	*Wavelength*	*Refractive index*
B	Red	687 nm	2.407
D	Yellow	589 nm	2.417
E	Green	527 nm	2.427
H	Violet	397 nm	2.465

the violet ray. As there are many red rays and many violet rays (wavelengths which cover these two colours) it is usual to measure the refractive index of the medium for the Fraunhofer B line of the solar spectrum (687 nm in the red) and the G line (430.8 nm in the blue-violet). Subtracting the value of the refractive index of the B ray from the index of the G ray, the dispersion of the medium for the B to G interval is found. For some purposes, especially in the case of optical glasses, the smaller interval between the Fraunhofer C line (656.3 nm in the orange-red) and the F line (486.1 nm in the blue) is used. *Table 30.1* illustrates the refractive indices of diamond for different colours of the spectrum.

Therefore the dispersion between these red and violet wavelengths gives the dispersion of diamond as 0.058, but between the more restricted B to G range (which is for practical purposes universally adopted) the value of dispersion for diamond is 0.044, and between the C and F lines is 0.026.

Plotted on a graph with the refractive indices as ordinates and the wavelengths as abscissae, the resultant 'curve' is found to be not a straight line but a curve with varying curvature. This is more prominent in some stones and occurs because the refractive index increases strongly on the short-wave side of the spectrum. The dispersion of light through glass prisms is made use of in the spectroscope, an extremely valuable instrument for the identification of gemstones by their absorption spectra, a subject which is discussed in Chapter 33.

Accurate measurements of the dispersion of gemstones are made by obtaining the refractive indices of the stones for red and blue light (the difference between the two measurements giving the dispersion) by using the method of minimum deviation (discussed later).

The effect of dispersion on the position of shadow edges seen on the refractometer is often misleading. It should be realised that, owing to the much higher dispersion of the dense lead glass used in standard refractometers compared with that of any of the stones tested, the position of the shadow edge as seen using light of different spectrum colours is the reverse of what might be supposed. However, using red and blue monochromatic light, and reference stones of known dispersion such as benitoite (0.047) and fluorite (0.007), Hanneman has shown that a dispersion calibration chart can be produced for any refractometer which enables the differences in red and blue refractive index readings for any gemstone to be related to its dispersion. On the Rayner Dialdex, for example, the zero difference for a highly dispersive gem such as benitoite indicates a large dispersion, while a gemstone with a large reading difference such as fluorite indicates a low dispersion.

Optical Effects

Lustre and Sheen

Certain characters of gemstones are due to reflection and refraction of light. Of these fire has already been referred to, but the surface brilliancy of a gemstone, known as the lustre, depends upon the quality and quantity of the reflected light, and this depends in turn upon the refractive index of the substance and the perfection of its polish. Since the perfection of polish depends largely on hardness, this also has a marked effect on the brilliancy of a stone. Among opaque substances metals have the highest lustre. In addition many sulphides (such as pyrites) and oxides (such as hematite) have a metallic or submetallic lustre. The majority of gemstones, however, have an index of refraction similar to that of ordinary glass, and hence are said to have a glassy or vitreous lustre. There is a division into other types which are listed in *Table 30.2*.

Table 30.2

Lustre	*Mineral*
Metallic	Silver
Adamantine	Diamond
Subadamantine	Demantoid garnet
Resinous adamantine	Certain zircons
Vitreous	Quartz
Resinous	Amber
Silky	Fibrous minerals such as satin-spar
Pearly	Usually seen only on cleavage surfaces
Waxy	Turquoise

Lustre is, therefore, a reflective effect from the surface of the stone, but reflection can occur at surfaces of differing refractive index within the stone, and such an effect is termed sheen. The most common of these is the whitish or bluish sheen, or schiller, seen in the moonstone variety of feldspar, which is termed adularescence, and is due to an intergrowth of albite and orthoclase feldspars in alternate layers. The silvery sheen seen in silver obsidian is likewise due to reflections from microscopic needles (microlites) because of incipient crystallisation in the natural glass. The flashes of colour so prominent in labradorite feldspar, known as labradorescence, may be in part a sheen effect but is more probably due to an interference effect at thin films, a phenomenon discussed later in the chapter.

The lustres listed in *Table 30.2* are qualitative descriptions. However, the lustre, or surface reflectivity, of a polished gem can also be measured in absolute terms as the ratio between the intensity of the incident ray and that of the reflected ray. Lustre, in terms of reflectance, is directly related to refractive index and can be used for the identification of polished gemstones. This, and the operation of the reflectance meter, is described more fully in Chapter 32.

Chatoyancy and Asterism

Other optical effects within the stone are those due to reflections from numerous parallel cavities or fine fibrous inclusions regularly oriented in accordance with the symmetry of the crystal. Of these, the cat's-eye effect, termed chatoyancy, is one of the more important. This effect was amply explained when the most important cat's-eye, chrysoberyl, was discussed in Chapter 5. Other species producing cat's-eyes include quartz, tourmaline, beryl, scapolite, diopside and apatite.

When the cavities or fine needle-like inclusions are parallel to more than one crystal face, a star-stone is produced when the stone is cut cabochon with the apex of the dome perpendicular to the plane of the included structures. The star is in general best seen by a single reflected light, and the effect is then known as epiasterism. When light is transmitted through the stone the effect is termed diasterism and this is common in rose quartz; the effect in this mineral is made use of in constructing a composite stone which produces an imitation of star sapphire. The best star-stones are produced by rubies and sapphires which show three bright rays crossing each other at 60 degrees at the centre and thus producing a six-pointed star. Occasionally a six-rayed (12-pointed) star is seen which is due to a second set of needles oriented on the second-order prism. A feeble star effect is sometimes seen in spinel and garnet, which may give a four-pointed star or, if the needles are oriented parallel to the faces of the dodecahedron, a three-rayed (six-pointed) star. Beryl is sometimes found with a star effect but this is usually very weak.

Opalescence

Another optical effect due to internal reflection is the scattering of light by particles of matter in the path of the light, making a visible 'beam' or 'cloud' such as is caused by a ray of light illuminating particles of dust floating in the air of a room. This is the so-called Tyndall effect and is the cause of the milky opalescence in some opal, and in opalescent glasses and some pastes. It also causes in part the optical effect in moonstone.

Interference

If light waves from a single source are split into two rays and then recombined after one of the parts has travelled a short extra distance, the two rays may be out of phase with one another, that is the crests of the two sets of waves are not accurately superimposed. Hence the phenomenon of interference occurs.

The iridescent colours which are exhibited by thin films of transparent substances are caused by this type of interference and may be explained by *Figure 30.13.* AC represents a ray of light incident on the thin film – magnified greatly in the diagram – at C. Part of this ray is reflected along CB and the other part refracted along CD. At D part of the ray is reflected along DJ and the other part is transmitted along DG. Of the ray DJ part is reflected, and the other part is refracted along JF. The two parallel rays CB and JF interfere when they are brought to a focus at the same place by any lens such as that in the eye, for the

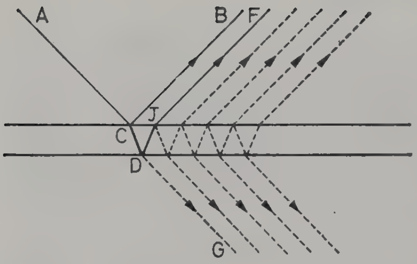


Figure 30.13 Diagram explaining the interference of light at thin films of differing refractive index

reflected ray at C has only to travel along CB whilst the ray CDJF has to travel the distance CD and DJ in the film. Therefore, there is a path difference between the two rays which is greater the greater the thickness of the film and the greater the obliquity of the ray. With monochromatic light (light of a single wavelength) reinforcement or darkness will occur according to whether the path difference is a whole number of wavelengths or an odd number of half-wavelengths. Since in white light the different colours of the spectrum are merely waves of different lengths the different colours will be reinforced with different thicknesses of film and with different obliquities. This is the explanation of the colours in a soap bubble and those seen on an oil film on a pool of muddy water. It is also a cause of the play of colour seen in opal, and similar flashes in labradorite feldspar, and in part the bluish schiller of moonstone.

Electron microscopy has shown that the effect may be due as much to diffraction from a 'lattice' as to 'interference at thin films'. In opal, particularly, it has been shown the structure consists of a regular arrangement of 'spheres' producing the so-called 'Bragg lattice' from which diffraction occurs. Thus white light will be split up into colours, depending on the angle of incidence of the rays.

Double Refraction and Polarisation

In treating with the reflection and refraction of light it has so far been assumed that the light travels through the medium as one ray. This is true in the case of singly refractive substances, termed isotropic media, such as glass, resins, gels, and minerals which crystallise in the cubic system. However, in the case of the crystals belonging to the remaining six crystal systems the light rays do not behave in such a simple manner, for on entering such media the rays divide into two parts, each of which, in general, travels with a different speed and hence has a different index of refraction. Such materials are known as doubly refractive or anisotropic media.

This splitting of a ray into two rays causes an object which is viewed through the medium to appear to have double edges, the amount of separation varying with the amount of the double refraction; the strength of the double refraction is the difference between the refractive indices of the two rays along the viewing direction. This doubling effect is particularly well seen in the case of the clear colourless variety of calcite called Iceland spar (*Figure 30.14*) and may be seen in

Figure 30.14 *The doubling of print as seen through a rhomb of Iceland spar*

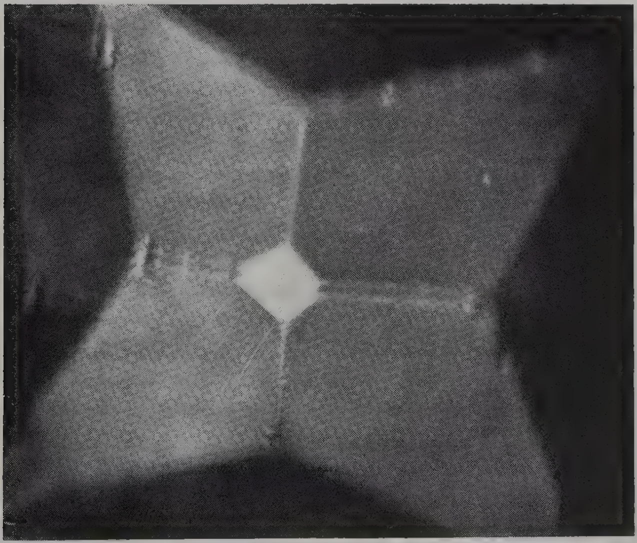


Figure 30.15 *The doubling of the back facets as seen through a tourmaline by the use of a microscope or lens*

most doubly refractive gemstones, which will show the rear facet edges doubled when they are viewed through the stone with the aid of a lens or microscope (*Figure 30.15*).

It must be pointed out that double refraction will not be seen along any direction parallel to an optic axis (see below). Nor will it be seen if a stone is viewed in a direction at right angles to such an axis, for then, despite the fact that the double refraction is at its maximum, the two images are superimposed on one another and cannot be seen as separate.

Ordinary light radiation from a luminous source consists of an amazing mixture of vibrations lying at all possible directions at right angles to the direction of travel of the ray of light. Such light is said to be unpolarised. When, for one reason or another, vibrations in one direction predominate over those in the other directions, the light is partially or completely plane polarised, that is the transverse waves are vibrating in one plane only (*Figure 30.16*). As has already been shown, when a dot is viewed through a piece of Iceland spar two dots are seen side by side. Then, if some suitable polariser be rotated over the first piece of spar the two images of the spots disappear and reappear alternately, showing that the rays have attained a one-sided nature; in fact they are plane polarised at right angles to each other. This polarisation of the two rays in doubly refractive stones is of considerable importance in gem testing.

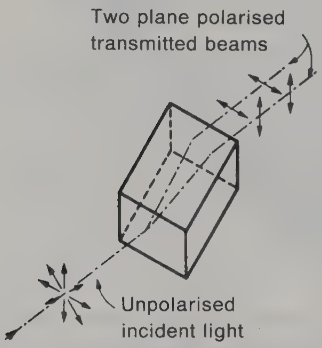


Figure 30.16 Double refraction and polarisation

Optic Axes

In crystals belonging to the tetragonal, hexagonal and trigonal systems there is one direction, that parallel to the vertical crystal axis, in which light behaves as if the crystal were singly refracting. Such a direction of single refraction in a doubly refracting crystal is known as an optic axis, and as there is one such axis in crystals of these three systems such crystals are termed uniaxial crystals. In any other direction in the crystal the ray is split into two rays with maximum divergence when the ray is travelling perpendicular to the optic axis. One of the rays obeys Snell's law, has a constant index of refraction which is denoted by the symbol ϖ, and is called the ordinary ray; this ray always vibrates at right angles to the optic axis. Depending upon the direction the other ray takes within the crystal the speed of the ray varies, that is the refractive index varies between that of the ordinary ray (ϖ) and a second limiting value; hence this ray is known as the extraordinary ray and is denoted by ε. In directions parallel to the optic axis only the ordinary ray is seen; in all other directions the extraordinary ray is also found, varying in its refractive index, and when it reaches its fullest divergence the ray vibrates parallel to the optic axis. The arithmetical difference between the refractive index of the ordinary ray and that of the extraordinary ray at its maximum divergence gives the birefringence (double refraction). Further, the speed of the extraordinary ray (ε) may be either slower or faster than the ordinary ray (ϖ); if it is faster, that is it has a lower refractive index than that of the ordinary ray, the crystal is said to be optically negative, and if slower to be optically positive, that is when the extraordinary ray has a higher index of refraction than that of the ordinary ray.

The optics of the other three systems, the orthorhombic, monoclinic and triclinic systems, are much more complex, for there are three optical directions and two optic axes in such crystals, which are hence termed biaxial crystals. The three mutually perpendicular critical vibration directions, to each of which belongs a definite refractive index, correspond to the maximum, intermediate and minimum light velocities. They are designated α, β and γ respectively, but β is not the arithmetical mean between α and γ; for the β refractive index is sometimes nearer to α than to γ, when the crystal is said to be optically positive, or is nearer to γ than to α, when the optical sign is negative. Further consideration is given to these optical directions in Chapter 32 on the measurement of refractive indices.

Gem Testing without Instruments

The various optical effects to be observed in transparent gemstones have been briefly described in the foregoing pages. It is the combined effect of these which determines the appearance of faceted stones, and not only contributes to their beauty but produces an impression which to the trained eye of a connoisseur is sufficiently characteristic to enable it to be recognised with some certainty. It is useful for the student of gems to realise that even without the use of instruments a knowledge of the properties of all the principal gemstones can assist in their identification. Thus, the SG of a stone can be roughly assessed by its 'heft', i.e. the feeling of weightiness in the hand; its hardness by the quality of the polish and the sharpness of its facet edges; and its heat conductivity by its degree of coldness when touched with the tongue.

With regard to its optical properties, the refractive index of a stone can be roughly gauged by the brightness of its lustre; its dispersion by the degree of 'fire' shown; its dichroism by a change of colour when the stone is viewed from different directions. Its double refraction (though more conventionally shown by the doubling of back facet edges when viewed with a lens through the table facet) can be assessed with considerable accuracy merely by holding the table facet of the stone close to the eye and observing the refracted images of a small source of light (such as a candle flame). In a doubly refracting stone the images of the flame will be seen to be 'doubled' to an extent depending on the facet angles and the nature of the stone. This effect was illustrated in Max Bauer's great book *Edelsteinkunde* published in 1896, the translation of which into English by Spencer is still available as *Precious Stones* in a two-volume paper-backed edition.

A more elaborate discussion of this 'stone to eyeball' technique, which included an estimate of dispersion by observation of the colour fringes produced in the images of the white light source, was given by Crowningshield and Ellison in *Gems and Gemology* in 1951. The general method has been elaborated into a 'system' by Alan Hodgkinson and termed 'visual optics', whereby the refractive index, double refraction, and dispersion of any faceted transparent gem can be assessed with a useful degree of accuracy (*Journal of Gemmology*, January 1979).

One inconvenient feature of the 'set-up' for the method was the provision formerly demanded for a darkened room and a single (and preferably distant) light source. An ingenious and convenient means of avoiding this difficulty has been provided by Hanneman in the form of a penlight torch with a slit orifice which can be held quite close to the gemstone being tested. A gemmologist practised in this technique can gauge the main optical properties of a faceted gemstone with sufficient accuracy to be reasonably sure of its identity. A powerful accessory to such tests is the careful study under a 10 × lens of any internal structures or inclusions shown by the specimen in question.

31

Colour and Colour Enhancement

Colour is of supreme importance to the lover of precious stones and forms the most important single guide to the identity of a gem so far as the eye is concerned. The subject of colour is a vast and complex one, and in these pages only certain aspects of it can be dealt with at all fully. Colour is the specific response of the eye and its attendant nervous mechanisms to certain kinds of light and, therefore, may be said to come under the category of psychology; it can thus be described and discussed with minimal reference to energy, wavelength or other physical concepts. Since physical phenomena are susceptible to exact measurement, it is the physical basis for colour sensations that can be studied with the greatest profit by the gemmologist. Colour as a sensation and the part played by the human eye will only be briefly dealt with in this work, and the physical and chemical aspects of the subject will be given greater detail.

Defining Colour

Colours of objects differ from one another in three ways, so far as their appearance goes: in their hue, in their value (tone, lightness), and in their chroma (intensity or saturation) (*Figure 31.1*). By hue is meant the dominant wavelength(s) of the colour or that attribute by which a colour can be described as red, green or blue. Tone, lightness or value is that quality of lightness which, in the case of neutral greys, approaches white at one end of the scale and black at the other. The terms chroma, saturation or intensity refer to the vividness of the colour, that is, the degree to which it differs from a grey of equivalent lightness or tone.

The terms tone, saturation and so on may be more useful in discussing the colours of paints and dyestuffs than in gemmology, where hue (usually simply called colour) is the main criterion. Ideally gemstones should have either no trace of colour at all or else a full-blooded (that is, saturated) colour to give true

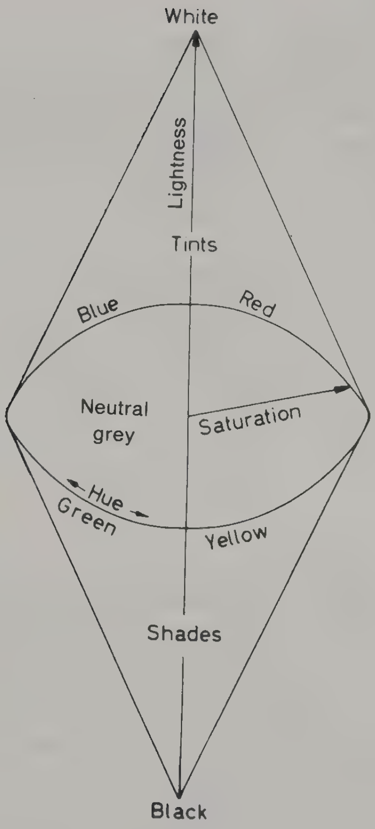


Figure 31.1 *The colour cone*

satisfaction to the eye; tints and shades, which are admirable for distempered walls and textiles, have an insipid effect when seen in transparent material, although in translucent stones such as jade and chalcedony they may be quite pleasing.

The sensation of hue, which is the psychological effect produced by physiological reactions to light, is closely connected with the wavelength of light – thus entering the realm of physics. White light from the sun, or from any other solid incandescent source at a comparable temperature of 6000 °C or so, consists of light of a vast number of wavelengths within the visible range, although the actual radiation from the sun extends far beyond the visible range at either end of the spectrum. This range of visible light extends from about 780 nm to about 380 nm; the longer waves represent red light and the shortest visible rays are violet, while in between are the range of spectrum colours orange, yellow, green and blue – shading imperceptibly into one another. The limits for the visual range given above are not sharp, but depend upon the individual observer and upon the conditions under which the light is presented to the eye; the limits given have been greatly exceeded when powerful emission lines have been received by a dark-adapted eye. On the other hand, the sensitivity of the eye to waves at the ends of the spectrum is so low (*Figure*

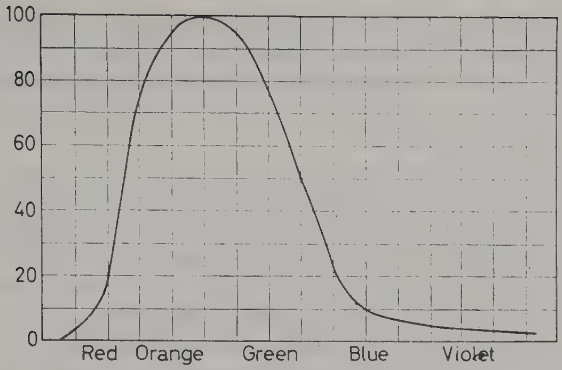


Figure 31.2 *Curve showing the colour response of the normal human eye*

31.2) that the importance of the extreme wavelengths from the colour point of view is entirely negligible. It is more convenient and practical to consider the range of visible light to extend from 700 to 400 nm.

It has already been explained that by passing a narrow beam of white light through a glass prism it can be spread out into a whole series of spectrum colours according to their wavelength. Although there are only six main colour names (or seven if one includes indigo) yet these can readily be subdivided by using such terms as 'orange-yellow', 'yellow-green' and so on, for intermediate hues. The systematic use of these colour terms is recommended by American gemmologists. In actual fact, by comparing small portions of the spectrum with one another, a trained eye can distinguish over a hundred pure hues which are perceptibly different from one another. When variations in saturation and lightness, possible for each hue, are considered there are said to be over a million perceptibly different 'colours'. Thus the perceived colour of an aquamarine could range from that of a lightly hued, unsaturated 'extremely light greyish-bluish green' to that of a strongly saturated, medium dark 'vivid deep blue'.

Elements of Colour Vision

There are three main factors which determine the colour of an object: the light by which it is viewed; the object itself; and the whole of that delicate receiving apparatus which for the sake of brevity may be called the eye.

Standard Sources of Light

The standard sources of light by which all colours are judged, directly or indirectly, is the mixed light from the sun which we call 'white', and artificial light which is from either an incandescent or a daylight fluorescent source, and approximates fairly closely to sunlight. Artificial light sources, recommended for colour grading diamond, must have a spectral distribution near that of glare-free north skylight, i.e. 'lightly but uniformly overcast north sunlight between 10 a.m. and 2 p.m. in the northern hemisphere', or equivalent south skylight in the opposite hemisphere. This slightly bluish-white light has a colour temperature, that is the temperature of an incandescent black body that best matches the colour or spectral distribution of the light, of about 6500 kelvin (degrees Celsius plus 273.15).

Traditional diamond dealers prefer to work by natural north or south skylight, for by this cold and constant light, little influenced by the position of the sun, they can exercise those delicate perceptions and comparisons of colour by which they are enabled to grade their diamonds correctly. The difference between reflected sunlight from the northern (or southern) sky and the direct rays of the sun is quite considerable, the 'cooler' light from the sky being due to the preferential scattering of the sun's blue rays by particles in the atmosphere.

As ideal north or south skylight is frequently unavailable in modern buildings, diamond dealers and coloured stone merchants may have to carefully select and use incandescent short-arc xenon lamps, or 'daylight' fluorescent lamps, as alternative standard light sources for colour grading. While these artificial colour grading light sources do emit wavelengths that closely approximate those of ideal north or south skylight, the same cannot be said of red-rich 2500–3100 K incandescent lamps, blue- and green-rich 4000–5000 K common white fluorescent lamps, or clear blue direct sky light that can attain a colour temperature of 25 000 K.

In darkness there can be no colour as there can be no vision of any kind, and in dim light colour vision is defective as can be demonstrated by looking at coloured objects in bright moonlight. The golden glare of sodium-vapour street lamps drastically affects the appearance of coloured objects, for their light consists virtually of one wavelength only; they are thus monochromatic, that is of one colour. Under such lighting objects can only appear yellow, or grey or black, according to how much of the yellow rays they reflect or absorb. A coloured object is simply one which absorbs certain colours (wavelengths) selectively from white light, transmitting or reflecting the other coloured rays more or less strongly. The combined effect of the residual rays is called the 'colour' of the object.

Residual Colour

As shown by Newton, white light is composed of all the colours of the rainbow intermingled. Therefore, when white light, for example, passes through a sheet of signal red glass, the glass absorbs practically all the blue, green and yellow rays, but transmits the red rays freely. Thus, the only sensation transmitted through the eye to the brain is red, and such a glass is spoken of as red. Similarly, if the light reflected from the cover of a book consists mainly of blue rays we speak of the book as blue. All coloured objects, in fact, derive their colour from the light falling upon them or transmitted through them. It is the rays they absorb and which we do not see which determine the rays that we do see; that is, the residual colour.

The residual colours of gemstones are, however, much more complexly generated. Some wavelengths, from incident light, may be specularly or diffusely reflected from the surface of the gem; some may interact with the atomic structure of the gem and be selectively absorbed, or re-emitted at lower wavelengths as luminescent emissions; some may be internally reflected and dispersed; and some may be scattered, interfered with, or diffracted by specific structures within the gem.

The Eye and Colour Vision

Before dealing with the causes of colour absorption in gemstones a few words may be said about the human eye – the only real arbiter of colour effects. The eye consists essentially of a flexible lens of variable focal length, limited by a diaphragm (the iris), through which light is focused to form an inverted image of the object viewed on the sensitive surface of the membrane known as the retina, which lines the back wall of the eye. The retina is connected with the brain (where all messages of light and colour are translated into sensations) by the optic nerve. The sensory layer of the retina consists of small rod-like structures interspersed with shorter conical bodies, which are known respectively as rods and cones. Only the cones are thought to be sensitive to colours and only the cones are capable of acute vision. A small central area known as the fovea or yellow spot near the emergence of the optic nerve contains cones only, and it is here that the image of an object is focused for the clearest possible vision.

The rods, on the other hand, are the structures which enable us to see to some extent in a dim light and provide brightness or tone to coloured vision. For this reason they are the chief feature in the retina of a nocturnal animal. The rods contain a reddish substance (rhodopsin), commonly called the visual purple, which is rapidly bleached on exposure to light. The visual purple can thus only begin to form in the dark, and its presence can make the sensitivity of the eye several thousand times greater than it is in bright light – hence the power of the dark-adapted eye to see objects which would be quite invisible before this transformation has had time to take place.

There have been many theories of colour vision, and a final answer to all problems connected with this intricate subject is still to be found. For most practical purposes, however, the Young-Helmholtz three-colour theory serves very well. According to the simplest form of this theory, the human retina contains three varieties of cone, which are sensitive to the red-yellow, green, and blue-violet parts of the spectrum, respectively. It is assumed that three light-sensitive chemical compounds are present in these different groups of cones, each of which undergoes a breakdown when exposed to light of the appropriate wavelengths, transmitting messages to the brain. The spectral regions where these receptors are active overlap considerably. Thus in the central part of the spectrum all three will be functioning, though the green receptors will be much more active than the other two, which will function alone at the extreme ends of the spectrum. The action of these three receptors in varying strengths permits all the familiar sensations of colour by persons of normal vision. About 10 per cent of men and less than 1 per cent of women are in some measure colour-defective, or are colour-blind. In such persons it is supposed that one or more of the red-, green- or violet-sensitive colour receptors is not functioning, thus limiting and distorting to a lesser or greater degree the perception of hue.

Causes of Colour in Gemstones

A complete explanation of the causes of colour in gemstones is quite complex, for understanding requires a knowledge of physics beyond the scope of most gemmologists. For interested readers, modern theories of the many causes of colour in gemstones have been detailed by Dr Kurt Nassau in his books *Gems Made by Man* (Chapter 26) and *The Physics and Chemistry of Colour*.

To assist understanding, gemstones may be considered to be coloured by the following:

1. idiochromatic or allochromatic transitional elements
2. colour centres
3. charge-transfer mechanisms between like and unlike ions
4. organic pigments
5. conductors
6. semiconductors
7. doped semiconductors
8. physical optical principles.

Idiochromatic and Allochromatic Minerals

The first and perhaps most significant group of coloured gem minerals consists of those in which a transitional element is present either as an essential element (idiochromatic or self-coloured gem), or as an impurity (allochromatic or impurity-coloured gem). Idiochromatic gems, such as malachite and turquoise, whose colours are due to copper, are noted for always having the same green-blue colour. Allochromatic gems, such as emerald and ruby, are essentially colourless minerals that owe their respective green and red colours to the presence of a chromium impurity.

Factually, the majority of gemstones would be colourless if they were chemically pure – that is if they contained only those elements ascribed to the species in its ideal chemical formula. Corundum, beryl, topaz, spinel, chrysoberyl, quartz and many others are examples of minerals which are colourless in the 'pure' state. The very fact that each of the above can be found in a colourless state and in a wide variety of colours is a sign that they have no characteristic colour of their own. Such minerals are known as allochromatic to distinguish them from the smaller group of idiochromatic or self-coloured minerals, in which the colour can be ascribed to an element which forms an essential part of their structure. For this reason idiochromatic minerals can show little variation in hue.

Examples of idiochromatic minerals, together with their chemical formulae and the element to which the colour may be ascribed, are given in *Table 31.1*. From the table it will be noticed that colouring propensities are ascribed to ions of copper, iron, manganese and chromium. There are several other ions of elements closely related to these in their electronic structure which are also known to give rise to coloured salts and to cause colour in allochromatic minerals when they enter these as 'impurities'. These are nickel, cobalt, vanadium and titanium. Of all the 92 elements it is these eight which are most noticeable for the effect they have on colour. They occupy consecutive

Table 31.1
Transition elements in idiochromatic minerals

Mineral	*Colour*	*Composition*	*Transition element*
Malachite	Green	$CuCO_3 . Cu(OH)_2$	Copper
Azurite	Blue	$2CuCO_3 . Cu(OH)_2$	Copper
Chrysocolla	Greenish-blue	$(Cu^{2+},Al)_2H_2Si_2O_5(OH)_4 . nH_2O)$	Copper
Dioptase	Green	H_2CuSiO_4	Copper
Turquoise	Sky-blue	$Cu^{2+}Al_6(PO_4)_4(OH)_8 . 4H_2O$	Copper
Almandine	Red	$Fe_3Al_2(SiO_4)_3$	Iron
Peridot	Green	$(Mg,Fe)_2SiO_4$	Iron
Rhodonite	Rose-red	$MnSiO_3$	Manganese
Rhodochrosite	Rose-red	$MnCO_3$	Manganese
Spessartite	Orange	$Mn_3Al_2(SiO_4)_3$	Manganese
Uvarovite	Green	$Ca_3Cr_2(SiO_4)_3$	Chromium

positions in the periodic table of the elements, with atomic numbers 22 (titanium) to 29 (copper). They are known as transitional or transition elements, because in them the regular process of adding one electron to the outer shell for each increase in atomic number is interrupted, and the extra unpaired electron is accommodated in the next shell, nearer the nucleus. It so happens that, when surrounded by the electrical forces existing in most ionic crystals, the unpaired electrons of these elements become 'tuned in' to the electromagnetic vibrations of particular frequencies in visible light, absorb energy from the light rays as they pass through the crystal, and become energised. This gives rise to absorption bands, and thus to colour in the residual rays.

Chromium

It is to chromium that the finest colours amongst the gemstones are mainly due. Why a chromium green or red should be brighter and clearer than the best colours that iron can produce, is something of a puzzle. The answer lies, without much doubt, in the intense and clear-cut nature of the absorption bands to which the chromium ion gives rise. This means that the colours which are not absorbed are left at almost full intensity. In the case of iron this is not so. There are here so many possible electronic transitions that there is some absorption at almost all frequencies, with the result that there is a general greying, or saddening as the dyer would call it, of the residual shade.

It is to chromium, then, that the magnificent crimson-red of ruby and the hardly less rich red of spinel is due, although only some 1–2 per cent is present in the stone, taking the place of alumina in the crystal lattice. Pyrope garnets contain enough of the almandine molecule to assume a faint purplish-red when iron is the only colorant, but when chromium enters the molecule the finest blood-red pyropes are produced. The influence of the surrounding crystal field on the particular wavelengths absorbed by an ion is well shown here, since uvarovite – the garnet containing essential chromium – transmits more green rays than red rays, and so is bright green in colour and not red. Green is in fact the most usual colour produced by the chromium ion in crystals. The incomparable colour of emerald and the lovely green shades seen in jadeite are chromium colours. Demantoid garnet, chrome enstatite, and chrome diopside are other examples of green stones where this element plays an important role as a colorant.

Unless some inhibiting factor, such as the presence of iron, is operative, minerals coloured by chromium tend to show a red fluorescence under ultra-violet light and X-rays. In the case of ruby a bright red fluorescence is produced in sunlight or intense artificial light, and this adds appreciably to the fine colour effect of the stone. Another feature of the colour absorption in many chromium compounds is the extreme transparency in the deep red, even where the coloured mineral is green. This transparency to red light is found, for example, in emerald, and causes this chrome-coloured variety of beryl to appear red when viewed through a Chelsea filter: this will be described later. Alexandrite is also transparent in the red, a fact which contributes to its colour change in artificial light. Alexandrite is an instance where the red and green colours produced by chromium are almost evenly balanced. In daylight the stone should have an almost emerald-green colour, while in ordinary electric light, which is richer in red and poorer in blue and violet, it appears raspberry red. This extreme colour change is seen only in fine Siberian specimens and recently discovered alexandrites from Brazil. In those from Sri Lanka it is usually not so pronounced.

Chrome alum, incidentally, displays a rather similar balance between green and red. Here, one gets the curious effect that strong solutions of the salt, seen in depth, appear purplish-red, while more dilute solutions or thinner samples appear green. The reason is that the salt is very transparent to deep red rays, and somewhat less so to green rays. The eye is more sensitive to the green rays, so that in fairly thin specimens or dilute solutions it is the green colour which impresses the eye. In greater concentration the green rays are all absorbed, and the red rays, which still suffer hardly any absorption, are then visible, since they are the only ones which remain. This curious phenomenon is sometimes referred to as dichroism, but is correctly called dichromatism.

Iron

The second of the colouring metals to consider is iron, which is the most ubiquitous colorant in nature. The yellows and browns of rocks and sands are largely ascribable to iron. It is present to greater or lesser extent in many of the gemstones, giving green, yellow, brown and even red colorations, according to its state of oxidation and the forces acting upon its ions in each crystal or glass. As remarked earlier, the colours due to iron are not so brilliant as those caused by chromium, but some of them, nonetheless, are very fine.

Trivalent ferric iron is the basis for the yellow and green tints seen in chrysoberyl, the green in green sapphire, the blue or bluish-green of aquamarine, and the yellow in orthoclase, andradite and spodumene. Divalent ferrous iron takes credit for such varied colours as the blue of blue spinel, the purplish-red of almandine garnet and the lovely yellowish-green of peridot. The influence of iron is seen in many other minerals not listed above, such as tourmaline of green or brown colour, epidote, nephrite, jadeite and many others.

Cobalt

Cobalt is usually associated in the mind with the colour blue – yet minerals containing cobalt, and most cobalt salts, are not blue but pink. The explanation of this apparent anomaly will be discussed later in the chapter; at the moment although only rarely is natural spinel found to be coloured blue with cobalt, gemmologists are familiar enough with cobalt blue in synthetic spinel, ranging from the pale blue of aquamarine or zircon to royal blue stones which are intended to represent sapphire. Blue pastes are often coloured by cobalt, and the blue glass bases of some garnet-topped doublets are similarly coloured.

Vanadium

In recent years the importance of vanadium in promoting an attractive green colour in certain gemstones such as emerald has been generally recognised. Hitherto the element was chiefly known to gemmologists as the colouring agent in the colour-change synthetic corundums designed to imitate alexandrite. This lack of recognition has been partly due to the fact that, in emerald, vanadium's absorption spectrum is hidden by that of its more brilliant cousin, chromium. While in emerald vanadium may play only second fiddle to the essential chromium, in the gem tracts of East Africa vanadium is remarkably prevalent, and the bright green grossular garnet, christened 'tsavorite' by the trade, contains some 3.3 per cent vanadium and only traces of chromium.

Titanium

The influence of titanium in colouring the gem minerals is difficult to trace, but it plays an undoubted part in the colouring of blue sapphire, tanzanite, and surely too in the rare gem benitoite. Traces of titanium and small amounts of iron are found in natural blue sapphires. These elements are included in the alumina powder used to produce synthetic blue sapphire by the Verneuil process. Curiously enough the iron seems to evaporate or otherwise disappear during the flame-fusion process as no sign of the iron absorption bands seen in native sapphires can be detected in their synthetic counterparts, and this forms a useful aid to distinction. Titanium in its trivalent state may be responsible for the pink colour of rose quartz, synthetic beryl, and some glasses.

Nickel

Nickel forms many coloured salts, but does not commonly occur in gemstones. True chrysoprase and green opal from Silesia and Kenya owe their pleasant shade of apple green to this element.

Manganese

This element produces a range of pink to red shades in the idiochromatic gems rhodochrosite, rhodonite and spessartite garnet. It is also present as an impurity in morganite beryl and pink tourmaline.

Copper

Copper is the only metal not yet mentioned in this brief survey of the influence as colouring agents of the transition elements. Actually, though copper plays a prominent role among the idiochromatic minerals, it very rarely appears as a colorant among the allochromatic gemstones.

Light Absorption by Transition Elements

The way in which the transition elements absorb light is often very characteristic, so that by noting the nature and position of the absorption bands with a spectroscope one can with confidence name the element giving rise to the absorption, and hence to the colour of the mineral. In other cases the absorption causing the colour is too vague and generalised to yield this information. Details of absorption bands are given in a later chapter. Here a broad summary may be given.

Chromium gives rise to fine absorption lines which have no influence on colour and to clear-cut absorption maxima in the yellow-green and violet regions of the spectrum, with free transmission in the deep red and blue. The position, intensity and breadth of the yellow-green band determines whether the stone acting as host to the chromic ions appears red or green.

Iron absorbs to some extent throughout the whole spectrum, but absorption bands are most marked in the blue and violet, giving rise to brown, green or yellow colorations. In nickel there is also an overall absorption, but with no clear-cut bands. The red is absorbed, but there is good transmission in the violet and beyond, so that cobalt-nickel 'black glass' is used with mercury vapour lamps to isolate ultra-violet for the study of luminescence.

The absorption due to vanadium is rather similar to that of chromium, but has fewer fine lines and less emphatic broad bands. Titanium in some way resembles iron but produces no clear absorption bands in the visible region. With manganese are found bands of increasing sharpness and intensity from the blue down to the violet and beyond, producing pink, orange or red colorations; while the absorption of the blue cobalt compounds is peculiarly distinctive, with their three strong bands in the orange-red, yellow and green, and free transmission in the deep red.

Other Causes of Colour

The first group of coloured minerals – those whose colour is caused by the transition elements – has been described above. This section covers the remaining groups of minerals according to the classification of colour causes based on Nassau's work and outlined earlier.

The second group of minerals owes its colours to 'colour centres', which is the name given to defects in a crystal at which an unpaired electron may be trapped in a location where it would not normally be present. Broadly speaking, a colour centre may be classified as either a hole centre, that is a vacancy in the crystal structure in which an unpaired electron can become trapped, or an interstitial or electron centre, where a dislodged electron is trapped in a location in which it would not normally reside. Gemstones coloured by colour centres include fluorspar, amethyst and smoky quartz, blue topaz, and coloured zircon.

In the third group the colour is said to be due to 'charge transfer', which involves a change of valency (transfer of an unpaired electron) between two different transition elements or between two ions of the same element having different valency states. A well-known example of this is found in sapphire in which the colour is dependent not only upon the presence of iron and titanium, but upon their valencies. Supposing a divalent iron ion and a tetravalent titanium ion occupy adjacent aluminium sites in a corundum crystal, it may happen that an electron from the divalent iron can be transferred to the tetravalent titanium with the result that both become trivalent. This transfer consumes a certain amount of energy which is derived from light absorption and thus produces colour.

For the fourth group, those dye-like organic substances found in such organic gem materials as amber and coral, the colour must be explained by the 'molecular orbital' theory. In organic dye molecules, the donation or acceptance of unpaired electrons between constituent atoms absorbs energy (wavelengths) from incident light, thus creating colour. Dyestuffs were in the past used to colour the agates cut and polished in Idar, but these were apt to fade and the more permanent results achieved by inorganic reagents are now preferred.

In the fifth group are placed the conductors, i.e. the metals, not often considered in this connection by gemmologists. The metal's typical brilliant lustre is ascribed to the free movement of the outer electrons from one atom to the next which makes them good conductors of electricity and of heat. The surge of electrons ensures that the metal is opaque and has a strong reflecting power. There are, however, slight differences from metal to metal as to which wavelengths of light are most strongly reflected, with the resulting differences in the colour of gold, copper, silver, and so on.

The sixth group embraces the semiconductors, among which one must place diamond as well as minerals such as galena and pyrites, both of which have a metallic lustre. In these crystals there is covalent bonding which involves a sharing of electrons between atoms rather than a transfer. The colours of these materials (apart from those due to impurities) depend upon the 'energy gap' between what are known as the 'conduction band' and the 'valency band'. Where there is a wide gap between these levels in terms of energy as there is in pure diamond, the crystal is essentially colourless in the visible region and does not conduct electricity. The colours produced in diamond by irradiation are the result of the formation of colour centres.

The introduction of atoms such as nitrogen, with its five as opposed to carbon's four outer electrons, into the diamond lattice means that the nitrogen atoms act as 'donors' and their presence can narrow the width of the band gap. This allows absorption of light in the violet region by the diamond crystal, inducing a yellow colour. Diamonds containing isolated substitutional nitrogen in amounts of about 100 parts per million are extremely rare and are classified as type Ib or 'canary diamonds'. Much more common are diamonds classified as Ia which contain groups of nitrogen atoms in greater quantity, but in these the nitrogen atoms can no longer function as donors as they have merged into larger clusters. Type Ia diamonds are thus essentially colourless.

The well-known series of 'Cape' absorption bands found in most yellow or yellowish diamonds are, according to Collins (*Journal of Gemmology*, April 1980) due to so-called N_3 centres, which are believed to consist of a triangle of three nearest-neighbour nitrogen atoms surrounding a vacant carbon atom site. The concentration of N_3 centres in diamond determines the intensity of its yellowish Cape colour. In silicon carbide crystals the colour is influenced by similar factors to those found in diamonds.

The seventh group includes 'doped' semiconducting crystals such as those of diamond containing boron atoms which are now thought to form the only major impurity in natural diamond crystals apart from nitrogen. Since boron atoms contain one less electron than carbon atoms the element when present introduces an 'acceptor' level containing a 'hole' for each boron atom introduced into the energy band gap. The result in this case is to produce a blue coloration in diamond which is found not only in the rare natural blue diamonds such as the Hope but also in synthetic diamonds into which boron has been introduced. As little as one part of boron per million induces the blue colour and enables the diamond to conduct electricity. Irradiation with electrons can also induce a blue tint in diamond, but in this case the effect is due to the formation of colour centres.

The remaining causes of colour in gemstones are due to physical optics, and the gems which show such effects may not be described as coloured stones by gemmologists or precious stone dealers, even where their value depends largely upon their colour phenomena. The physical causes involved are listed as dispersion, scattering, interference and diffraction. Dispersion is well understood and need not be explained here. It is interesting to note that while in diamond the play of colour due to dispersion is one of its claims to beauty, the much greater play of colour due to the same cause seen in synthetic rutile has an unnatural or gaudy look to the eye of a connoisseur. The effects of scattering, as in chatoyancy, asterism and schiller, are also seldom ranked as colour, and the colours due to interference and diffraction as in labradorite, and most importantly in opal, have been well discussed in previous pages.

Colour Enhancement Technologies

For several thousand years, man has artificially enhanced the colour and value of gemstones by foiling, oiling and dyeing lesser-valued gem materials. Over time, some of these treatments have become so well established that they are now considered legitimate trade practice. However, rapid advances in scientific knowledge, over recent years, have resulted in the discovery of many new colour enhancement technologies that are being used, legitimately and illegitimately, to add value to many gemstones.

At present, the artificial treatment of rough and cut gem materials, to modify their natural appearance and so increase their value, is accepted to be legitimate trade practice, provided that induced change(s) are stable under normal conditions of display, wear and storage, and that no deceptive trade practices are used to market the colour enhanced materials. Today, colour enhancement technologies are so routinely applied to both rough and faceted gemstones and gem materials that the only practical consideration the ethical gem merchant, jeweller or gemmologist now faces is how much of the known colour enhancement history of a gem or gem material should be disclosed to its potential buyer.

International jewellery trade organisations, such as the European-based International Confederation of Jewellery, Silverwear, Diamonds, Pearls, and Stones (CIBJO), have attempted to resolve this ethical dilemma by supplying members with sets of rules that govern disclosure of known and/or detected colour enhancement technologies to clients. For example, CIBJO recommends that diamonds, coloured stones and pearls which have been coloured or improved in colour by physical and/or chemical treatment, through irradiation, chemical treatment or coating, must be designated 'treated' under the approved name of the gem. Exceptions to this rule include colour enhanced agate, aquamarine, citrine, prasiolite, pink topaz, coloured tourmaline, tanzanite, ruby and sapphire, and minimally tinted cultured pearls that have undergone permanent colour enhancement.

Unfortunately the answers to various important questions are scattered through the voluminous literature. How can one recognise and identify the many value enhanced gemstones and gem materials currently being marketed? What stability do colour enhanced gems have under normal conditions of wear, storage or display? Which value enhanced gem materials should or should not be disclosed to buyers or clients? Some answers are provided in Dr Kurt Nassau's 1984 book *Gemstone Enhancement*.

There can be said to be four major methods by which the colour of stones may be changed or appear to be changed. These are surface coating, or painting or foiling the back of the stone; staining porous stones with dyestuffs or impregnating them with colourless materials; heat treatment; and bombardment with subatomic particles or high-energy electromagnetic radiations, usually followed by heat treatment.

Coating

For many centuries, coloured and/or reflective coatings have been applied to the pavilion facets of glass imitations, and paler-coloured gemstones, to enhance their colour and overall appearance. Although deceptive, these coatings can be efficiently detected by hand lens examination.

Pale emeralds and even colourless quartz may be mounted in a closed setting which contains a green-coloured foil either to enhance or to give colour to the stones. This green foil may cause the stones to show red through the Chelsea colour filter, an effect which, according to Lewis, is due to selective reflection. Thus care must be taken in using the filter, especially with 'emeralds' in old jewellery, for much Victorian jewellery had the stones foiled, for example, ruby, sapphire, and particularly topaz and amethyst. Another process sometimes used with stones in closed-back settings is to paint the rear facets with suitable colour, and this is sometimes done when the stones are open set. Mexican water opals are sometimes painted black on the back of the stone, or a piece of purple material is placed in the setting behind them.

A method of painting used by the unscrupulous to 'correct' the yellowish colour of off-colour diamonds is by coating the pavilion facets with a tinge of violet dye, a colour complementary to yellow. This treatment does not last and may be detected, sometimes by the accumulation of dye on the unpolished girdle edge, or better by washing the stone in hot water, or alcohol, which will remove the dye and leave the stone in its true colour. In the United States yellowish diamonds are being colour enhanced by vacuum sputtering areas on their pavilion facets with a very thin, strongly adhesive, soft bluish complementary-coloured film that visually resembles the magnesium fluoride anti-reflective coating found on camera lenses. These coated diamonds have a distinctive greyish overtone to their body colour and are quite difficult to detect, except when pavilion facets are examined at 20–40 × magnification in tangentially directed illumination. Observation of iridescent patches on pavilions that are frequently scratched, and/or contain surface bubbles, will identify this colour enhancement.

Tangential illumination, and moderate magnification, will also be required to detect such modern coated materials as colourless-plastic-coated jade, coloured-plastic-coated pale stones such as ruby, 'aqua aura' quartz, green-plastic-coated beryl crystals imitating emerald, and gemstones coated with diamond-like carbon (DLC).

While the characteristic lustre of, and presence of included bubbles in, plastic coatings are relatively simple to detect by hand lens examination in tangential illumination, detection of aqua aura quartz or DLC-coated stones is a little more challenging. As greenish-blue aqua aura quartz consists of faceted stones and crystals of colourless quartz, coated microscopically with a thin layer of vacuum-sputtered pure gold, examination of the external surfaces of aqua aura, with tangential illumination, will reveal an identifying coppery iridescence. Recent attempts to enhance the hardness of gemstones by using plasma jet technology to coat the stones with a very thin layer of transparent amorphous diamond-like carbon have yielded coated coloured stones of slightly brownish hue, which have a hardness between diamond and corundum, a refractive index of about 2.00, and a somewhat artificial adamantine lustre that is easily detected in reflected light.

As all coated stones have the potential to deceive, they should be disclosed.

Dyeing and Impregnation

Porous gem materials may be either dyed, to enhance their colour, or strengthened and colour enhanced by impregnation. Dyes used to colour enhance gem materials are usually based on colour-fast organic or inorganic pigments. In contrast, mostly colourless liquid impregnators are used to fill in the pore spaces and surface-reaching fractures in pale-coloured and friable gem materials. Impregnators may be deposited under vacuum, before being chemically or thermally solidified or set.

Iris quartz is a rock crystal with naturally occurring thin air-filled cracks which produce iridescent colours. The effect can sometimes be produced by heating the quartz and rapidly cooling it in water, and if the water is coloured by a dye the dye will dry out in the cracks and colour them. Such treated stones are known as firestones, and when the dye is a green colour this cracked quartz has been marketed under the misnomer 'Indian emerald'. Quartzite, a rock made up of grains of quartz, is carved into beads and dyed, the stain penetrating between the grains. Such stones are often dyed red and have been sold as red jade or tourmaline.

Materials which are in any way porous may be artifically stained, and the staining of agate (chalcedony) is a major industry at Idar-Oberstein in Germany.

The methods of staining depend upon the use of an aniline dye in which the material is soaked, or the formation of coloured chemical precipitates in the pores of the stone. Aniline dyes are not used to any extent for they tend to fade, chemical precipitation being the most common method for the staining of agate.

Black onyx is produced by boiling slabs of greyish chalcedony in a solution of sugar which enters the pores between the submicrocrystallites. The slab is then treated by soaking in sulphuric acid. Sugar has the chemical formula $C_{12}H_{22}O_{11}$. The final treatment with sulphuric acid removes water from the sugar, leaving finely divided carbon in the interstices of the chalcedony. Since the mid 1950s porous cream- to grey-coloured Andamooka matrix opal has been similarly impregnated by particulate carbon to create black-dyed Andamooka matrix opal. This superficially colour enhanced opal is manufactured by carbon impregnating of a fine-grained, porous, siliceous South Australian claystone that is included by pinpoints of precious opal. Hand lens examination will reveal that this colour enhanced opal consists of pinpoints of precious opal set in a black-stained, fine-grained matrix.

A blue colour is produced by soaking stone in potassium ferrocyanide and then in a solution of ferrous sulphate. When impure quartz (jasper) is so treated the imitation known as 'Swiss lapis' is produced. A red colour is obtained by soaking the stone in iron nitrate, or ferrous sulphate, and subsequently heating to red heat. This turns the iron compound into ferric oxide which remains in the interstices and gives an artificial cornelian colour, or if banded, where some bands of the agate do not take dye, sardonyx. Green colours are produced by nickel salts (rarely used) or chromium salts (more generally used) to give 'chrysoprase'. Hydrochloric acid will give a yellow colour. A pale-blue-dyed chalcedony, resembling to some extent the turquoise, may be coloured by a cobalt compound and show weakly the typical cobalt absorption bands. An unusual piece of staining was seen in a polished agate which depicted a black head. It was later established that the 'head' had been painted in from the back with silver nitrate, and possibly some organic compound, after which when exposed to light the silver nitrate was reduced to silver in the form of a black powder.

Turquoise and lapis are dyed to enhance their colours. Aniline-dyed turquoise and lapis can be detected by wiping the surface of the turquoise with a cotton swab moistened with acetone or nail polish remover, and noting any blue stain on the swab. However, some recently dyed lapis requires active scrubbing of its surface, with dilute hydrochloric acid, to reveal that it has been dyed. The pale colours of American turquoise, and Chilean lapis, are commonly enhanced by impregnating these quite porous materials with either paraffin wax, colourless plastic, or an aqueous silica solution. The effect of waxing does not dye the stone in any way but seems to act like wetting the stone with water which tends to increase the saturation of the colour. Water would evaporate away but the wax does not, so the deepened colour remains unless the wax is removed by some solvent, used accidentally or by design. Such waxed stones appear to be acceptable for trade purposes. More is told of the treatments used on turquoise in the description of that stone (Chapter 12). It has been reported that amazonite has been similarly waxed.

Greyish-white jadeite is stained to an 'Imperial jade' colour by the use of a combination of two organic dyes: a yellow dyestuff and a blue one. Such dyed jadeite is very convincing when fresh but fades after some months, even in the dark. The artificial nature of the colour in such pieces may be detected by the colour concentrating along cracks, and better by the abnormal absorption spectrum shown by them. This is due to the absorption bands of the dyestuffs which give a wide band in the orange-red at 650 nm and a narrower band at 602 nm. Further, the jadeite line at 437 nm is often obscured by the general absorption of the blue-violet produced by the dyestuffs. White jadeite is also stained to a strong mauve colour which is much deeper in hue than any natural mauve jadeite. This coloration is said not to fade.

A type of serpentine, probably near bowenite, is also stained to an Imperial jade colour, and possibly by a similar combination of dyes as used for the jadeite staining. Here again the spectrum is apparent. Alabaster is also dyed various shades and so is the stalagmitic calcite from Mexico; this latter material when dyed green has been marketed under the misnomer 'Mexican jade'. Light-coloured fractured Brazilian opal is being colour enhanced by vacuum impregnating it with an appropriately pigmented thermosetting plastic to yield opal with white, black, brown, blue and orange potch colours. Transillumination, by diffused light, will readily detect any dyed-polymer-filled internal fractures in Brazilian opal. Aventurine quartz has been dyed red and has been marketed as 'red jade' or 'topaz', and a red-dyed greyish-pink corundum has been reported. Both of these can generally be identified by the absorption spectrum of the dyestuff used. Organic materials are also susceptible to dyeing and this is done with ivory and coral as well as bone and possibly amber. Transillumination is an efficient method for detecting dye filled surface-reaching fractures in any dyed translucent gem material.

Japanese akoya bead-nucleated cultured pearls are routinely colour enhanced by dyeing, but need not be disclosed. This dispensation does not apply to dyed flesh-nucleated pearls, or black-dyed bead-nucleated cultured pearls. Observation of dye on the external surface of a pearl, surrounding the stringing hole, staining the central bead, or staining the string, will identify these colour enhanced pearls.

An unscrupulous trick sometimes met with is to 'oil' flawed and poor-quality rubies, sapphires or emeralds with a suitably coloured oil. This not only reduces the visibility of the flaws but also gives colour to the stone. The danger here lies in that if the stone be cleaned with an organic solvent, such as benzene, or even cleaned with detergents, the oil and colour will be removed. Not only does this result in loss of colour, but the cracks appear white and show up more readily. This treatment, which must be disclosed, is easily shown up by the coloured stain which will come off on the application of a piece of cloth or even blotting paper soaked in a suitable organic solvent.

Heat Treatment

The application of carefully controlled heat to a gemstone, or gem material, may induce colour changes in the material by one of the following:

1. changing the valence, by oxidation or reduction, of colour-generating ions of transitional elements;
2. modifying the hydration state of coloured minerals;

3. oxidising or reducing organic molecules;
4. moving light-absorbing unpaired electrons from colour centres;
5. diffusing coloured ionic impurities.

Over the decades, many simple heat-treatment regimes have been devised, sometimes by trial and error, to produce permanent commercially acceptable colour changes in a vast range of gems and gem materials.

Quartz, topaz, zircon and the gem corundums, ruby and sapphire, are examples of gemstones whose colours can be altered by heat treatment. Each of the minerals is colourless when pure; each displays an imposing variety of colour in nature; and in each the colour can be altered, in suitable specimens, by heat treatment. In some cases, blue zircon for example, the resulting colour is not matched by any of the naturally occurring varieties of the species.

Since the 'burning' of certain types of quartz and topaz gives rise to stones in which the colour is both attractive and permanent, it is understandable that this practice is considered legitimate in the gem trade – especially as it is hallowed by long custom. In the case of zircon, the method by which sky-blue or greenish-blue stones can be produced from reddish-brown rough is of fairly recent origin. A considerable percentage of the treated stones are by no means stable in colour, but the spectacular beauty and consequent saleability of the stones is such that this disadvantage is condoned, and the stones are an undoubted commercial success, though now increasingly rare.

Quartz in nature is usually colourless and water clear, or is milky white. Of the coloured varieties, amethyst is the most famous and may vary in tint from the merest blush of pinkish-violet to a deep violet of tremendous intensity. The colour used to be ascribed to the presence of manganese for no very sufficient reason – possibly because of a certain similarity in hue to dilute solutions of potassium permanganate. The correct solution – that amethyst owes its colour to a complex colour centre formed by irradiation of quartz containing traces of charge-compensated trivalent ferric iron replacing silicon – is discussed fully in Chapter 10.

Much amethyst is 'burnt' to produce the fine yellow, brown or reddish-brown stones. It has often been stated that smoky quartz can be used to produce similar stones, but according to Wild this is not so. Smoky quartz and citrine both remain completely clear up to 1000 °C and over (the 'smokiness' of the former disappearing above 250 °C), while when amethyst is heated above 500 °C a slight cloudiness appears which becomes very marked above the inversion point of alpha-quartz at 575 °C. resulting in stones which have almost the schiller of moonstone. The 'burning' of amethyst is complicated further by the fact that some amethyst turns green on heating. This creates prasiolite, such as that from Montesuma in Brazil. In the Zambesi escarpment of Zambia, amethyst is found which is parti-coloured green and purple; the green colour, it is suggested, might be due to heating by tropical conditions over long periods of time. According to recent research of Dr Kurt Nassau the green colour of prasiolite, sometimes referred to as 'greened amethyst', is also caused by a colour centre formed by irradiating quartz containing traces of charge-compensated divalent ferrous iron replacing silicon. Wild correctly maintains that the cause of colour cannot be the same for amethyst as for the natural brown or yellow quartz called citrine. He also was the first to note that the yellow stones produced by the heat treatment of amethyst are virtually non-dichroic, while in true citrine or smoky quartz the dichroism is quite distinct.

The heat treatment of amethyst must be carried out under carefully controlled conditions if a desired citrine or prasiolite colour is to be obtained. Citrine is produced by progressively raising the temperature of ferric iron containing amethyst, in about 25 °C intervals, from 150 °C to about 450 °C. A maximum 'burning' temperature of 400–500 °C must be applied to ferrous iron containing amethyst to produce prasiolite. The same is true for topaz, for here the nature of the raw material is also very important. Only the yellowish-brown topaz crystals from the Ouro Prêto district of Brazil have the curious property of becoming rose-pink when carefully heated at a dull red heat (300–450 °C). It is remarkable that these 'pinked' stones reveal a fluorescence and absorption doublet in the red end of the spectrum at 682 nm, albeit very faintly. This is undoubtedly due to the presence of traces of chromium, to which the colour may also be ascribed. Apparently the heat treatment allows the chromium to take up its position in the lattice and thus exert its influence on the light absorption in a manner not possible when scattered interstitially in the original sherry-brown-coloured crystal.

The colour changes in zircon under the influence of heat are still more complicated and puzzling; here, not only the nature of the rough and the degree of heating, but also the oxidising or reducing nature of the surrounding atmosphere, modify greatly the nature of the colours obtained. Fuller information on the native methods of 'cooking' zircons has been given in the chapter on zircon (Chapter 7).

Greenish-blue aquamarine turns a beautiful sky-blue when commercially heated at 250–500 °C. Occasionally a temperature as high as 700 °C may be required to convert greenish Brazilian or Indian aquamarine to a blue colour. Other gemstones and gem materials, which are heat treated to remove commercially unacceptable pleochroic or other colours, include khaki and purplish-blue tanzanite, dark-coloured tourmalines, strongly pleochroic gemstones such as andalusite, and the organic gem material amber.

Heat Treatment of Sapphire and Ruby

The effects produced by controlled heat treatment of the corundum gems have been the subject of much speculation and research. Ruby and sapphire, the highly prized varieties of corundum, have since the 1940s become increasingly scarce owing to some of the most famous localities such as the Mogok Stone Tract in Myanmar (Burma) being no longer open to the West. This scarcity has acted as a stimulus for experiments on the possibilities of improving the colour and transparency of stones from sources which, though yielding plenty of material, have not hitherto been known to produce stones of the highest quality. Some of the results obtained have been so startlingly successful in transforming unsaleable material into attractive gems that the traditional readiness of the trade to accept gemstones improved by heat treatment on level terms with untreated stones (provided the resultant colours were permanent) has become somewhat more cautious.

Over recent decades the commercial sapphire and ruby heat treaters of South East Asia have developed heat-treatment regimes which will achieve the following:

1. remove the silk from ruby and sapphire, or develop asterism in ruby and sapphire;
2. lighten dark blue hues in sapphire, or induce blue colours in whitish-yellow gueda sapphire;
3. predictably induce valuable red, blue, yellow-brown and green hues in poorly coloured ruby and sapphire rough;
4. remove strong colour banding from both natural and synthetic ruby and sapphire;
5. induce natural-looking fingerprint inclusions in synthetic ruby or sapphire.

Although in many cases skilled gemmologists have noted signs by which corundums which have been strongly heated can be recognised as such, laboratories might well be faced with insoluble problems in making decisions on this issue. The whole field of colour alterations in gem corundums, both natural and synthetic, has been explored from the point of view of a physicist and a gemmologist by Kurt Nassau and Robert Crowningshield, and what follows is largely derived from the reports of their valuable investigations.

The various types of heat treatment used can be conveniently divided into different categories.

Simple Heat Treatment

The heat treatment of over-dark sapphires from many deposits around the world in order to reduce their unacceptably dark colour has been practised for several decades and has often succeeded in producing stones of a greatly improved shade. The temperatures used must be very high, perhaps in the neighbourhood of 1600 °C, and an oxidising atmosphere is favourable, resulting after many hours of heating in the transformation of most of the iron present into the ferric rather than the ferrous condition, the deep blue colour of sapphire being probably due to a combination of ferrous iron and titanium.

The most spectacular improvement of a virtually worthless class of sapphire known in the trade as 'gueda' sapphire into stones of acceptable gem quality has been an achievement of the past few years. 'Gueda' is a term descriptive of patches of milky-white or yellowish material. On inspection under the microscope the milky effect is seen to be produced by a network of fine needles of rutile. Sapphires of this type contain an unusually high level of titanium, and experiments previously carried out in the manufacture of synthetic star corundums have shown how the presence of titanium may in certain circumstances cause the growth of oriented rutile needles which can be the basis for attractive star-stones when cut *en cabochon*, or alternatively may be absorbed into the lattice with the production of deep sapphire blue. The heat treatment of gueda sapphires must thus be critically controlled in order just to maintain a high enough temperature to melt and absorb the rutile and provide further heating in a reducing atmosphere to develop the blue colour. On the other hand, if the stones turn out to be too deep in colour, further prolonged heating in an oxidising atmosphere may lighten the colour. After such drastic treatment at temperatures not far from melting point, the surface of the stones is marred with pock-marks and if a cut stone is involved it will need repolishing.

Less is known about the colour enhancement of ruby by heat treatment, although it is thought that a large proportion of Thai rubies have been made more attractive by heating. According to the GIA's Robert Crowningshield, absences of brownish to purplish Thai rubies in the marketplace indicate that these stones are being heat treated to remove unacceptable brownish and purplish components from their red colour. This has most likely been achieved by heating the rubies, in an oxidising atmosphere, at a temperature several hundred degrees below the melting point of ruby.

As heat-treatment-induced colour enhancement of ruby and sapphire is colour stable, and significantly increases the value of the rough, virtually all rough is routinely heat treated before it is faceted. Although no disclosure is currently required for heat-treated ruby and sapphire, gemmologists should be aware that this treatment does increase the risk of fracture of this rough.

Heat-treated ruby or sapphire can be identified if careful examination by the gemmological microscope reveals more than one of the following features: an unusual absence of silk; colour banding that appears to have become diffused; stress fractures surrounding somewhat melted mineral inclusions; and exploded 'liquid' inclusions. Additional observations of a chalky green surface fluorescence to short-wave ultra-violet rays, a diminution in the strength of the 450 nm absorption in natural blue sapphire, and the less frequent observation of pock-marked or multi-planed girdles on faceted stones help to confirm that a ruby or sapphire has been heat treated.

Heat Treatment with Surface Diffusion

Another recent type of colour improvement method has made its appearance and has been encountered in the Gem Testing Laboratories of the GIA. The method or methods used involve an actual alteration in the composition of the surface layers of the stones concerned by means of a diffusion process carried out at high temperatures. Such methods can be used to redistribute or improve the colour of natural corundums, but also can induce the appearance of fingerprint types of inclusion in synthetic rubies or sapphires, thereby giving them a deceptively natural appearance.

Information on the processes involved is to be found in the specification of a US Patent assigned in 1975 to Carr and Nasivich of the Union Carbide Corporation, the avowed purpose of which is to 'correct non-uniform colour in a corundum crystal and for changing the colour of such crystals'.

The general type of treatment recommended involved the heating of preformed or polished pale-coloured sapphires at high temperatures for prolonged periods embedded in alumina containing suitable salts of colouring elements such as titanium, iron, chromium or nickel.

In one experiment, for instance, ruby crystals having too low a colour saturation were heated at 1750 °C for 96 hours in an oxidising atmosphere while embedded in powdered alumina mixed with 6 per cent chromic oxide and 22 per cent titania.

In the early 1980s commercial surface-diffusion-coated (coloured) sapphires became an economic reality when high temperatures were applied for long periods to faceted pale-coloured corundums that had been either coated with a paste of, or enclosed in a powder of, alumina to which appropriate amounts of titanium and ferrous oxides had been added. The end result of this heat treatment was that a very thin layer (<0.5 mm) of synthetic blue sapphire was fused to, and diffused into, the surface of the host natural corundum. By adding rutile to the powder, and then annealing the surface-diffused sapphire that results, asterism can also be induced into the product.

There is little argument that the diffusion coating of sapphire may be used to deceive the unwary; this heat treatment must be detected and disclosed. For best results the suspect diffusion-coated sapphire should be immersed in di-iodomethane, with a refractive index of 1.74, and then examined in diffused transmitted light for evidence of: a thin blue coating, of up to 0.4 mm thickness, that coats a pale-coloured sapphire seed; localised surface blotchiness where patches of the diffused coating have been removed during necessary repolishing; bleeding of the blue coating into surface-reaching defects in the seed; and accentuated facet edges, due to the presence of a double layer of synthetic corundum on these edges. A patchy surface fluorescence to ultra-violet rays may also be observed on surface-diffusion-coated sapphires.

Irradiation and Annealing

Irradiation of certain pale or poorly coloured gemstones, with either high-energy subatomic particles or electromagnetic radiations such as gamma rays, is commercially used to colour enhance these stones by artificially creating colour centres. These radiation-induced colour centres consist of defects in the crystal structure in which a trapped unpaired electron can be energised by absorbing specific energies (wavelengths) from incident light, thus creating colour. The complexity of these colour centres varies from single atomic vacancies and displaced interstitial electrons, to quite complex centres involving numerous components. Subsequent prolonged high-temperature annealing will repair some colour centres and modify dark radiation-induced colours. While immersion in a radium salt represented the first attempt at colour enhancing diamond, today several types of radiation are commercially used to colour modify diamond as well as other gem materials such as topaz, tourmaline, and cultured bead-nucleated pearl.

Radiations commercially used to colour enhance gemstones include: high-speed negatively charged electrons from a linear accelerator; high-speed alpha-particles (positively charged helium nuclei) from either a linear accelerator or a cyclotron; energetic neutrons from an atomic pile; and high-energy gamma rays from a cobalt-60 source. Owing to their small size, and their charge, electrons or alpha particles will induce colours that are only skin deep. In contrast, highly energetic neutron irradiation and gamma irradiation will colour the whole stone.

Colour enhancements made possible by irradiation include:

Beryl Colourless to yellow; blue to green; pale pink to deep blue maxixe colour.

Corundum Colourless Sri Lankan sapphire to yellow-brown; Sri Lankan pink sapphire to pinkish-orange padparadscha colour.

Cultured pearl Yellow-cream to grey and black.
Diamond Commonly off-colour yellow to green; subsequent heat yielding fancy-coloured yellow, brown, orange and rare pink stones.
Quartz Suitably iron- or aluminium-doped quartz to amethyst, prasiolite, smoky quartz.
Topaz Colourless to green-brown; but with subsequent heat treatment to blue.
Zircon Colourless to brown or red.

Diamond is the gem most commonly permanently colour modified by irradiation and annealing. Owing to the significant price differential existing between naturally coloured diamonds and irradiated fancies, disclosure of this treatment is mandatory.

Radiation-Induced Colour Changes in Diamond

Much more permanent alterations in colour can be produced in diamond, by exposing the stones either to the action of radium salts or radium emanation, or to bombardment by various atomic particles of high energy. Broadly speaking, the result of prolonged treatment of this kind is to induce in diamond a tourmaline-green colour. Beginning in 1904, Sir William Crookes carried out many thorough experiments on the action of radium on diamond, and he found that it was the so-called alpha-particles (that is, helium nuclei) emitted by radium which caused diamond to change gradually to green. He also found that the treated diamonds are strongly radioactive and that the radioactivity, like the colour, persisted for an indefinite number of years. The most vigorous chemical treatment had no effect, or only a temporary one, on the strength of the radioactivity, and none whatsoever on the colour. An octahedron of diamond 'greened' by Crookes was presented by him to the British Museum (Natural History) in 1914, and has retained its colour, and radioactivity, to the present day.

Later work by the American workers Lind and Bardwell showed that heating radium-treated diamonds at a dull red heat (450 °C) for several hours had the effect of destroying both colour and radioactivity: this was in addition to the method which Crookes had found effective, namely repolishing the stone. The later workers also found that the gas radon (radium emanation) acted more quickly than the salts of radium itself in inducing the green tint in diamond. Ten days in a tube of the gas produced a change of colour which it would have taken several months to effect by radium bromide.

The green tint produced is more attractive when it is not too pronounced, for when the diamond is overexposed the tint tends to be a blackish-green rather akin to that seen in some tourmalines. It is not at all like the apple-green tint seen in the very rare natural green diamonds. Nor has any marked radioactivity been observed in any untreated diamond of any colour. This fact suggests easy and certain methods whereby the laboratory worker can detect that suspected diamonds have been radium treated. Leaving the diamond in contact with a photographic film or plate overnight in a light-tight box will cause a marked blackening of the emulsion on development of the film, the resultant autoradiograph often showing the shape of the stone and a curious echo of the

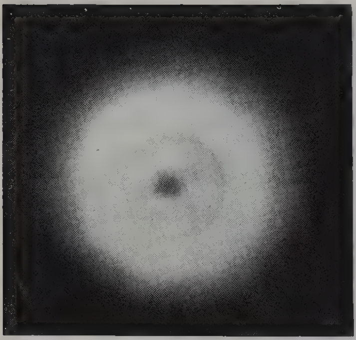


Figure 31.3 *An autoradiograph of a radium-treated diamond*

facet pattern beyond the borders of the stone (*Figure 31.3*). Heavily treated stones may even glow in the dark. Scintillations can also be seen when a radioactive diamond is placed on a zinc-sulphide screen in a dark-room, and the screen near the stone examined with a lens after the eye has become thoroughly dark-adapted. These scintillations are very beautiful and impressive, each tiny splash of light representing the effects of one alpha-particle striking the zinc-sulphide screen. There are countless numbers of such flashes in every second, and the fact that this could continue for years without any measurable diminution of the weight of the stone gives some inkling of the tiny proportions of an atom and the myriads that go to make the smallest appreciable speck of matter. A radium-treated diamond will also discharge an electroscope in a few minutes, providing the most sensitive test available, aside from a Geiger counter.

Radium is a fabulously rare and fabulously expensive substance, as well as being very dangerous to handle. Most of the world's supplies are locked up in lead-lined safes in hospitals and institutions. Thus the opportunity for the radium treatment of diamonds is limited. Nevertheless, a score or more 'radium-greened' diamonds are known to be on the market, and a demand by a collector for a fancy green diamond may result in some of these stones being hopefully offered. Always they are condemned by a laboratory test, their characters having already been recorded years before in the laboratory archives, and they are withdrawn again into retirement to await a later opportunity. The physiological danger of wearing a radium-treated diamond cannot be underestimated, in spite of the fact that one such diamond tested by a Geiger counter revealed that the radiation was no greater than that given off by a radium-dial wrist-watch.

Before leaving the subject of the radium treatment of diamond it is worth recording details of an interesting modern method of bombarding the mineral with α-particles which succeeds in turning the colour of the stone to a rich shade of green, and which by drastic cleaning methods is claimed to leave the stone devoid of any trace of radioactivity after the treatment.

The new process was the subject of a US Patent granted to Haynes in October 1971, and involved the use of the powdered oxide of the artificially produced element americium-241, which emits a powerful stream of α-particles. In one experiment, a 50 point cut diamond was embedded (all handling being by remote control) in the powdered americium oxide in a small container, where it was allowed to remain for 7–14 days. The diamond was then removed from the container and tumbled with sand for a few minutes before being repeatedly washed with fresh samples of pure nitric acid with ultrasonic agitation, and finally scrubbed in water containing a detergent. After this formidable treatment the diamond showed no trace of radioactivity when tested with a Geiger counter. The colour had changed to a clear emerald green and the surface of the facets had remained as bright and smooth as they were before the treatment. A word of warning, however. A recent examination of a green diamond treated with americium-241 oxide indicated not only that this stone was radioactive, but that it could not be safely worn until the year 5071.

A further surprising fact recorded in the patent specification was that the treated green stone could be changed to golden-yellow by subsequent heat treatment at 537 °C for 30 minutes. In Lind and Bardwell's experiments (as recorded above) heating for several hours at the lower temperature of 450 °C destroyed both the colour and the radioactivity of their radium-treated diamonds.

Another interesting point is that Haynes observed absorption bands at 504 and 498 nm in his treated green diamond, and observations by Anderson and Payne in the 1930s had also shown that the 504 nm band was frequently present in green diamonds which had been radium treated.

More recently, charged particles from a cyclotron or van de Graaff generator and fast neutrons from an atomic reactor have in turn been extensively used in the artificial coloration of diamonds and have given rise to a great deal of research. Each of these will be discussed separately.

Cyclotroned diamonds are coloured by bombardment with fast-moving charged subatomic particles and the colour produced is, like radium-treated stones, a green colour, or if overexposed, black. For treatment the diamonds are mounted on a long probe which is inserted into the vacuum chamber of the cyclotrons (in some types of apparatus), or on special holders, usually made of aluminium, for those cyclotrons which can produce external beams. The heat generated when the atomic particles hit the target, in this case the diamonds and the holder, is intense and some means of cooling must be used. The probe or holder is usually water-cooled and further cooling is carried out by a jet of liquid helium. If the cooling is not efficient and the stone heats, the resulting colour is brown and not green. Further, 'cyclotroned green diamonds' may be turned to a golden-brown or yellow colour by subsequent heat treatment at about 800 °C. In the short exposures used the coloration is only skin deep and disappears on recutting. In all cases, whatever the type of bombardment used, bombarded diamonds are intensely radioactive for some hours after treatment, but this dies out and the stones cease to be radioactive. The colour, however, remains and so far as is known, this colour is permanent.

A careful examination of cyclotroned green diamonds will reveal a series of reflections of triangular cubist patterns that show varying intensity of green, and a stone which has been treated through the table will, when examined with the pavilion up, show a dark ring around the girdle. A diamond treated through the pavilion will show a light ring round the girdle, and when viewed through the table will show a 'watermark' rather like an opened umbrella surrounding the culet (*Figure 31.4*). It is said that by irradiating the diamond through the side these tell-tale markings can be eliminated. In such a case the

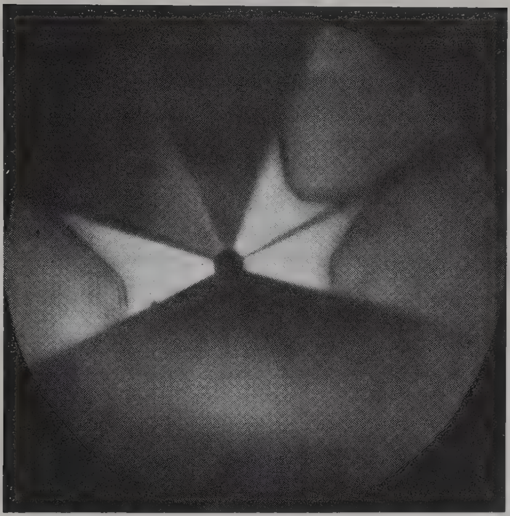


Figure 31.4 The 'umbrella' seen around the culet in a bottom-treated cyclotroned diamond

only distinction is that, as Crowningshield has pointed out, there is always a narrow absorption line at 594 nm in the treated yellow and brown stones, where this line is absent in untreated yellow and brown diamonds. It has been further reported that irradiated diamonds of a brownish-pink colour show absorption lines at 637 nm and a pair of lines at 620 and 610 nm in conjunction with the 594 nm line.

A similar state of affairs occurs with the pile-treated diamonds, in which neutrons are the particles, but here the coloration is throughout the stone. The colours produced are, like the cyclotroned diamonds, green, brown and yellow; the brown and yellow stones are obtained after heat treatment. The diamonds when they come from the pile are intensely radioactive and dark green in colour. The radioactivity quickly dies out, and by subsequent controlled heat treatment any of the colours named may be obtained. There are no characteristic markings to be seen in pile-treated diamonds and the differentiation between these and naturally coloured diamonds depends mainly upon the presence or absence of certain typical absorption bands – a complex subject which is discussed in some detail below.

As might be expected, the changes in colour of bombarded diamonds are accompanied by changes in absorption spectra and often by changes in fluorescence. Such changes are markedly dependent upon the subsequent heat treatment. Current knowledge of changes in absorption characteristics of irradiated and annealed diamond have been well summarised by Dr Gordon Davies, of King's College, and Dr Kurt Nassau. It would seem that when common nitrogen-containing diamond is irradiated, dose-dependent green to black colours will be induced as a result of the formation of a wide absorption band, the GR1 band, that extends from 741 nm in the infra-red well into the yellow-green region of the visible spectrum. Subsequent heating begins to destroy the GR1 absorption above 400 °C, with the formation of 497 nm (H3) and 503 nm (H4) bands, and the potentially identifying 594 (595 in the USA) nm absorption line. These absorptions increase in intensity up to about 800 °C, and are responsible for the yellow, orange or brown colours of annealed-irradiated diamonds. If the temperature is further raised to 1000 °C, the 595 nm absorption completely disappears without significantly altering the induced colour.

An important early advance in distinguishing between natural coloured diamonds, and those coloured by radiation and annealing, was made by Crowningshield, who recorded in *Gems and Gemology* (Winter 1957–1958) that virtually all the known treated yellow diamonds (loaned by a producer) showed a narrow absorption at 592 nm (the preferred measurement is now 594 nm) which could be clearly seen in a hand spectroscope so long as the stone was kept cool. At that time no natural cut brown or yellow diamond had shown this line, though it had been observed by Anderson in certain uncut brown diamond crystals from Obanghi in Central Africa. These observations were confirmed in many gem testing laboratories, and the presence of a 594 nm line has been taken as a valuable proof that a diamond has been irradiated and subsequently annealed. Conversely the absence of this line (even when examined by an experienced spectroscopist at low temperatures) provided strong evidence that the colour of a yellow diamond was natural in origin. Confirmation of this was usually forthcoming in the observed presence of strong 'Cape' absorption bands at 415 nm, 478 nm etc., to which the colour could be ascribed.

Unfortunately, two other discovered factors have made the issue less certain. The first, the discovery by Collins that by annealing (with due precautions) pile-treated diamonds at higher temperatures (e.g. 1000 °C), stones resulted which retained their yellow colour but no longer showed a 594 nm line. Fortunately, recent research by Woods and Collins (*Journal of Gemmology*, April 1986) has solved this problem of identification. These researchers showed that it was not possible to colour a diamond artificially, using radiation damage and heat treatment, without producing at least one absorption line at 595 nm in the visible, or at 1935 nm (H1c) or 2924 nm (H1b) in the infra-red. When all three of these absorptions were absent from the absorption spectrum of a coloured diamond, it could be safely identified as a naturally coloured diamond. However, if the 595 nm absorption band were absent from a coloured diamond, but either the H1b or the H1c absorption line was present, then its colour had to be artificially induced. The second factor was the observation that the 594 nm line could occasionally be detected in diamonds whose past history preceded the age when the bombardment process had been in use. Reference may be made to a useful survey by the experienced spectroscopist Scarratt of the London Gem Testing Laboratory published in the *Journal of Gemmology* (July 1979), while from the physicist's viewpoint Collins has produced a comprehensive review in the same journal (January 1982).

Radiation-Induced Colour Changes in Other Gemstones

Other gems that are commercially colour modified by irradiation and annealing include blue topaz, synthetic amethyst, bead-nucleated cultured pearl, pink to red tourmaline, and yellow-brown sapphire. Blue topaz is commercially produced by four types of irradiation: gamma rays, high-speed electrons in a linear accelerator, neutrons from an atomic pile, and a combination of an atomic reactor and a linear accelerator. Following annealing to remove unacceptable radiation-induced yellow to brown colours, light blue Cobalt Blue, Sky Blue, deep London Blue and mid Electra Blue topaz is produced.

Conventional gemmological testing cannot detect whether or not blue topaz has had its colour induced by man. As this material is colour stable it does not require disclosure. However, in the USA importers of irradiated blue topaz must have all blue topaz checked for potentially dangerous levels of residual radioactivity before it is released for sale.

Synthetic amethyst is also manufactured by irradiation and annealing of ferric-iron-doped synthetic quartz. Synthetic amethyst may be discriminated from natural amethyst by observation of its rare characteristic inclusions, such as segments of the seed plate on which the synthetic was grown or whitish 'breadcrumb' inclusions, and its lack of Brazil twinning, when examined along the *c*-axis between crossed polars.

Cream to yellowish bead-nucleated cultured pearls are colour enhanced by gamma irradiation to create greyish 'black' pearls. Irradiation darkens the shell beads of these pearls, through its reaction with their freshwater-derived manganese content. Observation of a greyish pearl, with a black nucleus and whitish nacre, will confirm this colour enhancement.

Pale pink tourmalines may be irradiated in a gamma cell to yield strongly hued pink to red tourmalines. These radiation-induced hues are quite colour stable, but the product may be residually radioactive.

Colour enhancement, by irradiation and annealing, is not without some problems, for some induced colours are not stable, and tend to fade when exposed to strong light or moderate heat. Be cautious of attractive gemstones such as dark blue maxixe beryl, brownish-orange topaz, and yellow-brown Sri Lankan sapphire, for their colour centres are not stable and their colours tend to fade under normal conditions of wear, display or storage. Colour-fading gemstones can only be detected by subjecting them to a fade test by exposing half of the gemstones to either light or heat.

32

Refractive Index, Reflectance and Thermal Conductance

Refractometer Methods

It has been explained that when a ray of light passes obliquely from a transparent medium to another of lower optical density the ray is refracted away from the normal, and, as the angle of the incident ray is increased, there is reached an angle where the refracted ray just grazes the surface of the two media in contact. This particular angle, where the refracted ray makes an angle of 90 degrees with the normal, is known as the critical angle. Any further increase in the angle of incidence will cause the ray to be reflected into the first medium, that is it is totally internally reflected. Upon this optical effect is based the principle of the gemmological refractometer.

Wollaston was the first to suggest that if the critical angle of a substance in optical contact with a block of glass having a higher index be measured, the refractivity of the substance of lower index could be assessed. This is the principle of the elaborate and very accurate Abbe-Pulfrich refractometer used in many laboratories (*Figure 32.1*). These instruments make possible accurate measurements of the critical angles but the result is only obtained after trigonometrical computation.

In gemmological refractometers all calculations are ingeniously avoided by projecting the rays of light reflected from the stone being tested on to a scale which is viewed by the observer through a suitable eyepiece (*Figure 32.2*). When a flat polished surface of a gemstone is placed upon the glass table of the instrument (having first applied a drop of highly refracting liquid to enable optical contact to be made between the two surfaces) the scale of the instrument can be seen through the eyepiece to be partly in shadow and partly brightly illuminated. The shadowed portion represents the partially reflected rays from the stone and the brighter portion is lit by the totally reflected rays. The position of the shadow edge enables the operator to read the refractive index from the scale or, in certain early instruments, to read numbers from which the correct indices can be obtained by reference to a calibration card.

Figure 32.1 The Abbe-Pulfrich refractometer in use

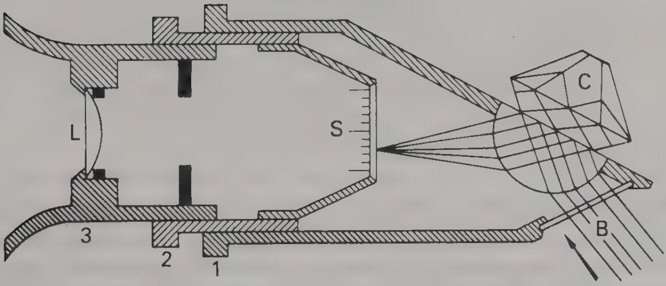


Figure 32.2 Diagram of the optical system of the Bertrand refractometer

The first direct-reading refractometer following these principles was designed by Professor Bertrand in 1885. The optical system of his little instrument was too simplified to enable really definitive readings to be obtained and the scale had to be translated into refractive indices from a calibration card.

In 1905, Herbert Smith of the Mineral Department of the British Museum (Natural History) designed a small refractometer (*Figure 32.3*) in which the optical shortcomings of the Bertrand instrument had been rectified. However, this also had its limitations: the scale again was an arbitrary one and the highest reading obtainable was only 1.76. Two years later Herbert Smith, bearing these deficiencies in mind, persuaded the makers, J H Steward, to produce a much improved model (*Figure 32.4*). The optical centre of this was a segment of a large

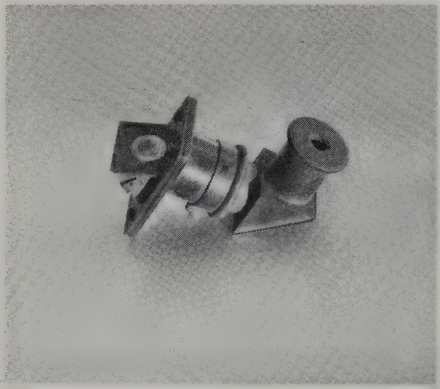


Figure 32.3 *The Herbert Smith refractometer, 1905 model*

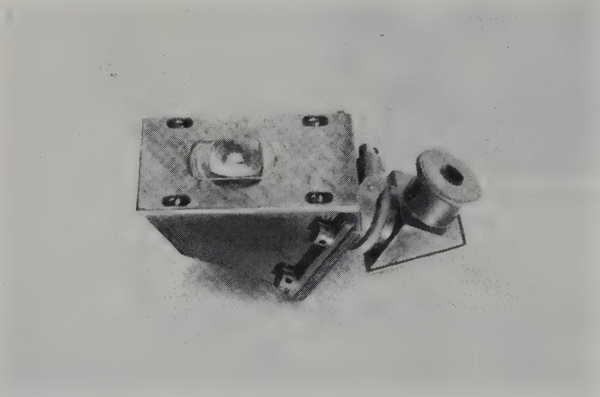


Figure 32.4 *The improved 1907 model Herbert Smith refractometer*

hemisphere of highly refractive lead glass, enabling readings to be taken for stones having an index up to 1.79 on a correctly calibrated refractive index scale. In all such instruments, as already mentioned, it is necessary to apply a small drop of highly refracting liquid to the refractometer surface in order to make optical contact with the stone being tested. This necessity imposes a further limiting factor since no index can be read which is higher than that of the contact fluid employed. The liquid provided with the Herbert Smith 1907 model was di-iodomethane saturated with sulphur, which was added while hot but crystallised out to some extent on cooling. In old samples the refractive index of the liquid might sink to 1.78 or even lower, and this could cause confusion when attempting to take readings with stones such as corundum or almandine garnet. For many years the Herbert Smith refractometer had the field virtually to itself in the jewellery world and was indeed still in production until after the Second World War, before its manufacture was at last discontinued.

From the later 1920s onward, however, other refractometers were designed and produced both in Britain and abroad. All depended upon the same principle but differed considerably in design. The most original and ambitious of these was made by the Rayner Optical Co. to a design by the gemmologist Tully. The

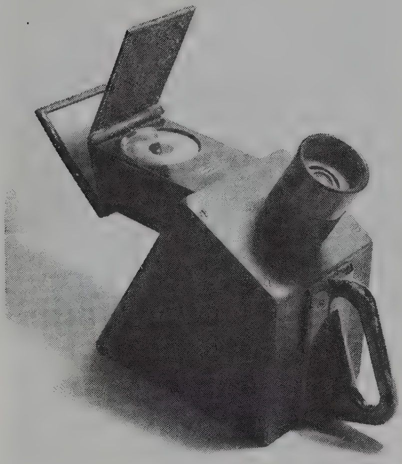


Figure 32.5 *The Tully refractometer*

Tully model (*Figure 32.5*) was a heavy table instrument which incorporated a hemisphere of unusually dense lead glass which was mounted by adhesive below a metal collar slotted into the instrument in a manner which enabled it to be rotated by the finger of the operator with the stone in position upon it, thereby greatly facilitating the measurement of birefringence in different orientations. The index scale, rendered upright by an erecting prism, extended to 1.86 (or in some cases to 1.90). The Tully instrument despite its attractions had certain disadvantages. The glass hemisphere was very soft and vulnerable to abrasion and chemical attack, and was sometimes not quite truly mounted, giving rise to slight 'wobble' in the readings when rotated, while in some cases the hemisphere disconcertingly dropped out if undue pressure was applied to the specimen under test. This enterprising model thus met with limited success.

Rayner's next commercial refractometer broke with tradition in using a truncated 60° prism instead of the usual hemisphere or segment of a hemisphere. Historically it is worth recording that the choice of a prism shape arose from experiments with refractometers using substances other than glass, which were constructed under guidance from Pike of the Rayner Optical Co at the instigation of Anderson and Payne in an attempt to increase the range of the instrument. Zinc blende (sphalerite) which has the high single refractive index of 2.37 seemed a sensible first choice and transparent pieces of the mineral were available from sources in Mexico and Spain. It was found much simpler and more economical to employ this in the form of a truncated 60° prism than a traditional hemisphere. Thus it happened that the first Rayner type refractometer, now so familiar throughout the world, was a blende model (*Figure 32.6*). This prototype instrument had a scale extending to 2.20 and with its aid Anderson had no difficulty in obtaining for the first time readings for the

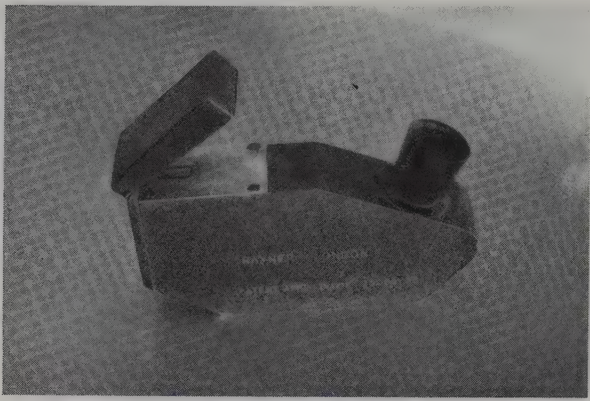


Figure 32.6 The Rayner blende refractometer (experimental model)

refractive indices and birefringence of the whole wide range shown by zircons of different colours. For this work a yellow phosphorus mixture suggested by West was employed as contact liquid, with due precautions against its spontaneous inflammability when exposed to air.

A logical extension of this idea was to employ diamond as the prism material and, with the generous aid of the Diamond Corporation, this was eventually made possible. An experimental model of a refractometer utilising a diamond prism was completed by Rayner in 1936. In this pioneer instrument the diamond as finally incorporated weighed 2.5 carats, but those made to order subsequently functioned quite adequately with prisms of less generous proportions. Diamond being chemically resistant, selenium bromide mixed as necessary with the normal contact liquid could be used.

An unexpectedly successful byproduct of Rayner's prism design lay in the realm of lower refractive indices and involved a prism of colourless synthetic spinel, having a refractive index of 1.726. This limited the readings to stones having a refractive index below 1.70, but this range includes the majority of gemstones, particularly those (such as synthetic and natural emeralds) where accuracy is essential, an accuracy which the spinel refractometer makes possible, partly on account of the more open scale, but more importantly due to the sharp shadow edges produced even in ordinary white light. The reason for this effect lies in the fact that spinel has a dispersion very similar to that of the stones within the refractometer's range, which means that the critical angle between the specimen and prism hardly varies for any of the coloured rays comprising the visible spectrum. One further obvious advantage lay in the hardness of the spinel prism, ensuring a permanently unscratched surface.

The standard Rayner refractometers using a lead-glass prism were soon in general use throughout the world, and underwent little change except in matters of finish and styling until 1972, when an entirely new idea was put into effect. In this, the Dialdex refractometer (*Figure 32.7*), there was no refractive index scale to be seen through the eyepiece. In its place there was a black ribbon-like 'cursor' or indicator, the position of which could be adjusted by

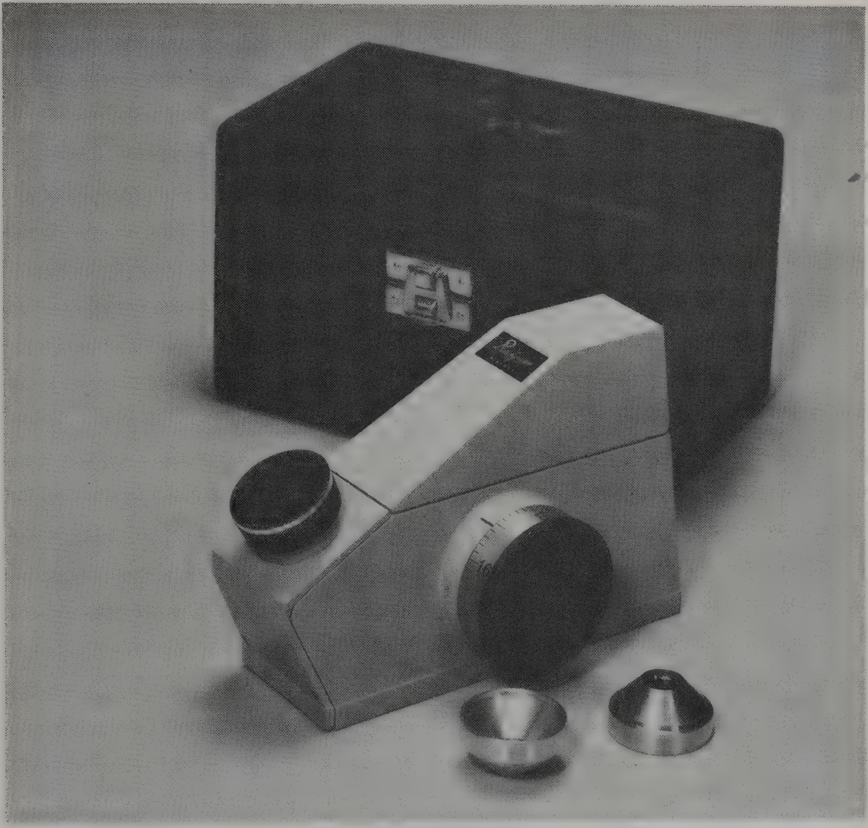


Figure 32.7 *The Dialdex refractometer*

turning a calibrated dial until it matched that of the shadow edge to be measured (*Figure 32.8*). The calibrations on the dial are marked in refractive indices enabling these to be read to three places of decimals against a fixed point alongside the moving dial. In the case of doubly refracting stones maximum and minimum readings can be taken in turn from which the birefringence can be quickly calculated by subtracting the lower reading from the higher one. The lack of need for a scale was welcomed by the manufacturers as the film graticules used for the scale attract dust and frequently become pitted. However, a substantial number of gemmologists continued to prefer the conventional scale and to satisfy their need an instrument with a scale was made available in what was designated the 'S' model of the Rayner refractometer.

The first gem refractometer of American design and manufacture did not appear until after the Second World War. This was the Erb and Gray instrument, which at first followed the Tully idea in using a revolving hemisphere of dense glass but, as this also gave readings which were subject to 'wobble', in a later version a fixed hemisphere was preferred. The Erb and Gray refractometer has a simple optical system which renders it particularly suitable for readings on cabochon or very small faceted stones by the 'spot' method (to be described

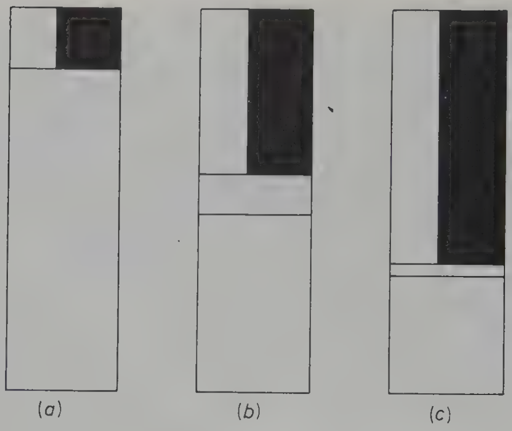


Figure 32.8 *Appearance of the field in the Dialdex refractometer showing the 'ribbon' brought down to be in juxtaposition with shadow edges. (a) Fluorite (singly refracting with index 1.434). (b) Peridot (doubly refracting; 1.66 and 1.69. Indicator edge on 1.66 reading). (c) Sapphire (doubly refracting; 1.76 and 1.77. Indicator edge on 1.76 reading)*

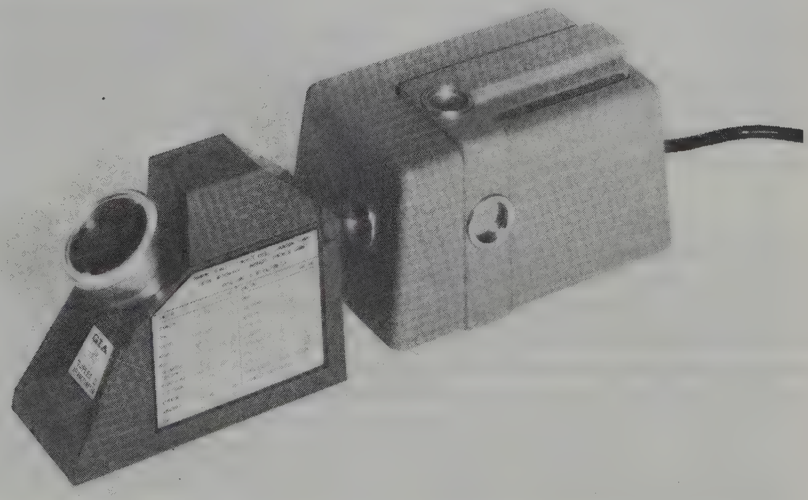


Figure 32.9 *The Duplex refractometer (Gem Instruments Corporation)*

later). Benson of the Gemological Institute of America designed the Duplex refractometer which employed a large segment of hemicylindrical form in place of a hemisphere, and utilised a movable mirror to facilitate readings in different parts of the scale. A later Duplex II model (*Figure 32.9*) was redesigned to eliminate the need for the movable mirror. A sensible feature of the Duplex refractometer is the provision of refractive index tables for gemstones attached to each side of the instrument.

Two other refractometers in present day use are the Ergo gemstone refractometer which is made in Germany by Krüss, and the Topcon refractometer, made in Japan. The latter is designed with the particular intention to enable the refractive index of cabochon stones to be determined with ease by using the 'spot' or 'distant vision' technique.

Contact Liquids Used with the Refractometer

Mention has been made in the foregoing pages that refractive index readings can only be obtained on a refractometer if a small drop of fluid is applied to the surface to enable optical contact to be made between the refractometer glass and the stone to be tested. Without the liquid a film of air would intervene between the two surfaces. For a result to be obtained it is necessary that the liquid used should have a refractive index higher than that of the stone being tested: if this precaution is not taken a shadow edge due to the liquid will be the only effect to be seen by the operator. It is thus important that he should know the refractive index of the fluid provided to prevent an elementary mistake being made. Havoc was actually caused during one practical examination where one of the contact liquids provided consisted of pure di-iodomethane (RI 1.742) instead of the standard fluid (RI 1.81). This standard fluid (RI 1.81) which is now almost universally used resulted from research work carried out in the 1930s by Anderson and Payne in the London Gem Testing Laboratory. It consists of a saturated solution of sulphur and the yellow crystalline compound tetra-iodoethylene in di-iodomethane which has a stable index at room temperature of 1.81 and no perceptible harmful effect on the glass of the refractometer.

West's solution, which has already been mentioned in connection with the blende refractometer, would be an excellent contact fluid with its high refractive index of 2.05 were it not for its dangerous flammability. It can be prepared by very gently warming 8 parts of yellow phosphorus with 1 part of sulphur and 1 part di-iodomethane under water when it forms a transparent yellow fluid. It must be kept under water in a stoppered bottle and the minimum requirement removed with a pipette when a reading is to be made. Immediately this has been completed the excess fluid should be wiped from the specimen and refractometer with filter paper which should be dropped at once into a vessel of water and then disposed of in accordance with approved site practice. If allowed to remain in the air the paper will begin to smoulder and finally burst into flame!

Over the years a number of high-index fluids or easily melted mixtures have been suggested by American mineralogists for use in immersion techniques for determining the refractive index of mineral fragments under the microscope, and compounds of this nature have been utilised with the Krüss Riplus and S & T CubicZ refractometers described later. A number of liquids having a range of refractive index from 1.82 to 2.00 were developed by Meyrowitz and Larsen in 1951. These contain arsenic salts, and are now prepared and supplied by the Cargille Laboratories in New Jersey. A further series containing selenium extends the range to 2.10. These, however, all require careful handling and are only used when really necessary.

Figure 32.10 The Krüss Riplus high-index refractometer

Recent High-Index Refractometers

Experiments in the 1930s in using truncated prisms of zinc blende and diamond to construct high-index refractometers have already been described. After a lapse of more than forty years two other ventures of the kind were successful, in each case making use of one of the numerous highly refractive man-made crystals which modern technology has made available. Undoubtedly the arrival of cubic zirconia as a highly plausible diamond simulant has acted as an added incentive for such ventures.

The first of these is now manufactured on a commercial basis by the optical firm of Krüss of Hamburg, following preliminary spade-work by Siber and Siber, dealers in gemstones, in Switzerland. The Krüss refractometer (*Figure 32.10*), aptly named Riplus, incorporates a prism of strontium titanate, a man-made crystalline material which has a cubic structure and is thereby isotropic. An added advantage is its high refractive index (2.418) equal to that of diamond for sodium light: against this, its hardness is only 6 on Mohs's scale and great care must be taken to avoid scratching the prism. The following notes on this new model are based on a published report by Read (*Journal of Gemmology*, January 1981).

The refractive index scale of the Riplus reads from 1.79 to 2.2: it is thus sensibly intended as a supplementary instrument to the standard forms of refractometer. The important problem of the contact liquid was solved by Siber and Siber in the concoction of a highly refractive viscous paste which must be heated to over 40 °C before becoming sufficiently fluid to serve its purpose. Both the bottle containing this mixture and the strontium titanate prism must then be heated by an electrical element before a reading can be taken, and arrangements for this are ingeniously incorporated in the specially designed plinth on which the refractometer stands. This warming-up process takes some 15 minutes. Since the dispersion of the prism is high a sodium light source is needed for accurate readings and this also is provided with the plinth unit. In testing the Riplus, Read found it possible to obtain readings for YAG (1.825), white zircon (1.930–1.990), GGG (1.960) and (most importantly) cubic zirconia (2.175). Sadly, the contact paste, in common with the earlier high-RI contact fluids, also proved to be toxic as it was found to contain arsenic salts.

The second of these high-reading refractometers uses a prism of cubic zirconium oxide, and was produced in 1983 by the S & T Electro-Optical Systems Corporation of Redondo Beach, California. This instrument is called the CubicZ, and has a range of 1.40 to 2.10. Like other high-range refractometers, to fully utilise the extended scale necessitates the use of corrosive or toxic contact fluids. However, there are other advantages in using a CZ prism in comparison with glass or strontium titanate. Because of its hardness (8 on Mohs's scale), cubic zirconium oxide takes a high optical polish, and is less easily scratched by the majority of gemstones. Its resistance to chemical attack also prevents any deterioration which might otherwise be caused by the various contact fluids.

Preparation of Refractometer for Use

To prepare the refractometer for use the instrument should be arranged in front of the light source (white light or a monochromatic source as necessary), and if a desk lamp is used it may be an advantage to stand the instrument on the closed box in which the refractometer is normally kept. The surface of the prism should be clean and an occasional rub with a rouged leather will keep it so. The scale is then viewed through the eyepiece to see that it is evenly illuminated, the instrument being adjusted in its position before the lamp until this is so. The scale should then be put into correct focus by adjustment of the rotatable eyepiece. On completion of this the figures and divisions of the scale should be clear and the whole scale have a uniform intensity of light. A small drop of the contact liquid supplied with the instrument should then be applied to the centre of the glass prism, and the stone to be tested, which should first be cleaned, carefully placed table facet down on to the centre of the prism. If possible the hinged lid of the refractometer should be lowered in order to exclude any top light. On looking into the eyepiece (*Figure 32.11*) the scale will be found to be divided into two portions, the top part (except in the Tully refractometer in which the scale is erect) being a dark greenish colour and the bottom part quite bright. The division between the two parts will appear as a colour fringe (when white light is used with a standard instrument) and the value of the refractive indices will be in this fringe where the green and yellow meet. For the best results the eye should be kept close and central to the eyepiece.

In the standard refractometers which have a prism or hemisphere of dense glass, the glass used is very soft: it is certainly far softer than the hard gemstones which are placed upon it. Hence, it is essential to ensure that the polished surface of the prism is not scratched by careless placing of the stone on it, for an instrument with a scratched surface can never give good readings. After use the contact liquid should be removed by absorbing it with blotting paper or wiping with a soft cloth, and if the instrument is only occasionally used a smear of petroleum jelly over the dense glass will be an advantage, but this needs to be thoroughly cleaned away before the refractometer is used again.

Figure 32.11 Observing the shadow edge with the refractometer (the lid has been left up for photographic purposes)

Sources of Light

Even singly refractive substances have an indefinite number of indices according to the wavelength of the light used: hence the spectral edge seen when white light is the source. It is usual therefore, when accurate readings are needed and in order to observe the two shadow edges in birefringent stones, to use a light source which is, so far as is practicable, monochromatic, that is consisting of light of one wavelength only. An example is sodium vapour, which consists of light of wavelengths 589 and 589.6 nm, which for our purpose may be considered as being monochromatic and on which refractive indices are usually based.

Sadly, the high cost of the miniature sodium lamp used in the Rayner light source has finally rendered it unavailable. For a short time a larger cheaper lamp was fitted to a redesigned Rayner sodium light source, but this too is no longer available. Alternatives range from the dark orange-yellow eyepiece filter supplied with some refractometers to improve the sharpness of the shadow edge when using a white light source, to light sources using yellow light-emitting diodes (LEDs), and interference filters. Of these, the LED units are relatively inexpensive, but as they have a much wider bandwidth of 35 nm (compared with the sodium lamp's 0.6 nm) are not truly monochromatic (see *Figure 32.12*). Interference filters centred on a wavelength of 589 nm have a much narrower bandwidth, but because of this they must be used with a high-intensity source of white light. Refractometers have been produced with internally fitted LED light sources.

Distant Vision Technique

From the foregoing it is assumed that a flat facet on the stone to be tested is essential for a refractometer reading of the shadow edges. This is perfectly true

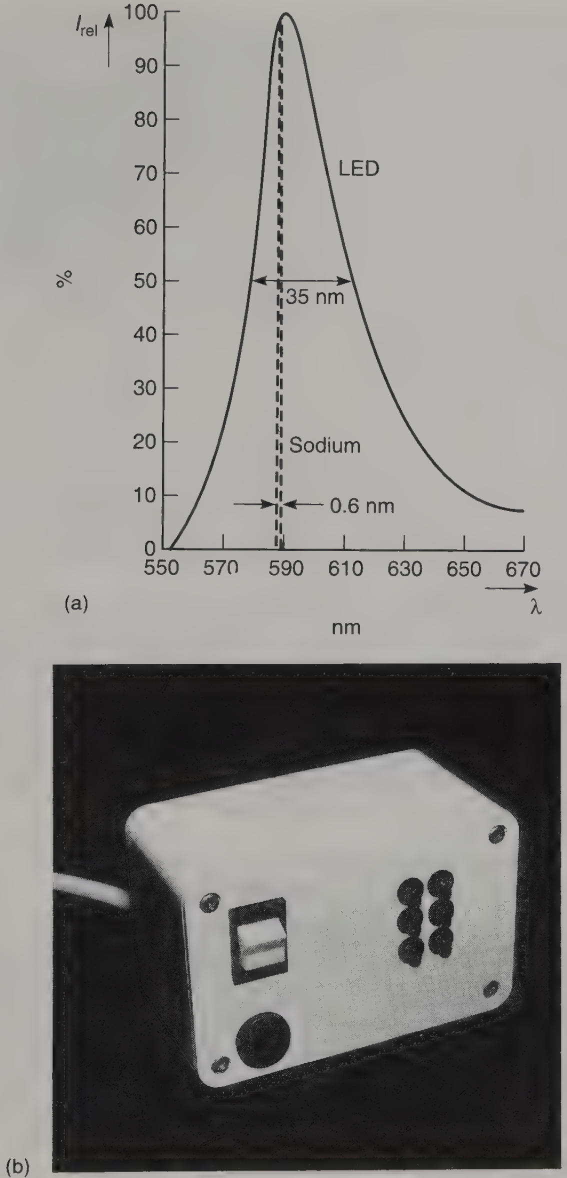


Figure 32.12 (a) Graph comparing emission bandwidth of an LED light source with that of a sodium lamp, (b) a mains-operated LED light source (Rubin)

if accurate readings to the third place of decimals are to be made. It has, however, been found that by a special technique the refractive indices of stones with curved surfaces, such as cabochon-cut or carved stones, may be measured with some degree of accuracy.

This method, devised by Benson, is variously termed the 'spot contact' or 'distant vision' method. It is more easily carried out with refractometers in which the optical train is simple and in which the eyepiece can be removed, as is the case with some American refractometers. However, the method can still be carried out with success with those instruments in which the eyepiece is fixed, as is the case with the Rayner refractometer. The scheme is to apply the smallest possible drop of contact liquid to the centre of the dense glass; then the curved surface of the piece to be tested is gently placed on the surface of the dense glass on this spot of liquid. On looking through the eyepiece – not in the normal way, but with the eye withdrawn to about 400 mm from the eyepiece – a small disc will be seen. When the eye is slowly moved in an up-and-down direction the small disc is seen to change from being fully dark in the low-index part of the scale to completely light in the high-index region. At some point between these two there will be a position where the disc is bisected half black and half white. When this position is found the eye should be moved slightly so that the scale of the refractometer, which was previously out of focus, can be read. A pinhole aperture, made in a piece of cardboard and held close to the eye, will help to make both disc and scale visible. Use of the Rayner Dialdex refractometer obviates this problem as it is easier to observe this instrument's 'ribbon' than read figures from a scale.

Practice will foster proficiency in this method, which is usually sufficiently accurate for the discrimination of stones of similar appearance but which have dissimilar refractive indices. There are special auxiliary lenses available which enable the refractometer scale and the disc to be focused more easily at the same time. With this method the measurement obtained is often found to be one or two digits low in the second place of decimals. The distant vision technique is also useful in the case of tiny faceted stones which give too faint an edge when the refractometer is used in the ordinary way.

Colour Fringe

The refractometer with a synthetic spinel prism will, owing to the similarity of dispersion of the prism to those of the gemstones which can be measured by such instrument, show sharp shadow edges in white light. However, paste stones are usually made of glass with a high dispersion and are at once noticeable for their strong and wide colour-fringed shadow edges. Thus most pastes may be identified easily by their colour fringe when a spinel refractometer is used. Another advantage of the spinel instrument is that owing to the restricted range of the scale, the divisions are more open and estimation of the third place of decimals is more easily made.

In the standard refractometer careful observation of the sharpness or otherwise of the coloured fringe of the shadow edge in white light will give some idea of the dispersive power of the stone under test and this may give useful confirmatory information.

Occasionally stones, especially pastes, do not give a shadow edge. This is sometimes due to surface tarnish or to the sputtering of 'coated' stones. If the film of tarnish or the film due to sputtering is removed by rubbing the stone with a rouged leather it may then be possible to obtain a refractive index measurement.

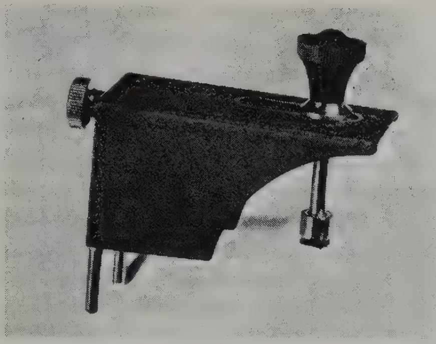


Figure 32.13 *The Rotagem*

Effect of Shadow on Refractometer

So far it has not been clearly explained that the stone under test needs to be rotated on the dense glass to ascertain whether the shadow edge is a single edge or may become a double line (as in the case of birefringent stones). To rotate the stone entails careful control with the fingers if the stone is not to be tilted with resultant damage to the soft dense glass of the instrument by the sharp and hard facet edges of the stone. In the early 1930s Halford Watkins designed a spring-holder which fitted on to the Herbert Smith refractometer and by gripping the stone allowed it to be turned without tilting by the manipulation of a knob. So far as is known this was never commercially marketed. In 1954, Field of Canada designed a fitting to take the place of the cover of a Rayner refractometer. This accessory, known as the Rotagem (*Figure 32.13*), held the stone on to the dense glass by a rubber pad on the end of a rotatable stem fitted with a control knob.

Isotropic materials including stones belonging to the cubic system of crystallisation – amorphous materials, such as glass (pastes), resins (amber), and gels (opal) – have only one index of refraction, that is they only show one shadow edge whatever the orientation of the stone on the dense glass, since in this case light is refracted equally in all directions and polarisation does not take place. In doubly refractive stones there are two edges to be seen and the behaviour of these edges on the refractometer when the stone is rotated on the dense glass can give diagnostic information, for the full double refraction of such a stone can be measured on any facet. These effects will now be considered.

Uniaxial Stones

It has already been explained that in uniaxial stones there are two indices of refraction, the ordinary ray which gives a shadow edge which is invariable in position, and the extraordinary ray which, in general, will be seen to yield a shadow edge moving to another limiting position when the stone is turned. If the moving edge has the higher RI the sign of refraction is said to be positive; if it is the lower RI edge which moves the sign is negative. The refractometer, although ingeniously projecting the shadow edge of the critical angle for the two media, the dense glass and the stone under test, on to a scale giving direct reading of refractive indices, these will only be those in the plane of the facet lying on the dense glass. The refractive index or indices seen on the scale will depend on the vibration directions in this particular facet. In uniaxial stones the vibration directions of the ordinary ray are at right angles to the optic axis (the direction of single refraction), while in directions within the crystal at right angles to the optic axis there are two vibration directions for any one ray, one at right angles to the optic axis (ordinary ray) and one parallel to the optic axis (extraordinary ray), which are thus vibrating at right angles to each other (*Figure 32.14*).

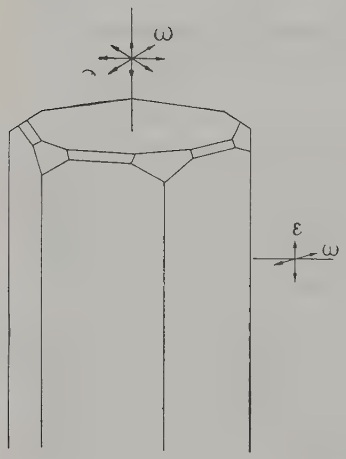


Figure 32.14 *The vibration directions in a uniaxial crystal*

A uniaxial stone cut with its table facet parallel to the optic axis will show the extraordinary ray to move from the position of greatest birefringence to the position of the ordinary ray. Thus, such a stone placed on the dense glass of the refractometer will, when the direction of the vertical crystal axis – which is also the direction of the optic axis – is parallel to a line drawn from the window of the instrument to the eyepiece, show a single edge due to the vibrations of the ordinary ray. When the stone is turned the extraordinary ray will be seen to separate until, when the angle turned is 90 degrees, the maximum separation of the two shadow edges is obtained. Careful measurement of these shadow edges at their maximum separation and the subtraction of the lowest numerical reading from the greatest will give the value of the birefringence of the stone.

If the facet tested is cut perpendicular to the optic axis the vibrations of both the ordinary ray and the extraordinary ray will be present and the full double refraction will be seen at all positions during a complete rotation of the stone; a test on another facet would be necessary before the optic sign could be determined. If the table facet does not lie in either of these planes, it will be seen that on turning the stone on the refractometer there will be the stationary shadow edge of the ordinary ray and that the extraordinary ray will move from some position between that of the ordinary ray and that of the full divergence of the extraordinary ray, but that the extraordinary ray will not at any time coincide with the ordinary ray.

Biaxial Stones

In biaxial stones there are two directions of single refraction (optic axes) and three critical refractive indices, α, β and γ, as explained earlier. Although there can be only two polarised rays passing along any one direction in the crystal the three refractive indices correspond to rays vibrating in three mutually perpendicular directions. One of these, α, has the lowest refractive index and consists of rays vibrating parallel to the acute bisectrix in optically negative crystals, and parallel to the obtuse bisectrix in positive crystals. Another ray, γ, has the highest refractive index and is vibrating parallel to the obtuse and the acute bisectrix respectively in the two instances mentioned. The third ray, β, has an intermediate index and consists of light vibrating at right angles to the plane of the optic axes, that is at right angles to α and γ. *Figure 32.15* illustrates the vibration directions in a biaxial crystal.

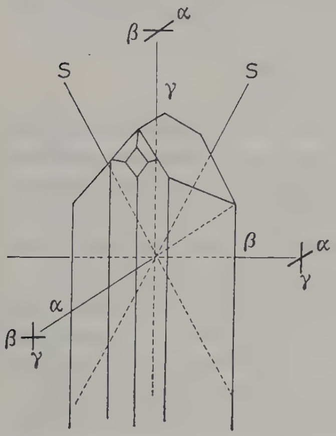


Figure 32.15 The principal vibration directions in a positive biaxial crystal (topaz). SS are the optic axes

The behaviour of the shadow edges on the refractometer is more complicated in the case of biaxial stones for, in general, both the shadow edges seen on the refractometer scale move and are thus both 'extraordinary'. The question of the β ray and the sign of refraction also needs comment. When the angle between the optic axes is small, either the shadow edge with the higher index or that with the lower index will move very little; then it will be easy to see whether the sign is positive (β nearer to α) or negative. When the facet tested happens to be cut at right angles to the vibration direction of one of the critical rays, this ray will be seen as an invariable edge when the stone is rotated on the refractometer. When this direction is β there will be four positions, during a rotation of the stone through a full circle, where the moving edge crosses over the invariable β position giving at four points a single edge – that of β. A table facet cut so that it is oriented haphazardly to the main optical directions, as is the case in most gemstones, will give readings much more difficult to interpret. Each of the principal refractive indices will be reached by one or other of the shadow edges at different positions of the stone. Both shadow edges move and it is a matter of taking the lowest reading reached by the lower and the highest reached by the higher edge to determine the full birefringence of the stone. The determination of β is difficult in such cases, but generally the optic sign may be obtained by noting which of the two shadow edges passes the half-way mark between the highest and lowest readings. If it is the higher RI one the stone is positive, and if the lower it is negative.

Monochromatic Light

The shadow edges seen in a refractometer when monochromatic light is used are sharp but may not be obvious. These edges may quite easily be missed if the observer has no notion where they should be. Therefore it is better first to use white light in order to find out more easily where the edges are, and then to use monochromatic light to see the two edges and to read their indices. A Polaroid disc rotated over the eyepiece will select each edge in turn and may help in the reading of weak shadow edges.

Liquid Immersion Methods

The refractometer provides the most convenient method for the measurement of the refractive indices of gemstones, but the constant can be measured either accurately or approximately by a number of other methods, and these will be discussed now. The methods depending upon the behaviour of gemstones in liquids of high refraction have some importance and will be dealt with first. When a transparent stone is immersed in a liquid of the same refractive index it becomes virtually invisible, as, for example, does ice in water, and this gives a simple and effective method of gauging the refractive index of gemstones whether they are rough or cut.

The stones are immersed in liquids of known refractive index contained in suitable glass vessels, and the stones will have a refractive index near to that of the liquid in which they most completely disappear. The method is most useful in the detection of 'intruders' in a parcel of small stones, for if a liquid matching the bulk of the stones is chosen any stones of a different species will show up by their different relief. This method is particularly useful for a multi-stone diamond brooch in which some synthetic white sapphires or spinels are suspected. In di-iodomethane, such stones would show up by their low relief against the high relief shown by the diamonds. The method is less satisfactory with white zircon, synthetic rutile or synthetic strontium titanate which have refractive indices near to that of diamond.

Becke Line Method

The above method is capable of greater refinement, when small fragments of the material, or even cut stones, are immersed in liquid and examined microscopically. The method, known as the Becke line method, needs considerable operational practice in order to obtain good results. An edge of the stone is sharply focused and when the focus is raised or lowered a bright rim of light will be seen passing from the stone into the liquid, or vice versa, according to which has the higher refractive index. Trial with several liquids will give a pair, one of which has a higher and one a lower refractive index than the stone;

therefore the index of the stone must lie somewhere between the indices of the two liquids. The closer together the differences in refractive indices of the two liquids the more accurate the final determination of the index of the stone will be. In white light the edges of the specimen appear coloured when a near match is obtained, but for accurate results monochromatic light should be used. The rule for the Becke line is simple and may be expressed as follows.

1. On lowering the focus the line of light passes into the substance of lower refractive index.
2. On raising the focus the line of light passes into the substance of higher refractive index.

The best results are obtained with the Becke method when small fragments scraped from a specimen are used, for much depends upon the shape of the piece examined. Hence the method is particularly useful in the testing of amber, stone carvings and rough stones where a tiny splinter can be removed and immersed in a pool of liquid on a glass microscope slide for examination.

Plato-Michell Method

First described by Plato, the method is a variation of the Becke line test. The method depends on the difference in behaviour of the light effects of the shadow edges of stones immersed in liquid as seen through the microscope. Briefly, when a stone is immersed in a liquid of a higher refractive index than that of the stone and the focus is in the liquid above the stone, the facet edges appear black; when the focus is lowered into the stone the appearance of the facet edges is white. This determines that the stone has a lower index than that of the liquid. Conversely, if the stone has a higher index than the liquid the effect is reversed, the facet edges appearing white when the focus is in the liquid, and black when in the stone. In birefringent stones it is the greater refractive index which seems to be the effective one, but Plato found that by using a polarising plate the two edges of a doubly refractive stone could be measured. With this method the best results are obtained when the substage diaphragm is partially closed; there may be some advantage in removing the substage condenser, but not, of course, the partially closed diaphragm.

Immersion Contrast Method

A much simpler method of refractive index measurement by immersion in liquids has been worked out by Anderson. Actually a modification of the Becke line test, this immersion contrast method, however, needs no microscope. The stones to be tested are placed in a glass dish and immersed in a suitable fluid. The cell with the stones in liquid is placed on a ground-glass sheet which is so placed that an underside view can conveniently be seen in a mirror. The stones in the cell are illuminated by a single overhead light and, on examining the stones through the underneath mirror, striking differences are seen in accordance with their refractive indices, in relation to the refractive index of the liquid in which they are immersed (*Figure 32.16*). Stones with a higher index than that of the liquid show a dark border and the facet edges appear as white lines. In stones with an index lower than that of the liquid this effect is reversed, the

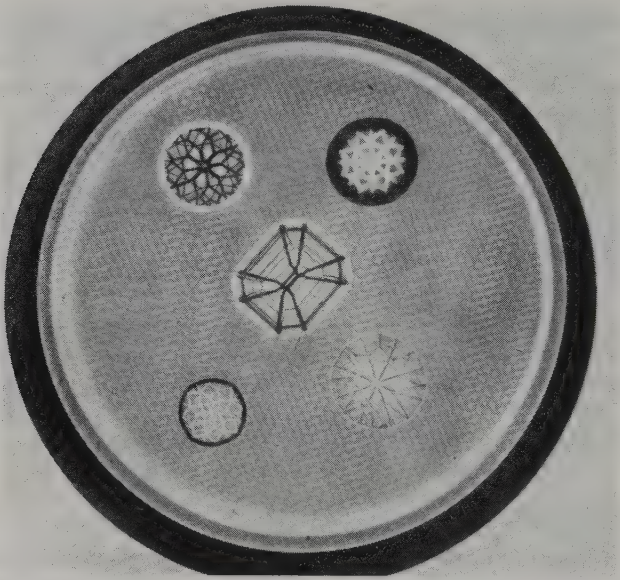


Figure 32.16 The effect of immersion contrast

borders being white and the facet edges appearing as black lines. Further, a good indication of the degree to which the index of the stone and liquid differs can be obtained by noting the width of the dark or pale border and of the lines denoting the facet edges. When a near match exists between the stone and the fluid these signs almost disappear and spectrum colours are seen at the margin of the stone, owing to the higher dispersion of the fluid, unless monochromatic light is used.

The effect can be obtained photographically, giving a permanent record, by placing a piece of slow film or bromide paper under the dish and exposing to an overhead light for a second or so before developing in the usual manner. The negative so obtained will be in reverse, that is the darks and lights will be reversed. This is important if bromide paper is used, but in the case of film, this will usually be printed on to paper afterwards, which corrects the effect to normal.

The immersion contrast method may be used for cabochon stones as well as for faceted stones. In some cases the method has been found to show up the curved structure lines in synthetic corundum which could not be seen during ordinary microscopic examination. If the refractive index of the immersion liquid is near to that of the stone the picture will produce a 'life-size' reproduction of the stone, showing clearly the symmetry and distribution of the facets, and any outstanding internal structures and zoning. Such a picture may be of considerable value in cases needing future identification of the stone. Photographic emulsions are more sensitive to blue than to yellow light and the refractive index of the liquid will be higher for the blue rays. This must be remembered when stones having an index of refraction near to that of the liquid are examined.

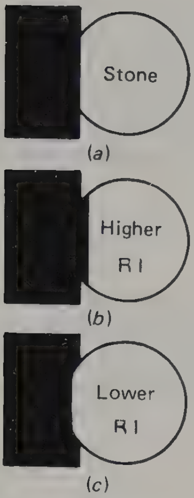


Figure 32.17 The shadow method (after Wild)

Shadow Methods

Similar in operation are various tests known as the shadow methods. The set-up is again similar. The specimen is immersed in oils of different refractive indices and, according to a method devised by Wild, the microscope can be dispensed with. The cell of liquid and stone is held over a bright surface, such as white blotting paper, with sufficient room below for a piece of black card with a straight edge to be passed from one side. When the stone and liquid match in index there is no deviation of the light rays (*Figure 32.17a*), but when the liquid in which the stone is immersed has the higher index the edge of the black card will advance into the stone (*Figure 32.17b*), or if the liquid is of lower refractive index the stone will cut into the edge of the card (*Figure 32.17c*).

The reason for this is explained by Eppler (*Figure 32.18*). Shown in vertical section is the corner outline of an aquamarine ($n = 1.57$) immersed in di-iodomethane. On looking at the specimen vertically from above the only

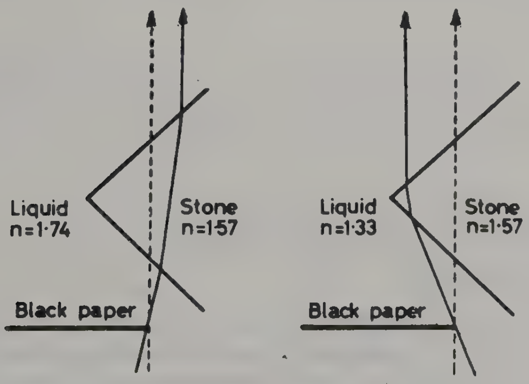


Figure 32.18 Explanation of the shadow method (after Eppler)

light from the card edge that can reach the eye is that which follows the indicated line. The light enters the eye from farther 'into' the specimen, on the right side of the view straight through the stone. This is shown as a dashed line. The black card thus seems to have proceeded into the stone. When the stone is immersed in water ($n = 1.33$) the edge of the card is visible on the left of the view straight through the stone and seems to have travelled farther out of the specimen.

Suitable Liquids for Immersion Methods

The liquids in *Table 32.1* are suitable for use with the immersion methods of measuring the refractive index. Slight differences in the purity of these oils and liquids occur in the commercial state and it is advisable to check these values on a refractometer if accurate work is contemplated. For usual routine operations these values may be accepted.

Table 32.1
Liquids for immersion methods

Water	1.33	Clove oil	1.54	Carbon disulphide	1.63
Alcohol	1.36	Ethylene dibromide	1.54	Acetylene tetrabromide	1.63
Amyl acetate	1.37	Nitrobenzene	1.55	Monobromonaphthalene	1.66
Chloroform	1.45	Brom-toluene	1.55	Monoiodonaphthalene	1.70
Petroleum	1.45	Dimethylaniline	1.56	Di-iodomethane (methylene iodide)	1.74
Carbon tetrachloride	1.46	Benzyl benzoate	1.56	Di-iodomethane and sulphur	1.78
Turpentine	1.47	Monobromobenzene	1.56	Di-iodomethane, S and C_2I_4	1.81
Olive oil	1.47	Orthotoluidine	1.57	Phenyldi-iodoarsine	1.85
Glycerine	1.47	Aniline	1.58	West's solution	2.05
Castor oil	1.48	Cinnamon oil	1.59		
Xylene	1.49	Bromoform	1.59		
Toluene	1.49	Cassia oil	1.60		
Benzene	1.50	Monoiodobenzene	1.62		
Cedar wood oil	1.51	Monochlornaphthalene	1.63		
Monochlorbenzene	1.53				
Canada balsam	1.53				

A number of these liquids are deleterious to the human system and they should not be inhaled, but for the short period during which they would be used they would not be harmful. The two last mentioned fluids are dangerous and should not be allowed to get on to the skin or blistering will occur.

Light Ray Deviation Method

Direct Measurement Method

The following three methods of refractive index measurement depend upon the amount of bending of a ray of light passing from one medium to another of greater optical density. The first of these, called the direct measurement method, or de Chaulnes method, depends upon the change of focus caused by placing a plate of the substance whose refractive index is required to be found

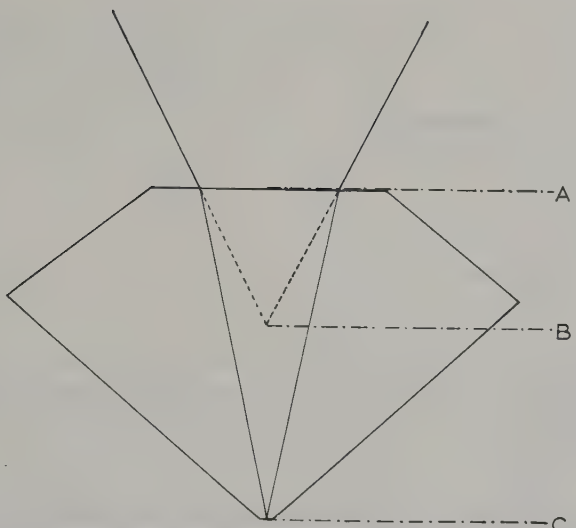


Figure 32.19 The principle of the direct measurement method of refractive index determination

over an object in the focus of a microscope (*Figure 32.19*). Two parallel surfaces of the medium are needed, such as the table and culet of a diamond, or the two parallel faces of an octahedral crystal. By using the calibrated fine adjustment of the microscope, or better by using a microscope fitted with a scale and vernier on the body tube, the real and apparent depth of the stone may be measured. The microscope is first focused on to a mark on the top facet and the vernier reading noted (A). Then a mark below the stone on the surface of the glass slide upon which the specimen is resting is focused through the stone and a second vernier reading taken (B). Finally a third reading is taken (C) when the microscope is focused on to the surface of the bare glass slide. The refractive index of the medium depends on the ratio of the real depth of the specimen and the apparent depth when seen through the specimen:

$$\frac{\text{real depth}}{\text{apparent depth}} = \frac{C - A}{B - A} = \text{refractive index}$$

The method is not very accurate but it can be useful with stones having a higher refractive index than can be measured on the refractometer.

The majority of microscopes do not have a measuring device, but this may be overcome by a method suggested by Tisdall. By the use of a slide gauge with vernier, and these usually incorporate a depth gauge, a measure of the difference in focus can be obtained. This is done by using the millimetre depth gauge to establish the distance between the top of the rack and the top of the plate which covers the coarse focusing pinion housed in the top of the limb. *Figure 32.20* illustrates this. The measurement of the real depth of the stone is made by carefully clamping it between the jaws of the slide gauge, and the apparent depth by using the microscope method with a 16 mm (two-thirds) objective and

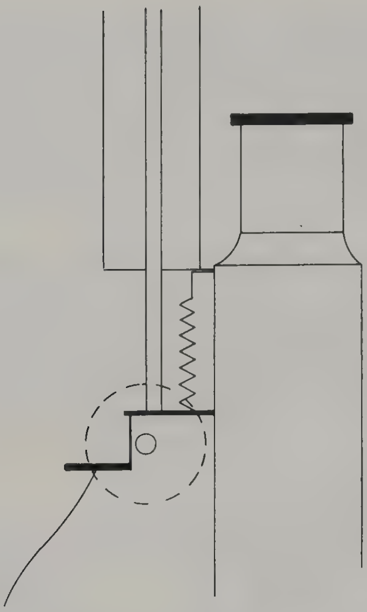


Figure 32.20 *The method by which the real and apparent depth of a gemstone can be obtained on a simple microscope which has no measuring fittings, by the use of a millimetre slide gauge fitted with a vernier*

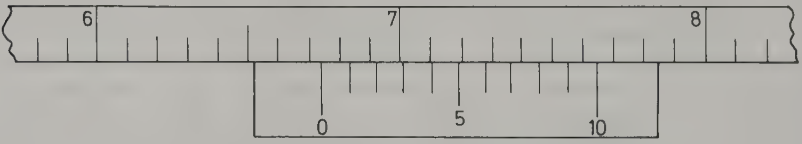


Figure 32.21 *The vernier. The reading is 6.74*

measuring the difference between the focus at the top of the stone and the focus of the culet through the stone.

For those who are not familiar with a vernier, invented by Pierre Vernier in 1631, it consists of a small auxiliary scale which slides along the main scale. The principal of the vernier may be made clear by reference to *Figure 32.21*. It will be seen that the zero mark (usually an arrow) on the vernier lies between 6.7 and 6.8. Calling the length of the vernier division v and the length of the scale division s, it will be found by inspection that $9s$ equals $10v$, or $v = 0.9s$. That is, $v = s - 0.1s$, and the difference in length of vernier division and scale division, or 'least count' as it is called, is equal to 0.1 scale division. To read the attachment it is only necessary to look along the vernier and see which vernier division is most nearly opposite to a division on the scale. The number of vernier divisions from the zero mark where this coincidence occurs will give the value of the next figure in the measurement.

Brewster's Angle Method

In the early years of the nineteenth century the Scottish physicist David Brewster found that when light was reflected from the surface of a transparent

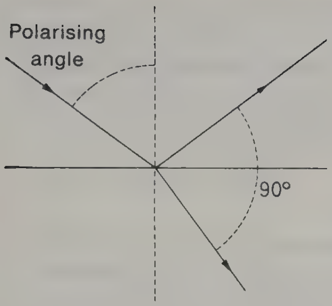


Figure 32.22 The principle of Brewster's angle

substance a maximum degree of polarisation in the reflected light was attained when the reflected and refracted rays were at 90 degrees from each other (*Figure 32.22*), and that the refractive index of the medium is in consequence given by tan *i*, where *i* is the angle of greatest polarisation. For convenience this angle is referred to as Brewster's angle. This suggests a fundamentally simple and universal method for measuring the refractive index of polished gemstones, but while finding an approximation to the angle of greatest polarisation can be a simple matter, to obtain an exact value presents considerable difficulties.

In the London Gem Testing Laboratory experiments in measuring Brewster's angle were carried out in various ways. The most successful made use of the accurate angle-measuring facilities provided by a table spectrometer (an instrument fully described later). In a darkened room the specimen to be tested was mounted with wax on the central platform of the spectrometer with the table facet in a vertical position. A powerful beam of light was directed through the slit of the collimating tube and the reflected signal from the stone facet observed through the telescope eyepiece. The eyepiece was then covered by a suitably oriented Polaroid disc and the reflected signal followed as the stone on its stand was slowly rotated, the aim being to find the angle of maximum polarisation which was indicated by virtual extinction of the reflected signal. The operation requires patience and skill, as the light is almost totally extinguished by the Polaroid as Brewster's angle is approached, and estimating the exact angle remains a matter of some difficulty, perhaps best overcome by approaching the critical point from either side and calculating the angle which represents the centre of the null area.

Renewed interest in this potentially valuable method has been shown in recent years, and two independent suggestions for measurement of the Brewster angle have been published almost simultaneously. In the first of these, Read (*Journal of Gemmology*, October 1979) described a model which dispenses with a moving detector by passing the powerful reflected ray from the specimen through a suitably oriented polarising filter and imaging the resultant beam on a translucent screen which is viewed by the operator, who adjusts the angle of the incident light until a minimum is reached. In the other model suggested by Yu (*Gems and Gemology*, winter 1979/80) light from an illuminated transparent plastic scale is observed through a suitably oriented Polaroid filter as seen reflected in the polished surface of the gemstone to be measured, and the minimum position of the shadow on the scale is estimated. A fairly accurate figure for the refractive index to two places of decimals can be achieved by a skilled operator by any of these methods, which is often sufficient for diagnostic purposes when dealing with stones beyond the range of a standard refractometer. A fully electronic method of detecting the Brewster angle of a faceted gem, and displaying it as an RI reading, was subsequently published by Read (*Journal of Gemmology*, January 1988).

Minimum Deviation Method

The most accurate method of refractive index measurement is by the method of minimum deviation, a method which can be applied to any unmounted transparent stone which has well-cut facets. The method, however, needs rather elaborate apparatus, a spectrometer, and a great deal of skill and calculation before a result can be obtained. It is, however, the best method for obtaining accurate values of dispersion, but unless the stone is specially oriented the full double refraction cannot be measured. The table spectrometer (*Figure 32.23*), which is normally used for this method, will be discussed first as an instrument using a glass prism, and then when the glass prism is replaced by a gemstone of which the index of refraction is required.

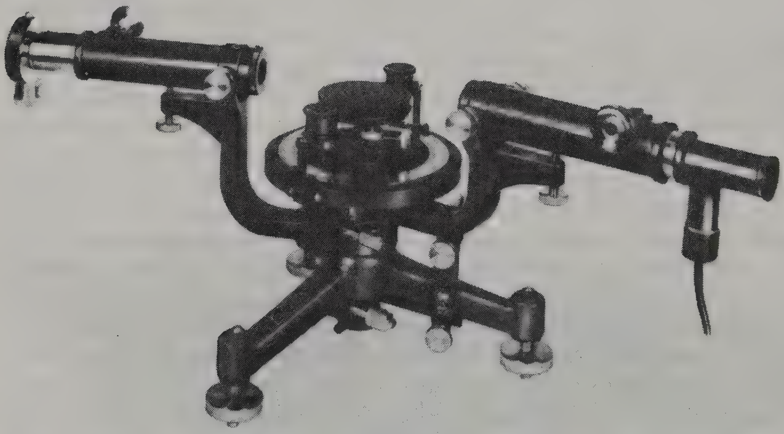


Figure 32.23 A Lang table spectrometer (Krüss)

Table Spectrometer and Use with Glass Prism

The table spectrometer consists essentially of a collimator, fixed rigidly. This has an adjustable slit at one end to control the amount of light needed; immediately behind the slit is a tube containing an optical system so arranged that the slit is placed exactly at the principal focus, ensuring that all the light transmitted is rendered parallel. This parallel light then falls on the prism and is refracted as already explained.

The prism is supported on a table which can be rotated, surrounded by a rigid graduated circle; a telescope, held by an arm rotating round the circle, gathers the light from the prism, revealing the spectrum.

In all this, so far, there is nothing radically different from hand spectroscopes. The real difference lies in the graduated circle, divided into degrees, half-degrees or even quarter-degrees. A vernier is attached to the arm of the telescope and angles can be measured on the circle to the nearest minute or half-minute (*Figure 32.24*).

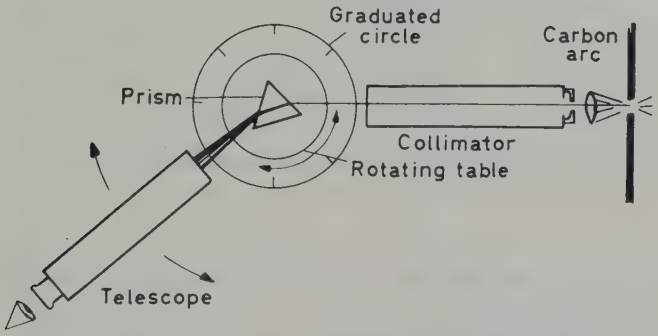


Figure 32.24 *Diagram of the spectrometer fitted with a glass prism*

It remains to describe the adaptation of this instrument for measurement of refractive indices, known variously as the minimum deviation, prism or goniometric method, and consisting of a measurement of the angle of the prism and the angle of deviation of the spectrum, and a calculation based on a formula.

For the initial experiment it is best to use the prism provided with the instrument. As already stated, this is of optical flint glass and has optically flat faces, giving an angle of 60 degrees (approximately). It is, in fact, from every point of view, the ideal object to measure; no stone that the author has ever measured is so perfectly suited to this purpose.

If the prism is adjusted so that the spectrum is visible it can be seen, by rotating the prism on the supporting table, that there is a position beyond which the rays forming the spectrum will not pass, whichever way the prism is turned. This is called the position of minimum deviation (where the spectrum is least deviated from the original path of the light). This is the position of symmetry where the angle of entry into the prism is equal to the angle of emergence: at all other positions the deviation will be greater. In the following argument it will be advisable to consider the light as being monochromatic (that is, of one wavelength).

In *Figure 32.25* let ABC be the prism, BAC being the refracting angle, OP the path of the incident ray, PQ of the refracted ray and QR of the emergent ray, and NN′ and MM′ the normals to the prism faces AB and AC at P and Q respectively. Let AD be the bisectrix of BAC cutting PQ normally at F and cutting NN′ at G. Let LK be the projection at either end of PQ.

Then in the triangles APG and PFG, APG = PFG (since they are both right angles), AGP is common, therefore FPG = PAG; but FPG is the angle of

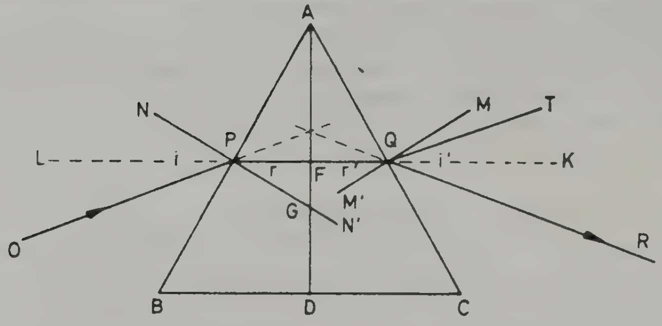


Figure 32.25 The principle of the minimum deviation method of refractive index measurement

refraction (r) and PAG is half the prism angle BAC, so that the angle of refraction is equal to half the prism angle.

Now OPN is the angle of incidence and is composed of LPO and NPL, but NPL = FPG (angle of refraction r) = half prism angle BAC.

If QT is drawn parallel to OP (the incident ray), then TOK = LPO by construction; but LPO = RQK, therefore LPO = half TQR; but TQR is equal to the angle of minimum deviation (d), since TQ is parallel to OP; therefore LPO = half angle of deviation d. Thus the angle of incidence OPN = half BAC + half TQR.

Thus if the prism angle is called A and the deviation angle is called D, we have

$$\text{refractive index} = \frac{\sin i}{\sin r}$$

But $i = \frac{1}{2}A + \frac{1}{2}D$ and $r = \frac{1}{2}A$; therefore

$$\text{refractive index} = \frac{\sin \frac{1}{2}(A + D)}{\sin \frac{1}{2}A}$$

From this it is obvious that if it is possible to measure the deviation and the prism angle, the refractive index may readily be calculated by means of mathematical tables.

The prism angle is turned towards the collimator and the reflections of the slit are measured on either side, according to the laws of reflection (angle of incidence = angle of reflection); the angle subtended by these two reflections is equal to twice the angle of the prism (*Figure 32.26*).

Great care should be taken to be absolutely sure of this angle. The measurements should be repeated several times until agreement is reached. It follows from this that if the reflection angle be measured to the nearest minute the angle of the prism can be calculated to the nearest half-minute.

The deviation angle should be measured on both sides and the mean of the two angles taken. It is perhaps enough to measure the angle subtended by the

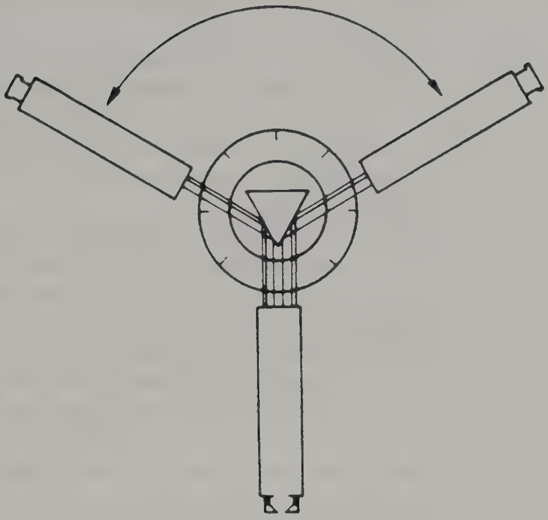


Figure 32.26 Angle of subtention

spectrum on both sides and halve the result. Deviation should be at its minimum.

The simple case has been presented of a glass prism using monochromatic light. The most useful light source is the carbon arc, which gives a strong, continuous spectrum in addition to the sodium emission lines (589.3 nm). Lithium (670.8 nm) and thallium (534.9 nm) can readily be introduced into the arc. In fact, all metallic emission spectra can be so introduced.

By measuring the deviations at the B and G Fraunhofer lines (687 and 430.8 nm respectively) the dispersion can also be calculated.

Other possibilities are the hydrogen 656.3 and 434.1 nm lines, while lithium (670.8 nm) to calcium (422.7 nm) is sometimes used, as these represent the emission lines readily obtained in a carbon arc, and values derived are very close to B–G.

A method devised by Hanneman enables dispersion to be determined by the use of a refractometer with red and blue filtered light, and is described later in this section.

Measuring Gemstone RIs with a Table Spectrometer

It is obvious that the glass prism can be replaced by a prism of another substance, and in applying this method to the study of gemstones it will be realised that it is possible to find two facets of a cut stone which together will form a prism suitable for the purpose. It is at this stage that the first trouble occurs. With the single exception of diamond very few stones are well enough cut to give good reflection images and, as a direct result, they yield poor spectra. The prism angle also is important. The glass prism has an angle of about 60 degrees, which is the desirable angle, but such angles, unfortunately, are not always obtainable. (The larger the angle the greater the deviation, and consequently the greater accuracy in the result.)

If the prism angle is too great there is total internal reflection at the second prism face, and consequently no spectrum can be seen. The rule governing this limit is that the prism angle must not exceed twice the critical angle. The only gemstones in which the prism angles are thus seriously limited are diamond and blende (critical angle 24 degrees). Zircon has a critical angle of 30.5 degrees and demantoid 32 degrees for sodium light.

It is necessary to adjust the prism so that both faces are in zone. In the case of the glass prism this can be achieved by means of the screws attached to the rotatable table for that purpose. A gemstone should be fixed on wax and is not readily adjustable. It is convenient to obtain the spectrum first by naked eye; this will generally be found to be slanting when the sodium line is seen through the telescope. The stone should be tilted until the spectrum moves horizontally when the stone is turned, not rising or falling; in this position the reflections of the slit can be brought into view by turning the stone to the required angle. Final adjustments can be made and the stone is then in position for the measurements.

The question now arises as to the optical nature of the stones. With cubic minerals such as diamond, blende, garnet, spinel, and fluorspar there is only one index of refraction, and in consequence any suitable pair of facets will suffice; the mineral has the same refractive index in any direction.

With doubly refracting stones complications arise. In uniaxial minerals (tetragonal, hexagonal and trigonal), the optic axis coincides with the principal crystallographic axis. Uniaxial stones have two indices; the ordinary ray has the same refractive index in any direction, the extraordinary ray is at its maximum (positive) or minimum (negative) in directions perpendicular to the optic axis. In practice this means that any prism will give the refractive index of the ordinary ray, but unless the prism is cut so that the direction of the light is normal to the optic axis, the maximum double refraction will not be obtained.

Actually very few species of gemstones are cut to obtain maximum double refraction. Tourmaline is an exception, since (especially in the green varieties) the ordinary ray is too strongly absorbed, and so the stone is cut with the table facet parallel to the crystallographic axis, the shape of the crystal guiding the lapidary's hand. It follows that a prism formed by the table facet and a back facet will have its edge (if projected) parallel to the optic axis, and so the beam of light will be normal to the axis, complete double refraction resulting. Quartz, owing to its natural crystal habit, is sometimes cut with the table facet parallel to the optic axis.

With corundum, however, the ordinary ray has a richer colour than the extraordinary ray in all colour varieties, so that the ideal cutting is with the table facet normal to the optic axis; since rubies and sapphires are usually rather shallow-cut stones it is impossible to use two of the back facets as a prism, and consequently the full double refraction is never obtainable unless the stone is specially cut for this purpose (in which case it would be less desirable as a gemstone). A curious fact about this valuable and highly prized species is that the facets, even the table (which is naturally the best polished), are rarely polished flat enough for the purpose.

Zircons are usually brilliant cut, with the table facet more or less parallel to the optic axis; a suitable pavilion facet may be found that will yield very nearly the full double refraction in conjunction with the table. The double refraction, however, is so large (0.058 to 0.059) that the orientation of the prism needs to be exactly perpendicular to the optic axis to obtain its maximum.

The case of biaxial stones is almost hopeless with normally cut gemstones, since there is no ordinary ray with a constant refractive index. In orthorhombic crystals, the plane of the optic axes is parallel to two of the crystallographic axes and normal to the third; that is, it can be parallel to any one of the three planes of orthorhombic symmetry. The optic axes are, of course, directions of single refraction, in this case the mean refractive index β, which can also be obtained in any direction parallel to the plane of the two optic axes; the direction of the acute bisectrix of the optic axes gives α and β (positive) or β and γ (negative), the obtuse bisectrix β and γ (positive) and α and β (negative). The optic normal, that is the direction normal to the optic axial plane, gives α and γ, the full double refraction. Unfortunately, stones are rarely cut so as to yield prisms oriented for any of these directions.

In monoclinic crystals the plane of the optic axes is related only to the ortho axis *b*; it must either be parallel or normal to *b*, so that the optic axes bear only a slight relationship to the external crystal symmetry.

Here again suitable cut stones are very rare, since the same rule concerning the indices and their directions applies as in orthorhombic crystals.

Triclinic minerals, having no axis or plane of symmetry, may have optic axial planes in any direction. Fortunately this, the lowest system of crystal symmetry, is very rare in gemstones. Among transparent stones only the rarely cut axinite and kyanite are triclinic.

Example Calculation

The following case in an actual example of measurements and calculations made by Payne. Diamond is chosen as an example since this species is beyond the range of any refractometer. The diamond was a silver Cape, emerald cut, of weight approximately 3.75 carats. All values are for the sodium D lines (589.3 nm).

Readings for prism angle:

Left =	$403^\circ 55'$	$395^\circ 24'$	$404^\circ 18\frac{1}{2}'$	$403^\circ 56\frac{1}{2}'$
Right =	$315^\circ 47\frac{1}{2}'$	$307^\circ 15\frac{1}{2}'$	$316^\circ 11'$	$315^\circ 49'$
2A =	$88^\circ 7\frac{1}{2}'$	$88^\circ 8\frac{1}{2}'$	$88^\circ 7\frac{1}{2}'$	$88^\circ 7\frac{1}{2}'$
A =	$44^\circ 3\frac{3}{4}'$	$44^\circ 4\frac{1}{4}'$	$44^\circ 3\frac{3}{4}'$	$44^\circ 3\frac{3}{4}'$

The best value appears to be $A = 44^\circ 3\frac{3}{4}'$.

Readings for deviation angle:

$$\begin{array}{rl} & 446^\circ 2' \\ & \underline{273^\circ 44'} \\ 2D = & 172^\circ 18' \end{array}$$

Therefore $D = 86°9'$.

$$\text{Refraction index} = \frac{\sin\frac{1}{2}(A + D)}{\sin\frac{1}{2}A} = \frac{\sin\frac{1}{2}(44°3\frac{3}{4}' + 86°9')}{\sin\frac{1}{2}(44°3\frac{3}{4}')}$$

$$= \frac{\sin 65°6\frac{3}{8}'}{\sin 22°1\frac{7}{8}'} = \frac{0.907}{0.3751} = 2.418$$

Measurement of Dispersion using a Refractometer

The following method by which dispersion of a gem can be determined on a standard refractometer was devised by Hanneman. Although red and blue filters can be used to simulate the B and G Fraunhofer lines when attempting to measure dispersion on a refractometer, the resulting readings are not necessarily related to the effective refractive indices of the gem at these wavelengths because of the dispersion of the refractometer prism. If the dispersion of the prism is known, a correction factor can be introduced, but this will not be the same for all makes of refractometer. A more practical approach is to produce a calibration scale for the particular make of refractometer in use.

Such a calibration scale can be constructed by using two reference gems: benitoite, having a dispersion value of 0.047, and fluorite, having a dispersion value of 0.007. Using red and blue filters, the difference between the refractive index readings at these two wavelengths for each of the two reference gems is plotted against their actual dispersion values. By drawing a straight line between these two points, a calibration scale for that instrument can be constructed.

When one is determining the dispersion value of an unknown gemstone, the blue and red filter readings are first obtained, and are subtracted from each other to obtain the difference reading. This is then applied to the calibration scale to obtain the true dispersion reading. (A full description of the method, and an accompanying calibration scale for the Dialdex and Duplex II refractometers, appeared in the April 1992 issue of the *Journal of Gemmology*.)

As this method is limited to gems within the range of the critical angle refractometer, Hanneman has proposed the determination of hitherto unmeasured dispersions for other high-RI gems by estimating their RIs at 930 nm (using a reflectance meter), and applying the following formula:

$$\text{dispersion} = \frac{(\text{RI at } 589\,\text{nm}) - (\text{RI at } 930\,\text{nm})}{1.332}$$

This gives dispersion in terms of the quoted 589 nm RI and the reflectivity-estimated RI at 930 nm. The 1.332 divisor compensates for the greater measuring interval compared with the standard B to G interval:

$$\frac{(930 - 589)\,\text{nm}}{(\text{B} - \text{G})\,\text{nm}} = \frac{341}{256} = 1.332$$

Reflectance

Until the past few decades the generally accepted upper limit of 1.81 for refractive index readings obtainable on standard gem testing refractometers did not represent a serious restraint upon their usefulness, since demantoid, zircon and diamond were the only three gemstones in common use which had refractive indices beyond this limit.

This no longer holds today. In recent years the development of crystal-growing techniques has resulted in the production of a number of gem-quality synthetic crystals having refractive indices well beyond the normal refractometer's reach and many of these, moreover, have a dangerous similarity in appearance to diamond. Thus there had arisen an urgent need for instruments enabling gemmologists, and even jewellers untrained in gemmology, to recognise these high-index substances, or at least to distinguish them from diamond itself.

It may be said that their lower hardness and greater SG enable these synthetics to be easily distinguished from diamond; but hardness can be a somewhat crude and damaging test, while SG determinations are, of course, only possible when the stone concerned is unmounted. An effective answer has been found in the measurement of the relative reflectance of the stones concerned.

A quantitative relationship between the refractive index and the theoretical reflecting power of transparent substances was established early in the nineteenth century by the French physicist Fresnel, who deduced his well-known formula for the percentage R of reflected light for a ray striking a polished surface at perpendicular incidence, where n is the refractive index of the substance and A is the refractive index of the surrounding medium (1 for air):

$$R = \frac{(n - A)^2}{(n + A)^2} \times 100$$

This theoretical reflecting power depends upon a perfectly plane polished surface and this is not always the case even on the table facet of a well-cut gemstone. To give two practical examples: the percentage of light reflected from a perfect plane polished surface of quartz at perpendicular incidence is 4.6 per cent, while at the upper limit is diamond for which there should be 17.2 per cent of reflected light.

As can be imagined, an optical system which enables measurements of the relative intensity of reflections at perpendicular incidence is not very easily contrived. Microscopists, for whom measurements of reflectance are routine requirements for identification, use special microscopes with a vertical illuminator. In practice the proportion of reflected light is often referred to an accepted standard such as polished pyrite, the reflectance of which is very constant at 54 per cent. The instruments concerned are expensive and their use calls for technical skill.

An ingenious design of reflectometer intended for use with gemstones was designed and constructed by Trumper in 1959. In the Trumper instrument rays from an evenly illuminated ground-glass screen forming a circular spot of light are conducted by means of totally reflecting prisms after passing through two different paths. One path retains the full brightness of the spot while the other presents an image of the spot reduced in brightness after reflection from the surface of the table facet of the gem under test – the two images being seen side by side. To make a reading of the reflectance of the stone, the brightness of the spot directly observed is reduced to match the brightness of the reflected ray by means of an annular neutral wedge. The amount of rotation of the annular wedge needed to make the two images of equal brightness is translated into figures giving the refractive index of the specimen with the help of a graph derived from a number of careful tests on gems of known refractive index. The range of refractive index covered is from 1.40 to 3.20. Observations are carried out in a light-tight box to avoid errors caused by stray light, and the size of the light spot can be controlled by means of diaphragms to suit the specimen tested. As with all methods involving the measure of reflecting power the surface of the stone must be flat, clean, and well polished if the accuracy of readings is to attain the ±0.02 claimed by the designer. The method does not provide a measure of the birefringence of the stone tested.

Reflectance Meters

Since 1975 a number of instruments enabling rapid measurements to be made of the reflectance of faceted gemstones have appeared on the market in response to the pressures suggested at the beginning of this chapter. So far as can be ascertained all these instruments have relied on a convenient source of radiation which is not visible light but a beam of infra-red rays of wavelength approximately 930 nm produced by a gallium arsenide light-emitting diode (LED) powered by a low-voltage cell. The infra-red beam reflected from the surface of the stone passes to a photodetector which gives readings on an analogue meter or a digital display to indicate the reflectance of the gemstone under test.

In carrying out a test with any of these reflectivity meters the carefully cleaned table facet of the stone is applied to a small orifice (sometimes shaped like a 'nipple'), the switch turned on and a reading taken on the meter. The stone should preferably be shielded from any overhead light, and the average of several readings taken.

In the Gemeter (*Figure 32.27*), an early reflectance meter of this type, the makers unwisely interpreted the meter readings in terms of refractive index, and since an infra-red beam was employed the figures obtained depended not only on the refractive index as normally reckoned for sodium light, but on the dispersion of the stone. Strontium titanate, for example, gave substantially lower readings on the scale than diamond on account of its far higher dispersion, whereas for yellow light their indices are virtually the same. This fact, when understood, makes distinction between strontium titanate and diamond on reflectance meters a much easier matter than might be expected. A disadvantage in early models was a variability in the readings owing to fluctuations in the power supply from the battery used.

A more successful reflectance meter was designed by Hanneman and manufactured by Hanneman Lapidary Specialties Inc. In this, The Jeweler's Eye (*Figure 32.28*), no attempt was made to calibrate the scale in terms of refractive

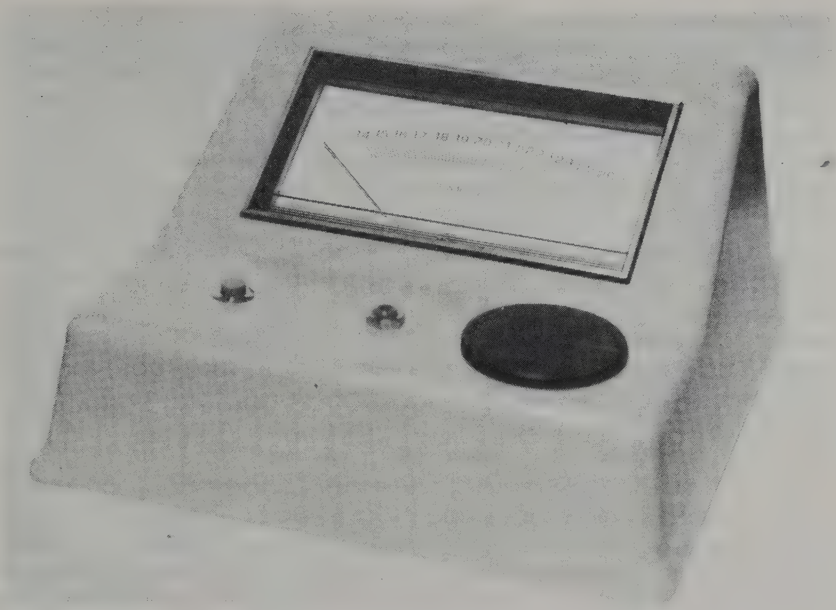


Figure 32.27 *The Gemeter reflectivity meter (Sarasota Instruments)*

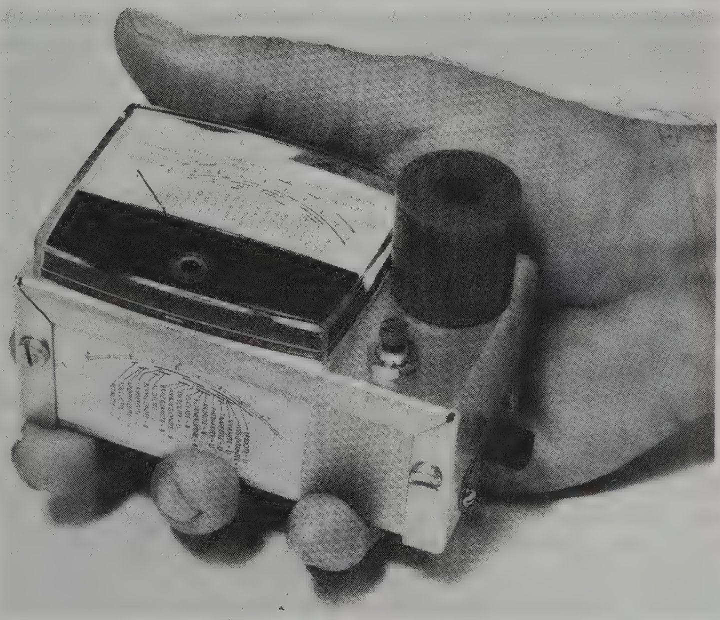


Figure 32.28 *The Jeweler's Eye (Hanneman Specialties)*

indices. Instead, the positions of the needle are marked with the names of the important gemstones for which each particular position can be expected. To avoid overcrowding the scale, a two-position switch and two pre-set resistors enable the intensity of the incident light to be adjusted in order to provide two alternative ranges. The lower scale starts with glass (of low-index types) and ends with garnets, while the upper scale ranges from quartz to rutile. For a reading to be taken the specimen is placed table facet down over a small orifice in a metal plate. The orifice is narrow enough to enable fairly small gems to be tested. The surface of the stone should be rigorously cleaned, and the specimen shielded from overhead light when a reading is being taken. The Jeweler's Eye is calibrated on its lower range against spinel, and on its upper range against diamond. The danger in such an instrument is that it makes gem identification seem too easy a matter, and in ignorant hands may lead to grave mistakes being made. This and similar reflectance meters must never be considered as a substitute for the refractometer, since the measurements are not of refractive index but of reflectance at a wavelength of 930 nm.

To emphasise this point Hanneman designed a second instrument based on similar principles of reflectivity, which he termed a Lustermeter, in which the indicating needle points to numbers which represent arbitrary L_H units. L represents the light-emitting diode (LED) source of radiation and H the name Hanneman as inventor of this first numerical lustre scale. On this scale Hanneman listed diamond as number 4, strontium titanate as 3, GGG as 2 and YAG as 1, the last three all being possible diamond substitutes.

One of the common reasons for inconsistent results in earlier models of infra-red reflectance meters was due to the failure of the battery forming the power source to stand up to the strain of frequent readings, resulting in voltage drift. This weakness was overcome in yet another instrument of the same general type. This was the Gem Analyser, manufactured by the Martin Precision Instrument Co. This unit is powered via a voltage stabiliser by a 9 volt battery, and the two integrated circuits are sealed against moisture and compensated against changes in temperature. Another innovation introduced in this instrument is the use of a pulsed infra-red light-emitting diode. This, together with a detector diode whose output is pulsed or 'gated' at the same rate, makes the Gem Analyser much less sensitive to extraneous light entering the test aperture through the back of the gemstone. It is still advisable, however, to shield the stone when making tests in strong ambient lighting conditions.

It is not surprising that these reflectance meters have proved to be popular, particularly amongst those who deal in diamonds and have been alarmed by the production of a succession of man-made simulants, culminating in the appearance of cubic zirconia.

With unmounted stones there should be no difficulty, since the SG of the diamond substitutes is in all cases so much higher than that of diamond that the mass of a given 'spread' of stone is noticeably higher than that indicated by experience or by standard tables connecting the two factors. Moreover the hardness is far lower, leaving a polished corundum test-piece unscathed when a scratch-mark is attempted.

In taking readings on a reflectance meter the importance of a clean well-polished surface must at all times be realised. Read has made the interesting

Table 32.2
Percentage of light reflected at perpendicular incidence

Mineral	*% reflected light*
Diamond	17.2
Blende	17.5
Rutile	20.2
Proustite	26.4
Cuprite	27.1
Hematite	27.5
Galena	43.2
Pyrite	54.5
Platinum	70.0
Gold	74.0
Copper	81.2
Silver	95.0

observation that Verneuil synthetic corundums give lower reflectance readings than natural corundum gems owing to their inferior degree of polish.

To correct the rather common conception amongst gemmologists that diamond, with its adamantine lustre, represents a peak of reflectivity only excelled by that of rutile (itself once a diamond simulant), it may be as well to quote in *Table 32.2* some well-established reflectivity figures for natural minerals having a very high refractive index which are occasionally used as gems, and, going farther up the scale, for ore minerals having a metallic lustre and some of the metals which have the highest reflectivity of all. For comparison the figure for diamond is placed at the beginning of this selected series.

Two more recent reflectance meters indicate the continuing development of this type of instrument. The Culti Diamond Checker (*Figure 32.29*) follows the

Figure 32.29 The Culti Diamond Checker is a single-range instrument whose meter is calibrated for diamond and its simulants. It uses pulse-coded infra-red illumination and detection to minimise errors caused by ambient light

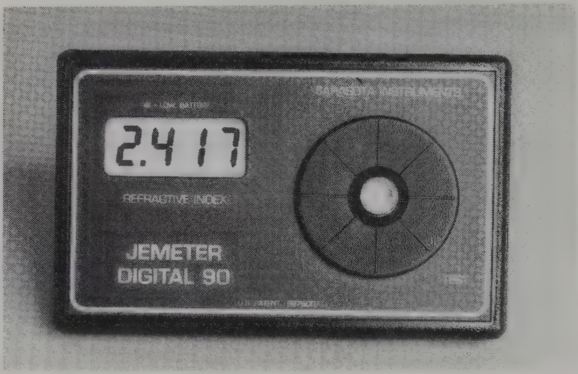


Figure 32.30 The Sarasota Jemeter Digital 90 uses a large liquid crystal display (LCD) to give a direct indication of the refractive index of gemstones. Its instruction booklet indicates the lower RIs to be expected, owing to the infra-red illumination, with high-dispersion gems. The instrument's diode detector is fitted with a polarising filter which enables double refraction to be measured down to 0.01

trend away from an all-purpose two-range instrument and is designed solely for the identification of diamond and its simulants. The Sarasota Jemeter Digital 90 (*Figure 32.30*) returns to the still controversial concept of providing a direct readout of refractive index. The lower than normal readings produced by high-dispersion gems (owing to the infra-red illumination) are indicated in the accompanying instruction book. An added innovation is the built-in polarising filter which enables double refraction down to 0.01 to be measured.

Thermal Conductance Probes

The Ceres Corporation of America, the chief producers in the USA of cubic zirconia, in a public-spirited endeavour to save jewellers from being deceived by this new and very effective diamond simulant, devised an instrument which succeeded in exploiting one of diamond's most outstanding physical properties, its high thermal conductivity. The ability of diamond to conduct heat is quite outstanding, being greater even than that of copper or silver. In the Ceres Diamond Probe, which was first produced in 1978, the 'probe' consists of a small copper tip, linked with two very small 'thermistors', which are ceramic elements whose resistance varies with temperature (*Figure 32.31*). One of these elements is fed with electric pulses at intervals of a second, thus functioning as a tiny heating device. The other acts as a thermal sensor which varies in resistance in response to the electrically warmed copper tip of the probe. When the probe is pressed firmly against a diamond surface the heat is conducted rapidly away through the diamond and is unable to rise to its normal electrically raised temperature, while when pressed against a poor conductor such as glass or cubic zirconia, the temperature rises to its normal level. In the Ceres instrument

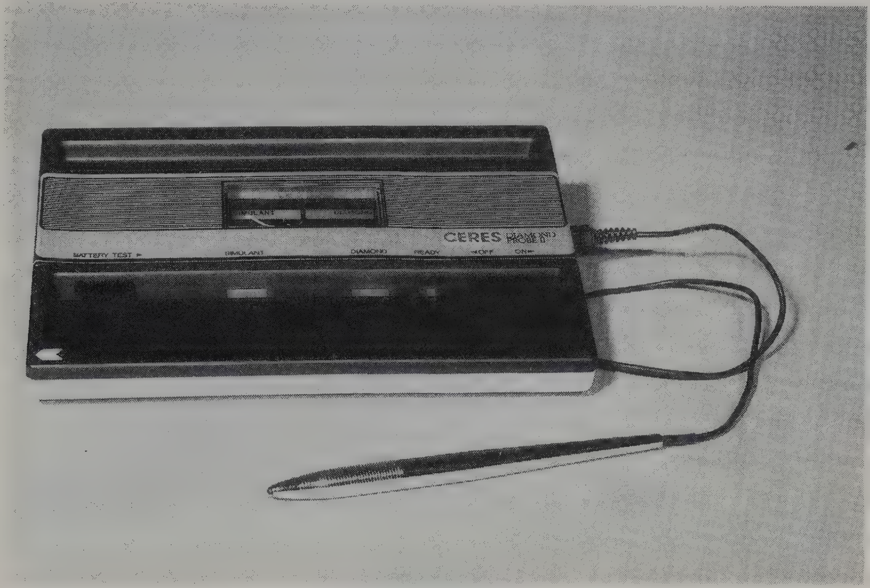


Figure 32.31 Ceres Diamond Probe II (Ceres Corporation)

the temperature is automatically measured at second intervals and is 'latched' to give a steady indication.

The delicate tip of the probe is spring-loaded to protect it from damage when it is firmly pressed against the surface of the stone under test. The meter scale is divided into three zones: a broad red zone on the left, a green zone on the right and a narrow amber zone in between these. If, on contact with the probe, the needle swings into the green zone, diamond is strongly indicated, and as an additional signal to the same effect small indicator lamps flash alternately green and amber. A reading in the red zone points firmly to a simulant, and the indicator lamps flash red and amber.

Read, in a thorough investigation of the Ceres Probe (*Journal of Gemmology*, April 1980) found that all the well-known diamond simulants gave signals in the red region, whilst only pure silver, pure gold, and aluminium foil gave a green signal.

An interesting observation was that a rolled gold ring gave a red signal, which suggested that the Ceres meter might have a further useful role to play in the hands of an interested jeweller or pawnbroker. An invaluable feature of the thermal probe is that positive results can be obtained on diamonds as small as 0.03 carats and that the test can function even when the stone is in a setting.

Other instrument makers concerned with the jewellery trade were not slow in following the lead given by the Ceres Corporation, and there are now many diamond probes on the market (*Figures 32.32* and *32.33*).

Because the advantages and disadvantages inherent in thermal conductance testers nicely complement those found in reflectance meters, several manufacturers have combined both techniques in the same instrument (*Figure 32.34*).

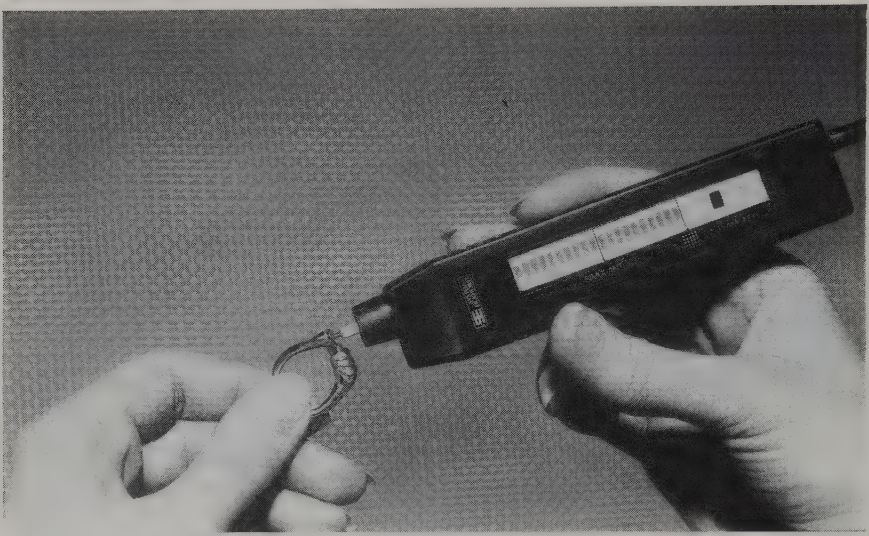


Figure 32.32 *The Eickhorst hand-held thermal probe uses a bar-graph indicator, and operates from a battery/mains pack*

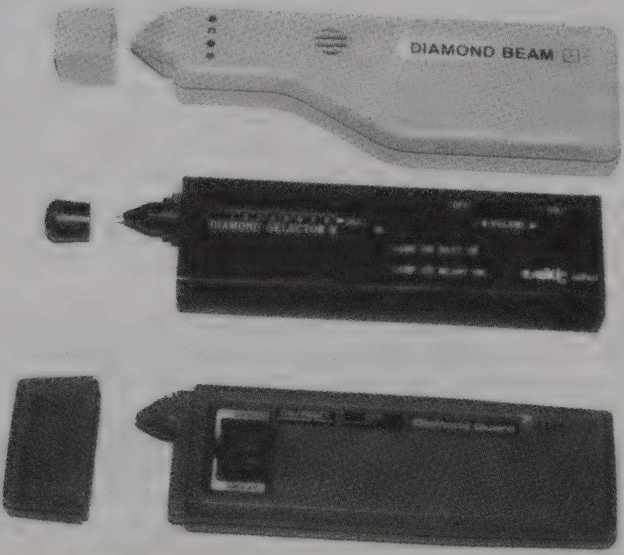


Figure 32.33 *Three hand-held battery-operated thermal probes. These all have visual and audio indicators for diamond. All but the Diamond Guard have a metal contact feature which produces an audible buzz if the probe tip makes contact with the metal of the gem mount*

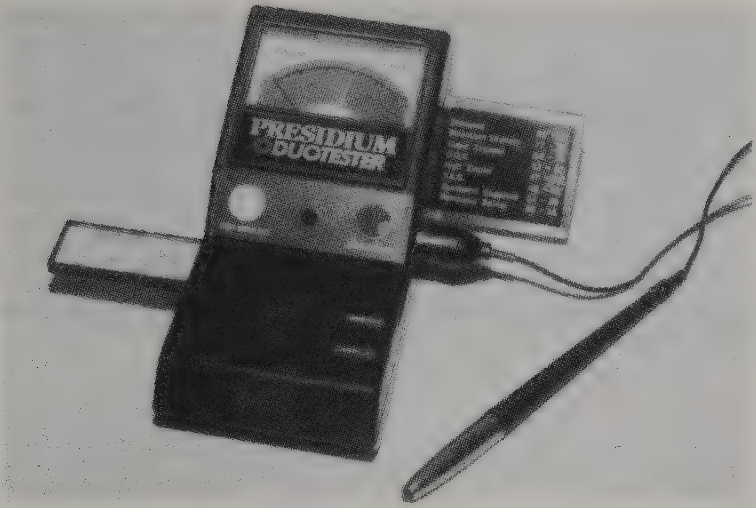


Figure 32.34 *The Duotester is a combined reflectance and thermal conductance tester. The slide drawer on the left contains diamond simulants for calibration checking. The right-hand pull-out panel indicates typical reflectance readings displayed on the unit's front-edge LED digital panel (Presidium)*

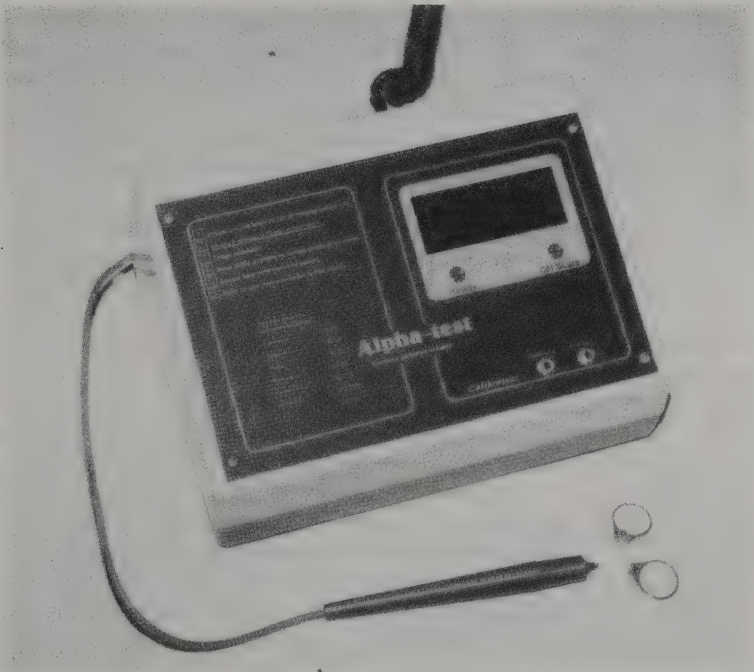


Figure 32.35 *The Alpha-Test instrument is a thermal conductance tester designed to differentiate between a wide range of gems (including diamond and its simulants)*

Although the majority of thermal testers are designed to distinguish between diamond and diamond simulants, a few instruments have been marketed which are able to identify both these and other gems by means of their thermal conductance (*Figure 32.35*). With the exception of diamond, gemstones occupy only a very limited range of thermal conductivities which extend from glass at 1.0 to corundum at 40. Because of this, such instruments have to be very sensitive in order to discriminate between these much smaller thermal differences, and their use involves several operating constraints. The test environment must be free from draughts and within a specified temperature range. The gemstone must also be stabilised at a fixed temperature before testing (usually body temperature), and the probe tip applied at right angles to the surface at a pre-set pressure.

33

Colour in Gem Testing

Filters

However exactly two colours may match one another to the unaided eye, there is still a strong possibility that so far as their spectral composition is concerned they are vastly different. This is certain to be the case if the colours belong to two gemstones of different species, or to a real and to an imitation stone made to resemble it. The simplest way in which differences in the spectral composition of two similar colours can be revealed is by using a suitable colour filter. A colour filter is a piece of coloured glass or gelatine, or in some cases a coloured solution, which filters light of mixed wavelengths passing through it. A filter allows certain colours to pass, others it absorbs. Any coloured transparent substance is in one sense a colour filter, but those most sought after, because they are most efficient for their purpose, are those which have sharp, well-defined absorption bands and relatively narrow regions in which they transmit.

Colour filters are much used in photography; a wide range is available from both Kodak and Ilford. One series represents an attempt to provide approximately monochromatic light in each of the main spectral regions by means of filters of almost pure colours. These are 'spectrum red', 'spectrum yellow' and so on, and transmission curves are provided by the makers showing the wavelength of the peak transmission and the rapidity with which this falls away on the long-wave and short-wave side. Another useful series is designed for use in conjunction with a mercury lamp. Mercury vapour emits light of only a few wavelengths in the visible spectrum, namely in the orange-red at 623.4 and 615.2 nm, a yellow doublet at 579 and 570 nm, a green line at 546.1 nm, a blue doublet at 435.9 and 434.8 nm, and violet lines at 407.8 and 404.7 nm. Filters are provided which transmit each of these but cut out all the others. Thus a 'mercury yellow' filter transmits only the yellow mercury doublet. Combined with a mercury lamp, these filters thus provide a much more efficient monochromatic source in the various regions of the spectrum indicated than can

Figure 33.1 The Chelsea colour filter

be expected with the more general type of filter designed for use with white light.

Chelsea Filter

The most generally useful filter for gemmological purposes, however, is not a monochromatic but a dichromatic type – that is one transmitting narrow bands of light in the two chosen regions of the spectrum. The most efficient of these so far produced is known as the Chelsea filter (*Figure 33.1*), which was originally devised in the laboratory of the London Chamber of Commerce, in 1934, and marketed shortly afterwards by the Gemmological Association. This transmits in the deep red near 690 nm and in the yellow-green near 570 nm. Through such a filter substances can only appear red or green or a brownish tint resulting from a mixture of the two. It so happens that emerald, though a green stone, absorbs considerably in the yellow-green region transmitted by the Chelsea filter and transmits freely in the deep red. Thus, through this filter, a typical emerald of good commercial quality (Colombian or Siberian) will appear decidedly red – almost a ruby red in favourable cases. The result is most striking when the stone is held close to an ordinary electric light and viewed through the filter held close to the eye (*Figure 33.2*). All green pastes, most soudé emeralds, green sapphire and most tourmalines show no red through the filter. On the other hand, green fluorspar, green zircon and demantoid garnet do show a pinkish appearance under the filter, though not the decided red of a good-class emerald.

Since neither South African nor Indian emeralds show a change to red the filter must be used with care and discretion if mistaken judgments are not to be made. In the hands of an experienced user it can undoubtedly be a most useful gadget where more precise tests cannot be applied. It may be of value also in arousing suspicion where synthetic emeralds are concerned, since these, with their colour entirely due to chromium, are remarkable for the tremendously strong ruby red seen through the Chelsea filter.

Another series of colours which appear unexpectedly red through this same

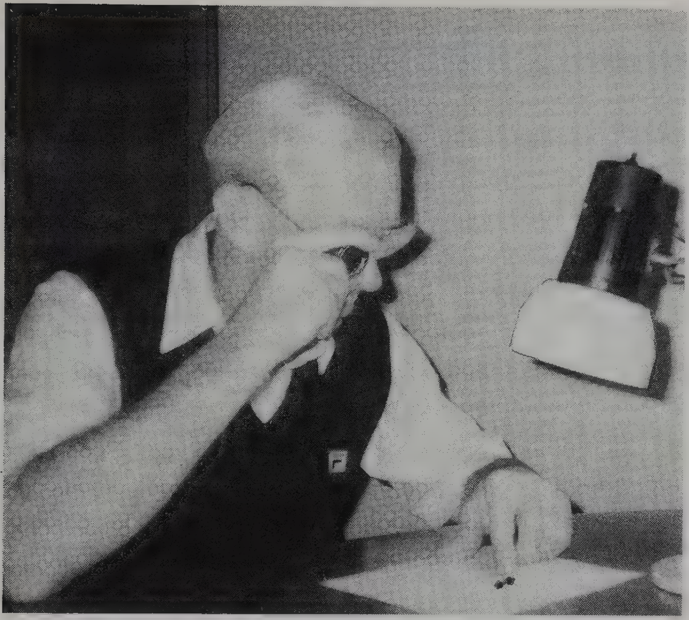


Figure 33.2 Using the colour filter

filter are the blue colours due to cobalt – whether in synthetic blue spinel, blue cobalt glass, or a doublet with the latter as a base. Cobalt in this form gives rise to three massive absorption bands, one of which covers the green transmission region of the filter, while on the other hand, deep red is freely transmitted. Thus, the Chelsea filter provides a quick means of checking the presence of those common fakes, the pale blue synthetic spinels which represent aquamarine and blue zircon. The genuine aquamarine and blue zircon cut out practically all the red from the spectrum, and thus through the filter have a distinctive green appearance, while the spinel imitation is either a bright red or a peculiar orange-brown colour. Unfortunately, natural blue spinel can appear reddish through the filter and so can a Sri Lanka sapphire containing a touch of chromium – that is a mauve or slightly purplish sapphire.

Other Filters

The Chelsea filter was by no means the first to be applied to the detection of emerald imitation. There were many such 'emerald loupes' issued on the Continent, mostly making use of cobalt glass as a basis. In none of these, however, were the regions of transmission so clearly cut, and many were so dark as to be nearly opaque.

Attempts have also been made to extend the filter technique to cover a wide range of stones. In Michel's Detectoscope a whole series of filters could be turned into position in a viewing instrument with a built-in light, and, by studying long lists of the reactions to be expected in each case with each of the well-known coloured stones, many of these could be identified with some degree of certainty. More recently, Trumper has had some success along similar lines, and has had the ingenious idea of using a slab of synthetic ruby as part of one of his filters. Although the results obtained by these means can be most interesting, so far as the accurate identification of gemstones is concerned more definite tests are desirable.

Dichroism and Pleochroism

A far more important form of colour analysis is possible in most doubly refractive transparent stones. A beam of light reaching the eye after passing through a doubly refractive crystal, as has been explained, consists in general not of one ray but of two, each of which is polarised and vibrating in a plane at right angles to the other. If the crystal is coloured, each of the rays will usually undergo a different degree or type of colour absorption in its passage through the stone, and will thus emerge differently coloured. It is not possible for the unaided eye to separate the two rays, which reach it simultaneously and are following an identical path, but by quite simple polarising apparatus the two rays can be observed separately, or, better still, side by side.

What the unaided eye can do, however, is to notice a change in colour or in depth of colour as the stone is viewed from different directions. This change in colour with direction is known as dichroism (two-colour effect), or by the more general term pleochroism (many-coloured effect). If dichroism can be detected it is a sure sign that the stone concerned is birefringent. By this means, therefore, ruby can quickly be distinguished from spinel or garnet of similar colour, since the latter are cubic minerals, and therefore singly refractive and non-dichroic. The absence of detectable dichroism does not necessarily mean that the stone is singly refractive, nor does the strength of the dichroism bear any relation to the extent of the birefringence. Thus the mineral zircon, despite its notable double refraction, is practically non-dichroic in its natural state, while blue apatite, aquamarine and iolite, none of which has strong double refraction, are all markedly dichroic stones.

Uniaxial Stones

The influence of the crystal direction upon colour is not merely of importance from the diagnostic point of view; it also greatly concerns the lapidary, though he may not think of it in scientific terms. For example, ruby is a colour variety of corundum – a uniaxial mineral – which means that along the optic axis there is one ray only, the ordinary ray, which always vibrates at right angles to the optic axis. In all other directions the ordinary ray is mingled with the extraordinary ray, although only in light travelling at right angles to the optic axis does this attain its maximum difference in refractive index and in colour from the ordinary ray. From a colour point of view, therefore, it is vitally important that, in a dichroic mineral, the better colour should be that belonging to the ordinary ray. In both ruby and sapphire this is so, and the lapidary gets his best effects where he can cut the table facet of the stone at right angles to the optic axis, so that the observer looking down at the stone is looking along the optic axis and receiving, undiluted, the fine colour of the ordinary ray.

In ruby, the ordinary ray is a fine crimson, while the extraordinary ray has a less pleasing yellowish tinge. In sapphire the ordinary ray is deep blue, the extraordinary ray a paler and more greenish or yellowish blue. The peculiar appearance of synthetic ruby and sapphire is partly due at least to the fact that they have been wrongly oriented when cutting. In most natural rubies the optic axis will be found nearly perpendicular to the table: the lapidary is guided in his choice not only by the run of the colour but by the squat habit of the crystals. The presence of strong dichroism through the table facet (as seen with a dichroscope) is at least an indication that the ruby may be synthetic. In sapphire the colour is seldom homogeneous, occurring in bands, patches and zones, and the distribution of these rather than the optical direction will determine the lapidary's choice of cutting.

Not all uniaxial gems are so obliging as to show their best colour along the optic axis. In both aquamarine and blue apatite, for instance, the ordinary ray is a feeble tint compared with the fine blue of the extraordinary ray. Since the ordinary ray must always be present to at least 50 per cent in terms of colour, this means that the best one can do in these cases is to cut the stone with its table facet parallel to the optic axis, and be content to see the blue of the extraordinary ray at half strength.

Even within one species, the strength of the dichroism varies considerably. Tourmaline is a good example of this. Tourmaline is often quoted as an extreme case of dichroism, and it is stated that the ordinary ray is almost completely absorbed. This is actually only true of the dark brown and dark green varieties; in the red, pink, yellow and paler green stones the dichroism is not nearly so intense. Thus, while with a dark green tourmaline crystal the lapidary is bound to make his table facet parallel to the crystal and the optic axis if he is to get any light and colour in the stone at all, in pink and other pale-coloured tourmalines he will want the deepest colour possible, and will get a better-coloured stone if the table facet can be oriented at right angles to the optic axis.

Biaxial Stones

In biaxial stones the matter is more complex. Although there can still only be two polarised rays passing along any one direction in the crystal, there are three critical refractive indices corresponding to rays vibrating in the three mutually perpendicular directions.

In a coloured biaxial crystal there will generally be a particular colour or shade of colour associated with each of these critical vibration directions. Rays travelling and vibrating in random directions willl have refractive indices and colours intermediate between those belonging to the principal directions. Coloured biaxial stones, therefore, are pleochroic or trichroic rather than dichroic, though the last expression is still commonly used for them.

Perhaps the most startling case of pleochroism is with the gem mineral iolite. The three colours in this attractive species are α pale brownish-yellow, β pale blue, and γ deep violet-blue. Stones cut parallel to the prism edge show a fine sapphire blue when viewed through the table, while at right angles to this it appears to be almost colourless. A gemstone of much greater commercial importance which also shows remarkable pleochroism is the chrome-rich type of chrysoberyl known as alexandrite. In fine Siberian specimens of this rare gemstone there are three contrasted colours belonging to the principal rays, the hues belonging to the least, mean, and greatest indices being raspberry red, orange, and an almost emerald green. In the larger and usually more flawless alexandrites from Sri Lanka there is less chromium, and therefore the above colours are far less pronounced. The lapidary has to take great care to cut the stone so that the reddish appearance can be seen through the table in artificial light. Another pleochroic stone in which red and green rays are often intermingled to give an interesting and elusive colour effect is andalusite, while in the variety of spodumene known as kunzite the rather insipid pink seen at right angles to the prisms of the crystal is replaced by a wonderful deep lilac colour when one looks down its length – a colour not quite equalled by any other gemstone.

The Dichroscope

When a dichroic stone is rotated under a polarising prism or Polaroid sheet, in orientations where the vibration direction of one of the coloured rays corresponds with that of the polariser, the colour of this ray only will be visible. Thus a change of colour will be noticeable if the stone or polariser be turned. It is usually more convenient, if it can be arranged, to view side by side both the coloured rays reaching the eye along any one direction. This can conveniently be done with the aid of a dichroscope (*Figures 33.3, 33.4*). This is a simple little instrument consisting essentially of a metal tube with a small rectangular window at one end and an eyepiece at the other. Within the tube is mounted a piece of optical calcite (Iceland spar) of sufficient size to present, by virtue of its strong double refraction, doubled images of the window of the instrument, which in a properly made and adjusted dichroscope are contiguous but not overlapping.

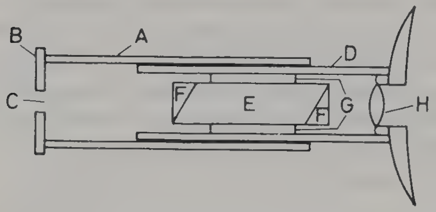


Figure 33.3 The optical system of a dichroscope: (A) sliding metal tube carrying the endplate (B) with rectangular aperture (C); (D) inner tube carrying the optical calcite (E), to the ends of which are cemented glass prisms (F) (these are not always present but do produce clearer images); (G) packing, usually of cork, to hold the doubly refracting rhomb in the tube; (H) the eye lens

In most commercial dichroscopes an attachment for holding and rotating the stone in front of the window of the instrument is fixed to the tube (*Figure 33.5*). This is convenient but not really necessary, since with practice the stone can easily be held in tongs, or if large in the fingers, and manipulated as desired. Most instrument work in gemmology can be carried out at least as well in artificial light as in daylight; but for the observation of dichroism, bright sunlight is undoubtedly superior.

It is absolutely essential that the stone be turned into different positions to obtain the fullest dichroic or pleochroic effects. Not only must it be remembered that there can be no dichroism visible in the direction of an optic axis, but also it should be realised that only when the vibration directions of the light forming

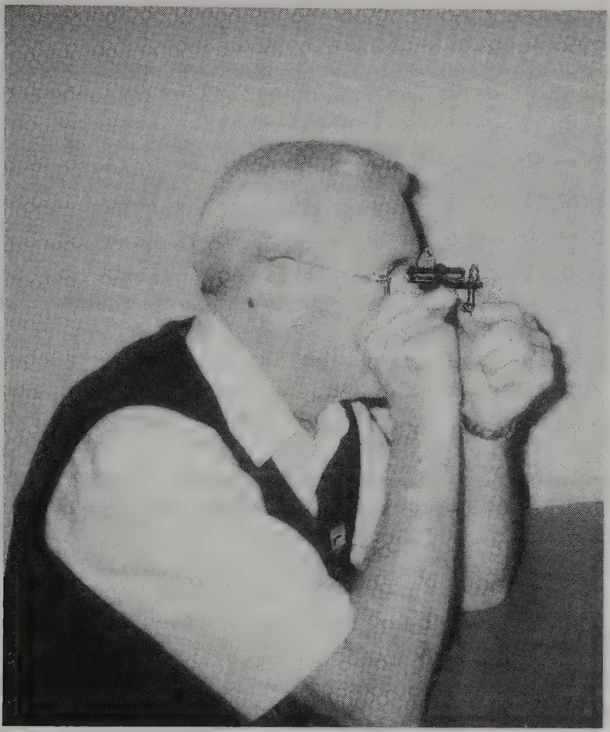


Figure 33.4 *Using the dichroscope*

Figure 33.5 Dichroscope by Rayner with arrangement for holding the stone during observation of dichroism

the images of the dichroscope window correspond exactly with those of the two dichroic rays can these be seen in their proper colours. In other orientations, part of each is resolved into each dichroscope image, and when the rays are at 45 degrees to those of the dichroscope, both dichroscope images will be of identical colour.

Dichroscopes making use of Polaroid have been constructed. In the first of these, designed by Thibaut, four sectors of Polaroid were cut and mounted at one end of the dichroscope tube. Opposite sectors were made to have identical vibration directions, perpendicular to those of light passing through the other two.

When the dichroic effect is exceedingly feeble no matter which way the stone is turned, it is better to disregard it, since it is very easy to imagine such effects and draw false conclusions. Light from the sky, or light reflected from any non-metallic surface, is to some extent polarised and will cause one image of the dichroscope to appear darker than the other; this again may be misleading on occasion.

For all its importance, dichroism is very seldom of great diagnostic value, that is it will not by itself enable one to identify with complete certainty any particular gem.

Spectrum Analysis

A more searching analysis of colour is made possible by using the spectroscope, which owed its beginning to the genius of Isaac Newton who, as told earlier in the book, analysed sunlight with the aid of a glass prism, producing the well-known series of rainbow colours known as the solar spectrum. Josef Fraunhofer (independently of Wollaston), at the beginning of the nineteenth century, first observed and mapped the dark lines which cross the spectrum of the sun, the principal members of which he labelled A, B, C, D and so on – Fraunhofer line symbols which are used to this day. Some 15 years later David Brewster suggested that these dark lines in the sun's spectrum were due to absorption of light in the vapours surrounding the sun, but it was left to Bunsen and Kirchhoff to first prove that the bright yellow double line seen in a spectrum when the glowing vapour of a sodium compound was examined are the same lines, seen in reverse, as the Fraunhofer D lines. The experiments of many other workers further contributed to the knowledge of spectra, and the study of the various types of spectra have led to great advances in the understanding of the physics of the atom, and in astronomy, medicine and the qualitative and quantitative analysis of the composition of materials. Through the work of Church, Wherry, Anderson and Payne, the examination of the absorption and fluorescence spectra of gemstones has now become a powerful method of gem testing.

Bright-Line Spectrum

A beam of white light from an oil, gas or ordinary electric lamp produces, when passed across a prism – as previously explained in Chapter 30 under dispersion – a ribbon of rainbow colours from red to violet. This type of emission spectrum is called a Newtonian or continuous spectrum, and is produced by incandescent solids. A similar spectrum from the light of the sun, which as mentioned above is crossed with dark lines, is known as the Fraunhofer or solar spectrum. One of Fraunhofer's drawings of the solar spectrum is shown in *Figure 33.6*. In 1834 Fox-Talbot, chiefly remembered as a pioneer of photography, found that he could distinguish the red flames given by lithium and strontium salts by observing them through a prism and noting the very different bright-line spectrum given by each. It is the differences in the position of the bright lines in the spectrum produced by different elements, either pure or in combination, when they are volatilised in a flame, electric arc or electric spark, which provide the basis of the spectrum analysis of materials.

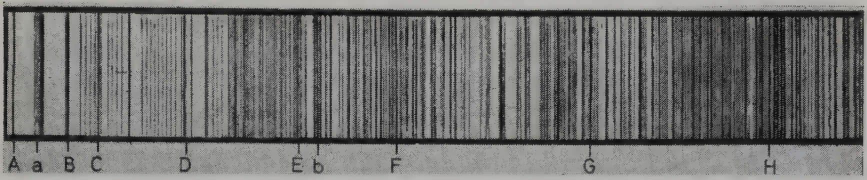


Figure 33.6 *One of Josef Fraunhofer's drawings of the solar spectrum*

Such a bright-line emission spectrum is due to electronic disturbances within the atom. With incandescent vapours of compounds, a band spectrum may occur: this is a curious banded or fluted formation, each band consisting of a group of very fine lines, comparatively wide apart at one end and crowded closer and closer together at the other until the last are so close as to appear to be one dense line at the 'head'. Band spectra refer to spectra in the molecular state; they are sometimes known as Swan spectra. It must not be taken as implied that the bright-line spectra are confined to the visible part of the electromagnetic spectrum. This is of course not so: the 'bright lines' extend right down through the ultra-violet.

Flame Spectra

Emission spectra of the alkali metals and the alkaline earths, and many rare-earth elements, which may be volatilised by the heat of the Bunsen flame, may be identified by the bright lines seen in the visible spectrum.

Such flame spectra are illustrated in *Figure 33.7*. In carrying out flame analysis with a direct-vision spectroscope a short length of platinum wire mounted on a piece of glass rod may be used, after it has first been cleaned by immersion in hydrochloric acid and heated. This cleaned wire is used to take up a small quantity of powder from the specimen which has been moistened with hydrochloric acid. The charged wire is then inserted into the cool part of the Bunsen flame and brought up into the hotter part (*Figure 33.8*) while the flame is examined spectroscopically. In this connection it must be mentioned that the yellow doublet of sodium inevitably appears – for one part in 40 million in any sample will produce the yellow lines – and these should be disregarded unless the flame is coloured strongly yellow and the yellow doublet appears in strength. Flame spectra have little value in gem determination, although in

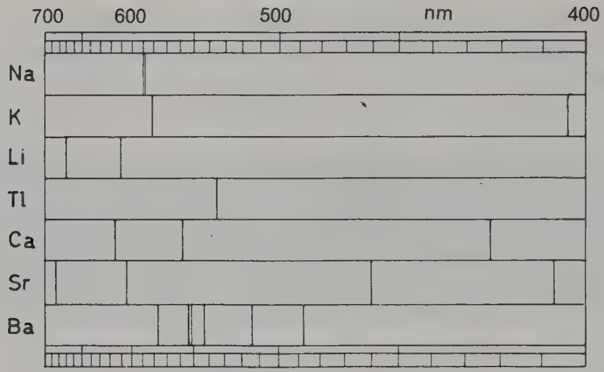


Figure 33.7 *Flame spectra of the three commoner alkali metals, the alkaline earths and thallium*

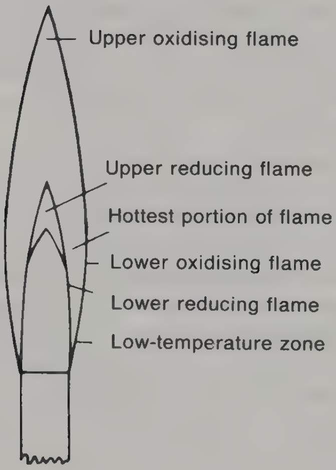


Figure 33.8 *The Bunsen flame*

some cases powder 'sneaked' from the girdle of a stone may be so analysed and information gained. Thus a flame test for lithium may be found useful in checking the identity of the rare mineral amblygonite – a fluophosphate of aluminium and lithium. As lithium is such a rare constituent in gem minerals proof of its presence has real significance.

Visual Examination with Spectrometer

Visual examination of the emission spectra, and the measurement of the wavelengths of the lines, can be carried out by the aid of a spectrometer, such as the instrument described for the method of refractive index measurement by the minimum deviation method (Chapter 32). The use of such an instrument enables the higher temperature of the electric arc using purified carbons, upon the lower one of which a sample of the substance to be analysed is placed, to be conveniently exploited, and thus allows less easily volatilised substances to be examined for their bright lines.

With the spectrometer, measurement of the wavelength of the lines is made possible by reference to a graph prepared for the glass prism used. The graph is made by plotting as a curve the angular readings of the telescope for a number of different bright lines of known wavelengths of various elements, and plotting them on the graph which has the angular measurements as abscissae (horizontal line) and wavelengths as ordinates (vertical line). The wavelength of any unknown line can then be found from its angular measurement by reference to the graph. The element to which that wavelength agrees is found by reference to published tables of wavelengths, such as Smith's *Visual Lines for Spectrum Analysis*, or *Wavelength Tables for Spectrum Analysis* by Twyman and Smith. Larger dispersions, hence greater accuracy, may be obtained by using a hollow prism filled with carbon disulphide or cinnamic aldehyde, or by a diffraction grating, the latter giving an even dispersion throughout the whole range of wavelengths. The diffraction grating will be discussed at greater length later in the chapter.

In the ultra-violet region lie the more diagnostic spectral lines which are so useful in spectrum analysis. A spectrometer with a glass prism is of little use in spectrum analysis in the ultra-violet, for the ultra-violet lines are not visible to the eye. Even if a camera were arranged to photograph the lines, owing to the strong absorption of the glass for wavelengths below 300 nm, half of the ultra-violet spectrum would be lost.

The Spectrograph

Spectrum analysis by the production of bright-line spectra, usually called line spectra, is carried out by means of a spectrograph using quartz (pure rock crystal) prisms and lenses, a material which transmits ultra-violet light down to well below 200 nm. Such instruments record the lines photographically, and if 'long-range spectrum plates', which have an emulsion which responds from the near infra-red right down to the shorter ultra-violet, are used, a very complete spectrum can be obtained. Spectrographs are totally enclosed and consist of an adjustable slit for the light to enter, and a collimating lens system to parallelise the rays from the slit on to the quartz prism which disperses the light. The dispersed rays, or really images of the slit, are then focused by a lens system (the camera lens) on to the photographic plate which is carried in a dark slide (cassette). The instruments are 'dog-leg' in shape if the bend due to the deviation of the rays through the prism is in a horizontal plane, but if in a vertical plane the bend is entirely enclosed within the instrument. The quartz prism, owing to the fact that quartz is not only birefringent but also has the power of rotating the plane of polarised light in the direction of its optic axis, is made in two halves, one of right-hand and one of left-handed rotation, each cut so that the rays pass along the optic axis. These two halves are cemented together so as to produce a 60 degree prism. The slit needs to be made accurately and the lenses carefully computed and designed. Finally, the plate holder must be oriented accurately to the beam of the rays.

Spectrum analysis using a quartz spectrograph is a laboratory technique and some experience is needed to carry it out successfully. Only the bare outlines of the method can be given in this résumé. The choice of electrodes for the arc will depend upon the electric current available and the nature of the work to be

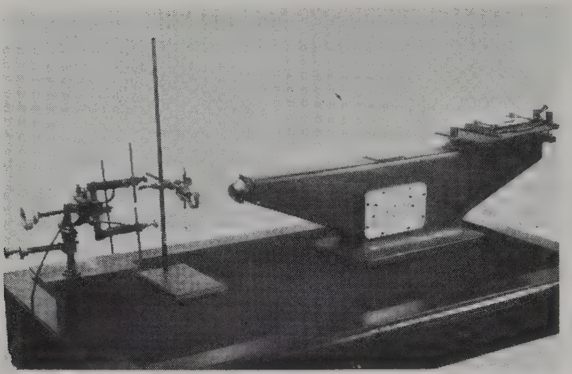


Figure 33.9 A quartz spectrograph set up for spectrum analysis

done. Pure carbons must be used if alternating current is the only source of electricity available. If direct current, either from the mains or through a suitable rectifier, is available metal electrodes may be used, the most useful being those of pure copper or the non-metal graphite.

It is necessary to ensure that the arc and the quartz condensing lens used to focus the light of the arc on to the slit are both correctly aligned with the optical system of the spectrograph, and that a photographic plate in its cassette is in position. *Figure 33.9* shows how a quartz spectrograph is set up. A photograph of the spectrum of the pure electrodes is then made by striking the arc with, of course, the dark slide of the cassette open. The plate is then readjusted and a small quantity of the powdered substance to be analysed is then placed in a shallow depression in the lower of the vertical electrodes and the arc struck again. The width of the slit and the exposure time, say 5–10 s, need to be found by experience. From three to six spectra can be accommodated on each plate, depending upon the length of the slit, which may be adjusted by a sliding V-shaped diaphragm.

On development of the plate a series of black lines will be seen which, owing to the optical system of the spectrograph, are usually slightly curved. The measurement of the spectral lines is carried out by identifying certain lines of the spectrum of the pure electrodes and using these as 'fixed points' from which the unknown lines in the spectrum of the substances analysed, which is superimposed on that of the electrodes, can be determined by interpolation; a measuring microscope is often used for such a purpose. In some large spectrographs a wavelength scale is provided which is printed on to the spectrum plate photographically. The wavelengths of the lines determined from the spectrum plate are then looked up in a table of wavelengths of the elements, and the elements in the sample thus found. For practical purposes the easiest and safest procedure is to rely on comparison with known spectra. Standard plates are taken of the elements most commonly encountered and these can be juxtaposed with the unknown spectrum. From this the presence or absence of each element can be systematically established. Such comparison spectra can, of course, be photographed on one plate if only certain elements are to be searched for. A variation of the above method is to use a high-tension electric spark in place of the arc.

Ultimate Lines

Hartley, and later de Gramont, found that it was not always the strongest spectral line of an element which is the most persistent when the substance is present in diminishing amount. Hartley's persistent lines were termed *raies sensibles* by de Gramont who gave the name *raies ultimes* for those which remained last when the quantity of the element was decreased almost to vanishing point. The *raies ultimes* lie mostly in the ultra-violet region, while the *raies sensibles* are more often found in the visible part of the spectrum and enable very small quantities of the elements concerned to be detected by quite simple apparatus. The strength of the lines, usually marked from 1 to 10, are given in the wavelength tables for both arc and spark spectra, the two of which need be in no way identical, the most persistent lines being marked by special symbols. Thus, if the *raies ultimes* of an element are missing the element is not present and this simplifies the search.

Fluorescence Spectrum

A number of substances which glow with a fluorescent light when irradiated with blue light, ultra-violet rays, X-rays or cathode rays may, when examined with a spectroscope, show this fluorescent light to be made up of bright and discrete bands. Such a fluorescence spectrum has a value in the distinction of ruby from red spinel and for some diamonds. More will be said of this when discussing the luminescent characteristic of gemstones.

Absorption Spectra

From the point of view of gemstone identification the absorption spectrum is the most important. When discussing colour it was mentioned that the absorption of light by a substance determines the residual colour. In many cases the colour absorption can only be interpreted by a curve produced from data obtained by the use of an elaborate instrument called a spectrophotometer. Such an instrument is not used in general gem testing, despite the valuable information that may be obtained with it. More often the absorption, particularly of coloured stones, is in well-marked bands or finer dark lines which cross the otherwise continuous spectrum, obliterating certain colours or wavelengths when white light is transmitted through or reflected from the stone. The distribution of these dark bands or lines provides, often without measurement, partial or complete identification of the gemstone.

Spectroscopes

A small hand spectroscope is the only additional instrument needed for this powerful method of gem identification to be carried out. The spectroscopes and the techniques of their use need to be discussed before telling of the absorption spectra themselves.

Direct-Vision Spectroscopes

There are two distinct types of hand, or as they are more often called direct-vision, spectroscopes available for use. The first of these is the prism type which operates by dispersing the light through a train of glass prisms. In the second type of instrument the spectrum is produced by diffraction of light from a finely ruled grating. The direct-vision prism instruments are the more commonly used for the spectrum produced is clearer and brighter, but the instrument must be carefully chosen, since, if the dispersion is too small, the bands in the red region are too cramped for the details to be seen. Owing to the unequal dispersion of the prism for the different wavelengths the spectrum produced by these instruments is closed up at the red end and expanded in the blue and violet end. Thus the absorption lines in the red end of the spectrum are sharper while the bands in the blue are more diffuse.

There are many different makes and designs of direct-vision spectroscopes (*Figure 33.10*), but all operate on the same principle. Prism spectroscopes are available in which a wavelength scale can be seen projected above the coloured spectrum (*Figure 33.11*), but such instruments have the disadvantage that some provision must be made for illuminating the scale in the accessory tube, and sometimes the scale is not quite accurate for all parts of the spectrum, especially when the focus is altered. Krüss produced a spectroscope unit which had a built-in quartz-halogen light source and a fibre-optic light guide (*Figure 33.12*). When used for transmitted illumination, light is deflected vertically via a mirror beneath the rotatable specimen platform. The firm of Rayner produced a spectroscope which has a series of slits of different widths which can be set into the optical axis by rotation of the eyepiece which may also be slid in or out to adjust the focus. This instrument is so constructed that it can be slipped into the body tube of a normal microscope, or can be used hand-held or on a Mitchell-type stand (*Figure 33.14*).

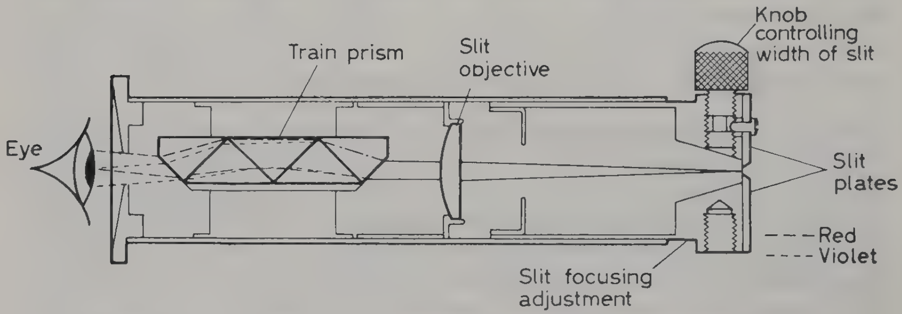


Figure 33.10 The construction of the direct-vision prism spectroscope (Beck 2458)

Diffraction Grating Spectroscopes

The diffraction grating spectroscopes produce their spectra by diffraction and interference of the incident light rays by a finely ruled grating of about 550 lines per millimetre. Such gratings are ruled on glass with a diamond point by the use

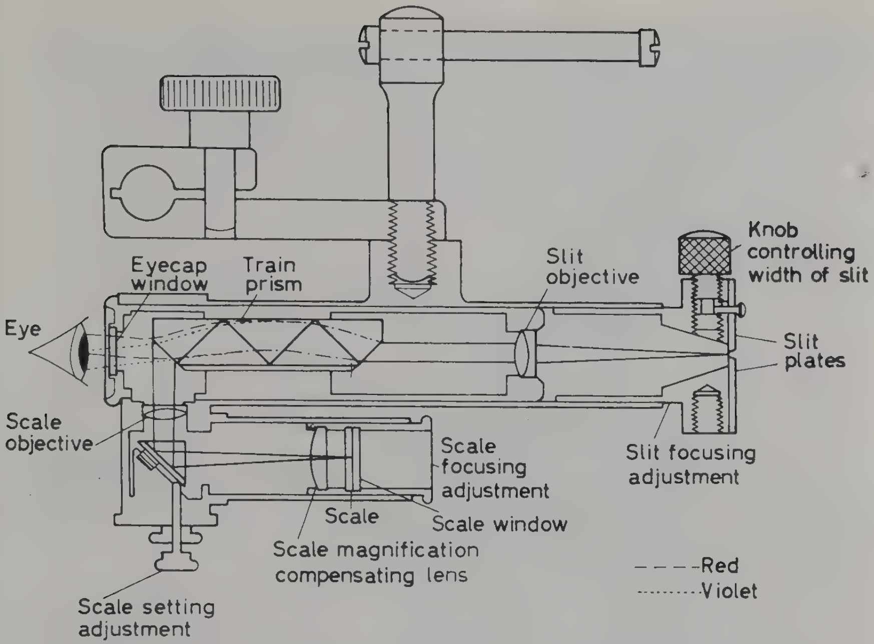


Figure 33.11 *The construction of the wavelength direct-vision spectroscope (Beck 2522)*

Figure 33.12 *The Krüss KL9 spectroscope (Krüss/GIA)*

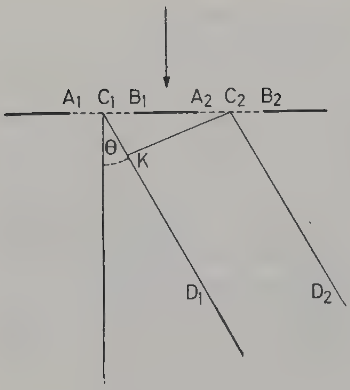


Figure 33.13 *The principle of the diffraction grating*

of an accurate dividing engine. The resulting effect is a number of effectively opaque lines, where the diamond has scratched the glass, with fine transparent spaces between each ruled line. As such glass gratings are expensive to produce celluloid casts, or replicas, are made and used for most of the commercial spectroscopes.

A diffraction grating consists of a number of equally spaced lines ruled on a transparent substance (some gratings are ruled on metal and the spectral effect is produced by reflected rays), the width of each line being equal to the space between two adjacent lines. If A_1A_2 (*Figure 33.13*), the width of the combined line and space, is d, and a plane wave with wavelength λ is incident perpendicularly on the grating, all the clear spaces will act as secondary sources and emit rays in all directions. If all the rays making an angle θ with the normal are considered, then all the rays from each space can be replaced by a resultant coming from the mid-point of that space, and the problem reduces to that of compounding a number of parallel rays C_1D_1, C_2D_2, and so on, from a number of equidistant points C_1, C_2. If C_2K is drawn perpendicular to C_1D_1, then the common difference of these rays is C_1K equals $C_1C_2 \sin C_1C_2K$ equals $d \sin \theta$, and the rays reinforce in the direction θ if $d \sin \theta$ equals $n\lambda$, where n has any integral value, positive or negative, and a bright line is seen at this angle.

As reinforcement occurs when $n\lambda$ equals $d \sin \lambda$, when n equals 0, $\sin \lambda$ equals 0; thus for all values of λ this will be a maximum, so the centre of the pattern, the direct image, is white with white light. If n equals 1, 2, 3 and so on, $\sin \theta$ is proportional to λ, so that with white light, spectra – called spectra of the first, second, third order – are formed. The first-order images form two first-order spectra, one on each side of the direct image. The second-order and third-order pairs of spectra are still farther away from the direct image, but these two pairs overlap each other. It is one of the first-order spectra which is used as the spectrum in diffraction grating spectroscopes.

It is usually maintained, with apparently good reason, that since the energy of light passing through the slit of a diffraction grating spectroscope is shared between a series of spectra into which it is resolved, the brightness of the first-order spectrum which is actually used by the observer must be considerably diminished, and moreover a large percentage of the light incident on the slit of the instrument passes through as an undispersed central image.

Figure 33.14 The Rayner direct-vision diffraction spectroscope with a series of slits of different widths which are put into the position by turning the eyepiece. The instrument as shown is held on a Mitchell stand for reflected light observation. The diameter of the instrument allows it to fit into the body tube of a standard microscope in place of the ocular

One would expect therefore that a prism spectroscope in which the light incident on the slit is concentrated into the production of a single spectrum would produce a far brighter image. However, this is not necessarily the case. By suitable selection of the shaped diamond points used in ruling the grooves for a grating, much of the light can be concentrated into one first-order spectrum, while on the other hand it should be realised that in the multiple train of five prisms commonly used in constructing hand spectroscopes as used in gemmology there are considerable losses of light owing to reflection at each of the glass interfaces.

A diffraction grating spectroscope (*Figure 33.14*) also has the advantage of being smaller and far lighter in weight than a prism instrument, as well as being considerably less expensive. Another advantage is the even spread of the spectrum. It may be advantageous to have both types of instrument available, as there are circumstances when either one or the other will provide the clearer image of the absorption bands. A factor which increases the cost of spectroscopy to an unnecessary degree derives from the assumption that a wavelength scale is essential. This expensive accessory is in fact quite unnecessary for the trained observer who recognises each characteristic series of bands without measurement by their character and pattern. After half a century of constant use of the spectroscope for testing purposes in the Gem Testing Laboratory of the London Chamber of Commerce, the instrument invariably relied upon was a Beck 2458 prism spectroscope without a scale. This particular model is no longer available; nor is the Rayner multislit model which yielded very similar results. A small but admirably efficient grating model is provided by Colin Winter (Genesis Ltd). For measurements of wavelengths a Beck wavelength spectroscope despite its awkward 'dog-leg' shape has proved most reliable. In this, fine cross-hairs in the eyepiece are brought into coincidence with the band to be measured by means of a calibrated drum. The Hartridge reversion spectroscope (also made by Beck) is another accurate instrument for wavelength measurement. Reversed images of the absorption spectrum are seen and the two images of the absorption band to be measured are brought into coincidence by turning a drum marked in wavelengths. With either of these two instruments measurements accurate to ± 1 nm are obtainable.

Digital Scanning Spectroscopes

These consist of diffraction grating spectroscopes in which the spectrum can be moved relative to a hairline cursor by an adjustment control. This control is coupled to an electrical transducer whose output is displayed digitally as a wavelength. Such instruments have been marketed by Gemlab, Power Tools Inc., and the GIA.

Video Spectroscopes

Video spectroscopes are produced by Hanneman Gemological Instruments and Gemlab. They combine a spectroscope with a video camera and display gemstone spectra on a TV monitor. This provides a large magnification of the spectral image on which a wavelength scale can be superimposed. Because the video camera is more sensitive to the blue/violet end of the spectrum than the eye, this makes absorption lines and bands easier to detect in this area.

Technique

The observation of the dark absorption lines in gemstones needs some practice and attention to a number of details. First, the parallel-jawed slit must be adjusted: in most of the spectroscopes used in gem testing the width of the slit may be narrowed or widened by means of an adjusting screw. When there is plenty of light the slit needs to be as narrow as possible, but open just enough to clear the horizontal streaks caused by the touching parts of the slit jaws or minute dust particles closing the gap. Heavy streaks are the sign of a dirty slit, and this should be corrected by opening the jaws widely and rubbing them gently with the wedge-shaped end of an orange stick or a sharpened match-stick. With dark stones which are not passing very much light the slit needs to be opened wider.

Another important factor is the focusing of the slit. Spectroscopes have a sliding inner tube enabling this to be accomplished, for without proper focusing the finer lines to be seen in the spectrum may well be missed. With prism instruments the focus is not necessarily the same for the red end as for the violet end of the spectrum and the instrument needs slight refocusing for the best viewing at either end of the spectrum. The suitability and adjustment of a spectroscope may conveniently be done by observing the Fraunhofer lines of the sun's spectrum which may be seen in the spectroscope from any part of the day sky. These Fraunhofer lines may also be seen, and used for focusing a spectroscope, from the light of the moon, in which case the instrument should be directed at the moon itself. The focus and slit width of the instrument should be adjusted until the dark lines are clearly and distinctly seen. The bright-line spectrum underlying the continuous spectrum of the fluorescent tube electric light is also useful for the adjustment of a spectroscope, and a good zircon will also provide suitable lines upon which to set the slit and focus of an instrument.

In European gemmology it is the convention to observe the spectrum with the red on the left, and all the illustrations of gem absorption spectra in this book are so drawn. Modern physics now usually postulates that spectra be viewed and illustrated with the wavelengths increasing in length from left to right, that is red on the right. In most American gem literature this system, which is the reverse to that used in Europe, is the convention which is used, and drawings need to be turned round (upside-down) to bring the lay-out into the European convention.

Illumination of Specimen to be Examined

Most important in the examination of the absorption spectra of gemstones is the illumination of the gem specimen to be tested. There are two techniques, the transmitted light method and the reflected light method, both needing a powerful source of light if the best results are to be obtained. In the past, the suitable source was a 300 or a 500 watt projection lamp suitably screened in an asbestos lined box fitted with ventilation louvres, or other suitable cover to prevent glare to the eyes and to allow the light to pass only in the required direction. Alternatively, a high-intensity quartz-halogen lamp will provide a useful source.

Microscope Method

It is then necessary to transmit a concentrated beam of this light through the specimen and to project it evenly on the slit of the spectroscope. A very satisfactory method adopted in the Gem Testing Laboratory of the London Chamber of Commerce (and still in use in the GA Gem Testing Laboratory) is worth consideration despite the development of the highly convenient illumination provided by quartz-halogen lamps and modern fibre optics which are described later.

The light from a 500 or 250 watt projection lamp housed in an asbestos lined box as described above is concentrated by means of a spherical flat-bottomed flask of 600 or 750 ml capacity (which acts as a coolant as well as a giant lens) on to the mirror of a traditional monocular microscope, and thence through an adjustable substage condenser and through the specimen under test which rests on the microscope stage on a diaphragm of slightly smaller aperture than the diameter of the stone. The eyepiece of the microscope is removed and the spectroscope, held in the hand, is rested lightly on top of the microscope tube. A few deft touches are needed to adjust the position of the mirror and the substage condenser, and to ensure that the most powerful and even beam possible reaches the slit of the spectroscope; while finally the width of the spectroscope slit and the focus of the instrument need adjustment according to the depth of colour of the stone and the position of the absorption bands in the spectrum. To a beginner this may seem to demand a formidable list of adjustments, but it is essential for success and in practised hands can be carried out in a few moments.

When adjusting the light passing through the specimen it is wise to place a piece of ground glass over the top of the microscope tube which will reveal the optimum light conditions without the eyes being dazzled by the glare. If possible the substage condenser should have a wide-aperture lens and it is important that it should be adjustable. A second-hand microscope of traditional design may prove cheaper and more suitable for this particular purpose than modern gemmological instruments which, being designed mainly for the study of inclusions, are understandably mostly of binocular design.

An extremely valuable and inexpensive accessory to the above arrangement is a second spherical flat-bottomed flask containing a clear filtered saturated solution of copper sulphate, obtainable as blue crystals from most pharmacists. This flask of blue fluid if used in place of the plain water flask will serve the concentrating and cooling functions of pure water but will act as a filter cutting off completely the rays at the red end of the spectrum, including the yellow, and enable the eye of the observer, free from the glare of the light to which the human eye is most sensitive, to see much more easily any important absorption bands in the blue and violet which might otherwise be missed. Obviously, common sense must be used and the whole spectrum be first scanned to ensure that bands of interest are not all or mostly situated at the long-wave (red) end of the spectrum.

A flask of copper sulphate solution can sometimes serve a double function, stimulating a strong red fluorescence in such stones as ruby and red spinel, the bright lines from which can then be clearly seen through the spectroscope against a black background. A further development of this kind will be found in the chapter on luminescence (Chapter 36).

With transparent stones of moderate refractive index enough light may be transmitted when they are placed, table facet down, on a glass slide or (with small stones) on a diaphragm as described above. Diamond and other highly refractive stones may not allow light to pass, but will transmit light freely when resting on their pavilion facets which are nearly parallel to the crown facets on the opposite side of the stone.

The general set-up described above can be seen in *Figure 33.15*, with the pure water cooling and condensing flask in use and the flask of copper sulphate in

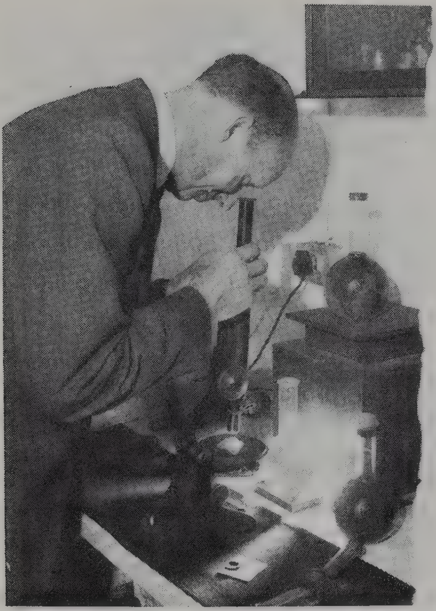


Figure 33.15 *Using the spectroscope by the microscope method*

readiness alongside. It should be realised that were it not for the flash-light used in taking this photograph the only light shown in the picture would have been that transmitted through the flask.

Reflected Light Method

Stones with weak spectra or translucent and opaque stones may be examined for their absorption spectrum by reflected, or scattered, light. In this case the stone is placed, for preference on a black cloth, in the pool of light directed by a fibreglass light guide or a lens from a strong light source (an intensity lamp is quite efficient in this method). The spectroscope is held at an angle of about 45 degrees with the slit 25–50 mm from the stone. Such a technique is particularly useful for the heat-treated zircons and for jade and turquoise. Mitchell has devised a stand to hold the spectroscope in order to simplify this form of observation (*Figure 33.16*).

Quartz-halogen Lamps and Fibreglass Guides

Some years ago two new inventions led to a revolution in the production of powerful light sources for use with apparatus such as slide projectors and the spectroscope. The first of these were small tungsten-filament bulbs formed from fused quartz and containing halogen vapour which ran on low voltages to provide a very intense source of white light, eminently suitable in particular for use in slide projectors, their chief drawback being that they had to be operated in conjunction with a cooling fan to prevent over-heating. The second was the production of 'light-guides' in the form of flexible metal-clad pipes containing

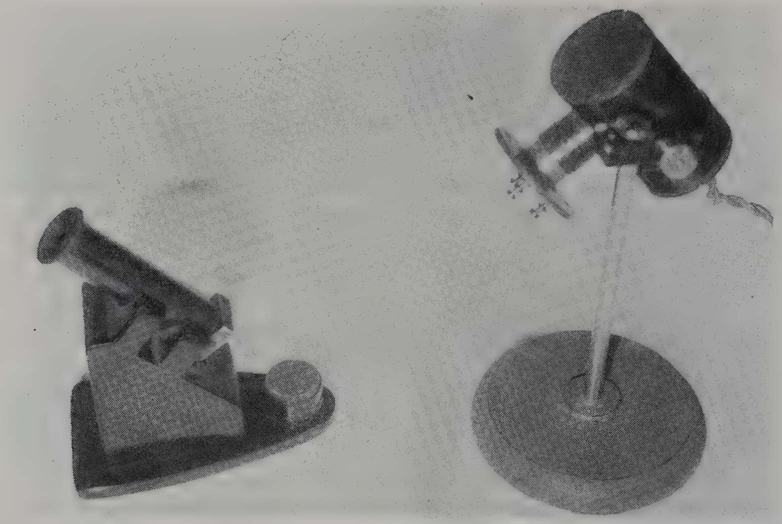


Figure 33.16 *The reflected light method of observing absorption spectra using the Beck prism spectroscope on a Mitchell stand and an intensity lamp as the light source*

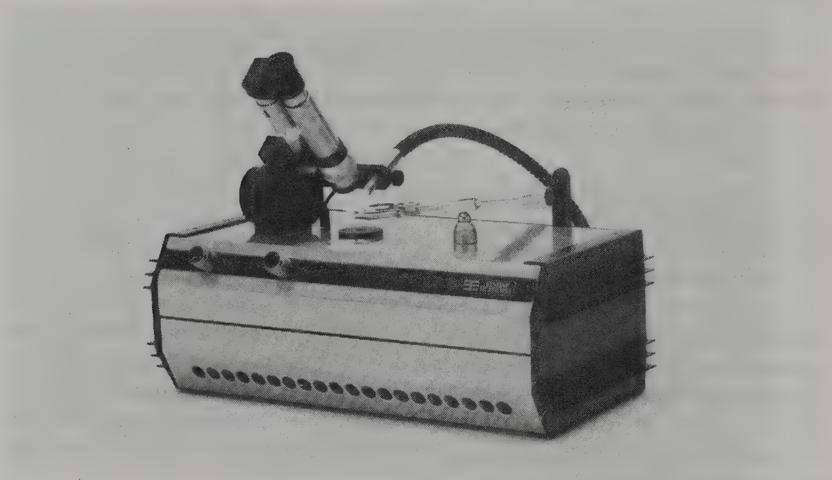


Figure 33.17 *The Coldlight spectroscope with fibre-optic light guide and illuminated wavelength scale (Eickhorst)*

masses of parallel glass fibres which were found to convey beams of light virtually without loss from a light source to the point where the light was needed. The emergent light moreover was virtually cold and thus ideal for use with a microscope or spectroscope.

Several manufacturers of gemmological instruments were glad to make use of this facility, the first being the Hamburg firm of Eickhorst who designed a Coldlight spectroscope (*Figure 33.17*) incorporating a light guide which can be used for observation of the absorption spectrum of a gemstone either by transmitted or by reflected light, and the wavelength measurements can be read from an illuminated scale to a claimed accuracy of 2 nm. As accessories, a blue filter can be incorporated to facilitate observation of lines at the blue end of the spectrum and a polarising filter to enable observation of the spectra of differently polarised rays. The whole compact apparatus is engineered to fit if required (and for those who can afford it) into other units forming a Gemmodul series including polariscope, refractometer, microscope, ultra-violet lamps, and so on. The spectroscope used in the Eickhorst apparatus may be either a Zeiss or a Beck instrument according to the preference of the purchaser.

The Use of a Pen Torch

The light from a pen torch, though small, can be very intense and can serve as a useful illuminant in gemmology when laboratory facilities are not available. The Japanese have produced such a torch provided with a slip-on fitting with a flexible limb having a crocodile clip at one end which can hold a stone securely over the light from the torch, enabling it to be examined through a small spectroscope.

A high intensity Penlite torch is also incorporated in a simple aid to spectroscopy designed and produced by Hanneman. This consists of a transparent plastic cube (described as a 'mini-cube') which is recessed on its underside to fit the Penlite. The top side, through which the light emerges, is fitted with a revolvable disc in which there are a series of circular diaphragms of different diameters for controlling and masking the light passed through stones resting upon them. With practice it is possible to hold the Penlite and cube with one hand, and the brightly illuminated stone is examined through a small grating spectroscope held in the other. A similar device is produced by Rayner/Rubin.

Effect of Strength of Absorption Spectrum

Variations in the strength of the absorption spectrum dependent upon the depth of the transmission may to some extent alter the appearance of the spectrum by causing adjacent bands to coalesce when they are intense. More noticeable is the fact that there may be important differences due to dichroism and pleochroism, and in such cases the absorption will differ along different directions. Such differences, however, seldom interfere with the recognition of the spectrum and may even need the aid of a piece of Polaroid or a nicol prism to isolate the vibration directions for the differences to be seen. A weak absorption spectrum may often be seen more clearly by introducing over the microscope eyepiece a piece of Polaroid turned into the optimum position.

The Infra-Red Spectrophotometer

So far the emphasis has been on the spectra produced in the visible and ultra-violet parts of the electromagnetic spectrum. Except for some cursory experiments in photographing gemstones in the near infra-red, infra-red

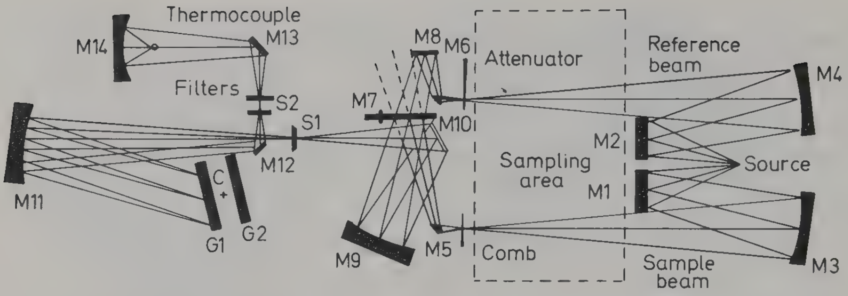


Figure 33.18 Optical layout of Model 621 Perkin-Elmer infra-red spectrometer with two gratings G_1 and G_2. M_7 is the rotating sector mirror, or as it is sometimes known, the chopper

radiations have rarely been used in determinative gemmology. In mineralogy and other sciences exploration in these longer-wavelength regions has been carried out by using the infra-red spectrophotometer, and similar instruments operate in the visible and ultra-violet regions.

There are many different types of infra-red spectrophotometers which produce a fully automated record of the absorption spectra in these regions. The most widely used instruments are those which use the double-beam principle (*Figure 33.18*). In these the primary infra-red beam, from a suitable burner, is split into two beams of equal energy. One of these, the reference beam, passes through a filter, the attenuator, which reduces the intensity; and the second beam is the one which is transmitted through the sample to be tested. By a series of mirrors these two beams are combined into one 'light' path, each beam being cut off by a sector mirror which operates as a change-over switch and allows one or other of the beams to fall alternately on the slit of the spectrometer grating. The grating, which may in some instruments be replaced by prisms made of infra-red transparent material, such as sodium chloride or potassium bromide, are usually in pairs which are automatically swung into the circuit so that two ranges of infra-red waves may be analysed. The grating disperses the infra-red beam into wavelengths, and this dispersed 'light' falls on a slit which isolates the monochromatic wavelengths. The monochromatic beam from the slit, the different monochromatic wavelengths being produced by constant alteration of the angle of the grating, falls on the radiation detector. This is usually a thermocouple which responds to differences in the intensities of the two beams – the reference beam and the test beam. The pulsating signal received by the detector is then electrically transferred to a servomotor which operates a pen which draws a curve on a suitable graph paper.

The preparation of the specimen needs comment. Ideally a parallel-sided specimen is needed, and, for most solid substances, this is prepared by grinding up scrapings (as little as 0.002 gram may be used) from the specimen with potassium bromide and consolidating this mixture in a press so as to produce a parallel-sided disc which will fit into the specimen holder. In the case of cut gemstones, such as diamond, a reflection rather than a transmission technique is used. Interpretation of the graph needs care for in different makes of machines there are differences in presentation. Some show a graph in which the 'peaks' indicate the absorption while in others it is the 'dales' which are the absorption

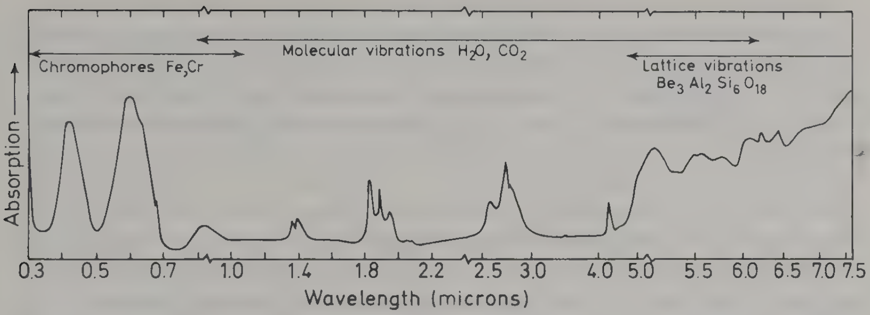


Figure 33.19 Composite spectrum of beryl showing: the region of lattice vibrations (4.5 μm toward longer wavelength), the region of molecular vibrations (water and CO_2 *from 0.84 to 6.5 μm), and the region of chromophoric absorptions (0.3 to 1.1 μm), with ordinary ray polarisation (after Wood and Nassau)*

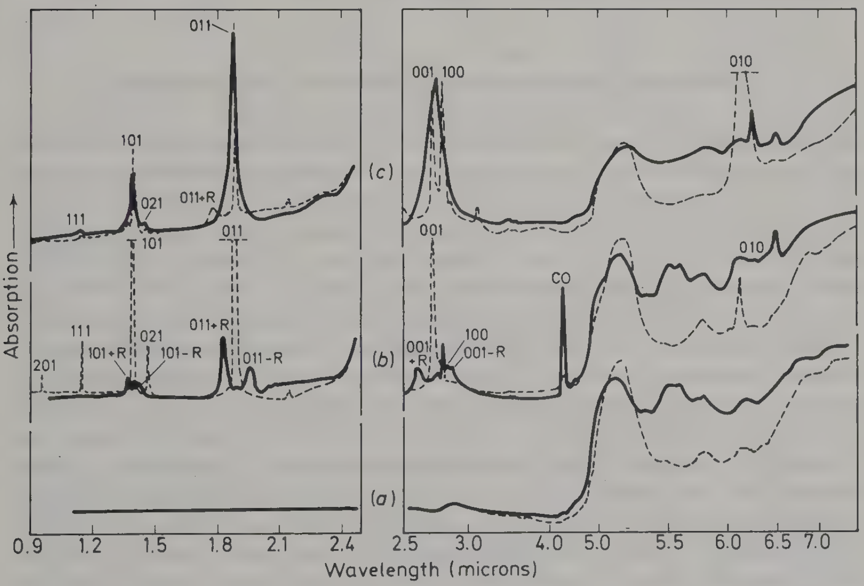


Figure 33.20 Spectrophotometer curves of (a) Chatham flux-grown synthetic emerald with no molecular lines only lattice lines; (b) natural emerald with nearly all type 1 water sites and strong CO_2 *line; (c) natural emerald with mostly type 2 water sites. Dashed lines are for the extraordinary ray and full lines for the ordinary ray (after Wood and Nassau)*

bands. In the first type the ordinates are marked 'absorptance - - - -' and in the second 'transmittance - - - -'; these must be taken into account when reading the graph. The horizontal lines (abscissae) are marked in wavelengths, usually in microns (1/1000 mm), or in wave numbers (cm^{-1}) which relate to the number of waves per centimetre.

The composite spectrophotometric absorption curves for emerald (*Figure 33.19*) illustrate the use to which they can be put. This curve ranges from 0.3 microns (300 nm) to 7.5 microns (7500 nm), and shows, in the visible region, the absorption bands due to colouring agents (chromophores), which in the case of emerald are chromium and iron. The near infra-red gives the bands due to molecular vibrations, in this case water and carbon dioxide, and those of longer wavelength from 4.5 microns to the end of the graph are the bands due to the crystal lattice, in this case beryl. The absence of water bands in most synthetic emeralds forms a confirmatory test in difficult cases (*Figure 33.20*). A system of absorption bands at about 741 nm in the near infra-red is used to prove whether a diamond has been artificially coloured by particle bombardment.

Using the spectrophotometer is a specialised task even if the apparatus is readily available, and is thus outside the normal work of a gemmologist. It is discussed here so that the reader can have some idea, however perfunctory, of the more technical advances in identification with which he might become much more involved in the future.

Elements Determining Colour of Gemstones

In the descriptions of gemstones in earlier chapters the absorption spectra for each species and variety have been given. The measurements of the various lines and bands have been given in nanometre units, but such a method of identifying spectra by measurement is not easy and certainly not practical. The visual arrangement of the bands is usually sufficient to identify or to aid in the identification of a great number of the gems, and in only a few cases would recourse be needed to measuring apparatus. Two of the plates in this book show some of the absorption spectra of gemstones as seen through a diffraction grating spectroscope, and in the Identification Tables section a fuller range of spectra, drawn as seen through a prism spectroscope, are shown in Table 15.

In a number of cases the element to which the gemstone owes its colour may be shown by the type of absorption spectrum produced. Thus chromium, which gives to ruby and spinel a red colour, and to emerald and alexandrite a green colour, shows a typical absorption spectrum consisting of fine lines, including a strong doublet, in the red part; there is a broad absorption of varying width and intensity in the yellow and green. There may be lines in the blue, and the violet part of the spectrum is invariably absorbed. There are, however, significant differences in the absorption spectra of these different stones which are sufficient to aid in their identification.

Chromium

Chromium usually enters the crystal lattice in minerals by small-scale isomorphous replacement of aluminium oxide; thus the presence of a chromium spectrum suggests a mineral containing aluminium. Another distinctive and remarkable phenomenon connected with chromium spectra is the 'reversibility' of the narrow lines in the red; these can be seen as bright emission lines due to fluorescence or as dark absorption lines, according to the conditions. The presence of iron is apt to mask the effect, and so can an excess of chromium.

Gems which show chromium spectra apart from the four mentioned above are pyrope garnet, pink topaz, jadeite, demantoid garnet, nephrite, diopside, hiddenite, uvarovite garnet, enstatite, euclase, kyanite, some peridot, green-stained chalcedony and some green glass, but in many of these cases the chromium spectrum is accompanied by that due to some other element.

Iron

The absorption spectra due to iron can be divided into two groups: the ferrous iron due to divalent or ferrous oxide (FeO), which often replaces magnesia, and the trivalent ferric iron corresponding to ferric oxide (Fe_2O_3) which replaces alumina. Divalent iron produces red-, green- or blue-coloured stones and the absorption bands are in the green and blue of the spectrum. Examples of stones coloured by ferrous iron are almandine garnet, peridot, sinhalite, blue spinel, diopside, kornerupine, axinite, iolite and idocrase. The gemstones which owe their colour to ferric iron are usually yellow, blue or green in colour and the bands in the absorption spectra are of shorter wavelength than those due to ferrous iron. They are found in the 450 nm region where the blue merges into the violet. Stones showing absorption spectra due to ferric iron are yellow-green, green and blue natural sapphires, brown and yellow chrysoberyl, aquamarine, yellow orthoclase and the similar colour spodumene, jadeite, demantoid garnet and epidote.

Manganese

The absorption spectra due to manganese, which gives a rose-pink or aurora-red colour to rhodonite, rhodochrosite and spessartite garnet, consist mainly of bands in the green, centred about 550 nm, and in the blue, the latter being in the general absorption of the short-wave end of the spectrum and being seen with difficulty. The absorption spectrum is not sufficient to separate rhodonite from rhodochrosite, but that of spessartite garnet is sufficiently distinctive, although usually accompanied by the almandine spectrum, to separate it from almandine, and certainly enough to separate the stone from the similarly coloured hessonite garnet. There is some support for the contention that pink and red tourmalines owe their colour chiefly to manganese, but the absorption spectrum of these stones – usually very weak, but particularly strong in the brownish-red or violet-red variety – shows little in common with manganese spectra. Of diagnostic importance are the two narrow bands situated at 448.5 and 423 nm in the violet, which are seen in the manganese-coloured yellow and greenish-yellow and greenish-blue synthetic spinels. These bands are, in the blue-toned stones, present in conjunction with the bands due to cobalt.

Cobalt

Cobalt, which produces a red colour in natural minerals, gives to some glass, plastics and synthetic spinel a blue colour. The presence of cobalt in these blue stones produces a striking and diagnostic spectrum of three bands centred in the orange, yellow and green, but these bands, although they have a general similarity, differ slightly in their arrangement in the three materials. In synthetic blue spinel the bands are centred at 630, 580 and 543 nm, and there is a much weaker band at 478 nm. In this spectrum the central band appears widest and the band in the green the narrowest. In blue glass the bands are centred at 656, 590 and 538 nm, and there is a vague line at 495 nm. In cobalt-blue glass it is the central band which is the narrowest. A specimen of cobalt-blue polystyrene plastic showed the centres of the bands to be at 652, 610 and 566 nm. The cobalt absorption bands have been discussed in more detail because they show the presence of cobalt, which at once proves the stone to be counterfeit for no natural gemstone (apart from a few blue spinels) is coloured by cobalt, and, further, the distribution of the bands will tell the nature of the material. In the case of a blue glass-based garnet-topped doublet it must be remembered that the almandine spectrum may also appear in conjunction with the cobalt bands shown by the glass. The rarely met synthetic spinel showing a colour change that imitates the alexandrite shows a cobalt spectrum.

Vanadium

The more popular alexandrite imitation, that is synthetic corundum, owes it colour to vanadium. In this stone the absorption spectrum is nearly unique and certainly diagnostic for this variety of synthetic sapphire, for in the bright blue there is an exceptionally clear and sharp, although not always strong, line at 475 nm. In only one type of natural stone has this line ever appeared, that is in a very rare type of colour-change natural sapphire from Myanmar (Burma), but in this stone the colour is decidedly different from either true alexandrite or the synthetic sapphire made to imitate it.

Copper

Copper, which in the monovalent state (cuprous) produces a red colour, and in the divalent state (cupric) gives a blue or green colour, has an importance as far as absorption spectra are concerned only with turquoise, for azurite and malachite do not show any distinct absorption bands. The bands in turquoise are a broad but faint absorption band centred at 460 nm, a strong band in the violet at 432 nm and another in the obscurity of the violet at 420 nm, which can rarely be seen by the eye. It is the 432 and 460 nm bands which provide the diagnostic spectrum, and which can be seen by light reflected from the surface of the stone, helped by the use of the copper sulphate filter before the light source. It must be mentioned that none of the usual turquoise imitations show these bands, but the plastic bonded turquoise marketed in the United States of America will show the absorption bands very clearly.

Selenium

Selenium, probably in conjunction with cadmium sulphide, gives a red colour to glass and these red glasses show a broad absorption band in the green. Bands centred at 532, 537, 540 and 560 nm have been measured in red glasses, from which it seems unlikely that all red glasses owe their colour to the same cause.

Uranium

The striking absorption spectrum of zircon was first noted (with that of almandine garnet) by Arthur Church in 1866, and these observations were the beginning of the study of the absorption spectra of gemstones. The absorption spectrum of zircon, ascribed to uranous uranium, consists of a number of sharp lines and bands distributed throughout the spectrum, and is a most convincing absorption spectrum when fully developed. Even so, the spectrum can vary considerably in the number of lines which can be seen. Myanmar (Burma) zircons show the greatest number of bands, while the Sri Lankan zircons rarely show more than about 14. In the untreated reddish-brown zircons from Vietnam the lines are difficult to detect, but in the colourless, blue and golden-yellow stones produced by heating this rough, the strongest line at 653.5 nm, usually accompanied by the weaker 660.5 nm line, may be seen, thus identifying the stone. These fine lines are best seen by the reflected light method. The low-type (metamict) green zircons show only the 653.5 nm line, but in this case not as a sharp line but as a rather diffuse band, a sign of depreciation of crystal structure.

Rare-Earth Spectra

The rare-earth spectra consist of fine lines whose wavelength is very little affected by the nature of the host crystal. This is due to the fact that the transition from one element to the next involves no change in the outer electron shell, but instead there is a steady filling up of a deeper-lying electron group. Thus the outer electrons are not involved in these absorption processes, but do act as a screen behind which the electron shifts, allowing absorption and fluorescence to take place relatively undisturbed. The most important rare-earth spectrum is that of didymium (a mixture of the absorption bands of praseodymium and neodymium) and which consists of a group of fine lines in the yellow and a weaker group in the green. This spectrum is seen most strongly in the yellow apatite and may serve to identify the mineral. The spectrum may, however, be observed, but usually very weakly, in green and colourless apatite, danburite, sphene, idocrase, scheelite, calcite and fluorite; in fact all minerals which have calcium as an ingredient. A case is recorded where a strong didymium spectrum has been observed in emerald, but this was found to be due to the spectrum from an inclusion of the mineral parisite in the emerald. Blue apatite shows a different rare-earth spectrum which has bands in the orange, green and blue. The rare-earth spectrum shown by the bright green andalusite from Brazil is now known to be due to manganese. Some of the man-made stones, such as YAG and scheelite, show very striking rare-earth spectra.

Diamond

The absorption spectra of diamond are now known not to be due to trace elements but to be dependent upon the structure of the diamond crystal itself, and indeed, many complex features are revealed by the study of the absorption spectra of diamond. As noted in the chapter on diamond (Chapter 2) the absorption characters can be linked up with those of luminescence to produce three groups. Most gem diamonds, particularly those of the Cape series, show a strong band in the obscurity of the violet at 415.5 nm. Brown diamonds and other naturally tinted diamonds usually show a sharp band at 504 nm. This line, and one at 594 nm, have importance with other characters in the identification of artificially coloured diamonds.

Miscellaneous Spectra

There are a few miscellaneous spectra which deserve mention. Zinc blende shows narrow absorption bands in the red end of the spectrum. There is in this stone a narrow band at 665 nm, which may be intense, very weak or even not observable. There is a feebler narrow band at 651 nm and a broader band at 692 nm. The blue mineral sodalite may show a strong and rather broad band at 680 nm and weaker bands at 595 and 540 nm. Bands at 441 and 410 nm and a weaker band at 462 nm have been observed in fibrolite: these may be due to iron. Synthetic rutile shows a band at about 423 nm beyond which there is practically no transmission.

Neither the quartz gems nor topaz, except the pink stones, exhibit any absorption bands of diagnostic value, and tourmaline is most uncertain in its display of absorption bands. Synthetic blue sapphires at best show only a very weak and vague smudge at about 450 nm, which is totally unlike the line in the natural blue sapphire. Natural yellow sapphires from Thailand and Australia show the full 450 nm complex strongly, while the similar coloured sapphires from Sri Lanka do not (they fluoresce strongly with an apricot-coloured light under ultra-violet light). The synthetic yellow sapphire only shows a vague smudge of the 450 nm line and in the brownish-yellow types there is a strong absorption from 450 nm downwards into the violet. Natural green sapphires show the 450 nm complex strongly while the synthetic green corundum does not show a distinctive spectrum. No spectrum of diagnostic value has been observed in the synthetic strontium titanate. In the natural chrysoprase there is a weak absorption line at 632 nm which seems to be due to nickel.

Canary or uranium glass, which is sometimes used as an imitation stone, shows vague bands in the blue and violet at 495, 460 and 430 nm which often appears as a cutoff to the violet. Orange glasses often show an abrupt cutoff near 590 nm beyond which they are nearly opaque, and are in fact a 'colour filter'. Fire opal, which resembles these orange glasses in colour, usually has a rather less defined cutoff and may transmit light down to 575 or even to 555 nm according to the depth of tint. The chromium bands in green glasses are much more diffuse than the chromium lines in minerals. These bands are usually at 682, 661 and 634 nm. Pink glasses owing their tint to didymium are sometimes cut as gems (the rare-earth spectrum is sometimes in association with the selenium band in deeper pinkish-red glasses). It will be prudent to mention here that the antiglare glass – known as Crookes glass and used in spectacles – is tinted by didymium and will show the didymium rare-earth spectrum. Students who customarily wear Crookes lenses, and who have not realised their peculiar absorption properties, have sometimes been sorely puzzled by the persistent absorption band in the yellow which they notice in all stones which they examine with the spectroscope, for these bands will show up even if the glass is on the eyepiece side of the spectroscope.

34

The Microscope

One of the most useful pieces of apparatus for the study and identification of gemstones is the microscope. Indeed with a suitably designed microscope nearly every necessary test can be accomplished, although many of them may be more conveniently carried out by the use of other instruments.

The microscope, as usually understood, consists mainly of a tube containing a number of lenses, but a simple microscope consists of one lens only – a lens consisting of a piece of glass or other colourless transparent isotropic material having curved surfaces. Such a simple lens is the ordinary magnifying glass.

Lenses and their Function

No full understanding of the microscope can be obtained without considering the function of lenses and their behaviour to rays of light. The surfaces of lenses may be of two types – convex or concave. Convex lenses, in which the thickness is greater at the centre, cause a pencil of light rays to converge towards a point, while the opposite type, concave lenses, cause divergence of a pencil of rays away from the axis of the lens. Convex lenses are the most important in the production of a magnifying system, but concave lenses are often used in intimate contact with them in order to rectify certain optical defects.

Focus

The convergence or divergence of light rays through a lens is due to refraction, and the action of the two types of lens may best be explained by consideration of the geometrical representation of the paths of light through them. Beams of parallel rays striking the lens surface parallel to its axis (the straight line joining the centres of curvature of its surfaces) are bent by refraction of the rays by the denser medium of the lens. After passing through a convex lens (*Figure 34.1*) the

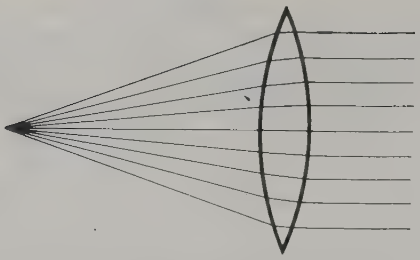


Figure 34.1 Principal focus and path of rays in a convex lens

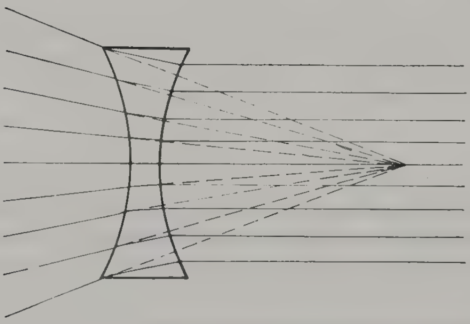


Figure 34.2 Principal focus and path of rays in a concave lens

rays meet at a point, called the focus of the lens; after passing through a concave lens (*Figure 34.2*) the rays diverge, but these divergent rays if produced backwards meet at a focus.

Where the incident light is parallel to the optical axis the distance from the centre of the lens to the focus is the focal length of the lens, and is generally denoted by the symbol *f*. The convention is that if the focal length, as measured from the lens, is in the same direction as that in which the incident light is proceeding, the lens is positive; whereas if it is measured in the opposite direction to the incident light, the lens is negative. It is for the above reasons that convex lenses are sometimes called positive lenses, while concave lenses are called negative.

As concave lenses play no part in magnifying instruments, except in combination, they need not be further mentioned and consideration is given to convex lenses only. When light rays from a distant object, such as the sun, are incident on a converging lens, they are brought to a focus, the principal focus, at some distance on the other side of the lens. It is also true that if a well-illuminated object is placed on one side of a convex lens, but at a greater distance than the principal focus, a real but inverted image of the object will be found focused at some point on the other side of the lens.

These two focal points, that where the object is positioned and that where the image of the object is formed on the other side of the lens, are

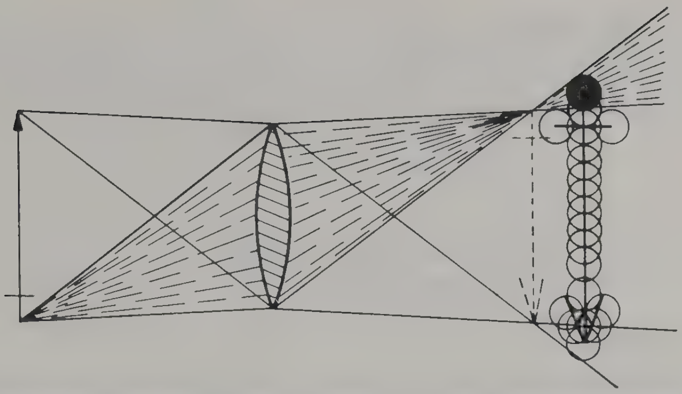


Figure 34.3 The formation of a real image by a convex lens and the cause of the 'out of focus' effect if the image is not at the conjugate focus

interchangeable and are called the conjugate foci. Since any luminous body is a collection of luminous points, the action of a lens on the lights from such a body is to form a collection of images, the total result being the image of the body. *Figure 34.3* illustrates the formation of a real image and also the effect when the image is not in focus.

When an object is placed at a considerable distance on one side of a convex lens, the image formed on the other side is small and at the focus; advancing the object to a position nearer to the lens causes the image to be farther away and to be larger, and if brought still closer so as to be near the principal focus of the lens the image is still farther away and is magnified several times (this is the principle of the magic lantern or slide projector).

If the object is brought nearer to the lens than the principal focus no real image is formed, a virtual image being formed on the object side, and the principal focus is the focus at infinity. What happens now is that the real image is lost; the virtual image then appears on the opposite side of the lens. The image no longer actually exists in space; it cannot be demonstrated by means of a screen. It is magnified and erect, and from observation one cannot tell that this so-called virtual image is not a real object. This is the principle of the magnifying glass and may be better understood by reference to *Figure 34.4.*

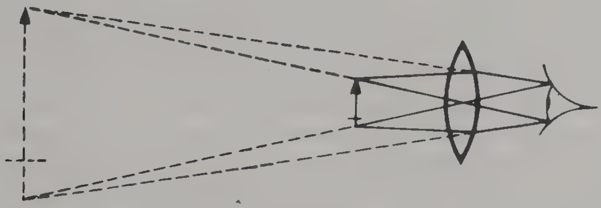


Figure 34.4 The formation of a virtual image by a convex lens. The principle of the magnifying glass

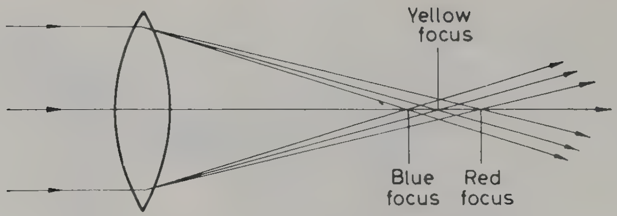


Figure 34.5 *How chromatic aberration occurs*

Lens Aberrations

It might be inferred from the foregoing remarks that a single lens will give a perfect image of an object, but this is not the case. Even a highly corrected lens will not do so completely; the reasons for this can only be grasped by a profound study of optics. There are many defects in lenses, termed aberrations, which preclude the ideal formation of an image – that is, a faithful and clearly defined copy of the object. There are two major types of aberration in lenses: chromatic aberration, which is due principally to the material of the lens; and spherical aberration, which is due to the form of the lens. There are other defects of a lesser nature, but these need not concern an elementary exposition as is intended here.

Chromatic Aberration

The most important of the single-lens defects is that of chromatic aberration. Refracting substances vary in their effects on light of different colours, refracting short wavelengths such as violet more than long wavelengths such as red. This is the effect known as dispersion or fire and has been explained in the chapter on light (Chapter 30). As the power of a lens is due to its refraction of light rays, and thus depends upon the refractive index of the lens material, an axial object point emitting white light will be imaged as a short spectrum lying along the axis, the blue or violet being focused nearer to the lens and the red farther away (*Figure 34.5*). This aberration can largely be corrected by combining a positive and a negative lens of suitable powers and made of different types of glass, having different dispersions, which combined together bring rays of two different colours, usually blue-violet and orange-red, to a uniform focus. Such composite lenses are termed achromatic lenses (*Figure 34.6*).

Achromatic lenses do not correct for all the colours and therefore have a small colour fringe which is known as the secondary spectrum. With certain

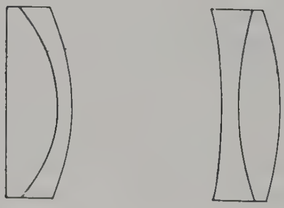


Figure 34.6 *Principal sections of achromatic lenses*

special types of glass, in combination with fluorite or a glass near to this in optical property, it is possible to produce a lens which will focus three colours in the same plane; the residual error is then extremely small. Such lenses are called apochromatic and are used in the highest class of instruments, but they require the use of compensating eyepieces.

Spherical Aberration

A spherical surface focuses the light which passes through the margin of the lens to a different focus from that passing through its centre (*Figure 34.7*). As every point source in the object is focused, therefore, not to a point but to a fuzzy disc, only an indistinct and badly defined image is formed. This effect is known as spherical aberration; it is corrected to a large extent by using combinations of lenses with surfaces of different curvatures, and often by limiting the aperture of the lens to the central part only by the use of a diaphragm, thus using only those rays which travel through the central part of the lens where the effect is not so pronounced.

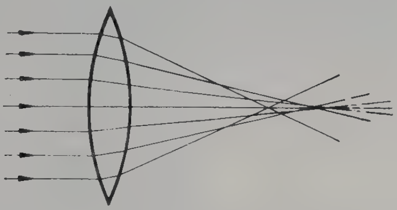


Figure 34.7 Spherical aberration

The Pocket Lens

It is now possible to discuss the various types of simple microscopes, such as the ordinary magnifiers with which jewellers are so familiar. These magnifiers, or loupes as they are sometimes called, must be considered with two points of view in mind. The greater the power of such lenses the more pronounced are the aberrations (unless corrected) and also the shorter is the focus (and working distance). Hence a watchmaker's eyeglass cannot usefully be more powerful than that giving four times the enlargement of the actual object; such a lens has a working distance of about 65 mm which allows space for the use of tools.

For the inspection of a surface or for the observation of inclusions inside a gemstone, working distance does not become so important and more powerful lenses may be used in such cases. The low-price folding magnifiers with from one to three single lenses, each of which may be folded in or out of the case and used separately, or in conjunction, to give various magnifications, can be useful but suffer from the usual defects of uncorrected lenses. For the study of gemstones the best type of hand lens is the aplanatic magnifier (*Figure 34.8*) which consists of a double-convex crown-glass lens cemented between

Figure 34.8 Krüss hand loupes; the lower one has a hinged supplementary lens giving a choice of magnifying powers

meniscus lenses of flint glass. Such corrected lenses have a flat field, that is they have a good definition over the whole field which is usually free from colour. Such a lens of 10 × magnification is recommended for use by gemmologists. As a lens is simply an adjunct to the eye to obtain the greatest field of view it should be held as close to the eye as possible. Care should be taken that the lens surfaces are not scratched, for scratches impair the visibility and may lead to an incorrect interpretation of the image seen.

It is difficult to exaggerate the importance to the gemmologist of a good-quality 10 × lens. Careful examination with its aid should always be the first approach to the testing of a gemstone and may often lead directly to a correct determination. To ensure a steady view of the stone it is essential to have contact between the hand holding the specimen and that holding the lens. Practised gemmologists can be recognised by the ease with which they assume the correct position (*Figure 34.9*). This fact is seldom realised by TV producers when showing a scene involving the examination of jewellery. Before examination the stone should be thoroughly cleaned and (if unmounted) should be held in stone tongs having internally serrated tips and a mild spring action when gripped.

Magnification of a Lens

The magnification of a lens depends upon the ratio of the size of the image to the size of the object when seen by the eye alone, but an object held at arm's length and observed by the eye appears to be much larger than the same object much farther away: hence it is necessary to have a standard. The nearer the object is brought to the eye the larger is the image on the retina of the eye and the more visible the fine detail becomes, until a point is reached where the internal lens of the eye, which adjusts itself for objects at different distances, is at its extreme limit. If the object is brought nearer such a position, the eye either cannot focus it or has to make an exertion to see it distinctly; therefore the gain in size is counterbalanced by the loss of definition. This near point or least

Figure 34.9 *Correct position when using a pocket lens*

distance of distinct vision, as it is termed, differs with different people, but for the greater part of adult life this distance measured from the near point is 250 mm. This distance is therefore taken as the standard of comparison and is generally denoted as D_v.

If the magnified image can be thrown on to a screen, as in the case of the real image produced by a film projector, both the object and the image can be measured and the magnification computed, but in the case of a magnifying lens the image is virtual, just a 'ghost', and cannot be measured. The magnification in the case of a simple lens is defined as the ratio between the angle subtended at the eye by the virtual image and the angle subtended by the object at the least distance of distinct vision.

Figure 34.10 shows the principle more clearly. The parallel bundles of rays leave the lens to enter the eye at an inclination θ to the axis. This is known as the visual angle. Now the inclination is dependent upon h and f and therefore the visual angle is h/f, which is the tangent of θ, that is, $\tan\theta$ equals h/f. The magnification may be expressed therefore as

$$\frac{\text{visual angle of image seen with lens}}{\text{visual angle of object seen at near point with the unaided eye}}$$

When the angles are small, this can also be expressed as h/f divided by h/D_v which can be further reduced to D_v/f; but f is the focal length of the lens, so that if this focal length is divided into the least distance of distinct vision the magnifying power of the lens is obtained. For example, a lens of 25 mm focal length has a magnifying power 250/25 and gives a magnification of 10 times. A lens of 50 mm focal length will have a magnifying power of 5, for 250/50 equals

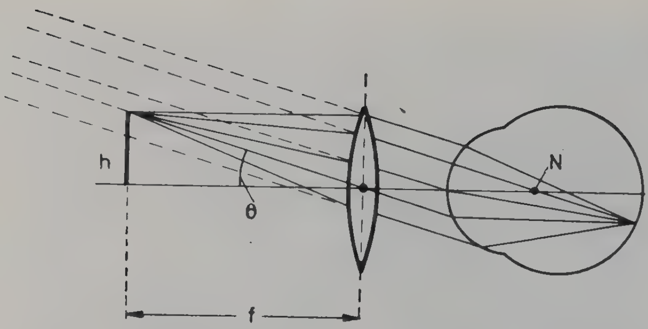


Figure 34.10 *Principle of magnification. N, nodal point or optical centre of the eye; f, focal length of lens; h, height of object above centre line; θ, visual angle*

5. Therefore, to find the magnifying power of a lens all that is required is to know the focal length, because the least distance of distinct vision is standardised at 250 mm. The focal length of a positive (convex) lens may be ascertained by holding the lens at right angles to a beam of sunlight – parallel light – and finding the sharp focus of the beam on the other side of the piece of white paper. The distance of the paper to the centre of the lens is the focal length.

The magnification is always expressed by linear diameters, that is by the relative lengths of object and image and not by their relative areas or cubic capacities. Magnification is usually represented by the multiplication sign and the number of diameters.

Compound Microscope

The simple microscope – the hand lens – has the limitation that it can only satisfactorily be used for low powers, and in order to obtain greater magnification it becomes necessary to employ the compound microscope. This instrument carries out the process of magnification in two stages: first by the object lens (or, as it is more often known, the objective); and then by the eye lens (known as the ocular) which is situated at the top of the tube, a lens which, acting as a simple magnifier, gives a much larger virtual image of the real image produced by the objective.

This double magnification is illustrated in a simple manner by *Figure 34.11.* The lens A, or objective, is of short focal length, and is so placed that the object PQ is just beyond its principal focus, so that a real inverted and slightly magnified image is produced as P′Q′. The second lens, or eyepiece, B, is placed at such a distance from the objective that the image formed by the latter is just inside the principal focus F, and hence the eyepiece, acting as a simple microscope, gives a virtual and magnified image P″Q″. In practice, in order to correct the various aberrations, both the objective and the ocular consist of combinations or trains of lenses. This is well shown by *Figure 34.12* which illustrates a modern microscope in section.

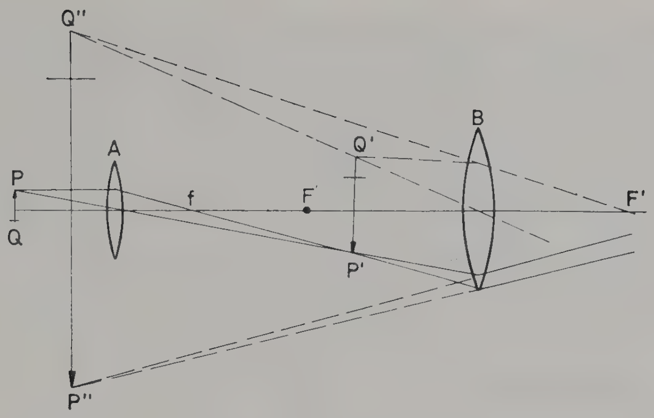


Figure 34.11 Double magnification

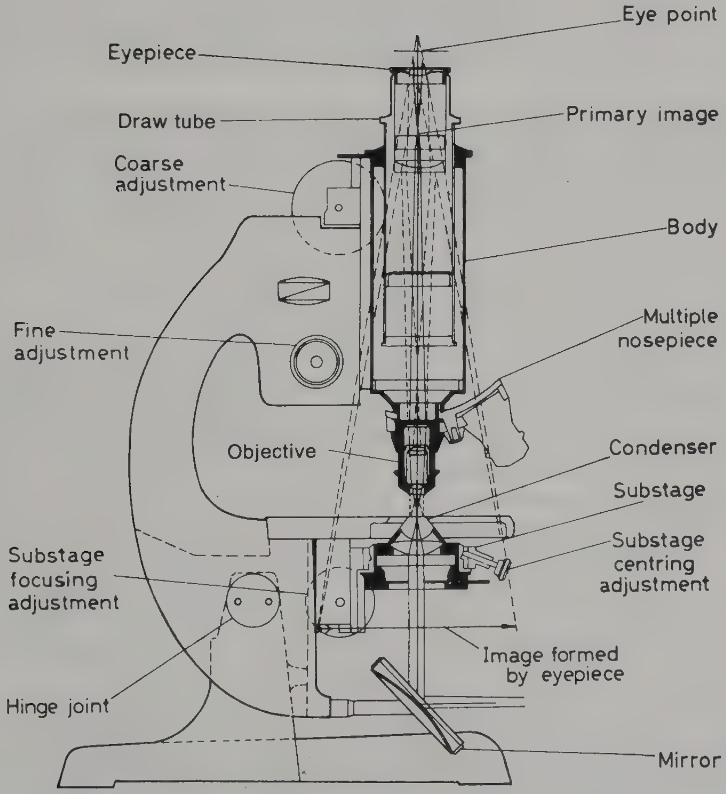


Figure 34.12 The parts of an ordinary compound microscope

Compound microscopes, although fundamentally similar in that they are constructed to produce an uncoloured and undistorted enlarged image of an object, may vary considerably in design and equipment.

Special types of instruments are built for the specialist sciences of petrology, metallurgy and biology, and although gemmology is not very exacting in its demands on the microscope – in general a comparatively low-power instrument is all that is needed – special instruments have been designed in order to facilitate the examination of gemstones. It is in binocular vision and in the special techniques required to illuminate the specimen in order to investigate the internal structure, and not in high magnification, that the microscopes built entirely for gemmological use are characterised.

Parts of the Microscope

The instrument may be divided into two sections: the optical system, the fundamental principles of which, except for the substage condenser, have been discussed; and the mechanical side, the so-called stand. The more important parts of the microscope are shown in *Figure 34.12.* The foot or base of the instrument is usually of a horse-shoe shape or of a trip form. It is essential that the foot has sufficient size and weight to give good stability to the limb which is hinged to it. The limb, which is usually constructed to accommodate the hand for carrying the microscope, carries at its upper and lower ends the working parts of the instrument.

At the top of the limb are the coarse and fine adjustments, knurled wheels for turning the pinion which engages with the rack on the body tube. The body tube, which carries the optical system, has a dove-tail beam sliding in a similarly shaped recess in the body which comprises the head of the limb. The rack is also incorporated in this slide and together they allow the body tube to be raised or lowered under the action of the coarse adjustment pinion. The body tube may have fitted into it, with a smooth sliding fit, a draw tube, which is the means of producing a change in separation between the objective and the eyepiece sometimes necessary when certain compensations are needed.

The upper end of the draw tube carries the ocular, or eyepiece, which should fit smoothly into the draw tube which has an internal diameter of 0.9175 in (23.30 mm), a standard laid down by the Royal Microscopical Society in 1899. This, one of four standard sizes, is known as the small-size RMS standard eyepiece, or the no. 1, and is the only one in general use today. The lower end of the body tube is made to take the screw fitting of the objective; the screw thread is also an RMS standard and conforms to a Whitworth pattern screw with 36 threads to the inch and with a diameter of 0.800 in (20.32 mm).

The fine adjustment produces the very slow motion required when focusing high-power objectives, and such fine adjustments are often supplied with a graduated drum or scale so that depth measurements may be taken.

At the lower end of the limb is mounted the rigid platform upon which the object to be examined is placed. This platform is known as the stage, and may be square or circular (in which case it is often rotatable); it has a central aperture to allow the light from the reflecting mirror placed below it to illuminate the object. The stage may be fitted with clips to hold the glass slide upon which the object is placed or mounted, or it may have a mechanical stage, which allows the slide to be moved slowly across the stage in two directions. Such a mechanical stage, which in some microscopes is built in the stage, has little application in gemmological practice.

Below the stage is the substage mount, a circular fitment, standardised with an internal diameter of 1.527 in (38.786 mm), into which may be fitted various accessories such as a plane or an iris diaphragm, a short-focus condensing lens or an aplanatic combination of such lenses, and polarising apparatus or light filters.

Many substages are made so that they can be raised or lowered by rack and pinion movement and also swung out and clear of the optical axis of the microscope.

Below the substage and fixed in gimbals attached to the tailpiece of the limb is the mirror, which is often two-sided: one mirror being plane and the other concave, or sometimes of white opal glass. Some microscopes are fitted with a multiple nosepiece into which may be screwed two or more objectives of different powers which may be clicked into the optical axis as required. Another practice is to screw each objective into special quick-change mounts having spring clips and these may be quickly slipped into a special fitting mounted on the lower end of the body tube. Such an arrangement provides better centring of the objective than is usual in the multiple nosepieces. In the best instruments the objectives are computed and mounted so that when a higher or lower power is put into position little refocusing is necessary. That is, they are said to be parfocal.

The function of the objective lens is to produce the primary magnified image with as little distortion as possible. Objectives are made with composite lenses, or a series of such lenses, and of various focal lengths or powers (*Figure 34.13*). The range of powers in which objectives can be obtained are as follows:

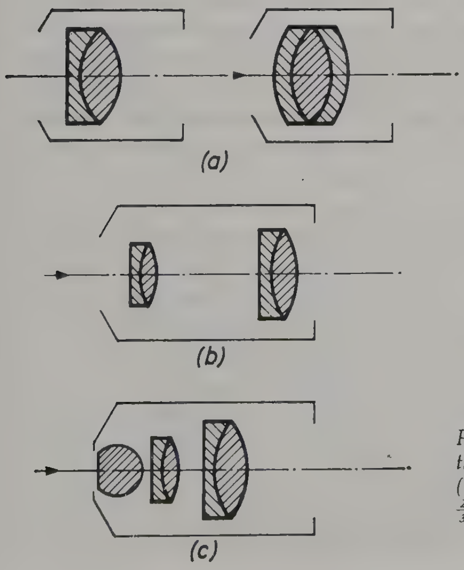


Figure 34.13 Arrangements of lenses in objectives of various powers: (a) low powers, 3 and 2 in (75 and 50 mm), (b) medium powers, $1\frac{1}{2}$, 1 and $\frac{2}{3}$ in (32, 25 and 16 mm), (c) high powers, $\frac{1}{2}$, $\frac{1}{4}$ and $\frac{1}{6}$ in (12, 6 and 4 mm)

3 in	75 mm	$\frac{1}{3}$ in	8 mm
2 in	50 mm	$\frac{1}{4}$ in	6 mm
$1\frac{1}{2}$ in	35 or 32 mm	$\frac{1}{6}$ in	4 mm
1 in	25 mm	$\frac{1}{8}$ in	3 mm
$\frac{2}{3}$ in	16 mm	$\frac{1}{12}$ in	2 mm
$\frac{1}{2}$ in	12 mm	$\frac{1}{16}$ in	1.5 mm

Most manufacturers employ their 32 mm object lenses for the $1\frac{1}{2}$ in.

It must clearly be understood that the focal length given above does not imply that this is the distance between the front lens of the objective and the object focused on. Apart from other optical considerations, it must be remembered that the focus of a lens system is taken from the centre of the system; thus the working distance in normal lenses is less than the focal length.

The gemmologist must have a sensibly large working distance, for he rarely works on thin sections and his objects are gemstones (often in settings) which have considerable depth; it is also necessary to see a fair amount of the specimen at once, that is to have a large field of view. Neither of these requirements can be satisfied if high powers are used. In practice it is found that the $1\frac{1}{2}$ in and the 1 in (32 and 25 mm) objectives are those most commonly used, with high powers up to $\frac{2}{3}$ in (16 mm) for special work.

It will be seen from the foregoing that the duty of the ocular is to produce an enlarged virtual image of the primary image formed by the objective. We have considered the eyepiece as a single lens, but for many reasons a single lens is impracticable. Hence the oculars of modern microscopes are made up of two positive (plano-convex) lenses: the first is termed the field lens, and the second, nearer the eye, the eye lens.

Eyepieces

There are two chief forms of eyepieces used in microscopes, the most commonly used being the Huygenian (*Figure 34.14*) which consists of two plano-convex lenses placed with their curved surfaces towards the incident light. They are separated by a distance equal of half the sum of their focal lengths, a condition which is only approximately fulfilled in practice. The ratio of the focal lengths of the field lens to the eye lens is usually about 2: 1, but may vary somewhat from this value. It will be seen that the image formed by the

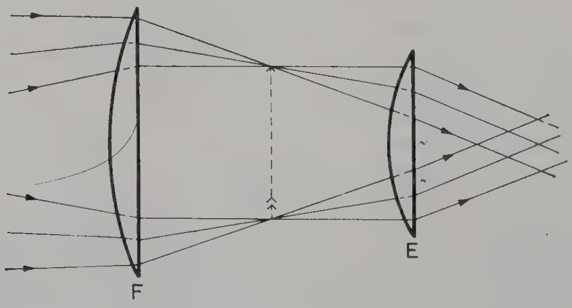


Figure 34.14 The Huygenian eyepiece

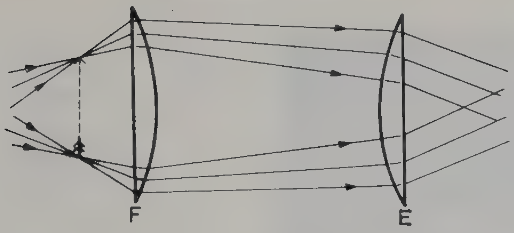


Figure 34.15 The Ramsden eyepiece

objective is situated between the lenses of the eyepiece, and at this focal plane is placed a diaphragm. The Huygenian eyepiece, which is practically achromatic, can only be used as a magnifier if it is the reverse way up, that is with the field lens used as an eye lens. This type is sometimes called a negative eyepiece.

The Ramsden eyepiece throws the eyepoint farther out. This type consists of two plano-convex lenses of the same focal length and the same material, placed at a distance from each other equal to two-thirds the focal length of either. In theory, this distance should be one-half of the focal length, but this brings the field lens into the focal plane, and any dirt or imperfection on this lens would then be sharply focused. In the Ramsden eyepiece the curved faces of the lenses are towards one another; the focal plane is in front of the field lens (*Figure 34.15*). As the pair can be used as a separate magnifier, this is sometimes termed a positive lens.

An inclined eyepiece is commonly available which may replace the normal ocular; such an accessory permits observation to be made while sitting down despite the microscope being in the vertical position, this also prevents much eyestrain (*Figure 34.16*).

Most oculars are marked either with the focal length, a code letter or number, or their magnification. *Table 34.1* will give some idea of the power of such eyepieces if they are marked.

The substage condenser is a system of lenses fitted below the stage, often in a focusing mounting, which is employed to converge the light received from the mirror on to the object being examined. There are several types of such lens systems, some of which are corrected for aberration, but this is not so important as in the case of objectives. The most useful type is that known as the Abbe substage condenser combined with an iris diaphragm (*Figure 34.17*). The use of the substage condenser is bound up with the illumination of the specimen; therefore further consideration of its use in gemmology will be left until a later discussion. It should be noted that substage condensers utilising lens systems are not commonly in use on today's gemmological microscopes. Mirrored reflector bases with built-in light sources have taken the place of the substage condenser lens system in microgemmology.

In the compound microscope, there are two separate magnifications: that given by the objective, the primary magnification; and that given by the eyepiece, the secondary magnification. These two magnifications multiplied together will therefore give the full magnification of the compound lens system providing that the eyepiece is placed at the distance of distinct vision (250 mm) from the objective. For example, a 25 mm objective, magnifying approximately 10 ×, in conjunction with an ocular (say no. 2) magnifying 6 × would give a

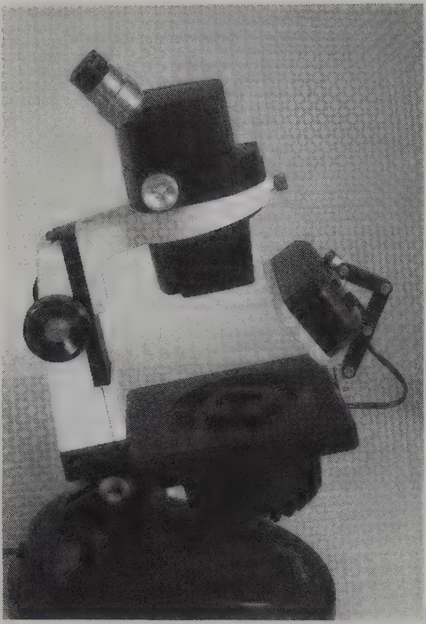


Figure 34.16 *An inclined binocular eyepiece*

Table 34.1

Old notation	*Numbered notation*	*Focal length in millimetres*	*Magnification**
A	1	50	5 ×
B	2	42	6 ×
C	3	30	8 ×
D	4	25	10 ×
E	5	20	12 ×
F	6	17	15 ×

*The magnification power is that for distance of distinct vision, namely 250 mm: 6 ×, 8 ×, and 10 × are most useful.

total magnification of 60 × providing the distance between the eyepiece and objective is 250 mm.

The earlier microscopes were constructed on this principle which accounts for the long tube length of such instruments. Modern microscopes have a tube length of approximately 165 mm, or two-thirds of the standard, which greatly lessens the magnification as computed by the multiplication of the primary and secondary magnifications. It is therefore necessary, if a tube length shorter (or longer) than 250 mm is used, to multiply by a fraction of which 250 mm is made the denominator and the actual tube length the numerator. For example, with a 25 mm (10 ×) objective and a no. 2 eyepiece (6 ×) separated by a tube length of 165 mm, the magnification would work out as follows:

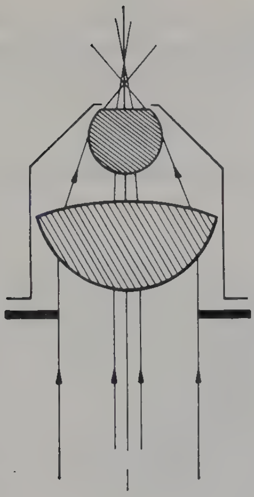


Figure 34.17 The Abbe substage condenser

$$60 \times \frac{165}{250}$$

which gives 39×.

For all ordinary purposes the tube length may be reckoned from the two ends of the adjustable tube into one end of which the objective screws and upon the other the eyepiece rests, and, indeed, it must be understood that magnification calculated on the above method is only approximately correct as there are other factors which play a part: these have not been considered. Calculation by the formula given will, however, give a satisfactory estimate of the magnification. It is of course assumed that the magnification of both the objective and the ocular are known, and this is generally the case, as manufacturers either mark their lens systems or give the required information in their literature.

Magnification, so often considered to be the primary criterion of a microscope, is in reality only of secondary importance, for the reason that the image of a point depicted by any optical system is not a point but a disc. Owing to the wave nature of light, a lens cannot produce a point image of a point object, but produces instead a bright spot of light surrounded by diffraction rings (the diffraction pattern or 'antipoint'), an effect known as the Airy disc. Therefore if, for example, two points in the object are so close together that in the image their diffraction discs overlap, the two points will no longer appear separate, but rather as one, and no amount of magnification will pull them apart. The power to define fine detail is termed the resolving power. Magnification above a microscope system's resolving power is useless, and in fact is termed empty magnification.

With the microscopes used in gemmology, the finer points of resolution and magnification are of no great consequence, for, owing to the depth of the specimens required to be examined, a long working distance is necessary and comparatively low powers are most often used. Indeed, when high magnification is employed, the field of view is so small that much of the structural appearance necessary for routine diagnosis can be missed. There are, however, times when high magnification (above 100 ×) is both useful and even necessary when the precise detail of an individual inclusion must be examined.

Instruments for the Examination of Internal Features of Gemstones

The most common use of the microscope in gemmology is to examine the internal features in a gemstone. For such work a simple type of low-power instrument is satisfactory providing the optical system is good (*Figure 34.18*). Should much work of a continuous nature be contemplated a binocular microscope with paired objectives and inclined eyepieces (*Figure 34.19*) is most valuable as it gives stereoscopic vision free of chromatic aberration, and provides an erect image rather than one that is reversed left to right and upside-down as in an ordinary monocular microscope. Further, the use of both eyes serves to avoid strain. Certain microscopes, such as the American GemoLite series (*Figures 34.20* and *34.21*), are built solely for gemmological requirements. These instruments have a built-in light source which gives both direct transmitted and dark-field (this will be mentioned later) illumination, and are fitted with special gem holders. A horizontal type of microscope (*Figure 34.22*) with a vertically positioned stone holder is also in use and this, like some others, is fitted with a variety of accessories which may replace the eyepiece.

Polarised Light

When polarised light is to be used in testing stones some form of polariser to produce such light is necessary as an adjunct to the microscope; and another is needed to analyse the polarised light. Such polarisers may be the prism invented by Nicol in 1828, or a disc of the material known as Polaroid. Of the two, the Polaroid material is the most commonly used in gemmology. The nicol prism depends upon the fact that the two rays in a doubly refractive crystal are plane-polarised in directions at right angles to one another. Therefore, if one of the rays is eliminated the other passing through will emerge from the crystal vibrating in one plane only.

Prisms

These nicol prisms, or 'nicols' as they are called, consist of a cleavage rhomb of optical-grade Iceland spar (calcite) suitably divided and recemented. A clear flawless cleavage rhombohedron of the spar, about three times as long as it is broad, is selected (ABCD in *Figure 34.23a*). By grinding and polishing, the inclination of the end faces AB and CD is altered to A′B and C′D which then make an angle of 68 degrees with the edges BC and AD respectively, the angle made by the natural faces being 70 degrees 53 minutes. The prism is then cut diagonally along plane A′C′, perpendicular to the faces A′B and C′D and parallel to the longer diagonals of these faces, that is EF in *Figure 34.23b*, which

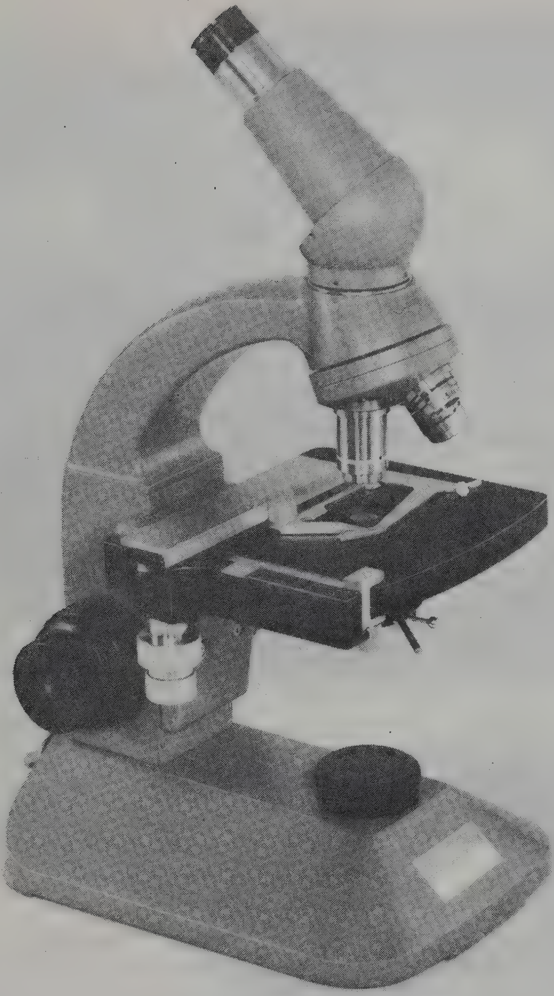


Figure 34.18 The Beck Diamex monocular student microscope (Ealing Beck)

shows a view of the upper face of the prism. After polishing the cut surfaces the halves are cemented together in their original positions with Canada balsam.

When a ray of ordinary light PQ in *Figure 34.23a* enters the prism in a direction parallel, or nearly parallel, to its length, the extraordinary ray, QRS, has a refractive index very close to that of the balsam film A′C′ and consequently passes out through it and emerges at the other end of the prism. The ordinary ray, QT, however, has a much higher index than the balsam film and strikes it at an angle beyond the critical angle; it is therefore totally reflected at the film and passes out through the side of the prism along TU, where it may be absorbed by the non-reflecting mounting of the prism. The only light

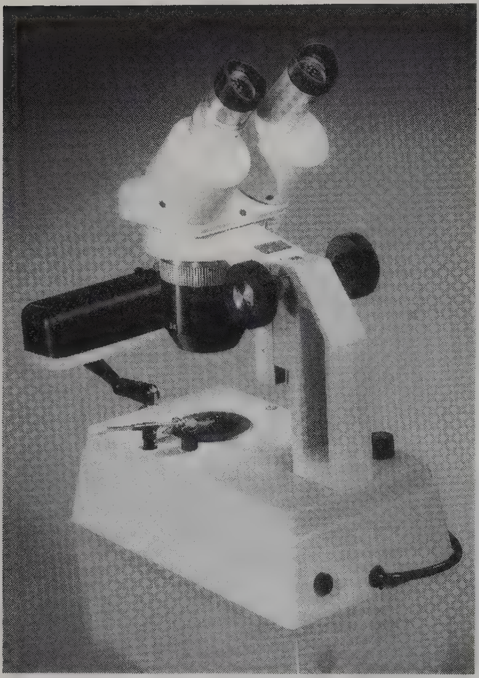


Figure 34.19 The binocular microscope

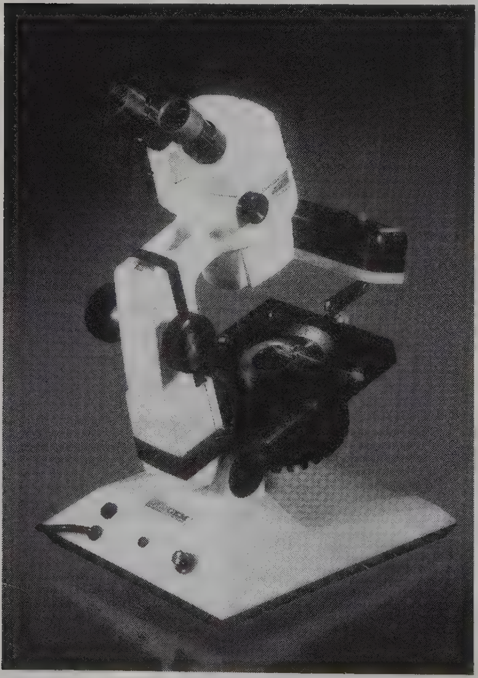


Figure 34.20 The GIA's Custom A Mark VII GemoLite, a microscope incorporating a zoom lens and provision for light- and dark-field illumination, as well as top lighting

Figure 34.21 The GIA's Ultima B Mark VII GemoLite, with zoom lens, transmitted and dark-field illumination, and top lighting

transmitted by the prism is the extraordinary ray which vibrates parallel to the shorter diagonal of the prism, indicated by the double-headed arrow in *Figure 34.23b*. There are certain other types of prisms made for the production of polarised light but they all operate on the same principle.

Polaroid

Polaroid is made from a vast number of submicroscopic crystals of quinine iodosulphate, known as herapathite, held in uniform alignment in a plastic base to produce a film, the polarising effect being due to the complete absorption of one ray – in fact, the phenomenon of extreme dichroism. More recently a method of producing a polarising film has been evolved, in which no re-formed crystals are used and the polarising action is based upon a careful linear control of the molecular structure of the plastic, forming a homogeneous and haze-free sheet. Its manufacture entails the formation of a brush-like structure inside a sheet of clear tough plastic called polyvinyl alcohol. This is first stretched in one direction so that the long tangled molecules straighten out, all parallel to the direction of the stretch. A dip into iodine solution brings out the polarising properties.

Equipment for Polarising Microscope

To equip a microscope for polarised light observation it is necessary to incorporate a nicol prism or Polaroid disc known as the polariser below the

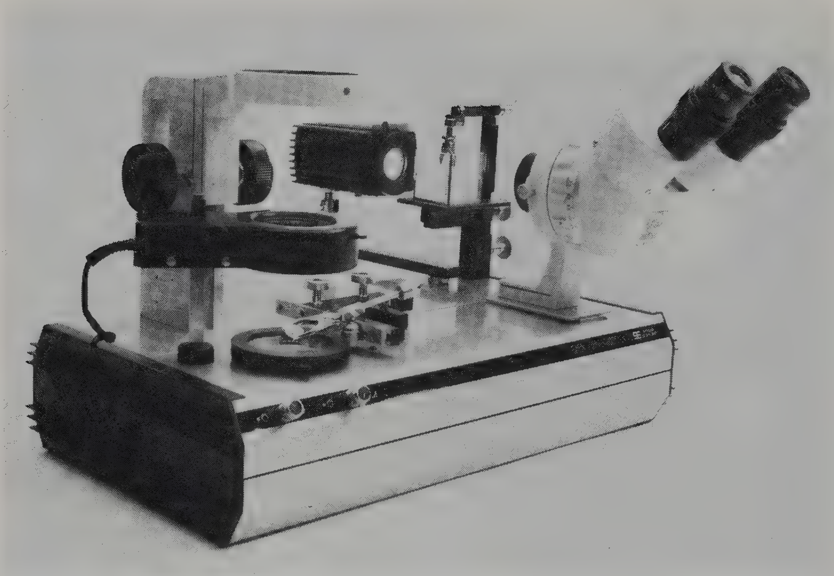


Figure 34.22 Eickhorst Gemmaster system

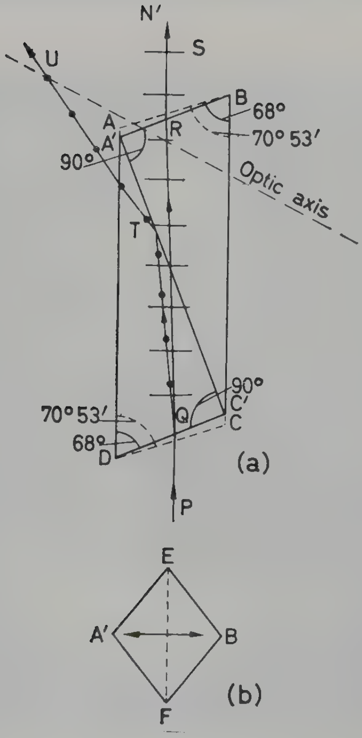


Figure 34.23 The nicol prism

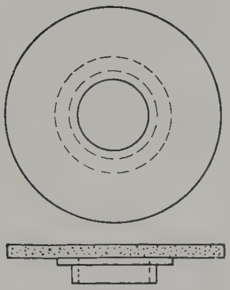


Figure 34.24 *A made-up rotating stage to fit into the stage aperture of an ordinary microscope. It may be turned-up from any non-ferrous metal or plastic*

subject being examined and another, the analyser, either in the body tube above the objective, over the eyepiece, or just below the objective but above the subject. A further consideration, which is sometimes useful, is that the stage should be rotatable. For the simple technique of determining the existence of double refraction all that is needed is a polariser which may be slipped into position below the subject, and an analyser to fit over the eyepiece or the lower end of the objective. At least one of the nicols or Polaroids should be capable of rotation. Some sort of rotatable stage can be extemporised by turning a metal disc, so that a projecting rim bounding a central aperture fits snugly into the aperture of the stage where it acts as a bearing. *Figure 34.24* shows such a made-up rotating stage and *Figure 34.25* shows accessory polarising fittings. *Figure 34.26* shows a modern microscope fitted with polarising equipment and a rotating stage.

Figure 34.25 *Auxiliary polarising equipment showing a Polaroid polariser that fits on the stage of the microscope below the subject, and an analyser designed for rotation that fits just below the objective lens and above the subject*

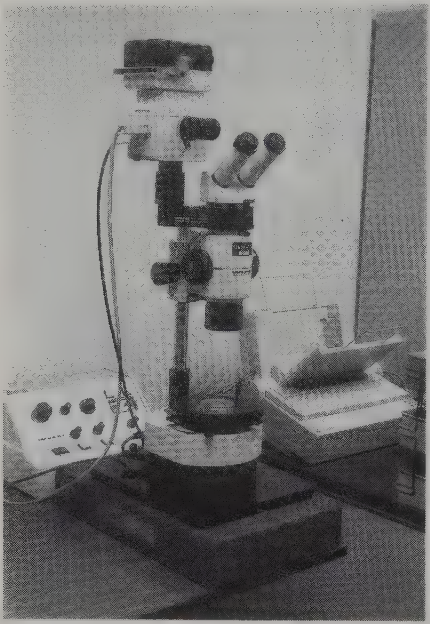


Figure 34.26 A modern microscope fitted with polarising equipment and a rotating stage

Petrological Microscope

The most complete microscope for polarised light observations is the instrument used by scientists for the study of rocks in thin section – the so-called petrological or petrographic microscope (*Figure 34.27*). These instruments incorporate nicol prisms, a built-in rotating stage which is divided into degrees on the edge and can be read to minutes of arc by vernier, and a substage condenser, which, like the lower nicol, can be swung in or out of the optical axis of the instrument. The analyser is usually fitted into a box which can be slid in or out of the body tube, or in some cases into a hinged box which can be turned over the eyepiece. Another addition is a Bertrand lens which can be pushed in or out of the optical axis; this is used to bring the focal plane in correct position with regard to the ocular when interference figures (to be discussed later) are to be obtained by the use of convergent polarised light. The oculars of petrological microscopes are fitted with cross-wires arranged parallel to the vibration directions of the polariser and analyser. As only the lower polariser is rotatable, it is usually so arranged as to click into the crossed position.

Technique of Focusing Microscope

If it does not already have a built-in light source, the microscope is set up about 200 mm in front of a strong light so that the light reflects off the microscope's mirror and up through the lens system (*Figure 34.28*), after a suitable objective has been screwed into the bottom of the body tube and the necessary ocular has been slipped into the top. Set a specimen slide on the stage with the object over

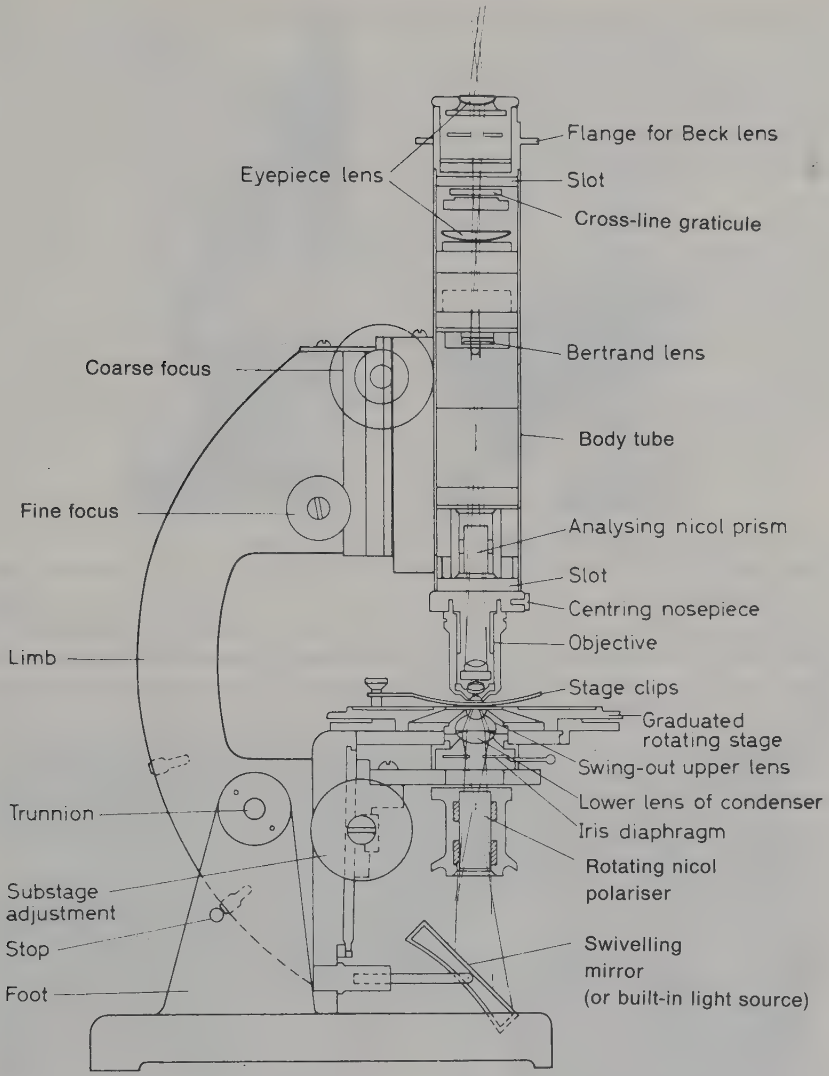


Figure 34.27 The optical system of the petrological microscope

the stage aperture: for practice a prepared slide of an insect or botanical specimen is convenient. Direct light on the object from the mirror. It will be assumed here that no substage condenser is to be used but only a rotating or iris diaphragm below the stage.

It now only remains to focus the microscope. Preliminary investigation will have shown that the movement of either the coarse or the fine adjustment in a clockwise direction will bring the body tube nearer the stage. It might therefore be thought that the best method of focusing would be to rack down. This

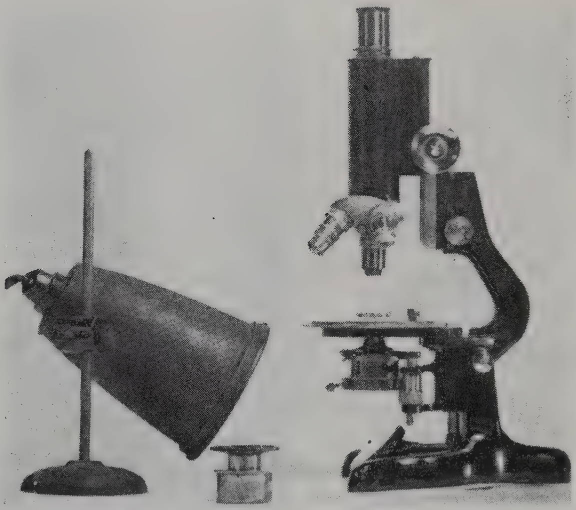


Figure 34.28 The microscope set-up if a built-in light source is not part of the microscope stage

should not be done, for it leads to disaster; it is only too easy to overshoot the focus, or to have started below the focus, with the consequence that the objective is pushed right through the slide which is irreparably smashed, and with possible damage to the expensive objective. The correct method is to start with the tube racked down until the objective nearly touches the slide (observing from the side, not through the eyepiece, while racking down). Then, looking through the eyepiece, rack the body tube upwards until the object is in sharp focus.

If, when racked up, the microscope does not focus on to the object, generally owing to missing the focus or to the object not being centred below the objective, begin again from the start and watch out for any specks to come into focus. These specks are dust or slight defects on the slide and will indicate that the object is not in centre and that the slide requires to be moved along. Alternatively, if the object cannot be located easily, the eyepiece may be removed and the object observed, and centred, by looking through the back lens of the objective.

The mirror should then be adjusted so that the light reflected up the tube travels coaxially through the objective of the microscope. To check this, rack up slightly; if the light is central the magnified object will remain stationary, but if oblique the object will appear to travel in the direction of the light. The centring of the light beam may be accomplished by removing the eyepiece and inspecting the rear lens of the objective while tilting the mirror until the light source appears central. At the same time, the diaphragm should be adjusted until about two-thirds of the area of the back lens of the objective remains clear. Replace the eyepiece and view the specimen. If the light is too bright, move the light source farther away or find other means of dimming it. A ground-glass screen is effective for this. Do not use the iris or disc diaphragm to moderate the light. The function of the diaphragm is to govern resolving power not to diminish intensity.

When using the Abbe substage condenser and plane mirror, it is necessary to ensure that the lens system is central in the optical axis of the microscope, and, what is even more important, that it is correctly focused. The centring of the condenser can be checked and adjusted by closing the iris diaphragm as far as possible and focusing on the central spot of light.

Following the rules outlined above will allow the worker continually to obtain images of good quality consistent with the limitations of the instrument. When using a monocular microscope learn to keep both eyes open. Learn to disregard the image produced by the unused eye, for eyestrain is practically non-existent if both eyes are kept open. If possible – it is not easy – use the eyes alternately to exercise both.

A modern innovation is to illuminate the specimen by 'piping' light through a fibre-optic system. There may be only one light fibre or paired fibres may be used (*Figure 34.29*).

Care and Cleaning of Instruments

Elementary as it may seem, some hints on the care and cleaning of instruments are called for. When not in use the microscope should be kept under cover, or in its case. A bell-glass cover is useful, but a clean cloth draped over it, or plastic bags, are much better than leaving the instrument open. Even if the instrument

Figure 34.29 The light source KL 1508, shown fitted to a special microscope light guide which gives shadowless incident illumination (Schott)

is left for a short time, cover it up, for dust is the major cause of all troubles. To clean the adjustments use paraffin oil on a clean rag and finally grease with a good-quality grease. The coarse adjustment is best cleaned by removing the body tube completely from the body by racking up the tube until out of the bearings. Most microscopes come with instructions for care and general maintenance as recommended by the manufacturer. It is always best to follow these, as it is very possible to over-clean and over-maintain a microscope, and thereby cause it damage.

It is sometimes found that the coarse adjustment becomes loose and the tube tends to rack down under its own weight. To cure this it is necessary to tighten either one or two screws on the top or at the rear of the limb carrying the pinion (different manufacturers place these screws in different positions). To get at the fine adjustment it may be necessary to remove the screws from the cover-plate: much care is required here, as there is generally an actuating spring bearing against the plate which will tend to fly out when the screws are loosened. The worker doubtful of his mechanical ability had far better let the manufacturer recondition the microscope.

Dust on the lenses is a common trouble and shows as specks in the field of view. First ascertain on which lens system – eyepiece, objective, condenser, or even the mirror – these specks are. This may conveniently be found by rotating the eyepiece and seeing whether the specks move; if they do then this is the offending part. Likewise by slightly unscrewing the objective, or by lowering and raising the condenser, or by slightly tilting the mirror, movement of the specks will indicate on which of the parts dust has collected.

To clean lenses, use a very soft, well-washed cotton handkerchief kept in a dust-proof box, sparsely moistened if necessary with xylol or alcohol (methylated spirits), or use the soft 'lens paper' sold by all optical dealers. It is permissible to unscrew the top and bottom lenses of the ocular to clean the internal surfaces, but care must be taken to replace them at the correct ends of the ocular tube. It is inadvisable to take the objective apart: leave that job to the manufacturer's technician. An eyepiece should always be left in the draw tube, so that dust will not collect on the sides of the tube or fall down on to the back lens of the objective.

Only clean lenses when absolutely necessary. It is always best to first try to remove dust and dirt from such surfaces with a gentle jet of air. Cans of compressed air are available at camera shops, as are camera blower brushes which shoot a stream of air from a thin tube when a rubber bulb is squeezed.

Examination of Internal Structure of Gemstones

When examining the internal structure of gemstones there are two fundamental differences to consider as against the examination of a prepared thin section on a slide. The first is the much greater thickness of the specimen which necessitates the use of comparatively low-powered objectives in order to have a sufficiently large depth of field and an adequate working distance below the objective. The second important point is that for light to pass evenly through the specimen it should be a parallel-sided plate. In the case of gemstones, except between the table facet and the culet (if one is present), there is no position

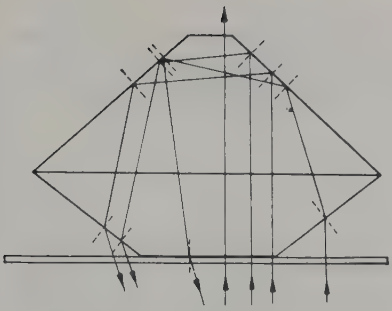


Figure 34.30 *The paths of parallel light rays from the microscope mirror through a corundum resting table facet down on a glass slide (refractive index of corundum is 1.77; the critical angle is 34.5 degrees)*

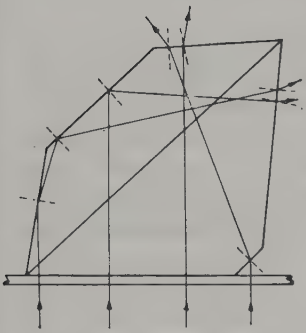


Figure 34.31 *The paths of parallel light rays from the microscope mirror through a corundum resting pavilion facet down on a glass slide (refractive index of corundum is 1.77; the critical angle is 34.5 degrees)*

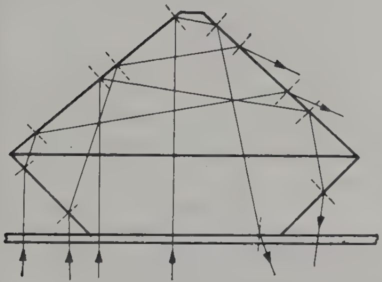


Figure 34.32 *The paths of parallel light rays from the microscope mirror through a rock crystal resting table facet down on a glass slide (refractive index of quartz is 1.55; the critical angle is just over 40 degrees)*

where this can occur in a well-faceted stone. Light rays from the light source of the microscope (parallel light rays being assumed for this initial discussion, that is the plane side of the mirror has a distant source of light, such as daylight, and the substage condenser is not being used) are reflected from the steep rear facets by total internal reflection (*Figure 34.30*). The same stone resting on a pavilion facet (*Figure 34.31*) does pass more light yet still leaves much of the interior of the stone in darkness. The greater the refractive index of the stone the greater is the total internal reflection, and naturally the converse is true. Compare *Figure 34.32* with *Figure 34.30*; yet even with the greater escape of light in the case of rock crystal, it is still difficult to see into the interior of the stone when using a microscope designed for the examination of specially prepared thin sections in polarised and transmitted light (bright field). Mounting the stone on the glass slide with a little Plasticine, so that it is table facet uppermost, or even with a little practice holding the stone in that position, may allow better inspection of the internal features.

Liquid Immersion

It is clear from the foregoing that some other method must be used if the worker is to 'get into' the stone to make a thorough examination of the internal features. It has been remarked that the optimum condition is a parallel-sided plate: therefore, if the stone could be embedded in a substance having the same refractive index as the stone under test and the sides made parallel, it should be possible to see clearly all the interior of the stone.

Can this be done? In some cases the optimum condition can be obtained quite simply, that is by immersing the stone in a liquid of essentially the same refractive index as that of the stone, such as beryl in *o*-toluidine (refractive index 1.575), white topaz in iodobenzene (refractive index 1.62) or hessonite garnet in di-iodomethane (methylene iodide, refractive index 1.74), to quote a few. Further, as a liquid in a flat-bottomed cell has a horizontal surface, the second requirement is met – that of a parallel-sided plate. This is illustrated in *Figure 34.33*.

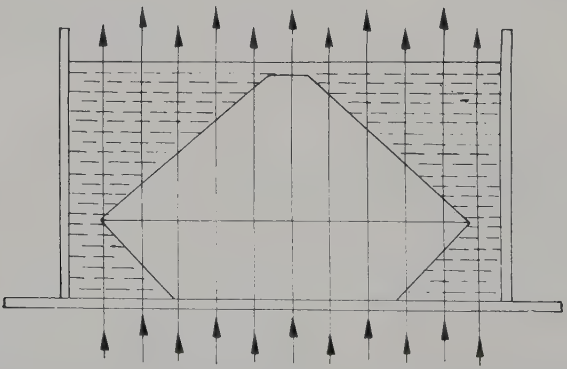


Figure 34.33 The paths of parallel light rays from the microscope mirror through a yellow apatite which is immersed in acetylene tetrabromide (refractive index of both stone and liquid is 1.63)

In practice it is not at all necessary to use a liquid of exactly the same refractive index as that of the stone being tested. A liquid having a refractive index comparatively near will suffice; as corundum gems are some of those most constantly requiring microscopic examination, owing to the synthesis of that species, di-iodomethane (methylene iodide, refractive index 1.74) will be the most useful. However, the cheaper, although less refractive, liquid α-monobromonaphthalene (refractive index 1.66) is now more commonly used and is nearly as effective as the more expensive di-iodomethane. *Figure 34.34* illustrates this quite clearly. In the absence of the more highly refractive liquids, cigarette lighter petrol (refractive index 1.49) or even water (refractive index 1.33) will be better than air if direct transmitted light is to be used.

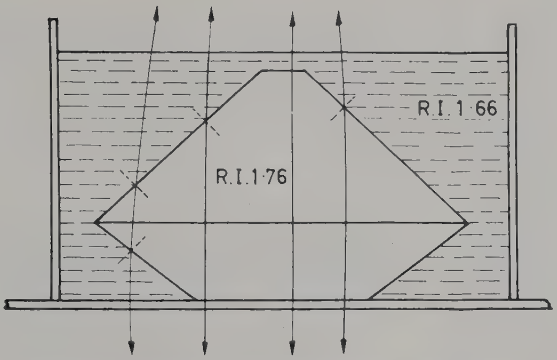


Figure 34.34 The paths of parallel light rays from the microscope mirror through a ruby which is immersed in monobromonaphthalene (refractive index of stone is 1.76 and that of the liquid 1.66)

One of the objections to the use of the liquids normally used, apart from the extra work involved in setting-up and in the added equipment needed, is that the stone requires cleaning from the liquids used after the examination is made. This is particularly a nuisance when examination is made of a stone in a setting: monobromonaphthalene is worse than di-iodomethane in this respect. A liquid which has been suggested as an immersion liquid and which leaves the stone in a perfectly clean condition is ethylene glycol mono-ethyl ether, which is sold under the names 'cellosolve' and 'oxitol'. The low refractive index of 1.408 does not seem to be detrimental.

Lighter fluid (petrol), or a weak solution of a wetting agent or one of the modern detergents, may be used as a cleaning agent. The final drying may best be carried out by the well-known method of placing the wet piece of jewellery in warm box-dust (fine sawdust) which dries up the moisture by absorption. This leaves the back of the stone, usually difficult to reach by ordinary drying methods, mirror-clean – a necessary attribute if the stone is to show its maximum brilliancy.

Monobromonaphthalene has a marked affinity for dust particles which cannot be removed from it except by constant filtering. To a novice such dust particles can look like minute bubbles which are so often seen in synthetic gems (or even like natural inclusions), and thus lead to a wrong conclusion. Quite large air bubbles often tend to cling to the surface of the stone when immersed in liquid, and a hasty worker may well accept these as bubbles inside the stone and arrive at an incorrect decision that a genuine stone is synthetic. A final consideration is in the toxicity of the liquid itself. Many immersion liquids, particularly those with higher refractive index, are somewhat poisonous and also may be carcinogenic (see 'Safety Precautions' in Chapter 29).

Dry Examination

To avoid, so far as possible, encountering such difficulties, modern usage suggests that the initial examination should be made dry, and the use of liquid

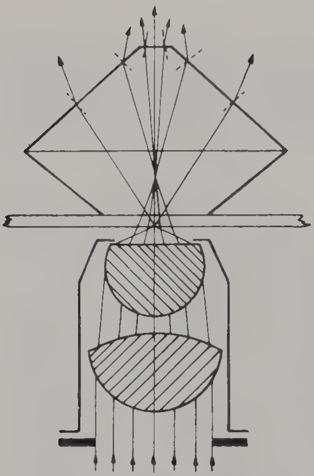


Figure 34.35 The path of light rays through a ruby after the parallel rays from the microscope illumination source have been converged by the substage condenser. The Abbe substage condenser is not compensated; therefore the rays from the edge of the lens do not come to a focus at the same point as the rays through the centre of the lens. It will readily be seen that if the condenser is adjusted the whole stone will be illuminated

resorted to only in difficult cases. How may this be done? It has already been stated that you cannot 'get into' a stone when not immersed in liquid; true, but in the cases considered, parallel light rays from the microscope mirror were postulated. If the light rays impinging on the stone are oblique, say convergent, the situation is much improved. This may be effected by the use of a substage condenser or lighting system which 'throws' the light into the stone in such directions that the beams meet the pavilion facets at angles less than the critical angle of total reflection. The effect is shown by *Figure 34.35*.

It can be seen from this illustration that if the condenser is adjusted the whole stone will be evenly illuminated and with the rays refracted out through the pavilion facets. Further, it will be found, rarely, that, as depicted in the drawing, the stone would be relatively so large compared with the lens of the substage condenser if such a microscope is used. There are, however, great variations in the size of condensers fitted to microscopes. Most gemmologically dedicated microscopes today have done away with the Abbe-type substage condenser and mirror in favour of a reflector system with built-in illumination that allows virtually any size of stone to be examined with relative ease, with or without immersion.

Glass Cells for Holding Immersion Oil

The selection of the glass cell to contain the immersion oil calls for some comment. Probably the best obtainable are those made from a glass ring fused to a plate of optical glass. These are somewhat expensive and are usually rather small, being mounted on a 75 × 25 mm glass microscope slide. Larger cells of this type are sold. Such cells are quite suitable for loose stones but are far too small to accommodate mounted specimens, especially brooches and pendants.

The large thin glass dishes, such as are used for certain chemical experiments, are quite useful as they take a sufficient depth of liquid to enable the pieces of jewellery to be kept immersed whilst being turned to allow observation to be made along different directions. Although somewhat shallow, the so-called Petri dishes used for bacteria culture are also useful, or, in fact, any glass dish with a tolerably flat base may be employed.

There is usually, however, a major defect inherent in these makeshift 'cells', in that they are rarely if ever made of optically clean glass, and therefore often exhibit the 'swirlmarks' and bubbles typical of the lower qualities of glass. When in use, if the focus of the microscope is lowered so that the base of the cell is in view, these defects become apparent and the inexperienced worker may well accept such structures as being within the stone, thus leading to a wrong diagnosis.

A second point, that of viewing the stone along different directions, may cause some difficulty. If the stone is loose this can be accomplished quite easily by turning it while holding it with tweezers in the liquid – the free hand being used to make the small adjustments of focus necessary. Likewise, pieces of jewellery may be similarly held and turned, but, as mentioned above, a deep cell and a depth of liquid are necessary.

Many attempts have been made to produce a cell with an arrangement whereby the stone may be turned whilst immersed in liquid, and these are at best only suitable for unmounted stones. Such cells have never been wholly successful for several reasons. Rotation along two axes, necessary for complete examination, is difficult to attain; and should the arrangement employ, as they mostly do, a control rod passing through the side of the cell, a liquid-tight fitting is required. The holding of the stone also presents some difficulty: wax, used in many cases, tends to deteriorate rapidly through contact with the immersion liquid; if metal grips are employed the liquid tends to corrode them.

An interesting type of glass cell has been devised by Wild. Essentially it is a fairly deep glass cell fitted with a neck at one side which is closed by an accurately fitted ground-glass stopper. The stone is held by wax to the inner end of the stopper and may be rotated around one axis only by rotation of the stopper itself, which is sufficiently tight fitting to prevent leakage of the immersion liquid (*Figure 34.36*). A type of cell once made by the Gemological Institute of America, known as the Shipley universal immersion stage, allows turning through two axes at right angles. It consists of a cell mounted on a glass base; a rod passing through the side is rotated by the external handle of dial form marked in degrees. Internally this rod engages a ring fitting which has a second ring rotatable on its inner circumference. To this inner ring, which is also graduated, is fixed the projecting stone-holder which carries the specimen at the centre of the two rotating axes.

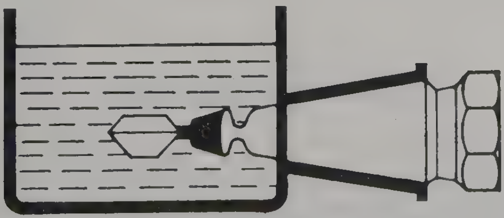


Figure 34.36 A glass cell with stopper arranged to carry the stone about one axis (devised by Wild)

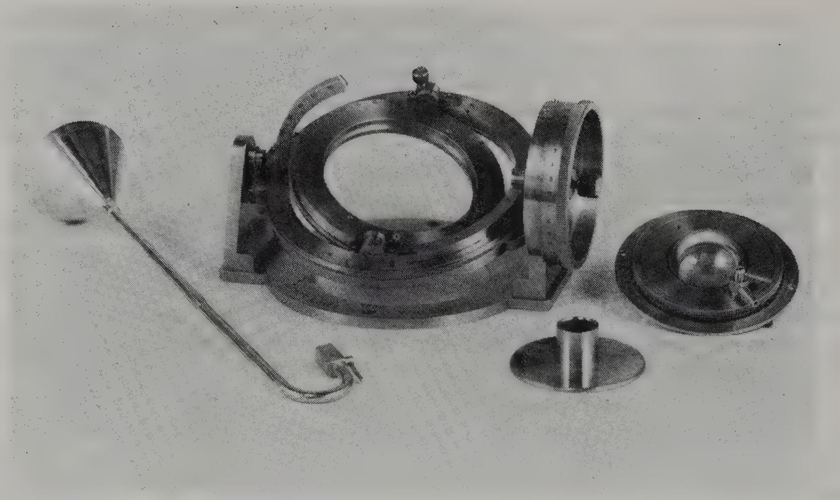


Figure 34.37 Klein and Schlossmacher's immersion sphere made by Leitz of Germany

Immersion Sphere

An ingenious device for viewing immersed stones from different directions, devised by Gübelin, employs a hollow glass sphere filled with liquid having the same refractive index as the glass and into which is inserted the stone fixed to a closely fitting stopper. The sphere is then placed on a wooden ring on the microscope stage so that it may easily be rotated. The prime advantage of this accessory is in the observation of interference figures and therefore it will be further discussed when polarised light effects are considered. A similar type of spherical stone-holder is the Interference Figure Bulb once made by the Gemological Institute of America. A more elaborate but similar apparatus, made by the firm of Leitz to the design of Klein and Schlossmacher, is shown in *Figure 34.37*.

There seems to be little added merit in employing the substage condenser in combination with immersion in highly refractive liquid. For convenience in those instruments where the substage condenser is not easily removable from the optical axis of the microscope, it can be well left in. If the condenser has an easy focusing adjustment (rise and fall), some adjustment of this may well be useful in picking up indistinct curved lines or fine 'silk'.

Dark-Field Illumination

So far it has been assumed that the specimen under examination is illuminated by light coming directly from the light source of the microscope; or through the substage condenser. This is the method of observation by transmitted light and is the method often adopted in Great Britain. In the United States of America and in Europe an indirect method of illuminating the specimen is usually favoured. This is by lateral illumination, or as it is termed dark-field illumination.

To explain adequately the use and effect of dark-field illumination it must be recognised that microscopic vision depends upon resolution and visibility – and visibility depends upon contrast. It is well known that a dark object, say a dark blue sapphire, is less visible when placed on a piece of black velvet than is, say, a ruby on a green background. In fact, there is little contrast in the first example and much in the second. It is common knowledge that the web of the spider is quite invisible against the bright sky, but if the gossamer web is illuminated by the sun and seen against a dark background, such as a bush, it is clearly seen as shining bright lines. It is to this effect that dark-field illumination owes its value. Therefore, if we can observe inclusions in gemstones as bright points of light (the inclusions being lit up by the lateral rays making them self-luminous) on the darker field of the rest of the stone, it may be possible to observe structures which would not be apparent when the stone is fully illuminated.

How may this dark-field illumination be obtained, and what is its precise value in gem testing? The necessary requirement is to cut out the central beams of transmitted light from the microscope light source, allowing only oblique rays in the form of a hollow cone which do not enter the objective directly, but only when reflected from inclusions making these appear self-luminous. This is usually carried out by placing a dark 'stop' or 'patch' centrally and below the substage condenser (*Figure 34.38*), or in the centre of the light path of the substage illumination system. Many forms of dark-field illuminators are available. When special microscopes with self-contained lighting are employed, the method becomes most effective and useful. Such internal illumination of the substage fitments is the basis of the special gemmological microscopes. Some firms have produced 'bowl' or 'ring' lights for open use or for use on the stage of

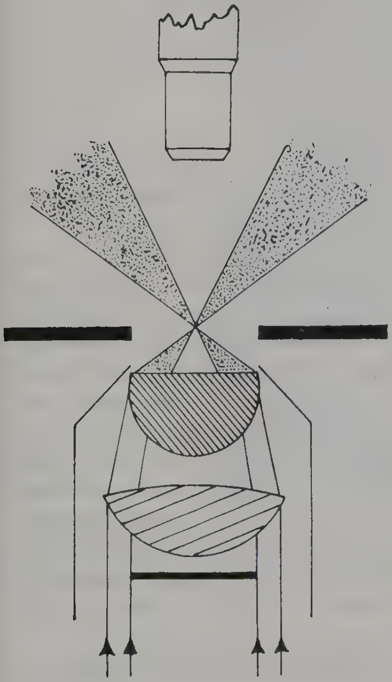


Figure 34.38 Arrangement for the production of dark-field illumination. Only the lateral rays which do not enter the objective are transmitted through the substage condenser

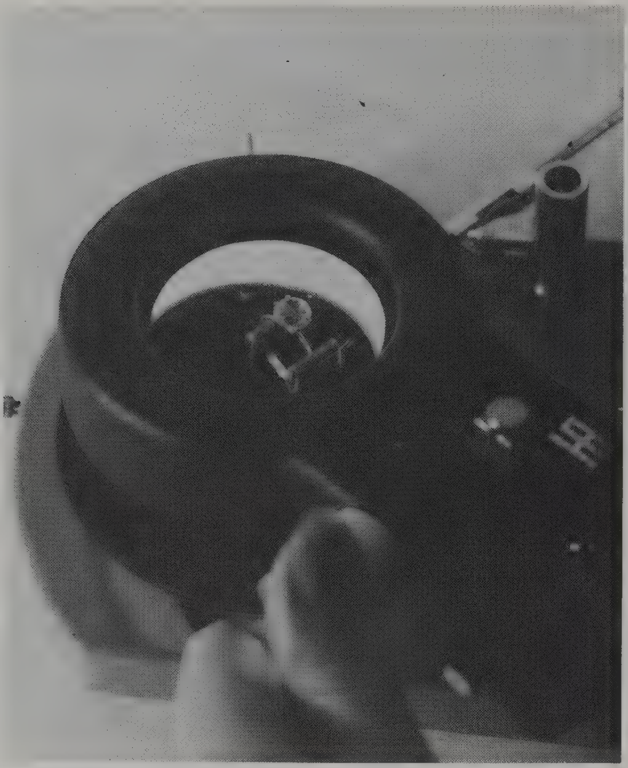


Figure 34.39 Adjustable 'ring' light for open or microscope stage use which will give incident or dark-field illumination

a microscope. Such a system is that made by Eickhorst of Hamburg in which the light source is adjustable for height so as to produce incident light or dark-field illumination. It is very useful for diamond examination (*Figure 34.39*).

Generally speaking dark-field illumination yields more striking pictures as the contrast of a white pattern on a dark field is always more arresting. However, one cannot easily generalise on the subject of whether to choose transmitted light or dark-field illumination, since both need to be given serious consideration. In most cases it is an advantage to use dark-field illumination when 'silk' is present, and liquid inclusions may produce more striking effects in this type of lighting, fine patterns being generally more conspicuous, while coarse patterns are better seen in transmitted light (*Figures 34.40* and *34.41*).

In most cases, dark-field illumination gives better results with included crystals, whether transparent or opaque, colourless or coloured, as transmitted light causes the crystal to appear as a coal-black blob, while dark-field illumination may well bring out the beauty of the crystal's habit, especially when the dark-field illumination is so constructed that the intensity can be varied on different sides.

A modified dark field, actually a mixture of the two types of illumination, is

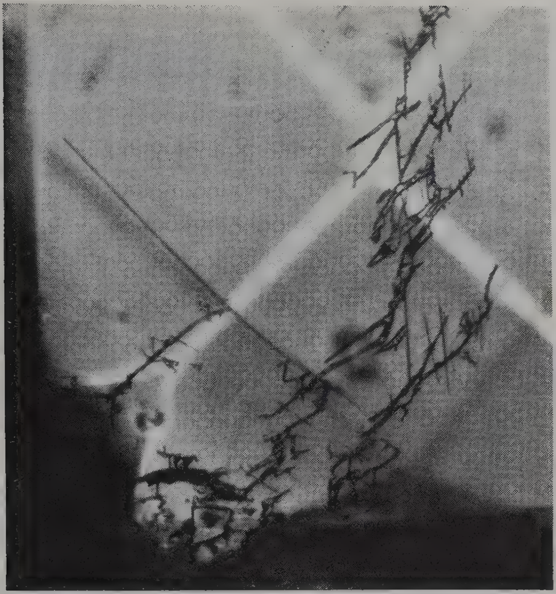


Figure 34.40 *Dendritic figures of liquid-filled fissures in a Montana sapphire as seen by transmitted light (by courtesy of E Gübelin)*

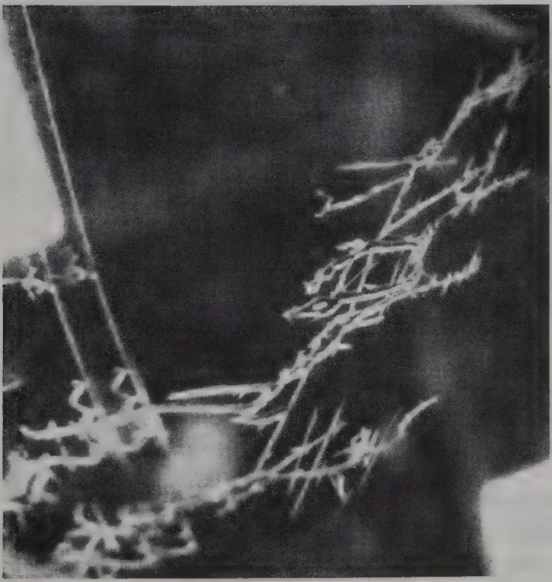


Figure 34.41 *The same inclusions as seen in Figure 34.40, but seen in dark-field illumination (by courtesy of E Gübelin)*

obtained when the mirror of the microscope is adjusted so that the reflected beam is 'off-centre' from the optical axis – the correct position for ordinary illumination. Experiment shows that such adjustment of the mirror will often bring out fine detail: especially is this so in the case of the very pale and indistinct curved striations of synthetic corundums. Movement of the mirror – wobbling it about – whilst observing the specimen often enables the worker to 'pick up' fine structure which would most likely be missed. When the substage condenser is in the optical train, lowering it will often perform a similar service, as will opening and closing the dark-field stop that blocks the direct transmission of light from below the subject in microscopes which are so equipped.

It was found by Zernike in 1932 that differences in optical path, causing what are generally referred to as phase differences, could be made visible in transmitted light microscopy as differences in intensity. By its use many fine structures are made more easily visible. Although this phase contrast method has recently been applied to mineralogy and to advanced techniques in gemmology, the difficulty and expense of modifying the polarising microscope for phase contrast work precludes the general use of the method, which will not be further discussed.

It has been found of value, especially when diamond is to be examined, that if it is suitably held on the stage of the microscope, and a strong and narrow beam of light from a fibre-optic lamp is directed on to the stone from the front or side of the stage, the interior of the gem may be examined with ease. This is always difficult to attain when ordinary lighting is used for stones of high refraction, but fibre-optic illumination is a great help in this area.

The observation of the surface structure of a specimen, whether it is transparent or opaque, is sometimes called for. It is rarely necessary in such cases where 'top-lighting' is required to employ anything more complicated than a desk lamp arranged to throw light down on to the surface, aided, perhaps, by the 'bull's-eye' stand condenser. There are various types of reflectors made to fit on the stage, or over the objective; and for metallurgical investigations vertical illumination through the objective itself is used. These techniques have no employment in gemmological microscopy.

Methods of Indicating Inclusion Positions

It may not be out of place to mention the usual methods of indicating to another person where, in the field of view of the microscope, a particular inclusion is situated. There are special indicating eyepieces obtainable, either single or double, whereby two workers can observe the same field at the same time. These eyepieces are fitted with a movable pointer which may be turned to indicate the position.

There are two usual methods of indicating the position of a point in the field of a microscope. Probably the best known is the clock-face method. The field is looked upon as the face of a clock and the indication given by naming the hour at which the inclusion is situated (*Figure 34.42*). The second method is more often used in the case of polarising microscopes, which generally have cross-hairs set in the ocular. This is the compass indication: the vertical hair is

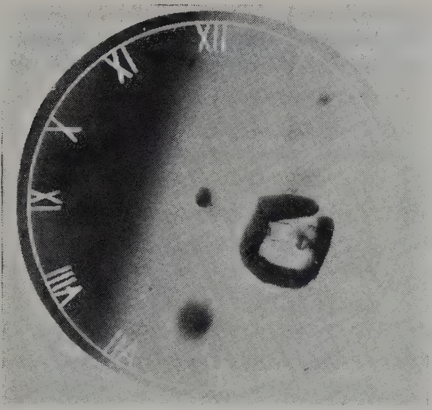


Figure 34.42 *The clock-face method of indicating position. The three-phase inclusion in the South American emerald is situated at 4 o'clock*

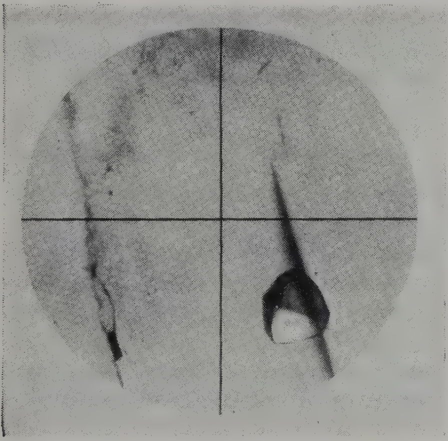


Figure 34.43 *Using the cross-hairs as position indicators. The vertical hair is designated north–south while the horizontal is east–west. The included crystal is therefore indicated as being in the south-east quadrant (by courtesy of E Gübelin)*

designated as north–south and the horizontal as east–west, indication being given as north-west, south-east and so forth (*Figure 34.43*).

Use of Polarising Microscope

In the case of the polarising microscope the general principle of setting-up is the same as for a normal instrument. It is in the arrangement of the optical and polarising apparatus that differences occur, and there are three such arrangements which may be used in gem distinction.

Arrangement of Optical and Polarising Apparatus

The first of these is when one polarising filter only is in the optical train of the microscope. The second arrangement, the most useful in gem testing, has both filters in the optical train; these are in the crossed position, but the substage condenser, if there is one, is usually removed from the microscope. Such an arrangement uses what is known as parallel polarised light. The third method is similar, with both the filters in the train and in the crossed position, but in this case a short-focus substage condenser is also placed in the train. This produces what is known as convergent polarised light and is used for the production of interference figures. In the best polarising microscopes a subsidiary magnifier, known as the Bertrand lens, may be placed in the axis of the microscope in order to focus the first image in the correct plane for it to be picked up by the ocular.

When one filter only is used – either the polariser or the analyser (usually the polariser) – and a coloured anisotropic stone is placed on the stage, the vibration direction of the filter will 'select' the vibration directions of the stone. Therefore, upon rotating the stage with the stone upon it, the field may vary in colour every 90 degrees, owing to the differential selective absorption of each of the two rays of the doubly refractive stone. Hence, such an arrangement allows pleochroism to be observed, much in the same way as with a dichroscope except that the pleochroic colours are not viewed side by side. Thus, there will be no doubt when the pleochroism is moderate to strong, but if it is weak it may be missed, for the eye cannot 'carry' the colour; in such cases the direct comparison, as in the dichroscope, is much to be preferred.

Crossed Polarising Filters

To examine stones in parallel polarised light, both polarising filters must be in the optical axis, and be 'crossed' to one another. In the standard petrological microscopes the polariser clicks into position when the crossed position is attained. In the 'built-up' instruments the crossed position must be found by trial, that is by rotating either the polariser or the analyser until it is seen that the field is darkest.

This 'crossing' and the dark field it gives may be explained as follows. Light transmitted by the polariser is, say, vibrating only parallel to an east–west direction, but the analyser has its vibration direction parallel to north–south. Thus the emerging extraordinary ray of the polariser now becomes the ordinary ray of the analyser and is totally reflected by the film of balsam and absorbed by the casing (or totally absorbed by the material if Polaroid discs are used). Consequently the light does not reach the eye and therefore the field is dark.

When a singly refracting stone, say a piece of glass or any isotropic mineral, is placed on the stage, that is, interposed between the crossed filters, no alteration of the conditions is produced, as such substances have no power to change the vibration direction of the entering light. Therefore, if any stone belonging to the cubic system, or any amorphous substance, is examined between crossed filters, it will give a dark field at all positions during a complete rotation of the stage.

In all experiments using polarised light the best results are obtained when the stone is immersed in a highly refractive liquid, such as monobromonaphthalene. This is in order to avoid surface reflections from the inclined facets of exterior light. True, if there are two parallel facets, such as table and culet, any effects can be observed at the top face, but immersion in liquid is safest.

When an anisotropic stone is examined between crossed filters, the field does not remain dark during a complete rotation of the stone; except when the direction of observation is parallel to an optic axis. In all other directions the field becomes four times light and four times dark during a rotation of the stone through a full circle: that is, it will become dark, or extinguish, in four positions at intervals of 90 degrees, and between those positions of darkness the field is illuminated, being at its brightest at 45 degrees from the dark position. Extinction occurs when the vibration directions of the stone are parallel to the vibration directions of the filters; for in such positions light from the polariser is not resolved by the stone but passes on to the analyser as if the microscope stage was empty. Hence darkness results.

In the foregoing remarks it may be assumed that a clear-cut decision as to whether a stone is singly or doubly refracting may be made by the simple observation of the effect between crossed filters. Although this is generally true there are many occasions when the results, unless the worker has had considerable experience, are not so clear. Many isotropic substances are under a state of strain, either wholly or more usually in patches, and thus do not exhibit a completely dark field during a complete rotation of the specimen through 360 degrees, but show a light and dark patchiness over the whole field. This effect is termed anomalous double refraction.

Anomalous Double Refraction

Such anomalies should not worry any worker who has had some experience of polarising effects, but they do in many cases cause trouble to the tyro. The characteristic difference in the extinction shown by true doubly refracting materials and the anomalous extinction shown by materials in strain is as follows. In true double refraction the extinction, that is the cutoff of the light, occurs regularly at every quarter of the circle of rotation (at every 90 degrees), and is quite sharp. The pattern due to anomalous double refraction is patchy, the whole field being made up of light and dark patches or stripes which may move across the field as the stage is rotated, but, in general, have no relation to any orientation at 90 degree intervals. This last observation may not be true in the case of some garnets, which do show a very good approximation to four times light and four times dark during a complete rotation of the stage. This effect has been remarked upon during the description of garnets (Chapter 8).

The strain causing this anomalous effect may be set up by a number of causes, such as that due to the rapid cooling of glass; hence some pastes may exhibit the phenomenon. It is, however, in the case of the synthetic spinel that the effect has most importance in diagnosis. Owing to the excess of the alumina present in the synthetic spinel the crystal lattice is in a state of some strain. This is shown by the characteristic anomalous double refraction: a field crossed with alternate light and dark stripes. This pattern has been likened to the stripes on a tabby cat, and the name 'tabby extinction' has been applied to it (*Figure 34.44*). The anomalous double refractive effect in the case of garnet has already been mentioned.

Several other effects of a minor nature, but disconcerting to the student, may with advantage be mentioned. As this method for the detection of double refraction is very critical, any double refractive inclusion in a singly refractive medium, for example an apatite or a diopside crystal in a garnet, will tend to

Figure 34.44 'Tabby extinction' and 'profilated' gas bubbles in a synthetic spinel

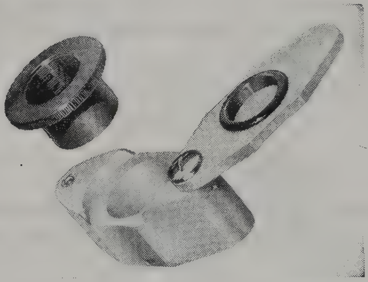


Figure 34.45 The Rutland polariscope

show up as a bright spot of light. Likewise, dust particles (often quartz grains) floating in the immersion liquid will also give bright spots of light. Practice soon begets proficiency in evaluating the various polarisation effects. In certain cases, notably in some corundums, twin planes which are evanescent when observed in ordinary light are much more prominent when viewed between crossed polarising filters, and this is true for a number of other inclusions.

Although polarising microscopes have been postulated, polarising apparatus need not necessarily have a lens system. Two Polaroids arranged in the crossed position and held over a light source, providing that an arrangement for rotating the specimen between them is incorporated, is all that may be required in order to detect double refraction. Indeed, small polarisers of this type have been designed by Shipley, Walton and Rutland. The small Rutland polariscope is little larger than a pocket lens and has been proved quite efficient (*Figure 34.45*). A useful polariscope is one based on the Meakin strain viewer, in which a circle of Polaroid about 50 mm in diameter fills an aperture in the base of the instrument which contains a low-voltage electric lamp. An arm above this carries another Polaroid disc which is in the crossed position to the lower polar. There is space between the upper and lower polars to comfortably hold and rotate the specimen under test. There is also room to place a lens over the specimen whereby it is often possible to observe the interference figure.

Interference Figures

The use of convergent polarised light for the production of interference figures needs the microscope to be set up with the polarisers crossed and a strongly convergent lens placed in the substage fitting. If the microscope is provided with a Bertrand lens a 6 mm objective is inserted and the eyepiece retained. If, however, there is no Bertrand lens a 25 mm objective is preferable and the eyepiece must be removed. Those microscopes which have a Bertrand lens and 6 mm and 25 mm objectives (all good petrological microscopes should have them) give the choice of either optical system. The former gives larger figures, while the latter, though yielding small figures, gives sharper definition; most workers prefer the Bertrand lens. When all these conditions have been observed the microscope is set to resolve interference figures.

Technique for Obtaining Interference Figures

The stone should be immersed in a liquid of approximately its own refractive index; the liquid should be contained in a small glass dish and the stone held in a pair of tongs. On turning the stone in the liquid, the interference figure will appear. The beginner may experience a little difficulty at this stage. The stone should be turned until interference colours appear; when this occurs the focus should be lowered until the objective nearly touches the stone and the interference figure will emerge. The best results are usually obtained when the objective is actually immersed in the oil, but special oil-immersion objectives should be used.

The most suitable liquid for general purposes is monobromonaphthalene (refractive index 1.66), which is suitable for topaz, tourmaline, andalusite, peridot, enstatite, spodumene, euclase, fibrolite, apatite, danburite and so on. It can be diluted with toluene or benzene (refractive index 1.50) for quartz, beryl, iolite, feldspars and scapolite, among others. For stones of higher refractive index, di-iodomethane is suitable, while for stones such as zircon, sphene and cassiterite, the only possible liquid so far known is a mixture of white phosphorus, sulphur and di-iodomethane (refractive index up to 2.05), discovered by West. This is rather an unpleasant liquid and is not recommended to beginners. It can be spontaneously flammable when exposed to air.

The Interference Phenomena

The figures occur only in crystals that are birefringent, and are caused by the interference of converging rays of the same wavelength when travelling out of phase as a result of their differing velocities within the crystal medium.

In the case of uniaxial crystals (tetragonal, hexagonal, and trigonal) the figure consists of a series of coloured rings intersected by a black cross (*Figure 34.46*).

Biaxial crystals (orthorhombic, monoclinic and triclinic) give a pattern as shown in *Figures 34.47* and *34.48*. In this case, however, there are variations depending on the nature of the refractive indices. Biaxial minerals have three indices of refraction, α, β, γ. Where β approximates closely to either α or γ, the 'brushes' (isogyres, as they are called) are close together as represented in *Figures 34.47* and *34.48*. Where β is about the mean of α and γ, the isogyres are

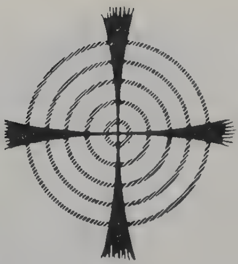


Figure 34.46 *Uniaxial*

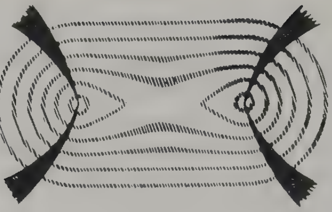


Figure 34.47 *Biaxial in 45 degree position*

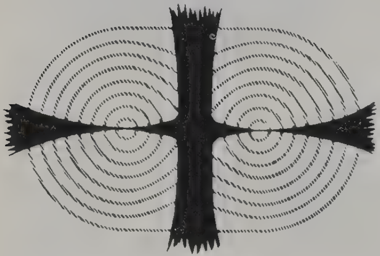


Figure 34.48 *Biaxial in straight position*

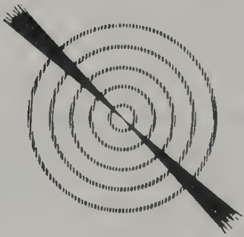


Figure 34.49 *Biaxial, large 2 V*

widely separated and only one can be seen in the field at a time (*Figure 34.49*).

In cases where β nearly coincides with α or γ, the figure appears to be uniaxial, distinction appearing on rotation. True uniaxial figures do not alter, whereas pseudo-uniaxial figures show a separation of the isogyres. Biotite (brown mica) is an excellent example of a pseudo-uniaxial mineral; this phenomenon is rare amongst gemstones.

In biaxial minerals the acute bisectrix is equidistant from the two eyes of the figure and is normal to a line joining them. The eyes or melatopes represent the emergence of the optic axes; the angles subtended by these axes and the acute bisectrix are invariably denoted by the symbol *V*; thus, the angle subtended by the two axes, that is, the optic axial angle, is 2 *V*. This angle can be measured if the stone is rotated on a spindle attached to a graduated circle; it is sufficient to measure it to the nearest degree. The greatest angle to be seen in the field of vision is about 30 degrees; when 2 *V* is greater than this, only one isogyre is visible at one time (*Figure 34.49*).

Unlike uniaxial figures, biaxial figures rotate when the stone is rotated; the 'straight' or extinction position is shown in *Figure 34.48* while *Figure 34.47* shows the 45 degree position.

In addition to the information that the stone is uniaxial or biaxial, the optical sign can be deduced from these figures. Various plates can be obtained for this purpose – the quartz wedge, the gypsum plate and the mica plate. Of these the mica plate is the easiest to use and is recommended to beginners.

It consists of a thin sheet of mica, cut in such a way as to retard light by one-quarter of a wavelength ($\frac{1}{4}\lambda$). This is inserted in the tube of the petrographic

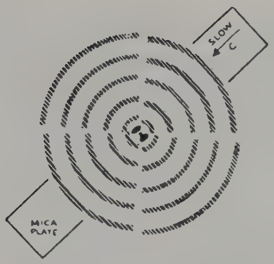


Figure 34.50 *Positive uniaxial*

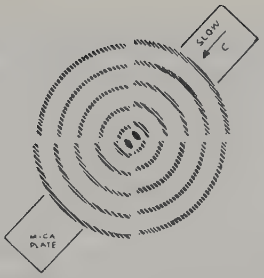


Figure 34.51 *Negative uniaxial*

microscope in a slot provided for it immediately above the objective. (If there is no slot, it should be held at an angle of 45 degrees just below the objective.)

In the case of a uniaxial mineral, the cross in the centre of the figure disappears, and two short bars or lenticular spots appear in its place. If the slow direction of the plate is lengthwise, and the slot is north-east to south-west, the bars will be seen disposed as in *Figure 34.50* for positive and *Figure 34.51* for negative minerals. It will be noticed that the dark spots appear in the enlarged quadrants.

In the case of quartz these quadrants are the only guide, since quartz has the peculiar property of rotating the polarisation of light, with the result that the cross does not appear in the inner ring; nor do any dark spots with the mica plate, since the spots are merely parts of the displaced cross.

In the case of biaxial figures the detection of the optical sign is more complicated. The figure has to be rotated into the straight or extinction position (*Figure 34.48*). When the mica plate is inserted the whole figure appears to divide along the horizontal axis, one half of each set of rings increasing in size and the other half decreasing; the process is reversed for either set. A black spot will appear in the centre of the enlarged half of either set of rings, adjacent to the dividing line. If the black spot is above the line on the left and below on the right, the optical sign is positive (*Figure 34.52*); if the spot is below on the left and above on the right it is negative (*Figure 34.53*). In cases where 2 *V* is large and only one isogyre and set of rings appear in the field of vision, the nature of the isogyre denotes whether it is the left or right part of the figure. The stone should be rotated first into the 45 degree position, when the isogyre will be

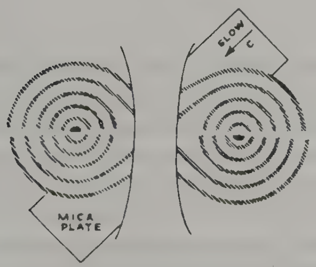


Figure 34.52 *Biaxial positive*

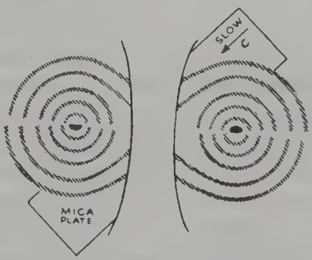


Figure 34.53 *Biaxial negative*

curved into a hyperbola. *Figure 34.47* shows the relation of the isogyres in the 45 degree position. It can be seen that the optical sign is determinable from one set of rings provided it is known which set of rings is under observation.

In extreme cases, where 2 *V* approximates to 90 degrees, the isogyres will be straight in any position, so that the mica plate is of no use for determining the optical sign unless 2 *V* is accurately measured beforehand. In such cases the mineral can be only weakly positive or negative, and to the ordinary student determination of its optical sign will not be of great assistance in determining the nature of the stone. Quartz wedges are used by experts in deciding the sign in such cases, but the technique is too complicated to be described here, and is generally done on specially prepared grain mounts and thin sections.

If monochromatic light is used instead of white light, the interference figure will be much sharper and clearer since it will consist of the colour of the source contrasted with black. In biaxial stones the optic angle, 2 *V*, varies according to the wavelength of light. In some cases this difference is very considerable, and is clearly discernible if red and blue colour filters are interposed. In extreme cases such as danburite, which has a large 2 *V*, the optical sign is negative for the red ray and positive for the violet, that is, the acute bisectrix becomes the obtuse. In this particular case the optic angle for red is less than for violet, this property being denoted in tables of optical constants as $r < v$. The effect is due to differences in dispersion of α, β and γ. In many minerals it is slight but in a few cases it is strong enough to be distinctive.

The size of interference figures is controlled by two factors – birefringence and thickness. The shallower the stone or the lower the birefringence, the larger the rings. This can be demonstrated with the white mica, muscovite, which, having a perfect cleavage, can be reduced to any required thickness, while a comparison of calcite (double refraction 0.172) and apatite (double refraction 0.004) of the same depth will demonstrate the influence of the other factor.

The value of these phenomena for purposes of identification is considerable in certain cases where the standard tests of specific gravity and refractive index are either inapplicable or inconclusive. As examples, on the one hand may be mentioned stones cut *en cabochon* and in settings as well as in the rough; and on the other hand species such as andalusite and tourmaline, which have similar physical properties but – being orthorhombic and trigonal respectively – yield biaxial and uniaxial figures.

Drawings from the Microscope

It is clear that with a petrological microscope, complete with graduated rotating stage and with cross-hairs in the ocular, measurement of the angles between the facets of a cut stone, between the cleavage directions, or between crystal faces of well-formed inclusions, may often be obtained. Such work can often provide useful additional information and can be carried out if necessary with an ordinary monocular microscope to which is fitted a goniometric ocular. Such a fitting consists of a Ramsden ocular which reads by means of a vernier to 5 minutes of arc (*Figure 34.54*). Any ocular fitted with cross-hairs has an added value in that the webs act as comparisons for straightness or curvature of fine striae, such as may be found in natural or synthetic corundum.

Figure 34.54 *The goniometric ocular*

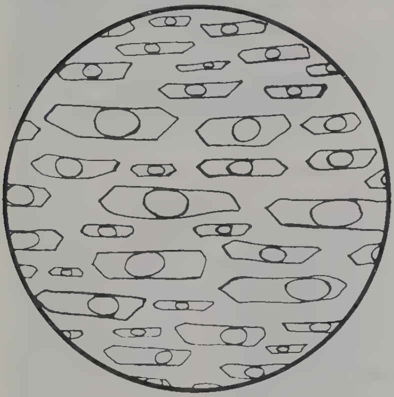


Figure 34.55 *A drawing of the two-phase inclusions seen in smoky quartz*

The inclusions seen in many gemstones when viewed by a microscope often invite a permanent record. Particularly is this so in those, often beautiful, patterns which indicate the provenance of the gem, or are typical of the species. Such pictorial representation provides a far better reference than the memory.

It is often suggested to the student that he draws on paper the picture he sees through the eyepiece of his instrument. Much can be learnt by this method, which has the advantage that a composite picture may be built up showing a number of typical inclusions of stones of one species, or of one locality (*Figure 34.55*). A simple aid to accurate drawing is to use a paper ruled with lines in squares in conjunction with a graticule with square rulings. Such graticules can be obtained as discs which can be placed in the ocular so that it rests on the stop between the field lens and the eye lens. At this position it will be in focus, or if it is not sharp it can easily be brought into sharp focus by slightly unscrewing the eye lens; this has to be unscrewed in the first place to allow the graticule disc to be dropped into position.

Objects sketched in this manner using the guide squares in the ocular to act as guides to the squares on the paper may also be measured by reference to a stage micrometer. This is a 75 × 25 mm glass slip with lines ruled on it at 1/10 mm and 1/100 mm intervals. If the micrometer is placed on the stage of the microscope and viewed under the same conditions as the object that has been drawn by means of the squared paper, it is easy to see how many tenths or hundredths of a millimetre are included in each square. This can be noted on the drawing and the dimensions of the objects may then be obtained by measuring the drawing.

Photomicrography

The most effective and fascinating type of reproduction is undoubtedly that of photographing the picture seen through the eyepiece. Photography through a microscope is correctly called photomicrography. It should not be called microphotography, which is the production of a very small picture, much smaller than the object and which has considerable use as 'microfilm recording' of documents. The art of photomicrography calls for some slight knowledge and a certain amount of ancillary apparatus. The 'camera' may be completely incorporated in the microscope, as in the very fine, but expensive, instruments specially built for visual and photomicrographic purposes, or the camera may be just a home-made arrangement which can be constructed by any enthusiastic amateur.

All that is actually needed for photomicrography in its simplest form is a suitable rigid and light-tight box or 'camera' to carry the photographic film or plate at a convenient distance from the eyepiece of the microscope and at right angles to the optical axis. The camera requires no lenses, for the optical system of the microscope performs the duties of the lenses in an ordinary camera. The only other requirement needed is for the box to be arranged to carry a viewing screen of fine ground glass for focusing the image, and which may be removed easily and replaced by the plate holder (dark slide).

Commercial microscope cameras may be just a conical or tapered metal box which fits over the eyepiece and clamps on to the draw tube of the microscope. The upper face of the box is fitted with a frame which carries a focusing screen which can be replaced by a plate holder (they usually take quarter plate or larger size; some take the 83 × 83 mm lantern plate size, but most popular is the 89 × 64 mm). The lower end of the box contains a shutter which is operated by a lever or by a cable release. A similar but more elaborate type of microscope camera has a separate ocular fitted to it so that the image of the subject can be observed up to and during the time of exposure. The ocular contains hair-lines which are focused by the eye lens, and when this is done the image seen in the ocular is focused by the microscope focusing adjustments. The image is then in focus in the correct plane of the photographic plate. A ground-glass screen is also provided so that the focus can be checked before the exposure, and to see the amount of light reaching the plate (*Figure 34.56*). Similar cameras may be obtained which take pictures on standard 35 mm film, in which case the carrier allows transport of the film, as in the ordinary 35 mm camera; there is no ground-glass viewing screen in such cameras. Many of the modern 35 mm single-lens reflex cameras are eminently suitable for photomicrography as special fitments are obtainable to go in place of the camera lens, which in this case is removed as the microscope optics act as the camera lens system (*Figure 34.57*). These fittings are made to clamp on to the draw tube of the microscope and the focusing can then be carried out through the reflex viewer.

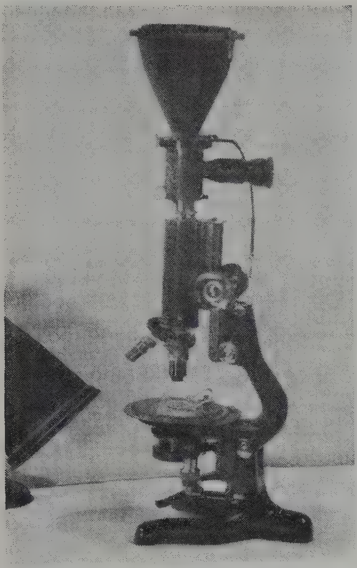


Figure 34.56 Eyepiece microscope camera fitted to petrological microscope

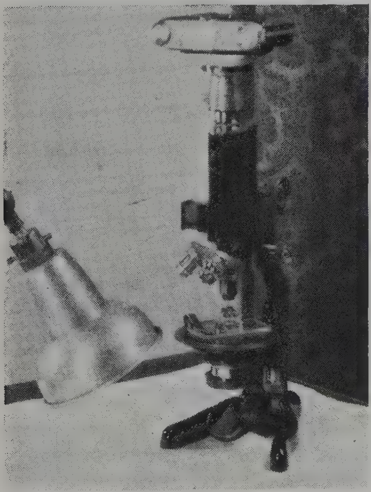


Figure 34.57 Single-lens reflex 35 mm camera used for photomicrography as mounted on a petrographic microscope

It is perfectly possible to use an ordinary hand camera to take pictures through the microscope. All that is needed is to construct a stand which will hold the camera steady so that the lens mount rests squarely on the eyepiece. Some 35 mm cameras may sit fairly steadily on the microscope ocular, or a tube support may be made in which the lens mount of the camera rests. It should be noted that when a hand camera is used the ocular is left in position. In this method the microscope is first focused as for the ordinary observation and then the camera is mounted on the eyepiece. The camera will have been first adjusted with the range scale at infinity, the aperture fully open, and the shutter set to time or bulb if the exposure needed is greater than allowed for the shutter's slowest speed.

The Gemological Institute of America found a method of adapting the Polaroid EE-100 automatic camera so that it can be used with a binocular microscope. This camera has a shutter which on being opened by the operator is closed electronically when the photocell beside the lens records enough light to correctly expose the film. The modifications made so that the camera can be used with a binocular microscope are an adaptor to carry the camera lens snugly over one eyepiece, and a 'lightwire' (made up of bundles of light-transmitting fibres) one end of which is in an adaptor holding it central over the other eyepiece. The other end of the 'lightwire' fits over the light cell aperture of the camera. In general this set-up will ensure correctly exposed negatives, but some adjustment can be made if necessary.

In the plate type of microscope cameras with eyepiece focusing, the focusing is done through that and then checked by examining the image on the ground-glass screen. With the simple type of microscope camera the focusing must be carried out by examining the image formed on the ground-glass screen, for the focus is not the same as when looking down the eyepiece of the microscope when the camera is not in position. The use of a clear spot in the centre of the ground-glass screen is often valuable in focusing. This clear area may be made by smearing a little petroleum jelly on the ground site of the glass, and final sharpness of focus can be determined better if the image is examined with a low-power lens. When the focus is satisfactory the viewing screen is replaced by a charged plate holder and, when ready, the dark slide of this carrier is slid open and the exposure is made either by operating the cable release or simply by operating the electric switch. After the exposure has been made the dark slide is closed over the plate and the plate carrier is removed to the dark-room for processing.

Film Taking with Microscope Tube Eyepiece Removed

A method sometimes favoured is to dispense with the camera completely and to take the picture of the real image formed by the objective. For this method the eyepiece is removed and a ground-glass screen laid across the top of the microscope tube, with the ground side facing the objective. The image of the object to be photographed is then formed on the glass by the ordinary method of focusing the microscope with the coarse and fine adjustments. The ground glass is then removed and a piece of bare film substituted for it, being held down on to the top of the tube by a flat opaque object. This must of course be carried out in darkness or in the feeble light of a red dark-room lamp (with slow 'line' film a yellow light may be used, but if panchromatic material is used a green light is necessary or complete darkness). The exposure is made by switching on the microscope light source for the time previously decided. This method can give very sharp pictures but the image is very small and needs to be enlarged by projection printing (by an ordinary enlarger). *Figure 34.58* shows a photomicrograph taken by this method, an enlargement of it, and a similar picture taken with an eyepiece microscope camera.

Illumination

In general the stronger the source of light used to illuminate the object to be photographed the better, for the stronger the light the shorter the exposure

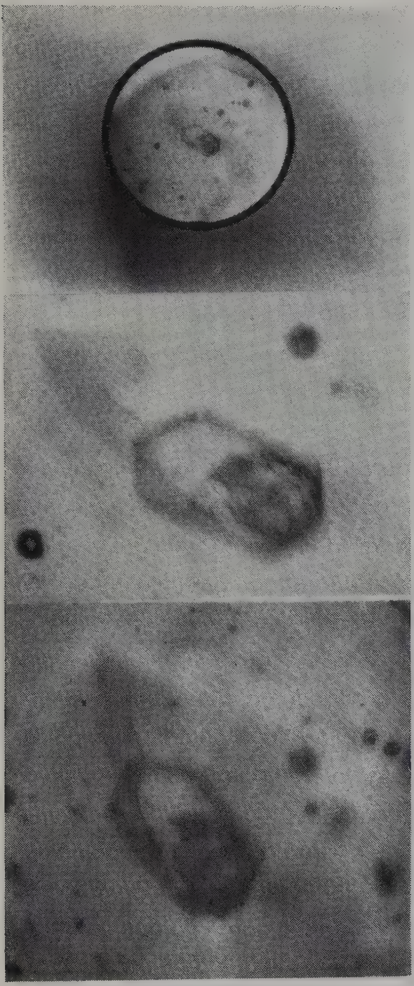


Figure 34.58 A photomicrograph taken on a piece of film placed over the microscope tube with the eyepiece removed, with below it an enlargement of the same negative. At the bottom is a picture of the same inclusion taken by the conventional microscope camera. The inclusion is an orthorhombic crystal in a blue apatite

needed. This can be of some consequence if the microscope set-up is not too rigid and is liable to suffer from the effects of surrounding movement, and it is certainly of importance if liquid is used to immerse the stone, for ripples are easily set up by vibration. If some vibration cannot be avoided the use of more viscous immersion liquids, such as glycerol (glycerine), may be used in the case of stones of low refractive index, but care must be exercised that bubbles are cleared away.

The use of the substage condenser is of considerable value as much may be achieved in 'sharpening' the image by lowering or raising the substage lens system. Likewise, considerable improvement may be made by adjusting the iris diaphragm to different apertures. The value of dark-field illumination versus transmitted light depends considerably upon the nature of the inclusion requiring to be photographed. Sometimes dark-field illumination gives more spectacular effects (*Figure 34.59a, b*), but this is not always so (*Figure 34.60a, b*).

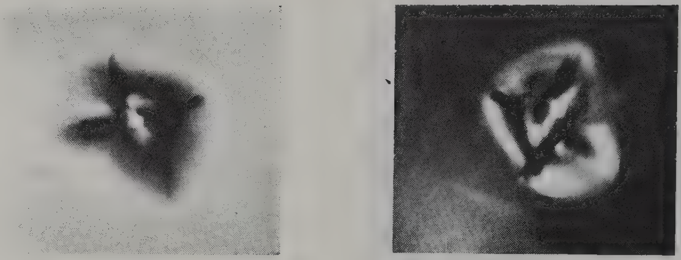


Figure 34.59 Zircon crystal surrounded with a halo in a Sri Lankan sapphire: (a) in transmitted light, (b) in dark-field illumination (by courtesy of E Gübelin)

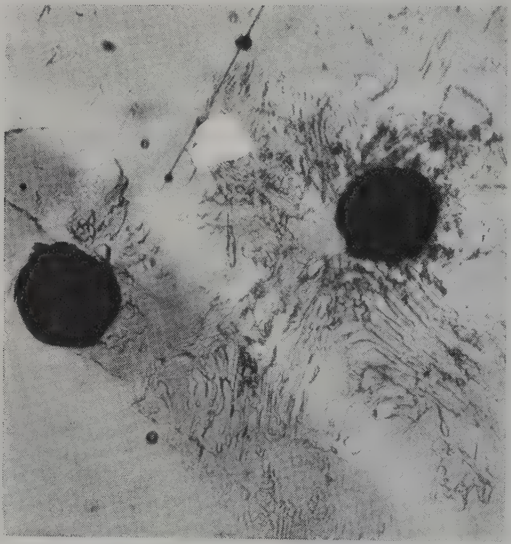


Figure 34.60a Typical inclusion picture of a Montana sapphire. Black opaque crystals surrounded by flat fluid inclusion haloes. The crystals do not appear interesting, while the fluid films betray their curious pattern (by courtesy of E Gübelin)

Often a combination of dark-field illumination and transmitted light is of advantage (*Figure 34.61*).

Exposure

Having selected the inclusion, or feature, of the stone it is wished to photograph by examination under the microscope, the gemmologist fixes the camera in position (it may be mentioned here that the use of the eyepiece is not essential but its employment is more common as it gives a wider field). The image is now focused for the camera and the substage equipment is adjusted to give the right

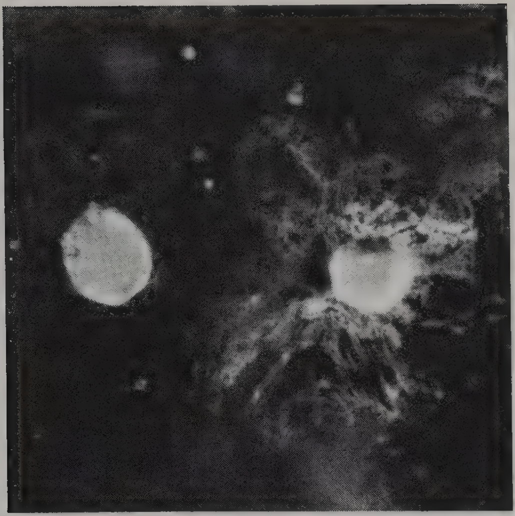


Figure 34.60b *The same inclusions as in Figure 34.60a but photographed in dark-field illumination show more clearly the characteristics of the crystals, while the fluid inclusions hardly show (by courtesy of E Gübelin)*

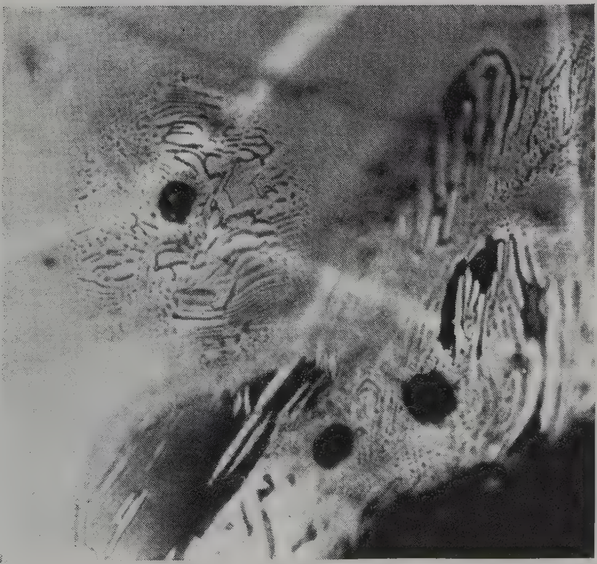


Figure 34.61 *Inclusions in a Montana sapphire taken in combined transmitted and dark-field illumination (by courtesy of E Gübelin)*

conditions of sharpness. Consideration is now given to the time of exposure required.

The exposure needed depends on the brightness of the field as seen in the ground-glass screen, and on the type of film or plate used. The use of a

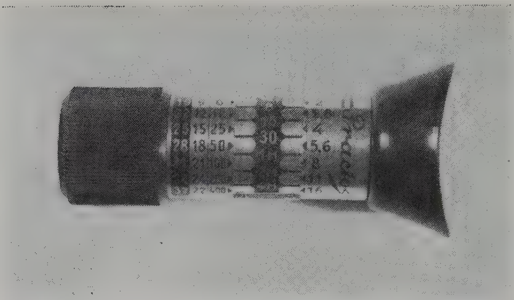


Figure 34.62 *An extinction exposure meter, the Practos*

photoelectric exposure meter is not completely successful, for the small area of light coming from the objective is not sufficient to fill the grid of the meter. The best type of exposure meter to use is probably the extinction type, such as the Practos (*Figure 34.62*). Even with these meters, unless some time is allowed for the eye to become accommodated, overexposure is probable. Experience will show how the meter can be calibrated so as to give a fair estimate of the exposure needed. The exposure can range from $\frac{1}{26}$ s to 30 min or more for very dark images and slow film. This is particularly so when the picture is taken in polarised light. With long exposures it is purely trial and error plus experience, for the exposure meters do not read beyond 4 or 5 min. The CdS electric exposure meter (*Figure 34.63*) has a much smaller 'grid' and such an instrument has been found useful for estimation of the exposure for photomicrography provided the exposure time required is not outside the range of the instrument. Some calibration is needed to ascertain the '*f* number' of the microscope eyepiece, for there is no camera iris diaphragm when the lens system of the camera is removed.

Variety of Film or Plate

The best type of film or plate to use depends upon the subject and upon the facilities available to the worker for processing. A rapid panchromatic plate is probably the most suitable for all-round work, despite that the changing of the dark slides and the development must be carried out in darkness or with a dark green safe-light. For those who have no effective dark-room, orthochromatic emulsions are more suitable and for the photography of inclusions are quite satisfactory. Such materials need only a red safe-light when charging cassettes (dark slides) and when developing. For fine detail a non-colour-sensitive film or plate, such as the 'Line' film used for copying drawings, is very suitable, especially when processed with a fine-grain developer. Such material needs about five times the exposure as ordinary 'ortho' film but has so great a latitude that small errors in exposure are of little consequence.

There are occasions when it is not felt justified to make a plate or film record of an inclusion but a record would make a useful addition to the 'library'. This may be carried out quite simply by using a suitable sized piece of bromide paper in place of the film: the bromide paper acts similarly to a film and, of course, needs similar development as for a film. Such a method saves expensive film,

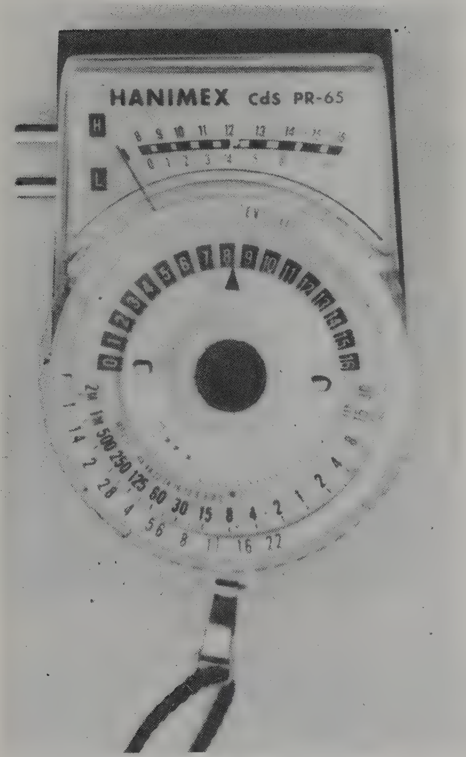


Figure 34.63 *A CdS electric exposure meter*

Figure 34.64 *Photomicrograph taken on bromide paper of two-phase inclusions in a white topaz*

but, of course, cannot be reproduced by printing; the fact that it is, strictly speaking, a negative does not always matter (*Figure 34.64*).

Colour films are applicable to photomicrography, and although colour prints from them are somewhat expensive and lose much detail, the 35 mm reversal colour films (Kodachrome, Fujichrome, Ektachrome, Gevacolor, Agfacolor, Ferraniacolor, etc.) produce transparencies which, when mounted as

50 × 50 mm slides, make most interesting subjects for projection. Even 35 mm negatives in black and white may easily be contact printed on to another film to make positives for projection.

Magnification

To ascertain the magnification of a photomicrograph when using the plate microscope camera, all that is necessary is to place on the stage of the microscope a finely divided scale (for the average magnifications used in gemmology an ordinary celluloid scale graduated in millimetres is sufficient). Focus this scale on the ground-glass screen of the camera and measure with a similar scale the distance between the two marks (units) of the magnified image of the lower scale. For example, a millimetre scale is projected on to the ground glass and the image is measured with a millimetre scale; the distance between the two marks representing 1 mm is found to be 25 mm. Therefore the magnification is ×25. In the case of the closed cameras, such as the 35 mm cameras, the image on the negative is smaller than the image seen through the eyepiece of the microscope by direct observation. It is quite feasible to open the back of the camera, hold the shutter in the open position, and by placing a piece of ground glass across the negative track to see the image produced and then measure the image as already detailed. Such a technique is not easy in 35 mm cameras. A far better procedure is to take a series of photomicrographs with the camera of a stage micrometer scale placed on the microscope stage. A picture of this scale is taken with each combination of ocular and objective and unchanged draw tube extension. The negatives, or prints taken from them, may be used to measure the magnification of any combination of objectives and oculars (using, of course, the same camera) by reference to the scale on the stage micrometer.

Dedicated Photomicrographic Systems

Over the last few years technology has improved dramatically in the field of gemmological photomicrography. Today there are microscope and camera systems available which are specifically designed for photomicrography. And just a few minor modifications to the illumination systems and bases of these photomicroscopes are all that is required to create a gemmologically dedicated photomicroscope (*Figures 34.26* and *34.65*).

Such instruments have 35 mm cameras which do not require removal during routine microscopic examination of a subject. They also have features such as automatic film advance and built-in computerised photometers to very accurately measure light levels and calculate proper exposure no matter what type of film is being used.

The modified bases for these instruments provide transmitted light, dark field, shadow-contrast enhancement through use of the built-in iris diaphragm, and polarised light with the proper accessories (*Figures 34.25* and *34.26*). If a fibre-optic illumination system is utilised (*Figure 34.66*), a number of other very useful lighting techniques can be employed such as pinpoint and directional-oblique illumination. The broad stability plates, made of metal and fixed to the bottoms of the photomicroscope bases, add additional weight to the system and provide greater rigidity for less vibration problems, even during very long exposures.

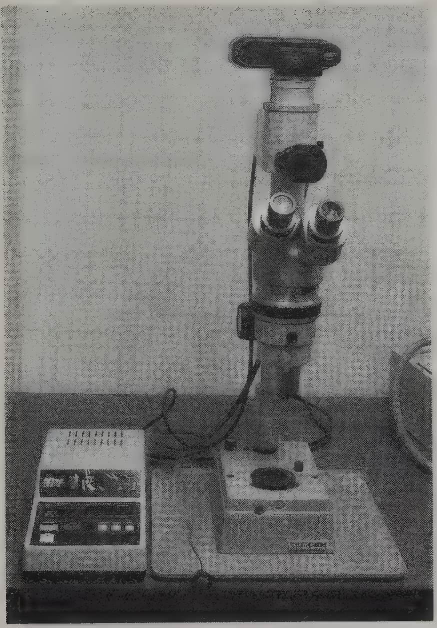


Figure 34.65 A modern automatic gemmologically dedicated photomicroscope

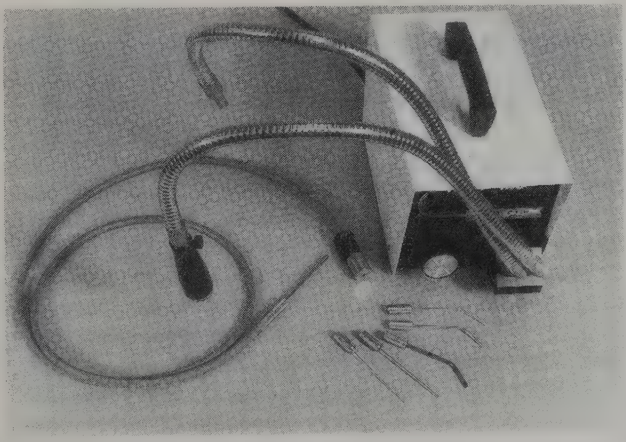


Figure 34.66 Gemmological fibre-optic illumination system including a number of pinpoint illumination wands with different diameters and curvature

The Electron Microscope

The electron microscope has been mentioned in relation to the experiments carried out on the structure of opal, so a short description is given of this instrument. The arrangement of the electron microscope may be compared to that of an optical microscope. Electrons are emitted from a hot tungsten

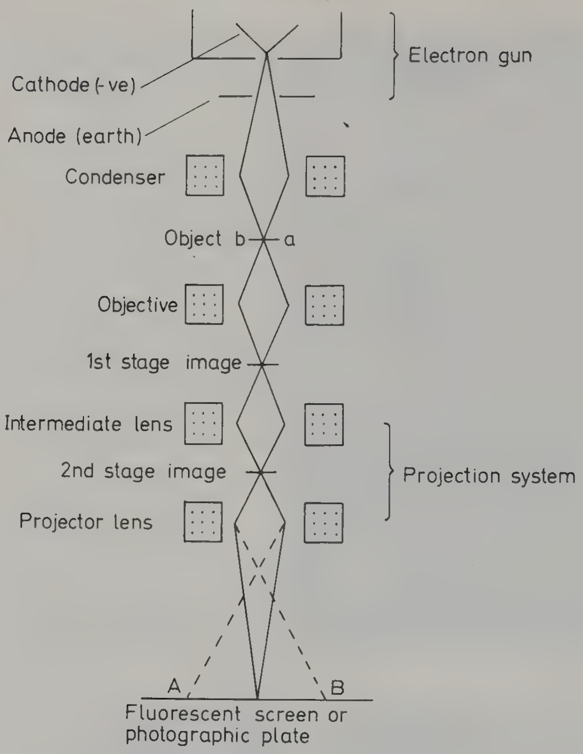


Figure 34.67 *Schematic diagram of the electron microscope*

filament situated at the head of a column which is continuously evacuated by an oil diffusion pump backed with a rotary pump. They are accelerated by a high negative potential, usually between 30 and 100 kV, and after a short distance they pass through a hole in an earthed plate (the anode). This electron beam is then regulated by one or two electromagnetic condenser lenses so as to 'illuminate' the specimen. This may be a very thin section or a replica made by depositing a film on the surface of the specimen, either by a solution technique or by vacuum deposition; this film is then stripped off to provide the specimen to be examined. After passing through the specimen the scattered electrons are focused with an electromagnetic objective lens and one or more projector lenses to give a highly magnified image on a fluorescent screen which may be viewed through a telescope, or the fluorescent screen may be replaced by a photographic plate or film (*Figure 34.67*). With a high-performance microscope the specimen can be magnified up to 150 000 to 250 000 times direct, and photographic records can be enlarged a further ten times, giving prints with magnifications up to more than 2 000 000.

While magnifications of one million times or more are very impressive, it should be noted that the electron microscope is in no way a substitute for the standard gemmological microscope. While gemmological microscopes have the capability of looking into the interior of a transparent or translucent fashioned gem or rough crystal and giving us images in true colour, the electron microscope can only examine surfaces, giving us essentially colourless or monochrome images. And those surfaces to be examined must be coated first in most cases with a film of gold or carbon. So while the electron microscope is most impressive scientifically, as a magnifying instrument it has very limited capabilities in gemmology.

35

Inclusions in Gemstones

Inclusions in Identification and Provenance

The microscope is the best means of observing the small inclusions seen in gemstones, so that it is fitting that notes on these included structures should follow the description of that instrument. In earlier chapters it has been shown by text and illustrations that these enclosures, better known as inclusions, provide a means of establishing whether a stone is of natural origin or whether it has been synthetically or artificially made, or in some cases artificially treated to improve appearance. There is, however, much more to the study of inclusions than that, for not only may the included structures give some information as to the species of the stone (*Figure 35.1*), but in many cases the country of its origin (*Figure 35.2*) is also discovered. Through the investigations of Eppler, Gübelin, Koivula, Michel, Roedder and Sorby, among others, inclusions have been found to supply considerable information concerning the genesis of gemstones.

The round or elliptical bubbles and irregular swirl marks so characteristic of glass imitation stones (*Figure 35.3*) and the round, tadpole-shaped, flask-shaped or bomb-shaped (profilated) bubbles of flame-fusion synthetic stones (*Figure 35.4*) give conclusive evidence of the nature of the stone. The typical picture of profuse crystals with a 'fused' look in conjunction with the swirls of colour so aptly called 'treacle' seen in the orange-brown hessonite garnets (*Figure 35.5*), the 'horsetail' asbestos fibres in demantoid garnet, the rows of octahedral crystals in natural spinel and the peculiar stress cracks seen in moonstone are examples of inclusions which identify the stone.

The following can be quoted as examples of inclusions which reveal the provenance of a gemstone: the typical three-phase inclusions of the emerald from Colombia; the three-phase carbon dioxide fluid inclusions containing daughter crystals of graphite in sapphires and rubies from Sri Lanka; the typical large, clear, rounded crystals with silk and treacle seen in the rubies from Myanmar (Burma); and the feathers with script-like design, often with a black

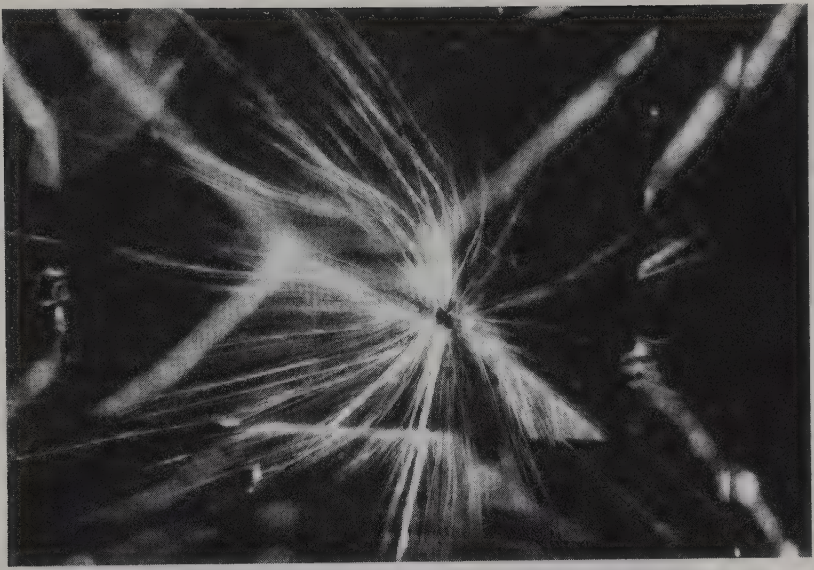


Figure 35.1 *Asbestos fibres in a radial or horsetail arrangement seen in a green stone betoken a demantoid garnet (by J I Koivula, Gemological Institute of America)*

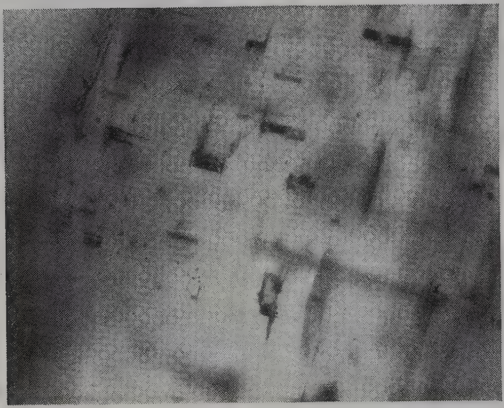


Figure 35.2 *Comma-like primary fluid inclusions typical of an Indian emerald*

crystal at the centre or towards the margin of the feather, which are characteristic of Thai corundums.

Classification

Gübelin has divided gemstone inclusions into three main groups. The first group, termed the pre-temporary, pre-existing or protogenetic inclusions, consist mostly of solid crystals or earthy or amorphous matter which were

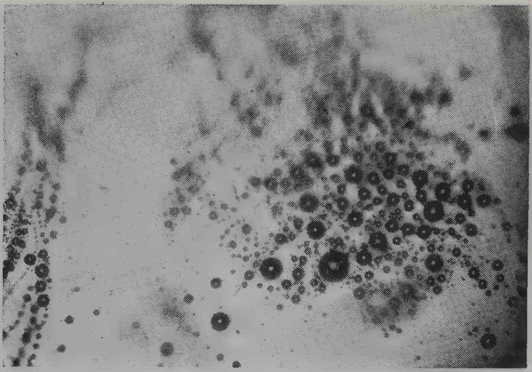


Figure 35.3 'Feather' of bubbles in a green paste

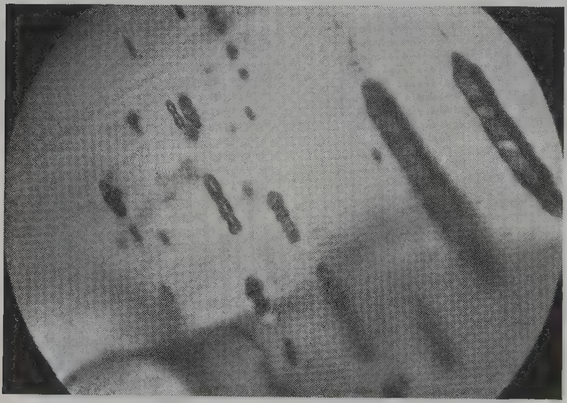


Figure 35.4 Profiluted bubbles and curved striae in a flame-fusion synthetic ruby bead

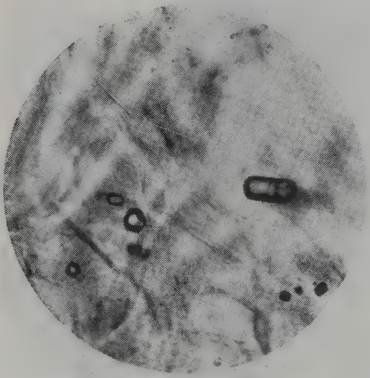


Figure 35.5 Crystals and swirls in a hessonite garnet. Swirls are primary autogenetic inhomogeneities, and the foreign crystals of apatite and calcite are primary xenogenetic inclusions (by courtesy of E Gübelin)

present before the gem crystal formed and which were enveloped in the new growth. The second group, the contemporary or syngenetic inclusions, are those formed at the same time as the host mineral. They may be due to the capture of fluids which were surrounding the growing gem crystal; or may be crystals of the same or another mineral species which grew at the same time and became enveloped in the larger host crystal. It seems at first sight inexplicable that inclusions can develop after the formation of the crystal, but this can occur and produces what are known as post-temporary, post-formed or epigenetic inclusions. Such an occurrence happens when certain areas in the crystal recrystallise by chemical alteration. The formation of such inclusions by the combination of independent elements not forming the basic composition of the host crystal, and which is termed exsolution, may be caused by natural heat treatment after the host crystal has formed. The infiltration of liquid impurities into cracks and fissures following the formation of the gem may crystallise out in the cracks, forming the so-called healing feathers which appear as flat fluid films or as irregular liquid shreds or as drops (*Figure 35.6*).

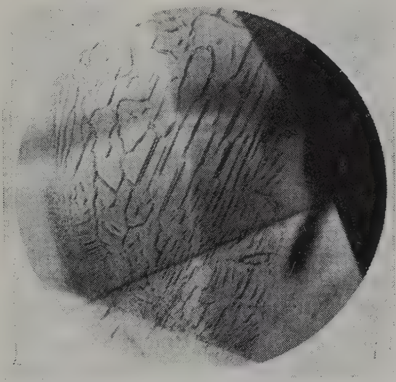


Figure 35.6 Healing feather in a Sri Lankan sapphire (by courtesy of E Gübelin)

A different classification of the inclusions seen in gemstones might be made by dividing them into two main classes, as primary inclusions and secondary inclusions. Primary inclusions may then be divided into autogenetic inclusions, which originate from the mother-liquor or magma and are caused by peculiarities of growth, and xenogenetic inclusions, which are foreign substances enclosed within the crystal at the time of growth. Secondary inclusions may be divided into healing fissures, or inclusions formed by exsolution.

Again, a division in four groups may be made: (1) solid inclusions which may be of the same material as the host or one completely foreign to it; (2) internal cavities containing liquid or gas or both, and even solids in the form of one or more small crystals; (3) cracks and fissures filled with gas or liquid which are termed flags or feathers; and (4) growth phenomena which include zonal structures and irregular distribution of colour.

Solid Inclusions

Examples of solid inclusions, either of the same mineral as the host or of a species foreign to it, are coarse or slender crystals of rutile, tablets of mica,

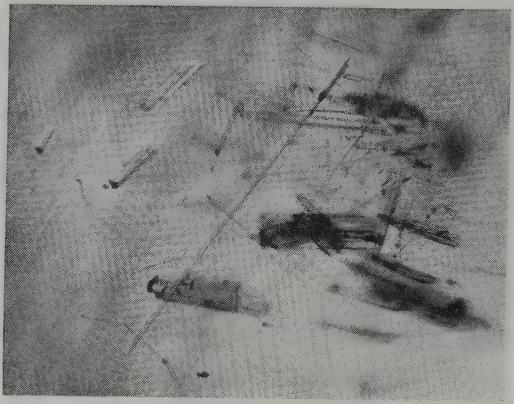


Figure 35.7 *Solid inclusions consisting of long and short tremolite needles in a Zimbabwean (Sandawana) emerald*

zircon crystals with haloes and well-developed crystals of many other species (*Figure 35.7*), including rhombohedral crystals or precipitations of platy crystals of calcite, and dendritic inclusions of chlorite, manganese and iron oxides.

Gas and Liquid

Internal cavities may be liquid or gas filled. The first named may include those cracks filled with solution from which the gem was formed, with water, carbonic acid and other liquids. The cavities in such cases obey the crystallographic laws of the host crystal and are termed negative crystals (*Figure 35.8*), but these cavities may not necessarily have the outline of the crystal forms. These cavities sometimes contain a bubble of gas in the liquid, sometimes called a libella in liquid inclusions, giving what is known as a two-phase inclusion, that is two phases of matter. A still higher development is where the filling consists of three states of matter. In these three-phase inclusions a gas bubble together with one

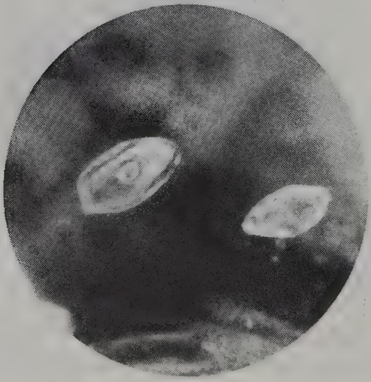


Figure 35.8 *Negative crystals in a Sri Lankan sapphire. A typical example of primary autogenetic inclusions (by courtesy of E Gübelin)*

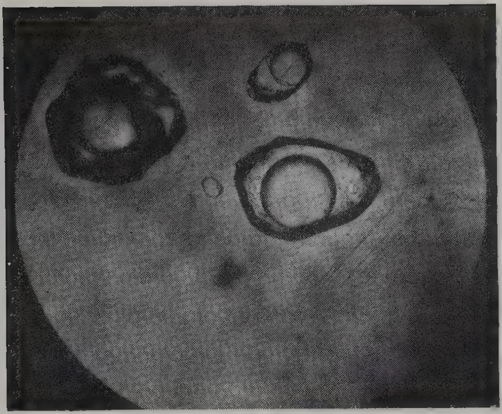


Figure 35.9 *Cavities with libella overlying a feather and with zonal silk in a sapphire. Small triangular markings may be pits in the surface wall of the cavity, or may be tetrahedral crystals, in which case the whole inclusion should be termed a three-phase inclusion*

or more types of liquids and one or more crystals are contained in the fluid inclusion chamber (*Figure 35.9*).

Gaseous inclusions occur as bubbles in natural glasses, such as moldavite and billitonite, and in synthetic stones, as well as in the cement layer of doublets, and in paste and imitation stones.

Internal cracks or fissures are usually classed as inclusions, especially when liquid or gas has entered the crack which may alter the chemical composition or molecular arrangement within the stone and form inclusions. Liquid, when present in the crack, is often distributed in small drops of bizarre shapes producing hieroglyphic or mesh-like patterns forming flags or feathers which have some similarity to the wings of insects (*Figures 35.10* and *35.11*). The liquid

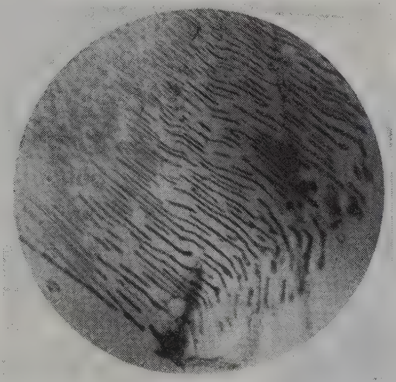


Figure 35.10 *Liquid-filled feather or healing feather in a Sri Lankan ~~sapphire.~~ ~~This~~ is a secondary inclusion (by courtesy of E Gübelin)*

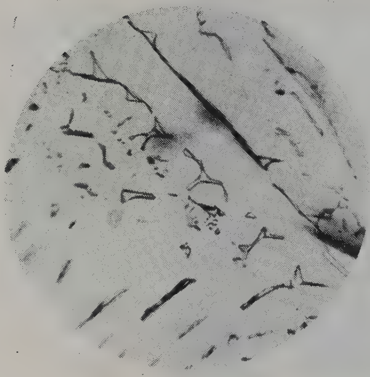


Figure 35.11 Almost completely healed crack with residual, bizarre-shaped droplets in a Sri Lankan sapphire (by courtesy of E Gübelin)

drops which make up such feathers are, on higher magnification, seen to contain a libella (gas bubble). Cracks which contain only fine films of air or liquid if examined under the microscope from above – looking perpendicularly through them – show only the delicate borders of the film, but on viewing the film obliquely a brownish hue may be seen, and in some positions the flag may appear dark owing to the total internal reflection of light. If such fluid inclusion films are thin enough then they are called thin films and will show bright rainbow-like iridescent colours when overhead oblique illumination is employed.

Growth Phenomena

Phenomena due to growth include the fine parallel lines due to repeated twinning (*Figure 35.12*), and zoning, which may be inferred as being due to interruptions or slight changes of composition of the mother-liquid (*Figure 35.13*). Such zoning may show as slight differences in the colour of the neighbouring layers, or it may be marked out by layers of small primary

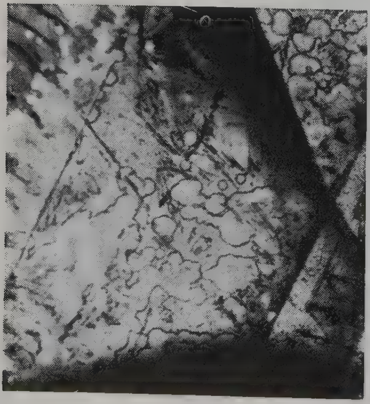


Figure 35.12 A practically healed crack which has run across various twin lines in a Myanmar sapphire (by courtesy of E Gübelin)

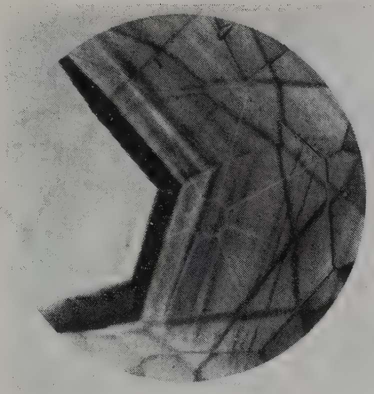


Figure 35.13 Hexagonal zoning. A primary autogenetic feature in a Myanmar sapphire (by courtesy of E Gübelin)

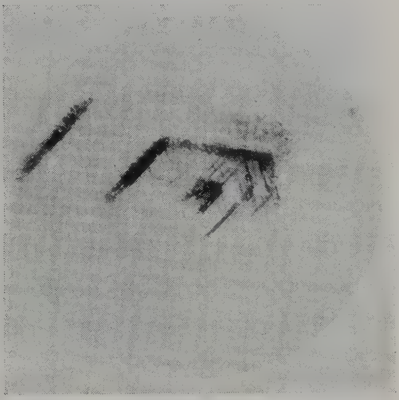


Figure 35.14 Zonal concentration of rutile needles marking previous phases of crystal growth. These are primary xenogenetic inclusions and in this case are in a Sri Lankan ruby (by courtesy of E Gübelin)

Figure 35.15 Primary exogenetic inclusions formed by the natural melting and rupturing of tiny inclusions which were captured during growth. The halos are stress fractures surrounding these inclusions. A sapphire from Thailand (by courtesy of E Gübelin)

xenogenetic crystals (*Figures 35.14* and *35.15*). Interrupted growth, which in natural species forms straight and angular striations, also causes the curved bands and lines in flame-fusion synthetic corundums, for the periodic accretion of material is made on the slightly arched dome of the boule.

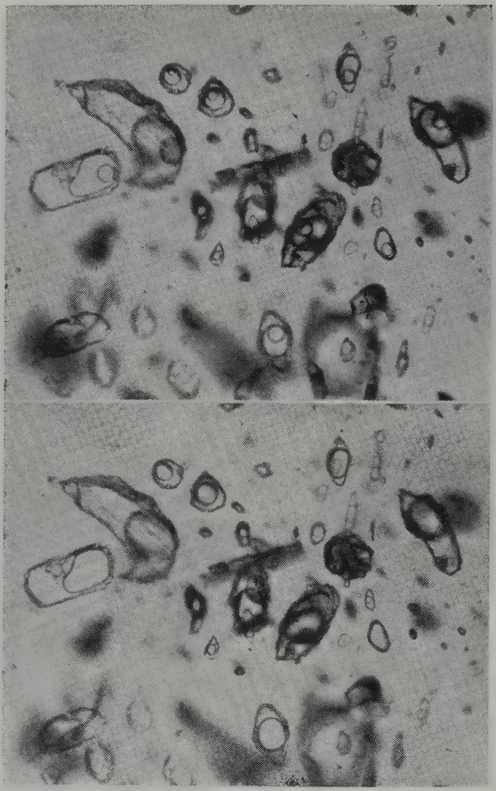


Figure 35.16 The disappearance of a gas bubble on warming in a cavity containing two immiscible liquids. Yellow beryl from Madagascar

Heat Effects on Fluid Inclusions

It often surprises observers to find that a bubble in an inclusion diminishes in size on gently warming the stone and finally disappears. This effect can occur in cavities containing only one liquid and one bubble, or in those where there are two immiscible liquids and one bubble, in which case only the bubble will disappear while the meniscus between the liquids will remain. The most active of these inclusions are ones in which the surrounding liquid is carbonic acid which has a critical temperature of 31.1 °C, and when the heat of the microscope lamp, or even of the fingers, warms the stone to the temperature at which the liquid surrounding the bubble becomes gaseous. *Figure 35.16* shows this effect in a yellow beryl.

With the prevalence of heat treatment today, any fluid inclusions are potential points of disaster for their hosts. Many fine gems, particularly sapphires and rubies, have been seriously damaged during attempted heat treatment owing to the presence of fluid inclusions. During heating the pressure builds up dramatically inside these inclusions. If the temperature of treatment

Figure 35.17 *Fluid inclusion in a Sri Lankan sapphire which exploded during heating, damaging the host (by J I Koivula, GIA)*

exceeds that of the original formational temperature of the gem, as it usually does, then the pressure will be violently released through explosion of the inclusion. Just such a fluid inclusion burst is shown in *Figure 35.17*. Sri Lankan corundums are particularly susceptible to this type of damage. That is because they contain carbon dioxide fluid inclusions which have been shown experimentally to explode when temperatures exceed 400 °C, which is considerably lower than the normal 1500 °C or more required to successfully heat treat corundum.

One other factor to consider here is the presence of solid inclusions. With temperatures exceeding 1500 °C many solid inclusions are actually melted during heat treatment. Once melted they then behave as would any fluid inclusion. This is the cause of the glassy-looking discoid fractures surrounding rounded anhedral inclusions in heat-treated corundums. Such inclusions have in fact become characteristic identification features for heat treatment (*Figure 35.18*).

Zircon Halo Inclusions

The so-called zircon halo inclusion which consists of brownish 'wings' surrounding a small zircon crystal (*Figure 35.19*) needs comment. The haloes round the small crystal were first thought to be due to local alteration of the substance of the host mineral by radioactivity from the included zircon. This notion is not now thought to be the true cause and the view is taken that the brownish marks are simply stress cracks caused by unequal thermal expansion of the zircon and the host mineral. Mitchell has suggested that the expansion

Figure 35.18 A solid inclusion in a natural sapphire which melted and ruptured its host during heat treatment, now forms a diagnostic discoid fracture (by J I Koivula, GIA)

Figure 35.19 Zircon halo inclusion in an almandine garnet

may not be thermal but may be due to an increase in the size of the included zircon crystal which has degenerated to the metamict type.

As a final note: all those interested in the study of inclusions are recommended to read Gübelin's book *The Internal World of Gemstones*, and the *Photoatlas of Inclusions in Gemstones* by Gübelin and Koivula.

36

Luminescence

Emission of Visible Light

The emission of visible light from a substance at room temperature has intrigued mankind from the earliest times, and is a phenomenon which today has many applications in art and industry. In the study of gemstones these various coloured glows may give useful diagnostic information, the value of which is increasingly being appreciated.

There are various types of this 'cold light', all of which depend upon the stimulation of the atoms of the substance by the reception of some form of energy. What may well have been the earliest observations of this phenomenon were of the luminous glow produced by fire-flies, glow-worms and decayed organic matter. This bioluminescence depends upon the oxidation of the chemical make-up of the substance, and is simply one manifestation of chemiluminescence, which is so well illustrated by the glow given off by oxidising phosphorus. Hence the effect was known under the name phosphorescence, a term now restricted to the afterglow which is a light emission after previous exposure of the substance to radiation.

Luminescence may be induced in some substances by rubbing. Termed triboluminescence, this effect has been known for more than 100 years. Ball mentions in his work on gems and ornamental stones of the American Indians: 'The Pueblo Indians of the upper Rio Grande during their rain ceremonies, beat the drum to imitate thunder and rubbed together pieces of quartz to produce an incandescent glow simulating lightning.' At Mecos, New Mexico, a cylinder was found set in a rectangle with a shallow groove into which the cylinder exactly fitted, both of white vein quartz. The cylinder is about 75 mm long and 12 mm in diameter. It was known that 'lightning sets' were still used in religious ceremonies at San Ildefonsa, and so experiment was made of rubbing the cylinder in the groove: finally the stones became visible in a strange pale glow which flickered and died for all the world like distant lightning. Here we have a perfected machine perhaps 700 years old. The first

Indian to observe the luminescence of quartz must have done so centuries earlier.

Sugar will give a similar effect if it is crushed by a spoon against the side of a basin and the luminescence is observed in complete darkness. The dull, cinder-like variety of zinc blende from Tsumeb, Namibia, exhibits orange-coloured 'sparks' if lightly rubbed or scratched by another mineral or metal blade.

Diamonds emit light when rubbed, as was discovered by Robert Boyle in 1663, and Kunz found that all the diamonds he tested exhibited the phenomenon after being rubbed on wood, wool or some metals. The effect was most markedly seen on rubbing against wood in a direction against the grain. Some materials exhibit luminescence on heating below the temperature of incandescence. This thermoluminescence, as it is termed, will be further mentioned when photoluminescence is discussed, for the effects have much in common.

Photoluminescence, the type of luminescence most useful to the gemmologist, is excited by an incident radiation of short wavelength, such as ultra-violet light and X-rays, causing the emission of light in the visible range during the period of irradiation. This effect is known as fluorescence, from the mineral fluorspar, which as a rule shows the phenomenon quite strongly. In some stones the emission of a visible glow continues for some time after the exciting radiation has been cut off. This afterglow is called phosphorescence.

Historically, the earliest observation of this type of luminescence was probably the fluorescence seen in aqueous extracts from woods which were employed in early pharmacy.

The beginning of the recognition of these effects in solid substances was the experiments of one Vicencio Casciarola, a bootmaker and alchemist of Bologna. Casciarola, in 1602, calcined the mineral barium sulphate, which, probably owing to the impurities present, produced a phosphorescent alkaline earth sulphide. This was known as Bologna stone.

The first really scientific investigation of the phenomenon of photoluminescence was carried out by Becquerel about 1859, who studied the luminescence of such materials as fluorspar, calcite, ruby and diamond. Other work was carried on about this time by Herschel and Sir David Brewster. Later Verneuil, of synthetics fame, and Lenard made further contributions to the knowledge of photoluminescence.

Right up to the time of Herschel the opinion was that fluorescence was nothing but diffusion or dispersion of the incident radiation. Stokes thought otherwise, and suggested that the light was a new creation due to the absorption of the more refrangible radiations. Experiment proved that the incident light, once having excited fluorescence, was unable to excite further fluorescence in a similar substance. From this, Stokes inferred that the rays which provoked the fluorescence were absorbed by the fluorescing material, and he established the general law, known as Stokes's law, that the fluorescent glow always has a longer wavelength than the exciting radiations.

In the closing decades of the nineteenth century, Sir William Crookes carried out a number of important experiments with diamond, in which he used cathode rays as a means of excitation. Luminescence developed by such means is termed cathodoluminescence (CL), and is the emission of visible light from a substance in response to the incidence of high-energy electrons. Cathodoluminescent properties of minerals and gems have become more widely known in the last thirty years with the increased use of electron microscopes and electron microprobes. These instruments use 'hot cathodes' which emit electrons from a high-temperature filament under high vacuum.

Perhaps of more convenience for gemmological studies are those instruments employing a 'cold cathode' technique under a relatively low vacuum and at voltages up to 20 kV. For this method, gems do not have to be coated (and subsequently cleaned), and so the whole process is potentially quicker and involves less interference with the sample.

The absorption spectra of gemstones are well understood as a ready means of distinguishing some gemstones. These absorbed wavelengths of light represent an apparent loss of energy; but in nature nothing is ever lost, so what has become of the energy? Most of the absorbed energy becomes converted into heat radiation, and this agrees with Stokes's theory that the absorbed light is re-emitted as radiation of longer wavelength. Stokes's law has since been found to be not universally true, but the 'anti-Stokes' effect need not be considered in detail for gemmological purposes.

So far we have considered the absorption in the visible part of the spectrum, but the same effect can be found to apply to those parts of the electromagnetic spectrum beyond the visible red and violet. Thus, if absorption takes place in the invisible part of the spectrum at shorter wavelength than the visible range it could be expected that any emission may be in the visible spectrum and produce a coloured glow. Such effects do occur and cause fluorescence.

Light and the Structure of the Atom

In the general understanding of light phenomena, gemmologists pay most attention to the wave theory of light propagation, which answers most of the problems encountered. To understand fluorescence it is more appropriate to refer to the 'quantum' theory concepts of Planck and Einstein. These postulate that though the wave character of light has to be maintained, the energy which is carried by these waves has a corpuscular nature in which light is assumed to be composed of units called 'photons' or 'quanta'. Further, an atom can only absorb or emit a definite quantity of light, this quantity being one photon of a given frequency (wavelength).

This principle was further developed by Niels Bohr, who stated that an atom can only exist in certain energy states (or levels). The lowest of these is termed the 'ground state', and those of higher energy are termed 'excited states'. Further, these energy levels are discrete and the atom can only absorb, or emit, light of certain discrete wavelengths.

Acquaintance with the terms used in describing the structures of atoms is necessary in order to understand some of the reasons for the fluorescent effects observed in gemstones. Effects such as phosphorescence after fluorescence, why some stones show stronger effects in long-wave ultraviolet while others have a stronger fluorescence in short-wave, and why some rubies containing iron show weaker fluorescence than those without (fluorescence quenching), may all be explained by current theories of atomic structure.

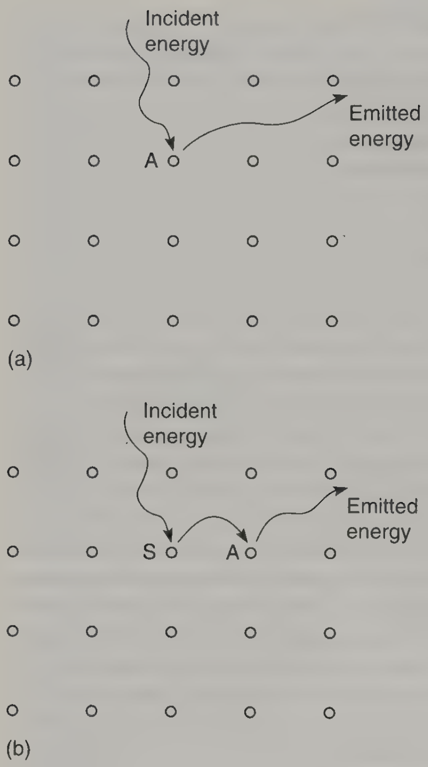


Figure 36.1(a) Atoms (○) of a substance containing an activator (A), and the process of luminescence. (b) Substance containing a sensitiser (S) atom next to an activator (A), and the process of energy transfer from S to A

Photoluminescent materials generally consist of a host crystal structure with a small amount of an activator; a few materials also contain a sensitiser, which enables the activator to function. These two situations are shown diagrammatically in *Figure 36.1*.

The energies of the ground and excited electronic states of a luminescent centre may be illustrated in a diagram showing energy levels and their variation at different distances from the nucleus (*Figure 36.2*). The lower curve shows the ground state profile of potential energy with different vibrational energy states; the minimum of the curve lies at the equilibrium bond length of two neighbouring atoms. The upper profile or curve is for a typical excited state.

The process of luminescence can be illustrated in the following way. Energy raises the active centre from its ground state A to level B in the excited state; some energy is then generally lost and the excited state falls a little to level C; the active centre then falls to level D or returns to level A, emitting energy. Since the energy of excitation A to B is higher than that of emission C to D or C to A, the emitted radiation is of longer wavelength, thus accounting for the Stokes shift.

Where activators and sensitisers are present in the crystal structure, the processes involved in luminescence are shown in *Figure 36.3*. The transition is known as non-radiative energy transfer and depends on the proximity of the

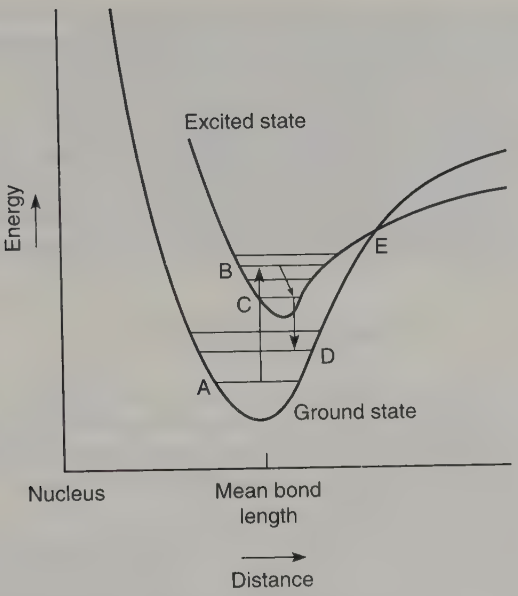


Figure 36.2 Fluorescence: an electron taking energy from the incident ultra-violet radiation moves from a vibrational level in the ground state to a vibrational level in the excited state. It may then relax to a different vibrational level before moving back to the ground state with the emission of light.

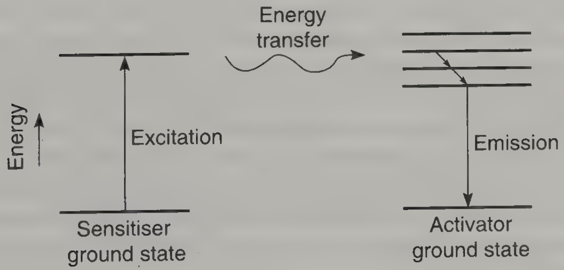


Figure 36.3 Energy transfer involved in the luminescence process with a sensitiser and activator in the crystal structure

activator and sensitiser atoms and on their having similar energy levels in their excited states. Emission takes place when the activator returns to the ground state.

In some crystals, activators or sensitisers may be close to atoms with so many energy levels that their energy is transferred, only to be lost to the host structure in the form of vibrational energy: in other words there is no emission of light. Such atoms quench or poison luminescence, and well-known examples included iron and nickel.

An absorption of energy which transposes an electron from the inner stable orbit round the nucleus of the atom (ground state) to an outer orbit (excited state) can be emitted as light (fluorescence) if the electron spontaneously returns to the ground state. When some of the excited electrons do not immediately return to the ground state but pass into a metastable level of somewhat smaller energy, they may be 'trapped' until further energy is available. This is generally in the form of heat, imparted by the surrounding medium, which allows a return to the initial excited state from which a return to the ground state with the emission of light is possible. By convention, when this emission occurs more than 10^{-8} s later than the incident radiation, it is termed phosphorescence.

Ultra-Violet Light

Photoluminescence may be stimulated by ultra-violet radiation, and for practical purposes, owing to the ease of their production and their isolation from other rays, those wavelengths which comprise ultra-violet light are most suitable for use by gemmologists. It is these rays, their production and their effects which will now be considered.

Ultra-violet light may be said to cover the wavebands from 400 nm, that is at the end of the visible violet, down to 10 nm, which may be said to be the commencement of X-rays. However, below 200 nm the rays are useless for practical purposes for they are intensely absorbed by air and any work with them needs to be done in a vacuum.

The region from 400 nm to 200 nm is the practically usable range of wavelength, and although the most spectacular effects are undoubtedly induced by near ultra-violet radiation, the short-wave ultra-violet light may in certain cases be the more diagnostic.

Ultra-violet radiation is produced by solar emission, but owing to atmospheric absorption no wavelengths shorter than 295 nm reach the earth. An electric arc set up between iron or carbon electrodes, or electric discharges through hydrogen, argon, xenon or mercury vapour at low pressure, also emit ultra-violet light, but all sources emit considerable visible light which masks any luminescent glow from a fluorescent substance. To overcome this a screen or filter, which will cut out the visible light but allow the required waveband to pass, must be interposed between the light source and the specimen to be irradiated, the specimen being in darkness with the invisible ultra-violet rays impinging upon it.

Wood's Glass Filter

The filter most commonly used to cut out the visible light from a radiating source, and yet pass the long-wave ultra-violet light, is a cobalt glass with about 4 per cent of nickel oxide. This filter, devised by Wood and usually known as Wood's glass, passes the wavelengths between 400 nm and 300 nm with the maximum transmission at 365 nm (*Figure 36.4*).

One of the simplest methods of observing long-wave ultra-violet luminescence can be carried out by screening a suitable source of radiation by a 'window' of Wood's glass and allowing the transmitted ultra-violet rays to impinge on the specimen which is itself in darkness. Thus a suitable dark box in

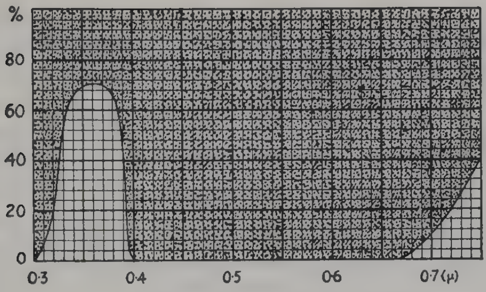


Figure 36.4 Spectrum of radiation transmitted by OX1 or Wood's glass

which to view the specimen may be fitted with a Wood's glass window, which, when directed to a ray of sunlight, will give some fluorescent effects; stronger effects are obtained from a photo-flood source.

Long-Wave Medium-Pressure Mercury Lamps

An easily controlled source of ultra-violet light is that produced by a medium-pressure mercury arc, having a pressure of 1–10 atm, generated between solid electrodes by a high-tension current, the electrodes and mercury being enclosed in a tube of fused silica. This is housed in a suitable reflector to the front of which is fitted a light-tight cover, containing a window of Wood's glass or other suitable filter.

The mercury arc produces an emission spectrum having strong lines in the visible part of the spectrum at 579, 577, 546, 435.8 and 404.6 nm, that is in the yellow, green, blue and violet, which account for the greenish-blue colour of the light emitted by the unshielded mercury arc lamp. In the invisible ultra-violet there is an exceptionally strong line at 365 nm with weaker lines at 398.4, 390.6, 365.4, 334.1, 313.1 and 312 nm. It is these lines which are passed by the Wood's glass filter and supply the long-wave ultra-violet light. Below 300 nm the only strong line is at wavelength 253.7 nm which is the resonance line of mercury.

Another type of ultra-violet lamp is the so-called 'black lamp'. This lamp gives a large spread of ultra-violet light, but if the Wood's glass in the bulb is thin, it transmits rather more of the deep red and violet visible light than is convenient for analytical employment. It is suggested that for the accurate use of such a lamp, a subsidiary Wood's glass screen be available to interpose between the lamp and the article being examined. Further, the employment of a quartz or quartz glass lens to concentrate the ultra-violet light on to the subject is of great advantage. This is particularly so when the fluorescing article is on the stage of a microscope and the luminescence is observed through the microscope – a technique which is of value for small items.

Medium-pressure mercury vapour lamps take from 2 to 4 minutes after switching on before they attain full brightness. If they are switched off, or if the electric supply is interrupted, they must cool down before they will relight; but if they are left switched on, relighting takes place automatically when they are sufficiently cool.

A long-wave ultra-violet lamp now more commonly used than the medium-pressure lamp is a modification of the fluorescent tubes so commonly used for office and workshop lighting. Such a lamp generates the bright visible light by an electrical discharge through mercury vapour at low pressure. This emits short-wave ultra-violet light which causes a highly fluorescing powder coated on the inside of the tube to glow with a bright light. The glass of the tube is of such a type that the harmful short-wave rays are not transmitted. The lamp for ultra-violet emission has as its internal coating a compound which luminesces with only ultra-violet light and some violet light, and again the glass does not transmit the short waves and much of the visible light. The range emitted by this lamp is from about 410 to 300 nm. Such a lamp is illustrated in *Figure 36.5*.

Figure 36.5 The Allen long-wave fluorescent ultra-violet lamp which produces continuous radiation between 410 and 300 nm

Short-Wave Filter

The short-wave region from 300 to 200 nm is of considerable value in gem diagnosis. *A priori* it might be thought that a suitable filter to isolate the strong mercury resonance line at 253.7 nm from the mercury arc produced in the medium-pressure lamp would provide the required source of short-wave ultra-violet light. If such a filter were available this may well be done, but such a filter does not exist commercially. Therefore some sort of a compromise is needed. Such a compromise is a filter which passes as much of the 253.7 nm line as possible and as little as possible of the 365 nm band and visible light, combined with a lamp which will not emit so much visible glow or long-wave ultra-violet light.

This is effected by using an electrical glow discharge through mercury vapour, in a quartz tube, at a low pressure of 1 or 2 mm Hg, and in this arrangement the 253.7 nm line is much more pronounced relative to the 365 nm band. The visible glow is very much reduced and bluer in colour. Further, the tube operates practically cold, unlike the medium-pressure lamp which gives off considerable heat. This is important because the Wood's glass filter can be made of heat-resisting glass whereas the filter used for short-wave operation cannot, and thus tends to crack easily. A short-wave filter, such as the Chance OX7 filter, becomes a much more efficient separator of the short-wave radiation when the low-pressure tube is used. The transmission of the OX7 filter is shown in *Figure 36.6*.

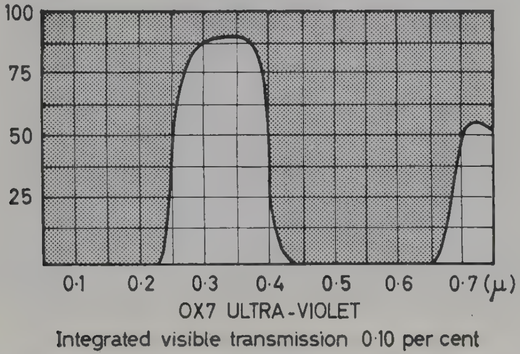


Figure 36.6 Spectrum of radiation transmitted by the Chance OX7 filter

Short-Wave Lamps

Short-wave ultra-violet lamps may be mains or battery operated and some are of sufficiently small size to be portable. *Figure 36.7* shows a hand-held battery-operated unit incorporating a 4 W lamp.

The germicidal lamp made by Philips, which consumes only 7 W, has an envelope which will pass ultra-violet light down to 185 nm. Such a lamp, owing to its richness in the 253.7 nm line, its lower intensity of the 365 nm band and its low emission of luminous glow (*Figure 36.8*), can be an efficient and comparatively inexpensive source of short-wave ultra-violet light in conjunction with an OX7 filter. *Figure 36.9* shows the make-up of the lamp itself which operates directly off the 200–250 V AC mains. The initial starting is brought about by a trace of neon which has no appreciable effect on the luminosity except for an orange glow surrounding the electrodes, the remaining visible light being the blue glowing column of light between the two electrodes due to the mercury vapour. It is a simple job to make a light-tight housing for such a lamp, with an aperture fitted with an OX7 filter which should be placed as near as possible to the lamp itself. A reflector made of polished aluminium, which is the most efficient reflector of ultra-violet, may be incorporated. The ranges of

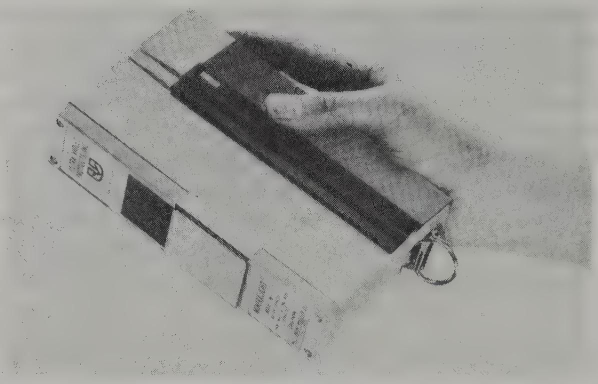


Figure 36.7 *A portable battery-operated LW/SW ultra-violet lamp (U-V Products Ltd)*

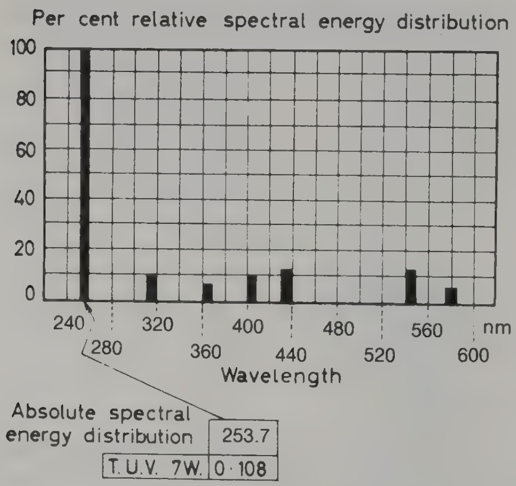


Figure 36.8 *Spectral energy distribution of Philips TUV 7 W germicidal ultra-violet discharge tube*

ultra-violet emission of a range of ultra-violet lamps is shown by the spectrograms in *Figure 36.10.*

Combined long-wave and short-wave ultra-violet lamps are also on the market. The two wavebands can be produced either by using two units and switchgear, changing the current from one to the other, or by moving a cover slide to expose one source and cover the other.

Photographing Fluorescence

The fluorescent glows given off by many gemstones may be photographed, as has already been mentioned in connection with the differential fluorescence of

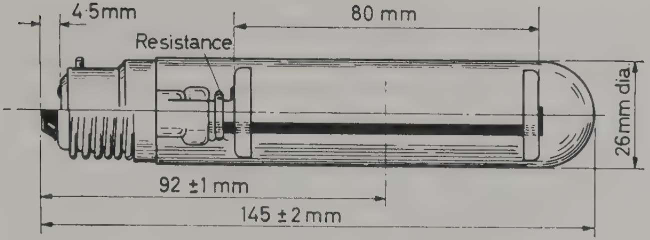


Figure 36.9 The Philips TUV 7 W germicidal ultra-violet discharge tube

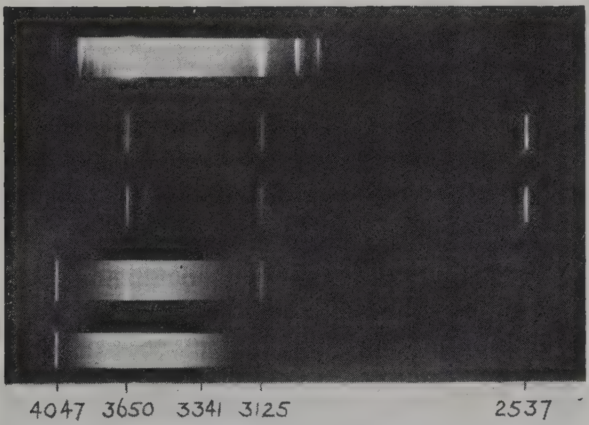


Figure 36.10 Spectrograms showing the emission of some ultra-violet lamps. From the top: Hanovia long-wave lamp with Wood's glass filter; Philips TUV 7 short-wave lamp with Chance OX7 filter; Mineralight short-wave lamp; Longlamp extra-long-wave ultra-violet lamp; Burton extra-long-wave ultra-violet lamp

diamond. All that is needed is a source of ultra-violet light screened by a suitable ultra-violet passing filter. The medium-pressure long-wave lamp with a Wood's glass filter is best, although the 'fluorescent' long-wave lamp or the short-wave lamp with their respective filters will also produce results, but it must be remembered that the luminescent response may be different when these lamps are used. There is also the fact that these lamps generate radiation further into the visible region and thus an ordinary picture may be superimposed on the photograph of the luminous glows.

Any suitable camera will do, but it is best to use one which has a focusing screen whereby the object can be viewed through the actual camera lens (studio camera or single-lens reflex camera). The camera should be held on a rigid support, especially if long exposures are necessary, and in front of the camera lens must be placed an ultra-violet absorbing filter. The ultra-violet lamp is placed in position to 'illuminate' the object, the camera is focused and usually set at full aperture, and a suitable exposure is given. This can range from seconds to hours, but much depends on the brightness of the stone(s), their fluorescent colours and the film used. Only experience can tell what is best. If the work is being carried out for, say, diamond certification, then details of the lamp, the distance from lamp to object, and the type of film must be appended to the certificate so as to ensure comparable results when new photographs are taken for checking purposes.

One method of examining phosphorescence is to employ an unscreened photoflash lamp. Such bulbs give a momentary 'burst' of light, often over 300 000 candelas in intensity, after which the phosphorescence of the specimen irradiated may be seen. The presence of weak phosphorescence (but, of course, not its colour) may be ascertained by placing the specimen on a photographic film in a dark-room and keeping for a few hours in a light-tight box. On developing the film a darkening showing the outline of the stone will be seen if the stone phosphoresces. These have been termed fluograms or luminograms (*Figure 36.11*). Indeed, should the emitted radiations be in the ultra-violet instead of the visible region the appropriate film will detect this ultra-violet phosphorescent response.

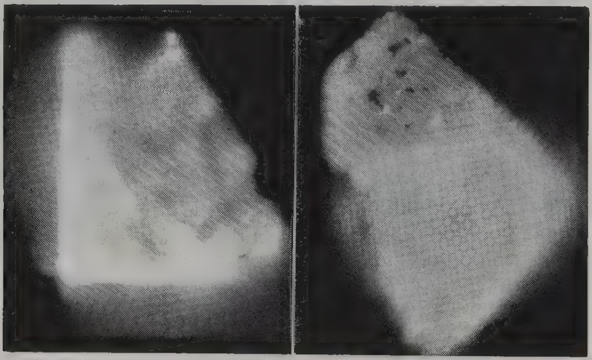


Figure 36.11 Images formed on film by phosphorescing fluorspar (fluograms)

Precautions in Use of Ultra-Violet Equipment

A word of warning is necessary regarding the use of any ultra-violet equipment, particularly short-wave equipment. The human eye is vulnerable to ultra-violet, and exposure can cause a burning and subsequent scarring of the epithelial layers of the cornea; also inflammation (conjunctivitis) may be felt some hours after irradiation. Longer exposures may also produce skin reddening similar to the initial stages of sunburn; this may cause discomfort without the benefit of a lasting skin tan. This effect does not appear until an hour or so after the exposure and may then last for hours or even days.

These observations are included for general guidance, but the worker need not be apprehensive of danger. It is not necessary to look directly at the ultra-violet source; even so, it is not dangerous to look directly at the beam from a long-wave ultra-violet lamp (providing that the Wood's glass filter is in position). True, in such a case the eyeballs tend to fluoresce and make everything appear misty. Do not, however, look directly at a medium-pressure

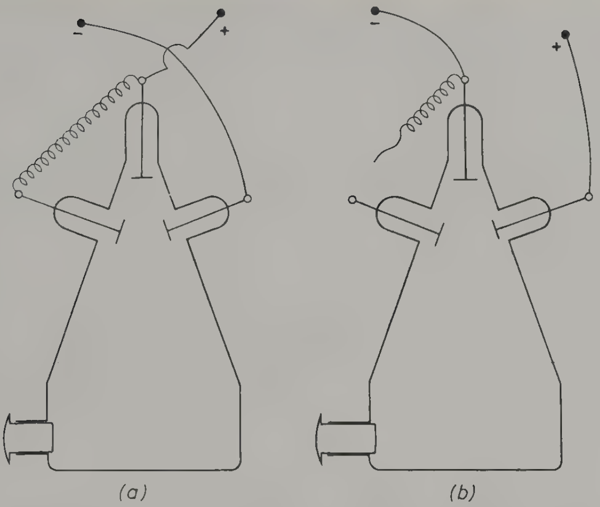


Figure 36.12 The arrangement of the electrodes in the dual-purpose bulb used in the Herz cathode ray and X-ray luminescence unit: (a) electrodes connected for production of X-rays (b) electrodes connected for production of cathode rays

mercury arc lamp (or an arc lamp) without the filter on, for there is nothing to stop the physiologically dangerous rays of short wavelength (around 253.7 nm). Thus, never look directly at a lamp passing these short-wave ultra-violet rays unless wearing glasses, which, even if made of ordinary plain glass, will stop the 253.7 radiation. They also afford a great measure of protection from direct rays and from the object and surrounding surfaces.

Cathode Rays and X-Rays

The excitation of luminescence by electrons or cathode rays (cathodoluminescence) requires the use of special apparatus which is generally available only in large laboratories. During the 1920s Michel and Riedl of Vienna commissioned the firm of G L Herz to make apparatus for the production of cathode rays and X-rays for the study of gemstone luminescence. The specimen to be irradiated was placed in the glass bulb and the air in this was subsequently evacuated by a mercury pump. The evacuated bulb contained three electrodes, which by altering the outer connections could be arranged to produce either electrons (cathode rays) or X-rays at will. *Figure 36.12* shows how this is done. The whole equipment – the cathode ray bulb, the X-ray bulb, the mercury pump and the induction coil and battery for the generation of the high-tension current – was housed in a portable cabinet. Michel and Riedl carried out a considerable amount of work on the luminescence of gemstones by this type of apparatus. One of the first investigations of cathodoluminescence in sapphires was carried out by St Clair, using the cathode ray tubes designed by Coolidge. St Clair found that synthetic sapphires phosphoresced while the natural stones did not, and, further, that synthetic stones turned decidedly brown when placed in a beam of cathode rays whereas the natural stones did not.

Recent work by Ponahlo describes the quantitative and spectral CL properties of natural and synthetic gems, particularly diamond, ruby and emerald, and the indications are that some distinction can be made by measuring CL intensities. One spectacular feature of CL studies and spectra has been the revelation of crystal growth detail in stones which look optically homogeneous, and this has considerable potential application in gem testing.

The apparatus needed to generate X-rays is fully discussed in the following chapter. The only procedures to be followed when luminescence effects are to be seen is to mask the light from the filament in a hot cathode tube, or to mask completely the fluorescence from the glass of the tube in gas tubes. As most of the modern tubes are completely shielded, with the exception of the window through which the X-rays are directed, all that is necessary is to fit a screen into this aperture to stop the light coming through.

In all observations of luminescence a dark-room, or dark-box, is necessary in order to see the sometimes weak luminescent effect.

The physiological dangers by radiation damage through X-rays are real, but if care is taken not to expose any part of the body to the direct X-ray beam – any observation of luminescence being studied through a thick lead-glass window – no harm will come to the operator. Modern X-ray sets are well shielded.

Crossed Filters

In the second part of the great paper by Stokes, published by the Royal Society in 1853, he described a very convincing technique for observing fluorescent effects which served to demonstrate the truth of his contention that the phenomenon of fluorescence involves a change in the 'refrangibility' (wavelength) of the incident light which stimulates the effect. It was, incidentally, in this part of his paper that he suggested and adopted the term 'fluorescence' to describe the phenomenon.

Stokes's method made use of pairs of complementary colour filters, coloured light transmitted through one being absorbed by the other, resulting in darkness. When a glow was produced by light passing through the first filter, then through a stone, and then through the second filter, it was quite clear that a change in wavelength had occurred within the stone. Anderson, in commemorating the centenary of Stokes's discovery, carried out similar experiments as a lecture demonstration and found the results so attractive that he recommended it to gemmologists in a paper 'Crossed filters for the study of fluorescence' (*Gemmologist*, March 1953). The term 'crossed filters' was suggested as more descriptive than Stokes's term 'complementary filters', since in their action they were clearly analogous to the familiar terms 'crossed nicols' or 'crossed polars'.

The most useful pair of filters for gemmologists was found to consist of a round flat-bottomed flask containing a concentrated solution of copper sulphate 'crossed' with almost any red filter as used for photography. With light from a 500 or 250 watt projection bulb or other powerful source passed through the screened-off flask on to gemstones such as ruby or spinel and examined through the red filter, a truly spectacular effect is seen of a bright red glow against a dead black background – a far more impressive demonstration than that given by the customary long-wave ultra-violet lamp.

Examination of the glowing stones through the spectroscope shows, in the case of ruby, the powerful red doublet at 692.8 and 694.2 nm, and their weaker accessory lines, while with red spinel the curious and completely diagnostic 'organ-pipe' group of fluorescence lines provides a strong indication that one is dealing with natural spinel since most synthetic red spinels display a strong 685 nm line with two weaker lines accompanying it (*Figure 36.13*). Of the other well-known gems coloured by chromium, pink topaz, alexandrite and emerald all show a red glow between crossed filters, the fluorescence of synthetic emeralds being usually much more pronounced than that shown by natural stones.

Mitchell has shown that if natural and synthetic emeralds are placed in a pool of blue light formed by a strong light source which has passed through a copper sulphate filter, and the stones are viewed through an infra-red filter (as used for infra-red photography), the synthetic emeralds will show up a brilliant red while the natural emeralds will scarcely show.

Characteristic Fluorescence of Stones Under Radiation

The use of luminescent effects in gem testing is based on the characteristic fluorescence given by the stone under radiations of different wavelength, for the response may not be the same for different ranges of radiation. In general, the long-wave lamp gives the more spectacular results so far as the production of visible light in luminescent substances is concerned, but often the usually much weaker glows induced by the short-wave lamp may be more diagnostic, and so may be the fluorescence induced by X-rays.

While the glow emitted by the stone under one type of radiation can aid diagnosis, the comparison of the results shown by the stone under two, or maybe even three, types of radiation can greatly increase the value of luminescence as a diagnostic method. Thus diamond, which usually gives a blue or violet glow of variable intensity under long-wave ultra-violet light, responds weakly to the short-wave ultra-violet rays, while under X-rays the stones fluoresce with a bright violet light or whitish-blue light. Further, diamonds which glow with a strong blue light under the long-wave lamp are found to show an afterglow (phosphorescence) of yellow colour; the blue fluorescence coupled with yellow phosphorescence is diagnostic for diamond as no other blue fluorescing mineral phosphoresces yellow. Synthetic gem-quality diamonds show nil or very faint fluorescence under long-wave ultra-violet, but fluoresce and phosphoresce greenish-yellow or orange-yellow under the short-wave lamp (see Chapter 18).

Synthetic colourless sapphires and spinels and colourless pastes, all stones which if small and mounted in jewellery can be difficult to determine, show only a weak response, if any, to radiations from the long-wave ultra-violet lamp. Synthetic white sapphire usually responds with a rather dim deep blue glow. Colourless synthetic spinels and colourless pastes, however, show a whitish-blue glow under short-wave ultra-violet. Under X-rays the synthetic white sapphires may show a red glow and the colourless spinels a green or blue glow.

Under the long-wave lamp, ruby, red spinel and alexandrite, which owe their colour to the chromium ion, fluoresce with a strong red glow, but emerald may

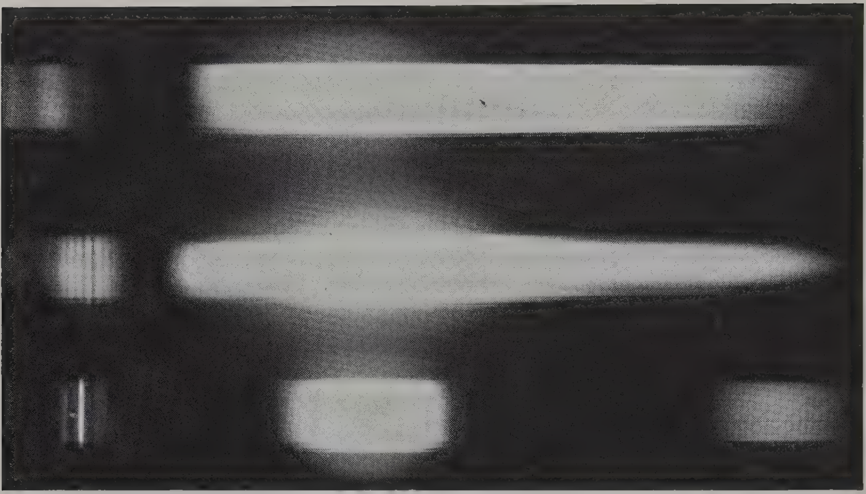


Figure 36.13 Fluorescence spectra of synthetic emerald (top), natural red spinel (centre), and ruby (bottom), excited by photoflood lamp and filtered through copper sulphate solution.

show red, brown or green. The synthetic green spinel which is coloured by chromium, and the synthetic blue spinel which is coloured by cobalt, also show the red glow under the long-wave ultra-violet lamp, but under the short-wave radiations the glow is the whitish-blue common to most synthetic spinels; this glow in coloured synthetic spinels is often modified by the body colour of the stone. The strong crimson glow shown by rubies and red spinels when under any of the radiation wavebands is of value in separating those stones from other stones of red or pink colour. Synthetic emeralds tend to show stronger luminescent effects under long-wave and short-wave ultraviolet radiation than natural stones, with red emphasised at the expense of green, but this method should not be used as a critical test.

It is well known that the chromium phosphor is strongly activated by blue and violet light, and that it is the long wavelengths of the near ultra-violet and the visible violet light emitted by the 'fluorescent-type' lamp which causes the strong fluorescence in synthetic emerald. The Wood's glass filter in the normal long-wave ultra-violet lamp does not pass these longer wavelengths and such lamps are less useful for the distinguishing of synthetic emerald. That such a crimson glow is not given off by some natural emeralds may be accounted for by a trace of iron as an impurity which quenches the fluorescence.

Benitoite, scheelite and most synthetic spinels, except the red synthetic spinel, glow with a blue light when irradiated with the short-wave ultra-violet rays (253.7 nm) but do not luminesce under the long-wave lamp (365 nm). Thus, benitoite can quickly be distinguished from blue sapphire which it so resembles. Synthetic blue sapphires can be detected, or at least suspected, by the stronger dull but deep green glow they show under the short-wave lamp since many natural blue sapphires are inert. In some synthetic blue sapphires the fluorescent glow is banded in conformity with the curved bands of the orginal boule, which can often be seen better under fluorescence conditions than in ordinary light.

Despite the undoubted usefulness of fluorescence properties in the identification of gem species, the results of tests should always be considered with other gemmological properties before reaching conclusions.

Fluorescence Spectrum

When the light from a fluorescing substance is examined by a spectroscope, it may be seen to be continuous or in discrete bands. Banded spectra occur particularly in substances which are activated by uranium, by chromium or, as in diamond, by lattice defects. The effect is important in distinguishing between the chromium-coloured ruby and red spinel. The ruby shows the strong bright doublet at 693.5 nm, with a broader and more diffuse brightish band on the shorter-wavelength side. The natural red spinel shows a group of bright lines around 680 nm (the strongest being 675 and 686 nm). These lines have aptly been called the 'organ-pipe' lines. Some synthetic red spinels show only a single strong line at 686 nm. *Figure 36.13* shows the fluorescence spectra of ruby, natural red spinel and synthetic emerald, and the picture illustrates that the emission in the synthetic emerald is much farther into the deep red. These chromium fluorescence spectra can most easily be examined through a spectroscope by illuminating the specimen with a strong light transmitted through a flask containing a saturated solution of copper sulphate. The bright fluorescent lines are then seen against a black background.

A list of the important fluorescent colours given by gem materials under the different ranges of radiation is given in the identification tables in this book.

37

X-Rays in Gem Testing

Discovery and Nature of X-Rays

The momentous discovery by the German physicist Röntgen in the year 1895, of a type of radiation which passed through material opaque to ordinary light, supplied the key which opened the door to vast advances in science and industry and to our understanding of the nature of matter.

The discovery was purely the result of an accidental or casual observation of something which had no bearing on the experiment being carried out. Röntgen was experimenting with the passage through gases of an electric current, for which purpose he was using a highly exhausted Hittorf tube, a type of vacuum tube where the cathode faces an enlarged end of the main tube, while the anode is situated in a side 'annex' tube (*Figure 37.1*).

The tube at the time of the experiment was completely covered with black paper. Hanging on a wall some distance away was a paper screen coated with barium platino-cyanide which had been used in other experiments. To Röntgen's surprise this fluorescent screen shone brightly when the Hittorf tube was switched on, and, like Fleming in the case of the discovery of penicillin, Röntgen turned from his original experiment to investigate something for which there was no apparent cause.

When objects were placed between the tube and the screen, shadows were

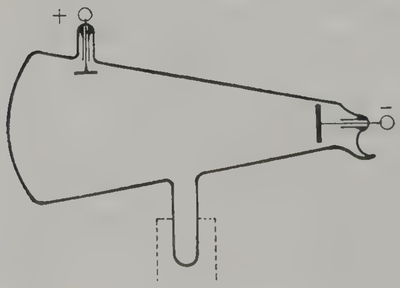


Figure 37.1 An early (Hittorf type) X-ray tube as used by Röntgen in his experiment during the course of which he discovered X-rays

cast; hence the rays were able to pass through black paper, a thing ultra-violet light could not do. Further, the radiations acted on a photographic plate even when the plate was shielded from ordinary and ultra-violet light. Röntgen called these radiations X-rays because their nature was then unknown, and, although they were officially called Röntgen rays after their discoverer, X-rays remains the ever popular term.

Relationship with Atomic Mass

Further experiments showed that the invisible radiations travelled in straight lines. They were, unlike ordinary light, not refracted by prisms or lenses, nor were they affected by a magnetic field, but they could ionise gases. It was quickly noticed that the greater the atomic mass of a substance the greater its opacity to the rays; in other words the absorptive power of a material to X-rays is a function of the atomic mass. For example, carbon, oxygen, nitrogen and hydrogen have low atomic masses and are therefore readily 'radiable' (the term used for the degree of transparency to X-rays); while iron, lead, gold and platinum are elements with high atomic masses and are much less transparent to the rays.

The flesh, made of the light-weight atoms of carbon, oxygen, nitrogen and hydrogen, is much more transparent to X-rays than the bones which contain the heavier calcium and phosphorus atoms; so, by their aid we can see the bones through the flesh when the effect of the radiations is made visible by a fluorescent screen or a photographic plate (*Figure 37.2*). Medical science was quick to realise the importance of the penetrating power of X-rays, and within a few months of Röntgen's discovery they were put to use in the location of a bullet.

Figure 37.2 Radiograph of a child's hand showing the difference in transparency (radiability) of the flesh and bones

Cathode Ray Experiments

When a stream of fast-moving electrons – cathode rays – in a highly exhausted tube with an applied potential greater than 30 000 V strikes a solid object, whether it be the glass walls of the tube or a subsidiary metallic electrode within the vacuum tube, X-rays are produced by the destruction of the cathode rays.

It may therefore appear strange that X-rays remained undiscovered for so long with all the experimental work with discharge tubes going on. Indeed, it was said that Sir William Crookes on one occasion sent back to the makers some photographic plates with the complaint that they were faulty, for when developed they had shadows on them. They had been on a bench and were actually the first X-ray pictures and were of his own fingers. Why these shadows were not recognised for what they were was, probably, due not only to another superimposed picture, but also the large area from which the X-rays were generated, that is the glass of the tube, producing not only the true shadow but a wide and overlapping penumbra as well. Professor Lenard also missed discovering the rays solely because he used in his cathode ray experiments fluorescence screens made of an organic compound which, brightly fluorescent when irradiated with ultra-violet light or cathode rays, was inert when X-rays are used, an effect common with organic materials.

Crystals and X-Rays

Quite early on Röntgen thought that X-rays were some form of light but no verification of the fact could at that time be found. The whole subject was the cause of much controversy which lasted for many years. It was not until 1912 that proof of the nature of X-rays was accomplished. In that year, Max von Laue, an assistant lecturer at Munich, having been approached by a student with a question on crystal optics, was reminded that the then general conception of the structure of a crystal was that it had a regular arrangement of its atomic constituents, and with a linear distance between them of one or two ångströms. He also knew that if X-rays were electromagnetic waves, they would probably be of the short wavelength of about one ångström, a length far too short to be diffracted by any ruled grating as may be used to diffract visible light (1 Å = 0.1 nm).

Laue realised that if a crystal was as so described it would act as a natural grating, and would, if X-rays are short-wavelength light, diffract a narrow beam, or rather, as he was inclined to suspect, scatter the X-rays. Barkla, in 1906, had discovered that matter containing 'heavy' atoms 'scattered' an X-ray beam producing 'characteristic X-rays', characteristic of the heavy atoms. Laue thought this scattering might produce diffraction patterns from a crystal. More will be said about these characteristic rays at a later stage; for the present it may be told that Laue's assumption was incorrect, and the proof he wanted did not come from scattered rays, but from rays transmitted through the crystal.

Two research students, Friedrich and Knipping, who had studied under Röntgen, co-operated in carrying out the experiments. A crystal of copper sulphate was used in the preliminary experiments; copper sulphate is of triclinic symmetry and complex structure. It was possibly the worst type of crystal that could have been chosen, and the fact that their first experiments were arranged to receive scattered radiation, with their photographic plates either between the source of the X-rays and the crystal or at the side and parallel to the narrow beam of X-rays, precluded any success from their initial trials.

Friedrich and Knipping then set up their apparatus so that an extremely narrow beam of X-rays, the beam being limited by a collimating tube of lead, was directed on to the face of the crystal and a photographic plate set up behind it, a position adopted in order to try out every avenue after the failure of the initial experiments. On developing the plate a pattern of spots was seen surrounding the heavy central spot due to the undeviated main beam. They were unsymmetrical but clearly proved the possibility of diffraction of X-rays by crystals.

Further experiments, in which crystals of high symmetry such as zinc blende, copper oxide, fluorspar, halite (salt) and in one experiment a diamond, were employed, supplied further proof of the nature of X-rays. Thus, in one classic experiment sufficient proof was obtained to substantiate the theory that X-rays were 'light' of short wavelength, and that crystals did have a regular atomic arrangement as suggested by theory, and this set the scene for the modern methods of X-ray crystallography.

Production of X-Rays

Continuous Radiation

In many modern X-ray tubes, and in particular for those tubes used for special purposes, such as for crystal diffraction, it is now the more general practice to mount the target so that its surface is at right angles to the cathode stream, and not at an angle of 45 degrees as was formerly universal.

When electrons, accelerated to a high velocity by the positive charge on the target or any positive anode, strike the surface of a solid body, X-rays are produced. If the electron is stopped without making any direct collision with an atom in the target, the violent deceleration is enough to produce a pulse of radiation. This is in accordance with the 'classical' theory of electromagnetic waves. The X-rays so produced form a continuous band of wavelengths whose lower limit is equal to 12.35 divided by the voltage (reckoned in kilovolts); thus the greater the voltage supplied to the tube the shorter is the minimum wavelength produced. This continuous, 'general' or 'white' X-radiation is analogous to white light of the visible spectrum in being a mixture of all wavelengths, down to but not below the shortest wavelength permitted by the impressed voltage.

The intensity of the continuous radiation, which in theory extends to the ultra-violet region (the longest X-rays which reach up to the shortest ultra-violet radiations are termed *Grenze* rays, after the German word for boundary), increases as the voltage increases, and has a maximum or 'hump' just before the minimum wavelength is reached: that is when the bombarding electrons have given up all their kinetic energy in the production of X-rays. Intensity, that is the amplitude of the waveform, is very much a function of the current, in milliamperes, passing across the tube.

Line Radiation

When the energy of the bombarding electrons is powerful enough to ionise the atoms of the target material, radiation of discrete wavelengths is produced. This so-called 'line spectrum', for it is analogous to the 'line' or emission spectrum of ordinary light rays, is known as the 'characteristic radiation', for it is characteristic of the element of the target. It is caused by ionisation by removal of one of the inner electrons which is replaced by an electron from a state of higher energy. Such a mechanism also operates, as Barkla found in 1906, when a beam of X-rays falls upon any material. For, provided that the wavelength of the X-rays incident upon the body is shorter than the characteristic wavelength of the element bombarded, these 'fluorescent' characteristic rays will be emitted. Such induced radiation may provide some of the so-called 'scattered' rays which can be a nuisance when X-rays are employed in certain forms of work.

Filters

It is now seen that X-rays may be produced by two different processes: a continuous band of wavelengths, and a 'line' spectrum. This may be better understood by reference to *Figure 37.3.* Further, it is possible to obtain a near approach to monochromatic X-rays (X-ray of one wavelength only) by the insertion of suitable filters. Such filters are very thin sheets of elements, usually metallic, which have an atomic number one or two lower than the atomic number of the metal of the target. For example: a copper target (atomic number 29) is filtered by a screen of nickel (28), or a molybdenum target (42) by a zirconium (40) filter. The reasons for selective filtering are rather outside the scope of this work and the reader is referred to the many excellent technical books on X-rays for the explanation.

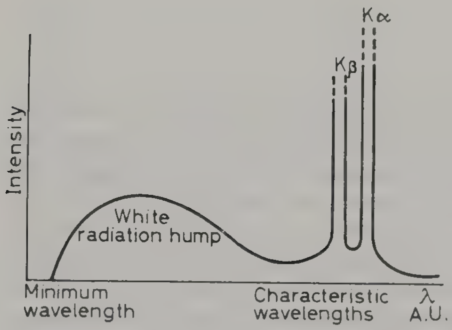


Figure 37.3 Continuous X-ray spectrum with characteristic line spectrum. Shortest wavelength on the left

Use of X-Rays in Gem Testing

The uses to which X-rays may be employed in gem testing depend first upon the fluorescent visible light induced in certain materials by the rays; secondly, upon the variable transparency of different materials to the rays; and lastly, to the effects of diffraction of the rays from the atomic planes of the material.

The most important use of X-rays for the gemmologist is in the testing of pearls. As this specialised subject has been thoroughly dealt with in Chapter 22, it will be omitted from what follows.

Fluorescence

The first of these, that of fluorescence, has pride of place in being the phenomenon which led to the discovery by Röntgen of these very rays. Some gemstones and pearls show a typical fluorescence when bombarded by X-rays, it being necessary to view the effects in a darkened room and to ensure that the visible light from the tube filament is obscured. It is only in recent years that much attention has been paid to the various 'glows' that emanate from a substance which is irradiated with invisible light, of which fluorescence by X-rays is but one example, and is coupled up with the similar phenomena induced by other forms of radiation. This aspect has been discussed in Chapter 36 on the luminescence of gemstones.

Transparency

The difference in transparency to X-rays of different substances has been remarked upon, and it has been found that the radiability depends to a great extent upon the atomic mass of the element or elements forming the substance. The greater the atomic mass the more opaque is the substance to the rays: thus diamond (atomic number of carbon is 6) would be expected to be most transparent; and zircon, containing the heavier zirconium atom (atomic number of Zr is 40), or the lead-glass imitations having the heavy lead atom with an atomic number of 82, would be expected to be comparatively opaque to the rays. This is borne out by experiment and is illustrated in *Figure 37.4*. It must be understood that for comparable results the operating conditions, that is, the voltage and current, the exposure time and the metal of the X-ray tube's target, must be the same.

The German scientist Doelter carried out a number of experiments on the transparency of gemstones to X-rays. He found that amber, diamond, phenacite and jet were quite transparent to X-rays, and corundum nearly so. Chrysoberyl, opal, andalusite and kyanite were less so, while topaz, feldspar, diopside, spodumene and quartz were translucent, and tourmaline, turquoise, peridot and sphene were nearly opaque. Almandine garnet, zircon, rutile, epidote and, surprisingly, beryl were found to be practically opaque to X-rays. The lustrous lead-glass imitations of diamond are very opaque to the rays, but it must not be assumed that all glass imitations are, for some glasses are moderately transradiant.

Comparative tests for the radiability of a substance to X-rays can have value when the difference is very great, for example diamond and zircon, and especially when taken together on one film at the same time. In Doelter's list there seem to be several inconsistencies, particularly in the case of beryl, which, taking into consideration the atomic numbers of the constituent elements, should have a pronounced transparency to the rays. An experimental radiograph of some gemstones, illustrated in *Figure 37.5*, shows a strong

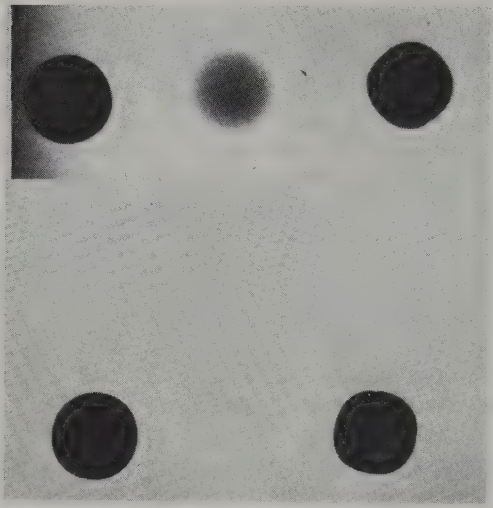


Figure 37.4 These two radiographs of a zircon (left), a diamond (centre) and a glass imitation gemstone with a refractive index of 1.63 (right) show that the zircon and the paste are opaque to the rays while the diamond is transradiant. The upper picture was taken on a very slow 'line' film (7 s exposure), while in the case of the bottom picture there was a 5 s exposure but fast X-ray film was used, and in this case the diamond was shown to be completely transradiant

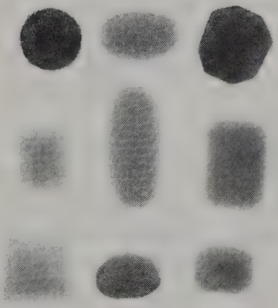


Figure 37.5 Comparison of the radiability of some equal sized gemstones to X-rays. Top row (reading from the left): zircon, aquamarine, almandine. Centre row: citrine, topaz, tourmaline. Bottom row: phenacite, corundum, chrysoberyl

disagreement with Doelter's results with regard to beryl, which in the photograph approaches more nearly to the transparency expected. Corundum also shows a departure from its position in the table, in being less transradiant than expected, both from Doelter's work and from the low atomic numbers of its constituents.

Although differences in the target material of the X-ray tube used, and in operating conditions, may cause spectacular differences, the occurrence of trace elements, such as caesium (atomic number 55) in beryl, and titanium (22), chromium (24) and iron (26) in corundum, may have a bearing on the inconsistencies. Also the close atomic packing of the latter species may have a bearing, as it does on the SG of 3.99, which is higher than expected from its composition.

The difference in the composition of the various parts of composite stones may well be shown by the difference in radiability of the two or more parts. This is clearly illustrated in the radiograph of a diamond doublet (*Figure 37.6*). The stone had a diamond crown and a synthetic white sapphire pavilion. Indeed, the glass used in fracture-filled diamonds is made evident by this technique.

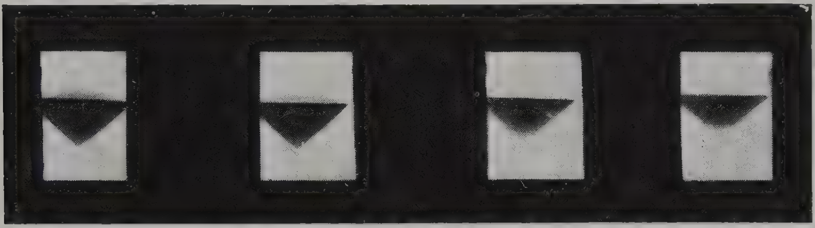


Figure 37.6 Radiographs of a diamond doublet. Diamond top and synthetic white sapphire base. These are four different exposures

This differential transmission of X-rays through materials which have a complex or irregular structure is used to produce the direct X-ray picture or skiagram, as it is sometimes called. This method has some value in the testing of pearls and the special X-ray technique used in such work was discussed when dealing with pearl testing in Chapter 22.

Diffraction

Laue Method of Diffraction

The diffraction techniques, which are simply the original method as used by Laue and his co-workers, or some modification of it, must now be considered. The most important from the gemmologist's point of view are the straight lauegram method, the X-ray 'powder' photograph and the back-reflection methods.

In all these cases it is necessary to limit the normal cone of X-rays to a very narrow beam. This is done by using a pin-hole (approximately 0.5 mm in diameter) collimating system of metal discs pierced with the pin-holes mounted in a metal tube so arranged as to be in perfect alignment with the focal spot on the target. Alternatively, just a lead block pierced with a fine hole will serve for most diagnostic work, and is the type used for pearl testing by the lauegram method, when an aperture of not more than 1.5 mm is usually employed. The narrow beam is passed into the stone or pearl which is suitably mounted on the end of the orifice from which the X-ray beam emerges.

At some distance from the specimen, approximately 75 mm in the case of pearls, and about 30 mm for diffraction pictures of crystals or stones, in which case a much smaller aperture is employed, is placed a film to receive the diffracted rays (*Figure 37.7*). As the diffracted beams are only a very small part of

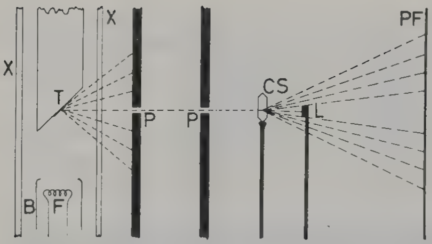


Figure 37.7 *Schematic diagram of the Laue method of X-ray diffraction. X, X-ray tube; T, target; F, filament; B, bias shield; P, pin-hole system; CS, crystal specimen; L, lead stop to limit central beam; PF, photographic film*

the main narrow beam of X-rays, which itself produces a heavy overexposed spot on the film, generally known as the main trace, their photographic intensity is not very great.

In order to avoid a very long exposure time, one or two intensifying screens are employed in conjunction with a fast single- or double-coated X-ray film. The function of these intensifying screens, which are simply cardboard coated with an X-ray fluorescent compound, is to enhance the weak photographic effect on the light-sensitive chemicals of the emulsion by the actinic action from the visible bluish light induced on the screen by the X-rays which have been transmitted through the specimen. With double-coated X-ray film it is practical to employ two screens, one on the tube side of the film and one on the back. The screen on the tube side has little absorptive effect on the rays which pass through it causing fluorescence on the coated side.

It must be clear that care is necessary to ensure that the coated side of the screens are facing the film, and, of course, the film must be bare against the intensifying screens, for, if covered by paper wrapping, none of the fluorescent light from the screens would be able to affect the emulsion and no amplification of intensity could occur. Indeed, the paper would tend to absorb the radiations and the weak beams of diffracted rays would be made weaker still. Loading the cassettes, as the film holders are called, with film must be done in a dark-room, for naked film must be employed, and if single-coated film is employed with the one screen necessary, it must be ensured that the emulsion side is against the screen.

When a crystal is so arranged that the narrow cylindrical beam of X-rays travels along, or parallel to, an axis of symmetry, the beam is reflected off the internal atomic planes and produces on a suitably placed film a series of symmetrically arranged spots surrounding the heavy main trace. This heavy central overexposed spot is generally 'stopped off' with a lead disc. These atomic planes act towards X-radiation in the same way as visible light is affected by diffraction gratings, except that with X-rays the planes behave as semi-transparent reflectors. Thus, a certain number of parallel planes make an additive contribution to the total reflection obtained and hence the general optical law of interference operates.

Figure 37.8 is a diagrammatic representation of this. When radiation from a source S is reflected from the planes that are d apart, the distances between the different reflected rays SXR, $S_1X_1R_1$, and so on are exact multiples of the wavelength λ. The difference between SXR and $S_1X_1R_1$ equals YX_1 plus ZX_1 and the angles YXX_1 and ZXX_1 are equal. Hence YX_1 equals ZX_1 equals $d \sin \theta$, or YX_1 plus ZX_1 equals $2d \sin \theta$. Hence $N\lambda$ equals $2d \sin \theta$, where N is the

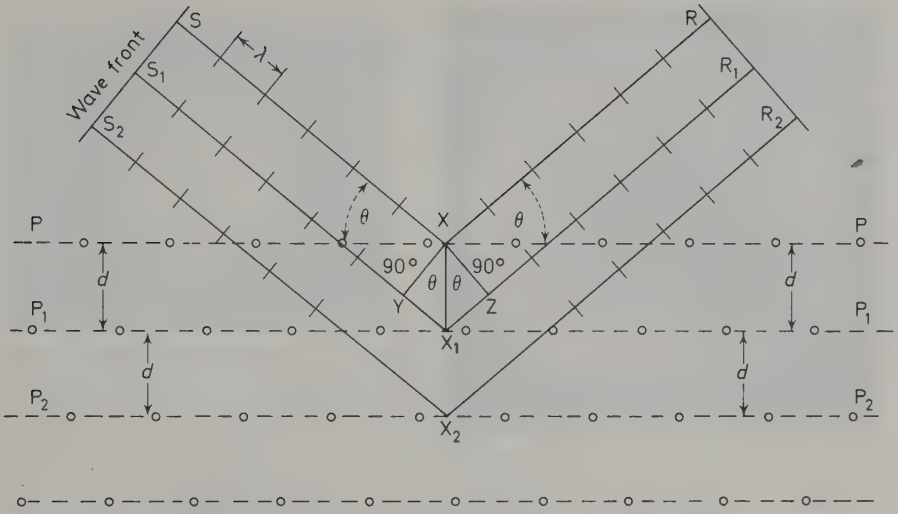


Figure 37.8 Diagrammatic representation of X-ray beams reflected off the internal atomic planes of a crystal that is so arranged that the narrow cylindrical beam of X-rays travels along or parallel to an axis of symmetry

number of wavelengths between the rays in ångströms and θ is the angle of incidence of the rays. Thus from this formula, known as Braggs' law, which is the basis of all X-ray crystal analysis, when two of the factors λ, d and θ are known, the third is calculable.

Laue Diffraction Patterns

For the production of spot diffraction Laue patterns, ordinary white radiation is suitable. This technique is employed for most gem testing by X-rays. In Laue diffraction X-ray work it must clearly be understood that the pattern of spots is influenced by the direction in which the X-ray beam passes through a crystal. Indeed the lauegram, as the spot pattern is called, shows the symmetry of the crystal along a given direction by the symmetry of the spot pattern photographed. The symmetry of the crystal is only shown perfectly when the narrow X-ray beam travels through the crystal parallel to an axis of symmetry, and it should therefore be clear to the reader that the spot pattern produced when the beam passes down the vertical crystal axis of a beryl crystal – a direction of sixfold symmetry (*Figure 37.9*) – will differ from a pattern which is obtained from an X-ray beam which enters a diamond crystal at right angles to the octahedral face, a direction of trigonal symmetry (*Figure 37.10*).

The use of the lauegram method in the testing of pearls is more fully discussed in Chapter 22.

Powder Diffraction

Laue pictures of a gemstone will only give information of the crystallographic symmetry of the crystal structure. There is, however, another method, of which

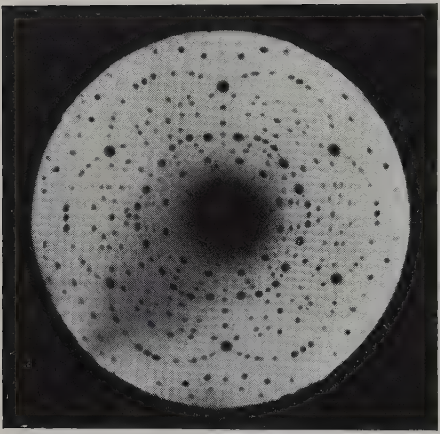


Figure 37.9 Laue diffraction pattern taken down the c-axis of a beryl crystal. The sixfold symmetry of this direction is shown by the arrangement of the spots

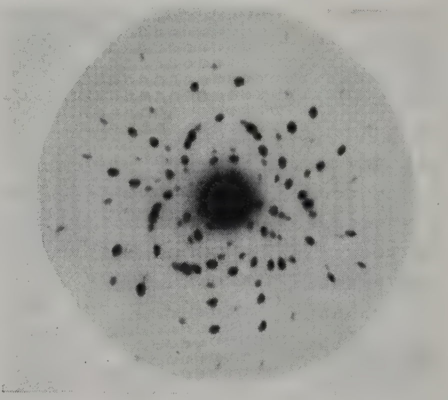


Figure 37.10 A lauegram taken down a trigonal axis of symmetry of a crystal

there are several variations. This is the powder method. Some powder scraped from the specimen to be examined is placed in a capillary tube of Lindemann glass or plastics, or even rolled on to an oil-covered hair. The specimen is then placed in front of the collimating tube as for an ordinary lauegram. Indeed, it is similar in every way to the lauegram technique except that the specimen is in powder form instead of a complete individual crystal.

A picture taken in this manner shows, as the particles of the powder are minute crystal particles in disorientation, a series of rings instead of a series of symmetrical spots. The strength and distance apart of these rings are characteristic for each substance and differ from others, so that if a 'control' picture is taken of a known substance (mineral), another specimen expected to be the same will give a similar picture provided that the specimen film distance is the same. *Figure 37.11* shows a powder photograph of a diamond.

The above is an elementary exposition of the X-ray powder photograph method which may be carried out on a normal pearl testing apparatus. A more advanced technique uses a so-called 'powder photograph' camera, in which the powder from the specimen, made into a fine rod, is mounted at the centre of a light-tight cylindrical box on the periphery of which is fixed a strip of

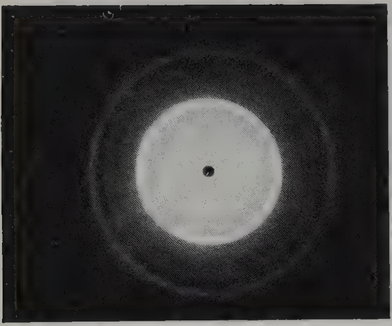


Figure 37.11 Powder diffraction photograph of diamond

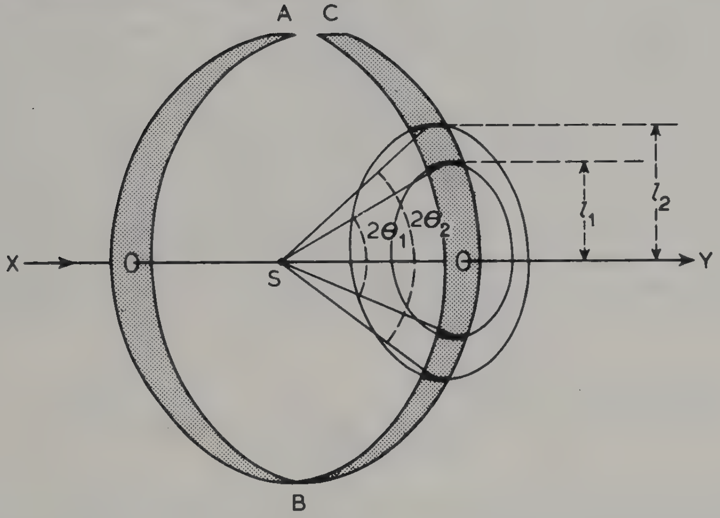


Figure 37.12 *X-ray powder crystallography. A cylindrical strip of X-ray film ABC is fixed symmetrically around the sample S, on which impinges a narrow beam of X-rays XY. These are diffracted through angles* $2\theta_1$, $2\theta_2$, . . ., *corresponding to the various interplanar distances* d_1, d_2, . . . *in the sample. The diffracted rays form a set of cones which intersect the film at distances* l_1, l_2, . . . *from the line of beam, giving a 'spectrum' on the developed film which is characteristic of the compound S. Measurement of these distances enables the values of* d *to be determined: small values of* d *produce large values of* θ *and* l *(illustration taken from 'Forensic Science' by courtesy of HJ Walls, the author, and Sweet & Maxwell, the publishers)*

photographic film. A narrow beam of suitably filtered monochromatic X-rays impinges on the rod of specimen powder which is continuously rotated by a low-speed motor. *Figure 37.12* illustrates the method. The result produced on the film is curved dark lines (actually the arcs of circles) and is called an 'X-ray spectrum' (*Figure 37.13*). Such 'spectra' can be compared directly with one of a known substance, or, if the wavelength of the X-rays and the dimensions of the camera are known, measurement of the *d* values may be obtained by simple calculation. These *d* values are internationally indexed for most minerals, so by reference to the index an identification can be made.

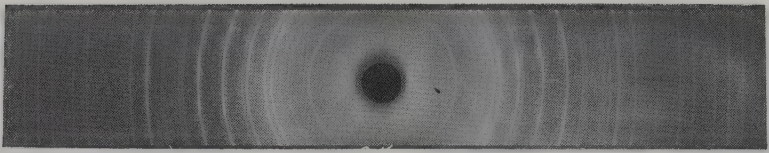


Figure 37.13 A positive print of an X-ray powder photograph of a tourmaline. Monochromatic cobalt K_α *was used (film by courtesy of The Institute of Geological Sciences)*

Back-Reflection Method

At the close of 1946, Holmes and Switzer, of the Gemological Institute of America, devised apparatus to give a rotating powder photograph from a crystal or gemstone. The method is a variation of the back-reflection method ascribed to Sachs. The gemstone is mounted on a special holder so constructed that the specimen is rotated about one axis and oscillated about another at 90 degrees to the first; the specimen is in the path of a narrow beam of X-rays. Secondary beams of X-rays are generated by reflection of the primary beam from planes of atoms within the specimen to produce an X-ray diffraction pattern of circles by back reflection. Like all pictures of this nature, control pictures are necessary. The method can be used for both single crystals, that is ruby, spinel and so on, and for crystalline aggregates, such as onyx, lapis and also turquoise, a material often difficult to test.

X-Ray 'Fluorescence' Spectrography and the Electron Microprobe

These new departures in the analysis of minerals are discussed together as they have much in common. Both depend upon the emission of 'characteristic' radiations from the elements contained in a mineral when they are bombarded with X-rays or electrons. Like the electron microscope, such large and expensive pieces of equipment require considerable expertise in their handling and are, therefore, to be found only in large commercial, university or state laboratories. Some notes on these types of apparatus are given here so that their potential can be realised.

If a specimen is irradiated with primary X-rays, 'characteristic' fluorescent X-rays whose wavelengths are indicative of the elements in the specimen will be emitted, provided the minimum wavelength of the primary X-rays is shorter than the characteristic wavelengths of the elements in the specimen. Therefore the wavelengths and intensities of the 'characteristic' X-rays emitted can be used to identify and provide an estimate of the concentration of elements in a mineral. This technique is known as X-ray fluorescence spectrography or X-ray fluorescence analysis, often abbreviated to XRF, and is commonly used for elements heavier than sodium with atomic number 11.

The apparatus used is known as an X-ray spectrograph or spectrometer. A beam of X-rays is directed on to the sample to be analysed, and fluorescent radiation emitted by the sample is passed through a collimator which directs a

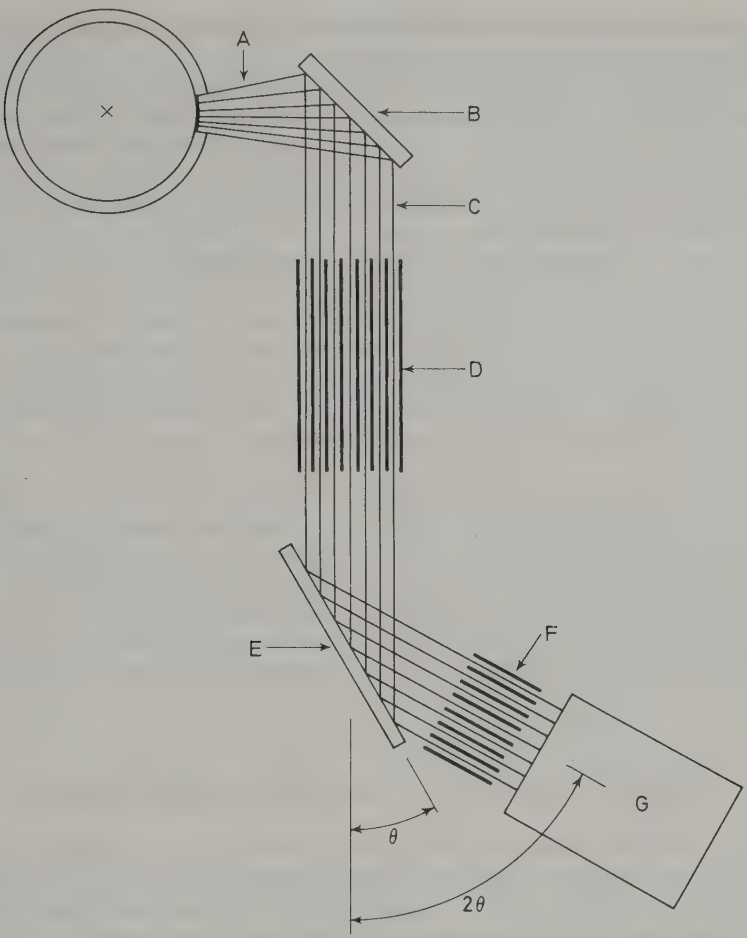


Figure 37.14 Schematic diagram of the X-ray spectrograph. X, X-ray tube; A, primary X-ray beam; B, specimen to be tested; C, secondary radiation; D, primary collimator; E, analysing crystal; F, secondary collimator; G, detector

narrow beam on to a suitably cut analysing crystal whose atomic planes diffract the characteristic X-rays according to Bragg's law. After diffraction the radiation passes through a secondary collimator to a detector, usually either a proportional or a scintillation counter, or a combination of both (*Figure 37.14*). Rays of different wavelengths are reflected by angular rotation of the analysing crystal, which enables X-rays of different wavelengths to be reflected, and these rays will pass into the detector provided the relative angular rotation of the detector is twice that of the analysing crystal. The 'pulses' of energy from the detector are amplified and transmitted to various kinds of recorders.

It must be realised that these 'fluorescent' X-rays are not visible and are not the same as the glow of visible light given off by a substance irradiated with

X-rays, a phenomenon which has been used so much in gem identification, and which is often called 'X-ray fluorescence'.

The electron microprobe virtually operates on the same principle except that, instead of an X-ray beam, a beam of electrons is used to generate the characteristic X-rays. An electron beam is focused into an area, which may be smaller than one micrometre (micron) in diameter, on the surface of the specimen to be analysed, and the characteristic X-rays emitted are analysed in one or more spectrometers.

The prime advantage of the electron microprobe is that an electron stream can be focused with magnetic lenses whereas an X-ray beam cannot. Hence a very much smaller area of the specimen can be irradiated which, as stated, may be smaller than one micrometre in diameter, and, further, the focus can be 'scanned' across the surface of the specimen and the distribution of a given element plotted. It is this small 'focal point' that has enabled the electron probe to identify inclusions in gemstones which have been brought to the surface by polishing.

In addition to the use of X-rays for distinguishing diamond from its simulants (which are all less transradiant than diamond), they have also been employed experimentally to produce an identifying 'fingerprint' of a specific diamond. A vertical beam of collimated X-rays is used to scan the diamond, which is positioned so that the beam is diffracted by the atomic layers in the crystal lattice. The emerging X-rays fall on a photographic plate to produce a projection topograph showing a pattern of distinguishing crystal defects within the stone (*Figure 37.15*).

Colour Change Following X-Ray Bombardment

Finally, a word of warning to those having access to X-ray equipment. X-rays may in certain cases alter the colour of stones bombarded by them. This induced coloration may be, and generally is, only temporary, but may require heat or some other form of light radiation to correct the colour to the original hue.

In some cases the change of colour is most spectacular. This is so in the case of kunzite which changes from the lovely lilac pink to an attractive green. In the weak yellow sapphires from Sri Lanka a good and better yellow, quite like the yellow of Brazilian topaz, can be induced by X-ray bombardment, and remains

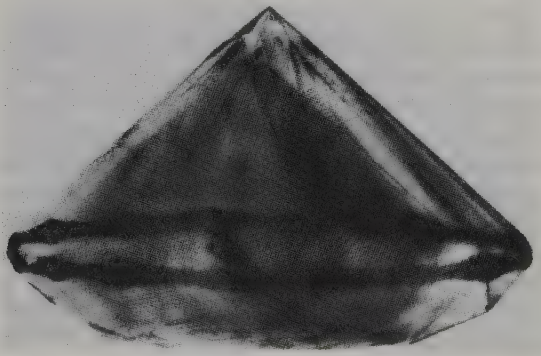


Figure 37.15 A projection X-ray topograph of a brilliant-cut diamond showing various crystal defects

for some time if the stone is not exposed to heat or sunlight. Such coloured stones usually revert to their original colour (cases have occurred where the new colour is not the same as the original) after a few minutes' heating at 230 °C or after about 3 hours' exposure to strong sunlight. This is the test for such 'artificially coloured' stones.

With particular reference to the testing of freshwater pearls (both natural and cultured) by the Laue technique, it should be noted that prolonged exposures may induce a small brown spot at the initial point of contact. This may be rectified following prolonged exposure to ultra-violet light.

38

Electrical and Magnetic Phenomena of Gemstones

Electricity

When the electrical nature of the atom is considered it will not be surprising that more tangible electrical effects may be induced in material structures, and this is true of gem materials. Such manifestations are those of frictional electricity (triboelectricity), pyroelectricity, piezoelectricity and electroconductivity.

Frictional Electricity

In many substances an electric charge can be induced by rubbing: this is frictional electricity. It is best known in the case of amber, for as early as 600 BC Thales knew that when amber was rubbed with silk it acquired the property of attracting light articles. Gilbert in the sixteenth century found that this property was shared by other substances, and he named the effect 'electrification' after *elektron*, the Greek word for amber. Thus the effect shown so well by amber of picking up small pieces of paper is no sure test, for some amber substitutes may behave similarly.

The production of electricity by friction lies in the ability of the rubber or the rubbed to part with some of the outer electrons of the surface atoms. The electrons which have parted from one of the two substances attach themselves to the other substance, or it may be said that the surface atoms of the two substances become ionised. Thus both of the materials, the rubber and the rubbed, become electrically charged. It is well known in electrostatics that like charges repel and unlike charges attract. All uncharged bodies contain atoms with equal charges of positive and negative electricity, but if a charged body, for example one with a positive charge, is brought near it attracts the negative charge within the uncharged body and repels the positive one. Hence, the end of the previously uncharged body nearest the charged body acquires a negative charge. Thus an uncharged body is attracted towards a charged one.

When a body is electrified by friction the nature of the charge produced depends upon the substance with which it is rubbed. Thus glass becomes negatively electrified when rubbed with flannel, but positively when rubbed with silk. When briskly rubbed with a cloth, such stones as diamond, tourmaline and topaz exhibit positive electricity (diamond also exhibits triboluminescence – see Chapter 36). The electrical sign of a charged body can be ascertained by the use of an electroscope but the methods of determining this need not be gone into here. Frictional or triboelectricity is of scant importance in gemmology.

Pyroelectricity

When certain crystals are heated, electrical charges are developed at polar positions. This effect, termed pyroelectricity, is common in some tourmaline crystals but apparently not in the black variety – schorl – and in untwinned quartz crystals. When such crystals are suspended over an asbestos mat heated from below to about 200 °C, they will, on cooling, show particular regions of the quartz and the ends of the tourmaline crystals to be oppositely electrically charged. That such a warmed crystal possesses electric charges may be demonstrated by the experiment devised by Kundt. A finely powdered mixture of red lead oxide and sulphur is blown through a muslin mesh, whereby the particles become electrically charged by friction – the sulphur negatively and the red lead positively – and will settle on the faces or regions of the crystal of opposite electrical sign. Thus on opposite ends of the tourmaline crystal one end will collect the yellow sulphur and the other red lead; and on alternate corners of the quartz crystal there will be either red lead or yellow sulphur. It is this pyroelectric effect of tourmaline which causes tourmalines on display in a jeweller's window to attract dust so readily. The heat of the window casement warms the stones so that an electric charge develops.

Piezoelectric Effect

During 1880 a phenomenon was observed and studied by the brothers Pierre and Jacques Curie in that some crystals when subjected to mechanical compression in particular directions develop electric charges on certain regions. This is known as the piezoelectric effect, a term introduced by Hankel of Leipzig who derived the term from the Greek *piezin* which means 'to press'. The effect is found to occur in hemihedral crystals, the most important of which are rock crystal and tourmaline. Others, but less hard and durable, are boracite (chloromagnesium borate) and Rochelle salt (sodium potassium tartrate), the last named showing the effect to a greater extent than any other crystal.

Of great importance is the 'converse effect', first predicted by Lippman of Paris in 1881, and later verified by the Curies. Reverse effect occurs when a difference of potential (voltage) is applied across opposite faces of a suitably cut plate of a piezoelectric crystal and there arise mechanical stresses which produce in the dimensions of the plate changes in the thickness and length. The length diminishes and the thickness increases when the electric field is in one direction, the thickness decreasing giving increased length when the field is applied in the opposite direction. The dimensional change is proportional to the magnitude of the applied potential difference. No change occurs along the direction of the optic axis in doubly refracting crystals.

Early in 1917, Langevin of France applied the piezoelectric properties of quartz to the transmission of ultrasonic waves under water. Later, during the latter part of 1917 and early 1918, Cady, whilst with a group working on piezoelectric crystals for submarine detection on behalf of the Navy of the United States of America, investigated the erratic electrical behaviour of the crystals and discovered that this peculiar behaviour when understood could be controlled and turned to good account. In 1922 Cady took out patents on electrically vibrating quartz crystals as a method for measuring and controlling frequencies in radio broadcasting.

If an alternating potential difference is applied to a plate cut from a quartz crystal it will be subject to a series of alternating extensions and contractions of the same frequency as the alternating current supply. In other words the crystal plate will undergo forced vibrations. These vibrations are normally very small, but if the frequency of the applied voltage is varied, a resonance effect is obtained, there being one particular point at which the vibration becomes very large and occurs over a frequency variation of a few parts in a million, so that it forms an ideal control for an oscillator.

Wild has explained how electric charges can be released by a suitably cut plate of quartz. The configuration of silicon and oxygen atoms in the unit cell of the quartz crystal consists of six negative oxygen atoms combined with three positive silicon atoms in such a manner that two oxygen atoms compensate one silicon atom at the termination of the electric axes, of which there are three in the unit cell (*Figure 38.1*). *Figure 38.2*, which shows only three oxygen atoms, while in fact there are two in each case with their centres at equal distance from the plane of the drawing, above and below, illustrates the piezoelectric effect. When pressure is exerted on the face which is normal to the electric axis the O (negative) atoms move towards one face while the Si (positive) atoms move towards the other, thus binding opposite charges, so that a positive charge appears near the O (negative) atoms and a negative one near the Si (positive) atoms.

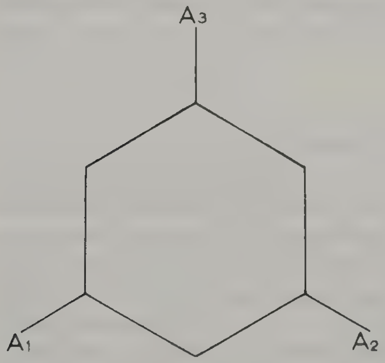


Figure 38.1 The electric axes in a quartz crystal (after G O Wild)

Quartz Oscillator Frequency

The actual frequency at which a crystal operates depends upon the manner in which the slice is cut from the whole crystal. The two most common types of

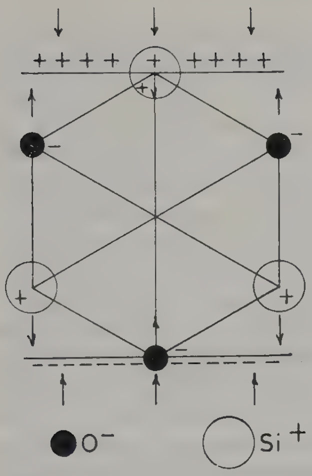


Figure 38.2 Diagrammatic representation of the piezoelectric effect. The arrows denote the direction of pressure (after G O Wild)

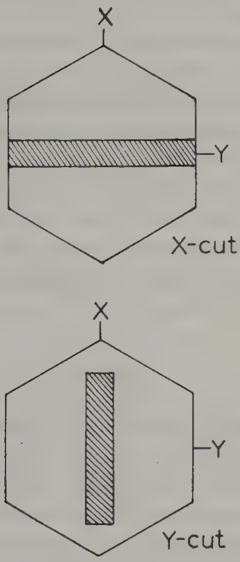


Figure 38.3 The directions of the X-cut and Y-cut slices of quartz for oscillator plates

slice are the X-cut in which the width of the slice is at right angles to the prism face of the quartz crystal, and the Y-cut in which the width is parallel to the prism face of the crystal (*Figure 38.3*). It is the thickness of the slice, however, which controls the actual frequency of the quartz oscillator. Another complication with the normal X-cut and Y-cut is that the temperature can affect the frequency; this defect has been to a great extent overcome by slices cut from quartz crystals at different orientations. Indeed, a quartz crystal can be sliced at many different angles to produce oscillating plates of different characteristics. Untwinned quartz is essential for the production of such oscillator plates; it was owing to the possible need of these for war potential during World War II that the synthesis of quartz was encouraged.

A simple oscillator circuit controlled by quartz crystal is shown in *Figure 38.4*. Electrical oscillations of the tuned circuit *LC* induce mechanical oscillations in

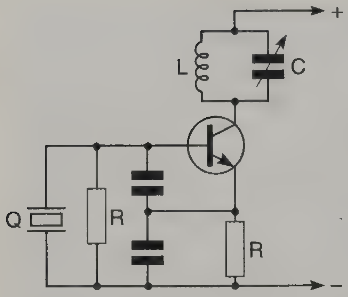


Figure 38.4 *A simple oscillator circuit controlled by a quartz crystal*

the quartz (Q). The resulting electrical charges react with the LC circuit via the base (control electrode) of the transistor and maintain the oscillations in the LC circuit at the precise frequency of the quartz crystal.

The controlling influence of a quartz piezoelectric crystal not only has been used to control the radiating frequency of radio transmitters, including radar, but is made use of in many other electronic devices, including the quartz clock. Further, quartz crystal oscillators can be used to produce ultrasonic (supersonic) waves, above 20 000 vibrations per second, which is the limit that the human ear can register. These waves, which can be produced in air and liquid, have been found to be of considerable value in science and medicine, and for some industrial requirements (e.g. ultrasonic cleaners which use man-made ceramic crystals of zirconate titanate to convert high-frequency electrical oscillations into mechanical vibrations in a liquid-filled cleaning tank).

Electroconductivity

The conduction of electricity through a metal occurs because metallic atoms possess one or more outer electrons which are easily removed from their orbits, leaving positive ions. A metal then may be considered as a closely packed collection of positive ions with 'clouds' of migratory free electrons. The application of a potential difference (voltage) between the ends of a piece of metal, say a wire, will cause these free electrons to travel to the positive end of potential difference, leaving a low electron density at the other end which is filled up by electrons from the negative pole. Thus there is a continuous flow of electrons as long as the potential difference is applied. An insulator is a substance through which it is impossible to pass an electric current, for such substances, for example glass and porcelain, possess no free electrons. Hence, no movement of electrons occurs when a potential difference is applied to their ends.

Electroconductivity is of interest to the gemmologist in the exceptional case of certain diamonds. Diamonds are normally good insulators, but in certain types, named by Custers as type IIb, there are lattice imperfections with loose electrons. A potential difference applied to such a diamond will cause a migration of electrons to the positive pole. This flow of electric current is small at first, only a few milliamperes, but the flow tends to heat up the crystal which liberates more and more electrons from the atoms and the current increases rapidly to several amperes; the diamond will get red hot if the current is not turned off.

It is known that most natural blue diamonds are of this type IIb and are electroconductive, while the artificially coloured blue diamonds treated by electron bombardment are of a type which is not electroconducting. Therefore proof of electroconductivity could be a means of testing for artificial coloration of blue diamonds. All that is necessary for this test is a simple circuit consisting of a source of current, a voltmeter and two electrodes between which the diamond is held. These are connected in series. Alternatively, a neon lamp circuit tester (usually sold in the form of a screwdriver) may be used. In use the stone to be tested is placed on an electrode which is connected to the line side of an alternating current supply (110–240 V). When the screwdriver blade is touched on the stone and the button at the end of the handle is touched with the finger, the neon lamp in the handle will, if the stone is conducting, light up. However, if a blue diamond is determined to be an insulator this may not be regarded as proof of treatment. Naturally coloured type Ia blue diamonds were recently discovered in Australia.

Type IIb diamonds are said to be semiconductors and are becoming of increasing importance in certain types of electronic apparatus, and they can also be used as counters of gamma rays.

Magnetism

It has long been known that an almandine garnet will affect a delicately poised magnetic needle and be attracted by a powerful electromagnet. Although the separation of mineral grains by magnetic methods has been used to a considerable extent, the magnetic susceptibilities of gemstones have not been investigated to any great degree.

There are two main types of magnetism. Paramagnetism is when the material becomes magnetised by induction, or is said to possess induced magnetism. Only a few substances, iron, steel, nickel, cobalt and certain alloys, exhibit to a marked degree the phenomenon of paramagnetism, and such strongly magnetic substances are termed ferromagnetic substances. The facility with which iron nails and steel needles may be picked up by an ordinary horseshoe magnet is obvious proof of the intense magnetic action of such substances.

However, when iron-rich minerals are considered there is less obvious correlation. True, magnetite (lodestone) is strongly attracted to a magnet, whereas both pyrites and hematite, with 46 and 70 per cent of iron respectively, are not affected by an ordinary hand magnet. In this connection reference can be made to the so-called 'hematine', which is used as an imitation of real hematite, for this material is attracted to a hand magnet and may be distinguished from the traditional hematite which is not attracted. However, as the granular hematite recently discovered in Brazil is attracted to a hand magnet, it may not be distinguished from hematine by this method.

The other type of magnetism, diamagnetism, shows the opposite effect, that is the substance is repelled by a magnet; bismuth is the type example of this effect. In any case these effects, except in the ferromagnetic substances, are small and of little importance in gem testing techniques. However, Anderson found that by the use of a sensitive aperiodic balance and a small powerful hand magnet some assessment could be made of paramagnetism.

The experimental procedure is to assess the magnetic 'pull' exerted on a specimen by noting its loss of weight when it is attracted by a magnet held closely above it. The aperiodic type of balance is used since the magnetic attraction exerted on the stone can be followed as it takes place and the weight read off directly on the scale, which is the projection of a transparent graticule attached to the pointer of the balance. As the metal of the balance pan may be found to exert a slight magnetic pull, a large cork of known weight is placed on the pan and the stone to be tested is placed on this cork pedestal. The cork and stone are then weighed together in the usual manner and are left on poise. The magnet is then held immediately above the stone and lowered slowly and steadily. When the poles have approached to within a quarter of an inch or so of the upper surface of the specimen, if the latter has any magnetic susceptibility, the scale will begin to record a marked loss in weight. The minimum weight which could be 'held' by the magnet is then taken as the required reading. The difference between this 'held' weight and the true weight of the specimen and cork is recorded, the mean of at least three readings being taken.

From the experiments it became clear that the size of the stone played a very important role, and that the smaller stones were 'saturated' with magnetic lines of force, while with a big stone much of the material would be outside the strongest field attraction. To 'iron out' irregularities due to size, Anderson used the entirely empirical formula

$$\text{pull} = \frac{\text{magnetic loss} \times 100}{\sqrt{\text{weight}}} \qquad \text{(in milligrams)}$$

From the results obtained by these experiments, iron-containing gemstones are the most strongly magnetic, but the mere percentage of iron in a mineral, as mentioned earlier in the case of pyrites, does not necessarily give a clue to the magnetic susceptibility; the nature of the other elements present and the structure of the crystal play an important part. The other strongly magnetic stones were found to be those which contain manganese. The results found by Anderson are given in *Table 38.1*.

As with care and patience an ordinary balance could be used for the magnetic determinations, a worker having no other apparatus than a good balance and a small magnet could differentiate between the following stones: the more magnetic of the two is mentioned first.

demantoid	from	green zircon, sphene or diamond
pyrope	from	ruby or spinel
hematite	from	black pearl or black diamond
spessartine	from	hessonite or zircon
rhodonite or rhodochrosite	from	thulite
brown peridot	from	sinhalite
stainless steel	from	marcasite (pyrites)

The last can, however, be distinguished simply by the attraction by an ordinary magnet.

Table 38.1
Magnetic determinations

Magnetism	*Stone*	*Pull (formula)*
Strong	Almandine*	290–410
	Spessartine	250–360
	Rhodochrosite	270 ±
	Rhodonite	280–370
	Hematite	220–310
Moderate	Demantoid	120–200
	Epidote	100 ±
	Pleonaste	80–130
	Peridot	50– 75
	Pyrope*	40– 75
	Dark green tourmaline	50– 70
	Hessonite	40 ±
	Indicolite	40 ±
Weak	Brown sinhalite	
	Green tourmaline	

*The term 'almandine' is confined to stones with a refractive index of 1.79 and over, while 'pyrope' is those stones with an index below 1.75. Intermediate members of the pyrope/almandine series give intermediate magnetic values

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Chemistry and Gemstones

Chemistry is a subject of only occasional application by the practical gemmologist, but some idea of the scope of the science in relation to gem materials is both interesting and useful. On the one hand it throws light on the suitability of the various gem materials for certain uses, and on the other it provides that knowledge of the principles of chemical reactions which is necessary if incorrect deductions are to be avoided on those occasions when the gemmologist does find it necessary to apply simple tests.

Chemical Compounds

All existing material, tangible or intangible, whether existing as solid, liquid or gas, is built up of simpler units. These, in fact, may in themselves be quite simple as with the metals, small groups as in the case of most inorganic compounds, or exceedingly complex units which go to build up many of the organic compounds.

The pure metals are built up of one type of matter only, referred to as elements, for example copper, silver or gold. Inorganic compounds are built up of two or more dissimilar elements: quartz = silicon oxide (SiO_2), two elements; calcite = calcium carbonate ($CaCO_3$), three elements; and so on to complex materials such as tourmaline which has a great number of elements present.

Organic compounds, on the contrary, are very often 'heavy' materials composed of few different elements but combined in various groupings and quantities resulting in some very complex compounds. In these compounds carbon is the essential element and may be in combination with varying quantities of hydrogen, oxygen, nitrogen and so on, joined in a very diverse number of ways. Organic compounds are, in fact, innumerable but here again the gemmologist is concerned with very few. These include certain materials of animal origin (actually these are usually mixtures of organic and inorganic compounds), several products of vegetable life, and a number of synthetic compounds which are basically wholly organic and of a definite composition. In the first class are the ivories (dentine); fossil ivory, not greatly different in composition; bone, where the organic and inorganic parts, though arranged in an orderly structure, are intimately dispersed; and what are probably the most interesting of all, pearls, which are built up of concentrically arranged 'shells' of the inorganic compound aragonite (calcium carbonate) and the organic compound conchiolin (a scleroprotein), the proportion being in round figures about 7 to 1, a small amount of water also being present. The second class is probably best represented by the so-called 'vegetable ivory' (the corozo nut which is substantially albumen) and the fossilised plant product, amber, which are entirely organic in composition. There are also other resins not fossilised or only part so. The last class is in the main made up of the synthetic resins and plastics. These are dealt with more fully in Chapter 19.

Nomenclature

It will be appreciated that to investigate the compounds mentioned above, covering only those in which the gemmologist is directly interested, some knowledge of the language of chemistry and the nomenclature used in identifying and referring to the various compounds is necessary. It is not intended here to go deeply into those natural laws governing the manner and proportions in which the various elements combine to produce the compounds enumerated. It will be sufficient if it is realised that a chemical formula is not merely a 'shorthand', but that every formula not only indicates the ingredient elements but also is a definite statement of the proportions of each and in many formulae the precise way in which the elements are connected.

The smallest unit of a chemical compound is called a molecule, an example being sodium chloride (common salt) containing one sodium atom (Na) united to one chlorine atom (Cl). Each atom is given a chemical symbol which consists of one or two letters usually derived from the Latin name of the element. This symbol, in addition to acting as an abbreviation, stands for one atom of the element and enables chemical formulae to be written which give at a glance the exact chemical composition of any pure substance. Thus, one atom of zinc (Zn) combined with one atom of sulphur (S) will form zinc sulphide, which when crystallised is the mineral zinc blende with the formula ZnS.

In the greater number of cases the formula indicates that more than one atom of a given element is in the compound. In the formula this is indicated by small subscript numbers written after the symbol. Such a formula is that of alumina, which when crystallised is corundum – ruby and sapphire. The formula for this pure substance is Al_2O_3 which means that the compound has a molecule consisting of two atoms of aluminium (Al) and three atoms of oxygen (O).

Such chemical formulae based on the use of letter symbols indicating atoms are empirical, giving only the relative numbers of atoms present in the compound and not representing the actual constitution. While it is unnecessary to go into details of structural formulae, it is often of value to employ the 'rational' system. Thus, while the formula for spinel can be written as $MgAl_2O_4$, it may be more enlightening to see the same formula as magnesia and alumina, that is $MgO.Al_2O_3$. This type of formula is specially useful in the case of synthetic spinel which has extra alumina, for this could not be expressed clearly with the normal formula, but a better idea can be gained by the rational formula: for example $MgO.2\frac{1}{2}Al_2O_3$.

Another variation in formula occurs when a chemical group has a value more than unity. This is exemplified by the formula for almandine garnet, the iron aluminium silicate, which is expressed as $Fe_3Al_2(SiO_4)_3$. The silica group, SiO_4, as indicated by the brackets and the subscript number outside the brackets, has three times the number of atoms given by the symbols in the brackets, for example three atoms of silicon and 12 atoms of oxygen. The composition of almandine garnet could be expressed, perhaps better, by the rational formula as $2FeO.Al_2O_3.3SiO_2$.

The use of brackets in formulae can have another significance. In this case two or more symbols in the brackets indicate that the elements are interchangeable in variable amounts. An example of this is in the formula for topaz, which is written as $Al_2(F,OH)_2SiO_4$, where the fluorine (F) and the hydroxyl (OH) radical are interchangeable to a greater or lesser extent.

It must be pointed out that the molecule, say of Al_2O_3, while being the smallest part of alumina which can remain alone, is not the smallest part of a crystal of corundum, for the smallest part of such a crystal is the unit cell, which contains Al_4O_6 in the trigonal unit.

Atomic Mass

The relative masses of all atoms are accurately known, and these atomic masses are the various atoms relative to oxygen which equals 16.00. Thus calcium, a metallic element (symbol Ca), has the atomic mass of 40.08; carbon, a non-metallic element, has the atomic mass of 12.00. Combined in certain proportions according to the formula $CaCO_3$ these elements form calcium carbonate, which in the crystalline form may be either calcite or aragonite. From the formula, therefore, calcium carbonate consists of

1 calcium	40.08
1 carbon	12.00
3 oxygen (16 × 3)	48.00
	100.08

The total gives the molecular mass. As the molecular mass in this case happens to approximate to 100, the other figures in this case give the approximate percentage composition of each element. If the composition does not work out to 100, then to find the percentage of any element in the compound it is necessary to divide the mass of the element with the mass of the entire molecule and multiply the result by 100. *Table 39.1* gives the accepted symbols, the atomic numbers and the atomic masses of the important elements.

Table 39.1
The chemical elements with their symbols, atomic numbers and approximate atomic masses

	Symbol	*At. no.*	*Approx. at. mass*		*Symbol*	*At. no.*	*Approx. at. mass*
Aluminium	Al	13	27.0	Molybdenum	Mo	42	95.9
Antimony	Sb	51	121.8	Neodymium	Nd	60	144.2
Argon	A	18	39.9	Neon	Ne	10	20.2
Arsenic	As	33	74.9	Nickel	Ni	28	58.7
Barium	Ba	56	137.4	Niobium	Nb	41	92.9
Beryllium	Be	4	9.0	Nitrogen	N	7	14.0
Bismuth	Bi	83	209.0	Osmium	Os	76	190.2
Boron	B	5	10.8	Oxygen	O	8	16.0
Bromine	Br	35	79.9	Palladium	Pd	46	106.4
Cadmium	Cd	48	112.4	Phosphorus	P	15	31.0
Caesium	Cs	55	132.9	Platinum	Pt	78	195.1
Calcium	Ca	20	40.1	Potassium	K	19	39.1
Carbon	C	6	12.0	Praseodymium	Pr	59	140.9
[Cassiopaeum = Lutetium]				Protactinium	Pa	91	231.0
Cerium	Ce	58	140.1	Radium	Ra	88	226.0
Chlorine	Cl	17	35.5	Radon	Rn	86	222.0
Chromium	Cr	24	52.0	Rhenium	Re	75	186.2
Cobalt	Co	27	58.9	Rhodium	Rh	45	102.9
[Columbium = Niobium]				Rubidium	Rb	37	85.5
Copper	Cu	29	63.5	Ruthenium	Ru	44	101.7
Dysprosium	Dy	66	162.5	Samarium	Sm	62	150.4
Erbium	Er	68	167.3	Scandium	Sc	21	45.0
Europium	Eu	63	152.0	Selenium	Se	34	79.0
Fluorine	F	9	19.0	Silicon	Si	14	28.1
Gadolinium	Gd	64	157.3	Silver	Ag	47	107.9
Gallium	Ga	31	69.7	Sodium	Na	11	23.0
Germanium	Ge	32	72.6	Strontium	Sr	38	87.6
Gold	Au	79	197.0	Sulphur	S	16	32.1
Hafnium	Hf	72	178.5	Tantalum	Ta	73	180.9
Helium	He	2	4.0	Tellurium	Te	52	127.6
Holium	Ho	67	165.0	Terbium	Tb	65	158.9
Hydrogen	H	1	1.0	Thallium	Tl	81	204.3
Indium	In	49	114.8	Thorium	Th	90	232.0
Iodine	I	53	126.9	Thulium	Tm	69	168.9
Iridium	Ir	77	192.2	Tin	Sn	50	118.7
Iron	Fe	26	55.8	Titanium	Ti	22	47.9
Krypton	Kr	36	83.8	Tungsten	W	74	183.9
Lanthanum	La	57	138.9	Uranium	U	92	238.0
Lead	Pb	82	207.2	Vanadium	V	23	50.9
Lithium	Li	3	6.9	Xenon	Xe	54	131.3
Lutetium	Lu	71	175.0	Ytterbium	Yb	70	173.0
Magnesium	Mg	12	24.3	Yttrium	Y	39	88.9
Manganese	Mn	25	54.9	Zinc	Zn	30	65.4
Mercury	Hg	80	200.6	Zirconium	Zr	40	91.2

Element Groups and Periodic Classification

Elements in general naturally fall into two groups, metals and non-metals. A few possess one or more properties common to both groups, for example arsenic occurring in realgar and there showing the properties of a metal, and in smaltite where it takes the place usually associated with a non-metallic radical. Metals usually, but not always, play the part of the basic or positive element in a simple compound, while non-metals play the negative or acidic part. Therefore elements can be divided into electro-positive or electro-negative elements, depending on whether they ionise with a deficiency of electrons (positive) or an excess of electrons (negative).

Mendeleyev, in 1869, enunciated a periodic classification of the elements based on the order of their atomic mass in which at regular stages elements of similar nature occur and thus form well-defined groups. It is now known that a more fundamental order than atomic mass is the atomic number which represents the positive charge on the nucleus of the atom of each element, neutralised by an equal number of planetary electrons in the normal atom (see *Figure 39.1*). This and the relative sizes of atoms and ions have been mentioned in the discussion on crystals in Chapter 27.

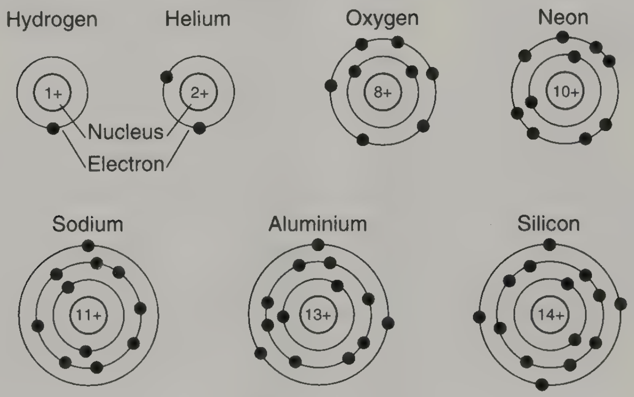

Figure 39.1 The Danish physicist Niels Bohr's representation of the atom consists of a central nucleus containing a number of positively charged protons (e.g. one in the case of hydrogen or 14 in the case of silicon) surrounded by an equal number of negatively charged orbital electrons. The charges on the nucleus and electrons balance out, and the atom is normally neutral

The structure of the atom can be visualised as a miniature solar system, with the nucleus taking the place of the sun at the centre, and the electrons forming the orbital planets (see *Figure 39.1*; for simplicity the electron orbits are shown lying in the same plane). The nucleus consists of protons and neutrons: a proton possesses a single positive charge, and a neutron, which has the same mass as the proton, is electrically neutral. The electron, whose mass is much smaller than that of the proton and neutron, has a single negative charge. Atoms are normally electrically neutral, having equal numbers of protons and electrons.

The 90 naturally occurring elements in the earth's crust range from hydrogen, which is the lightest, to uranium which is the heaviest. In their normal state all of these elements, with the exception of hydrogen, have both protons and neutrons in their nuclei. Those elements containing neutrons in excess of their normal number are called isotopes. On the rare occasion when the nucleus of hydrogen contains a neutron, it is called deuterium, which is the isotope of hydrogen.

The number of protons in an element's nucleus is called its atomic number. The atomic mass of an element is its mass compared with that of an atom of oxygen (which is assigned a value of 16.0 atomic mass units, or 16.0 amu for short). From this the approximate atomic mass of hydrogen is 1.0 amu, and that of carbon is 12.0 amu.

When atoms combine together they form a new entity which is called a molecule. The molecule is the smallest part of a substance which can have a separate stable existence. Groups of molecules formed by the combination of different elements are called compounds. Even the atoms of an individual element often become more stable when they join together to form a molecule. For example, oxygen and hydrogen atoms are more stable whey they join together in pairs, and these elements are termed diatomic (O_2 and H_2). The atoms of many elements such as helium (He) are quite stable in the single state, and by definition they exist as both atom and molecule in this condition. Such elements are called monatomic.

The distinction between a substance which is produced by mechanically mixing together two or more elements, and one in which these elements have combined together chemically to form a compound, is also important to the understanding of minerals. A substance produced by simply mixing elements together will retain something of the properties of the individual elements, and the proportion of the constituents is unimportant.

When a compound of two or more elements is formed, however, this involves a more fundamental change (i.e. a chemical reaction) which is usually accompanied by the emission or absorption of heat. The properties of the compound produced in this way are always quite different to those of the individual elements, and the proportions of these elements are usually in a strict relationship governed by the resulting compound.

For example, two diatomic molecules of hydrogen can be combined with one diatomic molecule of oxygen to produce the compound water, whose properties are dramatically different from those of the individual gases. The chemical reaction which occurs between hydrogen and oxygen can be expressed in the following simple equation (here and in more complicated reactions between elements and compounds, the equation must balance in that it must show the same number of atoms of each substance on each side):

$$2H_2 + O_2 = 2H_2O$$

As mentioned earlier, the number in front of the chemical symbols indicates the number of molecules, while the subscripts indicate the number of atoms in each molecule.

Of the 90 naturally occurring elements in the earth's crust, only eight account for the bulk of the crust. Of these eight elements, oxygen and silicon are the dominant pair, and it is these two elements which combine together with the remaining six elements – aluminium, iron, calcium, sodium, potassium and magnesium to form silicate minerals such as the aluminium-silicate feldspars. Any remaining silicon combines with oxygen to form silica (SiO_2). Silica is found world-wide as quartz and makes up around 12 per cent of the world's crust and upper mantle.

Valency

The electron orbits surrounding the atom's nucleus can be thought of as concentric 'shells', each shell representing an energy level. In some atoms such as aluminium there are several electron energy levels (this concept was particularly relevant in Chapter 36 when we considered the mechanisms of luminescence). The outer electron shell of an atom is called the *valence* shell.

Elements form compounds by gaining, giving up or sharing electrons with each other in order to produce a stable arrangement of two or eight electrons in their outer shells. The number of electrons which are gained, donated or shared in this way is called the *valency* of the element.

An example of the practical effect of valency can be seen in the compound which forms aluminium oxide (i.e. the mineral corundum, Al_2O_3, whose varieties are ruby and sapphire). Aluminium has three electrons in its outer shell, and oxygen has six. For the two elements to combine as a stable compound, it is necessary for them to end up with eight electrons in their outer shell. Each oxygen atom requires an extra two electrons to become stable in a combination. This situation can only be resolved by a combination of two aluminium atoms (providing a total of six electrons) and three oxygen atoms (requiring a total of six electrons for stability). As oxygen is a diatomic molecule, the balanced chemical reaction equation looks like this:

$$4Al + 3O_2 = 2Al_2O_3$$

Aluminium, with its three outer electrons, is said to have a valency of three (i.e. it is *trivalent*), and oxygen, with its need to find two extra electrons, is said to have a valency of two (i.e. it is *divalent*).

However, with some elements, such as iron and copper, both the outer shells and the inner shells can take part in a chemical reaction to form compounds. As a result, these elements possess more than one possible valency. Iron, when it behaves as a divalent element, forms ferrous compounds; as a trivalent element, with a valency of three, it forms ferric compounds (this distinction was relevant in Chapter 31 when the heat treatment of gems was discussed). Copper, with a valency of one, forms cuprous compounds; with a valency of two it forms cupric compounds.

To complete the valency picture it should be mentioned that there are several elements which already possess stable valency shells containing either two or eight electrons (i.e. they have a zero valency). These are virtually inert elements in that they do not easily form compounds with other elements. Examples, are the so-called 'noble' gases helium (two electrons), and neon, argon, krypton, xenon and radon (eight electrons). Gold, silver, platinum and the platinum group metals are also termed 'noble' (although they do not have stable valency shells) because they are relatively resistant to chemical action and (except for silver) do not tarnish in air or water.

Atomic Bonding

The chemical joining together of elements into a compound is called *bonding*, and the forces which hold the elements together are called *bonds*. There are two types of bond which are relevant to the study of gemmology. One of these, called *ionic bonding*, is found in salts, and the other, *covalent bonding*, is found in almost all crystals that are neither salts nor metals. A description of these bonds has been given in the discussion on crystals in Chapter 27, but is included here for completeness.

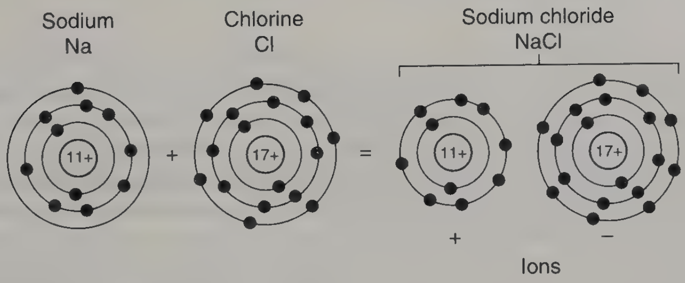

Figure 39.2 The chemical combination of sodium and chlorine to form sodium chloride is an example of ionic bonding in which the sodium atom donates an electron to the chlorine atom. This unbalances the atomic charges and results in a positively charged sodium ion and a negatively charged chlorine ion

A simple example of ionic bonding is that which occurs between sodium metal and chlorine gas to form sodium chloride (i.e. common salt: see *Figure 39.2*). The balanced chemical reaction equation is as follows:

$2Na + Cl_2 = 2NaCl$

In this form of bonding, one element donates one or more electrons, while the other acquires the appropriate number according to its valency. By donating its single outer electron, the sodium atom becomes unbalanced electrically with an overall positive charge (Na^+). Atoms which are no longer electrically neutral are known as *ions*. A positive ion is called a *cation*.

In acquiring an extra electron to add to its existing seven, the chlorine atom becomes negatively charged (Cl^-). This type of ion is called an *anion*. As exactly the same number of electrons have been both donated and acquired, the overall electrical charge again becomes neutral. However, it is the electrical force of attraction that exists between the positive cation and negative anion ions in the compound that produces the bond between them. Corundum (Al_2O_3), hematite (Fe_2O_3), spinel ($MgO.Al_2O_3$) and chrysoberyl ($BeAl_2O_4$) are examples of gem minerals which have ionic bonding between their atoms, as do most metallic salt minerals.

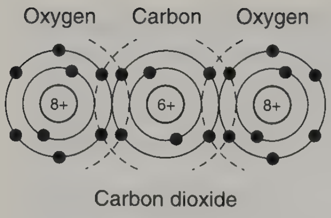

Figure 39.3 The chemical combination of two oxygen atoms with one carbon atom to produce carbon dioxide is an example of covalent bonding. In their outer valency shells, the two oxygen atoms each share two electrons with the carbon atom, and the carbon atom shares two electrons with each oxygen atom. Unlike ionic bonding, the individual atoms remain electrically neutral

In *covalent bonding*, electrons are shared by an interlinking of the valency shells of the combining atoms to produce an electrically stable configuration. A simple example of this type of bonding is illustrated in *Figure 39.3*, where carbon dioxide is formed by the combination of one carbon atom with two atoms of oxygen:

$$C + O_2 = CO_2$$

In forming the gas carbon dioxide, the two oxygen atoms each share two of the carbon electrons, while the carbon atom shares two electrons from each of the oxygen atoms. With this type of bonding there is no donating or acquiring of electrons, and as a result no ions are produced. The bonding force in this case is the need for both elements to produce a stable arrangement of eight orbital electrons in their valency shells.

Diamond, which is composed of the element carbon, is a prime example of covalent bonding and, unlike carbon dioxide, has a more immediate link with the study of gemmology. Carbon has two crystalline forms, a property called polymorphism. When it crystallises as diamond its atoms all share two electrons with each neighbouring atom in the crystal lattice to achieve the ideal eight-electron outer shell. In diamond, all carbon–carbon bond distances are equal and the resulting structure forms the strongest and hardest substance known. In contrast to this, carbon can also crystallise as graphite to produce one of the softest and most slippery substances known.

The reason for the dramatic differences in the two crystalline forms of carbon is that in graphite only three of the four carbon bonds are covalent bonds. The fourth bond is very much weaker and is known as the *van der Waals* bond. This results in the formation of large, very strong sheets of carbon 'chicken wire' which are only weakly bonded together and easily cleave or slip one against the other.

Like diamond, quartz is another gem mineral formed by covalent bonding. In general, however, minerals seldom contain bonds which are solely ionic or covalent, and there is often a transition between both types of bond.

As electronics and electrics play an increasing role in gem test instruments, it is relevant to mention yet another form of bonding. This is called *metallic bonding* and occurs in most metals. The metallic atoms exist as positive ions, but are surrounded by a cloud of valence electrons which are not bound to any particular atom's valency shell. This comparative freedom allows the electrons to wander randomly between the atoms, while the bulk of the material remains electrically neutral. When a potential difference (i.e. a voltage) is applied across the metal, these electrons move through the metal under the influence of the applied electric field to form an electric current. This type of bonding makes metals good *conductors* of both electricity and heat.

While metals are good electrical conductors, the strong attachment of valence electrons to their atoms in other materials results in a very poor conduction of electricity. Materials of this kind are classed as electrical *non-conductors* or *insulators*, and are usually poor conductors of heat. The majority of diamonds are unique among minerals in this respect as they are virtually non-conductors of electricity and yet can conduct heat better than most metals.

In between the conductors and non-conductors of electricity there are the semiconductors such as carbon, germanium, silicon and one particular type of diamond. With these materials it is necessary to apply a larger electrical field than that required in metals to persuade valence electrons to break out of their shells and travel through the material as a current.

The Relationship between Chemical Composition and Durability

With the exception of diamond, which is the most durable of all the minerals, and one which exists as a single element (carbon), all of the gemstones are compounds of elements. For gemmological purposes, these can be divided into four main groups of oxides, carbonates, phosphates and silicates, and their durability can be related to these groups.

Gem oxides consist of a metal combined with oxygen. These are generally hard and resistant to chemical attack. Examples are:

chrysoberyl	$BeAl_2O_4$
corundum	Al_2O_3
quartz and chalcedony	SiO_2
spinel	$MgO.Al_2O_3$

Gem carbonates are formed by the action of carbonic acid on metals. These are soft and easily attacked by acids. Examples are:

calcite	$CaCO_3$
malachite	$Cu_2(OH)_2CO_3$
rhodochrosite	$MnCO_3$

Gem phosphates are produced by the action of phosphoric acid on metals. These are soft and not very resistant to acid attack. Examples are:

apatite	$Ca_5(F,Cl)(PO_4)_3$
turquoise	a complex hydrated phosphate of copper and aluminium

Gem silicates result from the action of silicic acids on metals. These are hard and very durable, and represent the majority of gems. Examples are:

feldspar group gems	aluminium silicates in combination with calcium, potassium or sodium

garnet group gems	silicates of various combinations of magnesium, manganese, iron, calcium, aluminium and chromium
jadeite	$NaAl_2(SiO_3)_6$
nephrite	complex calcium magnesium or iron silicate
peridot	$(Mg,Fe)_2SiO_4$
rhodonite	$MnSiO_3$
topaz	$Al_2(F,OH)_2SiO_4$
tourmaline	a complex borosilicate of aluminium and iron
zircon	$ZrSiO_4$

Identification Tables

Table 1
Refractive indices, optical characters, hardnesses and specific gravities

Refractive indices are the most important testing factor, so the values given for these are printed in ascending order. The specific gravity values, rather less used in gem testing, in most cases increase with increasing refractive index and fall within limits into defined groups, and therefore may be readily found in the table. Where constants are outside the given range, or may not easily be found within that range, they are printed in italics; the materials are then repeated in the appropriate places, with the contents in ordinary type. (Non-gem materials with SGs less than 1 are not repeated.) The word 'to' between figures implies variation in range, while '–' indicates the greatest and least readings in doubly refractive stones. 'I' means isotropic, 'U' uniaxial, and 'B' biaxial. The names of liquids are printed in italics.

Glass imitation stones may be said to have refractive indices which lie between 1.50 and 1.70, and such stones are rarely found outside these limits. So, as there are few natural singly refractive stones which lie between these values, an isotropic stone having any refractive index between 1.50 and 1.70 may be suspected to be a paste.

Refractive index	*Birefringence*	*Optic sign*	*Optical character*	*Hardness*	*Specific gravity*	*Name*
1.3					**1.0**	
1.334	—	—	—	—	1.00	*Water*
1.36	—	—	—	—	*0.79*	*Ethanol*
1.37	—	—	—	—	*0.88*	*Pentyl acetate*
1.378–1.390	0.012	Positive	U	5 to 6	*3.15*	Sellaite
1.4						
1.408	—	—	—	—	*0.936*	*Cellosolve*
1.54	—	—	I	2 to 2.5	1.03 to 1.10	Amber
1.54	—	—	I	2	1.03 to 1.10	Copal resin
1.59	—	—	I	2.25	1.05	Polystyrene
1.53 (mean)	—	—	—	2	1.00 to *2.00*	Meerschaum
1.64 to 1.68	—	—	I	2.5 to 4	1.10 to 1.40, usually 1.30 to 1.35	Jet
1.56	—	—	—	3.5	1.34	Black coral
1.434	—	—	I	4	*3.18*	Fluorite
1.44 to 1.46	—	—	I	5.5 to 6	1.98 to *2.20*	Opal
1.435 to 1.455					1.97 to *2.06*	Fire opal
1.60 to 1.63	—	—	I	2	1.15 to 1.20	Vulcanite (hard rubber)
1.50	—	—	I	2	1.18 to 1.19	Perspex
1.45	—	—	—	—	*mean 0.85*	*Petroleum*
1.45	—	—	—	—	1.498	*Chloroform*
1.46	—	—	I	6	*2.21*	Silica glass
1.460–1.485	0.025	—	B	3.5	*2.71*	Creedite
1.464–*1.500* to 1.468–*1.507*	0.031 to 0.043	Negative	U	3.5	1.88 to 1.90	Thaumasite
1.47	—	—	—	—	1.26	*Glycerin*
1.61 to 1.66	—	—	—	2.25	1.25 to *2.00*, usually 1.26 to 1.30	Bakelite
1.47	—	—	—	—	*0.87*	*Turpentine*
1.47	—	—	—	—	*0.91*	*Olive oil*
1.47	—	—	—	—	*approx. 0.95*	*Castor oil*

Table 1 *(cont.)*

Refractive index	*Birefringence*	*Optic sign*	*Optical character*	*Hardness*	*Specific gravity*	*Name*
1.48	—	—	I	5.5 to 6	*2.15 to 2.35, usually 2.25 to 2.30*	Sodalite
1.487	—	—	—	5 to 5.5	*2.22 to 2.29*	Analcime
1.480–1.493	0.013	Positive	B	5.5	*2.20 to 2.25*	Natrolite
1.48 to *1.54*	—	—	I	5.5	*2.34 to 2.39*	Moldavite
1.48 to *1.51*	—	—	—	5	*2.33 to 2.42*	Obsidian
1.486–*1.658*	—	—	—	3	*2.71*	Calcite (marble)
1.54	—	—	—	2.5	1.26 to 1.35	Tortoise-shell and horn
1.49	—	—	—	—	*0.87*	*Toluene*
1.49	—	—	—	—	*0.87*	*Xylene*
1.490 to *1.505*	—	—	I	1.5	1.26 to 1.80, usually 1.29 to 1.40	Cellulose acetate plastic
1.55 to 1.56	—	—	I	2.25	1.32 to 1.34	Casein (protein plastic)
1.495 to *1.510*	—	—	I	*1.5*	1.36 to 1.80, usually 1.36 to 1.42	Celluloid
1.54	—	—	—	2.5	1.38 to 1.42	Vegetable ivory
1.49 to *1.53*	—	—	I	5	*2.36 to 2.51*	Tektites
1.490–*1.650*	0.160	Positive	B	2.5	*2.23*	Whewellite
1.492–*1.504*	0.009	Positive	B	4.5	2.19 to 2.22	Yugawaralite
1.496	—	—	I	5.5 to 6.5	*2.4*	Hauyne
1.496–*1.502*	0.006	Positive	U	6	*2.36 to 2.57*	Tugtupite
1.56	—	—	—	2.5	1.60 to 1.85	Deer horn
1.54	—	—	—	2.25 to 2.5	1.70 to 1.98	Dentine ivory
					1.70 to 1.85	Elephant
					1.85 to 1.98	Hippopotamus
						walrus and narwhal
1.5					**2.0**	
1.45	—	—	I	5.5 to 6	2.00 (mean)	Opal
1.464–1.500 to *1.468*–1.507	0.031 to 0.043	Negative	U	3.5	1.88 to 1.90	Thaumasite
1.502–*1.681*	0.179	Negative	U	3.5 to 4	2.8 to 2.9	Dolomite
1.492–1.504	0.009	Positive	B	4.5	2.19 to 2.22	Yugawaralite
1.54	—	—	—	2.5	2.00	Bone
1.54	—	—	—	—	2.19	*1,2-dibromoethane*
1.50 (mean)	0.011	Positive	U	2 to 4	2.00 to 2.45	Chrysocolla
1.48	—	—	I	5.5 to 6	2.15 to 2.35, usually 2.25 to 2.30	Sodalite
1.50 (mean)	—	—	I	5.5	2.70 to 2.90	Lapis lazuli
1.50	—	—	I	2	*1.18 to 1.19*	Perspex
1.495–1.505	—	—	—	1.5	*1.29 to 1.40*	Cellulose acetate
1.487	—	—	I	5 to 5.5	2.20 to 2.29	Analcime
1.480–1.493	0.013	Positive	B	5.5	2.20 to 2.25	Natrolite
1.46	—	—	I	6	2.21	Silica glass
1.512–1.523	0.011	Negative	B	5 to 5.5	2.21	Scolecite

Table 1 *(cont.)*

Refractive index	*Birefringence*	*Optic sign*	*Optical character*	*Hardness*	*Specific gravity*	*Name*
1.50 (mean)	0.001	Positive	B	5	2.29	Mesolite
—	—	—	—	4 approx. unglazed	2.3	Porcelain
1.490–1.650	0.160	Positive	B	2.5	2.23	Whewellite
1.48 to 1.54	—	—	I	5.5	2.34 to 2.39	Moldavite
1.48 to 1.51	—	—	I	5	2.33 to 2.42	Obsidian
1.496–1.502	0.006	Positive	U	6	2.36 to 2.57	Tugtupite
1.504–1.516	0.012	Positive	B	6 to 6.5	2.39 to 2.46	Petalite
1.495–1.510	—	—	I	1.5	*1.36 to 1.42*	Celluloid
1.496	—	—	I	5.5 to 6.5	2.4	Hauyne
1.51	—	—	—	—	*approx. 0.95*	*Cedar wood oil (microscope objective immersion oil)*
1.51 (mean)	0.020	Positive	B	1	*1.65 to* 2.00	Ulexite
1.51 (mean)	0.001	Positive	U	5.5 to 6	2.45 to 2.50	Leucite
1.512–1.523	0.011	Negative	B	5 to 5.5	*2.21*	Scolecite
1.517 to 1.525	—	—	I	6.5	2.85 to 2.94	Pollucite
1.51 (mean)	0.022	Negative	U	6	2.42 to 2.50	Cancrinite
1.515–*1.717*	0.202	Negative	U	3.5 to 4.5	*3.00 to 3.12*	Magnesite
1.518–1.524	0.006	Negative	B	—	2.57 to 2.58	Sanidine
1.49 to 1.53	—	—	I	5	2.36 to 2.51	Tektites
1.52–1.53	0.010	Positive	B	1.5 to 2	2.30 to 2.33	Gypsum (alabaster)
1.52–1.55	0.027	Negative	U	2.5	2.15 to 2.22	Stichtite
1.52–1.54	0.028	Positive	B	5 to 5.5	2.3 to 2.4	Thomsonite
1.52–1.53 to 1.53–1.54	0.008	Negative	B	6	2.56 to 2.59	Orthoclase feldspar (moonstone)
1.522–1.527	0.005	Negative	B	6	2.56	Yellow orthoclase feldspar
1.522–1.530	0.008	Negative	B	6.5	2.56 to 2.58	Microcline feldspar
1.529–1.532 to 1.548–1.551	0.003	Negative	U	5.5 to 6	2.46 to 2.61	Milarite
1.530–*1.685*	0.155	Negative	B	3.5 to 4	2.93 to 2.95	Aragonite
1.553–*1.625* to 1.559–*1.631*	0.072	Positive	B	7.5	2.35	Hambergite
1.586–*1.614*	0.028	Positive	B	4.5	2.42	Colemanite
1.54	—	—	—	—	—	*Canada balsam*
1.53	—	—	—	—	*1.106*	*Chlorobenzene*
1.535–1.537	0.002	Pos/Neg	U	4.5 to 5	2.30 to 2.50	Apophyllite
—	—	—	—	6 to 6.5	approx. 2.5	Nevada wonderstone
1.530 to 1.539	0.004(?)	Negative	B	7	2.58 to 2.62	Chalcedony
1.53 (mean)	—	—	—	2	*1.00* to 2.00	Meerschaum
1.53–1.54 to 1.54–1.55	0.008 to 0.012	Negative	B	7	2.57 to 2.66, usually 2.57 to 2.61	Iolite
1.530–1.556	0.026	Negative	B	3.5 to 4	2.80 to *3.30*, usually 2.8 to 2.9	Lepidolite
1.532–*1.680*	0.148	Negative	B	3.5	*4.27 to 4.35*	Witherite
1.54	—	—	—	—	2.19	*1,2-dibromoethane*

Table 1 *(cont.)*

Refractive index	*Birefringence*	*Optic sign*	*Optical character*	*Hardness*	*Specific gravity*	*Name*
1.54	—	—	—	3.5	*1.34*	Black coral
1.54	—	—	—	—	*1.08*	*Clove oil*
1.54	—	—	—	2.5	*1.38 to 1.42*	Vegetable ivory
1.54	—	—	—	2.5	2.00	Bone
1.54	—	—	—	2.5 to 2.75	*1.70 to 1.98*	Dentine ivory
1.54	—	—	I	2 to 2.5	*1.03 to 1.10*	Amber
1.54	—	—	I	2	*1.03 to 1.08*	Copal resin
1.54	0.004	Negative	U	5.5 to 6	2.55 to 2.65	Nepheline
—	—	—	—	3.5	2.6 to 2.7	Coral
1.54 approx.	—	—	—	7	2.58 to 2.91	Jasper
1.54 approx.	0.011	Positive	B	6 to 6.5	2.62	Albite feldspar (peristerite)
1.518–1.524	0.006	Negative	B	—	2.57 to 2.58	Sanidine
1.54 approx.	—	—	B	1 to 2	2.7 to 2.8	Soapstone
—	—	—	—	3.5 to 4	2.20 to 2.78	Pearl
					2.69 to 2.73	Fine pearl
					2.40 to 2.65	Blue pearl
					2.67 to 2.78	Australian pearl
					2.70 to 2.78	Cultured pearl
					2.20 to 2.66	Black clam pearl
1.542–1.549	0.007	Negative	B	6 to 6.5	2.62 to 2.65	Oligoclase feldspar (sunstone)
1.544–1.553	0.009	Positive	U	7	2.65	Quartz
1.544–1.560	0.016	Negative	U	6	2.63	Scapolite (pink and white)
1.548–1.568	0.020	Negative	U	6	2.71	Scapolite (yellow)
1.460–1.485	0.025	—	B	3.5	2.71	Creedite
1.55	—	—	—	—	*1.198*	*Nitrobenzene*
1.55	—	—	—	—	*1.42*	*2-bromotoluene*
1.55	—	—	—	2.5	*1.26 to 1.35*	Tortoise-shell and horn
1.550–1.559	0.009	Positive	B	5 to 6	2.54 to 2.68	Charoite
1.553–1.562	0.009	Negative	B	5.5 to 6	2.80 to 2.85	Beryllonite
1.553–*1.625* to 1.559–*1.631*	0.072	Positive	B	7.5	2.35	Hambergite
1.55 to 1.56	—	—	I	2.25	*1.32 to 1.34*	Casein plastic
1.55–*1.60*	—	—	—	1.5	2.8	Pyrophyllite
1.56	—	—	—	—	*0.99*	*N,N-dimethylaniline*
1.56	—	—	—	—	*1.12*	*Benzyl benzoate*
1.56	—	—	—	—	1.499	Bromobenzene
1.56	—	—	—	2.5	*1.60 to 1.85*	Deer horn
1.56 (mean)	—	Negative	B	5	2.4 to 2.6	Variscite
1.560–1.568 to 1.565–1.573 (yellow)	0.008	Positive	B	6 to 6.5	2.68 to 2.69	Labradorite feldspar
1.56	—	Negative	B	2.5 4	2.5 to 2.7 2.58 to 2.62	Serpentine (bowenite)

Table 1 (*cont.*)

Refractive index	*Birefringence*	*Optic sign*	*Optical character*	*Hardness*	*Specific gravity*	*Name*
1.558–1.563	0.003	Negative	U	7.5	2.65	Synthetic emerald (flux melt)
1.56–1.57 to 1.59–1.60	0.006 to 0.007	Negative	U	7.5	2.69 to 2.75	Emerald
1.571–1.577	0.006				2.69	Colombia (Chivor)
1.578–1.584	0.006				2.71	Colombia (Muzo)
1.578–1.585	0.007				2.74	Tanzania
1.566–1.571	0.005				2.69	Brazil (some)
1.581–1.588	0.007				2.74	Russia and Brazil
1.586–1.593	0.007				2.75	Transvaal
1.586–1.593	0.007				2.75	Zimbabwe
1.585–1.595	0.007 to 0.010				2.73 to 2.74	India
1.584–1.591	0.007				2.74	Habachtal
1.588–1.595	0.006				2.76	Pakistan
1.583–1.590	0.007				2.74	Zambia
1.567–1.576	0.009	Negative	B	6 to 6.5	2.73	Bytownite feldspar
—	—	—	—	2.5	2.60 to 2.85	Pinite
1.57	—	—	—	—	*1.004*	*Orthotoluide*
1.57	0.003	Pos/Neg	B	2.5	2.60 to 2.85	Pseudophite
1.57	—	Negative	B	2.5	2.61	Serpentine (williamsite)
1.57 approx.	—	—	—	3 to 4	2.7 approx.	Ophicalcite (Connemara marble)
1.486–1.658	0.172	Negative	U	3	2.71	Calcite
					2.5 to 2.6	Marble
1.570–1.575 to 1.580–1.586	0.005 to 0.006	Negative	U	7.5	2.68 to 2.73	Aquamarine; yellow and some pink beryls
1.571–*1.614*	0.043	Positive	B	3 to 3.5	2.90 to 2.98	Anhydrite
1.574–1.588	0.014	Positive	B	5	2.7	Augelite
1.57 to 1.58	—	Negative	B	3.5 to 4	2.5 to 2.7	Bastite
1.57–*1.63*	—	—	—	5	*3.00 to 3.10*	Odontolite
1.58	—	—	—	—	*1.022*	*Aniline*
1.50	—	—	I	5.5	2.70 to 2.90	Lapis lazuli
1.58 (mean)	—	—	—	3	2.80 to 2.99	Verdite
1.580–*1.627*	0.047	Positive	B	2	2.6	Vivianite
1.58–1.59 to 1.59–*1.60*	0.008 to 0.009	Negative	U	7.5	2.80 to 2.90	Some white and pink beryls
1.582–*1.627*	0.028	Positive	U	6	2.73 to 2.90	Catapleiite
1.583–1.593	0.010	Positive	B	5 to 6	2.7	Xonotlite
1.586–*1.614*	0.028	Positive	B	4.5	2.42	Colemanite
1.59	—	—	—	—	2.86 (2.90 pure)	*Bromoform*
1.59	—	—	—	—	*approx. 1.05*	*Cinnamon oil*
1.59 (mean)	0.020	Negative	B	3.25	2.58	Howlite
—	—	—	—	Varies	2.7 to 2.8	Kakortokite
1.59	—	—	I	2.25	*1.05*	Polystyrene

Table 1 *(cont.)*

Refractive index	*Birefringence*	*Optic sign*	*Optical character*	*Hardness*	*Specific gravity*	*Name*
1.598–1.602 to 1.610–1.611	0.004	Positive	U	5 to 6	2.8 to 3.1	Eudialyte
1.607–1.610	0.004	Negative	U	5.5 to 6.5	2.74	Sugilite
1.595 (mean)	0.009	Positive	U	5	2.81	Wardite
1.593–1.612	0.019	Negative	U	3.5	3.00	Melinophane
1.595–1.616	0.021	Positive	B	3.5	3.1	Phosphophyllite
1.595–1.633	0.038	Positive	B	5 to 6	2.62 to 2.88	Pectolite
1.606–1.608	0.002	Negative	U	6 to 7	2.76 to 2.90	Sogdianite
1.597	—	—	I	6 to 6.5	3.28	Ekanite
—	—	—	—	3.5 to 4	approx. 2.8	Mollusc shell
—	—	—	—	3.5 to 4	2.84 to 2.89	Conch pearl
1.61–1.64	0.030	Positive	B	6	2.80 to 2.95, usually 2.88 to 2.94	Prehnite
1.61–1.65	0.040	Positive	B	5.5 to 6	2.6 to 2.85	Turquoise
					approx. 2.6	American
					approx. 2.8	Persian and Egyptian
1.603–1.623	0.020	Positive	B	5.5	2.980 to 2.995	Brazilianite
1.502–1.681	0.179	Negative	U	3.5 to 4	2.8 to 2.9	Dolomite
1.616–1.631	0.015	Negative	B	4.5 to 5	2.8 to 2.9	Wollastonite
1.517 to 1.525	—	—	I	6.5	2.85 to 2.94	Pollucite
—	—	—	—	6 to 7	2.85 to 3.20	Unakite
1.530–1.685	0.155	Negative	B	3.5 to 4	2.93 to 2.95	Aragonite
1.63	—	—	—	—	2.95	*Tetrabromoethane*
1.66 to 1.67	—	—	I	7	2.96	Boracite
1.654–1.670	0.016	Positive	U	7.5 to 8	2.95 to 2.97	Phenakite
1.60–1.62	0.02	Negative	B	5.5 to 6	2.98	Tremolite
1.625–1.669	0.044	Negative	B	5	2.90–3.00	Datolite
1.62 (mean)	0.027	Negative	B	6.5	2.90 to 3.02	Nephrite
1.6					**3.0**	
1.720–1.735	0.015	Positive	U	9	3.00 to 3.02	Bromellite
1.597	—	—	I	6 to 6.5	3.28	Ekanite
1.60	—	—	—	—	1.05	*Cassia oil*
1.598–1.602 to 1.610–1.611	0.004	Positive	U	5 to 6	2.8 to 3.1	Eudialyte
1.606–1.608	0.002	Negative	U	6 to 7	2.76 to 2.90	Sogdianite
1.620–1.642	0.022	Negative	B	5 to 5.5	3.05	Actinolite
1.378–1.390	0.012	Positive	U	5 to 6	3.15	Sellaite
1.60 (mean)	—	Positive	B	6.5	3.1 to 3.2	Chondrodite
1.58–1.59 to 1.59–1.60	0.008 to 0.009	Negative	U	7.5	2.80 to 2.90	Some white and pink beryls
1.602–1.639	0.037	Negative	B	7.5	3.0	Grandidierite
1.603–1.623	0.020	Positive	B	5.5	2.980 to 2.995	Brazilianite
1.607–1.610	0.004	Negative	U	5.5 to 6.5	2.74	Sugilite
1.593–1.614	0.019	Negative	U	3.5	3.00	Melinophane
1.586–1.614	0.028	Positive	B	4.5	2.42	Colemanite
1.665–1.684	0.019	Positive	B	7 to 8	3.09	Lawsonite
1.595–1.616	0.021	Positive	B	3.5	3.1	Phosphophyllite
1.60–1.62	0.02	Negative	B	5.5 to 6	2.98	Tremolite

Table 1 *(cont.)*

Refractive index	*Birefringence*	*Optic sign*	*Optical character*	*Hardness*	*Specific gravity*	*Name*
1.60 to 1.63	—	—	—	2	*1.15 to 1.20*	Vulcanite (hard rubber)
1.60–1.63 to 1.62–1.65, mean 1.62	0.027	Negative	B	6.5	*2.90 to 3.02*	Nephrite
1.57 to 1.63	—	—	—	5	3.00 to 3.10	Odontolite
1.595–1.633	0.038	Positive	B	5 to 6	*2.62 to 2.88*	Pectolite
1.600–*1.820*	0.220	Negative	U	4	3.45 to 3.70, usually 3.50 to 3.65	Rhodochrosite
1.61 (mean)	0.030	Positive	B	5	3.00	Herderite
1.612–1.633	0.021	Positive	B	5	*3.44*	Hemimorphite
1.610–1.620	0.010	Positive	B	8	3.56	Topaz (white and blue)
1.571–1.614	0.043	Positive	B	3 to 3.5	*2.90 to 2.98*	Anhydrite
1.616–1.634 to 1.630–1.652	0.014 to 0.022	Negative	U	7 to 7.5	3.00 to 3.12	Tourmaline
1.553–1.625 to *1.559*–1.631	0.072	Positive	B	7.5	*2.35*	Hambergite
1.616–1.631	0.015	Negative	B	4.5 to 5	*2.8 to 2.9*	Wollastonite
1.61–1.64	0.030	Positive	B	6	*2.8 to 2.95, usually 2.88 to 2.94*	Prehnite
1.61–1.65	0.040	Positive	B	5.5 to 6	*2.6 to 2.85*	Turquoise
1.611–1.637	0.026	Positive	B	6	3.01 to 3.03	Amblygonite
1.615–1.645	0.036	Negative	B	5.5	3.1	Lazulite
1.70 (mean)	—	—	B	5 to 6	3.1 to 3.5	Chlorastrolite
1.61 to 1.66	—	—	—	2.5	*1.25 to 1.30 (higher if filled)*	Bakelite
1.62	—	—	—	—	*1.83*	*Iodobenzene*
1.620–1.642	0.022	Negative	B	5 to 5.5	3.05	Actinolite
—	—	—	—	6 to 7	2.85 to 3.20	Unakite
1.623–1.651 to 1.632–1.662	0.024 to 0.037	Positive	B	6 to 6.5	3.18	Clinohumite
1.625–1.669	0.044	Negative	B	5	2.9 to 3.00	Datolite
1.625–1.635	0.010	Positive	B	3.5	*3.97 to 3.99*	Celestine
1.62–*1.85*	0.230	Negative	U	5	*4.30 to 4.35*	Smithsonite
1.582–1.627	0.028	Positive	U	6	*2.73 to 2.90*	Catapleiite
1.629–1.664	0.035	Negative	U	4 to 5	3.06 to 3.19	Friedelite
1.63	—	—	—	—	*1.26*	*Carbon disulphide*
1.63	—	—	—	—	*1.93*	*1-chloronaphthalene*
1.63	—	—	—	—	2.95	*Tetrabromoethane*
1.630–1.636	0.006	Negative	B	7	3.00	Danburite
1.630–1.638	0.008	Positive	B	8	3.53	Topaz (brown and pink)
1.63–1.64	0.002 to 0.004	Negative	U	5	3.17 to 3.23	Apatite
1.634–1.644 to 1.641–1.648	0.007 to 0.011	Negative	B	7.25	3.15 to 3.17	Andalusite
1.700–1.706	0.006	Negative	B	6	3.09 to 3.12	Thulite (zoisite)
1.434	—	—	I	4	3.18	Fluorite
1.633–*1.873*	0.240	Negative	U	3.5 to 4	3.83 to 3.88	Siderite

Table 1 *(cont.)*

Refractive index	*Birefringence*	*Optic sign*	*Optical character*	*Hardness*	*Specific gravity*	*Name*
1.636–1.648	0.012	Positive	B	3	*4.3 to 4.6*	Barite
2.65–2.69	0.043	Positive	U	9.25	3.17	Carborundum
1.74 to 1.81	—	Neg/Pos	B	4	3.22	Scorodite
1.639–1.648	0.009	Negative	U	6.5 to 7	3.29–3.31	Jeremejevite
1.639–1.667	0.026	Negative	B	5	3.23	Vayrynenite
1.64 to 1.68	—	—	—	2.5 to 4	usually *1.20 to 1.30*	Jet
1.640–1.645 to 1.668–1.680	0.028 to 0.035	Negative	B	4.5	3.1	Eosphorite
1.644–1.697 to 1.658–*1.709*	0.053	Positive	U	5	3.28 to 3.35	Dioptase
1.70	—	—	—	6.5	3.0 to 3.4	Saussurite
—	—	—	—	5 to 5.5	3.25	Smaragdite
1.486–1.658	0.172	Negative	U	3	*2.71*	Calcite
1.490–1.650	0.160	Positive	B	2.5	*2.23*	Whewellite
1.652–1.672	0.020	Positive	B	7.5	3.10	Euclase
1.650–1.689 to 1.653–1.693	0.040	Positive	B	3 to 4	3.19	Ludlamite
1.654–1.667, mean 1.66	0.013	Positive	B	7	3.30 to 3.36	Jadeite
1.654–1.670	0.016	Positive	U	7.5 to 8	*2.95 to 2.97*	Phenkite
1.654–1.689	0.036	Positive	B	6.5	3.34	Peridot
1.656–1.668	0.012	Negative	B	6.5 to 7	3.18	Magnesioaxinite
1.658–1.668	0.010	Positive	B	5.5	3.25	Enstatite (colourless)
1.658–1.678	0.020	Positive	B	6.5 to 7	3.25	Fibrolite
1.65–*1.90*	0.25	Negative	B	4	3.74 to 3.95, usually 3.8	Malachite
1.66	—	—	—	—	*1.49*	*Monobromonaphthalene*
1.66 to 1.67	—	—	I	7	*2.96*	Boracite
1.660–1.675	0.015	Positive	B	7	3.17 to 3.19	Spodumene
1.660–1.688	0.028	Positive	B	4.5 to 5	3.32	Serandite
1.662–*1.712*	0.050	Negative	B	5	3.94 *to 4.07*	Durangite
1.663–1.673	0.010	Positive	B	5.5	3.26 to 3.28	Enstatite
1.665–1.678 to 1.668–1.680	0.013	Negative	B	6.5	3.28 to 3.35	Kornerupine
1.665–1.684	0.019	Positive	B	7 to 8	3.09	Lawsonite
1.67–*1.70*	0.030	Positive	B	5.5	3.29	Diopside
					3.23	Violane
1.670–1.689 to *1.700–1.772*	0.019 to 0.083	Negative	B	5 to 6	3.20 to 3.28	Kaersutite
1.67–*1.71*	0.038	Negative	B	6.5	3.47 to 3.49	Sinhalite
1.675–1.685	0.010	Negative	B	7	3.27 to 3.29	Axinite
—	—	—	—	—	3.28	*Klein's solution*
1.68 (mean)	—	—	B	7	3.26 to 3.41	Dumortierite (massive)
1.668–1.685 to 1.673–1.688	0.011	Negative	B	8 to 8.5	3.26 to 3.41	Dumortierite (transparent)
1.74	—	—	—	—	3.32	*Di-iodomethane*
1.660–1.688	0.028	Positive	B	4.5 to 5	3.32	Serandite
1.702–1.750	0.048	Positive	B	6.5 to 7	3.30 to 3.35	Diaspore
1.532–1.680	0.148	Negative	B	3.5	*4.27 to 4.35*	Witherite

Table 1 *(cont.)*

Refractive index	*Birefringence*	*Optic sign*	*Optical character*	*Hardness*	*Specific gravity*	*Name*
1.67–1.68 to 1.71–1.73	0.010 to 0.020	Negative	B	5 to 6	3.4 to 3.5	Hypersthene
1.689–1.695 to 1.694–1.702	0.006 to 0.008	Positive	B	4 to 5	3.42 to 3.52	Triphylite
1.69	—	—	I	8	3.4	Rhodizite
1.69–1.72	0.028	Positive	U	5.5	3.89 to 4.18	Willemite
1.692–1.700	0.008	Positive	B	6	3.35	Zoisite
1.700–1.712	0.005 (mean)	Neg/Pos	U	6.5	3.32 to 3.47	Idocrase
					3.25 to 3.32	Californite
1.72	—	—	I	7.25	3.36 to 3.55	Massive grossular garnet
1.736–1.770	0.034	Negative	B	6.5	3.25 to 3.50, usually 3.4	Epidote
1.72–1.73	0.010	Positive	B	6 to 6.5	3.37 approx.	Clinozoisite
1.73	0.010	Positive	B	6	3.40 to 3.70, usually 3.6 to 3.7	Rhodonite
1.612–1.633	0.021	Positive	B	5	3.44	Hemimorphite
1.700–1.743	0.006	Positive	B	6.5 to 7	3.42 to 3.52	Serendibite
1.705–1.711	0.006	Positive	B	7.5	3.40 to 3.58	Sapphirine
1.732–1.744	0.010	Positive	B	7	3.49	Chambersite
2.42	—	—	I	10	3.52	Diamond
1.885–1.990 to 1.915–2.050	0.105 to 0.135	Positive	B	5.5	3.52 to 3.54	Sphene
1.630–1.638	0.008	Positive	B	8	3.53	Topaz (brown and pink)
1.610–1.620	0.010	Positive	B	8	3.56	Topaz (white and blue)
—	—	—	—	—	3.58	*Rohrbach's solution*
1.72 usually	—	—	I	8	3.58 to 3.61	Spinel
1.737	—	—	I	6	3.55 to 3.60	Periclase (synthetic)
—	—	—	—	—	3.60	*Di-iodomethane with iodine and iodoform*
1.718–1.722	0.004	Negative	U	8	3.60 to 3.61	Taaffeite
1.724 to 1.729	—	—	I	8	3.61 to 3.65	Spinel (synthetic)
1.77 to 1.80	—	—	I	8	3.63 to 3.90	Spinel (Ceylonite)
1.742 to 1.748	—	—	I	7.25	3.65	Hessonite garnet
1.757–1.804	0.047	Positive	U	6.5	3.65 to 3.68	Benitoite
1.715–1.732	0.017	Negative	B	5 to 7 directional	3.65 to 3.68	Kyanite
1.739–1.750 to 1.747–1.762	0.011 to 0.015	Positive	B	7 to 7.5	3.65 to 3.78	Staurolite
1.73 to 1.75	—	—	I	7.25	3.65 to 3.70	Pyrope garnet
1.75 to 1.78	—	—	I	7.5	3.70 to 3.95	Pyrope/almandine series garnet
1.75–1.76	0.008 to 0.010	Positive	B	8.5	3.71 to 3.72	Chrysoberyl
1.65–1.90	0.25	Negative	B	4	3.74 to 3.95, usually 3.8	Malachite
1.74 (mean)	—	—	I	8	3.75 (mean)	Gahnospinel

Table 1 (*cont.*)

Refractive index	*Birefringence*	*Optic sign*	*Optical character*	*Hardness*	*Specific gravity*	*Name*
1.736–1.753	0.017	Positive	B	5 to 6	3.76 (mean)	Pyroxmangite
1.87	—	—	I	7.25	3.77	Uvarovite garnet
1.73–1.84	0.110	Positive	B	3.5 to 4	3.77 to 3.89	Azurite
1.752–1.815	—	—	—	6	3.8	Shattuckite
1.89	—	—	I	6.5	3.82 to 3.85	Damantoid garnet
1.69–*1.72*	0.028	Positive	U	5.5	3.89 to *4.18*	Willemite
2.493–2.554	0.061	Negative	U	5.5 to 6	3.82 to 3.95	Anatase
1.633–*1.873*	0.240	Negative	U	3.5 to 4	3.83 to 3.88	Siderite
2.583–2.705	0.122	Positive	B	5.5 to 6	3.87 to *4.08*	Brookite
1.760–1.768 to 1.770–1.779	0.008 to 0.010	Negative	U	9	3.90 to *4.00*	Corundum
1.78 to 1.81	—	—	I	6	3.90 to *4.10*	Zircon (low type)
1.720–1.746	0.026	Negative	B	4.5 to 5	3.95	Hodgkinsonite
1.78 to 1.81	—	—	I	7.5	3.95 to *4.20*	Almandine garnet
1.625–1.635	0.010	Positive	B	3.5	3.97 to 3.99	Celestine
1.662–*1.712*	0.050	Negative	B	5	3.97 to *4.07*	Durangite
1.671–*1.772*	0.101	Positive	U	4.5	4.33	Parisite
1.675–*1.735*	0.060	Positive	B	5	3.98 to *4.04*	Legrandite
1.7					**4.0**	
1.670–1.689 to 1.700–1.772	0.019 to 0.083	Negative	B	5 to 6	*3.20 to 3.28*	Kaersutite
1.689–1.695 to 1.694–1.702	0.006 to 0.008	Positive	B	4 to 5	*3.42 to 3.52*	Triphylite
1.704	—	—	—	—	—	1-*iodonaphthalene*
1.70 approx.	—	—	—	5	4.00	Arandisite
1.70 approx.	—	—	—	5 to 5.5	*3.25*	Smaragdite
1.70 (mean)	—	—	B	5 to 6	*3.1 to 3.5*	Chlorastrolite
1.700–1.706	0.006	Negative	B	6	*3.09 to 3.12*	Thulite (zoisite)
1.700–1.743	0.006	Positive	B	6.5 to 7	*3.42 to 3.52*	Serendibite
1.705–1.711	0.006	Neg/Pos	B	7.5	*3.40 to 3.58*	Sapphirine
1.702–1.712	0.005	Neg/Pos	U	6.5	*3.32 to 3.47*	Idicrase
					3.25 to 3.32	Californite
1.702–1.750	0.048	Positive	B	6.5 to 7	*3.30 to 3.35*	Diaspore
1.662–1.712	0.050	Negative	B	5	*3.97* to 4.07	Durangite
1.64–1.69 to 1.66–1.71	0.053	Positive	U	5	*3.28 to 3.35*	Dioptase
1.67–1.70	0.030	Positive	B	5.5	*3.29*	Diopside
1.67–1.71	0.038	Negative	B	6.5	*3.47 to 3.49*	Sinhalite
1.710–1.759 to 1.742–1.773	0.031 to 0.050	Positive	B	3.5	4.30 to 4.68	Adamite
1.715–1.732	0.017	Negative	B	5 to 7 directional	*3.65 to 3.68*	Kyanite
1.67–1.68 to 1.71–1.73	0.010 to 0.020	Negative	B	5 to 6	*3.4 to 3.5*	Hypersthene
1.69–1.72	0.028	Positive	U	5.5	*3.89* to 4.18	Willemite
1.718–1.722	0.004	Negative	U	8	*3.60 to 3.61*	Taaffeite
1.714 to 1.736	—	—	I	8	*3.58 to 3.64*	Spinel
1.724 to 1.729	—	—	I	8	*3.61 to 3.65*	Synthetic spinel

Table 1 *(cont.)*

Refractive index	*Birefringence*	*Optic sign*	*Optical character*	*Hardness*	*Specific gravity*	*Name*
1.72	—	—	I	7.25	*3.36–3.55*	Massive grossular garnet
1.72–1.73	0.010	Positive	B	6 to 6.5	*3.37*	Clinozoisite
1.720–1.735	0.015	Positive	U	9	*3.00 to 3.02*	Bromellite
1.720–1.746	0.026	Negative	B	4.5 to 5	*3.95*	Hodgkinsonite
1.73	0.010	Positive	B	6	*3.6 to 3.7*	Rhodonite
1.675–1.735	0.060	Positive	B	5	*3.98–4.04*	Legrandite
1.73 to 1.75	—	—	I	7.25	*3.65 to 3.80*	Pyrope garnet
1.732–1.744	0.010	Positive	B	7	*3.49*	Chambersite
1.736–1.753	0.017	Positive	B	5 to 6	*3.76 (mean)*	Pyroxmangite
1.737	—	—	I	5	*3.55 to 3.60*	Periclase
1.73–*1.84*	0.110	Positive	B	3.5 to 4	*3.77 to 3.89*	Azurite
1.739–1.750 to 1.747–1.762	0.011 to 0.015	Positive	B	7 to 7.5	*3.65 to 3.78*	Staurolite
1.736–1.770	0.034	Negative	B	6.5	*3.25 to 3.50, usually 3.4*	Epidote
1.74	—	—	—	—	*3.32*	*Di-iodomethane*
1.74 (mean)	—	—	I	8	*3.75 (mean)*	Gahnospinel
1.74 to *1.81*	—	Neg/Pos	B	4	*3.22*	Scorodite
1.742 to 1.748	—	—	I	7.25	*3.65*	Hessonite garnet
1.75–1.76	—	Positive	B	8.5	*3.71 to 3.72*	Chrysoberyl
1.75 to 1.78	— to 0.010	—	I	7.5	*3.80 to 3.95*	Almandine/pyrope garnet
1.752–*1.815*	—	—	—	6	*3.8*	Shattuckite
1.757–*1.804*	0.047	Positive	U	6.5	*3.65 to 3.68*	Benitoite
1.760–1.768 to 1.770–1.779	0.008 to 0.009	Negative	U	9	3.90 to 4.00	Corundum
1.77 to *1.80*	—	—	I	8	*3.63 to 3.90*	Spinel (Ceylonite)
1.78 to *1.81*	—	—	I	7.5	3.95 to 4.20	Almandine garnet
1.787–*1.816*	0.029	Negative	U	7.5	4.01	Painite
1.78 to *1.81*	—	—	I	6	*3.90* to 4.10	Zircon (low type)
1.79	—	—	—	—	—	*Di-iodomethane with sulphur*
2.40	—	—	B	6	4.05	Calcium titanate
1.79 to *1.81*	—	—	I	7.25	4.12 to 4.20	Spessartine garnet
1.795–*1.845*	0.05	Positive	B	6	5.2	Monazite
2.583–2.705	0.122	Positive	B	5.5 to 6	*3.87* to 4.08	Brookite
2.368 to 2.371	—	—	I	3.5 to 4	4.08 to 4.10	Zinc blende
1.68	—	—	—	—	4.15	*Clerici's solution*
2.1	—	—	I	5.5	4.1 to 4.9	Chromite
2.21	—	—	B	5 to 6	4.1 to *6.2*	Samarskite
2.62–2.90	0.287	Positive	U	6 to 6.5	4.2	Rutile (natural and synthetic)
—	—	—	—	3.5 to 4	4.2 approx.	Chalcopyrite
1.532–1.680	0.148	Negative	B	3.5	4.27 to 4.35	Witherite
1.62–1.85	0.23	Negative	U	5	4.30 to 4.35	Smithsonite
1.636–1.648	0.012	Positive	B	3	4.3 to 4.6	Barite
1.671–1.772	0.010	Positive	U	4.5	4.33	Parisite
1.710–1.759 to 1.742–1.773	0.031 to 0.050	Positive	B	3.5	4.30 to 4.68	Adamite

Table 1 *(cont.)*

Refractive index	*Birefringence*	*Optic sign*	*Optical character*	*Hardness*	*Specific gravity*	*Name*
1.974–1.984	0.010	Positive	U	3.5	4.34	Powellite
1.95–1.99	0.020	Positive	B	4.5	4.35	Bayldonite
—	—	—	—	7	4.35 approx.	Psilomelane
1.80	—	—	—	7.5 to 8	4.40	Gahnite
—	—	—	—	—	4.6	*Retger's salt*
1.83	—	—	—	8 to 8.5	4.57 to 4.60	Yttrium aluminium garnet
2.21–2.30	0.090	—	—	6	4.64	Lithium niobate
1.925–1.984	0.059	Positive	U	7 to 7.5	4.67 to 4.70	Zircon (high type)
2.06 to 2.26	—	—	—	6.5	4.7 to 5.0	Euxenite
2.505–2.529	0.024	Positive	U	3.5	4.83 to 4.90	Greenockite
1.92	—	—	I	7.5 to 8	4.84	Yttrium oxide
—	—	—	—	6 to 6.5	4.85 to 4.90	Marcasite
—	—	—	—	3	4.9 to 5.4	Bornite
—	—	—	—	6.5	4.95 to 5.10	Pyrite
2.94–3.22	—	—	U	6.5	4.95 to 5.16	Hematite
1.8					**5.0**	
—	—	—	—	3.5 to 4	5.0	Pentlandite
2.030–2.050	0.020	Negative	U	3.5	5.05	Boleite
1.80	—	—	I	7.5 to 8	4.40	Gahnite
1.77–1.80	—	—	I	8	3.63 to 3.90	Spinel (Ceylonite)
1.757–1.804	0.047	Positive	U	6.5	3.65 to 3.68	Benitoite
1.804–2.078	0.274	Negative	B	3 to 3.5	6.46 to 6.57	Cerussite
1.81	—	—	—	—	—	*Di-iodomethane with sulphur and tetraiodoethylene*
1.74 to 1.81	—	Neg/Pos	B	4	3.22	Scorodite
1.78 to 1.81	—	—	I	7.5	3.95 to 4.20	Almandine garnet
1.752–1.815	—	—	—	6	3.8	Shattuckite
1.787–1.816	0.029	Negative	U	7.5	4.01	Painite
1.79 to 1.81	—	—	I	7.25	4.12 to 4.20	Spessartine garnet
1.79 to 1.81	—	—	I	6	3.90 to 4.10	Zircon (low type)
1.60–1.82	0.220	Negative	U	4	3.50 to 3.65	Rhodochrosite
1.83	—	—	—	8 to 8.5	4.57 to 4.60	Yttrium aluminium garnet
1.73–1.84	0.110	Positive	B	3.5 to 4	3.77 to 3.89	Azurite
1.62–1.85	0.23	Negative	U	5	4.30 to 4.35	Smithsonite
1.87	—	—	I	7.5	3.77	Uvarovite garnet
1.633–1.873	0.240	Negative	U	3.5 to 4.5	3.83 to 3.88	Siderite
1.877–1.894	0.017	Positive	B	2.75 to 3	6.30 to 6.39	Anglesite
1.88–1.99	0.105	Positive	B	5.5	3.52 to 3.54	Sphene
1.89	—	—	I	6.5	3.82 to 3.85	Demantoid garnet
2.41	—	—	I	6	5.13	Strontium titanate
—	—	—	I	6	5.17	Magnetite

Table 1 *(cont.)*

Refractive index	*Birefringence*	*Optic sign*	*Optical character*	*Hardness*	*Specific gravity*	*Name*
1.795–1.845	0.05	Positive	B	6	5.2	Monazite
1.92	—	—	—	6.5	5.30	'Yttralox'
1.938–1.955	0.017	?	B	8	5.35	Rhombic yttrium aluminate
—	—	—	—	3 to 3.5	5.3 to 5.65	Millerite
1.93	—	—	I	5.5	5.5	Microlite
—	—	—	—	6	5.5 to 5.7	Magnetoplumbite
2.7 to 3.0	0.300	Negative	U	2 to 2.5	5.57 to 5.64	Proustite
2.013–2.029	0.016	Positive	U	4 to 4.5	5.66	Zincite
2.85	—	—	I	3.5 to 4	5.86 to *6.15*	Cuprite
2.40	—	—	—	6 to 6.5	5.90	Barium titanate
1.918–1.934	0.016	Positive	U	4.5 to 5	5.9 to *6.1*	Scheelite
2.31–2.66	0.35	Positive	B	2.5 to 3	5.9 to *6.1*	Crocoite
2.09 to 2.18	—	—	I	8 to 8.5	5.95 to *6.06*	Cubic zirconia
1.9					**6.0**	
1.91–*2.05*	0.135	Positive	B	5.5	*3.52 to 3.54*	Sphene
1.65–1.90	0.25	Negative	B	4	*3.74 to 3.95, usually 3.8*	Malachite
2.06	0.100	—	U	7	6.00	Simpsonite
1.918–1.934	0.016	Positive	U	4.5 to 5	5.9 to 6.1	Scheelite
1.92	—	—	I	7.5 to 8	*4.84*	Yttrium oxide
1.92	—	—	—	6.5	*5.30*	'Yttralox'
1.925–1.984	0.059	Positive	U	7 to 7.5	*4.67 to 4.70*	Zircon (high type)
1.93	—	—	I	5.5	*5.5*	Microlite
1.938–1.955	0.017	?	B	8	*5.35*	Rhombic yttrium aluminate
1.95–1.99	0.020	Positive	B	4.5	*4.35*	Bayldonite
1.974–1.984	0.010	Positive	U	3.5	*4.34*	Powellite
2.85	—	—	I	3.5 to 4	5.86 to 6.15	Cuprite
2.36–2.66	0.35	Positive	B	2.5 to 3	5.9 to 6.1	Crocoite
—	—	—	I	5.5	6.0 to 6.3	Cobaltite
2.114–2.140	0.026	Positive	U	3	6.2	Phosgenite
2.21	—	—	B	5 to 6	4.1 to 6.2	Samarskite
1.877–1.894	0.017	Positive	B	2.75 to 3	6.30 to 6.39	Anglesite
2.27	—	—	—	6	6.43	KTN
1.804–2.078	0.274	Negative	B	3 to 3.5	6.45 to 6.57	Cerussite
2.304–2.402	0.098	Negative	U	2.75 to 3	6.7 to 7	Wulfenite
2.003–2.101	0.098	Positive	U	6.5	6.8 to 7	Cassiterite
2.0 and over					**7.0**	
2.003–2.101	0.098	Positive	U	6.5	*6.95*	Cassiterite
2.013–2.029	0.016	Positive	U	4 to 4.5	*5.66*	Zincite
1.915–2.050	0.135	Positive	B	5.5	*3.52 to 3.54*	Sphene
1.92–2.03	—	—	I	6.5	7.05	Gadolinium gallium garnet
2.030–2.050	0.020	Negative	U	3.5	*5.05*	Boleite
2.05	—	—	—	—	—	*West's solution*
2.06	0.100	—	U	7	*6.00*	Simpsonite
1.804–2.078	0.274	Negative	B	3 to 3.5	*6.45 to 6.57*	Cerussite

Table 1 *(cont.)*

Refractive index	*Birefringence*	*Optic sign*	*Optical character*	*Hardness*	*Specific gravity*	*Name*
2.06 to 2.26	—	—	—	6.5	4.7 to 5.0	Euxenite
2.09 to 2.18	—	—	I	8 to 8.5	5.98 to 6.06	Cubic zirconia
2.1	—	—	I	5.5	4.1 to 4.9	Chromite
2.114–2.140	0.026	Positive	U	3	6.2	Phosgenite
2.120–2.135	0.015	Negative	U	3.5	7.0 to 7.25	Mimetite
2.14–2.22 to 2.19–2.34	0.008 to 0.015	—	B	5.5–6	7.73–7.97	Manganotantalite
2.21	—	—	B	5 to 6	4.1 to 6.2	Samarskite
2.21–2.30	0.90	—	—	6	4.64	Lithium niobate
2.27	—	—	—	6	6.43	KTN
2.304–2.402	0.098	Negative	U	2.5 to 3	6.5 to 7	*Wulfenite*
2.31–2.66	0.35	Positive	B	2.5 to 3	5.9 to 6.1	*Crocoite*
2.39–2.46	0.07	Positive	B	5.5 to 6	7.46	Stibiotantalite
2.368–2.371	—	—	I	3.5 to 4	4.08 to 4.10	Zinc blende
—	—	—	—	4.5 to 5	7.54	Breithauptite
2.40	—	—	B	6	4.05	Calcium titanate
2.40	—	—	—	6 to 6.5	5.90	Barium titanate
2.41	—	—	I	6	5.13	Strontium titanate
2.42	—	—	I	10	3.52	Diamond
2.493–2.554	0.061	Negative	U	5.5 to 6	3.82 to 3.95	Anatase
2.505–2.529	0.024	Positive	U	3.5	4.83	Greenockite
2.583–2.705	0.122	Positive	B	5.5 to 6	3.87 to 4.08	Brookite
2.62–2.90	0.287	Positive	U	6 to 6.5	4.2	Rutile
2.65–2.69	0.043	Positive	U	9.25	3.17	Carborundum
2.7–3.0	0.30	Negative	U	2 to 2.5	5.57 to 5.64	Proustite
2.85	—	—	I	3.5 to 4	5.85 to 6.15	Cuprite
2.94–3.22	—	—	U	6.5	4.95 to 5.16	Hematite
—	—	—	U	5 to 5.5	7.33 to 7.67	Niccolite
—	—	—	—	3.5	7.2 to 7.9	Domeykite
—						
—	—	—	—	3.5	8.38	Algodonite

Table of OPTICAL PROPERTIES

The optical properties of gem materials are explained by this short table.

Single refracting or isotropic	Amorphous substances and cubic crystals		One index of refraction, n
Doubly refracting or anisotropic	Hexagonal Trigonal Tetragonal	Uniaxial	Two indices of refraction, ω and ε; positive, ω less than ε; negative, ε less than ω
	Rhombic Monoclinic Triclinic	Biaxial	Three indices of refraction, α, β and γ; positive, $\alpha\beta$—γ; negative, α—$\beta\gamma$*

*When the intermediate index of refraction β is nearer to α, the optic sign is positive; when nearer to γ, the optic sign is negative.

Table 2
Refractive indices

Readers are referred to Table 1 and to the main text for birefringence values, optical character and sign, and for further information on the range of RI values in minerals listed below. Liquids are listed in italics. (I) signifies the RI range of an isotropic mineral or other material.

Refractive index liquids listed in this table should be used with great care. Always use in a well-ventilated area or, for prolonged use, a fume cupboard.

Water	1.33
Ethanol	1.36
Pentyl acetate	1.37
Sellaite	1.37–1.39
Cellosolve	1.40
Fluorite	1.43
Opal	1.45
Petroleum	1.45
Chloroform	1.45
Silica glass	1.46
Creedite	1.46–1.48
Thaumasite	1.46–1.51
Glycerin	1.47
Turpentine	1.47
Olive oil	1.47
Castor oil	1.47
Sodalite	1.48
Analcime	1.48–1.49 (I)
Natrolite	1.48–1.49
Moldavite and other tektites	1.48–1.54 (I)
Obsidian	1.48–1.51 (I)
Calcite	1.48–1.65
Whewellite	1.48–1.65
Toluene	1.49
Xylene	1.49
Celluloid	1.49–1.51 (I)
Tugtupite	1.49–1.50
Yugawaralite	1.49–1.50
Hauyne	1.49–1.50 (I)
Chrysocolla (Webster)	1.50 (mean)
or (Ahrem)	*c.*1.59 (mean)
silicified	as for quartz
Lapis lazuli	1.50 (mean)
Perspex	1.50
Mesolite	1.50 (mean)
Petalite	1.50–1.51
Leucite	1.50–1.51
Dolomite	1.50–1.68
Cedar wood oil	1.51
Ulexite	1.51 (mean)
Cancrinite	1.51 (mean)
Magnesite	1.51–1.70 (mean)
Pollucite	1.51–1.52 (I)
Scolecite	1.51–1.52
Sanidine feldspar	1.51–1.52
Thomsonite	1.51–1.54
Orthoclase feldspar	1.51–1.53
Microcline feldspar	1.51–1.53
Albite feldspar	1.52–1.54
Gypsum	1.52–1.53
Milarite	1.52–1.55
Stichtite	1.53 (mean)
Chlorobenzene	1.53
Meerschaum	1.53 (mean)
Chalcedony	1.53–1.54
Oligoclase feldspar	1.53–1.54
Iolite	1.53–1.55
Casein	1.53–1.56 (I)
Witherite	1.53–1.67
Apophyllite	1.53–1.54
Aragonite	1.53–1.68
Canada balsam	1.54
Nepheline	1.54 (mean)
1,2-dibromoethane	1.54
Bone	1.54
Vegetable ivory	1.54
Clove oil	1.54
Ivory (dentine)	1.54
Amber	1.54
Copal resin	1.54
Jasper	1.54
Horn	1.54
Lepidolite	1.55 (mean)
Scapolite	1.54–1.58
Quartz	1.54–1.55
Tortoiseshell	1.55
Soapstone (steatite)	1.55 (mean)
Nitrobenzene	1.55
2-bromotoluene	1.55
Beryllonite	1.55–1.56
Hambergite	1.55–1.63
Polyester resin	1.55–1.56 (I)
Pyrophyllite	1.60 (mean)
N,N-dimethylaniline	1.56
Bromobenzene	1.56
Benzyl benzoate	1.56
Deerhorn	1.56
Black coral	1.56
Variscite	1.56 (mean)
Bowenite serpentine	1.56 (mean)
Labradorite feldspar	1.56–1.57
Synthetic emerald (some flux melt)	1.55–1.56
Natural emerald and hydrothermal synthetics	1.566–1.590 (see Table 1)
Aquamarine	1.56–1.59
Anhydrite	1.57–1.61

Table 2 (*cont.*)

Vivianite	*1.56–1.67*
Orthotoluide	1.57
Pseudophite	1.57 (mean)
Williamsite serpentine	1.57 (mean)
Ophicalcite	1.57 (mean)
Bastite	1.57–1.58
Bytownite feldspar	1.57–1.58
Augelite	1.57–1.58
Odontolite	1.57–1.63 (I)
Aniline	1.58
Verdite	1.58 (mean)
Xonotlite	1.58–1.59
Colemanite	1.58–1.61
Catapleiite	1.58–1.62
Bromoform	1.59
Cinnamon oil	1.59
Howlite	1.59 (mean)
Polystyrene	1.59
Wardite	1.59 (mean)
Ekanite	1.59
Eudialyte	1.59–1.60
Melinophane	1.59–1.61
Herderite	1.59–1.62
Phosphophyllite	1.59–1.62
Pectolite	1.60 (mean)
Cassia oil	1.60
Chrondrodite	1.60 (mean)
Sogdianite	1.60 (mean)
Sugilite	1.60–1.61
Brazilianite	1.60–1.62
Grandidierite	1.60–1.63
Vulcanite	1.60–1.63 (I)
Tremolite	1.60–1.64
Rhodochrosite	1.60–1.82
Topaz (white, blue, yellow, brown)	1.61–1.62
Hemimorphite	1.61–1.63
Prehnite massive	1.61–1.64 1.63 (mean)
Pargasite	1.61–1.63
Amblygonite	1.61–1.63
Lazulite	1.61–1.64
Bakelite	1.61–1.66 (I)
Nephrite	1.62 (mean)
Turquoise	1.62 (mean)
Wollastonite	1.63 (mean)
Iodobenzene	1.62
Celestine	1.62–1.63
Tourmaline	1.62–1.64 (mean)
Actinolite	1.62–1.65
Friedelite	1.62–1.66
Datolite	1.62–1.67
Clinohumite	1.62–1.67
Smithsonite	1.62–1.84
Carbon disulphide	1.63
1-chloronaphthalene	1.63
1,1,2,2-tetrabromoethane	1.63
Danburite	1.63–1.64
Topaz (red, pink, yellow, orange)	1.63–1.64
Apatite	1.63–1.64
Barite	1.63–1.64
Jeremejevite	1.63–1.64
Vayrynenite	1.63–1.66
Siderite	1.63–1.87
Andalusite	1.64–1.65
Eosphorite	1.64–1.68
Magnesioaxinite	1.65–1.66
Euclase	1.65–1.67
Phenakite	1.65–1.67
Boracite	1.65–1.67
Enstatite	1.65–1.68
Fibrolite	1.65–1.68
Peridot	1.65–1.69
Ludlamite	1.65–1.69
1-bromonaphthalene	1.66
Jadeite	1.66 (mean)
Spodumene	1.66–1.68
Durangite (Webster) or (Gunther)	1.66–1.71 1.63–1.68
Dioptase	1.65–1.70 (mean)
Lawsonite	1.66–1.68
Sinhalite	1.66–1.71
Kornerupine	1.66–1.69
Kaersutite	1.67–1.77
Diopside	1.67–1.70
Serandite	1.67–1.70
Axinite	1.67–1.69
Legrandite	1.67–1.73
Parisite	1.67–1.77
Dumortierite	1.68 (mean)
silicified	as for quartz
Triphylite	1.68–1.70
Rhodizite	1.69
Willemite	1.69–1.72
Zoisite var. Tanzanite	1.69–1.70
var. Thulite	1.70 (mean)
Arandisite	1.70 (mean)
1-iodonaphthalene	1.70
Smaragdite	1.70 (approx.)
Chlorastrolite	1.70 (mean)
Hypersthene	1.70–1.71 (mean)
Idocrase (yellow)	1.70–1.71
Serendibite	1.70–1.74
Sapphirine	1.70–1.71
Diaspore	1.70–1.75
Spinel	1.71–1.73 (I)
Kyanite	1.71–1.73
Taaffeite	1.71–1.72 (up to 1.74)
Hydrogrossular garnet	1.72–1.74 (I)
Bromellite	1.72–1.73

Table 2 (*cont.*)

Clinozoisite	1.72–1.73
Hodgkinsonite	1.72–1.74
Spinel (synthetic)	1.72
Pyroxmangite	1.73–1.75
Chambersite	1.73–1.74
Rhodonite	1.73 (mean)
Pyrope garnet	1.73–1.76 (I)
Azurite	1.73–1.84
Epidote	1.73–1.77 (mean)
Periclase	1.73
Di-iodomethane	1.74
Gahnospinel	1.72–1.75 (I)
Hessonite garnet	1.72–1.74 (I)
Staurolite	1.74–1.75 (mean)
Chrysoberyl	1.74–1.75
Shattuckite	1.75 (mean)
Benitoite	1.75–1.80
Almandine garnet	1.76–1.81 (I)
Corundum	1.76–1.77
Pleonaste (Ceylonite)	1.77–1.78 (I)
Scorodite	1.78–1.81
Painite	1.78–1.81
Zircon (low type)	1.78–1.85 almost isotropic
Di-iodomethane with sulphur	1.79
Spessartine garnet	1.79–1.81 (I)
Gahnite	1.80
Monazite	1.80–1.85
Cerussite	1.80–2.07
Di-iodomethane with sulphur and tetraiodoethylene	1.81
Yttrium aluminate (YAG)	1.83
Malachite	1.85 (mean)
Uvarovite garnet	1.87
Anglesite	1.87–1.89
Demantoid garnet	1.89
Sphene	1.90–2.02
Scheelite	1.92–1.93
'Yttralox'	1.92
Yttrium oxide	1.92
Zircon (high type)	1.92–1.98
Microlite	1.93
Rhombic yttrium aluminate	1.93–1.95
Bayldonite	1.95–1.99
Gadolinium gallium garnet (GGG)	1.92–2.03 (I)
Simpsonite	1.97–2.04
Cassiterite	2.00–2.10
Zincite	2.01–2.02
Boleite	2.03–2.05
West's solution	2.05
Euxenite	2.06–2.24
Chromite	2.08–2.16 (I)
Cubic zirconia	2.09–2.18 (I)
Phosgenite	2.11–2.14
Mimetite	2.12–2.14
Manganotantalite	2.14–2.22
Samarskite	2.20
Lithium niobate	2.21–2.30
KTN	2.27
Crocoite	2.31–2.66
Wulfenite	2.28–2.40
Stibiotantalite	2.37–2.45
Zinc blende (sphalerite)	2.37–2.43 (I)
Barium titanite	2.40
Calcium titanate	2.40 (mean)
Strontium titanate	2.40–2.42 (I)
Diamond	2.42
Anatase	2.49–2.55
Greenockite	2.50–2.52
Brookite	2.58–2.71
Rutile	2.62–2.90
Silicon carbide (carborundum)	2.65–2.69
Proustite	2.79–3.08
Cuprite	2.84
Hematite	2.94–3.22

Table 3
Specific gravities

Meerschaum	1.00–2.00
Amber	1.03–1.10
Copal resin	1.03–1.10
Polystyrene	1.05
Benzyl benzoate	1.12
Vulcanite	1.15–1.20
Perspex	1.18–1.19
Jet	1.20–1.30
Bakelite	1.25–1.30
Tortoise-shell and horn	1.26–1.35
Cellulose acetate	1.29–1.40
Casein	1.32–1.34
Black coral	1.34
Celluloid	1.36–1.42
Vegetable ivory	1.38–1.42
1-bromonaphthalene	1.49
Deer horn	1.60–1.85
Ivory (dentine)	1.70–1.98

Table 3 *(cont.)*

Thaumasite	1.88–1.90
Opal	1.98–2.20
Ulexite	1.99
Bone	2.00
Chrysocolla	2.00–2.45
Stichtite	2.15–2.22
1,2-dibromoethane	2.19
Yugawaralite	2.19–2.22
Natrolite	2.20–2.25
Analcime	2.20–2.29
Black clam pearls	2.20–2.66
Silica glass	2.21
Whewellite	2.23
Sodalite	2.25–2.30
Mesolite	2.29
Porcelain	2.30
Alabaster	2.30–2.33
Thomsonite	2.3–2.4
Apophyllite	2.3–2.5
Obsidian	2.33–2.42
Moldavite	2.34–2.39
Hambergite	2.35
Tektites	2.36–2.51
Tugtupite	2.36–2.58
Petalite	2.39–2.46
Hauyne	2.4
Milarite	2.4–2.6
Blue pearls	2.40–2.65
Variscite	2.40–2.60
Colemanite	2.42
Cancrinite	2.42–2.50
Leucite	2.45–2.50
Rhyolite (Nevada wonderstone)	2.5 (approx.)
Bastite	2.5–2.7
Nepheline	2.55–2.65
Yellow orthoclase feldspar	2.56
Microcline feldspar	2.56–2.58
Moonstone feldspar	2.56–2.59
Iolite	2.57–2.66
Sanidine feldspar	2.57–2.58
Howlite	2.58
Chalcedony	2.58–2.62
Bowenite serpentine	2.58–2.62
Jasper	2.58–2.91
Coral	2.6–2.7
Vivianite	2.6
Marble	2.6–2.7
Pinite	2.60–2.85
Pseudophite	2.60–2.85
Turquoise	2.60–2.85
Williamsite serpentine	2.61
Albite feldspar	2.62
Oligoclase feldspar	2.62–2.65
Pectolite	2.62–2.84
Scapolite	2.63–2.71
Quartz	2.65
Synthetic emerald (some)	2.66–2.68
Pearl	2.67–2.78
Charoite	2.68
Labradorite feldspar	2.68–2.69
Beryl	2.68–2.90
Natural emerald	2.69–2.76
Augelite	2.7
Ophicalcite	2.7
Xonotlite	2.7
Lepidolite	2.7–2.8
Kakortokite	2.7–2.8
Lapis lazuli	2.70–2.90
Calcite	2.71
Creedite	2.71
Bytownite feldspar	2.73
Sugilite	2.74
Catapleiite	2.73–2.90
Sogdianite	2.76–2.90
Pyrophyllite	2.8
Mollusc shell	2.8
Beryllonite	2.80–2.85
Dolomite	2.8–2.9
Lepidolite	2.8–2.9
Wollastonite	2.8–2.9
Verdite	2.80–2.99
Eudialyte	2.8–3.1
Wardite	2.81
Conch shell	2.84–2.89
Pollucite	2.85–2.94
Unakite	2.85–3.20
Bromoform	2.86
Prehnite	2.88–2.94
Datolite	2.90–3.00
Nephrite	2.90–3.02
Anhydrite	2.91–2.98
Aragonite	2.93–2.95
Tetrabromoethane	2.95
Phenakite	2.95–2.97
Boracite	2.96
Tremolite	2.98–3.03
Brazilianite	2.980–2.995
Melinophane	3.00
Herderite	3.00
Danburite	3.00
Grandidierite	3.00
Odontolite	3.00–3.10
Tourmaline	3.00–3.12
Bromellite	3.00–3.02
Saussurite	3.0–3.4
Amblygonite	3.01–3.03
Hornblende	3.02–3.45
Actinolite	3.05
Friedelite	3.05–3.07
Lawsonite	3.09
Thulite	3.09–3.12

Table 3 (*cont.*)

Eosphorite	3.1
Phosphophyllite	3.1
Lazulite	3.1
Ludlamite	3.1
Euclase	3.1
Chondrodite	3.1–3.2
Chlorastrolite	3.1–3.5
Sellaite	3.15
Andalusite	3.15–3.17
Carborundum	3.17
Spodumene	3.17–3.19
Apatite	3.17–3.23
Magnesioaxinite	3.178–3.190
Gedrite	3.18–3.37
Clinohumite	3.18
Fluorite	3.18
Kaersutite	3.20–3.28
Scorodite	3.22
Vayrynenite	3.23
Diopside	3.23–3.29
Fibrolite	3.25
Smaragdite	3.25
Californite	3.25–3.32
Epidote	3.25–3.50
Enstatite	3.26–3.28
Dumortierite	3.26–3.41
Axinite	3.27–3.29
Klein's solution	3.28
Ekanite	3.28
Jeremejevite	3.29–3.31
Dioptase	3.28–3.35
Kornerupine	3.28–3.35
Diaspore	3.30–3.35
Jadeite	3.30–3.36
Di-iodomethane	3.32
Idocrase	3.32–3.47
Peridot	3.34
Zoisite	3.35
Hydrogrossular garnet	3.36–3.55
Clinozoisite	3.37
Rhodizite	3.4
Sapphirine	3.40–3.58
Rhodonite	3.40–3.70
Hypersthene	3.4–3.5
Serendibite	3.42–3.52
Sinhalite	3.47–3.48
Chambersite	3.5
Rhodochrosite	3.50–3.65
Triphylite	3.51
Diamond	3.52
Sphene	3.52–3.54
Topaz	3.53–3.56
Rohrbach's solution	3.58
Spinel (natural)	3.58–3.61
Periclase	3.59
Taaffeite	3.60–3.61
Spinel (synthetic)	3.61–3.65
Pyroxmangite	3.61–3.80
Ceylonite	3.63–3.90
Hessonite garnet	3.65
Benitoite	3.65–3.68
Kyanite	3.65–3.68
Pyrope garnet	3.65–3.70
Staurolite	3.65–3.78
Almandine/pyrope garnets	3.70–3.95
Chrysoberyl	3.71–3.72
Malachite	3.74–3.95
Gahnospinel	3.75–4.06
Uvarovite garnet	3.77
Azurite	3.77–3.89
Shattuckite	3.8
Demantoid garnet	3.82–3.85
Anatase	3.82–3.95
Siderite	3.83–3.88
Brookite	3.87–4.08
Willemite	3.89–4.18
Corundum	3.98–4.00
Zircon (low type)	3.90–4.10
Hodgkinsonite	3.95
Almandine garnet	3.95–4.20
Celestine	3.97–3.99
Durangite	3.97–4.07
Legrandite	3.98–4.04
Painite	4.01
Calcium titanate	4.05
Zinc blende (sphalerite)	4.08–4.10
Chromite	4.1–4.9
Samarskite	4.1–6.2
Spessartine garnet	4.12–4.20
Clerici's solution (*max*)	4.15
Rutile	4.2
Chalcopyrite	4.2
Witherite	4.27–4.35
Smithsonite	4.30–4.35
Barite	4.3–4.6
Adamite	4.30–4.68
Powellite	4.34
Bayldonite	4.35
Psilomelane	4.35
Gahnite	4.40
Yttrium aluminate	4.57–4.60 (YAG)
Retger's salt	4.6
Lithium niobate	4.64
Zircon (high type)	4.67–4.70
Euxenite	4.7–5.0
Greenockite	4.83
Yttrium oxide	4.84–4.90
Marcasite	4.85–4.90
Bornite	4.9–5.4
Pyrite	4.95–5.10
Hematite	4.95–5.16
Pentlandite	5.0

Table 3 *(cont.)*

Strontium titanate (Fabulite)	5.13	Simpsonite	6.00
		Cobaltite	6.0–6.3
Magnetite	5.17	Phosgenite	6.2
Rhombic yttrium aluminate	5.35	Anglesite	6.30–6.39
		KTN	6.43
'Yttralox'	5.30	Cerussite	6.45–6.57
Millerite	5.3–5.65	Wulfenite	6.7–7.0
Boleite	5.4	Cassiterite	6.8–7.0
Microlite	5.5	Mimetite	7.0–7.2
Magnetoplumbite	5.5–5.7	Gadolinium gallium garnet	7.05
Cubic zirconia	5.54–6.06	Domeykite	7.2–7.9
Proustite	5.57–5.64	Niccolite	7.33–7.67
Zincite	5.66	Stibiotantalite	7.46
Cuprite	5.85–6.15	Breithauptite	7.54
Barium titanate	5.90	Algodonite	8.00–8.39
Crocoite	5.9–6.1		

Table 4
Colour dispersions of gemstones

The values given are the differences between the refractive indices of the stones for the Fraunhofer B line, a red ray at 687.0 nm, and the G line, a blue ray at 430.8 nm. Except where stated the values given are for the ordinary ray in uniaxial stones and the alpha direction in biaxial stones, for as indicated, the dispersion is in some cases considerably different for the different rays in doubly refractive stones.

Rutile	0.28–0.30	Kyanite	0.020
Anatase	0.213†	Spinel (natural and synthetic)	0.020
	0.259‡	Peridot	0.020
Strontium titanate	0.19	Taaffeite	0.019
Zinc blende	0.156	Idocrase	0.019
Lithium niobate	0.13	Sinhalite	0.018
Cassiterite	0.071	Kornerupine	0.018
Cubic zirconia	0.058–0.066	Sodalite	0.018
Demantoid garnet	0.057	Corundum	0.018
Sphene	0.051	Scapolite	0.017
Yttrium oxide	0.050	Iolite	0.017
Gadolinium gallium garnet	0.038–0.045	Spodumene	0.017
Anglesite	0.044	Tourmaline	0.017
Diamond	0.044	Danburite	0.017
Benitoite	0.044	Crown glass	0.016*
Flint glass	0.041*	Datolite	0.016
Zircon	0.039	Euclase	0.016
Dioptase	0.028†	Andalusite	0.016
	0.036‡	Fibrolite	0.015
Epidote	0.030	Chrysoberyl	0.015
Yttrium aluminate (YAG)	0.028	Phenakite	0.015
Hessonite garnet	0.027	Hambergite	0.015
Spessartine garnet	0.027	Smithsonite	0.014†
Willemite	0.027		0.031‡
Almandine garnet	0.027	Topaz	0.014
Scheelite	0.026	Brazilianite	0.014
Staurolite	0.023	Beryl	0.014
Pyrope garnet	0.022	Quartz	0.013

Table 4 *(cont.)*

Apatite	0.013	Leucite	0.010
Feldspar	0.012	Silica glass	0.010
Pollucite	0.012	Calcite	0.008‡
Beryllonite	0.010		0.017†
Cancrinite	0.010	Fluorite	0.007

*These are mean values for glasses of these two types. The dispersion of glasses can vary considerably.
†Ordinary ray.
‡Extraordinary ray.

Table 5
Mohs's scale

1	Talc	6	Orthoclase feldspar
2	Gypsum	7	Rock crystal
3	Calcite	8	Topaz
4	Fluorite	9	Corundum
5	Apatite	10	Diamond

Fingernail is about 2.5; copper coin is about 3; window glass is about 5.5; knife blade is about 6; steel file is about 6.5.

Table 6
Gemstones in order of their hardness according to Mohs's scale

10	Diamond
	Borazon*
9.5	Boron carbide*
9.25	Carborundum*
9	Corundum
	Bromellite
8.5	Chrysoberyl
	Yttrium aluminate (YAG)
8–8.5	Cubic zirconia
8	Rhodizite
	Spinel
	Taaffeite
	Topaz
7.5–8	Gahnite
	Phenakite
	Yttrium oxide
7.5	Almandine garnet
	Andalusite
	Beryl
	Euclase
	Fibrolite
	Grandidierite
	Hambergite
	Sapphirine
	Lawsonite
	Painite
	Uvarovite garnet
7.25	Hessonite garnet
	Pyrope garnet
	Rhodolite garnet
	Spessartine garnet
7–7.5	Iolite
	Staurolite
	Tourmaline
	Zircon
7	Axinite
	Boracite
	Chambersite
	Danburite
	Dumortierite
	Jadeite
	Quartz
	Simpsonite
	Spodumene
6.5–7.5	Sugilite
6.5–7	Diaspore
	Jeremejevite
	Serendibite

Table 6 *(cont.)*

6.5	Benitoite
	Cassiterite
	Chalcedony
	Chondrodite
	Demantoid garnet
	Epidote
	Euxenite
	Hematite
	Idocrase
	Kornerupine
	Nephrite
	Peridot
	Pollucite
	Sinhalite
	'Yttralox'
	Zircon (low type)
6–7	Sogdianite
6–6.5	Ekanite
	Barium titanate
	Clinohumite
	Magnetite
	Marcasite
	Microcline feldspar
	Petalite
	Plagioclase feldspar
	Pyrite
	Rutile
6	Amblygonite
	Calcium titanate
	Cancrinite
	Catapleite
	Columbite
	KTN
	Lithium niobate
	Orthoclase feldspar
	Periclase
	Prehnite
	Rhodonite
	Scapolite
	Silica glass
	Strontium titanate
	Tugtupite
	Xonotlite
	Zoisite
5.5–6.5	Gadolinium gallium garnet
	Hauyne
	Opal
	Psilomelane
	Sugilite
	Anatase
	Brookite
	Gedrite
5.5–6	Hornblende
	Leucite
	Melinophane
	Nepheline
	Pyroxmangite
	Sodalite
	Stibiotantalite
	Tremolite
	Turquoise
5.5	Brazilianite
	Chromite
	Cobaltite
	Diopside
	Enstatite
	Lazulite
	Lazurite (lapis-lazuli)
	Microlite
	Milarite
	Moldavite
	Natrolite
	Smaltite
	Sphene
	Willemite
5–7	Kyanite (varies with direction)
5–6	Charoite
	Chlorastrolite
	Eudialyte
	Glass (normally)
	Hypersthene
	Kaersutite
	Samarskite
	Sellaite
5–5.5	Actinolite
	Analcime
	Datolite
	Niccolite
	Scolecite
	Thomsonite
5	Apatite
	Augelite
	Beryllonite
	Dioptase
	Durangite
	Herderite
	Legrandite
	Mesolite
	Obsidian
	Odontolite
	Pectolite
	Smithsonite
	Variscite
	Wardite

Table 6 *(cont.)*

4.5–5	Apophyllite
	Breithauptite
	Scheelite
	Wollastonite
4.5	Bayldonite
	Colemanite
	Eosphorite
	Hodgkinsonite
	Pseudomalachite
	Yugawaralite
4–5	Bowenite serpentine
	Friedelite
	Triphylite
4–4.5	Zincite
4	Cuprite
	Fluorite
	Malachite
	Rhodochrosite
	Scorodite
3.5–4	Algodonite
	Aragonite
	Azurite
	Bastite
	Chalcopyrite
	Dolomite
	Domeykite
	Magnesite
	Marble
	Pentlandite
	Siderite
	Zinc blende
3.5	Boleite
	Celestine
	Cerussite
	Coral
	Creedite
	Greenockite
	Howlite
	Lepidolite
	Millerite
	Mimetite
	Phosphophyllite
	Powellite
	Thaumasite
	Witherite
3–4	Ludlamite
3	Anglesite
	Anhydrite
	Barite
	Bornite
	Phosgenite
	Verdite
2.5–4	Jet
	Serpentine
2.5–3.5	Pearl
2.5–3	Crocoite
	Wulfenite
2.5	Albertite
	Ivory
	Proustite
	Pseudophite
	Stichtite
	Tortoise-shell
	Vegetable ivory
	Whewellite
2–4	Chrysocolla
2–3	Bone
	Plastics
2–2.5	Amber
	Meerschaum
	Alabaster (gypsum)
2	Vivianite
1.5–2	Gedanite
	Pyrophyllite
	Soapstone
1	Ulexite

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*Synthetically produced abrasives.

Table 7
Gemstones in order of their crystal systems

Cubic

Analcime
Barium tantalate
Boracite
Bornite
Chromite
Cobaltite
Cubic zirconia
Cuprite
Diamond
Fluorite
Gadolinium gallium garnet (GGG)
Gahnite
Garnet
Hauyne
Lazurite (lapis-lazuli)
Leucite
Magnetite
Microlite
Pentlandite
Periclase
Pollucite
Pyrite
Rhodizite
Smaltite
Sodalite
Spinel
Strontium titanate
Yttrium aluminate
Yttrium oxide (YAG)
Zinc blende (sphalerite)

Tetragonal

Anatase
Apophyllite
Boleite
Cassiterite
Chalcopyrite
Idocrase
Leucite (pseudocubic)
Melinophane
Phosgenite
Powellite
Rutile
Scapolite
Scheelite
Sellaite
Tugtupite
Wardite
Wulfenite
Zircon

Hexagonal

Algodonite
Apatite
Benitoite
Beryl
Breithauptite
Bromellite
Cancrinite
Greenockite
Jeremejevite
Magnetoplumbite
Milarite
Mimetite
Nepheline
Niccolite
Painite
Simpsonite
Sogdianite
Sugilite
Taaffeite
Thaumasite
Zincite

Trigonal

Calcite (marble)
Corundum
Dioptase
Dolomite
Eudialyte
Friedelite
Hematite
Magnesite
Millerite
Phenakite
Proustite
Quartz
Rhodochrosite
Siderite
Smithsonite
Stichtite
Tourmaline
Willemite

Orthorhombic

Adamite
Andalusite
Anglesite
Anhydrite
Aragonite
Barite
Bronzite
Brookite
Calcium titanate
Celestine
Cerussite
Chambersite
Chlorastrolite
Chrysoberyl
Columbite
Danburite
Diaspore
Dumortierite
Enstatite
Eosphorite
Gedrite
Grandidierite
Hambergite
Hypersthene
Iolite
Jeremejevite
Kornerupine
Lawsonite
Marcasite
Natrolite
Olivine (*peridot*)
Prehnite
Pyrophyllite
Rhombic yttrium aluminate
Samarskite
Scorodite
Sillimanite (*fibrolite*)
Sinhalite
Staurolite
Stibiotantalite
Thomsonite
Topaz
Triphylite
Variscite
Witherite
Zoisite

Monoclinic
Actinolite
Augelite
Azurite
Bayldonite
Beryllonite
Brazilianite
Catapleite
Charoite
Chondrodite
Clinohumite
Colemanite
Creedite
Crocoite
Datolite
Diopside
Durangite
Epidote
Euclase
Gypsum
Herderite
Hodgkinsonite
Hornblende
Howlite
Jadeite
Kaersutite
Lazulite
Legrandite
Lepidolite
Ludlamite
Malachite
Meerschaum (?)
Mesolite
Nephrite
Orthoclase feldspar
Pectolite
Petalite
Phosphophyllite
Pseudomalachite
Pyrophyllite
Sanidine
Sapphirine
Scolecite
Serandite
Serpentine
Shattuckite
Sphene
Spodumene
Spurrite
Talc (soapstone)
Tremolite
Ulexite
Vivianite
Whewellite
Wollastonite
Xonotlite
Yugawaralite

Triclinic
Amblygonite
Axinite
Kyanite
Microcline feldspar
Plagioclase feldspar
Pectolite
Pyroxmangite
Rhodonite
Serendibite
Turquoise

Amorphous
Amber
Billitonite
Chrysocolla (?)
Copal resin
Coral (black & golden)
Ekanite
Glass
Ivory
Jet
Moldavite
Obsidian
Odontolite
Opal
Plastics
Silica glass
Tortoiseshell
Vegetable ivory

Table 8
Gem materials according to colour

Colourless
- Adamite (Tr–Op)
- Amblygonite (Tr)
- Analcime (Tr)
- Anglesite (Tr)
- Apatite (Tr)
- Apophyllite (Tr)
- Aragonite (Tr)
- Augelite (Tr)
- Barite (Tr)
- Barium titanate (Tr)
- Beryl (Tr)
- Beryllonite (Tr)
- Bromellite (Tr)
- Calcium titanate (Tr)
- Catapleite (Tr–Tl)
- Celestine (Tr)
- Chrysoberyl (Tr)
- Colemanite (Tr)
- Corundum (Tr)

Colourless (cont.)
- Cubic zirconia (Tr)
- Danburite (Tr)
- Datolite (Tr)
- Diamond (Tr)
- Diopside (Tr)
- Dolomite (Tr)
- Enstatite (Tr)
- Euclase (Tr)
- Feldspar var; orthoclase (Tr)
- Fluorite (Tr)
- Gadolinium gallium garnet (Tr)
- Hambergite (Tr)
- Jeremejevite (Tr)
- KTN (Tr)
- Lawsonite (Tr)
- Leucite (Tr)
- Lithium niobate (Tr)
- Magnesite (Tr)
- Periclase (Tr)

Table 8 *(cont.)*

Petalite (Tr)
Phenakite (Tr)
Pollucite (Tr)
Quartz (Tr)
Rutile (synthetic) (Tr)
Sanidine (Tr)
Scolecite (Tr)
Sellaite (Tr)
Spinel (synthetic) (Tr)
Spodumene (Tr)
Strontium titanate (Tr)
Thaumasite (Tr)
Topaz (Tr)
Tourmaline (Tr)
Vivianite (Tr)
Whewellite (Tr)
Yttrium aluminate (Tr)
Yttrium oxide (Tr)
Yugawaralite (Tr)
Zircon (Tr)

Yellow and orange
Adamite (Tr–Op)
Amber (Tr and Tl)
Amblygonite (Tr)
Anglesite (Tr)
Apatite (Tr)
Aragonite (Tl)
Axinite (Tr)
Barite (Tr)
Beryl (Tr)
Beryllonite (Tr)
Brazilianite (Tr)
Calcite (Tr)
Cancrinite (Tl–Op)
Cassiterite (Tr)
Catapleite (Tr–Tl)
Chalcedony (Tl–Op)
Chrondrodite (Tr)
Chrysoberyl (Tr)
Clinohumite (Tr–Op)
Copal resin (Tr)
Corundum (Tr)
Danburite (Tr)
Datolite (Tl–Op)
Diamond (Tr)
Dolomite (Tl)
Eosphorite (Tr)
Eudialyte (Tr–Op)
Feldspar var; orthoclase (Tr), var; sunstone (Tr–Tl)
Fluorite (Tr–Tl)
Friedelite (Tr–Tl)
Garnet vars; hessonite, spessartine and topazolite (Tr)
Greenockite (Tr)
Idocrase (Tr)

Yellow and orange (cont.)
Jadeite (Tl)
Jeremejevite (Tr)
Legrandite (Tr)
Marble (Tl–Op)
Melinophane (Tr)
Millerite (Tl)
Mimetite (Tl)
Opal var; fire opal (Tr–Tl)
Ophicalcite (Tl–Op)
Phenakite (Tr)
Phosgenite (Tl)
Quartz (Tr)
Rutile (synthetic) (Tr)
Scapolite (Tr)
Scheelite (Tr–Tl)
Serandite (Tr–Tl)
Serendibite (Tr)
Silica glass (Tr)
Simpsonite (Tr)
Sinhalite (Tr)
Smithsonite (Op)
Soapstone (Op)
Sphene (Tr)
Spinel (Tr)
Spodumene (Tr)
Staurolite (Tr–Op)
Stibiotantalite (Tr)
Thomsonite (Op)
Topaz (Tr)
Tourmaline (Tr)
Triphylite (Tr–Tl)
Willemite (Tr)
Wulfenite (Tr–Tl)
Zinc blende (Tr)
Zircon (Tr)

Brown
Amber (Tr–Tl)
Anatase (Tr)
Andalusite (Tr)
Axinite (Tr)
Barite (Tr–Op)
Beryl (Tr)
Brookite (Tl)
Cassiterite (Tr)
Chalcedony (Tl–Op)
Chondrondite (Tr–Tl)
Chrysoberyl (Tr)
Corundum (Tr)
Datolite (Tl–Op)
Diamond (Tr)
Diaspore (Tr–Tl)
Dolomite (Tl–Op)
Eosphorite (Tr)
Epidote (Tr)
Fibrolite (Op)

Table 8 *(cont.)*

- *Brown (cont.)*
  - Fluorite (Tr)
  - Garnet var; hessonite and spessartine (Tr)
  - Hornblende (Tr)
  - Hypersthene (Tl–Op)
  - Idocrase (Tr)
  - Jadeite (Tl–Op)
  - Kornerupine (Tr)
  - Marble (Op)
  - Microlite (Tr–Tl)
  - Moldavite (Tr)
  - Nepheline (Tr–Tl)
  - Obsidian (Tr–Tl)
  - Peridot (Tr)
  - Powellite (Tr)
  - Prehnite (Tl)
  - Quartz (Tr)
  - Rhodochrosite (Tl–Op)
  - Rutile (synthetic) (Tr)
  - Sapphirine (Tr)
  - Scheelite (Tr)
  - Serpentine (Op)
  - Siderite (Tl)
  - Sinhalite (Tr)
  - Soapstone (Op)
  - Sphene (Tr)
  - Staurolite (Op)
  - Stibiotantalite (Tr)
  - Thomsonite (Op)
  - Topaz (Tr)
  - Tourmaline (Tr)
  - Tugtupite (Tl–Op)
  - Willemite (Tr)
  - Zinc blende (Tr)
  - Zircon (Tr)
- *Red and pink*
  - Adamite (Tr–Op)
  - Amber (Tr–Tl)
  - Andalusite (Tr)
  - Barite (Tr)
  - Beryl (Tr)
  - Cassiterite (Tr)
  - Chalcedony (Tl–Op)
  - Chambersite (Tr)
  - Chrondrodite (Tr–Tl)
  - Coral (Tl–Op)
  - Corundum (Tr)
  - Crocoite (Tr–Tl)
  - Cuprite (Tr)
  - Danburite (Tr)
  - Datolite (Tl–Op)
  - Diamond (Tr)
  - Dolomite (Tl–Op)
  - Durangite (Tr–Tl)
  - Eosphorite (Tr)
  - Eudialyte (Tr–Op)
  - Fluorite (Tr)
  - Friedelite (Tr–Tl)
  - Garnet var; pyrope and almandine (Tr)
  - Hodgkinsonite (Tr)
  - Jadeite (Tl–Op)
  - Marble (Op)
  - Microlite (Tr–Tl)
  - Nepheline (Tr–Tl)
  - Opal (fire opal) (Tr–Tl)
  - Painite (Tr)
  - Pearl (Tl–Op)
  - Phenakite (Tr)
  - Powellite (Tl–Op)
  - Pyroxmangite (Tr–Op)
  - Quartz var; rose quartz (Tr–Tl)
  - Rhodizite (Tr)
  - Rhodochrosite (Tl–Op)
  - Rhodonite (Tl–Op)
  - Rutile (Tr)
  - Sapphirine (Tr)
  - Scapolite (Tr–Tl)
  - Serandite (Tr–Tl)
  - Smithsonite (Tl)
  - Spinel (Tr)
  - Spodumene (Tr)
  - Staurolite (Op)
  - Stichtite (Op)
  - Thomsonite (Op)
  - Thulite (Op)
  - Topaz (Tr)
  - Tourmaline (Tr)
  - Tremolite (Tr)
  - Tugtupite (Tr–Op)
  - Vayrynenite (Tr)
  - Wulfenite (Tl)
  - Xonotlite (Tr–Op)
  - Zincite (Tr)
  - Zircon (Tr)
  - Zoisite (Tl–Op)
- *Purple and violet*
  - Adamite (Tr–Op)
  - Apatite (Tr)
  - Axinite (Tr)
  - Beryl (Tr)
  - Charoite (Tl–Op)
  - Corundum (Tr)
  - Creedite (faint) (Tl)
  - Diopside var; violane (Op)
  - Dumortierite (Op)
  - Fibrolite (Tr)
  - Fluorite (Tr–Tl)
  - Garnet var; almandine and rhodolite (Tr)
  - Jadeite (Tl)
  - Lepidolite (Op)
  - Marble (Op)

Table 8 *(cont.)*

- *Purple and violet (cont.)*
    - Quartz (Tr–Tl)
    - Scapolite (Tr–Tl)
    - Sogdianite (Tr–Op)
    - Spinel (Tr)
    - Spodumene (Tr)
    - Spurrite (Tl–Op)
    - Stichtite (Op)
    - Sugilite (Tl–Op)
    - Taaffeite (Tr)
    - Tourmaline (Tr)
    - Zircon (Tr)
- *Blue*
    - Anhydrite (Tr–Tl)
    - Apatite (Tr–Tl)
    - Anatase (Tr–Tl)
    - Anglesite (Tr)
    - Azurite (Op)
    - Barite (Tr–Tl)
    - Benitoite (Tr)
    - Beryl (Tr)
    - Boleite (Tl–Op)
    - Catapleite (Tr–Tl)
    - Celestine (Tr)
    - Cerussite (Tl)
    - Chalcedony (Tl–Op)
    - Chambersite (Tr)
    - Chrysocolla (Tl–Op)
    - Corundum (Tr)
    - Diamond (Tr)
    - Diopside var; violane (Op)
    - Dumortierite (Op)
    - Euclase (Tr)
    - Fibrolite (Tr)
    - Fluorite (Tr)
    - Grandidierite (Tr)
    - Hauyne (Tl–Op)
    - Idocrase var; cyprine (Tl–Op)
    - Iolite (Tr)
    - Jadeite (Tl–Op)
    - Jeremejevite (Tr)
    - Kyanite (Tr)
    - Lapis lazuli (Op)
    - Lawsonite (pale) (Tr)
    - Lazulite (Op)
    - Odontolite (Op)
    - Pearl (Op)
    - Pectolite (Tl)
    - Quartz var; hawk's eye (Op)
    - Rutile (synthetic) (Tr)
    - Sapphirine (Tr)
    - Scapolite (Tr–Tl)
    - Scorodite (Tr–Tl)
    - Serendibite (Tr)
    - Shattuckite (Op)
    - Smithsonite (Tl–Op)
    - Sodalite (Op)
    - Spinel (Tr)
    - Topaz (Tr)
    - Tourmaline (Tr)
    - Turquoise (Op)
    - Vivianite (Tr)
    - Wardite (Op)
    - Zircon (Tr)
    - Zoisite (Tr)
- *Green*
    - Actinolite (Tr)
    - Adamite (Tr–Op)
    - Andalusite (Tr)
    - Anglesite (Tr)
    - Apatite (Tr)
    - Bayldonite (Tl–Op)
    - Bastite (Op)
    - Beryl (Tr)
    - Boracite (Tr)
    - Cerussite (Tl)
    - Chalcedony (Ti–Op)
    - Chlorastrolite (Op)
    - Chrysoberyl (Tr)
    - Chrysocolla (Tl–Op)
    - Corundum (Tr)
    - Datolite (Tr–Op)
    - Diamond (Tr)
    - Diopside (Tr)
    - Dioptase (Tr–Tl)
    - Dolomite (Tr–Op)
    - Ekanite (Tl)
    - Enstatite (Tr)
    - Epidote (Tr)
    - Euclase (Tr)
    - Feldspar var; microcline (Tr–Op)
    - Fibrolite (Tr)
    - Fluorite (Tr–Tl)
    - Gahnite (Tr)
    - Garnet var; demantoid and uvarovite (Tr)
    - Garnet var; massive grossular (Tl–Op)
    - Grandidierite (Tr)
    - Idocrase (Tr) var; californite (Tl–Op)
    - Jadeite (Tl–Op)
    - Kornerupine (Tr)
    - Kyanite (Tr)
    - Ludlamite (Tr)
    - Malachite (Op)
    - Marble (Op)
    - Milarite (Tr)
    - Moldavite (Tr)
    - Nepheline (Tr–Tl)
    - Nephrite (Tl–Op)
    - Ophicalcite (Tl–Op)
    - Peridot (Tr)
    - Phosphophyllite (Tr)

Table 8 *(cont.)*

Green (cont.)
- Prehnite (Tl–Op)
- Pyrophyllite (Op)
- Pseudomalachite (Op)
- Pseudophite (Op)
- Quartz (Tr)
- Rhodizite (Tr)
- Sapphirine (Tr)
- Serpentine (Tl–Op)
- Smaragdite (Op)
- Smithsonite (Tl–Op)
- Soapstone (Op)
- Sphene (Tr)
- Spodumene (Tr)
- Thomsonite (Op)
- Topaz (rare) (Tr)
- Tourmaline (Tr)
- Tremolite (Tl)
- Turquoise (Op)
- Variscite (Op)
- Verdite (Op)
- Willemite (Tr–Op)
- Wulfenite (Tl)
- Yttrium aluminate (Tr)
- Zircon (Tr)
- Zoisite (Tr)

White
- Alabaster (Tl–Op)
- Anhydrite (Tr–Tl)
- Amber (Tl–Op)
- Barite (Tl)
- Bone (Op)
- Cerussite (Tl)
- Chalcedony (Tl–Op)
- Colemanite (Tl)
- Coral (Tl–Op)
- Creedite (Tl)
- Datolite (Tl–Op)
- Dolomite (Tr)
- Gypsum var; satin spar (Tl)
- Howlite (Tl–Op)
- Ivory (Tl–Op)
- Jadeite (Tl–Op)
- Marble (Op)
- Meerschaum (Op)
- Mesolite (Tl)
- Nephrite (Tl–Op)
- Opal (Tl–Op)
- Pearl (Tl–Op)
- Pectolite (Tl)
- Pyrophyllite (Tl–Op)
- Quartz var; milky (Tl–Op)
- Scapolite (Tr–Tl)
- Scolecite (Tl–Op)
- Thaumasite (Tl–Op)
- Thomsonite (Op)

White (cont.)
- Ulexite (Tl)
- Witherite (Tl–Op)
- Wollastonite (Tl–Op)
- Wulfenite (Tl–Op)
- Yugawaralite (Tl)

Grey
- Apophyllite (Tl)
- Cerussite (Tl)
- Chalcedony (Tl)
- Diamond (Tr–Tl)
- Feldspar var; labradorite (Op)
- Herderite (Tl–Op)
- Marble (Op)
- Obsidian (Tl–Op)
- Pectolite (Tl–Op)
- Pyrophyllite (Tl–Op)

Black
- Amber (Op)
- Anatase (Op)
- Cassiterite (Op)
- Chalcedony (stained) (Op)
- Coral (Op)
- Diamond (Op)
- Garnet (Op)
- Jadeite (Op)
- Jet (Op)
- Kaersutite (Op)
- Marble (Op)
- Obsidian (Op)
- Opal (with play of colour) (Tl–Op)
- Pearl (Op)
- Quartz var; morion (Op)
- Rutile (Op)
- Spinel (Op)
- Tourmaline var; schorl (Op)

Metallic colours

White	Cobaltite
Tin white to steel grey	Algodonite
Tin white to steel grey	Domeykite
Tin white to steel grey	Smaltite
Brass yellow	Pyrite
Bronze yellow	Pentlandite
Golden yellow	Chalcopyrite
Grey yellow	Marcasite
Copper red	Breithauptite
Pale copper red	Niccolite
Brownish-black	Euxenite
Black	Columbite
Black	Tantalite
Black	Magnetite
Black	Magnetoplumbite
Iron black	Chromite
Brilliant black	Hematite
Brilliant black	Psilomelane

Tr – transparent; Tl – translucent; Op – opaque

Table 9
The pleochroic colours of the principal gemstones

Actinolite	Yellow; dark green
Anatase (distinct)	Pale blue or yellowish; dark blue or orange
Andalusite (strong)	Yellow; green; red
Apatite (weak except in Myanmar stones)	
Yellow (asparagus stone)	Golden-yellow; greenish-yellow
Blue green (moroxite)	Pale yellow; sapphire-blue
Axinite (strong)	Violet; brown; green
Benitoite (strong)	Colourless; greenish to indigo-blue
Beryl (distinct)	
Green (emerald)	Yellowish-green; bluish-green
Greenish-blue (aquamarine)	Colourless to pale yellowish-green; pale bluish-green
Blue (aquamarine)	Colourless; sky-blue
Pink (morganite)	Pale rose; bluish-rose
Yellow (heliodor)	Pale yellowish-green; pale bluish-green
Violet	Violet; colourless
Red	Purplish-red; orange red
Chrysoberyl (strong in deep colours)	
Yellow	Colourless; pale yellow; lemon-yellow
(Cat's-eye)	Reddish-yellow; greenish-yellow; green
Green (alexandrite)	
Natural light	Emerald-green; yellowish; columbine-red
Artificial light	Emerald-green; reddish-yellow; red
Corundum (strong)	
Red (ruby)	Pale yellowish-red; deep red
Blue (sapphire)	Pale greenish-blue; deep blue
Green	Yellowish-green; green
Violet	Yellowish-red; violet-red
Yellow	Imperceptible
Corundum synthetic (alexandrite type)	
In natural light	Pale brownish-green; deep mauve
In artificial light	Brownish-yellow; deep mauve
Other synthetic corundums show dichroic tints in general agreement with the natural corundums of similar colour	
Danburite (very weak)	Pale yellow; very pale yellow; pale yellow
Dioptase (weak)	Dark green; light green
Dumortierite	Blue-black; blue; colourless. Also black; brown; reddish-brown
Enstatite (distinct)	Green; yellowish-green; brownish-green
Epidote (strong)	Green; yellowish-green; yellow
Euclase (distinct to strong)	Colourless; pale green; green
Deep blue	Azure blue; Prussian blue; greenish-blue
Fibrolite (distinct)	Colourless; pale yellow; sapphire-blue
Grandidierite	Colourless; dark blue-green; dark green
Iolite (strong)	Pale blue; pale yellow; dark violet-blue
Kornerupine (strong)	
Yellowish-green	Yellowish; brown; greenish
Chromian	Emerald-green; bluish-grey; reddish-purple
Kyanite (distinct)	Pale blue; blue; dark blue
Peridot (distinct)	Yellow-green; green
Quartz (weak)	
Yellow (citrine)	Yellow; slightly paler yellow
Violet (amethyst)	Purple; reddish-purple

Table 9 *(cont.)*

Smoky quartz	Brown; reddish-brown
Rose quartz	Pink; pale pink
Heat-treated amethyst 'topaz' colour	Imperceptible
Scapolite (distinct)	
Pink and violet	Dark blue to lavender blue; colourless to violet
Colourless and pale yellow	Colourless to pale yellow; yellow
Sinhalite (distinct)	Pale brown; greenish-brown; dark brown
Sphene (titanite) (strong)	Colourless; yellow; reddish-yellow
Spodumene (strong)	
Pink (kunzite)	Colourless; pink; violet
Green (hiddenite)	Bluish-green; grass-green; yellowish-green
Yellow	Pale yellow; deep yellow; yellow
Staurolite (distinct)	Red; brown; yellow
Zincian	Green; yellow; red
Topaz (distinct)	
Yellow	Honey-yellow; straw-yellow; pinkish-yellow
Blue	Colourless; pale pink; blue
Pink	Colourless; very pale pink; pink
Green	Pale green; bluish-green; colourless
Tourmaline (strong)	
Red (rubellite)	Pink; dark red
Blue (indicolite)	Light blue; dark blue
Green	Pale green; dark green
Brown	Yellowish-brown; deep brown
Wide colour range gives rise to great variation in pleochroic colours.	
Zircon (weak except in blue)	
Red	Columbine-red; clove-brown
Blue	Colourless; sky-blue
Green	Brownish-green; green
Yellow	Brownish-yellow; honey-yellow
Brown	Yellowish-brown; reddish-brown
Zoisite	
Blue (tanzanite)	Blue; purple; sage green
Pink (thulite)	Dark pink; pink; yellow

Table 10
Colour filter

A table of the effects seen when the stone is viewed through a dichromatic filter, such as the Chelsea colour filter, which transmits a band of green and a band of red light. The residual colour will be more intense the stronger the body colour of the stone. The best results are seen when the stone is illuminated with light from a tungsten electric lamp (desk lamp) and the filter held close to the eye.

Green stones		*Green stones (cont.)*	
Alexandrite	red	Enstatite	green
Aquamarine	distinctively green	Fluorite	reddish
Aventurine quartz	reddish	Glass (pastes)	green
Chrome chalcedony	red	Hiddenite	slight pink
Chrysoprase	green	Jadeite	green
Demantoid garnet	reddish	Peridot	green
Emerald	pink to red	Sapphire	green
(some emeralds from South Africa and India may not show a red hue, but remain greenish)		Soudé emerald	green
		(The old type soudé emerald may show red)	

Table 10 (*cont.*)

Green stones (cont.)	
Stained bowenite	red
Stained chalcedony	red
Stained jadeite	red
Synthetic corundum (Alexandrite colour)	red
Synthetic emerald (most)	strong red
Synthetic sapphire	red
Synthetic spinel	red
(Some old types may show green)	
Tourmaline	green
(Certain anomalous green tourmalines have been found to show red)	
Zircon	reddish
Red stones	
Garnets	dark red (no fluorescence)
Garnet-topped doublets	dark red (no fluorescence)
Glass (pastes)	dark red (no fluorescence)
Ruby (natural and synthetic)	strong fluorescent red
Spinel	fluorescent red
Spinel (synthetic)	fluorescent red
(The pink synthetic spinel does not show a red colour through the filter)	
Blue stones	
Aquamarine	distinctive green
Garnet-topped doublets	greenish-blue
Glass (pastes)	
Dark blue	red
Light blue	greenish
Lapis lazuli	weak brownish-red
Sapphire	blackish-green
(The blue sapphire which shows a purple colour under artificial light usually shows red under the filter)	
Sodalite	slightly brownish
Spinel	reddish
Spinel (natural) coloured by cobalt	red
'Swiss lapis'	greenish-blue
Synthetic sapphire	dark greenish-blue
(The natural and synthetic sapphire are indistinguishable under the colour filter)	
Synthetic spinel	
Dark blue	red
Light blue	orange
'Zircon' colour	orange to red
'Lapis lazuli colour'	bright red
Zircon	greenish
Purple stones	
Amethyst	reddish
Violet sapphire	bright red

Table 11
The light spectrum (nm)

Ultra-violet	100–390
Violet	390–430
Blue	439–490
Blue-green	490–510
Green	510–550
Yellow-green	550–575
Yellow	575–590
Orange	590–630
Orange-red	630–650
Red	650–700
Deep red	700–780
Infra-red	780–1 000 000

Table 12
The major Fraunhofer lines (nm)

A	oxygen	759–762
B	oxygen	687–688
C	hydrogen	656.3
D1	sodium	589.6
D2	sodium	589.0
E	iron	527.0
F	hydrogen	486.1
G	iron	430.8
H	calcium	396.8
K	calcium	393.4

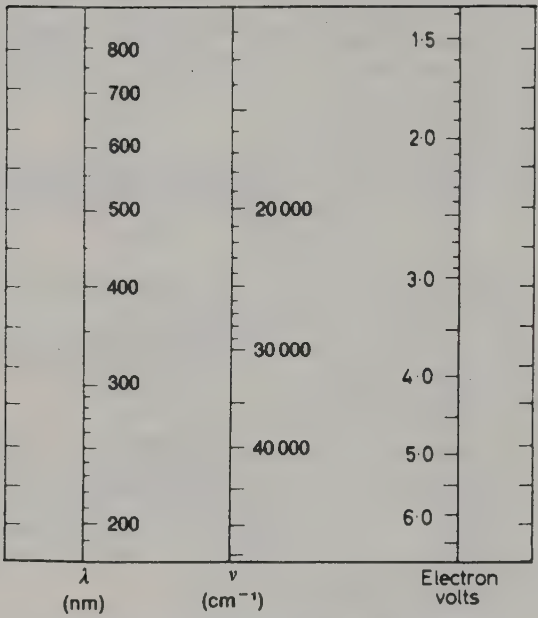
Table 13

The principal emission lines useful for calibration (nm)

Barium	588.1 (yellow) 577.8 (yellow) 553.6 (yellow-green) 551.9 (yellow-green) 542.5 (green) 513.7 (green) 493.7 (blue-green) 487.4 (blue) 455.4 (blue)	Barium lines are better produced by arc than by bunsen flame
Calcium	616.2 (orange) 559.0 (yellow-green) 422.7 (violet)	Calcium lines can usually be obtained by inserting a calcium compound in the bunsen flame
Copper	521.8 (green) 515.3 (green) 510.6 (green)	Copper lines are best produced by arc excitation
Lithium	670.8 (red) 610.3 (orange)	Given by lithium compound in bunsen flame. Red line is strong, orange line is weak
Mercury	623.4 (orange) 615.2 (orange) 579.0 (yellow) 577.0 (yellow) 546.1 (green) 435.9 (blue) 434.8 (blue) 407.8 (violet) 404.7 (violet)	The mercury lines are best obtained from a mercury vapour electric discharge lamp. The lines may be observed underlying the continuous spectrum of a fluorescent lighting tube
Potassium	766.9 (deep red) 766.5 (deep red) 404.7 (violet) 404.4 (violet)	Can be induced by potassium compound in bunsen flame
Sodium	589.0 (yellow) 589.6 (yellow)	Sodium compound in bunsen flame
Strontium	687.0 (red) 606.0 (orange) 460.7 (blue) 407.8 (violet)	Strontium compound in bunsen flame
Thallium	535.0 (green)	Thallium compound (Clerici's solution) in bunsen flame

Table 14
Interconversion of wavelength (nm), wave numbers (cm^{-1}), and electron volts

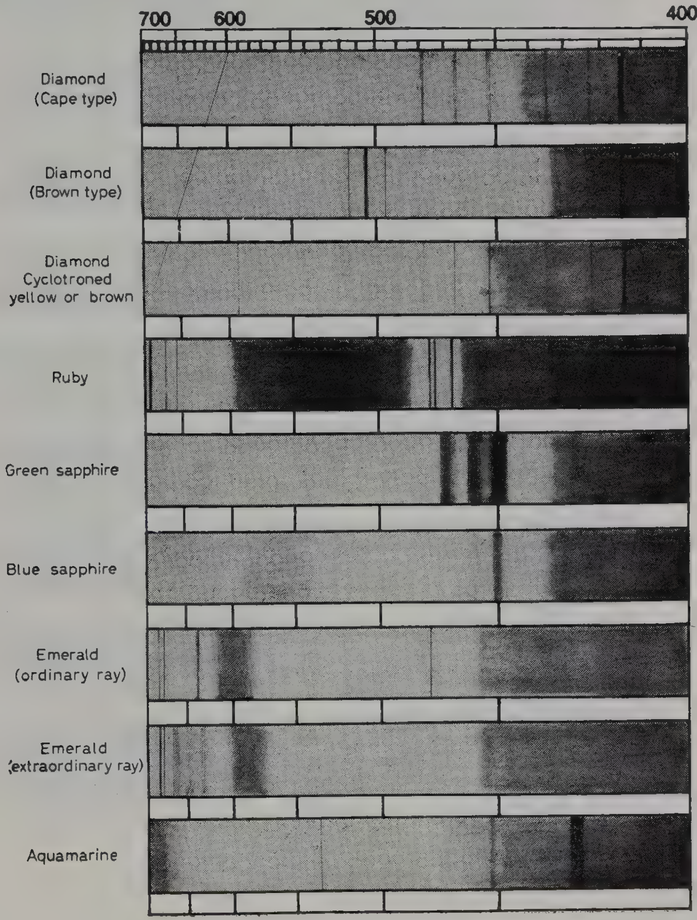
A straight edge placed horizontally across the diagram, using the two outer scales as guides, will give interconversion between the different energies.



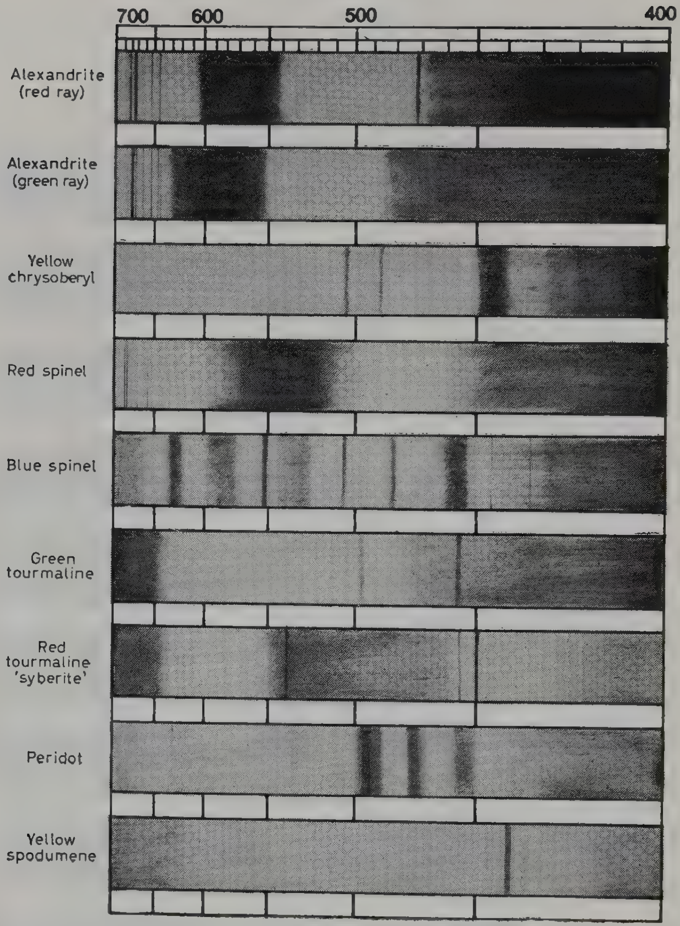
1 electron volt (eV) equals 8066 cm^{-1} (ν); cm^{-1} equals number of waves in a centimetre

Table 15
The absorption spectra of gemstones

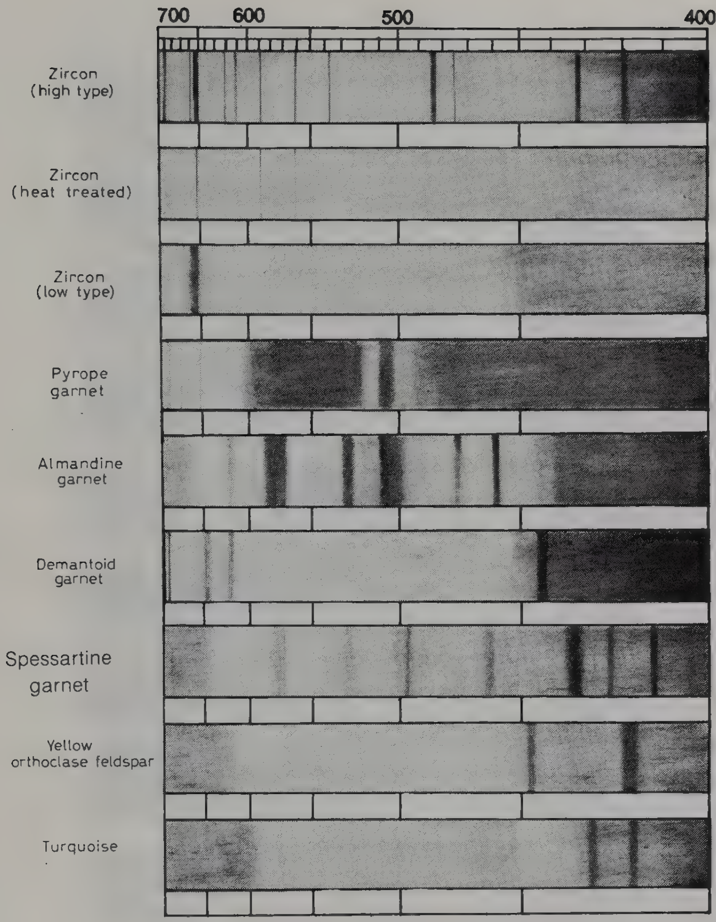
The following spectra are drawn as seen through a prism-type spectroscope.



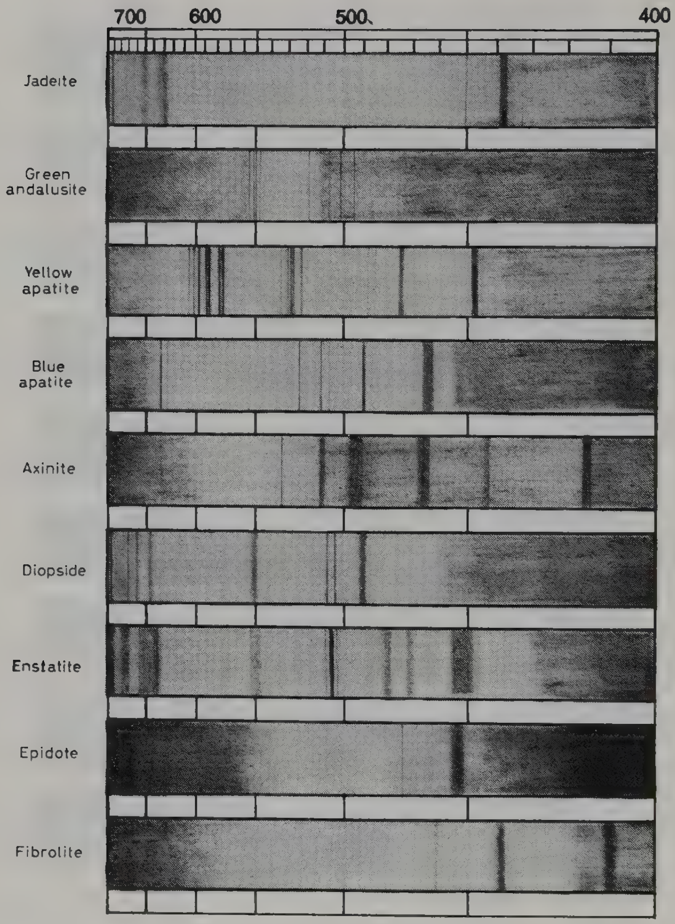
Spectrum plate 1



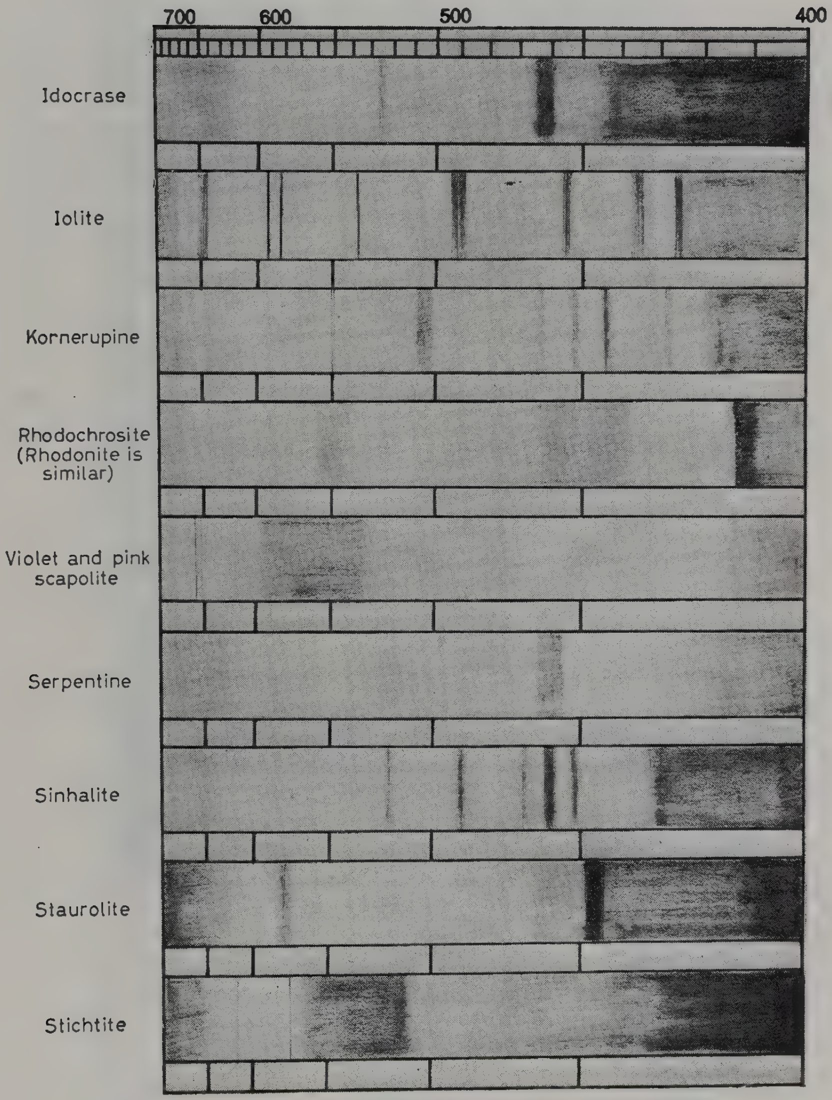
Spectrum plate 2



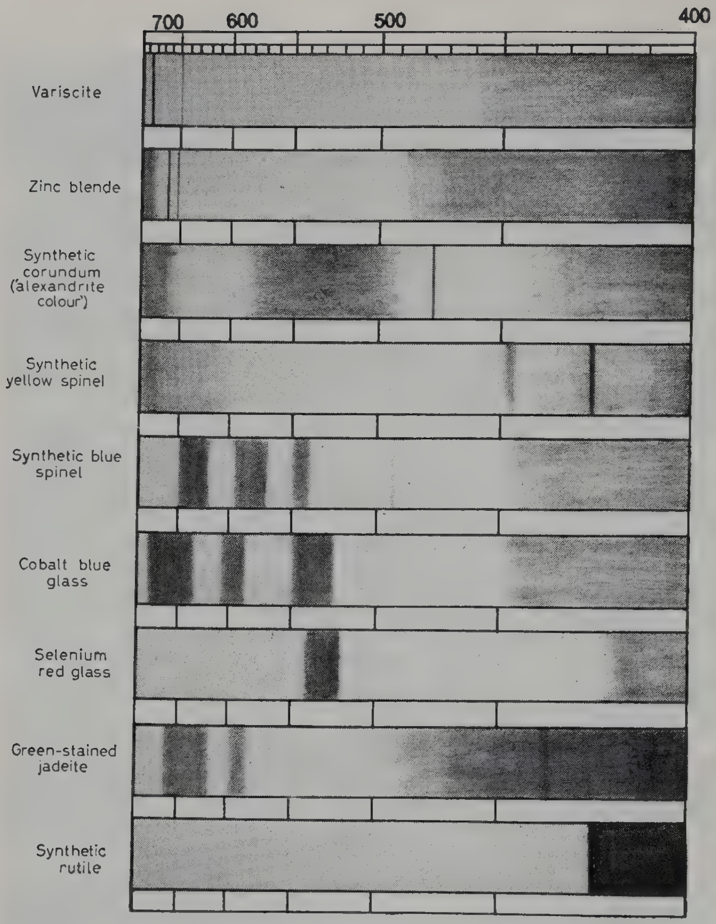
Spectrum plate 3



Spectrum plate 4



Spectrum plate 5



Spectrum plate 6

Table 16
The fluorescent colours of the principal gemstones and their simulants

The following table gives the more common luminescent colours shown by gem materials under each of the three types of radiation – long-wave ultra-violet, short-wave ultra-violet and X-rays. As it is extremely difficult to analyse the shades of colour in the various groups, the wide division into the six colours of the Newtonian spectrum, with the addition of white, has therefore been adopted. It must be understood that under *red* the shade may vary from deep plum-red, through crimson, to rose and pink; and *blue*, from a rich dark blue to a bright whitish-blue. The lilac-coloured glow is listed under violet. In the case of synthetic emerald the red glow is much stronger when the stones are irradiated with the additional long-wave ultra-violet and near violet wavelengths present in the fluorescent-type ultra-violet lamp. In many gem species, fluorescence varies in intensity from specimen to specimen.

Colour	*Long-wave ultra-violet light (365.0 nm)*	*Short-wave ultra-violet light (253.7 nm)*	*X-rays (mean 0.1 nm)*
White	Ivory Casein Copal resin Amber Tortoise-shell Opal Jadeite (some)	Synthetic white spinel Paste (some) Ivory Casein Copal resin Amber Tortoise-shell Opal Jadeite (some)	Diamond Scapolite Synthetic white spinel (some) Cubic zirconia
Red	Synthetic ruby Natural ruby Natural and synthetic pink sapphire Natural and synthetic red spinel Synthetic orange sapphire Natural and synthetic alexandrite Synthetic (alexandrite) sapphire Synthetic green sapphire Synthetic blue spinel Sri Lanka blue sapphire Synthetic emerald Emerald (some) Calcite (some) Kyanite Fire opal (brownish-red) Synthetic green spinel Diamond Green grossular Benitoite	Natural and synthetic ruby Natural and synthetic pink sapphire Natural and synthetic red spinel Synthetic orange sapphire Calcite (some) Natural and synthetic alexandrite Synthetic (alexandrite) sapphire Synthetic emerald Sri Lanka blue sapphire Diamond Natural emerald (some) Fire opal (brownish-red) Synthetic blue spinel Synthetic green spinel Scapolite	Natural and synthetic ruby (synthetic shows phosphorescence) Natural and synthetic pink sapphire Natural and synthetic red spinel Synthetic orange sapphire Sri Lanka blue sapphire Synthetic (alexandrite) sapphire Synthetic blue spinel (some) Synthetic green spinel Synthetic emerald Morganite Natural emerald Thulite Blue apatite Yellow apatite

Table 16 *(cont.)*

Colour	*Long-wave ultra-violet light (365.0 nm)*	*Short-wave ultra-violet light (253.7 nm)*	*X-rays (mean 0.1 nm)*
Orange	Kunzite Sri Lanka yellow sapphire Scapolite Diamond Sri Lanka blue sapphire Synthetic (alexandrite) sapphire Natural white sapphire Synthetic green sapphire Synthetic orange sapphire Natural mauve spinel (some) Topaz (some) Sodalite (orange spots) Lapis lazuli (orange spots) Coral, light red and orange Jadeite dyed lavender (some) Synthetic emeralds (early Gilson) YAG (some)	Sri Lanka yellow sapphire Scapolite Diamond Sri Lanka blue sapphire Synthetic orange sapphire Synthetic green sapphire (brownish-orange) Natural white sapphire Synthetic (alexandrite) sapphire Synthetic pale blue spinel Synthetic emerald (early Gilson) GGG	Kunzite Sri Lanka yellow sapphire Calcite (including marble) Scapolite Synthetic white sapphire Synthetic (alexandrite) sapphire Synthetic green sapphire Massive green grossular ('Transvaal jade') Petalite Pale yellow sinhalite Topaz (some)
Yellow	Diamond Amber Apatite Zircon Topaz Fire opal (brownish) Paste Kornerupine (some) Scapolite White opal Oiled emerald Synthetic pale green spinel GGG Yellowish-green YAG Cubic zirconia (some)	Diamond Zircon Amber Green apatite Violet apatite White opal Paste (some) Yellowish-green YAG Cubic zirconia (some)	Diamond Zircon Cassiterite Cultured pearl Freshwater pearl Rhodizite Diopside Lapis lazuli Sodalite (yellow spots) Yellow apatite Green apatite Violet apatite YAG

Table 16 *(cont.)*

Colour	*Long-wave ultra-violet light (365.0 nm)*	*Short-wave ultra-violet light (253.7 nm)*	*X-rays (mean 0.1 nm)*
Green	Synthetic yellow spinel Synthetic yellow-green spinel Willemite Opal (some) Diamond Pale blue natural spinels (some) Emerald (some) Apatite Paste (some) Amber Synthetic white spinel and sapphire (very weakly) Natural and cultured pearl (some)	Synthetic yellow and green spinels Willemite Opal (some) Synthetic green spinel Diamond Amber Paste Natural and cultured pearl (some) Synthetic blue sapphire (some) Cubic zirconia Emerald (some)	Synthetic yellow spinel Synthetic yellow-green spinel Synthetic white spinel Diamond Paste Opal (some) Natural spinels (some) Taaffeite Rhodizite Amblygonite Topaz Synthetic blue Sapphire (some)
Blue	Diamond Danburite Fluorite (Blue John is inert) Paste Pearl Casein Ivory Amber Moonstone Blue apatite Natural and cultured pearl Synthetic dark blue spinel	Benitoite Scheelite Fluorite Danburite Diamond Synthetic blue spinel Synthetic blue sapphire Paste (some) Ivory Amber Copal Blue apatite Natural and cultured pearl Synthetic dark blue spinel Synthetic white spinel Plastic (some)	Fluorite Benitoite Beryllonite Diamond Scheelite Synthetic blue sapphire Kyanite Phenakite Synthetic white spinel (some) Synthetic blue spinel Paste (some) Lapis lazuli Sodalite Topaz Zircon Moonstone
Violet	Fluorite (Blue John is inert) Diamond Apatite Scapolite Morganite Diopside Alexandrite-like sapphire (some) Synthetic pink sapphire Violet apatite Yellow apatite	Fluorite Diamond Morganite Synthetic pink sapphire Alexandrite-like sapphire Violet apatite Yellow apatite	Fluorite Danburite Synthetic yellow sapphire (some) Synthetic white sapphire (some) Scapolite Pink tourmaline Zircon GGG

Table 17
The chemical composition of gemstones

Elements	
Diamond	C
Halides	
Boleite	$Pb_9Ag_3Cu_8Cl_{21}(OH)_{16}.H_2O$
Chambersite	$Mn_3B_7O_{13}Cl$
Fluorite	CaF_2
Sellaite	MgF_2
Sulphides	
Bornite	Cu_5FeS_4
Chalcopyrite	$CuFeS_2$
Cobaltite	$CoAsS$
Greenockite	CdS
Marcasite	FeS_2
Millerite	NiS
Pentlandite	$(Fe,Ni)_9S_8$
Proustite	Ag_3AsS_3
Pyrite	FeS_2
Zinc blende (sphalerite)	ZnS
Oxides and hydroxides	
Anatase	TiO_2
Barium titanate	$BaTiO_3$
Bromellite	BeO
Brookite	TiO_2
Calcium titanate (perovskite)	$CaTiO_3$
Cassiterite	SnO_2
Chalcedony	SiO_2
Chromite	$FeCr_2O_4$
Chrysoberyl	$BeAl_2O_4$
Corundum	Al_2O_3
Cuprite	Cu_2O
Diaspore	$AlO(OH)$
Gadolinium gallium garnet (GGG)	$Gd_3Ga_5O_{12}$
Gahnite	$ZnAl_2O_4$
Hematite	Fe_2O_3
Magnetoplumbite	$(Pb,Mn)_2Fe_6O_{11}$
Magnetite	Fe_3O_4
Opal	$SiO_2.nH_2O$
Painite	$Ca_4Al_{20}BSiO_{38}$
Periclase	MgO
Psilomelane	Manganese oxide with barium and water
Quartz	SiO_2
Rutile	TiO_2
Spinel	$MgAl_2O_4$
Strontium titanate	$SrTiO_3$
Taaffeite	$BeMg_3Al_8O_{16}$
Yttrium aluminium garnet (YAG)	$Y_3Al_5O_{12}$
Yttrium aluminate (orthorhombic)	$YAlO_3$
Yttrium oxide (Yttralox)	Y_2O_3
Zincite	ZnO
Zinc titanate	$ZnTiO_3$
Zirconium oxide (cubic zirconia)	ZrO_2
Carbonates	
Aragonite	$CaCO_3$

Table 17 *(cont.)*

Azurite	$Cu_3(CO_3)_2(OH)_2$
Calcite	$CaCO_3$
Cerussite	$PbCO_3$
Dolomite	$CaMg(CO_3)_2$
Magnesite	$MgCO_3$
Malachite	$Cu_2CO_3(OH)_2$
Phosgenite	$Pb_2Cl_2CO_3$
Rhodochrosite	$MnCO_3$
Siderite	$FeCO_3$
Smithsonite	$ZnCO_3$
Stichtite	$Mg_6Cr_2CO_3(OH)_{16}.4H_2O$
Silicates	
Actinolite	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$
Analcime	$NaAlSi_2O_6.H_2O$
Andalusite	Al_2SiO_5
Apophyllite	$KCa_4Si_8O_{20}(F,OH).8H_2O$
Axinite	$(Ca,Mn,Fe,Mg)_3Al_2(BO_3)Si_4O_{12}(OH)$
Benitoite	$BaTiSi_3O_9$
Beryl	$Be_3Al_2Si_6O_{18}$
Cancrinite	$(Na,K,Ca)_{6-8}(Al,Si)_{12}O_{24}(CO_3,SO_4Cl)_{1-2}$
Catapleite	$(Na,Ca)_2ZrSi_3O_9.2H_2O$
Charoite	$K(Ca,Na)_2Si_4O_{10}(OH,F).H_2O$
Chrysocolla	$(Cu,Al)_2H_2Si_2O_5(OH)_4.nH_2O$
Chlorastrolite (pumpellyite)	$Ca_2MgAl_2(SiO_4)(Si_2O_7)(OH)_2.H_2O$
Chondrodite	$Mg_5Si_2O_8(F,OH)_2$
Clinohumite	$Mg_9Si_4O_{16}(OH,F)_2$
Danburite	$CaB_2Si_2O_8$
Datolite	$CaBSiO_4(OH)$
Diopside	$CaMgSi_2O_6$
Dioptase	$CuSiO_2(OH)_2$
Dumortierite	$(Al,Fe)_7O_3(BO)_3(SiO_4)_3$
Ekanite	$K(Ca,Na)_2ThSi_8O_{20}$
Enstatite	$MgSiO_3$
Epidote	$Ca_2(Al,Fe)_3Si_3O_{12}(OH)$
Euclase	$BeAlSiO_4(OH)$
Eudialyte	$Na_4(Ca,Fe,Ce,Mn)_2ZrSi_6O_{17}(OH,Cl)_2$
Feldspar group	
Orthoclase	$KAlSi_3O_8$
Microcline	$KAlSi_3O_8$
Albite	$NaAlSi_3O_8$
Anorthite	$CaAl_2Si_2O_8$
Fibrolite (sillimanite)	Al_2SiO_5
Friedelite	$(Mn,Fe)_8Si_6O_{18}(OH,Cl)_4.3H_2O$
Garnet group	
Almandine	$Fe_3Al_2(SiO_4)_3$
Andradite	$Ca_3Fe_2(SiO_4)_3$
Grossular	$Ca_3Al_2(SiO_4)_3$
Pyrope	$Mg_3Al_2(SiO_4)_3$
Spessartine	$Mn_3Al_2(SiO_4)_3$
Uvarovite	$Ca_3Cr_2(SiO_4)_3$
Grandidierite	$(Mg,Fe)Al_3BSiO_9$
Hauyne	$(Na,Ca)_{4-8}Al_6Si_6O_{24}(SO_4,S)_{1-2}$
Hodgkinsonite	$MnZn_2SiO_5.H_2O$
Howlite	$Ca_2B_5SiO_9(OH)_5$
Hypersthene	$(Fe,Mg)SiO_3$
Idocrase	$Ca_{10}(Mg,Fe)_2Al_4(SiO_4)_5(Si_2O_7)_2(OH)_4$

Table 17 *(cont.)*

Iolite (cordierite)	$(Mg,Fe)_2Al_4Si_5O_{18}$
Jadeite	$NaAlSi_2O_6$
Kornerupine	$Mg_3Al_6(Si,Al,B)_5O_{21}(OH)$
Kyanite	Al_2SiO_5
Lawsonite	$CaAl_2(Si_2O_7)(OH)_2.H_2O$
Lazurite	$(Na,Ca)_8(Al,Si)_{12}O_{24}(S,SO_4)$
Lepidolite	$K(Li,Al)_3(Si,Al)_4O_{10}(F,OH)_2$
Leucite	$KAlSi_2O_6$
Meerschaum (sepiolite)	$Mg_3Si_4O_{11}.5H_2O$
Melinophane	$(Ca,Na)_2Be(Si,Al)_2(O,OH,F)_7$
Mesolite	$Na_2Ca_2(Al_2Si_3O_{10}).8H_2O$
Milarite	$KCa_2AlBe_2Si_{12}O_{30}.H_2O$
Natrolite	$Na_2(Al_2Si_3O_{10}).2H_2O$
Pectolite	$NaCa_2Si_3O_8(OH)$
Petalite	$LiAlSi_4O_{10}$
Peridot	$(Mg,Fe)_2SiO_4$
Phenakite	Be_2SiO_4
Pollucite	$(Cs,Na)AlSi_2O_6.H_2O$
Prehnite	$Ca_2Al_2Si_3O_{10}(OH)_2$
Pyrophyllite	$Al_2Si_4O_{10}(OH)_2$
Pyroxmangite	$(Mn,Fe)SiO_3$
Rhodonite	$MnSiO_3$
Sapphirine	$(Mg,Fe^{2+},Fe^{3+},Al)_8O_2[(Al,Si)_6O_{18}]$
Scapolite group	
Marialite	$Na_4Al_3Si_9O_{24}Cl$
Meionite	$Ca_4Al_6Si_6O_{24}CO_3$
Serandite	$Na(Mn,Ca)_2Si_3O_8(OH)$
Serendibite	$Ca_2(Mg,Al)_6O_2[(Si,Al,B)_6O_{18}]$
Serpentine	$Mg_3Si_2O_5(OH)_4$
Shattuckite	$Cu_5(SiO_3)_4(OH)_2$
Sodalite	$Na_4Al_3Si_3O_{12}Cl$
Sogdianite	$(K,Na)_2Li_2(Li,Fe,Al,Ti)_2Zr_2(Si_2O_5)_6$
Sphene	$CaTiSiO_5$
Spodumene	$LiAlSi_2O_6$
Staurolite	$(Fe,Mg,Zn)_2Al_9Si_4O_{23}(OH)$
Steatite	$Mg_3Si_4O_{10}(OH)_2$
Sugilite	$(K,Na)(Na,Fe)_2(Li_2,Fe)(Si_{12}O_{30}) + Mn$
Thaumasite	$Ca_3Si(CO_3)(SO_4)(OH)_6.12H_2O$
Thomsonite	$NaCa_2Al_5Si_5O_{20}.6H_2O$
Topaz	$Al_2(F,OH)_2SiO_4$
Tourmaline group	
Buergerite	$NaFe_3Al_6B_3Si_6O_{30}F$
Chromdravite	$NaMg_3Cr_6(BO_3)_3Si_6O_{18}(OH)_4$
Dravite	$NaMg_3Al_6B_3Si_6O_{27}(OH)_3(OH,F)$
Elbaite	$Na(Li,Al)_3Al_6B_3Si_6O_{27}(OH)_3(OH,F)$
Ferridravite	$(Na,K)(Mg,Fe)_3Fe_6(BO_3)_3Si_6O_{18}(O,OH)_4$
Liddicoatite	$Ca(Li,Al)_3Al_6B_3Si_6O_{27}(OH)_3(OH,F)$
Schorl	$Na(Fe,Mn)_3Al_6B_3Si_6O_{27}(OH)_3(OH,F)$
Tsilaisite	$Na(Mn,Al)_3Al_6(BO_3)_3Si_6O_{18}(O,OH,F)_4$
Uvite	$CaMg_3(Al_5Mg)B_3Si_6O_{27}(OH)_3(OH,F)$
Tremolite	$Ca_2Mg_5Si_8O_{22}(OH)_2$
Tugtupite	$Na_4BeAlSi_4O_{12}Cl$
Willemite	Zn_2SiO_4
Wollastonite	$CaSiO_3$
Xonotlite	$Ca_6Si_6O_{17}(OH)_2$
Yugawaralite	$CaAl_2Si_6O_{16}.4H_2O$

Table 17 *(cont.)*

Zircon	$ZrSiO_4$
Zoisite	$Ca_2Al_3Si_3O_{12}(OH)$
Sulphates	
Anglesite	$PbSO_4$
Anhydrite	$CaSO_4$
Barite	$BaSO_4$
Celestine	$SrSO_4$
Creedite	$Ca_3Al_2(SO_4)(F,OH)_{10}.2H_2O$
Gypsum	$CaSO_4.2H_2O$
Phosphates	
Amblygonite	$(Li,Na)AlPO_4(F,OH)$
Apatite	$Ca_5(PO_4)_3(F,OH,Cl)_3$
Augelite	$Al_2PO_4(OH)_3$
Beryllonite	$NaBePO_4$
Brazilianite	$NaAl_3(PO_4)_2(OH)_4$
Eosphorite	$(Mn,Fe)AlPO_4(OH)_2.H_2O$
Herderite	$CaBePO_4(F,OH)$
Lazulite	$(Mg,Fe)Al_2(PO_4)_2(OH)_2$
Ludlamite	$Fe_3(PO_4)_2.4H_2O$
Phosphophyllite	$Zn_2(Fe,Mn)(PO_4)_2.4H_2O$
Triphylite	$Li(Fe,Mn)PO_4$
Turquoise	$CuAl_6(PO_4)_4(OH)_8.5H_2O$
Variscite	$AlPO_4.2H_2O$
Vayrynenite	$BeMn(PO_4)(OH,F)$
Vivianite	$Fe_3(PO_4)_2.8H_2O$
Wardite	$NaAl_3(PO_4)_2(OH)_4.2H_2O$
Borates	
Boracite	$Mg_3B_7O_{13}Cl$
Colemanite	$Ca_2B_6O_{11}.5H_2O$
Hambergite	$Be_2BO_3(OH,F)$
Jeremejevite	$Al_6B_5O_{15}(OH,F)_3$
Rhodizite	$CsAl_4Be_4B_{11}O_{25}(OH)_4$
Sinhalite	$MgAlBO_4$
Ulexite	$NaCaB_5O_9.8H_2O$
Arsenates	
Bayldonite	$(Pb,Cu)_3(AsO_4)_2(OH)_2$
Durangite	$NaAl(AsO_4)F$
Legrandite	$Zn_2(AsO_4)(OH).H_2O$
Mimetite	$Pb_5(AsO_4)_3Cl$
Tungstates	
Powellite	$Ca(Mo,W)O_4$
Scheelite	$CaWO_4$
Chromates and molybdates	
Crocoite	$PbCrO_4$
Wulfenite	$PbMoO_4$
Oxalates	
Whewellite	$CaC_2O_4.H_2O$
Niobates and tantalates	
Columbite	$(Fe,Mn)(Nb,Ta)_2O_6$
Euxenite	$(Y,Er,Ce,La,U)(Nb,Ti,Ta)_2(O,OH)_6$
Lithium niobate	$LiNbO_3$
Microlite	$(Ca,Na)_2(Ta,Nb)_2O_6(O,OH,F)$

Table 17 *(cont.)*

Samarskite	$(Y,Ce,U,Ca,Pb)(Nb,Ta,Ti,Sn)_2O_6$
Simpsonite	$Al_4Ta_3O_{13}(OH)$
Stibiotantalite	$Sb(Ta,Nb)O_4$
Arsenides	
Algodonite	Cu_6As
Domeykite	Cu_3As
Niccolite	NiAs
Smaltite	$(Co,Ni)As_{2-3}$
Carbides	
Boron carbide	B_4C
Silicon carbide	SiC
Antimonides	
Breithauptite	NiSb

Table 18
Specific gravity correction tables for toluene and 1,2-dibromoethane

Commercial samples of toluene and more particularly of 1,2-dibromoethane may vary appreciably in SG from the figures given below. For really accurate determinations, therefore, it is wise to purchase a fair quantity (say 500 g) which can then be calibrated and will last for years if kept in a stoppered bottle.

A convenient method of calibrating a sample is to carry out a hydrostatic determination with a large piece of pure quartz (say 50 carats) and to work 'backwards', assuming the SG of quartz to be 2.651, according to the formula

$$\text{specific gravity of liquid} = 2.651 \times \frac{\text{loss of weight in liquid}}{\text{weight of stone}}$$

Supposing the SG of a sample of toluene at 11.3 °C is found on calibration to be 0.8734 – a figure corresponding to a temperature of 10.3 °C in the tables – the worker will know that it is necessary to subtract 1 °C from his actual temperature in all future experiments before referring to the table.

Note
Refer to the safety precautions in Chapter 29.

(a) SGs of toluene from 5 °C to 25 °C

°C	SG	°C	SG	°C	SG	°C	SG
5.0	0.8787	6.5	0.8772	8.0	0.8757	9.5	0.8742
5.1	0.8786	6.6	0.8771	8.1	0.8756	9.6	0.8741
5.2	0.8785	6.7	0.8770	8.2	0.8755	9.7	0.8740
5.3	0.8784	6.8	0.8769	8.3	0.8754	9.8	0.8739
5.4	0.8783	6.9	0.8768	8.4	0.8753	9.9	0.8738
5.5	0.8782	7.0	0.8767	8.5	0.8752	10.0	0.8737
5.6	0.8781	7.1	0.8766	8.6	0.8751	10.1	0.8736
5.7	0.8780	7.2	0.8765	8.7	0.8750	10.2	0.8735
5.8	0.8779	7.3	0.8764	8.8	0.8749	10.3	0.8734
5.9	0.8778	7.4	0.8763	8.9	0.8748	10.4	0.8733
6.0	0.8777	7.5	0.8762	9.0	0.8747	10.5	0.8732
6.1	0.8776	7.6	0.8761	9.1	0.8746	10.6	0.8731
6.2	0.8775	7.7	0.8760	9.2	0.8745	10.7	0.8730
6.3	0.8774	7.8	0.8759	9.3	0.8744	10.8	0.8729
6.4	0.8773	7.9	0.8758	9.4	0.8743	10.9	0.8728

Table 18 *(cont.)*

°C	SG	°C	SG	°C	SG	°C	SG
11.0	0.8727	14.6	0.8691	18.1	0.8656	21.6	0.8621
11.1	0.8726	14.7	0.8690	18.2	0.8655	21.7	0.8620
11.2	0.8725	14.8	0.8689	18.3	0.8654	21.8	0.8619
11.3	0.8724	14.9	0.8688	18.4	0.8653	21.9	0.8618
11.4	0.8723	15.0	0.8687	18.5	0.8652	22.0	0.8617
11.5	0.8722	15.1	0.8686	18.6	0.8651	22.1	0.8616
11.6	0.8721	15.2	0.8685	18.7	0.8650	22.2	0.8615
11.7	0.8720	15.3	0.8684	18.8	0.8649	22.3	0.8614
11.8	0.8719	15.4	0.8683	18.9	0.8648	22.4	0.8613
11.9	0.8718	15.5	0.8682	19.0	0.8647	22.5	0.8612
12.0	0.8717	15.6	0.8681	19.1	0.8646	22.6	0.8611
12.1	0.8716	15.7	0.8680	19.2	0.8645	22.7	0.8610
12.2	0.8715	15.8	0.8679	19.3	0.8644	22.8	0.8609
12.3	0.8714	15.9	0.8678	19.4	0.8643	22.9	0.8608
12.4	0.8713	16.0	0.8677	19.5	0.8642	23.0	0.8607
12.5	0.8712	16.1	0.8676	19.6	0.8641	23.1	0.8606
12.6	0.8711	16.2	0.8675	19.7	0.8640	23.2	0.8605
12.7	0.8710	16.3	0.8674	19.8	0.8639	23.3	0.8604
12.8	0.8709	16.4	0.8673	19.9	0.8638	23.4	0.8603
12.9	0.8708	16.5	0.8672	20.0	0.8637	23.5	0.8602
13.0	0.8707	16.6	0.8671	20.1	0.8636	23.6	0.8601
13.1	0.8706	16.7	0.8670	20.2	0.8635	23.7	0.8600
13.2	0.8705	16.8	0.8669	20.3	0.8634	23.8	0.8599
13.3	0.8704	16.9	0.8668	20.4	0.8633	23.9	0.8598
13.4	0.8703	17.0	0.8667	20.5	0.8632	24.0	0.8597
13.5	0.8702	17.1	0.8666	20.6	0.8631	24.1	0.8596
13.6	0.8701	17.2	0.8665	20.7	0.8630	24.2	0.8595
13.7	0.8700	17.3	0.8664	20.8	0.8629	24.3	0.8594
13.8	0.8699	17.4	0.8663	20.9	0.8628	24.4	0.8593
13.9	0.8698	17.5	0.8662	21.0	0.8627	24.5	0.8592
14.0	0.8697	17.6	0.8661	21.1	0.8626	24.6	0.8591
14.1	0.8696	17.7	0.8660	21.2	0.8625	24.7	0.8590
14.2	0.8695	17.8	0.8659	21.3	0.8624	24.8	0.8589
14.3	0.8694	17.9	0.8658	21.4	0.8623	24.9	0.8588
14.4	0.8693	18.0	0.8657	21.5	0.8622	25.0	0.8587
14.5	0.8692						

(b) SGs of 1,2-dibromoethane from 10 °C to 20 °C

°C	SG	°C	SG	°C	SG	°C	SG
10.0	2.1998	11.1	2.1976	12.2	2.1954	13.3	2.1932
10.1	2.1996	11.2	2.1974	12.3	2.1952	13.4	2.1930
10.2	2.1944	11.3	2.1972	12.4	2.1950	13.5	2.1928
10.3	2.1992	11.4	2.1970	12.5	2.1948	13.6	2.1926
10.4	2.1990	11.5	2.1968	12.6	2.1946	13.7	2.1924
10.5	2.1988	11.6	2.1966	12.7	2.1944	13.8	2.1922
10.6	2.1986	11.7	2.1964	12.8	2.1942	13.9	2.1920
10.7	2.1984	11.8	2.1962	12.9	2.1940	14.0	2.1918
10.8	2.1982	11.9	2.1960	13.0	2.1938	14.1	2.1916
10.9	2.1980	12.0	2.1958	13.1	2.1936	14.2	2.1914
11.0	2.1978	12.1	2.1956	13.2	2.1934	14.3	2.1912

Table 18 *(cont.)*

°C	SG	°C	SG	°C	SG	°C	SG
14.4	2.1910	15.9	2.1880	17.3	2.1852	18.7	2.1824
14.5	2.1908	16.0	2.1878	17.4	2.1850	18.8	2.1822
14.6	2.1906	16.1	2.1876	17.5	2.1848	18.9	2.1820
14.7	2.1904	16.2	2.1874	17.6	2.1846	19.0	2.1818
14.8	2.1902	16.3	2.1872	17.7	2.1844	19.1	2.1816
14.9	2.1900	16.4	2.1870	17.8	2.1842	19.2	2.1814
15.0	2.1898	16.5	2.1868	17.9	2.1840	19.3	2.1812
15.1	2.1896	16.6	2.1866	18.0	2.1838	19.4	2.1810
15.2	2.1894	16.7	2.1864	18.1	2.1836	19.5	2.1808
15.3	2.1892	16.8	2.1862	18.2	2.1834	19.6	2.1806
15.4	2.1890	16.9	2.1860	18.3	2.1832	19.7	2.1804
15.5	2.1888	17.0	2.1858	18.4	2.1830	19.8	2.1802
15.6	2.1886	17.1	2.1856	18.5	2.1828	19.9	2.1800
15.7	2.1884	17.2	2.1854	18.6	2.1826	20.0	2.1798
15.8	2.1882						

(c) The relation between refractive index and SG of Clerici solution and di-iodomethane with suitable dilutants

If a specimen under test is found to be freely suspended in the liquid, the SG of that liquid may be ascertained from its index of refraction.

Clerici solution: water

Refractive index	*SG*	*Refractive index*	*SG*	*Refractive index*	*SG*	*Refractive index*	*SG*
1.500	2.584	1.550	3.008	1.600	3.432	1.640	3.770
1.510	2.669	1.560	3.093	1.610	3.517	1.650	3.854
1.520	2.753	1.570	3.178	1.620	3.601	1.660	3.939
1.530	2.838	1.580	3.263	1.630	3.685	1.670	4.023
1.540	2.923	1.590	3.348				

The above table is based on the work of Anderson, Payne and Franklin.

Di-iodomethane: toluene

Refractive index	*SG*	*Refractive index*	*SG*	*Refractive index*	*SG*	*Refractive index*	*SG*
1.610	2.007	1.650	2.403	1.690	2.809	1.720	3.106
1.620	2.106	1.660	2.502	1.700	2.908	1.730	3.205
1.630	2.205	1.670	2.601	1.710	3.007	1.740	3.304
1.640	2.304	1.680	2.710				

Note: See Safety Precautions in Chapter 29.

Appendices

Weights and Measures

Units of Weight

The unit of weight for gemstones is the metric carat, more usually referred to as the carat, and weighs one-fifth (0.200) of a gram, or 200 milligrams. It is thus firmly and conveniently linked to the metric system of which the most frequently used units are the milligram (one-thousandth of a gram), the gram, and the kilogram, which is 1000 grams. The weight of the gram was defined as the weight of a cubic centimetre of water at 0 °C.

Until the present century the value of the carat (which was based on the average weight of the seeds of the carob tree, *Ceratonia siliqua*) was not strictly defined and varied slightly but inconveniently from country to country, the extremes being 0.1885 and 0.2135 gram. In England the traditional value was equivalent to 0.2053 gram and subdivisions of the carat were expressed in fractions of which $\frac{1}{64}$ was the lowest value in use. It was not until April 1914 that the metric carat became the legal standard in Britain and decimals replaced fractions to the greater convenience of all.

Although pearls, like precious stones, are weighed in carats their value and the verbal expression of their size is by long tradition the pearl grain, of which there are four to the carat. In metric terms therefore the pearl grain equals 0.25 carat or 0.050 gram. In the diamond trade the term 'grain' was used in exactly the same sense. It is important to understand that the pearl and diamond grain have no exact connection with those used in the troy and avoirdupois systems described below.

For precious metals the ancient troy system established in 1414 by Henry V is still employed, though the only troy unit which is now legal for trade in Britain is the ounce, smaller weights being expressed as decimal subdivisions.

In former times the troy weights went thus:

24 grains (gn) = 1 pennyweight (dwt)
20 pennyweights = 1 ounce (oz)
12 ounces = 1 pound (lb)

The avoirdupois system of weights was established even earlier by Edward III and a set of standard weights deposited at Winchester in 1340. This system was intended for bulky goods such as wool and foodstuffs and was the most familiar system in Great Britain until the introduction of the metric weights officially used by members of the European Community. As the British systems of weights and measures were used throughout the former empire, it is still customary to refer to these as 'imperial' weights and measures.

The avoirdupois table of weights is as follows:

16 drams = 1 ounce (oz)
16 ounces = 1 pound (lb)
14 pounds = 1 stone
28 pounds = 1 quarter (qr)
4 quarters = 1 hundredweight (cwt)
20 hundredweight = 1 ton

Avoirdupois weights are occasionally used in gemmology, since gem materials of low quality for tumbling etc. are offered by some dealers at so much an ounce or pound.

The following conversion factors between the imperial and metric systems of weights may prove useful:

1 ounce troy = 31.1035 grams = 155.517 carats
1 ounce avoirdupois = 28.3495 grams = 141.7475 carats
1 pound avoirdupois = 0.4536 kilograms
1 kilogram = 2.2046 pounds avoirdupois
1 pennyweight = 1.5552 grams

Although the metric carat is now almost universally used in the precious stone trades of all countries, some of the undermentioned foreign weights may occasionally be encountered:

India

1 ratti = 0.91 carat
1 tola = 58.32 carats
1 mangelin = 1.75 carats
64 rattis = 1 tola

Myanmar (Burma)

1 ratti = 0.91 carat
1 bali = 58.32 carats
1 tickal = 80 carats (88 rattis)
1 viss = 880 carats
1 lathi = 1.15 carats

Sri Lanka

1 chevill, chow or tank = 21.84 carats
1 manchadi = 1.15 carats

Thailand

1 catty = 3015 carats approx.

Iran

1 miscal = 36.40 carats (40 rattis)
2 miscals = 1 dirhem

Turkey

1 checky = 1600 carats

Brazil

1 oitava (octavo) = 17.5 carats approx.

Japan

1 momme = 18.75 carats

Units of Length

The units of length used in science are those of the metric system, which were planned by the French Academy of Science at the end of the eighteenth century. According to this system, the basic length is the metre, which was originally intended to represent one ten-millionth part of the earth's polar quadrant. In practice it is the length of the standard metre as represented on a polished bar of platinum-iridium held by the International Bureau of Weights and Measures in Paris. Nearly 100 years were to pass before there was complete international agreement and exact copies of the original standard metre were distributed to the contributing countries. Decimal multiples of the unit metre were denoted by prefixes of Greek derivation: deca-, hecto-, and kilo-, representing 10, 100, 1000, while prefixes of Latin origin, deci-, centi-, milli-, stood for sub-multiples one-tenth, hundredth and thousandth.

The units derived from the metre have been revised and slightly altered as the result of discussions at a General Conference on Weights and Measures completed in 1973 with the purpose of devising a logical system of multiples and sub-multiples of the main unit.

Units of mass and volume were also considered and the recommendations published. These SI (Système International) units, as they are called, were recommended by the Royal Society in 1976, and for pure scientists these provide a precise modern guide which must be followed. The carat is not included in the SI, but its continued use should cause no confusion since it is clearly linked to the metric system.

A list of SI units contains two terms introduced to fit the logic of the scheme. The first of these, the 'micrometre' (not to be confused with the micrometer measuring device) is one-thousandth of a millimetre. This is simply a new name for the micron – a term which is deeply entrenched in the vocabulary of those concerned with diamond technology since it is used to define the dimensions of diamond grits and powders.

The second unit is the nanometre, the prefix 'nano' being derived from the Greek for 'dwarf'. This was new to science as a name but not as a unit: it was formerly well known as the 'millimicron'. The nanometre has replaced the ångström as a measure for wavelengths of light in spectroscopy, the nanometre being equal to ten ångströms. The irony of this is that the nanometre under its old name of millimicron was formerly much used for this purpose by chemists, but that spectroscopists for more than a hundred years preferred their chosen unit, the ångström, as this largely eliminated the need for a decimal point in quoting often-used important wavelengths such as the 5896 Å line of the sodium doublet, which in nanometres is 589.6 nm.

The following conversion factors between the imperial and metric system units of length may prove useful:

1 mile = 1.6093 kilometres
1 yard = 0.9144 metre
1 inch = 25.54 millimetres
1 km = 0.2137 mile
1 m = 39.37 inches
1 cm = 0.3937 inch

Units of Capacity

The metric unit of capacity is the litre, which is defined as the volume of 1 kilogram of pure water at 4 °C.

1 millilitre (ml) = 1 cubic centimetre (cm^3) = volume of 1 gram of pure water at 4 °C
1 litre = 1.7598 pints
1 pint = 0.5682 litre
1 gallon = 4.544 litres

Birthstones

Official list issued by the National Association of Goldsmiths of Great Britain and Ireland.

Month	*Colour*	*Official stone*
January	*Dark red*	*Garnet*
February	*Purple*	*Amethyst*
March	*Pale blue*	*Aquamarine*
April	*White (transparent)*	*Diamond*
May	*Bright green*	*Emerald*
June	*Cream*	*Pearl*
July	*Red*	*Ruby*
August	*Pale green*	*Peridot*
September	*Deep blue*	*Sapphire*
October	*Variegated*	*Opal*
November	*Yellow*	*Topaz*
December	*Sky-blue*	*Turquoise*

Gemstones for the Days of the Week

Day	*Stone*
Sunday	Topaz or diamond
Monday	Pearl or crystal
Tuesday	Emerald or ruby
Wednesday	Amethyst or loadstone
Thursday	Cornelian or sapphire
Friday	Emerald or cat's-eye
Saturday	Diamond or turquoise

Emblems of the Twelve Apostles

Apostle	*Stone*
Andrew	Blue sapphire
Bartholemew	Red cornelian
James	White chalcedony
James-the-less	Topaz
John	Emerald
Matthew	Amethyst
Matthias	Chrysolite
Peter	Jasper
Philip	Sardonyx
Simeon	Pink hyacinth
Thaddeus	Chrysoprase
Thomas	Beryl

Glossary of Unusual Names

This list includes alternative or disused gem names, misnomers and trade names. Misnomers are printed within inverted commas and trade names in italics.

Accarbaar (Akabar)	black coral
Accidental pearl	natural pearl
Achirite	Dioptase
Adamantine spar	silky brown sapphire
Adamite	artificial corundum powder
'Adelaide ruby'	red South African garnet
Adinol	a silicified porphyry or diabase
Aeroides	pale sky-blue aquamarine
'Afghan turquoise'	dyed magnesite
'African emerald'	green fluorite
'African jade'	massive green grossular garnet
African Star Coral	the coral *Allopora nobilis*
Agalmatolite	Steatite; pyrophyllite or pinite
Agaphite	vitreous variety of Persian turquoise
Agstein	Jet
Akori Coral	the coral *Allopora subviolacea*
'Alabandine ruby'	Almandine garnet
Alalite	Diopside
'Alexandrite' or 'Alexandrine'	synthetic colour change sapphire or spinel
'Alexandrite garnet'	misnomer for a colour-change garnet
'Alaska black diamond'	Hematite
'Alaska diamond'	rock crystal
'Alaska jade'	Pectolite
Alasmoden pearls	freshwater pearls
'Alençon diamond'	rock crystal
Aleppo stone	eye agate
'Almandine spinel'	natural violet spinel
'Almandite'	synthetic spinel
'Almaschite	Romanian amber
Alomite	Sodalite
Aloxite	aluminium oxide powder
'Alpine diamond'	Pyrite
Alshedite	Sphene
Alumag	synthetic spinel
Alundum	aluminium oxide powder
Amarillo stone	figured chalcedony (Texas)
Amaryl	light green synthetic corundum
Amatrix (Amatrice)	mixture of variscite, chalcedony and quartz
Amause	glass (strass)
'Amazon jade'	green microcline feldspar
'Amberine'	yellowish-green moss agate
'America jade'	Californite (idocrase)
'American ruby'	(1) Pyrope garnet: (2) rose quartz
'Amethyst'	synthetic purple sapphire
Ametrine	Quartz showing mixed amethyst and citrine
Ammolite	fossilised ammonite shell composed of aragonite
Amourant	synthetic white sapphire top/strontium titanite bottom composite stone
Ampullar pearl	Pearl from the epidermis of the oyster
'Ancona ruby'	Rose quartz
'Andalusite'	brown tourmaline
'Andesine jade'	Andesine feldspar
Angelite	opaque, bluish-grey anhydrite

Angelo pearl	imitation pearl comprising plastic-coated mother-of-pearl
Aphrizite	black tourmaline
Apricotine	apricot-coloured garnets or quartz from New Jersey
Apyrite	peach-coloured tourmaline
Aqua Aura	blue, iridescent quartz crystals coated with gold, platinum or silver
Aquagem	light blue synthetic spinel
'Aquamarine'	synthetic pale blue spinel
'Arabian diamond'	rock crystal
'Arabian magic diamond'	synthetic colourless or yellow sapphire
Argillite	a slate-like rock from British Columbia
'Arizona ruby'	pyrope garnet
'Arizona spinel'	garnet
'Arkansas diamond'	rock crystal
Arkansite	transparent brookite
Armenian stone	lapis lazuli
Asparagus stone	yellow-green apatite
Astrilite	lithium niobate
Astryl	synthetic rutile
'Atlas pearls'	beads of white satin-spar
'Australian ruby'	garnet
Australite	tektite
Awabi pearl	abalone pearl (Japanese)
Axe stone	nephrite
Aztec stone	smithsonite
Azules opal	water opal with red and green flecks with bluish haze
Azurite	synthetic blue spinel
Azurite	sky-blue smithsonite
Azurlite	pale blue chalcedony
Bacalite	amber from Lower California
'Baffa diamond'	rock crystal
Bal de Feu	strontium titanate
'Balas ruby'	red spinel
Bamboo-pearl	Tabasheer
Baroda Gem	foiled back colourless glass
'Bastard emerald'	peridot
Bayate	ferruginous jasper (Cuba)
BC jade	nephrite from British Columbia
Beccarite	green zircon
Beckerite	succinite
Beekite	agatised coral
Bell pearl	drop pearl
Belomorite	moonstone (Russia)
'Bengal amethyst'	purple sapphire
Berigem	synthetic greenish-yellow spinel
Bernat	polyester resin imitation of amber
Binghamite	Chatoyant quartz with goethite inclusions
Bird's-eye pearl	freshwater pearl with dark rings
Bird's-eye quartz	jasper with colourless spherulites
Bishop's stone	amethyst
'Black amber'	jet
'Black diamond'	hematite
Blackfellows buttons	tektites from West and South Australia
Black moonstone	Labradorite feldspar
Blackmorite	reddish-yellow common opal from Montana
'Blue alexandrite'	change colour sapphire
Blue chrysoprase	chalcedony with included chrysocolla
'Blue malachite'	azurite

'Blue opal'	lazulite
Blue point pearl	pearls from the *Quadrula undulata*
'Blue zircon'	synthetic green-blue spinel
Boakite	brecciated green and red jasper
Bobrowka garnet	demantoid garnet
'Bohemian chrysolite'	moldavite
'Bohemian diamond'	rock crystal
'Bohemian ruby'	(1) pyrope garnet; (2) rose quartz
'Bohemian topaz'	citrine
Boke	rose-coloured coral (Japanese)
'Bone turquoise'	odontolite
'Bornholm diamonds'	rock crystal
Bourguignon pearls	wax-filled imitation pearls
'Brazilian aquamarine'	blue topaz
'Brazilian diamond'	rock crystal
'Brazilian emerald'	green tourmaline
'Brazilian emerald'	synthetic yellowish-green spinel
'Brazilian peridot'	light green tourmaline
'Brazilian ruby'	red or pink topaz
'Brazilian sapphire'	blue tourmaline
'Briancon diamond'	rock crystal
'Brighton diamond'	rock crystal
'Brighton emerald'	green glass
Brilliante	synthetic rutile
'Bristol diamond'	rock crystal
Brilliant-glass	flat diamond used as portrait stone
Brown pearl	conchiolin-rich pearls of low value
'Burma sapphire'	synthetic blue sapphire
Burnt amethyst	heat-treated yellow quartz
'Buxton diamond'	rock crystal
Byewater	a colour grade of yellowish diamond
Cabra stone	fluorite
Cacholong	porcellaneous common opal
Calaite (Kalaite)	turquoise
'Calao ivory'	casque of a hornbill
Calbenite	myrickite
Calcentine	fossilised ammonite shell composed of aragonite
Californian tiger's eye	chatoyant bastite (serpentine)
'Californian jade'	californite (idocrase)
'California moonstone'	chalcedony
'California onyx'	banded stalagmitic calcite and aragonite
'California ruby'	garnet
'California turquoise'	variscite
Callainite	near turquoise (Brittany)
Cambay stone	Indian carnelian
Canada moonstone	peristerite feldspar
Canadian jade	nephrite from British Columbia
Canary diamond	yellow diamond
Canary stone	yellow carnelian
Cand (Cann)	fluorite (Cornwall)
Candite	blue spinel
'Cape chrysolite'	prehnite
'Cape emerald'	prehnite
'Cape ruby'	pyrope garnet
Capra Gem	trade name (USA) for synthetic rutile
Carnegiegem	a doublet with synthetic spinel top and strontium titanate base
Carneol	pink-dyed chalcedony
Catalin	phenolic resin plastic
Catalinaite	jasper from Catalina Island

Cathaystone	glass simulating cat's-eye
Catlinite	a clay-like mineral used by early American Indians
'Cat's-eye'	operculum
'Cat's-eye jade'	chatoyant tremolite or actinolite
Cat's-eye opal	Harlequin opal showing a streak of light
Cedarite	amber from Manitoba, Canada
Celestial stone	turquoise
Cellon	cellulose acetate plastic
Ceragate	waxy yellow-coloured chalcedony
Cerulene	calcite coloured green and blue by malachite and azurite
'Ceylon chrysolite'	yellow-green tourmaline
'Ceylon diamond'	colourless zircon
'Ceylon opal'	moonstone
'Ceylon peridot'	yellow-green tourmaline
Ceylon sapphire	synthetic sapphire
Chalchichuitl	Mexican name for jade or other green stone
Chalcomalachite	malachite-calcite mixture
Chalcomalachite	mixture of malachite, calcite and gypsum
Chameleonite	change colour tourmaline
'Champlain marble'	massive dolomite from Vermont, USA
Changhua	altered silicic tuff containing cinnabar
Chank pearl	pearl from the *Turbinella scolymas*
Cherry opal	red-coloured common opal
Chicken Blood Stone	altered silicic tuff containing cinnabar
Chicken bone jade	yellowish burned or buried jade
Chicot pearl	natural blister pearl
Chi Ku Pai jade	chicken bone jade
'Chinese cat's-eye'	shell cat's-eye
Chinese jade	jadeite
'Chinese turquoise'	mixture of calcite, quartz and soapstone dyed blue
Ch'iung Yü	red jadeite
Chloropal	(1) green common opal (2) an opal-like hydrous silicate of iron
Chlorophane	fluorite which fluoresces on heating
Chlorospinel	green spinel
Chlor-utahlite	variscite
Chrome idocrase	emerald-green idocrase
Chromepidote	chrome-rich epidote from Myanmar, also known as tawmawite
Chrysanthemum stone	a radial aggregate of xenotime and zircon (Japan)
'Chrysoberyllus'	greenish-yellow beryl
Chrysocarmen	red to brown copper-bearing stone with blue or green spots
Chrysolite	undesirable name for yellow-green chrysoberyl or for peridot, etc.
Chrysolithus	yellow beryl
Chrysopal	green common opal
Chrysoprase	green-dyed chalcedony
Chrysoquartz	green aventurine quartz
Cinnabar matrix	quartz with red cinnabar inclusions
Cinnamon stone	Hessonite garnet
Ciro Pearl	imitation pearl
Cirolite	yttrium aluminium garnet (YAG)
Cleiophane	zinc blende
Cloud agate	agate with dark cloud-like markings
Coconut pearl	pearls from the clam of Singapore
'Coconut pearl'	round concretions found in coconuts: of no value
Collophane	massive fibrous carbonate-hydroxyl apatite
'Colorado diamond'	transparent smoky quartz

Colorado goldstone	aventurine quartz
‘Colorado jade’	green microcline feldspar
‘Colorado ruby’	pyrope garnet
‘Colorado topaz’	yellow quartz
Coltstone	acrylic resin plastic
Common opal	opal without play of colour (may be coloured)
Comptonite	variety of thomsonite
‘Congo emerald’	dioptase
Contra Luz opal	opal with play of colour produced by transmitted and reflected light
‘Copper lapis’	azurite
Coral agate	agate with a coral-like design, or agate pseudomorphous after coral
Coralline	red-dyed chalcedony
‘Cornish diamond’	rock crystal
Coro Pearl	imitation pearl
Corsican green	Serpentine-bastite with schiller
Corundolite	synthetic white spinel
Cotterite	quartz with inclusions of white clay
Craquelées	crackled rock crystal (fire-stones)
Creolin	brecciated jasper
Creolite	red and white banded jasper (California)
Crispite	quartz or agate with green hair-like needles
Crocidolite opal	opal with included crocidolite (an opal cat's-eye)
Crop pearl	baroque pearl
Cross-grained stones	irregularly shaped and intergrown diamond crystals
Cross stone	(1) staurolite twin crystals (2) chiastolite (andalusite)
Crown Jewels	synthetic sapphire
Crusite	chiastolite
‘Crystal opal’	water opal
Crystolon	carborundum powder
Cymophane	chrysoberyl cat's-eye
Cyst pearl	natural whole pearl
Dallasite	a green and white rock from Vancouver Island, British Columbia
Danburite	synthetic light red corundum
‘Danburite’	synthetic yellow sapphire
Daourite	red tourmaline
Darwin glass	tektite
‘Dauphiné diamond’	rock crystal
Davidsonite	yellow-green beryl
Dear pearl	lustreless natural pearl
Dekorite	phenolic plastic
De la Mar Pearl	imitation pearl
Delatynite	Romanian amber
Delawaritea	aventurine feldspar
Delta pearls	imitation pearls
Demidovite	blue compact chrysocolla
‘Desert amethyst’	solarised glass
Desert glass	obsidian or moldavite
Diagem	strontium titanate
Diakon	acrylic resin plastic
Dialite	strontium titanate/synthetic spinel doublet
Diamanite	yttrium aluminate (YAG)
Diamantine	crystallised boron abrasive powder
Diamolin	yttrium aluminium garnet (YAG)
Diamonair	yttrium aluminium garnet (YAG)
Diamondite	synthetic white sapphire
Diamone	yttrium aluminium garnet (YAG)
Diamonique	yttrium aluminium garnet (YAG)

Diamonte	yttrium aluminium garnet (YAG)
Diamontina	strontium titanate
Diamothyst	synthetic rutile
Diaspore	hydrous aluminium oxide mineral
Dirigem	synthetic green spinel
Disthene	kyanite
Distrene	polystyrene resin plastic
Ditroite	sodalite
Di' Yag	yttrium aluminium garnet (YAG)
Djevalite	cubic zirconia
Dragomite	rock crystal (Galicia)
Duluth agate	Agate from Lake Superior
Durosol	aluminium oxide abrasive powder
Dust pearls	very small seed pearls
Dynagem	strontium titanate
Earth stone	mined amber
Eastenite	chrome enstatite-hypersthene
Ebonite	vulcanised india rubber
Eclogite	pyroxene garnet rock in South African diamond pipes
Edinite	prase
Egeran	idocrase
Egg pearl	natural egg-shaped pearl
Elbaite	pink tourmaline (Elba)
Elco Pearls	imitation pearls
Eldoradoite	blue chalcedony
El Doradoite	yellow quartz (California)
'Electric emerald'	green glass
'Elie ruby'	pyrope garnet
Elite Pearls	imitation pearls
Elixirite	banded rhyolite from New Mexico
Ellandra Pearls	imitation pearls
Emeralda	synthetic yellow-green spinel
'Emerald malachite'	dioptase
'Emerald matrix'	green fluorite
Emeraldine	dyed green chalcedony
'Emeraldite' or 'Emeralite'	pale green tourmaline
Emeraldolite	synthetic emerald coating on natural colourless beryl
'Emeraudine'	dioptase
Emildine (Emilite)	spessartine garnet (South Africa)
Empirite	name for tektites found in Georgia
Endura Emerald	green glass
Enhydros	chalcedony nodules partly filled with water
Epidosite	epidote
Erinide	yellowish-green synthetic spinel
Erinoid	casein plastic
'Esmeralda'	green tourmaline
Essonite	hessonite garnet
'Evening emerald'	peridot
Eye agate	banded agate with cutting so that bands are concentric
Eye diamond	fish-eye diamond
Eye stone	thomsonite
Fabulite	strontium titanate
Fairburnite	fortification agate (South Dakota)
Fairy stone	staurolite crystal (twinned) or an imitation of same
Falcon's eye	silica pseudomorph of blue crocidolite
Fales	any stone with differently coloured layers
'False amethyst'	purple fluorite
'False chrysolite'	moldavite
'False emerald'	green fluorite

'False lapis'	lazulite, or dyed jasper
'False topaz'	citrine or yellow fluorite
Falun Brilliants	lead-glass imitation stones
Fancy pearls	coloured natural nacreous pearls
'Fashoda garnet'	pyrope garnet
Feather gypsum	satin-spar
Fei-ts'ui	jade
'Feldspar-apyre'	andalusite (French)
Ferrers (Ferros) Emerald	green glass
Ferrolite	black iron slag proposed for use as a gem
Fianite	Cubic zirconia
'Fire jade'	a rock consisting mostly of opal, having a tiger's-eye appearance (due to grunerite)
Fire Pearl	billitonite
Flame spinel	orange-red natural spinel
Flash opal	Opal with a single-hued flash of colour
Flèches d'amour	rutilated (sagenitic) quartz
'Flinder's diamond'	white topaz
Flohmig amber	fatty amber, full of bubbles
Flower agate	chalcedony with flower-like inclusions
Foil back	chatons
Forcherite	orange-yellow opal coloured by orpiment
Fossil pineapple	opal pseudomorph after crystals of glauberite, gaylussite, or gypsum
Fowlerite	rhodonite
Framesite	an aggregate of diamond, bort and carbon from Premier mine
French colour rubies	light red rubies
Frost agate (Frost stone)	agate with white markings
Fuh yu	abalone shell and pearl
'Fukien jade'	soapstone
Futuran	phenolic resin plastic
Gava gem	synthetic rutile
Galalith	casein plastic
Galliant	a trade name (German) for a diamond simulant, gadolinium gallium garnet (GGG)
'Garnet jade'	massive green grossular garnet
Gagat	jet (German)
Gemerald	beryl doublet or synthetic emerald coated beryl
Geminair	yttrium aluminium garnet (YAG)
Geneva ruby	reconstructed ruby
'German diamond'	rock crystal
'German lapis'	blue-dyed jasper
German Mocoas	imitation moss agate
Gibsonite	pink thomsonite
'Gibsonville emerald'	greenish quartz
Giguku	jade (Japanese)
Giogetto	black opal
Girasol	(1) fire opal; (2) a type of water opal; (3) moonstone, etcetera
Girasol	trade name for glass used for imitation pearl beads
Girasol pearl	imitation pearl
Girasol sapphire	sapphire cat's-eye
'Glass agate'	obsidian
Glass lava	obsidian
Glass meteorite	moldavite
Glass opal	hyalite
Glass stone	axinite
Gles or geits	small cleavage cracks in diamond

Goldfluss	aventurine glass
Gold opal	fire opal
Gold quartz	(1) small particles of gold in quartz or quartzite; (2) golden-coloured crystal quartz
'Gold sapphire'	lapis lazuli
Goldstone	aventurine glass
'Gold topaz'	golden quartz
Goniobasis agate	agate replacing the fossil gastropod *Goniobasis*
Goodletite	marble forming the matrix of rubies (Myanmar)
Green ear	ear-shaped freshwater pearls
'Green garnet'	enstatite
Green John	massive green fluorite
'Green onyx'	stained green chalcedony
'Green quartz'	fluorite
Green star-stone	chlorastrolite
Greenstone	(1) Nephrite; (2) chlorastrolite
Grenalite	staurolite
Griqualandite	crocidolite (tiger's-eye)
Gualdalcanal cat's-eye	operculum
Guarnaccio	yellowish-red garnet
'Guizhou jadeite'	mixture of quartz, green dickite and an organic substance
Gum animé	copal resin
Haida slate	argillite
Hair amethyst	sagenitic amethyst
Hairstone	sagenitic quartz
Hakik	Agate (Indian)
Hammer pearls	baroque (hammer-head-shaped) pearls
Hard mass	imitation gems in hard glass
'Hawaiian diamonds'	rock crystal
Hawaiite	peridot (Hawaii)
Haystack pearl	natural high-domed button pearl
Heliolite	(1) aventurine feldspar; (2) transparent red labradorite
Heliotrope	bloodstone (quartz)
Hematine	imitation hematite
Hematinon, haematinon	opaque red glass
Hematite garnet	a synthetic iron-rich garnet
'Herkimer diamond'	rock crystal
Herrerite	blue and green smithsonite
Hinge pearls	elongated baroque pearls from the hinge of the freshwater mussel
'Hinjosa topaz'	yellow quartz
Höden, hoting	casque of a hornbill
Holstein	fossil wood
'Honan jade'	soapstone (agalmatolite)
Hope Sapphire	synthetic sapphire-blue spinel
'Horatio diamond'	rock crystal
'Hornbill ivory'	casque of a hornbill
Horn coral	black coral
'Hot Springs diamond'	rock crystal
Hsi jade	clear water or clear black jade
Hsieh jade	ink black jade
Hsiu Yen	green and white jasper
Hungarian cat's-eye	quartz cat's-eye
Hyacinth	(1) orange-brown zircon; (2) hessonite garnet
Hyacinth of Compostella	reddish iron-rich quartz
Hyaline	opalescent milky quartz
Hyalite	clear colourless opal
Hyalithe	red, brown, green or black opaque glass

'Iceland agate'	obsidian
'Iimori jade' (*Iimori Stone*)	a type of glass (Japan)
Image stone	agalmatolite
Imperial jade	fine green Chinese jade
Imperial sodden snow jade	white nephrite
Imperial topaz	sherry-coloured topaz
Imperial Yu stone	green aventurine quartz
Inamori (Crescent Vert) Emerald	synthetic emerald
Inanga	grey nephrite (New Zealand)
Inca emerald	emerald from Ecuador
Inca stone	pyrites
Indian agate	moss agate
Indian cat's-eye	chrysoberyl cat's-eye
'Indian emerald'	green-stained crackled quartz
'Indian jade'	green aventurine quartz
'Indian topaz'	yellow sapphire
Invelite	phenolic resin plastic
Iolanthite	banded reddish jasper
'Irish diamonds'	rock crystal
Iron opal	red or yellow common opal
Iserine (Iserite)	black iron mineral used to imitate hematite
'Isle of Wight diamond'	rock crystal
Isle Royale greenstone	chlorastrolite
Italian chrysolite	idocrase
'Italian lapis'	stained jasper
Itali	Aztec name for obsidian
Ivorina	casein plastic imitation of ivory
'Ivory pearls'	spherical ivory 'beans' found in tusk cavities
'Ivory turquoise'	odontolite
Jacinth	(1) red-brown zircon; (2) hessonite garnet
Jadeolite	green syenite resembling jade, possibly pseudojadeite
'Jade Tenace'	saussurite
Jadine	Australian chrysoprase
Japan pearl	old name for cultured blister pearl
Japanese coral	dark red coral with white core
Jargoon	colourless or pale-coloured zircon
Jarra Gem	synthetic rutile
Jasp agate	intermediate between jasper and agate
Jaspe fleuri	jasp agate
Jasperine	banded jasper
'Jasper jade'	green jasper, serpentine, etcetera
Jaspillite	banded hematite and jasper
Jasponyx	banded jasp agate
Jasponal	intermediate jasper and opal
Jet stone	black tourmaline (schorl)
Johannes Gem	synthetic rutile
Johnite	vitreous and scaly turquoise
Jourado Diamond	synthetic colourless spinel
Kahurangi	pale green translucent nephrite
Kalmuck agate (opal)	cacholong
'Kandy spinel'	almandine garnet
Kan Huang jade	light yellowish jade
Kaolite	moulded imitation cameos, etcetera, in baked clay
Karlsbad Spring stone	banded gypsum used for carvings
Kashgar jade	inferior nephrite
Kawakawa	nephrite (Maori)
Kenneth Lane Jewel	strontium titanate
Kenya Gem	synthetic rutile
Keweenaw agate	agate from Lake Superior
Keystoneite	chalcedony coloured blue by chrysocolla

'Khoton jade'	inferior nephrite
'Kidney stone'	nephrite
Kikukwaseki	a radical aggregate of zircon and xenotime (chrysanthemum stone)
'Killecrankie diamond'	colourless topaz
Kima Gem	synthetic rutile
Kimberlite Gem	synthetic rutile
Kimpi	red or brown jadeite
Kingfisher jade	bluish-green jadeite
'King Topaz'	natural yellow sapphire
Kinradite	orbicular jasper
Kismet Pearls	imitation pearls
Kollin garnet	almandine garnet
'Korea jade'	bowenite serpentine
Korite	fossilised ammonite shell composed of aragonite
Kyauk-ame	black jadeite
Kyauk-átha	white translucent jadeite
La Beau Pearls	imitation pearls
Labrador moonstone	Labradorite feldspar
Lactoid	Casein plastic
Laguna Pearls	imitation pearls
'Lake George diamonds'	rock crystal
'Lake Superior agate'	thomsonite, or correctly agate
'Lake Superior fire agate'	glass imitation of opal
Lake Superior greenstone	chlorastrolite
Lao Kan C'hing jade	bluish jade
La Paz Pearls	mostly grey and bronze pearls from the Gulf of California; or for coloured pearls from the hammer-head clam
Lapis crucifer	staurolite crystals
Lapis Nevada	thulite-diopside skarn
Lardite	agalmatolite
Larimar	blue pectolite from the Dominican Republic
Laser Gem	a doublet with a synthetic sapphire top and strontium titanate base
La Tausca Pearls	imitation pearls
Lat yay	clouded jadeite
Laurelite	idocrase
Lavendrine	amethyst quartz
Lavernite	synthetic periclase
Lazurfeldspar	bluish orthoclase (Siberia)
Lazurquartz	blue quartz (chalcedony)
Lechosos opal	opal with deep green and red flashes of colour
Leonite	Tibet stone (eosite)
Leuco-sapphire	colourless sapphire
Ligament pearl	hinge pearl
Linde Simulated Diamond	yttrium aluminate (YAG)
Lingah pearl (shell)	pearls (shell) from Persian Gulf
Lintonite	variety of thomsonite
'Lithia amethyst'	kunzite
'Lithia emerald'	hiddenite
Lithoxyle (Lithoxylite)	opalised wood
Litoslazuli	massive purple fluorite
Liver opal	menilite (impure opal)
Lluvisnando opal	yellowish water opal with pronounced flames
Love arrows	sagenitic quartz
Love stone	aventurine quartz
Lucinite	variscite
Lusterite	synthetic rutile
Lustigem	strontium titanate

'Lux sapphire'	iolite
Lynx eye	Labradorite with green flash
'Lynx sapphire'	Iolite
Macusanite	natural glass from Macusani, Peru
'Madeira topaz'	brown quartz or brown synthetic sapphire
Magalux	synthetic spinel
Maiden pearl	newly fished pearl
'Majorica pearls'	imitation pearls
Malacon	glassy brown variety of zircon
Malaya	a variety of East African garnet
'Manchurian jade'	soapstone
Manganese spar	rhodochrosite
Man Yu	jade of blood-red colour
Maori stone (jade)	nephrite
'Marcasite' (cut stones)	pyrite
'Mari diamond'	rock crystal
Mariposite	a foliated rock with bright green streaks of mica
'Marmarosch diamond'	rock crystal
'Marmora diamond'	rock crystal
Marvelite	strontium titanate
Marvella Pearls	imitation pearls
Mascot Emerald	Soudé emerald
'Mass aqua'	hard glass imitation
Mass opal	opal matrix
'Matara (Matura) diamond'	colourless zircon from Sri Lanka
Matorolite/Matorodite	a suggested name for chrome chalcedony
Maxixe aquamarine	boron-rich deep blue aquamarine (easily fades)
Mayaite	diopside jadeite (Central America)
Mecca stone	cornelian
Medfordite	a type of moss agate
Medina Emerald	green glass
Melanite	black andradite garnet
Melichrysos	yellow zircon
Menilite	banded grey and brown common opal
'Meru sapphire'	blue zoisite
'Meta-jade', *Meta-hsui*	a type of glass (Japan)
'Mexican agate'	banded calcite or aragonite
'Mexican diamond'	rock crystal
'Mexican jade'	green-dyed stalagmitic calcite
'Mexican onyx'	stalagmitic calcite
Micatite	phenolic resin plastic
Midge stone	moss agate
Milhama Pebbles	jasper pebbles
Milk opal	milky white common opal
Miridis	synthetic rutile
Mixte	composite stone, half real and half imitation
Mock pearl	imitation pearl
'Mogok diamond'	white topaz
Molochites	green jasper
'Montana jet'	obsidian
'Montana ruby'	red garnet
'Mont Blanc ruby'	rose quartz
Morion	dark brown quartz
Moro	blood-red coral (Japanese)
Moroxite	greenish-blue apatite
'Mother of emerald'	prase
Mountain crystal	rock crystal
'Mountain jet'	obsidian
'Mountain ruby'	red garnet
Mozarkite	a chert or flint

Muller's glass	hyalite glassy opal
Muscle pearls	small distorted pearls found near the muscle of the oyster
Mussel egg	freshwater pearl
Mussite	diopside
'Mutzschen diamond'	rock crystal
Mya yay	best-quality green jadeite
Nassau pearl	pink conch pearl
Nautilus pearl	oval section of Indian nautilus (coq de pearl)
Needle stone	sagenitic quartz
'Nerchinsk aquamarine'	blue topaz
'Nevada diamond'	obsidian
'Nevada topaz'	obsidian
'Nevada turquoise'	variscite
New Zealand greenstone	nephrite
Nicolo	black or dark brown onyx with thin bluish-white layer
'Night emerald'	peridot
Nigrine	black rutile
Nixonoid	cellulosic plastic
Noble opal	precious opal
Norbide	boron carbide abrasive
Nuummite	iridescent gedrite
Occidental agate	poor-quality agate
Occidental amethyst	real amethyst (violet quartz)
Occidental cat's-eye	quartz cat's-eye
Occidental chalcedony	poor-quality chalcedony
Occidental cornelian	poor-quality cornelian
'Occidental diamond'	rock crystal
'Occidental topaz'	citrine
'Occidental turquoise'	odontolite
Oeil de boeuf	ox-eye labradorite feldspar
'Olivene (olivine)'	demantoid garnet
Onegite	amethyst with needle-like inclusions
'Onyx obsidian'	parallel banded obsidian
'Onyx opal'	banded opal
Opal agate	alternate bands of opal and chalcedony
Opalite	impure common opal, or chert from Lander Co, Nevada
Opalite	plastic imitation of opal
'Orange topaz'	brownish-yellow quartz
'Oregon jade'	dark green jasper
'Oregon moonstone'	chalcedony
'Oriental agate'	good-quality agate
'Oriental alabaster'	stalagmitic calcite
'Oriental almandine'	purple-red sapphire
'Oriental amethyst'	violet sapphire
'Oriental aquamarine'	aquamarine-coloured sapphire
'Oriental cat's-eye'	girasol sapphire
'Oriental cat's-eye'	chrysoberyl cat's-eye
'Oriental chalcedony'	good-quality chalcedony
'Oriental chrysoberyl'	yellowish-green sapphire
'Oriental chrysolite'	greenish-yellow chrysoberyl or sapphire
'Oriental cornelian'	deep-coloured cornelian
'Oriental emerald'	green sapphire
'Oriental topaz'	yellow sapphire
Orletz	Russian name for rhodolite
'Osmenda pearl'	same as coq de perle
Owl-eye	eye agate with two similar eyes
Ox-eye	Labradorite feldspar
Ox-eye agate	similar to owl-eye

Ozakite	thomsonite
Pacific cat's-eye	operculum
Padparadscha (h)	orange variety of Sri Lankan sapphire
Pagoda stone (pagodite)	(1) agalmatolite; (2) fossil limestone (3) translucent agate with pagoda-like markings
Pai Yu (Pao Yu)	white jadeite or nephrite
'Palmeira topaz'	brown synthetic sapphire
Panabase	copper ore, properly tetrahedrite but often copper pyrites in a quartz base
Panama pearls	slate blue to black pearls from the Gulf of Mexico
Pantha	white translucent jadeite
'Paphros diamond'	rock crystal
Paragon pearls	round pearls of large size
Paragon Pearls	imitation pearls
Paris Pearls	imitation pearls
Paredrite	one of the 'favas' of the Brazilian diamondiferous gravels (TiO_2 plus H_2O)
Passau pearl	freshwater pearl from Central Europe
Paste	glass imitation stones
Pate ce riz	glass imitation of jade
Patona Pearls	imitation pearls
Patricia Pearls	imitation pearls
Pauline Trigere	strontium titanate
Paulite	nearly black hypersthene with coppery inclusions
Peacock stone	malachite
Pearl doublet	cultured blister pearl
Pearl opal	cacholong
'Pecos diamonds'	rock crystal
'Pectolite jade'	pectolite
Peganite	variscite
Peiping (Peking) jade	any true jade but usually nephrite
Pelhamine	precious serpentine
'Pennsylvania diamond'	pyrite
Peredell topaz	greenish topaz
Peridine	green heat-treated quartz
Perigem	synthetic light yellow-green spinel
Petal pearls	distorted flattened pearls
Petoskey stone (agate)	fossil limestone (Michigan)
Phainite	cubic zirconia
Picotite	black spinel
Picrolite	serpentine
Pigeon-blood agate	cornelian
'Pilbora Jade'	ornamental serpentine
Pingoes d'agoa	colourless water-worn pebbles (Brazil)
'Pink moonstone'	scapolite
Pinna pearls	pearls from the Pinna mussel
Pin-fire opal	precious opal with play of colour in small patches
Pipe stone	a red siliceous clay (catlinite)
Pistacite	epidote
Pi Yu	jadeite or nephrite with a vegetable green colour
Plexiglas	acrylic resin plastic
Plume agate	moss agate (flower agate)
Point chalcedony	grey chalcedony with red spots
Polka-dot agate	translucent chalcedony with small red, brown or yellow dots
Polyphant stone	serpentine diabase (Cornwall)
'Pomegranate ruby'	red spinel
Pompadour Pearls	imitation pearls
Poppy stone	orbicular jasper
Porcelainite	metamorphosed baked clay

Potch	miners' term for opal which is colourful but 'dead'
Prasemalachite	chalcedony filled with malachite
Prase opal	nickel-stained green opal
'Prismatic moonstone'	chalcedony
'Prismatic quartz'	iolite
'Pseudochrysolite'	moldavite
Pseudojadeite	probably a green albite feldspar
Pudding stone jade	lighter-coloured nodules of nephrite cemented by darker material
Purpurine	opaque red glass
Pyralin	cellulosic plastic
Pyralmandite	name suggested for the intermediate garnets of the Py/Al series
Pyrandine	alternative to pyralmandite
'Pyroemerald'	green fluorite
'Quartz topaz'	citrine
'Quebec diamond'	rock crystal
Quetzalztli	translucent green jade (Mexico)
Quincite (Quinzite)	(1) pink sepiolite; (2) pink common opal
Radient	synthetic white spinel
'Radium diamond'	smoky quartz
Rainbow agate (chalcedony)	iridescent agate
Rainbow Diamond	synthetic rutile
Rainbow Magic Diamond	synthetic rutile
Rainbow obsidian	iridescent obsidian
Rainbow quartz	Iris quartz
Raspberry spar	rhodochrosite
Redmanol	phenolic resin plastic
'Red Sea pearls'	coral beads
Regency Created Emerald	synthetic emerald
Resinoid	phenolic resin plastic
Retinalite	honey yellow serpentine
'Rhine diamond'	rock crystal
'Rhodesian moonstone'	bluish-white translucent quartz from Mtoko, Zimbabwe
Rhodoid	cellulose acetate plastic
Riband agate	banded agate
Riband (Ribbon) jasper	jasper with stripes of alternating colour
Richlieu Pearls	imitation pearls
Ricolite	banded serpentine
Ripe pearls	pearls with good orient
River agate	water-worn moss agate pebbles
River pearls	freshwater pearls
Rock Crystal	glass
Rock glass	obsidian
'Rock (Rocky mountain) ruby'	pyrope garnet
Rodingite	grossular-vesuvianite ornamental rock
Rogueite	greenish jasper (Oregon)
Roman Pearls	imitation pearls
Romanzovite	dark brown grossular garnet
Rosaline	thulite
'Rosaline'	deep pink synthetic sapphire
Rose garnet	xalostocite, or incorrectly for rhodonite
Rose de France	pinkish-violet amethyst, or synthetic sapphire of similar colour
Roseki	agalmatolite
Rose Kunzite	synthetic pink sapphire
Roselite (Rosolite)	xalostocite
'Rose moonstone'	pink scapolite
Rosinca	rhodochrosite

Rossini Jewel	strontium titanate
Rosterite	rose-red beryl (Elba)
Rothoffite	yellow to brown andradite garnet
Royal Azel	sugilite
Royalite	purplish-red glass
Royal Lavulite	sugilite
Royal topaz	blue topaz
Rozircon	pink synthetic spinel
Rubace (Rubasse)	red-stained crackled quartz
Rubasse	quartz coloured red by scales of iron oxide
Rubicelle	orange-red spinel
Rubolite	red-coloured common opal
'Ruby balas'	red spinel
'Ruby spinel'	red spinel
Ruin agate	brecciated agate or agate with patterns of ruins
Sabalite	banded green variscite
Safirina	blue spinel or blue quartz
Safranite (Saffronite)	citrine
Sagenite	quartz with needle-like inclusions
'Salamanca topaz'	fiery-coloured citrine
'San Diego ruby'	red tourmaline
Sang-i-yeshan	dark green bowenite serpentine
Saphir d'eau	iolite
'Sapphire quartz'	blue chalcedony, also blue silicified crocidolite
'Sapphire spinel'	blue spinel
Sapphirine	correct for Mg.Al silicate mineral. Used also for (1) blue chalcedony; (2) blue spinel (3) blue glass
Sard	translucent brown to reddish chalcedony
Sardium	artificially coloured sard
Sardoine	dark cornelian
Satelite	fibrous serpentine
'Saxon chrysolite'	topaz
'Saxon diamond'	topaz
'Saxon topaz'	yellow quartz
'Schaumberg diamond'	rock crystal
Schiller spar	bastite
Schmelze	glass
Schnide	blue glassy common opal
Schorl	black tourmaline
'Scientific brilliant'	synthetic white sapphire
'Scientific emerald'	green beryl glass
'Scientific topaz'	synthetic pink corundum
'Scotch (Scottish) topaz'	yellowish-brown quartz
Seed pearls	small pearls less than 0.25 grain
Serra stone	Brazilian agate
'Shanghai jade'	steatite or talc
Shell marble	lumachella
Siam Aquamarine	blue zircon
'Siberian chrysolite'	demantoid garnet
'Siberian ruby'	red tourmaline
'Siderite'	blue quartz
Siliciophite	chrysotile in common opal
'Silver Peak jade'	malachite
'Sinopal or sinople'	reddish aventurine quartz
Sioux Falls jasper	quartzite (South Dakota)
Sira	abrasive aluminium oxide
Slocum Stone	glass imitation of opal
Smaragdite	green zoisite type of rock resembling jade
Smaragdolin	green beryl glass

'Smoky topaz'	smoky quartz
'Soapstone'	serpentine
Sobrisky opal	opal from Death Valley, California
'Soldered emerald'	soudé emerald (composite stone)
Soldier's stone	amethyst
'Soochow jade'	bowenite serpentine or soapstone
Sorella	strontium titanate
'South African jade'	massive green grossular garnet
Spalmandite (spandite)	names suggested for intermediate almandine-spessartine garnets
'Spanish emerald'	green glass
'Spanish lazulite'	iolite
'Spanish topaz'	yellowish-brown quartz
Sparklite	colourless zircon
Spectrolite	iridescent labradorite from Finland
Sphalerite	zinc blende
Spinach jade	nephrite
'Spinel ruby'	red spinel
St Stephen's stone	red-spotted white chalcedony
Stantienite	black amber, possibly produced by lightning strike
Starlite	blue zircon
Starolite	star rose quartz doublet
Star-tania	synthetic rutile
'Star topaz'	yellow star sapphire
'Stolberg diamonds'	rock crystal
Strawberry pearl	pink-coloured baroque freshwater pearl with a pimply surface
Stremlite	blue zircon
Strongite	synthetic spinel
'Styrian jade'	pseudophite
Sugar stone	pink datolite (Michigan)
Sun opal	fire opal
Sweetwater agate	fluorescent moss agate from Wyoming
Sweetwater pearls	freshwater pearls
'Swiss jade'	green-dyed jasper
'Swiss lapis'	blue-dyed jasper
Synthetic Alexandrite	synthetic corundum or spinel
Synthetic Aquamarine	synthetic corundum or spinel
Synthetic Turquoise	an imitation turquoise
Syntholite	synthetic corundum imitating alexandrite
Syriam (Syrian or Suriam) garnet	almandine garnet
Tabasheer	amorphous opal-like silica found in the joints of some types of bamboo
Taiwan cats'-eye	chatoyant tressolite or actinolite
Takin	engraved emerald (India)
Taltalite	green tourmaline (Brazil)
Tama	jade (Japanese)
Tangiwai(te)	bowenite (New Zealand)
Tania-59	synthetic rutile
Tanzanite	purple-blue zoisite
'Tasmanian diamond'	rock crystal
Tauridian topaz	blue topaz
Tawmawite	massive chrome-rich epidote
Taxoite	green serpentine (Pennsylvania)
Tecla Pearls	imitation pearls
Tibet stone	mixture of aventurine quartz and quartz porphyry (Eosite)
Tigerite	tiger's-eye
Tirum Gem	synthetic rutile

Titangem	synthetic rutile
Titania Brilliante	synthetic rutile
Titania Midnight Stone	synthetic rutile
Titanium	synthetic rutile
Titanium Rutile	synthetic rutile
Titanstone	synthetic rutile
Tokay lux sapphire	hungarian obsidian
Tomb jade	buried jade which has turned to a red or brown colour
'Tooth turquoise'	odontolite
'Topaz'	yellow-brown quartz
'Topaz'	synthetic yellow sapphire
'Topaz cat's-eye'	chatoyant yellow sapphire
Topazolite	greenish-yellow to yellow andradite garnet
'Topaz quartz'	brownish-yellow quartz
'Topaz saffronite'	brownish-yellow quartz
Tosa coral	Japanese coral
'Tourmaline green'	synthetic dark green spinel
Trainite	a type of banded variscite
Traversellite	green diopside
Tree stone (tree agate)	mocha stone (moss agate)
'Trenton diamond'	rock crystal
Triamond	yttrium aluminium garnet (YAG)
Trillium	green or blue-green apatite
Tripletine	emerald-coloured beryl triplet
Tsavorite, Tsavolite	transparent green grossular garnet from Kenya
Tsilaisite	manganese tourmaline
Tube agate	Agate with tubes (often filled) running through it
Turkey fat ore	cadmium-coloured yellow smithsonite
Turquerenite	dyed magnesite
'Turritella agate'	misnomer for goniobasis agate
Turtle back	(1) chlorastrolite; (2) turquoise or variscite matrix
Turtle-back pearl	oval natural blister pearl with a fairly high dome
Tuxtlite	sodium/magnesium pyroxene, the principal constituent of mayaite
Uigite	chlorastrolite from Skye
Ultralite	red-violet synthetic sapphire
Unionite	pink zoisite (thulite)
Unripe pearls	poor-quality pearls
'Ural chrysolite (emerald or olivine)'	demantoid garnet
'Uralian sapphire'	blue tourmaline
'Utah turquoise'	variscite
Utahlite	variscite
Vabanite	brown-red jasper specked with yellow (California)
Valencianite	adularia feldspar
'Vallum diamond'	rock crystal
Variolite	dark green orthoclase with lighter-coloured globules
Vashegyrite	an aluminium phosphate mineral, said to be like variscite, but may be yellow or brown
Verde de Corsica	green dialage and labradorite
'Verdelite'	green tourmaline
'Vermeil', 'Vermeille'	orange-red stones, may be zircons, garnets or spinels
Vermilite	cinnabar in opal
'Vesuvian garnet'	leucite
'Vesuvianite jade'	californite
Victoria Stone	a type of glass (Japan)
'Vienna (Viennese) turquoise'	a turquoise imitation
Vigorite	phenolic resin paste
Viluite	idocrase
Vinegar spinel	yellowish-orange spinel

Violan(e)	violet massive diopside
Violet stone	iolite
Violite	purple synthetic sapphire
Viridine	green andalusite
Viscoloid	cellulosic plastic
'Volcanic chrysolite'	idocrase
Volcanic glass	obsidian
Vorobeyevite	pink beryl
Vulcanite	hard black rubber
Walderite	synthetic white sapphire
Wart pearl	baroque pearl
'Washita diamond'	rock crystal
'Water sapphire'	Iolite
Water stone	glassy orthoclase, or hyalite opal
Wax agate	yellow to yellowish-red agate with waxy lustre
Wax opal	yellowish opal with waxy lustre
Wellington	strontium titanate
'White garnet'	leucite
'White jade'	Grossular garnet
Wilconite	purplish-red scapolite
Wild pearl	natural pearl
Wilsonite	purplish-red scapolite
Wiluite	idocrase
Winchellite	lintonite (thomsonite)
Wing pearl	baroque pearl shaped like a wing
Wisconsin pearls	fine coloured freshwater pearls from the *Unio* of the Mississippi
Wolf's-eye	(1) moonstone; (2) tiger's-eye
Wood agate	agate pseudomorph after wood
Wood opal	Opal pseudomorph after wood
Wood stone	fossil stone
Xihuitl	Turquoise (Aztec)
Xyloid jasper	jasperised wood
Xylonite	cellulosic plastic
Xylopal	opalised wood
Yanolite	violet axinite
'Yaqui onyx'	'onyx marble' from Baja, California
Yttralox	an optical ceramic mixture of 90% yttria and 10% thoria; RI = 1.92, dispersion = 0.039, SG = 5.30 and hardness = 6.5; may simulate diamond
Yu	jade
Yui ko lu jade	tomb jade coloured green from bronze objects buried near it
Yu Yen Stone	a massive greenish-grey serpentine
Zaba Gem	synthetic rutile
'Zabeltitzten diamond'	rock crystal
Zarafina	blue spinel or blue chalcedony
Zeasite	wood opal
Zebra stone (jasper)	vari-coloured blue and green tiger's-eye (crocidolite), or limonite with lighter brown layers of shell material
Zenithite	strontium titanite
Zeuxite	green tourmaline (Brazilian)
Zircolite	synthetic white sapphire
Zircon Spinel	synthetic pale blue spinel
Zirctone	synthetic bluish-green sapphire
Zonite	chert or jasper (Arizona)
Zonochlorite	near chlorastrolite
Zylonite	cellulosic plastic

Famous Diamonds and Named Large Diamonds

Name	*Locality*	*Weight rough*	*Weight cut*
Abadia do Dourades (light brown)	Brazil	104 Mcts	
Abaete (rose-pink)	Brazil	238 Mcts	
Akbar Shah	India	116 cts	73.60 Mcts
Algeiba Star (yellow)	South Africa?		133.03 Mcts square brilliant
Formerly the Mahjal, recut and renamed			
Al-Nader	?		115.83 Mcts pear
Amsterdam (black)	?	55.85 Mcts	33.74 Mcts pear
Arc	South Africa	381 cts	
Ashberg (amber)	South Africa?		102.48 Mcts cushion
A Steyn	South Africa	141.25 Mcts	
Austrian Yellow	*See Florentine*		
Banjarmasin	Kalimantan		40 cts approx. square
Barkly Breakwater	South Africa	109.25 cts	
Baumgold Brilliant	South Africa	167.25 Mcts	55 Mcts
Baumgold Pears	South Africa	609.25 Mcts	Two pears at 50 Mcts each and 12 others
Bazu	India	104 cts	
Beaumont	South Africa	273 cts	
Beau Sancy	India?		34 cts
Berglen (brown)	South Africa	416.25 Mcts	
Black Diamond of Bahia	Brazil	350 cts	
Black Star of Africa	South Africa?		202 cts
Bob Craig	South Africa	100.50 Mcts	
Bob Gove	South Africa	337 cts	
Brady	South Africa	330 cts	
Braganza	*Probably a topaz of 1680 cts*		
Brazilia (light blue)	Brazil	176.20 Mcts	
Broderick	South Africa	412.50 cts	
Brunswick Blue	?		?6–7 cts
Thought to be part of the Tavernier Blue			
Burgess	South Africa	220 cts	
Cape (canary yellow)	South Africa	167.00 Mcts	
Carmo do Paraneiba (brown)	Brazil	245 Mcts	
Carns	South Africa	107 cts	
Cartier	South Africa		107.7 Mcts pear
Cartier (NY)	South Africa	240.80 Mcts	69.42 Mcts pear and others
Largest stone is known as the Taylor-Burton			
Centenary	South Africa	599 Mcts	273.85 Mcts modified heart
Cent Six	?		106 cts
Cleveland	South Africa	100 + cts	50 cts cushion
Colenso (pale yellow)	South Africa	133.145 Mcts	
Coromandel I	Brazil	180 Mcts	
Coromandel II	Brazil	141 Mcts	
Coromandel III	Brazil	226 Mcts	
Coromandel IV	Brazil	400.65 Mcts	

Name	*Locality*	*Weight rough*	*Weight cut*
Cross of Asia (champagne)	?		109.26 Mcts
Cuban Capitol	South Africa	23 cts	
Cullinan	South Africa	3106 Mcts	9 principal stones and 96 others
Cullinan I			530.20 Mcts pear
Also known as the Great Star of Africa. Largest cut stone of fine quality in the world, second largest overall. Set in the sceptre of the British Regalia.			
Cullinan II			317.40 Mcts cushion
Cullinan III			94.40 Mcts pear
Cullinan IV			63.65 Mcts square
Cullinans II, III, and IV are also known as the Lesser Stars of Africa			
Cullinan V			18.80 Mcts heart
Cullinan VI			11.50 Mcts marquise
Cullinan VII			8.80 Mcts marquise
Cullinan VIII			6.80 Mcts oblong brilliant
Cullinan IX			4.40 Mcts pear
Cumberland	India		32.82 Mcts triangular
Dan Campbell	South Africa	192.50 Mcts	32 Mcts
Darcy Vargas (brown)	Brazil	455 Mcts	
Dary-i Nur (pink)	India		estimated between 175 and 195 Mcts rectangular step cut
Major part of the Great Table			
De Beers (yellow)	South Africa	439.86 Mcts	234.5 Mcts cushion
Deepdene (yellow)	?		104.88 Mcts cushion
Dewey	USA	23.75 Mcts	11.15 Mcts
Diario de Minas Geraes	Brazil	375.10 Mcts	
Dresden Green	India		40.07 Mcts
Dresden White	*See Saxon White*		
Dresden Yellow	India		4 brilliants, largest 38 Mcts
Dudley	*See Star of South Africa*		
Du Toit I (yellowish)	South Africa	250 cts	
Du Toit II (yellowish)	South Africa	127 cts	
Earth Star (brown)	South Africa	248.9 Mcts	111.59 Mcts pear
Edna Star	?		115.0 Mcts emerald cut
Emperor Maximillian	Brazil		41.94 Mcts cushion
English Dresden	Brazil	119.5 cts	78.53 Mcts pear
Eugénie	Brazil?		52.35 Mcts oval brilliant
Eureka	South Africa	21.25 Mcts	10.73 Mcts oval brilliant
Excelsior	South Africa	995.2 Mcts	21 brilliants, largest 69.68 Mcts
Fineberg Jones	South Africa	206.5 cts	
Florentine (light yellow)	India		137.27 Mcts irregular double rose cut
Fly	South Africa	60 cts	
Golconda 'D'	India		47.29 Mcts brilliant

Famous Diamonds and Named Large Diamonds

Name	*Locality*	*Weight rough*	*Weight cut*
Golconda Doré (yellow)	India	130 Mcts	95.40 Mcts
Golden Door (yellow)	?		104.95 Mcts shield
Golden Hue (yellow)	South Africa?		132.42 Mcts cushion
Governador Valadares	Brazil	108.30 Mcts	
Goyaz	Brazil	600 Mcts	80.00 Mcts and others
Great Brazilian	Brazil		130.00 Mcts
Great Chrysanthemum (brown)	South Africa	198.28 Mcts	104.15 Mcts pear
Great Mogul	India	787 cts	280 cts
Great Star of Africa	*See Cullinan I*		
Great Table	A legendary stone said to be 242 cts – *See Dary-i-Nur*		
Great White	*See Jacob*		
Guinea Star	Guinea	255.1 Mcts	89.01 Mcts
Hanger (pale yellow)	South Africa	123 cts	
Harry Young	South Africa	269.5 cts	
Hope (blue)	India		45.52 Mcts
Probably part of the Tavernier Blue; the Hope is now in the Smithsonian Institution			
Hope of Africa (yellow)	South Africa		151.91 Mcts
Ice Queen	*See Niarchos*		
Idol's Eye	India		70.20 Mcts
Imperial	*See Jacob*		
Incomparable (brownish-yellow)	Africa	890 Mcts	407.48 Mcts triolette
Independencia	Brazil	106.82 Mcts	
Indien	India?		250 cts
Iranian I (cape)	South Africa		152.16 Mcts rectangular old brilliant
Iranian II (cape)	South Africa		135.45 Mcts high old cushion
Iranian III (cape)	South Africa		123.93 Mcts cushion
Iranian IV (yellow)	South Africa		121.90 Mcts multi-faceted octahedron
Iranian V (cape)	South Africa		114.28 Mcts high old cushion
Ituiutaba	Brazil	105 Mcts	
Jacob	South Africa		184.5 Mcts oval
Formerly known as the Victoria, Imperial or Great White			
Jagersfontein	*See Winston*		
Jahan Akbar Shah	*See Akbar Shah*		
Jahangir	India		83.03 Mcts drop-shaped engraved
Jonker	South Africa	726 Mcts	125.65 Mcts largest and 11 others
Jubilee	South Africa	650.8 Mcts	245.35 Mcts brilliant
Julius Pam (yellow)	South Africa	248 cts	123 cts
Juscelino Kubitschak	Brazil	174 Mcts	
Khedive (light yellow)	?		36.61 Mcts rectangular emerald cut
Kimberley (champagne)	South Africa	490 Mcts	55.09 Mcts rectangular emerald cut
Kirti Noor (pink)	India		15 Mcts

Name	*Locality*	*Weight rough*	*Weight cut*
Koh-i-Noor or Koh-i-Nur	India	said to be 800 cts	191 Mcts recut to 108.93 Mcts oval brilliant
Kruger	South Africa	200 cts	
La Belle Helene	South Africa	160 Mcts	Two pears 30.38 Mcts and 29.71 Mcts and a marquise 10.5 Mcts
Lesotho B	Lesotho	527 Mcts	
Lesotho C	Lesotho	338 Mcts	
Lesotho Brown	Lesotho	601.25 Mcts	18 stones, largest 71.73 Mcts
Libertador or Liberator	Venezuela	155 cts	4 stones, 3 emerald cuts 39.80 Mcts 18.12 Mcts and 8.93 Mcts; a marquise 1.44 Mcts
Light of Peace	Sierra Leone	435 Mcts	130.27 Mcts pear
Litke	South Africa	205.5 cts	
Mahjal	*See Algeiba Star*		
Marie Antoinette Blue			5.46 Mcts heart
Maria	Russia	106 Mcts	
Matan or *Mattam*	Kalimantan	*Probably a quartz of 367 cts*	
McClean	?		31.26 Mcts cushion
Meister (yellow)	South Africa?		118.05 Mcts cushion
Minas Gerais	Brazil	172.5 Mcts	
Moon	South Africa?		183 Mcts round brilliant
Moon of Baroda (light yellow)	?		24 Mcts
Moon of the Mountains	India	*Legendary*	121 cts
Mountain of Splendor	India?		135 cts
Nassak	India		89.75 cts recut to 80.3 cts, then to 43.38 Mcts emerald cut
Nawanager	Russia?		148 Mcts
New Star of the South	Brazil	140 cts	
Niarchos	South Africa	426.50 Mcts	128.5 Mcts pear
Rough first called 'Ice Queen' or 'Pretoria'			
Nizam	India		277–340 cts (estimated) partially cut
Nooitgedacht	South Africa	325 Mcts	
Nur ul-Ain (pink)	India		60 Mcts (approx.) oval brilliant
May be part of the Great Table			
Oppenheimer (yellow)	South Africa	253.70 Mcts	
O'Reilly	South Africa	21.25 cts	
Orlov or Orloff	India	about 300 cts	189.6 Mcts rose above, flat, unfaceted below
Orpen-Palmer	South Africa	117.75 cts	

Name	*Locality*	*Weight rough*	*Weight cut*
Otto Borgstrom	South Africa	121.50 cts	
Pam	South Africa	115 Mcts	56.6 Mcts
Paragon	Brazil		137.82 Mcts kite
Pasha of Egypt	India		41.06 Mcts recut to 38.19 Mcts, then to 36.22 Mcts
Patos (brown)	Brazil	324 Mcts	
Patrocino	Brazil	120.375 Mcts	
Paul I (pink)	India		13.35 Mcts cushion
Paulo de Frontin	Brazil	49.5 Mcts	
Peace	India		12.25 Mcts heart
Penthièvre (yellow)	?		10 cts oval
Pigott or Pigot	India		48.63 Mcts
Said to have been destroyed			
Pitt	*See Regent diamond*		
Pohl	South Africa	287 Mcts	
Polar Star	India		41.285 Mcts cushion
Porter-Rhodes	South Africa	153.5 Mcts	56.60 Mcts emerald cut, recut to 54.99 Mcts
Portuguese	South Africa?		127.02 Mcts nearly octagonal emerald cut
Premier Rose	South Africa	353.9 Mcts	137.02 Mcts pear
President Dutra	Brazil	409 Mcts	36 stones
President Vargas	Brazil	726.6 Mcts	29 stones, largest 48.26 Mcts, recut to 44.17 Mcts emerald cut
'Punch' Jones	USA	34.46 cts	
Queen of Albania	India		49.03 Mcts
Queen of Holland (white, with blue tint)	India?		136.25 Mcts recut to 135.92 Mcts cushion
Raulconda	India		103 cts
Red Cross (yellow)	South Africa	370 cts approx.	205.07 Mcts square brilliant
Regent (white, with blue tinge)	India	410 cts	140.5 Mcts cushion
Regent of Portugal	Brazil	215 cts	
Reitz	*See Jubilee diamond*		
Rojtman (yellow)	South Africa		107.46 Mcts cushion
Sancy	India		55.23 Mcts pear-shaped double rose
The Sancy has been confused with a similarly shaped stone weighing 60.4 Mcts			
Saxon White	India		49.71 cts
Shah	India	95 cts	88.8 Mcts partially cut, engraved
Shah Jahan or Javeri	India		56.71 Mcts table cut
Sierra Leone II	Sierra Leone	115 Mcts	2 stones, 27.14 Mcts and 15.78 Mcts
Soleil D'Or (yellow)	?		105.54 Mcts emerald cut
Southern Cross	Brazil	118 cts	
Spaulding	*See Stewart diamond*		
Spoonmaker or Kasikci	India		86 Mcts rose-cut pear

Name	*Locality*	*Weight rough*	*Weight cut*
Stalingrad	Russia	166 Mcts	
Star of Africa	*See Cullinan*		
Star of Arkansas	USA	15.33 Mcts	8.27 Mcts marquise
Star of Denmark	South Africa	105 Mcts	34.29 Mcts
Star of Diamonds	South Africa		107.5 cts
This stone may be the Rojtmann diamond			
Star of Egypt	India		106.75 Mcts emerald cut
Star of Este	India		26.16 Mcts
Star of Minas	Brazil	179.30 Mcts	
Star of Sierra Leone	Sierra Leone	968.90 Mcts	17 stones, largest 53.96 Mcts
Star of South Africa	South Africa	83.50 Mcts	47.69 Mcts pear
Star of the South	Brazil	261.88 Mcts	128.8 Mcts, oval brilliant
Stewart (light yellow)	South Africa	296 Mcts	123 Mcts brilliant
Sunrise (yellow)	?		100.52 Mcts emerald cut
Tablet of Islam (black)	?		160.18 Mcts emerald cut
Tai Hang Star	South Africa	120 cts	60 cts
Taj-i-mah	India		115.06 Mcts Mogul cut
Taylor-Burton	*Largest stone cut from the Cartier (NY) (see Cartier)*		
Tennant	South Africa	112 cts	68 cts brilliant
Tereschenko (blue)	?		42.92 Mcts pear
Tiffany (yellow)	South Africa	287.42 Mcts	128.51 Mcts cushion
Tiger-eye (amber)	South Africa	178.5 cts	61.5 cts brilliant
Tiros I (brown)	Brazil	354 Mcts	
Tiros II (pink)	Brazil	198 Mcts	
Tiros III	Brazil	182 Mcts	
Tiros IV (brown)	Brazil	173 Mcts	
Unzue Heart (dark blue)	?		30.82 Mcts heart
Erroneously known as the 'Eugenie Blue'			
Vainer Briolette (yellow)	Southern Africa	202.85 Mcts	116.6 Mcts briolette
Van Zyl	South Africa	229.25 cts	
Vargas	*See President Vargas*		
Venter	South Africa	511 cts	
Victoria	*See Jacob*		
Victory	*See Woyie River diamond*		
Vitoria	Brazil	328.34 Mcts	44 stones, largest 30.39 Mcts
Webster kopje	South Africa	124 cts	
Williamson (pink)	Tanzania	54.5 Mcts	23.60 Mcts brilliant
Windsorten	South Africa	104 Mcts	
Winston	South Africa	154.50 Mcts	62.05 Mcts pear
Wittlesbach (blue)	India		35.50 Mcts oval brilliant
Woyie River	Sierra Leone	770 Mcts	30 stones, largest 31.35 Mcts emerald cut

The following large cut diamonds are unnamed:

(brown)	South Africa	755.5 Mcts	545.67 Mcts fire-rose cushion
The largest cut diamond in the world			

Name	*Locality*	*Weight rough*	*Weight cut*
(yellow)	?		200.87 Mcts pear
(yellow)	?		180.95 Mcts briolette
(yellow)	?		150 M?cts emerald cut
—	?		141.23 Mcts pear
—	?		118 ct
(yellow)	India		114.28 Mcts briolette
(yellow)	South Africa?		114.03 Mcts cushion
(white)	?		111.82 Mcts heart
(yellow)	?		108.04 Mcts emerald cut
(brown)	?		107.10 Mcts cushion
(white)	?		106.00 Mcts modified pear
(yellow, treated)	?		104.52 Mcts cushion
—	?		102.65 Mcts antique round
—	?		102.61 Mcts cushion
(light brown)	?		102.42 Mcts pear
(white)	?		101.84 Mcts pear
—	India		101.25 Mcts
(yellow)	?		101.25 Mcts briolette
(white)	?		101.14 Mcts kite

Mcts: metric carats cts: old carats

Bibliography

The literature of gemstones is surprisingly large and had never been subjected to scholarly bibliographical techniques until the publication of *Gemology. An Annotated Bibliography,* by John Sinkankas. This two-volume work was published by Scarecrow Press, Metuchen, New Jersey in 1993 and gives full and scholarly details of all gemstone-related books largely but no means exclusively in English, irrespective of date of publication. Many important title-pages are reproduced. In this bibliography the writer has attempted to show something of the development of gemstone study, ranging from early classics to modern scientific books on gem identification. As with any scientific study the bulk of the useful published literature is found in papers in journals rather than in monographs, but considerations of space and the necessity for wholesale citation if this material were to be included have restricted coverage here to separate works.

Literature Guides

O'Donoghue, M (1986) *The Literature of Gemstones.* The British Library. Modern bibliography with comments on many items, based on the resources of the British Library.

Gill, J (1978) *Gill's Index to Journals, Articles and Books Relating to Gems and Jewelry.* GIA, Santa Monica. The only extant guide to some at least of the periodical literature.

Sinkankas, J (1976) *Gemstones of North America.* Van Nostrand Reinhold, Princeton. The largest and best area bibliography with considerable material of general gemmological interest. The bibliography is in the second volume.

O'Donoghue, M (1988) *Gemstones.* Chapman and Hall, London. Large bibliography containing many older items.

O'Donoghue, M (1986) *The Literature of Mineralogy.* The British Library. Includes much detail of use to the scientific gemmologist with coverage of abstracting services, maps and dictionaries. Based on the resources of the British Library.

Abstracts

The only way to find out what papers have been published in serious scientific journals is to use hard copy or on-line abstracting services. The best hard copy is *Mineralogical Abstracts*, published by the Mineralogical Society of London from 1922 (covering from 1920). This is now available on-line via the GeoRef host and includes notices of monographs; it covers all major Western languages. Russian and Slavonic material is found in *Referativnyi Zhurnal. Geologiia*, from 1956. This deals with earth science as a whole; it is not translated and is hard to use. Readers should consult curatorial staff in very large libraries and museums, the only places where this item can be found.

General Earth Science Literature Overview

Anyone beginning a serious academic study of any branch of the earth sciences should be able to find his way round the general literature. The only current guide is the following:

Wood, D, Hardy, J and Harvey, A (eds) (1989) *Information Sources in the Earth Sciences.* Butterworths, London. Includes critical descriptions of bibliographies, indexes and abstracts by M O'Donoghue and of earth science databases by D McKay and M O'Donoghue.

Major Mineralogical Works

Gemmologists will inevitably need to refer to standard mineralogical texts (see O'Donoghue, 1986, under 'Literature Guides'). Some of the more important are listed below; though some date back many years they are still alive even when volumes appear only at very long intervals. Those engaged in gemstone taxonomy (classification and naming) will particularly need to consult mineralogical sources.

The standard detailed classification of minerals is:

Dana, J (1944–) *The System of Mineralogy.* 7th edn. Wiley, New York. Currently edited by C Palache and others. Lacks the silicate group, for which the 6th edition (1892, supplement 1899) or other works should be consulted.

A complementary work, also still in progress, is:

Hintze, C (1899–) *Handbuch der Mineralogie* (1889–1971) with *Ergänzungsbande und Register.* Revised by Karl Chuboda. Von Veit, Leipzig (and other publishers). An enormous work, by far the finest for locality information even today. Currently extending to 11 volumes in all.

As mineral science proceeds, many species are found to belong to groups. These, with details of chemical composition, crystal system and in some instances colour, can be found conveniently in the various editions of:

Fleischer, M and Mandarino, J (1991) *Glossary of Mineral Species.* The Mineralogical Record Inc., Tucson. Updated about every five years in monograph and from time to time in *Mineralogical Record.*

General Comprehensive Works

Arem, J (1987) *Color Encyclopedia of Gemstones.* Van Nostrand Reinhold, New York. Alphabetical listing of a very large number of species with accurate scientific comment and the best colour photographs of any extant book on gemstones. First published in 1977.

Cavenago-Bignami, S (1980) *Gemmologia* (in Italian). 4th edn. 3 vols. Hoepli, Milan.

O'Donoghue, M (1988) *Gemstones.* Chapman and Hall, London. A survey of a wide range of gem species from the point of view of the geologist and mineralogist with considerable topical detail appropriate to these disciplines.

Smith, G F (1972) *Gemstones.* Chapman and Hall, London. First published in 1912, this last (14th) edition was revised by F C Phillips.

In all studies dealing with the natural world, taxonomy (classification and naming) is a continuing duty, and for this reason older surveys which were comprehensive for their time should still be kept to hand. The best of these is:

Bauer, M (1895–6: 1969) *Precious Stones.* Latest reprint. Tuttle, Rutland, Vermont. English translation by L J Spencer of *Edelsteinkunde,* originally published in parts. The Tuttle reprint has some additional comment. A Dover Press reprint was published in 1968.

Gem Testing

Anderson, B (1990) *Gem Testing.* 10th edn, revised by E A Jobbins. Butterworth, London. First published 1942 as *Gem Testing for Jewellers,* a title which still accurately describes its coverage. Written in essay form; tables somewhat sketchy.

Liddicoat, R (1987–8) *Handbook of Gem Identification.* 12th edn. GIA, Santa Monica. Covers the same ground as Anderson (above) but with less theory and less introduction to important areas of discussion.

Schlossmacher, K (1969) *Edelsteine und Perlen.* 5 Aufl. Schweizerbart'sche, Stuttgart. The standard German textbook on gem testing until the 1970s. Illustrations poor by modern standards.

Poirot, J-P (1976) *Elements de gemmologie.* Institut National de Gemmologie, Paris. Issued in 2 loose-leaf volumes. Good provision of tables and diagrams.

Smirnov, V (1973) *Dragotsennye i tsvetnye kamni poleznoe iskopaemoe.* Nauka, Moscow. A general gem testing work in Russian.

Conference Proceedings

Proceedings of the First International Gemological Symposium, 1982. GIA, Santa Monica.

Proceedings of the Second International Gemological Symposium, 1991. GIA, Santa Monica.

These proceedings are of limited value. Little new information was presented.

Gemstone Occurrence and Mineralogy

Bancroft, P (1984) *Gem and Crystal Treasures.* Western Enterprises and Mineralogical Record, Fallbrook, CA. Superbly illustrated and accurate survey of major gem and mineral occurrences world-wide.

Kivienko, E (1980) *Prospecting and Evaluation of Deposits of Precious and Economic Stones* (in Russian). Nedra, Moscow.

Scalisi, P and Cook, D (1983) *Classic Mineral Localities of the World: Asia and Australia.* Van Nostrand Reinhold, New York. Includes useful information, otherwise hard to find, on older gemstone deposits. Welcome reprints of crystal diagrams from Goldschmidt (see under 'Crystals').

Keller, P (1990) *Gemstones and their Origins.* Van Nostrand Reinhold, New York. One of the first attempts to place gemstones in their geological context. Very well illustrated.

Crystals

The study of crystals is important for the gemstone prospector and for the student. The all-time most comprehensive survey is still:

Goldschmidt, V (1916–23) *Atlas der Krystallformen.* Carl Winters Universitätsbuchhandlung, Heidelberg. 9 vols. Partly text and diagrams, the latter drawn from journals up to the dates of publication. More than one reprint has been issued in recent years.

Phillips, F (1971) *An Introduction to Crystallography.* 4th edn. Oliver and Boyd, Edinburgh. As lucid as this rather complex topic can be made.

Colour

Nassau, K (1983) *The Physics and Chemistry of Color.* Wiley, New York. Admirably lucid.

Nassau, K (1985) *Gemstone Enhancement.* Butterworths, London. Gemstone colour alteration is the serious topic of the late twentieth century: this treatment is by far the best introduction to this vexed question.

Inclusions

Koivula, J and Gübelin, E (1992) *Photoatlas of Inclusions in Gemstones.* 2nd edn of a work first published in 1986. ABC Edition, Zurich. Gübelin and later Koivula have made the study of inclusions their own. Gübelin's first book, *Inclusions as a Means of Gemstone Identification,* was published by the GIA in 1953 and was followed in 1979 by the 2nd edition of *Internal World of Gemstones.* The current joint work has contributions by Meyer, Roedder, and Stalder on diamond inclusions and genesis, fluid inclusions, and quartz inclusions, respectively.

Chikayama, A (1973) *Gem Identification by the Inclusions.* Tokyo. English title of *Inkūrujon ni yoru hō seki no kanbetsu: kenbikyō shasin to sono nanbetsuhō. Illustrated entirely in colour with English headings only.* (In Japanese.)

Gem Testing Instruments

Read, P (1983) *Gemmological Instruments.* 2nd edn. Butterworths, London. The only guide in English from one of the pioneers in the field.

Quick Reference Publications and Tables

Webster, R (1937–) *The Gemmologist's Compendium.* Various editions. NAG Press, London. First published in 1937 as *Gemmologist's Pocket Compendium.* The current title, revised by E A Jobbins, is published regularly but is closer to a reissue than a thoroughgoing revision.

Read, P (1988) *Dictionary of Gemmology.* 2nd edn. Butterworths, London. Reference source for principal gem materials, gemmological terms and test instruments.

Sinkankas, J (1972) *Gemstone and Mineral Data Book.* Winchester Press, New York. Later reissued as *Field Collecting Gemstones and Minerals.* The only place to find numerical data, conservation details and much more.

Gunther, B (1981) *Bestimmungstabellen für Edelsteine, synthetische Steine, Imitationen.* Lenzen, Kirschweiler. Virtually in German and English and set out in tabular form.

Textbooks

Webster, R (1966) *Practical Gemmology.* 4th edn. NAG Press, London. A now dated attempt to teach gemmology but too heavily didactic at the expense of lucid presentation. Readers are advised to study Read (see below).

Read, P (1991) *Gemmology.* Butterworth Heinemann, Oxford. The only topical text of gemmology at student level, with specimens of examination questions. Update of *Beginner's Guide to Gemmology* (1980).

Hurlbut, C and Kammerling, R *Gemology.* 2nd edn. Wiley, New York. Covers gemmology for students. Previous edition was by Hurlbut and Switzer (1979).

Synthetic and Imitation Stones

Arem, J (1973) *Man-Made Crystals.* Smithsonian Institution Press, Washington DC. Excellent and well-illustrated account of crystal growth with many gem examples.

Nassau, K (1980) *Gems Made by Man.* Chilton, Radnor, PA. Unrivalled account of the history and current growth techniques used to manufacture gemstones.

O'Donoghue, M (1983) *Identifying Man-Made Gemstones.* NAG Press, London. The standard guide to testing synthetic and imitation gemstones with notes (for 1983) on the alteration of colour. US edition has the title *A Guide to Man-Made Gemstones.*

O'Donoghue, M (1976) *Synthetic Gem Materials.* Worshipful Company of Goldsmiths, London. A literature survey with citations from scientific as well as gemmological literature.

Balitskii, V and Lisitsyna, E (1981) *Sinteticheskie analogi i imitatsii pririodykh dragotsennykh kamnei* (in Russian). Nedra, Moscow.

Michel, H (1926) *Die kunstlichen Edelsteine.* Leipzig. Very useful account of early gemstone manufacturing methods.

Macinnes, D (1973) *Synthetic Gem and Allied Crystal Manufacture.* Noyes Data Corporation, Park Ridge, NJ. Reproduces patents which are otherwise hard to locate.

Yaverbaum, L (1980) *Synthetic Gems Production.* Noyes Data Corporation, Park Ridge, NJ. Updates Macinnes (see above).

Fashioning

Sinkankas, J (1985) *Gem Cutting.* Van Nostrand Reinhold, New York. The best book on the subject.

Watermeyer, B (1980) *Diamond Cutting.* Purnell, Cape Town. Good and exhaustive account.

Pricing

Sinkankas, J (1968) *Van Nostrand's Standard Catalog of Gems.* Van Nostrand Reinhold, New York. Later issues have a supplementary page updating the text but prices are now out of date; the criteria by which they are reached remain the same, however, and there is a good deal of additional material.

Gemstones of Particular Localities

North and Central America

Sinkankas, J (1959, 1976) *Gemstones of North America.* Van Nostrand Reinhold, New York. The 1976 volume is additional to the first and partly updates it. Central American locations are included. Outstanding bibliography in the 1976 text.

Myanmar

Iyer, L (1953) *The Geology and Gem-Stones of the Mogok Stone Tract, Burma.* Geological Survey of India, Calcutta. Forms vol. 82 of *Memoirs of the Geological Survey of India.*

Sri Lanka

Gübelin, E (1968) *Die Edelsteine der Insel Ceylon.* Published by author. Luzern.

Pakistan

Kazmi, A and O'Donoghue, M (1990) *Gemstones of Pakistan: Geology and Gemmology.* Gemstone Corporation of Pakistan, Peshawar. The first geological/gemmological survey of a single country with fine colour photographs.

Australia

Chalmers, R (1967) *Australian Rocks, Minerals and Gemstones.* Angus and Robertson, Sydney.

Brazil

Sauer, J (1982) *Brazil, Paradise of Gemstones.* Rough gem crystals beautifully illustrated in colour.

Asia and Australia

See entry for Scalisi and Cook under 'Gemstone Occurrence and Mineralogy'.

Africa

Keller, P (1992) *Gemstones of East Africa.* GIA, Santa Monica.

Individual Gem Species

Diamond

Bruton, E (1978) *Diamonds.* 2nd edn. NAG Press, London. An adequate survey, useful for beginners and students.

Copeland, L (1960–) *The Diamond Dictionary.* Various edns. GIA, Santa Monica.

Liddicoat, R (1992) *The GIA Diamond Dictionary.* GIA, Santa Monica.

Orlov, Y (1977) *The Mineralogy of the Diamond.* Wiley, New York. Translation of *Mineralogiia alamaza,* Moscow, 1973. Invaluable for its discussion of diamond crystals and of the diamond deposits of the former USSR.

Balfour, I (1992) *Famous Diamonds.* 2nd edn. NAG Press, Colchester. The best up-to-date account of named diamonds, their description and whereabouts.

Wilks, J and Wilks, E (1991) *Properties and Applications of Diamond.* Butterworth-Heinemann, Oxford. The best scientific survey currently in print.

Williams, A (1932) *The Genesis of the Diamond.* Benn, London. 2 vols.

Williams, G (1906) *The Diamond Mines of South Africa.* Buck, New York. First published in 1902. 2 vols. Alpheus F and Gardner F Williams were related, and their two books are the finest study of diamond occurrence and mining extant.

Lenzen, G (1970) *The History of Diamond Production and the Diamond Trade.* Barrie and Jenkins, London. Translation of *Produktions- und Handelsgeschichte des Diamanten.*

Lenzen, G (1983) *Diamonds and Diamond Grading.* Butterworths, London. Translation of *Diamantenkunde,* 1979.

Pagel-Thiessen, V (1973–) *Handbook of Diamond Grading.* Various edns. Frankfurt. Well illustrated.

Bobrievich, A (1957) *Almazy sibiri.* Gosgeoltekhizdat, Moscow.

Bobrievich, A (1959) *Almaznye mestorozh deniya Yakutii.* Gosgeoltekhizdat, Moscow. Two authoritative accounts of the Siberian diamond deposits.

Freire de Andrade, C (1953) *Diamond Deposits in Luanda.* Companhia de Diamantes de Angola, Lisbon. 2 parts.

Beryl

Sinkankas, J (1981) *Emerald and Other Beryls.* Chilton, Radnor, PA. Contains an exhaustive

bibliography. A shorter version edited by Read is published by Butterworth. Likely to remain the standard work on beryl for many years.

Vlasov, K and Kutukova, E (1960) *Izumrudnye kopi.* Akademiya Nauk SSSR, Moscow.

Kazmi, A and Snee, L (eds) (1989) *Emeralds of Pakistan: Geology and Genesis.* Geological Survey of Pakistan and Van Nostrand Reinhold, New York. Multi-author coverage in depth and a model of what such a study should be. Each section has its own bibliography.

Jade Minerals

Keverne, R (ed.) (1991) *Jade.* Anness, London. A multi-author coverage of the jade minerals and of the artefacts made from them.

Hansford, S (1968) *Chinese Carved Jades.* Faber, London. Originally published as *Chinese Jade Carving*, 1950. The best scholarly study with a good bibliography.

Nott, S (1936) *Chinese Jade throughout the Ages.* Batsford, London. Reprinted by Tuttle, Rutland, Vermont, 1962. A comprehensive study and good for the time.

Leaming, S (1978) *Jade in Canada.* Geological Survey of Canada, Ottawa. Papers of the Geological Survey of Canada, no. 78-19. A good geological/mineralogical study. Coverage is not confined to Canada.

Bulletin of the Friends of Jade. 5004 Ensign St, San Diego, California 92117, USA. Occasional series with good quality papers.

Turquoise

Pogue, J (1915) *The Turquoise.* National Academy of Sciences, Washington DC. *Memoirs of the National Academy of Sciences*, vol. 12, part 2. The best coverage with considerable detail on artefacts. A reissue with a memoir of Pogue was published by Rio Grande Press, Glorieta, New Mexico in 1973.

Menchinskaya, T (1981) *Biryuza* (in Russian). Nedra, Moscow. Very extensive bibliography and authoritative text.

Quartz

O'Donoghue, M (1987) *Quartz.* Butterworths, London. An up-to-date scientific study with an extensive bibliography.

Dake, H (1938) *Quartz Family Minerals.* Whittlesey House, New York. A shorter study than the above but still useful.

Liesegang, R (1915) *Die Achate.* Dresden. Despite its age, the best treatment of agate dyeing.

Opal

Kalokerinos, A (1971) *Australian Precious Opal.* Nelson, Melbourne. Very fine colour photographs and original ideas on varietal nomenclature.

Eyles, W (1964) *The Book of Opals.* Tuttle, Rutland, Vermont. The best coverage of opal finds in the USA.

Leechman, G (1978) *The Opal Book.* Ure Smith, Sydney. Excellent overall coverage. Reprint of 1961 original.

Gunn, J (1971) *An Opal Terminology.* University of Sydney Australian Language Research Centre, Sydney. Occasional paper no. 15.

Wollaston, T (1924) *Opal, the Gem of the Never-Never.* Murby, London. Excellent for the early days of Australian opal.

Cody, A (1991) *Australian Precious Opal: a Guide Book for Professionals.* Andrew Cody, Melbourne. One of the best short studies.

Cram, L (1991) *Beautiful Queensland Opal.* Robert Brown, Buranda, Queensland. The best book on Queensland opal with a short history of the fields.

Garnet

Rouse, J (1986) *Garnet.* Butterworths, London. Surprisingly the only monographic study of the garnet group in English.

Tourmaline

Kuz'min, V (1979) *Turmalin* (in Russian). Nedra, Moscow. Includes a 300-entry bibliography.

Benesch, F (1991) *Der Turmalin: eine Monographie.* 2 durchgesehene und verbesserte Aufl. Urachhaus, Stuttgart. An extremely large-format book with superb colour photographs and paintings. Fine coverage of geochemistry, paragenesis and also of the place of tourmaline in religious literature.

Dietrich, R (1985) *The Tourmaline Group.* Van Nostrand Reinhold, New York. The only major study in English and of a high standard.

Corundum

Hughes, R (1990) *Corundum.* Butterworths, London. The best and almost the only modern coverage of this major species.

Mumme, I (1988) *The World of Sapphire.* Mumme, Port Hacking, NSW. A good and the only coverage of sapphire in English at the time of writing.

Pearl

Kunz, G and Stevenson, C (1908) *The Book of the Pearl.* Macmillan, London. Very large comprehensive study which is still valuable.

Farn, A (1986) *Pearls: Natural, Cultured and Imitation.* Butterworths, London.

Strack, E (1982) *Perlenfibel.* Rühle-Diebener, Stuttgart.

Amber

Fraquet, H (1987) *Amber.* Butterworths, London.

Rice, P (1974) *Amber, the Golden Gem of the Ages.* Van Nostrand Reinhold, New York.

Schlee, D (1980) *Bernstein-Raritäten.* Staatliche Museum für Naturkunde, Stuttgart. Very fine coloured photographs of inclusions in amber.

Larsson, S (1978) *Baltic Amber: a Paleobiological Study.* Scandinavian Science Press, Klampenberg. Entomonograph no. 1.

Jet

Muller, H (1987) *Jet.* Butterworths, London.

Crystal Growth

Gemmologists need to know something of this complex and often unpredictable process. The best modern guide is:

Brice, J (1986) *Crystal Growth Processes.* Blackie, Glasgow. Up-to-date coverage of all commercial and experimental growth methods.

A guide to the literature (which is often hard to find) including conference papers is:

O'Donoghue, M (1988) *Crystal Growth: a Guide to the Literature.* The British Library. Many accounts of the growth of crystals are concealed in conference proceedings, which are set out here, as well as monographs and journals in all languages.

Journals

Association Journals

All students of gemmology should subscribe to at least one of the official journals (i.e. the organ of a major gemmological association). The following is a selection (published quarterly unless indicated otherwise):

Journal of Gemmology. Gemmological Association and Gem Testing Laboratory of Great Britain. 27 Greville St, London, EC1N 8SU, UK. Scientific papers of a high standard; very comprehensive coverage of abstracts and reviews in all languages.

Gems and Gemology. Gemological Institute of America. 1660 Stewart St, Santa Monica, California 90404, USA. Illustrated entirely in colour; valuable country surveys and notes from GIA gem testing laboratories.

Australian Gemmologist. Gemmological Association of Australia. PO Box 35, South Yarra, Victoria, Australia. Particularly valuable for studies of organic materials and for Gemmology Study Club reports on a very wide variety of materials. (*Wahroongai News,* the organ of the Queensland branch of the GAA, has a very wide informal coverage and is well worth consulting. PO Box 7184, East Brisbane, Queensland, Australia.)

Zeitschrift der Deutschen Gemmologischen Gesellschaft. Deutsche Gemmologische Gesellschaft, Postfach 122260, D-55743 Idar-Oberstein, Germany. Papers of high scientific standard. Irregular.

Revue de Gemmologie. Association Française de Gemmologie, 14 rue Cadet, Paris 75009, France. Emphasis on French jewellery history.

La gemmologia. Istituto Gemmologico Italiano, Viale Gramsci 228, 20099 Sesto S. Giovanni, Milan, Italy. High-quality papers with English abstracts.

Boletin del Instituto Gemológico Español. Instituto Gemológico Español, Victor Hugo 1,3°, 28004 Madrid, Spain. Irregular.

Current Awareness Journals

Gemmologie Aktuell. Published several times a year and reproduced from typewriting. Covers new species, man-made substances etc. Address as for *Zeitschrift* above.

Gemmological Newsletter. Michael O'Donoghue, 7 Hillingdon Avenue, Sevenoaks, Kent, TN13 3RB, UK. During the academic year 30 issues are published covering all aspects of gemstones including book reviews and current developments in the wider earth science world which may be relevant to gemmology.

Synthetic Crystals Newsletter. Michael O'Donoghue, address above. News of all kinds of crystal growth developments, many of them of gemmological interest. Twelve issues during the academic year.

ICA Gazette. International Colored Gemstone Association. ICA, 609 Fifth Avenue, New York, NY 10017, USA. Bimonthly.

Popular and Trade Journals

Lapidary Journal. PO Box 80937, San Diego, California 92138–0937, USA. A monthly survey with many trade advertisements and with particular reference to amateur collecting and cutting. The best of its kind.

Retail Jeweller. 2nd floor, Scriptor Court, 155 Farringdon Rd, London EC1R 3AD. Newspaper format coverage of British jewellery trade, with 25 issues a year. Excellent trade news, unremarkable gem news.

Jewelers' Circular-Keystone. Chilton Company, Chilton Way, Radnor, Pennsylvania 19089, USA. Very good trade and gemstone coverage. Monthly.

Mineralogical Journals

Mineralogical Record. PO Box 35565, Tucson, Arizona 85740, USA. Superb coverage of the

mineral world with fully illustrated papers (many of gem interest) successfully bridging the gap between educated amateur and professional.

Mineralogical Abstracts. Mineralogical Society, 41 Queen's Gate, London SW7 5HR, UK. Quarterly. World-wide coverage of all earth science journals with mineral (including gem) content. Also available on-line.

Map

World Map of Gemstone Deposits. Swiss Gemmological Society and Kummerly and Frey, Bern, Switzerland. In colour.

Jewellery History

Jewellery Studies. Society of Jewellery Historians, c/o Dept of Prehistoric and Romano–British Antiquities, The British Museum, London WC1B 3DG, UK. An occasional journal with papers of a high scholarly standard. Appears irregularly.

Jewellery Pricing

This often vexed topic can be studied conveniently by subscribing to or at least consulting the major saleroom catalogues. These have descriptions of the lots with notes of major stones (Myanmar) rubies and Kashmir sapphires often have certificates of origin) and notes of estimates (before sale) of price for all but the most important and debatable items. In catalogues of the major houses the lots are illustrated in colour and thus form an invaluable record of fashion and of important stones. Long runs of the best sale catalogues are valuable, but they should be completed by notes on the prices actually paid (and of where items are withdrawn for one reason or another). The major catalogues are those of:

Christie's, 8 King St, London SW1Y 6QT, UK
Sotheby's, 34–35 New Bond St, London W1A 2AA, UK.

Both houses hold sales in their home country, in the USA and in major European cities, particularly in Switzerland where the most prestigious sales are held.

Indexes

Name Index

Subject Index

Since it was first published in 1962, *Gems: Their Sources, Descriptions and Identification*, written by Robert Webster and revised in its fourth edition by Basil Anderson, has become universally recognised as the most comprehensive and authoritative treatise on gem materials in the English language. In this fifth edition, edited by Peter Read, the forty chapters, appendices and tables have been revised by fifteen gemmologists chosen for their expertise in the relevant sections.

The new edition includes additional gem minerals, new gem sources and the most recently introduced gem test equipment and techniques. In addition to extensive revisions, several chapters have been completely rewritten and opal, formerly included with gems of the silica group, is now covered in a separate chapter. The book includes many new illustrations.

Still primarily aimed at the professional jeweller and student gemmologist, *Gems* also caters for the collector of gems and the layperson who is interested in precious stones.

Extracts from reviews:

...Mr Anderson's revised edition of the Webster book ensures its continuation as an excellent work of reference, the epitome of gemmological information.
Retail Jeweller

There is no doubt that the fourth edition of *Gems* will retain its place as the most comprehensive textbook of gemmology currently published. It is a welcome addition.
The Australian Gemmologist

Any serious gemmologist should have a copy available for ready reference.
Gems and Gemmology

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