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and

PROCEEDINGS OF THE
GEMMOLOGICAL
ASSOCIATION
OF GREAT BRITAIN

THE GEMMOLOGICAL ASSOCIATION
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Vol. II, No. 6 APRIL 1950

HARDNESS TESTS

by

M. D. S. LEWIS, A.R.C.S., B.Sc., F.G.A., C.G.

ALTHOUGH hardness tests are not employed where other means of identification are available, the subject remains of interest as hardness is one of the principal factors to be considered in assessing the durability of a stone. There may also be rare occasions where optical examination is not feasible and an unusual diamond might be quickly identified by ability to scratch corundum. Since stones are set with steel instruments a paste is often indicated where scratch marks are visible on the setting edge.

From the theoretical aspect hardness is not a simple subject and is difficult to define or assess quantitatively. One cannot measure absolute hardness like temperature ; it depends on the test employed. When two substances are pressed together it is usually the softer one which gives way ; its atoms are more easily separated and in general hardness is considered as a measure of resistance to separation of the atoms under pressure. Obviously, then, the hard substances must have very strong interior binding forces.

The attraction between two oppositely charged bodies depends both on the magnitude of the charges and the distance between them, and is greatest when the former are big and the latter small. Thus the loosely packed bivalent barium oxide is about as hard as closely packed monovalent lithium fluoride. A substance, therefore, can only be hard if its constituent ions are highly charged (tri- or quadrivalent) and at the same time small (and hence light), so that when in contact with each other the distance between their centres of gravity is a minimum. These two requirements narrow down the choice of elements to very few: carbon, silicon, aluminium, boron, etc. In crystals, simplicity of composition is also called for, since where there are more than two elements, the variations in ionic size tend to make the structure less compact, increasing interionic distances and so decreasing hardness.

Atoms tend to become separated by heat. Through increasing thermal agitation the ions move further away from each other and the force of attraction between them decreases. Eventually they part company and the substance melts. Strong interionic binding forces oppose this process and for the same reason most hard substances have high melting points.

A closer examination of hardness(1) shows that it may embrace many properties, some very closely related to each other, e.g., resistance to abrasion, resistance to scratching, ability to cut other materials, resistance to plastic deformation, high modulus of elasticity, high yield point, high strength, absence of elastic damping, brittleness, cleavage, lack of ductility and malleability, chemical inertness, etc.

Any one test will, in general, call into action only some of these factors and the " hardness value " arrived at is the integrated effect of just those particular factors. Another type of test may involve quite a different set and thus give another result. Roughly speaking, however, hardness phenomena may be resolved into two main classes exhibiting deformation and fracture respectively.

There are at least three types of deformation: immediately reversible (springy metals), permanent (many plastic materials) and an intermediate variety which develops slowly and is ultimately recovered. All three may be present in the same experiment. In

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(1) " Strength of Plastics and Glass," by R. N. Haward.

tests to measure " fracture hardness " the surface is broken when the stresses set up exceed the breaking stress of the material *under the conditions of the test.* If the point of loading is moved the rupture becomes a scratch.

It is impossible to mention more than a few of the numerous tests employed for assessing hardness and, as already indicated, they do not give uniform results. Quartz(2), by the indentation or scratch tests, is much harder than brass, but softer according to abrasion tests. Some plastics would appear to be harder than mild steel under a rebound test.

A ball may be dropped on the material under test and the indentation measured. Alternatively, the height of rebound may be observed ; obviously a ball dropped on soft lead will deform the metal and thereby lose much of its energy, whereas the rebound will be higher from a hard elastic surface which does not suffer permanent deformation or indentation in the process. A hard pointed substance (e.g. a diamond pyramid) may be pressed on the substance and the penetration measured. Deformation tests are primarily suitable for metals, a characteristic of which is the ease with which the atoms glide over each other (malleability). It is interesting to note that the metals of highest symmetry—copper, gold, silver, etc.—are soft and malleable owing to the larger number of planes of symmetry on which gliding may take place. Conversely, metals of lower symmetry—chromium, vanadium, molybdenum, etc.—are hard and brittle. The introduction of foreign atoms in alloys disturbs regularity of arrangement, impedes gliding, and for this reason impurities generally cause hardness. The supreme position occupied by iron among the metals is due to its ability, through heat treatment, to adopt either a symmetrical soft form, or a harder variety, consequent upon lower symmetry. Since deformation occurs within the material under test, chemical influences play no part, but in some cases cleavage effects might be noticed. The usual gemmological minerals are, however, not easily deformed because their atomic structure is so different from that of metals, and deformation tests of this type are less suitable for them. Massive glass (as distinct from thin sheets or fibres) exhibits elastic deformation, but irreversible deformations are almost impossible to

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(2) " Industrial Diamond Review," December, 1949, W. V. Engelhardt, p. 369.

measure at ordinary temperatures and the same probably applies to most ordinary gemstones.

Another test for hardness depends on abrasion resistance, the loss of volume being measured after grinding. Since diamond cannot be scratched by any other material, this is the only feasible test for measuring its variations in hardness with crystallographic direction. Here again absolute hardness cannot be assessed, comparative values only being obtainable, because the amount abraded depends on the lubricant used. The chemical forces at play between abrasive, sample and lubricant largely determine the amount of attrition. In this process the polishing grains remove small particles of material, not by simple pressure as would be involved, say, by snapping off a protuberance, but rather by causing a series of fractures in different directions. F. W. Preston has found([3]) that when glass is ground, the abrasive grain causes stresses in the brittle material which eventually lead to fractures running partly in the direction of and partly crosswise to the movement. When these intersect chips are broken out and the loose material comes away. There is reason to believe that quartz and other crystalline materials behave similarly, and this illustrates the difficulty of defining hardness, because the fundamental process here seems to be the reduction of the sample to powder. Yet this same result is also easily obtained merely by hammering in the case of crystals with suitable cleavage. According to P. Grodzinski([4]), 5 carats of diamond can be reduced to powder by repeated hammering (hand operated hammer) in a mortar within 30 minutes. If hardness were solely defined as " resistance to separation of atoms " the hardness of jadeite might exceed that of diamond if assessed in this manner.

In the scratch tests, a sharply pointed substance, usually diamond, is moved under constant load and speed over the various surfaces and the amount of material removed or depth of penetration measured. The crudest scratch test is, of course, that of Mohs' and strictly speaking this should only be performed between dissimilar substances, otherwise chemical forces can give quite anomalous results. Practically all ordinary glasses will scratch each other—whether they be hard or soft—and it will no doubt occasion

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(3) " Industrial Diamond Review," December, 1949, W. V. Engelhardt, p. 367.

(4) " Industrial Diamond Review," January, 1950, p. 24.

some surprise that glass will often scratch gemstones of greatly superior " hardness." If an ordinary solid glass rod (hardness about $5\frac{1}{2}$ and easily marked with a steel file) be rubbed hard against a polished quartz, beryl, tourmaline or other gemstones of hardness about 7, a definite scratch is left on the stone. Harder gems, such as topaz, are less easily marked. This is due to similarity of structure ; when two substances of similar constitution (in this case silicates) are brought into sufficiently close contact with each other they weld together, and if fractured the break does not necessarily take place at the original join. Of course, any substance may wear away another much harder one by continued friction. Some stone steps are worn away by leather shoes or even bare feet, and who has not heard of the bronze foot of St. Peter's statue in Rome which has partly vanished merely through the touch of millions of lips? This phenomenon, however, is somewhat different, as a hard steel file merely slides off a polished quartz, whereas the softer glass rod " bites " on the surface with quite a different feel and sound.

In the study of gemmology the approach to hardness is usually via Mohs' test, which, although derided from a purely practical point of view, still remains a background against which the property is judged. It is still held to be theoretically sound, even if not prudent, to employ on account of possible damage to a costly stone. When topaz is stated to be harder than quartz, a subconscious picture probably forms of a pencil-like piece of topaz being drawn across the surface of the softer material, leaving a satisfactory scratch. Actually, this view is valid only under very limited conditions. Mohs' test does not solve the hardness problem ; it merely assesses resistance to fracture using *suitably shaped instruments.* If a cut topaz were pressed hard against a quartz it is quite possible that the thin girdle or culet might chip owing to cleavage and the hard stone thus suffer more " abrasion " than the softer one. When a hardness value is stated, the conditions of the test should be specified. The fact that a pencil-shaped piece of topaz produces a scratch on quartz does not automatically guarantee that topaz will suffer less abrasion than quartz under another process—say, perhaps, on a grinding wheel. In many questions of gemmological hardness, cleavage is a factor never far in the background. This makes a definition even more difficult than is the case with other materials. The best is probably that of R. N. Haward(1), which states that it is " the capacity of a surface of the material in question to remain unaltered in shape when subject to relatively concentrated mechanical forces which do not break the specimen as a whole."

The durability of a stone depends mainly on abrasion resistance, freedom from cleavage, chemical inertness and texture. A porous substance gives a lower hardness value than a compact one, whilst gaseous or liquid inclusions may impair the stability of a stone. Some American gemmologists integrate all these factors into the property of " toughness," and Briggs' " Encyclopaedia of Gems " contains a comparative table, headed by diamond, followed by cassiterite, jadeite, ruby, etc. Topaz, in spite of its hardness, is well down the list, below quartz, due, no doubt, to its easy cleavage.

IMPROVEMENTS in the PRODUCTION of SYNTHETIC QUARTZ

(continued from page 227)

thick-walled steel chamber by a supporting bar (see diagram). The bottom of the chamber is filled to a depth of several inches with finely powdered silica, which provides the nutrient, and the remaining space is filled with an aqueous alkaline solution. Growth of the quartz crystal commences when the temperature at the bottom of the chamber reaches 750 degrees F., and the pressure 15,000 pounds to the square inch.

This combination of heat and pressure dissolves the powdered silica, and when the diffused molecules reach the cooler region at the top of the chamber they deposit one by one on the quartz " seed," producing, in due course, a flawless, transparent crystal of synthetic quartz.

Up to the present, no attempt to produce coloured gem crystals has apparently been made, but this could conceivably be done without much difficulty through the introduction of suitable colouring agents.

The largest crystal so far produced weighs about a quarter of a pound and took two weeks to grow.

It is very probable that some variation of the process described above is employed by Chatham in the production of his synthetic emerald crystals.

D. S. M. F.

IMPROVEMENTS in the PRODUCTION of SYNTHETIC QUARTZ

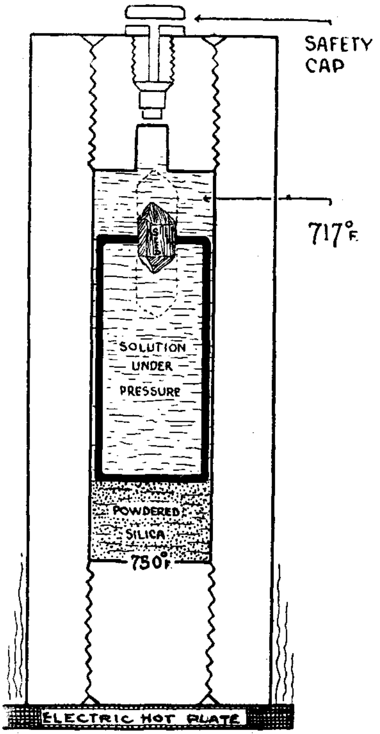
FOR the first time, clear crystals of synthetic quartz (rock crystal) are being produced in quantities sufficiently large to warrant more than the passing interest of the gemmological world.

Announcement of the achievement was made, late in February, 1950, by Dr. Albert C. Walker, of the Bell Telephone Company laboratories, before a gathering of scientists in Ithaca, N.Y.

Dr. Walker described the method of production and told how Bell Company engineers have improved upon the German process developed during World War II, until it is now possible to produce quarter-pound crystals of water-clear quartz in a short time and at relatively low cost.

The process differs entirely from that utilized for the synthesis of corundum, spinel and rutile. These man-made gem materials require furnaces patterned after the inverted blowpipe constructed by Auguste Verneuil, the French chemist who successfully synthesized the red variety of corundum, called *ruby*.

The quartz crystals produced in the Bell laboratories (for use in the electrical industry) are grown from a small natural " seed " crystal or fragment of quartz, held near the top of a



(continued on page 226)

SOME OPTICAL NOTES

by D. S. M. FIELD, A.G.A.

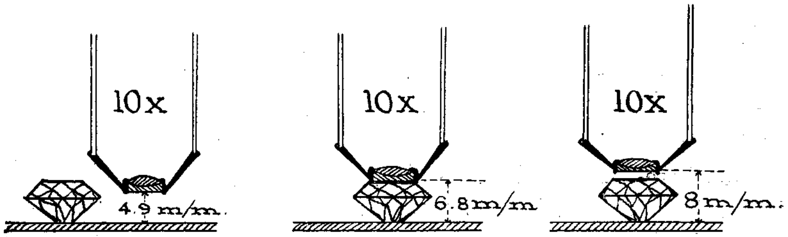
On Choosing a 10x Objective

THE working distance of a microscope objective is the distance between the foremost lens of the objective and the object, when the microscope is in sharp focus. This is always considerably less than the stated focal length, which is that for a single lens of similar magnifying power.

When purchasing objectives for gem testing, the buyer should be aware that working distance is of the utmost importance, particularly in the case of the higher powers ; for the longer the working distance, the greater will be the reachable depth.

The advantage of long working distance can be fully appreciated only by one who has tried to focus into a transparent gem, only to have the foremost lens of his objective touch the table facet before any appreciable depth has been reached.

In practice, of course, the careful worker would *raise* the focus from a point nearly touching the table facet, in order to avoid physical contact with the gem and possible resultant damage to the outside lens of his objective ; but if the stone should be fairly thick and the working distance short, it would be impossible at that point to bring the culet or lower pavilion facets into focus.



Relative working distances of 10x objectives by various makers.

It might be supposed that all objectives of a given power or focal length possess the same amount of working distance. This is not always the case. The writer has lately consulted the catalogues and descriptive price lists of a number of manufacturers in Great Britain, Continental Europe and the United States, and has found that there is a wide variation not only in working distance but in price, both of which are important considerations for many gemmologists.

The 10x objective of one of the foremost North American manufacturers has a working distance of only 4.9 mm. (too short for stones above a carat or so in weight), while a new model recently introduced by a second well-known firm has a working distance of 6.8 mm.—apparently the longest available in America.

In this respect, one British maker at least seems to have produced the most efficient objective for use in gem testing, for, without any appreciable sacrifice of resolution, the firm in question has achieved a working distance of 8 mm. for its objective of the same focal length and magnifying power. The stated numerical aperture —which, in practice, means simply resolving power—is also similar (0.25).

When powers below 10 are used, little thought need, of course, be given to the working distance, since this is in all cases great enough to permit one to explore the entire stone, regardless of its size or refracting power.

The above notes apply to achromatic lenses employed on monobjective binocular or monocular microscopes of standard (160 mm.) tube length.

With few exceptions, prevailing high prices for microscopes and accessories manufactured in the United States makes it virtually impossible for the Canadian student of modest means to acquire even second-hand American equipment for gem testing.

A fine microscope purchased from the United States costs the Canadian consumer at least twice as much as its British counterpart, and the prices of American-made accessories range from 100 to 200 per cent. above those of similar fittings manufactured in Great Britain.

Fortunately, all microscopes and microscope accessories valued at 50 dollars or more are admitted to Canada free of duty and are exempt from the Consumption or Sales Tax.

Great Britain, through the Royal Microscopical Society, has set the universal standards in the manufacture of optical equipment for microscopy, and, as might be expected of the acknowledged leader in this field for nearly a century and a half, her post-war instruments and accessories are second to none on the market to--day.

An Aid to Gem Spectroscopy

A small but extremely useful accessory attachment that can be used to facilitate the examination of tiny stones is supplied by Messrs. R. & J. Beck, Limited, for use in conjunction with their standard makes of spectroscopes. The attachment consists of a cylindrical lens conveniently mounted in a metal fitting held in place by two clamping screws.

This inexpensive accessory (No. 2496—£1 5s.) concentrates and extends the transmitted or scattered light, so that it completely fills the adjustable slit on the front of the instrument. This results in clear and brilliant absorption spectra, even when very small stones are examined.

Threaded holes for the accommodation of the attachment have been provided in all modern Beck spectroscopes of standard design —excepting the small fixed-slit and Beck-Hartridge reversion models.

A New Eye Shade

Messrs. Bausch and Lomb (Canada), Ltd., are offering an attractively designed black zylonite microscope eye-shade [priced at about one dollar (Can.)] to cover the eye not in use when looking through a monocular microscope. This accessory relieves completely the strain of suppressing the vision in the eye not in use, thereby adding greatly to the comfort of the user.

The shade is firmly held in place by a flexible plastic loop encircling the eyepiece of the microscope. It is equally effective when used in conjunction with the Beck hand spectroscopes, and creates the illusion of binocular vision.

Gemmological Abstracts

PUBLICATIONS

" Welke Edelsteen is dit? " J. Bolman, 105 pp., 2 plates, Leiden, Netherlands, 1950.

This publication consists mainly of tables giving principal physical properties of gemstones. An informative glossary (59 pp.) is arranged in five columns, the first giving the correct gem name, the second unusual or misleading names, the third the correct mineralogical designation, the fourth the degree of transparency and the fifth additional remarks. Tables of specific gravity and refractive indices are subdivided according to the colour of the gems. Special tables are provided dealing with translucent and opaque stones, stones displaying asterism, chatoyancy and glittering inclusions. A mineralogical list (14 pages) in the more conventional form in nine columns gives the chemical and physical properties of interest to the gemmologist. Other tables refer to crystal systems, double refraction, dispersion and other information usually found in the standard works on gemmology. The publication should be of considerable value to the growing number of gemmologists in the Netherlands.

" Die Enstehung der Agate "—the genesis of agates. Prof. K. Schlossmacher.

Article expounding new theory that volcanic magma consisted mainly of basic melt in which were included non-miscible drops of acid melt rich in silica. The drops, which were of lower specific gravity than the surrounding magma, are our agates. " Schmuck und edles Geraet," 1950, 1, 23-26 (No. 1, January). E. S.

" The Genesis of Agates," By Prof. Schlossmacher.

Continuation of article in preceding issue, pp. 23-26. " Schmuck und edles Geraet," 1950, *1*, 55-57. E. S.

The monthly periodical " Edelsteine und Schmuck," for which Prof. K. Schlossmacher was responsible, has ceased to appear. Papers and information relating to gemmology and gem industry will be published under the heading " Edelsteine und Edelsteinindustrie," editor Prof. Schlossmacher, in the new periodical, " Schmuck und edles Geraet " (publishers: Rudolk Grimm Verlag, Frankfurt/Main).

" Jeweler's Pocket Reference Book." R. M. Shipley, 1950. Ed. U.S.A.

A fourth edition of a reference book intended for jewellers in the U.S.A. and Canada. The gemmology section is good but it is regrettable to see that the term topaz-quartz is advocated for yellow and brown quartz. Topaz and quartz should be regarded as distinct gem species. A list of incorrect names for gemstones contains many that have long been regarded as obsolete in the U.K.

A. G.

" Edelstenen." By P. Terpstra, 178 pp., 34 figs., The Hague, 1949.

Written in Dutch, this is a small book following conventional form of text-books on gemstones. Physical and optical characters of all important gemstones are dealt with, but no reference is made to gem materials of organic origin. Modes of occurrence and chemical composition are also omitted.

A. G.

" How Synthetic Rutile was Produced in Czechoslovakia." By Dr. J. Kasper, D.S. " The Gemmologist," Vol. 18, No. 221, p. 291. December, 1949.

A report on the production of rutile single crystals in Czechoslovakia during the years 1942 to 1945 (during the German occupation of that country) and the commencement this year of industrial production.

R. W.

" Grinding Hardness and Possibilities of Influencing It." By K. F. Chudoba. " Schmuck und edles Geraet," 1950, *1*, 57-60.

The gemmologist is mostly concerned with scratch hardness. The gem cutting industry is interested in the resistance to grinding. This grinding hardness can be affected by using different lubricants. This article reports mainly on investigations by W. v. Engelhardt (1942-1946), who experimented with various lubricants and gem materials. The grinding hardness of four gem materials (basal plane) varied as follows:—

	Benzine	Water	Octanol-2
Quartz	103	100	59
Tourmaline ...	68	61	68
Topaz	55	52	55
Rutile	137	105	105

E. S.

" Synthetic Star Rubies and Star Sapphires." By John N. Burdick and John W. Glenn, Jr. (to Linde Air Products Co.). U.S. 2,488,507, November 15th, 1949.

A process is described for developing asterism in single crystals of ruby and sapphire containing oxide of Ti ; for obtaining gemstones from the non-asteriated single crystals containing oxide of Ti ; and for intensifying asterism in asteriated ruby and sapphire crystals. Synthetic ruby and sapphire of gem quality are made by the Verneuil process. Asterism is developed in a single crystal of gem-quality ruby or sapphire which contains Ti oxide dissolved in alumina. The crystal is heated between 1100° and 1500°, and kept at such a temperature until a compound of Ti ppts. along prominent crystallographic planes of the crystal. The length of the heating period required varies as an inverse function of the temperature, e.g. asterism was produced successfully in both synthetic ruby and synthetic blue sapphire boules after 72 hours at 1100°, after 24 hours at 1300°, and after 2 hours at 1500°. Below 1100° no asterism developed. Above 1500° there was no pptn. of the Ti oxide. For best results, the alumina powder should contain not less than 0.1 per cent. and not more than 0.3 per cent. of TiO^2. In gems prepared by this process the ppt. of Ti compound concns. in a surface skin, while the inner part of the boule is almost free from pptd. Ti compound. After cutting the asteriated stone, the visibility of the star can be intensified by heating from 1100° to 1500°. The synthetic asteriated crystals, both cut and uncut, have curved growth lines and microscopic or submicroscopic oriented acicular crystals. Also they often show curved striae in the cloudy ppt. zone. The star effect is believed to be caused by refraction and interference-diffraction of reflected light from the oriented ppt. crystals.—Abstract from "Chemical Abstracts," Vol. 44, No. 5. G. S. M.

BOOK REVIEWS

"*The Armytage Collection of Maori Jade.*" By Webster K. Athol. Photography by John Queenborough, A.R.P.S. The Cable Press, London.

Other than fiction, the success of any book, surely, is the ability of the author, figuratively speaking, to take the reader by the hand and show him round. The word *success* means here, primarily, the appreciation of the reader . . . the feeling that not only was the book worth its weight in time (one of our most precious commodities to-day), it awakened an interest in a subject that adds up to individual understanding. A *success* book, therefore, must not just amuse or skim the surface of one's attention, however knowledgeably ; it must cause the reader to sit up and take notice. Many subjects to-day are so specialized that there is a tendency to ignore them entirely, feeling that ninety-five per cent. of one's fellow creatures will do the same. A few question the integrity of these subjects, and have a right to do so, since they make demands on one's time. It is a question of whether there is not an aptitude to specialize for the sake of specializing.

To anyone other than a student of the Maori race, "The Armytage Collection of Maori Jade, by K. Athol Webster, a slim, illustrated monograph of Maori jade artifacts, might pass as only of interest to collectors or specialists. Yet as an introduction to the subject one can think of no better type of approach. Here is a representative and carefully described collection, pictorially, before one's eyes. The author tells us that this was probably one of the finest private collections of Maori jade items in existence. For this reason it is possible for the layman to be taken by the hand and shown round. One doesn't have to listen to some collector's running commentary even, nor elbow one's way over a museum case. When Edward Armytage died in 1946, his studiously acquired collection showed every evidence of going the way of many another collection. Mr. Webster's efforts saved it from this dreary end. Finally the jade went home, and the collection may now be scrutinized in New Zealand museums.

To make a study of Maori jade is to brush against several Sciences. And any such study must contribute to gemmology. Could the illustrations in this monograph have appeared in colour, since the range covers whitish grey-green to dark green, with brownish-greens and blackish-greens thrown in for full measure, the gemmologist would have been treated indeed. Maori jade is essentially a study of neolithic jade—not based on some airy hypothesis but on something contemporary man has discovered, and is still discovering.

"***Brillanten und Perlen (Brilliants and Pearls).***" By W. Maier, 188 pp., 17 tables, 80 illustrations. E. Schweizerbart, Stuttgart, 1949.

The author is a mineralogist who has occupied himself for several years with gems. His disregard for conventional terminology is most irritating. Brilliants, thus, are not only diamonds but all gem materials that shine. The two outstanding sections of the book are concerned with the different cuts of gems and with the registration methods for outer and inner reflections. The description of cuts is called " Brilliantography " (Brillantographie) and the section on reflections is headed " Brillianceometry " (Brillanzométrie) and the instrument used is a " brillianceoscope " (brillanzoskop). Apart from these formidable words, the two sections are interesting and useful. In 14 tables, 100 different cuts are depicted, nearly always in plan and elevation. The author has evolved a sort of shorthand description, giving together with the drawings the number of facets on crown and pavilion, the symmetrical arrangement and the shape of the facets. The instrument to register reflections consists of an upright glass cylinder which is either covered with a transparent screen or photographic paper.

The cut gem is held in the centre of the cylinder, the crown usually facing the light beam, which is directed horizontally through an opening in the cylinder periphery. Described also is a method of observing the light path in a stone which is placed in a smoke chamber. Other sections of the book are either conventional or no improvement on existing presentations. The section on natural gems, in which the author enumerates individual gem varieties, could be omitted altogether, as so many good reference books are available. Colour prints in this section are extremely poor. The section on synthetic gems gives an incomplete survey. In contrast to the author's opinion, the specific gravity of synthetic spinel is a clue to the genesis. An interesting suggestion is contained in a patent held by the author, allowing synthesis in a Verneuil type furnace but under pressure and in selected atmospheres. Nothing is said about any practical results. The suggestion to use large corundum bearings in industry (p. 147) and not only rubies in watches reveals that the author is neither familiar with the jewel bearing nor with the machine-producing industries. Should a second edition be contemplated, no doubt many errors will have to be rectified. Ruby, for instance, does not display light and dark green pleochroism (p. 4). Sapphire is the unhappy choice for the demonstration of double refraction (p 19), while Asterism in ruby is mentioned when probably corundum is meant (p. 32). The word cape-ruby is mis-used for garnet (p. 37). In the section on cutting, a saw for machining diamonds is represented as gem-sawing machine (p. 58). The diamond polisher's scaifes consist of cast-iron, not steel (p. 61), the method of charging the scaife is wrongly described, and in illustration 45 the tail-end pin holding the tang in position is omitted. The claim that theoretical considerations allow determination of the most favourable grinding direction on a particular diamond facet (p. 67) has not been substantiated yet in practice. Boron crystals are not as hard as diamonds and also boron carbide is softer (p. 146). The fact that diamond can be abraded slowly with boron carbide is certainly a very misleading argument, as in many instances the harder material is polished with a softer abrasive. Gem testing by means of hardness pencils (p. 150), however discretely applied, ought to be strongly discouraged. In the paragraph on pearl testing (p. 178) reference to the endoscope is omitted.

W. S.

CLEAVAGE
AND THE STRUCTURE OF GEM MINERALS

●

By R. KEITH MITCHELL, F.G.A.

THE long-standing problem of the causes of cleavage belongs rather to the broad science of mineralogy than to our own specialized subject of gemmology. The very nature of the property renders those minerals exhibiting it strongly undesirable in jewellery, since they violate the elementary requirement that a gem should be durable. There are, in spite of this, several gems, such as diamond and topaz, which possess perfect cleavage in one or more directions. Fortunately, the property cannot be said to be facile in these cases, since a fairly considerable force is generally required to produce it.

Usually described by mineralogists as " the result of the grained structure of minerals," cleavage is by no means an uncommon property among crystalline substances. The great majority of minerals possess it in some degree or other. Some, like quartz, exhibiting it scarcely at all, while others such as the micas are so easily cleavable that the property achieves major utilitarian importance.

From the time of the French mineralogist Haüy, who first recognized that the cleavage of a crystal was characteristic and common to all crystals of the same mineral, many theories have been formulated to explain the phenomenon, none of which can be said to apply universally. This seemingly simple structural property of crystalline minerals must, in fact, be due to highly complicated causes intimately connected with the atomic and electronic structure and forces of the mineral. The further we delve into the theories and facts of modern crystal chemistry, the more evident it becomes that cleavage is far from having a simple explanation.

Bravais, in 1881, explained the phenomenon on a purely geometric basis, stating that cleavage was most easily obtained parallel to those planes of the crystal lattice which contained the most atoms per unit area. In other words, parallel to the planes of greatest net density. And, since the distance between planes is inversely proportional to the net density of the planes, he gave as an alternative that cleavage will be found to occur parallel to the net planes most widely separated. Minerals exhibiting more than one crystallographic direction of cleavage were held to possess facility of cleavage in direct proportion to the degree of compliance with the above requirements.

This is a neat and logical explanation which would be very convenient if true, but unfortunately it has been shown that although many mineral cleavages apparently comply with Bravais' theory, there are many others which do not.

Other workers have carried the theory further to apply to conditions in which atomic layering exists as in the double tetrahedral arrangement of atoms found in mica. The atoms being held together by bonds other than those in the direct atomic plane parallel to which cleavage may be expected. Again complete agreement has not been found.

In 1912 the experiments of Max von Laue on the diffraction of X-rays led to the discovery by Sir William Bragg of the methods of examining the spacing and positions of atoms in the crystal lattice. For the first time scientists were able to " see " by means of direct calculation the structure of crystalline matter. The regular lattice or net patterns which had been deduced crystallographically were now capable of being proved, corrected and measured with considerable accuracy. The far-reaching effects of this discovery upon the whole of science cannot be over-estimated, and from that time on, crystallography has been enriched by research which has revealed lattice details of mineral after mineral. New light has been thrown on the comparatively unimportant matter of cleavage and new facts have been provided upon which to formulate further theories.

Some investigators have summed the electrons in the atoms of given planes and layers, thus elaborating on the theories of Bravais without advancing greatly towards a satisfactory answer to the problem.

Another line of thought has occupied itself with the question of atomic bonds and valencies, it being suggested that cleavage will take place in directions in which the fewest bonds are broken.

However, this approach is complicated by the nature and strength of the bonds concerned.

M. L. Huggins concluded, among other things, that cleavage faces should be electrically neutral, and that weak bonds (i.e. those between the most widely separated planes) would be ruptured before strong bonds.

Other workers have carried the question still further, recognizing that differences in bond types have considerable bearing on the subject ; calculating the forces binding atoms across various possible cleavage planes and considering those with the lowest value to be the most cleavable.

Several writers, including Wooster and Shappell, separate ionic and covalent (or homopolar) minerals as requiring different treatment. Shappell has calculated the bond strengths and the relative " cleavability " between given crystal planes, basing his findings upon the facility of cleavage rather than on the perfection of surface obtained. His calculations are based on broad approximations, and although the percentage of agreement with observed cleavages is high, there are several discrepancies among the 25 minerals treated that are not easily explained.

GENERAL SURVEY

A survey of cleavage throughout the mineral kingdom reveals certain facts that are indisputable.

The property is exhibited to a greater or lesser extent by almost all crystalline minerals. It is closely related to the primary crystallographic directions and can be referred to facial indices of low order, as (111) for the cleavage of diamond or fluor. It takes place parallel to existing or possible crystal faces or forms, and if present parallel to one face of a form, must be equally present parallel to all other faces of that form. Thus in the cubic mineral diamond, cleavage parallel to a set of two opposite octahedral faces necessitates identical cleavage parallel to each of the other three sets of faces.

In the cubic system it is therefore impossible to have less than three directions of cleavage (cubic (100) as in galena), if the property is present at all. While four directional (octahedral (111), in diamond or fluor) is quite common, and six directional (dodecahedral (110) as in zinc blende) is possible.

In all other crystal systems a single pinacoidal direction of cleavage is possible, or the tendency may be present in two or more directions parallel to one or more forms.

Cleavage quite obviously does not depend exclusively upon chemical composition, as consideration of such polymorphs as calcite and aragonite, cyanite, fibrolite and andalusite will show. Nor can it be said that similar crystal lattices yield similar cleavage. The case of diamond and zinc blende is an example of geometrically similar lattices which yield totally different cleavages.

INTER-ATOMIC BONDS.

It is customary to refer the bonds between atoms to four main types. Such division is largely arbitrary and one of convenience, since, according to Sir W. Lawrence Bragg, mathematical methods of lattice calculation show no fundamental difference between them.

The four bond types are known as ionic, covalent, metallic and Van der Waals, and they may be regarded as predominating in inorganic and organic compounds, metals and the inert gases respectively. Although any one or more of them may be present in varying degrees in one compound.

Generally mineral bonds consist of either or both of the first two types, ionic or covalent, and a brief description of the characteristics of each is necessary. But before going on to the complexities of atomic bonding some basic idea of the structure of the atom may be helpful.

The present state of knowledge and theory of atomic structure has been reached by observation, experiment and mathematical calculation largely based upon such direct information as may be obtained by X-ray diffraction methods and other less complex physical and chemical measurements. In the course of the past few decades, as we know too well, immense strides have been made in atomic physics, with the result that the atom, which was once regarded simply as a combination of electrons and protons, now has been found to contain other less simply explained charges, such as neutrons, deuterons, mesons, etc.

However, it will be sufficient for the immediate purpose if the simple picture is understood, and the atom considered as a central nucleus bearing a positive charge and surrounded by one or more orbital " shells " of electrons whose negative charge balances the positive charge of the nucleus.

The electron shells are normally designated as K, L or M shells, and so on, up to Q shell, the latter being found only in a few of the heaviest radio-active atoms, notably radium and uranium. These shells are in turn divided into sub-shells.

It is the electron configuration of the outer shell or shells that largely determines the chemical activity of the atom, and it has been found that atoms possessing eight electrons in their outer shell are those of the chemically inactive " inert " gases, neon, argon, krypton, and others. These are in a state of electronic stability, while atoms possessing numbers of electrons other than eight in this outer shell are unstable, and tend to reach the stable configuration by an exchange of electrons, combining with another element. Since in the heavier atoms the outer shell can contain more than eight electrons, it has been found that stability is also reached when there are eighteen electrons in that outer shell. It is of interest to note that such inactive elements as gold, platinum, palladium and iridium are all very close to this latter condition.

Either of these states of stability may be reached by shedding the odd one, two or three electrons of the outer shell, reducing the atom to the completed penultimate shell of eight or eighteen electrons ; or by adding one or two electrons to complete the outer shell. Therefore we have the fact that an atom when in chemical combination with another atom has either more or less electrons than when in a balanced state of electrical neutrality (a state not often found in nature). It has become an electrically charged atom, or an " ion." If it has acquired electrons it is a negative ion or " anion," since the negative electrons more than balance the positive charge of the nucleus. An atom which has parted with electrons is a positive ion or " cation," since the nucleus now has a greater charge than that of its surrounding electrons.

Anions are generally considerably larger than metallic cations and tend to assume close-packed structures as though they were spherical bodies of definite radius. The shape of a crystal structure is in the main due to the sizes and relative forces of the cations filling the interstices.

The difference of charge between anion and cation constitutes the ionic bond, the first of the bond types with which we are concerned. It is often illustrated by the instance of fluor, CaF_2.

In this mineral the calcium atom has two electrons in its outer shell. By losing them it attains the stable configuration of the inert gas argon. The fluorine atom is one electron short of the configuration of another inert gas, neon. Interchanges take place leaving Ca^{++} cations and F^{-} anions. These charges may be expressed alternatively in terms of valency.

The Ca atoms, carrying a double charge (divalent) are able to combine with twice their number of singly charged (univalent) F atoms. Hence the composition CaF_2.

Crystals having purely ionic bonds are generally transparent to visible light and often possess good cleavage. Colour is frequently idiochromatic. They are of moderate hardness and refractivity.

In some elements the outer electron shell is so balanced between two stable configurations that no exchange of electrons is possible. In such cases two or more atoms share their outer electrons by forming electron-pair bonds. This is the case with diamond, each carbon atom sharing its four outermost electrons with four neighbour-atoms in the structure. Bonds of this type are generally known as covalent or homopolar and are usually of considerable strength. This bond is probably responsible for such physical attributes as hardness, transparency and high refractivity.

The remaining two bonds, metallic and Van der Waals, are of little importance to the mineralogist. The former, as its name suggests, is the bond responsible for the cohesion of metals. It is generally characterized by extreme electronic fluidity giving rise to malleability, ductility and other properties common to metals and is responsible for their high electrical and thermal conductivity.

The Van der Waals bond is a very weak force and is responsible for, among other things, the slight cohesion that occurs when an inert gas or a molecular gas is liquified. It is the residual force holding molecules one to another when all direct bonds are satisfied within the molecule. It is found in minerals in a few instances only, graphite and talc being two outstanding examples.

An important factor in mineral structures which has a profound effect on cleavage is the composite negative ion. This is a group of atoms held together by partly covalent bonds, which act collectively as the negative ion in a predominantly ionic bond with another cation. A good example is provided by the SiO_4 tetrahedron of the silicates, in which four oxygen atoms are strongly bonded to a central silicon atom. Such composite ions, in some cases known as acid radicals, are generally considered incapable of being broken by cleavage.

While on the subject of negative ions, it should be emphasized again that anions are generally considerably larger than cations and tend to assume close packed structures as though they are spheres of definite radius cemented together by small cations in the holes between. By far the commonest anion is oxygen ($O^{=}$), which forms the main part spatially of the vast majority of crystal structures. Other important anions are fluorine (F^{-}) and the hydroxyl ion (OH^{-}). In the latter, half of the normal double charge of the oxygen anion has been taken up by the absorption of a hydrogen atom. Another anion found occasionally in mineral structures is chlorine, but it is rarely present in gem minerals.

Minerals consisting of approximately close-packed oxygen anions may be expected to have densities of 3.50 or more. In minerals of lower density the oxygen structure has been distorted out of the close-packed formation and gaps are left in the structure. Good examples of this are to be found among silicates of low density. In cases where the holes are sufficiently large they accommodate water molecules of crystallization, and even, as in the case of the zeolites, allow the free passage and interchange of large cations.

Before discussing individual mineral structures in relation to cleavage, it should be mentioned once more that the majority of minerals contain both ionic and covalent bonding, and that a bond may be partly covalent and partly ionic. Also, since an ionic bond is due to electrostatic attraction, the number of bonds between a given cation and its surrounding anions is limited only by their relative sizes, while the number of covalent bonds between, say, a silicon cation and oxygen, can only be four, since there are only four spare electrons in the outer shell of the silicon atom. Other covalent cations are similarly limited by the number of their outer electrons.

THE CLEAVAGE OF GEM MINERALS.

In the following descriptions of gem mineral cleavages no attempt is made to explain the phenomena on mathematical grounds. Such work would be almost impossibly involved and would probably serve very little purpose. Certain conclusions have necessarily been drawn, for direct information on cleavage as such is scarce. The references listed at the end have been used freely both for information on structures and as sources of structure drawings upon which to base most of the present illustrations.

The problem of conveying an adequate conception of complex crystal structures in two dimensional drawings is a considerable one, and it is often only possible to indicate some of the probable cleavage directions. For the sake of clarity the drawings for the most part represent atoms as small circles connected by lines indicating bonds. It is important to remember that, in fact, atoms behave as though they are spheres *in contact,* and that generally in bond directions little or no space between them exists.

DIAMOND.

The crystal lattice of this hardest of all minerals was among the first to be investigated. It was chosen because, being an element and having very high symmetry, its laue pattern was comparatively simple to interpret. Results have shown that the lattice is not only simple in form but is also remarkably perfect. The X-ray diffraction photographs are sharply defined and argue a perfection far above that of other crystals.

The unit cell of diamond consists of two interpenetrant face-centred cubes, the one displaced from the other by a quarter of the cube diagonal, as shown in Figure 1. This puts each carbon atom at the centre of a regular tetrahedron of four other carbon atoms.

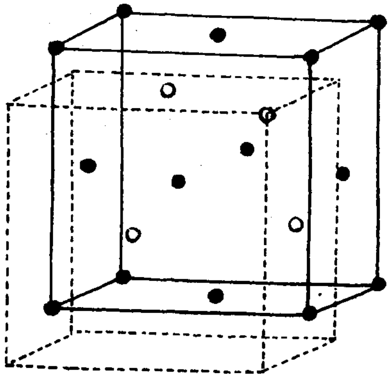


FIG. 1 (*a*)
The basic structure of diamond can be related to two interpenetrant face-centred cubes.

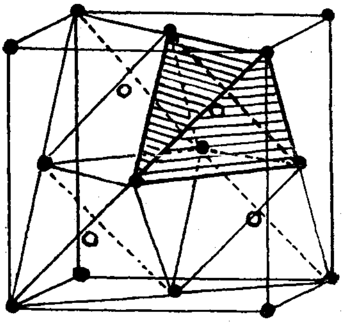


FIG. 1 (*b*)
Demonstrates the intimate relationship of tetrahedral and octahedral forms to the diamond structure.

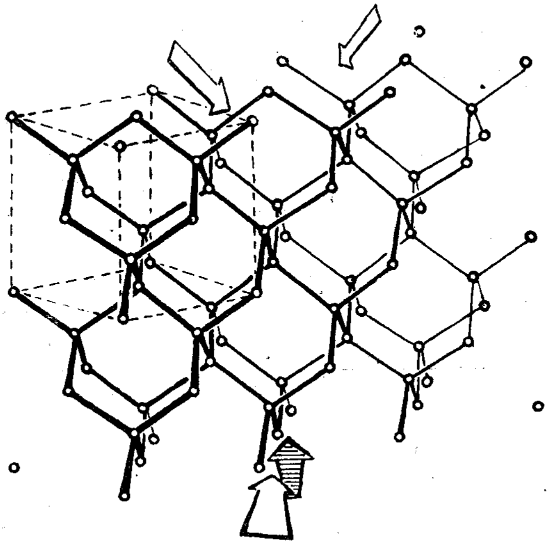


FIG. 2
Six unit cells of the diamond point lattice. The two cleavage directions indicated at the top of the diagram are clearly seen. The remaining two follow exactly similar paths although they are somewhat obscured by the perspective of the drawing.

Since the crystal consists only of carbon atoms and is not metallic, it follows that the bonding is covalent. There are four electrons in the outer shell of the carbon atom and therefore four bonds may be expected from each atom. This bonding is strong and in its perfection is responsible for the immense hardness of the gem.

In Figure 2 six unit cubes have been placed together and it is possible to see the layering of the atoms in the octahedral planes between which perfect cleavage may occur. Such cleavage is normal to and breaks only one bond from each tetrahedral group. This cleavage in four directions is generally recognised as the only one found in diamond, but the writer was recently informed by Sir C. V. Raman, of Bangalore University, that he has detected other cleavage planes in minute fragments of diamond, notably dodecahedral (110) and cubic (100) planes. These are directions of atomic layering but such cleavages would break more than one bond in each tetrahedron. It therefore seems obvious that if such cleavages exist they can only be obtained with difficulty and are, in ordinary conditions, completely masked by the perfection and comparative ease of the octahedral cleavage.

GRAPHITE.

This, of course, is not a gem mineral in any possible sense, but in the consideration of cleavage is of such interest as to warrant its inclusion. It is a soft, black and opaque mineral, the very antithesis of diamond, and has a cleavage so pronounced that a complete crystal has probably never been found.

The carbon atoms are arranged in flat hexagonal rings (Figure 3) similar to the puckered rings of diamond, but in this case, although each atom is surrounded by only three other atoms, the direct bonds are apparently satisfied within the layers. The carbon atoms within the layer are closer than in diamond, but the distance between layers is considerably greater. Bonding between layers is probably of the very weak type known as Van der Waals, and the sheets of carbon atoms part, slip or glide under the slightest pressure. To this property graphite owes its remarkable usefulness as a dry lubricant.

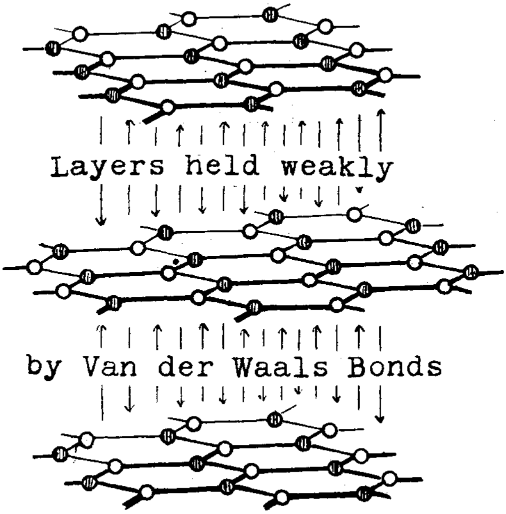


FIG. 3
The layered six-sided rings of graphite.

The high electrical conductivity, opacity and peculiar lustre of the mineral argue an essential difference in the bonding within the layers as compared with the bonding in diamond. The suggestion is that in the case of graphite the fourth electron pair is shared by a condition known as resonance, between the three main bonds. This argues a certain fluidity of electrons which would account for the good electrical conductivity of the mineral.

Charcoal has been found to possess the same bonding as graphite, but without the ordered layering of the atoms. The amorphous order results in many unsatisfied bonds which in turn account for the remarkable absorptive properties of this form of carbon.

It will be noted that in both diamond and graphite the carbon atoms form hexagonal rings (in diamond they are puckered by the tetrahedral formation). This hexagonal ring of carbons dominates the whole vast family of hydrocarbons and is probably responsible for the lubricant properties of so many of them. In the case of diamond it undoubtedly explains the affinity of that stone for grease.

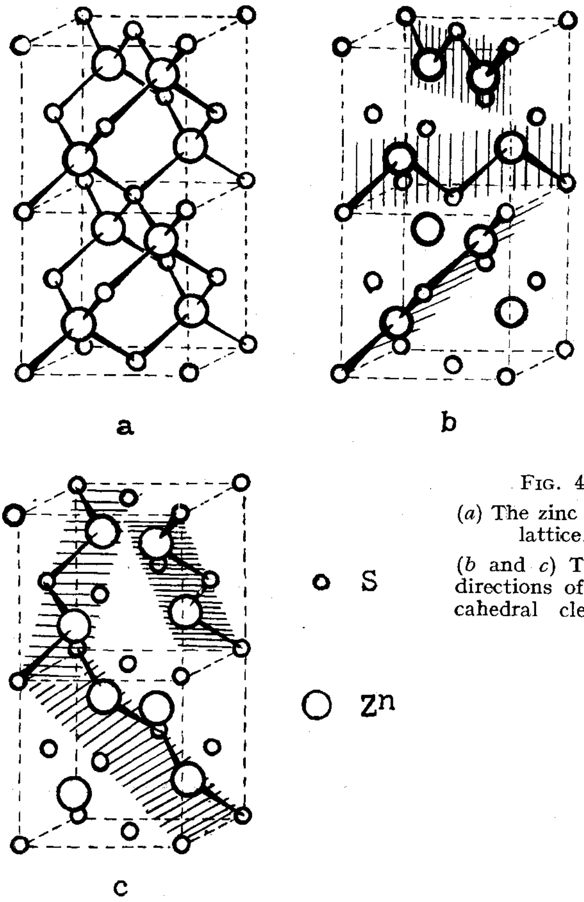


FIG. 4

(*a*) The zinc blende lattice.

(*b* and *c*) The six directions of dodecahedral cleavage.

ZINC BLENDE. ZnS. Cubic, hemihedral. Cleavage: Dodecahedral (110).

Not normally a gem mineral, zinc blende has occasionally been cut to provide those collectors' stones so dear to the heart of the keen gemmologist. It is another of the simple structures which were investigated in the early days of X-ray crystal analysis, and since it provides a fairly straightforward picture of atomic structure it is worth while including in the present discussion. It should, perhaps, be pointed out that these simple lattices for the most part contain no oxygen, and are by no means so typical of the mineral kingdom as a whole as are the more complex structures based on the oxygen anion. The underlying principles of nature may be simple, but the edifice built upon those principles is usually complex to an extreme.

The space lattice of zinc blende is the same as that for diamond except for size. Each zinc atom is at the centre of a regular tetrahedron of sulphur atoms, and vice versa. It is generally considered as an illustration of the transition between the covalent and ionic types of structure. The high refractive index of the mineral (often a feature of sulphur compounds) suggests that the bonding is, in fact, mainly covalent.

The cleavage is parallel to the six dodecahedral planes and is very easily produced. The planes are indicated in Figure 4. It will be noticed that they are the most widely separated planes containing equal numbers of both zinc and sulphur atoms. Separation

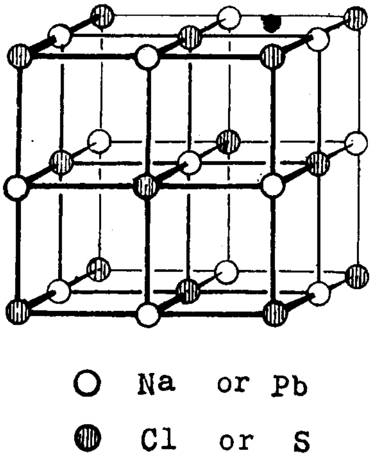


FIG. 5

The cubic lattice of rock-salt or galena. In either mineral cleavage parallel to the cube faces will separate like planes of mixed atoms.

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parallel to the cube planes would involve leaving one face of zinc atoms and one of sulphur atoms—an impossibility in cleavage. Puckered octahedral layering exists as in diamond, but here the sheets are polar (which accounts for the hemihedral crystal habit), with zinc to one side and sulphur to the other, a condition which would leave cleavage surfaces similar to those obtained if the cleavage were cubic.

GALENA (PbS) AND ROCK SALT (NaCl). Cubic. Cleavage: Cubic (100).

Other simple cubic crystal lattices are those of galena and rock salt. Neither is gem material, but both provide excellent examples of cleavage in simple structures. They both comply with the lattice shown in Figure 5. The cubic cleavage leaves like planes containing equal numbers of anions and cations. Octahedral or dodecahedral cleavage would not meet this requirement.

FLUOR. CaF_2. Cubic. Cleavage: Octahedral (111).

Although a mineral of small importance to the jeweller, fluor is a well-known feature of the gemmologist's curriculum, possessing

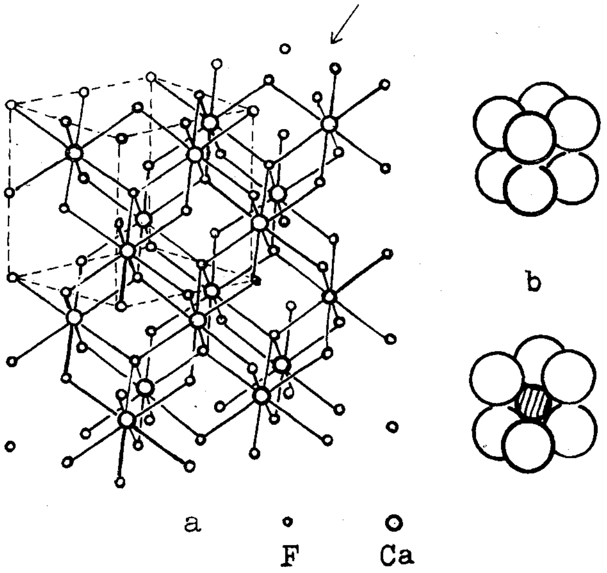

FIG. 6

(*a*) Four unit cubes of the fluor point lattice. Only one direction of octahedral cleavage is indicated

(*b*) Demonstrates that cleavage will remove one fluorine from the cube formation, leaving calcium cations exposed at a lower level.

as it does a well developed and highly characteristic crystal habit and a facile, although hackly, octahedral cleavage.

The crystal lattice is a simple one, on the lines of that of zinc blende, but since fluorine is univalent there are twice as many F atoms as there are sulphur in blende. This leads to an 8:4 co-ordination, each Ca $^{++}$ cation being surrounded by eight F^- anions at the corners of a cube, and each F^- by four Ca $^{++}$ at the corners of a regular tetrahedron (see Figure 6). These additional fluorine anions remove the polarity of the octahedral planes which exists in the blende structure, make the crystals holohedral and allow the octahedral planes as possible cleavage directions. The planes exposed would consist of identical sheets of F anions with Ca cations partly exposed at a lower level. The dodecahedral planes would also consist of like sheets of mixed F and Ca atoms, but would involve the breaking of twice the number of Ca-F bonds if cleavage took place in that direction. Since the bonding is ionic it is to be expected that the cleavage will be, as in fact it is, octahedral.

SPINEL. $MgAl_2O_4$. Cubic. S.G. 3.50. Cleavage: Octahedral (111), imperfect.

Chemically, the mineral spinel is not as simple as its formula might suggest, and it is, in fact, one of an important isomorphous series of some dozen or so minerals in which the magnesium and aluminium cations may be partly or wholly replaced by Fe $^{++}$, Zn or Mn, and by Fe^{+++}, Mn^{+++} or Cr respectively ; and in the case of artificial spinels, by several other metallic cations.

The oxygen structure of the mineral is approximately that of cubic close packing. The available diagrams do not give a sufficiently clear conception of the layer structure to form a definite conclusion regarding cleavage, but it is evident that the aluminium cation is at the centre of an octahedral group of six oxygens, while the magnesium atom is surrounded by a tetrahedral group of four oxygens. The Al-O bonding is strong and, according to A. F. Wells, partly covalent. It is therefore in all probability stronger than the essentially ionic Mg-O bond, and is unlikely to be ruptured by cleavage. It appears likely, therefore, that the octahedral cleavage follows planes containing Mg cations, and is largely influenced by the AlO_6 octahedra. The matter is further complicated by the isomorphous replacement of either of the cations, and by the fact that a second type is known in which some of the metal cations have changed places. It is, perhaps, significant that, as in the case of some other isomorphous mineral series with close-packed structures (e.g. tourmaline and garnet), the cleavage is difficult and imperfect.

An interesting feature of synthetic spinel is that it often has a tendency to cleave parallel to the cube directions. This may be in some way due to an excess of γ alumina in the structure.

CORUNDUM. Al_2O_3. Hexagonal, trigonal. S.G. 4.00. Parting: Basal pinacoid (111) and rhombohedral (100).

This mineral raises the question of parting as opposed to cleavage, and it is perhaps as well to explain the difference between them. The general conception of " parting " is a splitting along planes of twinning or other comparatively coarse structural faults or defects. Cleavage, on the other hand, is due to the actual atomic structure of the crystal and can, in theory, be carried down to atomic dimensions.

It has been suggested that the accepted definition of splitting in corundum as " parting " is open to query, and that it is, in fact, true cleavage. Sir Henry Miers states:—

> " . . . . the parting or apparent cleavage parallel to R (the (100) or rhombohedral faces) seems to be due to . . . lamellar twinning, which may perhaps be in many cases secondary, and caused by pressure, planes parallel to R acting as glide planes. The parting parallel to the basal plane (111) appears to be due to incipient decomposition. Crystals of corundum often exhibit a pearly lustre on the base and a platey structure parallel to the same ; these are due to microscopic cavities produced along horizontal planes (111) which are therefore to be regarded as ' solution-planes ' along which corrosion takes place most easily. Somewhat similar, though less distinct, is a third parting, parallel to the hexagonal prism (101)."

The oxygen structure is approximately hexagonal close-packed, and the aluminium cations, as usual, occupy octahedral positions at the centres of groups of six oxygen anions. All three directions of parting are parallel to main directions of atomic layering.

The Al-O bond, as has already been stated, is strong, and the parting/cleavage is not produced easily in most gem specimens. Crystals showing the twinning and partial decomposition upon which the property is apparently conditioned are obviously unsuited for gems.

γ alumina is a polymorphous form of the oxide which can be produced synthetically, and which crystallizes with the spinel structure. This fact was used to considerable purpose by German technicians during the recent war. By using an excess of alumina in the manufacture of spinel, boules were obtained containing γ alumina in solid solution. These were capable of being worked into various forms for use as abrasion or cutting tools for industrial use and were then hardened by a process which caused the alumina to expand into the corundum structure (α alumina). The resultant material possessed considerable toughness and little or no tendency to cleave. Its use to a country short of industrial diamonds and other super-hard abrasives is obvious.

CHRYSOBERYL. $BeAl_2O_4$. Orthorhombic. S.G. 3.71. Cleavage: (010) and (011), imperfect.

It is a recognized fact that chrysoberyl has considerable resemblances crystallographically to the magnesium silicate, olivine. The crystal habits and dimensions are practically the same, and one of the two cleavage directions is identical. X-ray analysis has shown that they are fundamentally the same in structure. The positions occupied by Al and Be cations in the one being taken by Mg and Si atoms in the other.

In chrysoberyl, BeO_4 tetrahedra take the place of the discrete SiO_4 tetrahedra in olivine, while Al atoms, being larger, take their usual place between six octahedrally placed oxygens. The bonding of Be and Al to oxygen is covalent to about the same degree, but, since the beryllium atom is smaller, the bond strength is greater and is shared with only four oxygens, while the Al cation is shared with six. It is therefore to be expected that the cleavage planes will be those between oxygen anions bound by aluminium cations. An examination of the diagram of the olivine structure (Figure 10), which serves also for chrysoberyl, will show that in the case of the brachypinacoidal (010) cleavage such conditions do exist.

The case of the second cleavage (011) is not so clear, especially as it apparently does not occur in olivine. The possible reasons for a discrepancy will be dealt with under that heading.

THE CLEAVAGE OF THE SILICATES.

Practically all the remaining gem minerals of importance are to be found in the vast mineral family known as silicates. The only notable exception is quartz, which, with its polymorphs tridymite and cristobalite (not gem minerals), is normally considered with the oxides. The distinction is man made, however, and in the natural order of things quartz may be regarded as the end species of all the immense series of minerals classified as silicates. The Si-O bond is of such importance in its bearing on cleavage that the inclusion of the three silica minerals under this heading is logical.

It has been estimated that the two elements silicon and oxygen together comprise more than 70 per cent. of the earth's crust, and that the latter consists practically entirely of silicates and silica, the weights of other ores of metals being insignificant in comparison. That being the case, we are justified in concluding that the two elements have a very strong affinity for each other and that the bond between them is strong.

Silicon is the second element in the periodic table to have the four electron outer shell and, with oxygen, it forms four bond tetrahedra which are reminiscent of the tetrahedra of diamond. According to Pauling, the bonding is considered to be 50 per cent. covalent, which undoubtedly adds to its strength.

An interesting compound of the two elements carbon and silicon exists in the artificial abrasive carborundum (SiC). This substance crystallizes in some half-dozen forms, at least three of which are referable to the diamond lattice. It is interesting to note that carborundum is second only to diamond in hardness. Silicon itself, however, exhibits no outstanding hardness.

From a structural point of view silicates are generally divided into several main groups according to the type of Si-O composite ion involved. These are, briefly:—

(*a*) The orthosilicates, in which discrete SiO_4 tetrahedra occur. No oxygen atom in this type of structure can be common to two such tetrahedra. (Figure 7a.)

(*b*) Structures in which pairs of SiO_4 tetrahedra are linked through one of their oxygens, but are otherwise discrete. (Figure 7b.)

(*c*) Structures in which the SiO_4 tetrahedra each share two oxygens and are linked up to form closed three-fold, four-fold and six-fold rings. (Figure 7c.)

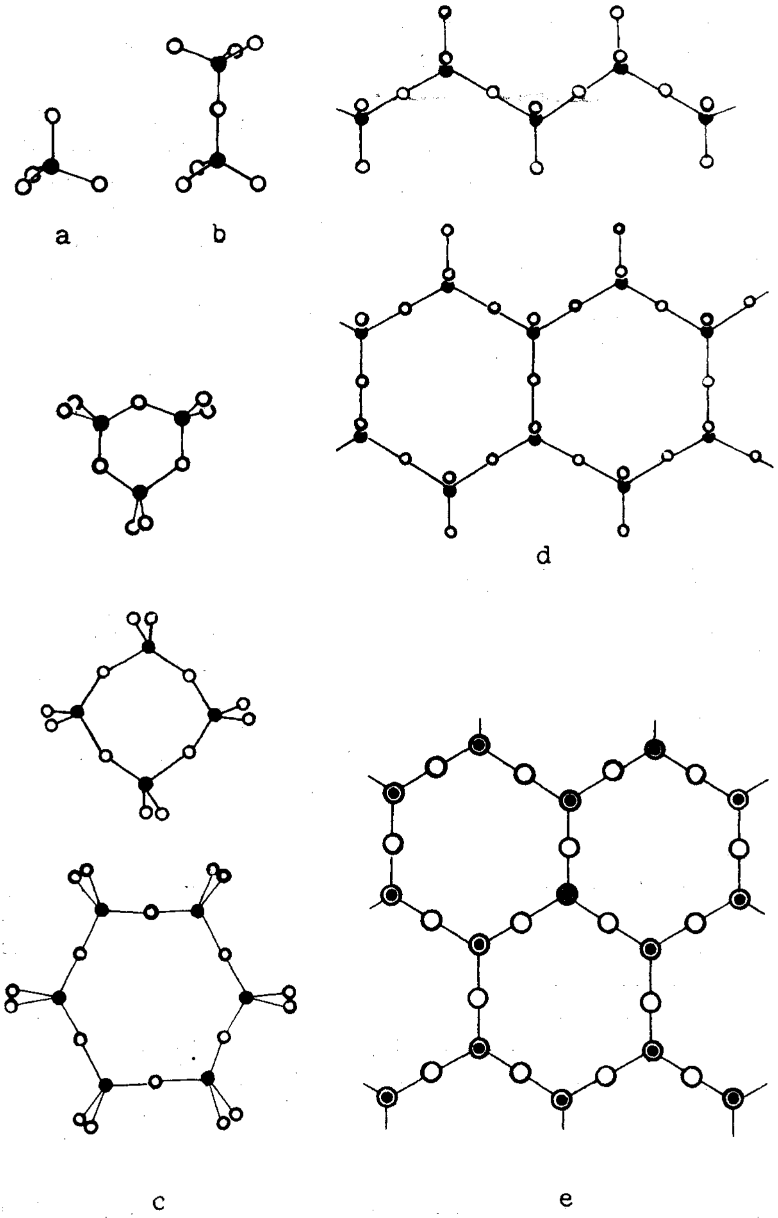

FIG. 7

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(*d*) Fibrous structures in which the SiO_4 groups are linked as in (*c*) by each sharing two oxygens with neighbouring groups, but in which endless chains are formed. (Figure 7d.)

(*e*) Structures in which the SiO_4 tetrahedra each share three oxygens to form infinite sheets. (Figure 7e.)

(*f*) Structures in which each oxygen atom is shared by two tetrahedra to form an infinite three-dimensional framework. This type in its pure form gives us quartz and its polymorphs. But many instances occur in which the structure includes other metallic ions and the framework is of mixed tetrahedra. The feldspars and zeolites are of this latter type.

ORTHOSILICATE GEMS.

Under this heading we find such well-known gems as topaz, zircon, peridot, tourmaline and the garnets ; and others less known, as andalusite and its polymorphs, and the rarely cut euclase, epidote and phenacite.

In all these gem structures the silicon-oxygen tetrahedra are isolated from each other and are connected only through metallic cations. It follows that the influence of the strong Si-O bond is not so obvious as in the chain and layered silicate structures.

TOPAZ. AlF_2SiO_4. Orthorhombic. S.G. 3.55. Cleavage: Basal (001), perfect.

After diamond, topaz is probably the most cited instance of cleavage in gem minerals. It possesses the property to a remarkable degree when its use as a gemstone is considered, and careless handling in setting or in use has resulted in badly damaged stones.

It is one of the few silicates to contain fluorine anions, and although the cleavage is due in part to the strength of the silicon-oxygen bonds, its facility and perfection can be attributed to the presence of the fluorine, or of the hydroxyl anions with which they are sometimes replaced.

These anions are both univalent, as opposed to the divalent oxygen anion. Their sizes are not dissimilar and replacement of F by OH occurs, with a consequent increase in the refractivity of the crystal. This may perhaps be considered rather as a lowering of the refractive indices due to the increase of fluorine content, an influence which is noticeable in all substances containing that element. In gem topaz the yellow, brown and pink stones contain more hydroxyl than do the blue and white specimens.

This replacement has no appreciable effect on the cleavage. The absorption of the single electron hydrogen atom into an oxygen anion reducing the composite ion to the same univalent state as fluorine. The mass of the hydrogen atom is small and makes no apparent difference to the size of the resultant ion.

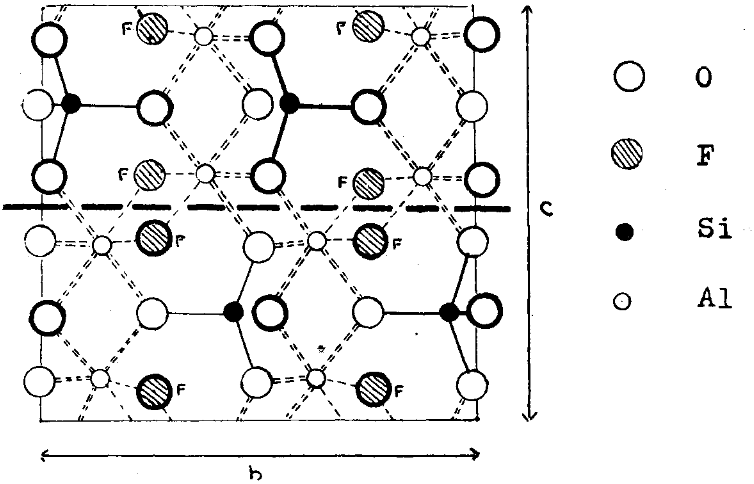

FIG. 8

The topaz structure projected on a plane normal to the *a* axis. Al-O bonds are indicated by double dotted lines and those between Al and F atoms by single ones. The heavy broken line and the top and bottom edges of the drawing indicate possible cleavage planes.

The actual structure of the gem is not simple to interpret in diagram form. Figure 8 shows the lattice projected on the plane normal to the *a* axis. The cleavage is indicated by the broken heavy line. The top and bottom edges of the diagram are also lines of possible cleavage. Al-O bonds are indicated by double dotted lines and the Al-F bonds by similar single lines. It will be seen that cleavage separates two layers of aluminium cations and breaks only Al-O and Al-F bonds. The staggered and alternated positions of the SiO_4 tetrahedral groups preclude the possibility of any other cleavage.

ZIRCON. $ZrSiO_4$. Tetragonal. S.G. 4.00 to 4.70. Cleavage: Prismatic (110), imperfect ; Pyramidal (111), less distinct.

Zircon is an instance in which X-ray investigation has confounded the original allocation of axes in the crystal, so that the true lateral axes of the unit cell are at 45° to those to which faces are normally referred. Thus the normal crystal forms, which are also the cleavage directions, should be prism (100) and pyramid (101).

The perspective diagram of the unit cell is fairly easy to interpret (Figure 9). The silicon-oxygen tetrahedra are there as usual, while each zirconium atom, being larger than silicon, is surrounded by eight oxygens: four from vertically situated silicon groups and four from laterally situated groups. These are indicated only in the case of the centre zirconium atom in the diagram.

Although the *c* axis of the unit cell has been shown to be shorter than the *a* axis, the vertical zirconium-oxygen bonds are somewhat longer than the lateral ones. However, the prismatic (100) cleavage will separate sheets of silicon-oxygen tetrahedra and zirconium atoms, only zirconium-oxygen bonds being broken. The more difficult pyramidal (101) cleavage undoubtedly separates the double sheets of zirconium atoms which occur in these directions.

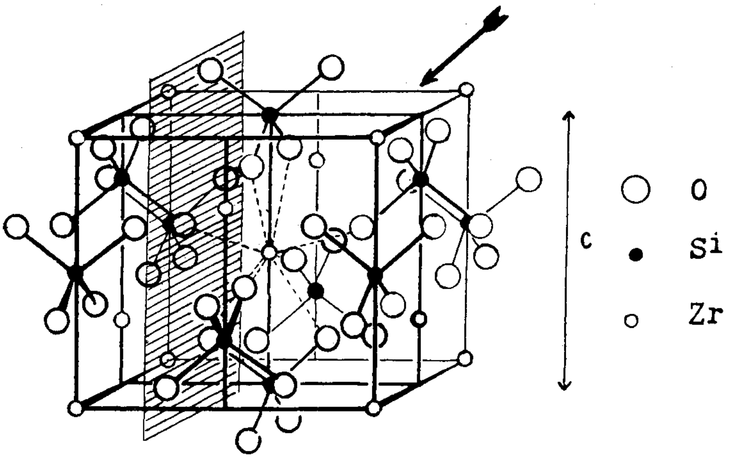

FIG. 9

The unit cell of zircon. The shaded vertical plane indicates one of the prismatic (100) cleavages, breaking only one of the eight Zr-O bonds from each Zr cation. For the sake of clarity these bonds are shown only in the case of the centre Zr atom. The (101) pyramidal cleavage (indicated by the arrow) separates layers of Zr cations, breaking three Zr-O bonds from each Zr atom.

This involves the breaking of more bonds than in the first instance, hence the increased difficulty of the cleavage.

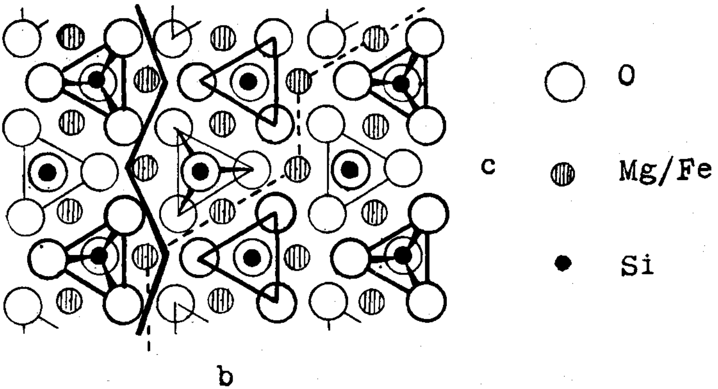

FIG. 10

The idealized olivine structure projected on a plane normal to the *a* axis. The (010) cleavage would probably follow the zig-zag path indicated, Mg/Fe atoms alternating on the exposed faces. The (100) cleavage would be parallel to the plane of the paper and is obscured by the alternation of the SiO_4 tetrahedra.

Chrysoberyl, which is almost identical in structure, can be referred to this diagram. The (010) cleavage is the same as in olivine, but the lesser (011) cleavage marks a divergence in the two structures and possibly follows the path indicated by the dotted line.

OLIVINE (Peridot). $(MgFe)_2SiO_4$. Orthorhombic. S.G. 3.40.
Cleavage: (010) and (100), imperfect.

The similarity of the structure of this gem to that of chrysoberyl has already been mentioned.

From the diagram (Figure 10) it will be seen that, although the SiO_4 tetrahedra are discrete, they do in fact group themselves into sheets separated by Mg/Fe cations which are in contact with octahedral groups of six oxygens. This grouping is responsible for the (010) cleavage parallel to the brachypinacoid. It is not a facile or a perfect cleavage because the Mg-O bond is far from a weak one, and although in the idealized plan of the structure the division is clearly defined, the actual positioning of the atoms at the cleavage face is not planar, as will be seen from the second illustration (Figure 11).

The second cleavage direction is parallel to the macropinacoid (100). From the available diagrams it seems that the silicon-oxygen tetrahedra are pointed in alternate directions, and the cleavage planes are even less planar than in the previous instance. This cleavage is difficult and obscure, as is the (011) cleavage of chrysoberyl, and it is these cleavages that mark the divergence of otherwise very similar structures. The difference is probably due to the smaller sizes of Al and Be cations when compared with those of Mg and Si.

The fact that twinning, which has been referred to (011) planes, is a frequent feature of chrysoberyl and a very infrequent one of olivine may have some indirect connection with the subject.

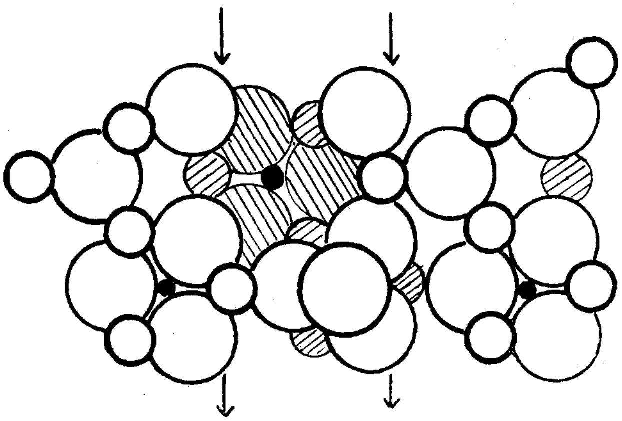

FIG. 11

The olivine/chrysoberyl structure, drawn to show the spacing of atoms (after Bragg). The atoms along the (010) cleavage path are to some extent interlocked, which probably reduces the facility with which the cleavage may be produced.

(Figure reproduced from W. L. Bragg's "The Atomic Structure of Minerals" by permission of the Cornell University Press and the Oxford University Press.)

TOURMALINE. A complex boro-silicate of several metals. S.G. 3.05. Hexagonal, trigonal. Cleavage: Parallel to flattened pyramid and prism faces, very imperfect.

The complexity of the composition of the tourmaline series is a byword among gemmologists, and the degree of isomorphous interchange of cations known in the mineral is almost impossible to understate. F. Machatschki published in 1929 ("Zeit. Krist.," 70, 211) a list of 28 analyses of the NaCaMgAl tourmalines. Added to this we have to consider replacement of Na by K, Mg by Fe^{++} or Mn, Al by Fe^{+++}, Ti or Cr, and hydroxyl by fluorine. The possible combinations appear to be almost limitless, and it is easy to realize that the structure is not yet fully understood. It is thought, however, that when analysed it will prove comparatively simple, as have other seemingly endless series.

The cleavage of the mineral is not by any means marked and probably is observable only in thin sections. There may be some variation in its degree of perfection and facility as the formula varies. The same may be said of other isomorphous series, although, except in the cases of mica and feldspar, data in evidence are apparently not available.

THE GARNETS. Cubic. Isomorphous series of silicates of bivalent and trivalent cations. S.G. 3.40 to 4.20. Cleavage or parting: Dodecahedral, difficult and imperfect.

This is another good instance of the homogeneity of structure in some isomorphous series. The unit cell has been determined by X-ray diffraction methods, but available drawings do not assist greatly in the matter of cleavage.

There is a difference of opinion among mineralogists as to whether the occasional and imperfect splitting along dodecahedral planes is in fact cleavage, or is parting due to coarser imperfections. The possibility of lamellar twinning cannot be overlooked, although, since the mineral is isotropic, except for strain patches, it would be difficult to prove.

Altogether, it seems evident that the bi-, tri- and tetravalent metal cations of the garnets establish a very effective balance of bond throughout this highly symmetrical cubic lattice. The somewhat doubtful cleavage is difficult and probably only observable in thin sections.

KYANITE. Al_2SiO_5. Triclinic. S.G. 3.60. Cleavage: Pinacoidal, (100) perfect, (010) less perfect.

ANDALUSITE. Al_2SiO_5. Orthorhombic. S.G. 3.15. Cleavage: Prism (110) distinct, pinacoidal (100) less perfect, (010) traces only.

FIBROLITE. Al_2SiO_5. Orthorhombic. S.G. 3.25. Cleavage: Pinacoidal (010), very perfect.

These three minerals provide an interesting example of polymorphism, for, although they are chemically identical, they are in fact minerals of very different appearance and widely variant physical properties.

The essential difference in their atomic structure lies in the number of oxygens surrounding the Al cations. Half the latter are at the centres of octahedral groups of six oxygens while the remainder are surrounded by six, five or four oxygens in kyanite, andalusite and fibrolite respectively.

A characteristic of all three is the existence of chains of Al-O octahedra parallel to the *c* axis in each mineral. These are no doubt contributory to the fact that none of the cleavages cut this axis.

Kyanite, with its close-packed oxygen structure, is the densest of the three, and the perfect (100) cleavage apparently occurs between layers of oxygen anions sparsely bonded by aluminium cations. The less perfect (010) cleavage is not well defined and apparently follows a more step-like path in which again Al-O bonds only are broken.

The structures of andalusite and fibrolite are slightly more open and have the higher symmetry of the orthorhombic system. In fibrolite the Al-O octahedral chains are paralleled by chains of alternate Si-O and Al-O tetrahedra. The single pinacoidal direction of cleavage is not easily traced in diagrams of the structure. The name, *fibro*lite, suggests that a secondary cleavage may exist, but mineralogical text-books make no reference to it.

Andalusite, which is the best known of the three to gemmologists, possesses a structure between those of kyanite and fibrolite. The unusual position of half the aluminium atoms, between five oxygens, complicates the lattice and makes planes of possible cleavage hard to locate in the existing diagrams. It seems probable, however, that the more pronounced cleavages follow planes of oxygen layering.

SPHENE. $CaTiSiO_5$. Monoclinic. S.G. 3.50. Cleavage: (110), (100) and (112), imperfect.

The monoclinic symmetry of this mineral is undoubtedly due in the main to the large size of the calcium cation which occupies a position between seven oxygens. The lattice is thereby distorted a little from the close-packed condition, although the specific gravity might suggest otherwise, the density of the titanium cation being high.

The unit cell is complex and difficult to interpret from a two-dimensional drawing, but it is noticeable that the metallic cations

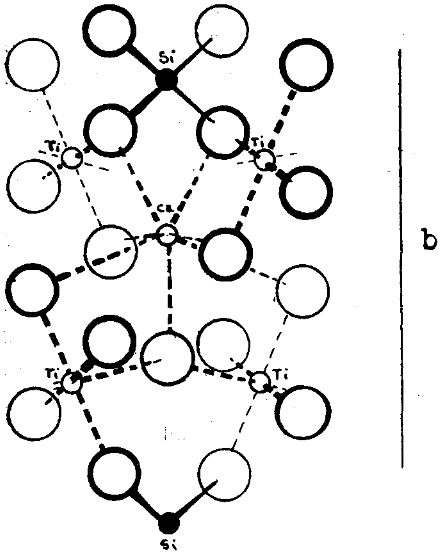

FIG. 12

The sphene structure projected on a plane normal to the *a* axis. Showing the interrupted Si-O-Ca sequence, which may contribute to one or more of the cleavages. This monoclinic structure is difficult to interpret from diagrams, but it is probable that models, if available, would show that bond angle and gaps in the structure are largely responsible for the weaknesses that produce the rather imperfect and ill-defined cleavages.

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are layered parallel to the three main pinacoid directions. Layers of Ti between six oxygens alternating between mixed layers of Si between four, and Ca between seven oxygens. This might be pre-supposed to indicate cleavage in all three of these planes. But, in fact, only the (100) plane of the three is a cleavage direction, and this between the least widely separated cation planes. It seems likely that in this direction the gap structure due to the large Ca atoms produces a weakness which, together with changes in bond angles, results in imperfect cleavage.

In the direction of the *b* axis there appears at first sight to be a chain of alternate Si-O and Ca-O structures. Closer examination shows (Figure 12) that the chain is interrupted by the seventh oxygen around the Ca cation, and bonding proceeds by laterally placed Ti cations., It seems probable that this diversion of bond contributes considerably to the (110) cleavage. It is to be noted that none of the three cleavages are at all prominent.

SI_2O_7 STRUCTURES.

Few minerals have this type of silica structure, and idocrase and danburite are the only gem minerals among them.

IDOCRASE. $Ca_{10}Al_4(MgFe)_2Si_9O_{34}OH_4$. Tetragonal. S.G. 3.40. Cleavage: (110) indistinct, (100), (001) less distinct.

The unit cell of this mineral contains 252 atoms and is an example of the complexity of structure which can be unravelled by X-ray diffraction methods. Some parts of it can be directly related to parts of the garnet structure.

Of the nine silicons in the formula only four form Si_2O_7 groups, the remainder forming discrete SiO_4 tetrahedra.

Diagrams of this structure are extremely complex, and show no obvious cleavage directions. The presence of the large Ca cations and weak hydroxyl anions no doubt contributes in some way.

DANBURITE. $CaB_2(SiO_4)_2$. Orthorhombic. S.G. 3.00. Cleavage: (001) very indistinct.

This gem has been compared to topaz on the strength of its appearance, crystal system and similarity of formula. The presence of the Si_2O_7 complex radical does not help the comparison, although the occurrence of very poor basal cleavage may be an argument once more in its favour. It is perhaps due to a layering of oxygen anions parallel to the basal plane, but lacks the weak fluorine-aluminium bonds of topaz to make it perfect.

SI_3O_9 THREEFOLD RINGS.

This is a very rare type of silicon grouping and occurs only in the rare barium titanium silicate, benitoite, and in the calcium silicate, wollastonite. The former has been cut to yield small and rather beautiful blue gems.

BENITOITE. $BaTiSi_3O_9$. Hexagonal. S.G. 3.65.

The mineralogies consulted do not mention cleavage in connection with this gem, and I think that it may be assumed that it is not a strong feature. The threefold Si-O rings lie parallel to the basal plane, and, as in beryl, they are bound both laterally and vertically by the remaining cations, titanium and barium. It is therefore possible that difficult basal cleavage may occur.

Two other observations may be made. Firstly, that the threefold ring is most obviously reflected in the trigonal symmetry of the mineral, and is an excellent example of the immense influence of the silicon-oxygen bond on the crystallography of silicates. Secondly, since the threefold ring formation, unlike the sixfold rings of beryl, does not create gaps at the centres of the rings, the specific gravity may be expected to be higher than that of the latter gem. The heavy barium and titanium atoms contribute greatly to this, but the S.G. of 3.65 must indicate a fairly close oxygen structure.

Si_6O_{18} RINGS.

These, of course, are the silicon-oxygen rings found in beryl and so obviously reflected in the symmetry of that gem.

BERYL. $Be_3Al_2Si_6O_{18}$. Hexagonal. S.G. 2.70. Cleavage: Basal, (0001), very indistinct.

The profound effect of the Si-O bond on symmetry is very obvious in this mineral. In Figure 13 two layers of sixfold rings of

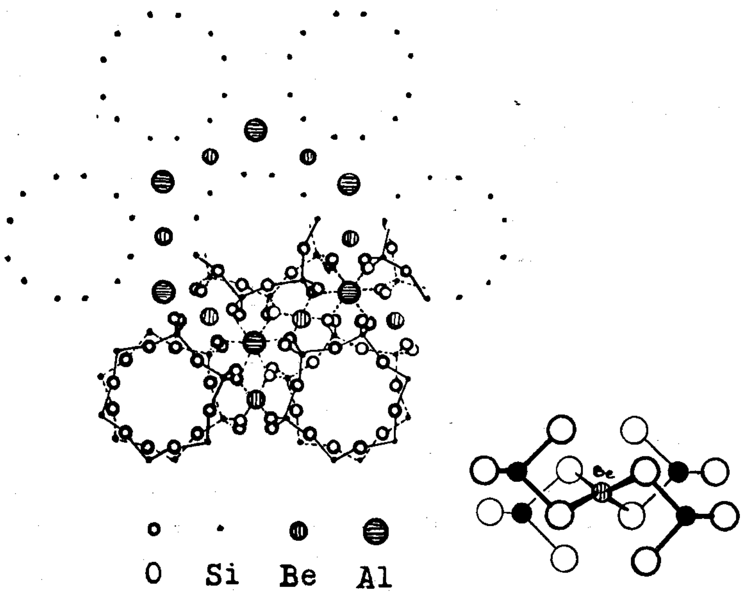

FIG. 13

The hexagonal Si-O rings of beryl. Rings at adjacent levels alternate in position, giving the impression of being 12-sided. To emphasize the perfect hexagonal symmetry the positions of further rings are shown by dots representing their silicon atoms only. The rings are strongly cemented vertically and laterally by the Al and Be cations between them, as seen in the smaller diagram.

tetrahedra are shown, and in order that the hexagonal repeat pattern may be understood the positions of further rings are indicated by dots representing the silicon cations.

The silicon-oxygen rings are layered parallel to the basal pinacoid and would probably lead to strong cleavage were it not for the positions of the other metallic cations. From the smaller drawing it will be seen that these serve to bind the rings tightly together both laterally and vertically.

Both Al and Be are fairly small cations and their bonds with oxygen are strong, being partly covalent. Between them they achieve a strength of bond which cancels out the possibility of vertical cleavage and leaves the basal (0001) cleavage poor and very ill-defined.

The low density of the mineral is in part due to the presence of two light metals, Al and Be ; but it is decreased by the gap structure occasioned by the open centres of the Si-O rings. The gaps are insufficient to accommodate water molecules or other such " fillings " found in more open structures.

SI-O CHAINS.

This type of structure is represented by two large families of minerals, the pyroxenes and the amphiboles, the former having single chains of tetrahedra and the latter double chains.

The pyroxenes include, among other minerals, the gems spodumene, diopside and enstatite. Jadeite is a massive pyroxene with a characteristic fibrous structure.

Amphiboles are represented among gems by the massive nephrite and the fibrous mineral crocidolite, which, when oxydized and partly replaced by quartz, provides the chatoyant golden stone known as Tiger's Eye. Asbestos is perhaps the best example of the amphiboles, and amply illustrates their fibrous and facile cleavage.

SPODUMENE. $LiAl(SiO_3)_2$. Monoclinic. S.G. 3.18. Cleavage: (110) perfect.

ENSTATITE. $(Mg,Fe)SiO_3$. Orthorhombic. S.G. 3.27. Cleavage: (110) easy.

DIOPSIDE. $CaMg(SiO_3)_2$. Monoclinic. S.G. 3.29. Cleavage: (110) rather perfect.

These three are not of great importance among gems, although spodumene in its lilac-coloured variety, kunzite, has appeared occasionally in modern jewellery. The ready cleavage may account for this to some extent, but the rarity of good gem quality specimens is probably the main reason for their lack of popularity.

The silicon-oxygen chains in each case are a simple sequence of tetrahedra each joined by two corners to neighbouring tetrahedra. They invariably run parallel to the *c* axis of the crystal, and are bound laterally by the remaining metallic cations. The sizes of these cations control the symmetry of the crystal, the Mg and Fe of enstatite giving balanced orthorhombic symmetry, while the larger Ca cations of diopside and the smaller Li and Al cations of spodumene both shift the arrangement of silica chains to give monoclinic symmetry. The cations between the chains are in positions of six or eight co-ordination with the oxygen anions of the chains. The bonds in each case are mainly ionic and are weaker than the Si-O bonds within the chains.

The (110) prismatic cleavage is quite typical of pyroxenes and is entirely due to the comparative strength of the silica chains. The angle between the two prism planes is invariably about 93° and is the result of a step-like path between the chain structures, as shown in Figure 14.

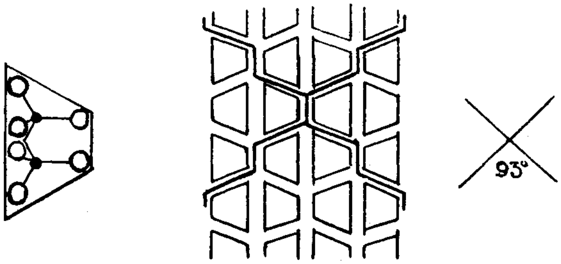

Fig. 14

PYROXENES.—An end-on view of the Si-O chain formations, looking down the *c* axis of a pyroxene crystal. The step-like prismatic cleavage paths are indicated, intersecting at 93°.

In enstatite the (010) direction has also yielded cleavage. Possibly the slight shift of cations due to the lower symmetry prevents this in the other two gems.

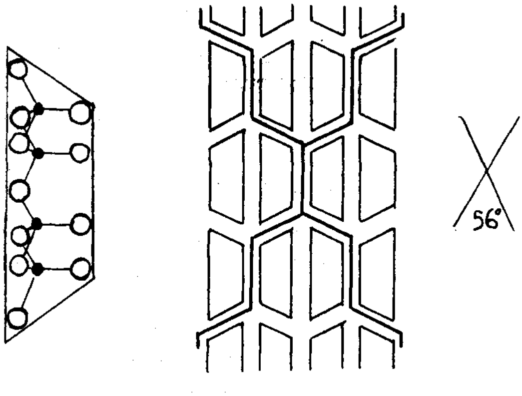

FIG. 15

AMPHIBOLES. — End-on view of the double chains. The " steps " of the cleavage paths are steeper than in pyroxenes and result in cleavage planes inclined at 56°.

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THE AMPHIBOLES.

The (110) cleavage of the amphiboles follows a similar path to that of the pyroxene cleavage, but since the silicon-oxygen chains are double the step-like path is steeper (Figure 15) and the angle between the two prism directions is about 56°.

Regarding amphiboles, A. F. Wells states that they invariably contain some hydroxyl and that aluminium may replace some of the silicon in the double chains. Isomorphous replacement is very common.

Crysotile, which is often used commercially as asbestos, is closely related to the amphibole group, but contains more hydroxyls and more Mg, with the result that the chains are coated with OH anions. Bonding between chains is usually between Mg and OH or water molecules, and separation of the fibres in this mineral is facile to an extreme.

SI_2O_5 SHEETS.

Having digressed to deal briefly with the amphiboles, the writer may perhaps be excused for going on to an even less gem-like family—the micas. A family, nevertheless, of vast importance in the consideration of cleavage. The clay minerals and talc are also examples of this type of layered Si-O structure.

The simplest form of the structure is an infinite sheet of Si-O tetrahedra, each linked to its neighbours by three oxygens (Figure 7e). In the clays and talc the remaining negative charge of the fourth oxygen is taken up in various ways with hydroxyl and Al groups forming layers which have no residual charge and hence no outside cations to bind them together. They are held only by the small residual charges known as Van der Waals bonds and can slip, glide, cleave or break with a minimum of applied energy. This is a factor which contributes greatly to the slipperiness of clays and to the lubricating qualities of talc.

In the micas the structure is more complex. The layers consist of two single layers of SiO_4 tetrahedra with their vertices pointing inwards and bonded together by Al or Mg cations and OH anions. One in four of the tetrahedra in the structure is centred by aluminium instead of silicon. The resultant double sheets carry a negative charge and the hexagonal holes which are apparent in Figure 7e accommodate large potassium or other alkali atoms which bind the sheets together. These large K atoms are univalent and are situated between twelve oxygens. The bonding between layers is therefore not only comparatively sparse, but also very weak when compared with the bonds within the layers. From this fact arises the cleavage for which mica is so well known. Figure 16 is an idealized picture of the layered structure.

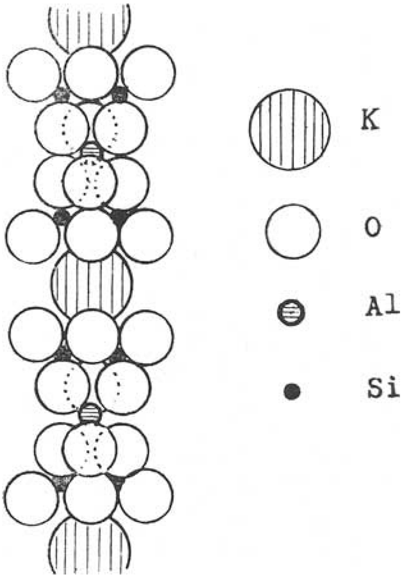

FIG. 16

The sequence of the atom layers in mica. Two of the six anions surrounding the Al cations between the SiO tetrahedral layers are hydroxyls.

Cleavage separates the sheets which are weakly held by large alkali cations.

A group known as the brittle micas has equal numbers of Al and Si atoms in the double layers, with the result that they carry twice the normal negative charge. The atoms between the layers are then smaller bivalent calciums, and the layers are held more strongly. This, combined with the weakening of the layers by the additional aluminium atoms, causes the mica to be harder, and brittle and rather less cleavable.

THREE-DIMENSIONAL SILICATE FRAMEWORKS.

Structurally the various forms of quartz and its polymorphs are examples of this type of lattice, but before we discuss these there is one other gem series to be considered.

There are actually three important mineral classes possessing " framework " silicate structures: the feldspars, zeolites and ultramarines. The two latter do not greatly concern us, although lapis lazuli is a massive mixture of three ultramarines. The zeolites are of importance as water softeners, the gaps in their structures being of sufficient size to permit the free interchange of large sodium and calcium atoms.

THE FELDSPARS.

These are the commonest of all rock-forming minerals and are of great importance in that connection. But, being rather soft and of low density and refraction, they have not achieved much importance as gems. They are known in this connection only by moonstones, microcline, labradorite and occasional cut specimens of yellow orthoclase, blue oligoclase and other colours.

Broadly the feldspars are divided into monoclinic (the orthoclase feldspars) and triclinic (plagioclase feldspars), the latter consisting of an isomorphous series between the sodium-feldspar, albite, and the calcium-feldspar, anorthite. The small size of the Na and Ca cations when compared with the K and Ba atoms of the monoclinic group is responsible for the lower symmetry.

The fundamental structure of all feldspars is a complex chain of Si-O tetrahedra (best described as fourfold rings of tetrahedra joined vertically by alternate edges (Figure 17)). The external oxygens of such chains connect directly to other silicon atoms in other such chains, so that the entire crystal is filled with a three-dimensional network of silicon and oxygen atoms which is in effect one vast negative ion.

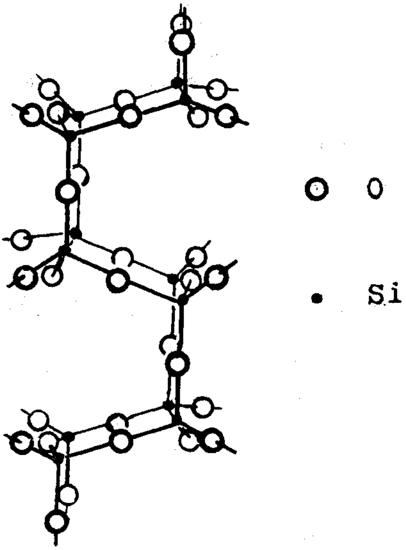

FIG. 17

An idealized version of the feldspar Si/Al-0 chain. Chains of this type run parallel to the *a* axis in feldspar crystals and are held one to another by comparatively sparse Si-O bonds and weak alkali-oxygen bonds.

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The fact that the structure is negative needs some explanation, since, if it consisted only of silicon and oxygen, there would be no surplus negative charge to take up other cations in the structure. The reason for the charge is that in feldspars, as in micas, trivalent Al cations replace one in four of the tetravalent silicons in the network. (In anorthite the ratio is 2:2.) It has not so far been possible to assign definite positions to these Al atoms, although everything points to an orderly rather than a haphazard arrangement.

The chain structure obviously gives rise to considerable gaps capable of accommodating the large K, Ba, Na and Ca cations which are present to balance the negative charges. It is noticeable that the smaller cations, such as Fe, Mg and Cr, so common in other minerals, find no place in the feldspar formulae. The available spaces are all too large.

The low density of the feldspars is further evidence of the considerable departure from a close-packed oxygen structure.

Treated simply, the feldspar crystal consists of comparatively strong chains of Si/Al-O tetrahedra running parallel to the *a* axis. Laterally these chains are held together by a lesser number of Si/Al-O bonds and by the very much weaker bonds to the larger alkali metal ions. Cleavage, which is parallel to these chains, necessarily involves breaking some Si-O bonds as well as those weaker ones between alkali and oxygen.

The cleavage of plagioclase feldspars is to some extent affected by the alteration of symmetry, and the two pinacoidal cleavages are not equally defined. There is another imperfect cleavage apparently cutting across the chains in the sodium-feldspar, albite. All of these triclinic feldspars are brittle and it seems probable that this factor increases and ease of cleavage lessens as the anorthite end of the series is approached, owing to the greater proportions of Al and Ca cations.

The X-ray analysis of the feldspars is by no means complete and many puzzling factors have yet to be solved. The problems of twinning, intergrowths and near isomorphism are among the many that are still only partly understood.

QUARTZ. SiO_2. Hexagonal, trigonal. S.G. 2.65. Cleavage: Pyramidal (1011), difficult and seldom observed ; prismatic (1120), more difficult ; basal (0001), more difficult.

TRIDYMITE. SiO_2. Hexagonal, trigonal. S.G. 2.30. Cleavage: Prismatic (1010), not distinct.

CRISTOBALITE. SiO_2. Cubic. S.G. 2.35. Cleavage: None observed.

Finally, we come to the most concentrated " silicate " of them all, the pure oxide quartz. No longer are any silicons replaced by aluminium, allowing the inclusion of other metal cations. The framework structure consists simply of an infinite lattice of silicon-oxygen bonds, every silicon bound directly to four oxygens and every oxygen to two silicons. The 2:4 co-ordination has been reached.

As may be expected, the unity of bond type in every direction throughout the structure produces a strong crystal. But when the comparative strength of the Si-O bond and the Al-O bond is considered, the low hardness of quartz (7) is perhaps difficult to understand. However, the densities of quartz, and of polymorphs, tridymite (2.30) and cristobalite (2.35), are low and indicate structures in which the oxygens are not close-packed. This is undoubtedly due to the *small* size of the silicon cations, and is probably the reason for the lower hardness of these minerals when compared with that of corundum (9), in which the structure is close-packed.

At the same time, the strength of the Si-O bond is effective in the matter of cleavage. Quartz shows an obscure pyramidal cleavage, very difficult to produce, and two others even more difficult. No cleavage has been observed in cristobalite, and only one indistinct direction is known in tridymite. All these are probably due to the distortion of the lattices into gap structures.

It has been suggested that the three minerals, the exceedingly common quartz and the very rare tridymite and cristobalite, are temperature modifications of each other. Each of them certainly has a low and high temperature form, and quartz, when sufficiently heated, can be made to change slowly to tridymite and finally to cristobalite. The change is a difficult and complex one involving the breaking and reshuffling of Si-O bonds. This difficult transition accounts for the fact that all three are known at ordinary temperatures. Neither tridymite nor cristobalite have been found in crystals large enough to warrant their being cut as gems. Their only claim to gemmological fame lies in the fact that it has been suggested that the fissures in the silica gel, opal, are lined with cristobalite.

In quartz, the silicon-oxygen tetrahedra are joined in spirals parallel to the *c* axis. The right- or left-hand twist of these spirals is responsible for the right- and left-handed crystals which are a feature of the mineral.

Quartz is well known for its invariability of physical constants. This may be taken as further evidence of the strength of the Si-O bond, which permits no isomorphous intrusions of other cations. Coloured varieties are allochromatic and contain the colouring matter as colloidal inclusions in no way assimilated into the chemical structure of the crystal.

The difference between the three minerals lies basically in the way in which adjoining SiO_4 tetrahedra are related. This is best seen in Figure 18.

The conclusions and inferences which may be drawn from this discussion of cleavage are necessarily broad, for the analysis of atomic structures is still in its youth, and a great deal of research will be needed before anything like a complete understanding can be reached. Many of the structures discussed have not been com-

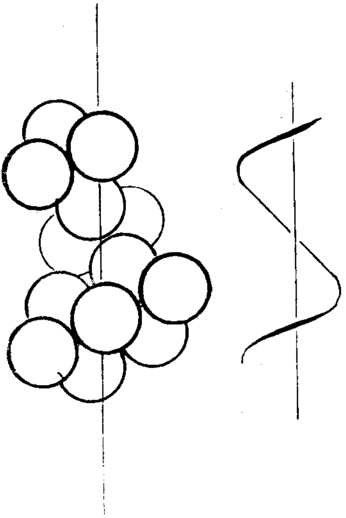
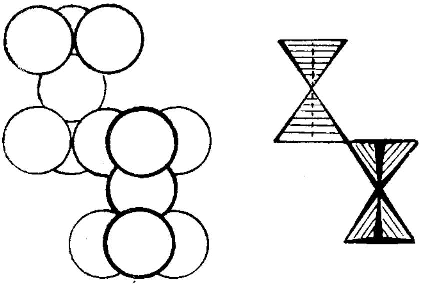


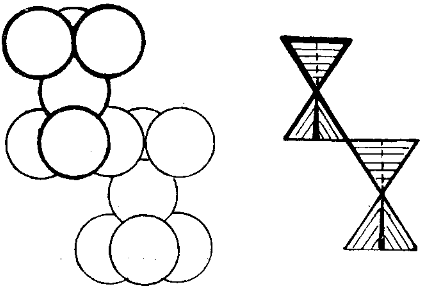
Fig. 18

Diagrams showing the linking of silicon-oxygen tetrahedra in the structures of quartz, tridymite and cristobalite.

The spiral sequence in quartz is responsible for that mineral's unique rotatory polarization. This is the most close-packed SiO_2 structure and has the highest specific gravity (2.65).



In tridymite the Si-O-Si angle has straightened from the 145° of the quartz spiral to 180°, with a resultant opening-out of the lattice, lowering the S.G. to 2.30.



In cristobalite the Si-O-Si angle is again 180°, but the inversion of juxtaposed tetrahedra closes up the lattice a little, and the S.G. is slightly higher at 2.35.

Such cleavage as exists in these minerals must be due to the gap structures and possibly, in the case of the pyramidal direction in quartz, to direct oxygen layering.

pletely analyzed, and in many cases the texts available take little or no account of their cleavage.

However, certain general rules seem to apply, and it may, for instance, be assumed that cleavage surfaces are neutral, that the smaller cations tend to be more strongly bonded to their anions than are the larger ones. The importance of the silicon-oxygen complex ion cannot be over-emphasized. The inclusion of fluorine or hydroxyl anions generally produces weak planes in a crystal structure. Gap structures are obviously not as strong as close-packed ones, a fact reflected in both hardness and cleavage.

A perfect crystal structure probably does not exist, although diamond approaches that state. Other minerals are far from perfect either chemically or crystallographically and their cleavage is undoubtedly affected thereby.

There is still an enormous amount of work to be done before the structure of crystalline matter is fully understood. And while atomic physicists are side-tracked at the other end of the periodic table tracing down bigger and better destructive agents among the radio-active elements, it will probably be a long time before sufficient work is done on the common elements, which largely comprise our mineral heritage, to enable final and conclusive arguments to be made.

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ASSOCIATION NOTICES

ANNUAL MEETING, 1950

The twentieth (fourth since date of Incorporation) Annual General Meeting of the Association was held at the British Council Cinema, Hanover Street, London, W.1, at 5.30 p.m., on Wednesday, March 22nd, 1950.

Mr. F. H. Knowles-Brown, Chairman, who presided, welcomed members and expressed regret at the inability of the President to be present because of indisposition.

The Annual Report and Accounts for the year ended December 31st, 1949, were presented to the meeting and it was moved from the Chair "That the Report of the Council and the audited Accounts for the year ended December 31st, 1949, be and are hereby approved and adopted." Mr. Gordon Blythe, Southend, seconded the resolution and expressed appreciation of the work of the Association. The resolution was unanimously approved.

There being no other nominations, the following Officers were declared to be re-elected:—

President: Dr. G. F. Herbert-Smith.
Chairman: Mr. F. H. Knowles-Brown.
Vice-Chairman: Dr. G. F. Claringbull.
Treasurer: Mr. S. F. Bones.

Mr. J. H. Saunders and Mr. A. S. Braunfeld were appointed to act as scrutineers for the postal ballot for election of Fellows to serve on the Council. As the result of the ballot, Mr. B. W. Anderson and Sir James Walton were re-elected and Mr. A. R. Popley and Dr. W. Stern elected.

Messrs. Watson Collin and Co., Chartered Accountants, were re-appointed as Auditors to the Association.

After the Annual Meeting a short film was shown dealing with the Microscope. Following this, Mr. F. H. Knowles-Brown gave a review of some of the more important gemmological developments during 1949. He referred to the technique of measuring curved surfaces on the refractometer which had been developed by a member of the Gemological Institute of America. He also referred to the question of synthetic stones. It seemed that man was struggling all the time to do something as well as, if not better than, nature. Why should there be this curious desire to produce something which nature does? It should be realized that of diamond, sapphire, ruby, emerald and pearl only one was not produced synthetically or artificially. The Chairman dealt at length with the production of synthetic emerald in the United States and submitted that the people in this country were not likely to be enamoured with the recently produced synthetic rutile. He felt it was too gaudy for the average British taste.

Reference was also made to various instruments devised by Fellows of the Association, the most outstanding being the balance made by Sir James Walton. This had been on show at the Association's 1949 Gemmological Exhibition and later in the evening Sir James himself explained the balance to members. Two students at Chelsea had devised simple and inexpensive polariscopes. One in Scotland—Mr. D. J. Ewing—had experimented with light sources for absorption spectra tests.

Mr. Knowles-Brown continued: " I personally was particularly interested to read and also see details about the heat-treating of zircons. When I was much younger and studying gemmology, all I was told was that the colour of blue and golden zircons was caused by heating, but it was not until this year that I was made aware of what really went on, and I am sure we are grateful to Mr. Lindley and Mr. Buckingham for making this information available to us."

After referring to new books published on gemmology, both in this country and elsewhere, the Chairman thanked those Fellows of the Association who had given talks to institutes, clubs and similar organizations. He felt that their work in telling the public about gems was an influence for the good of the jewellery trade. Specifically he added: " I mention jewellery trade, for it must always be remembered that it was from the jewellery trade that this Association has emerged and our roots extend long and deeply into the trade."

In concluding his remarks, Mr. Knowles-Brown referred to the extent that the technique of testing by absorption spectra was used in this country and to the debt which was owed to Dr. E. Gübelin, of Switzerland, for making us more aware of the diagnostic importance of gemstone inclusions.

Mr. B. W. Anderson spoke at length on the new technique of obtaining refractive indices of cabochon stones on the refractometer, and acknowledged the debt we owe to the two members of the Gemological Institute of America—Lester B. Benson and R. Crowningshield—who had developed it. It was a simple method which required care and practice. A drop of liquid was placed on the refractometer and then the curved surface of the stone was applied as if it were an ordinary flat surface. The eye was withdrawn from the eye-piece to about ten inches, when there should be seen a little disc in the eye-piece, representing the contact of the stone with the refractometer. What the viewer had to do was to poise his eye to divide the area into dark and light sections and then to focus on the scale to see at what point the division takes place. To do that is easier if the eyepiece was removed and a low power lens used.

There was more in this use of the refractometer than that. Sometimes it was difficult to get a reading on a stone with a flat facet, particularly with paste. The distant vision method did enable a reading to be got where the ordinary method failed. The same applied with quite small stones. One limitation was still the detection and measurement of double refraction. Probably with a polaroid disc this might be achieved.

Mr. Anderson ended with a few further guiding words. Be sparing with the contact liquid. Get the stone surface positioned in the centre of the refractometer table. The rest was largely a matter of practice. It was best to start with a synthetic cabochon in the middle register. At the lower and upper ends of the scale there was some optical distortion. Finally, persevere.

Sir James Walton then spoke about his balance, saying for many years they had been trying to get an instrument which would give an accurate reading of specific gravity, easily and quickly. Apparatus now existing had to be corrected often or was slow. He then described his balance, a working one being on the table, which would handle from one up to forty carats and could also be quickly adapted as an ordinary balance to give a reading up to two places of decimals.

The meeting concluded with the showing of a film in technicolour on the making of " Optical Glass."

COUNCIL MEETING

At a meeting of the Council of the Association held on Wednesday, February 15th, 1950, the following were elected to membership:—

FELLOWS:

R. J. Barker, London.
C. M. L. Carr, Montreal, Canada.
D. Dresme, Amsterdam, Holland.
J. M. Duncan, Glasgow.

PROBATIONARY:

R. W. Batty, Liverpool
M. A. N. Caffoor, London.
H. A. Clarke, London.
R. H. Corfield, London.
E. G. H. Drury, Birmingham.
F. L. D. Ekanayaka, Colombo, Ceylon.
H. C. Fishberg, Edgware.
Miss B. M. Henn, Bridgnorth.
H. Myhre, Ljan, Norway.
John F. Scott, Lincoln.

ORDINARY:

Kurt Decker, Stockholm, Sweden.

GIFTS

The Council of the Association acknowledges with grateful thanks small parcels of gemstones for the Association's collection from Mr. F. E. Lawson Clarke, Chairman of the National Association of Goldsmiths, and Mr. W. E. Payne, Bromley.

TALKS BY FELLOWS

F. E. Leak: "The Science of Jewellery." January 19th, the "Ark" Club, Westburn Park, Bristol; February 6th, King Street (Bristol) Methodist Church Youth Club; February 14th, Eastville (Bristol) Townswomen's Club. "Diamonds." March 13th, "20/40" Club, Bristol.

R. Webster: "Pearls." January 27th, Central School of Arts and Crafts, London, W.C.1.

Letters to the Editor

HORIZONS OF GEMMOLOGY

Dear Sir,

Regarding Mr. Pearl's article in your January issue, "Broadening Horizons of Gemmology," we think it a pity that his very reasonable plea against the imposition of arbitrary limits to gemmology should be vitiated by a sample of the patronage which the mineralogist too frequently inflicts upon the gemmologist. We refer to the passage, "It is largely because they are primarily professional mineralogists that such men as Herbert Smith, Kraus, Alexander, Pough, and others of that high calibre qualify as gem experts; otherwise the only gem experts would be practising jewellers, who, after all, were making a livelihood from their untechnical knowledge of gems long before science invaded the field."

However true this may be in the States, it certainly doesn't apply over here, where the pioneers of gemmology were persons actively engaged in the trade, such as Tully and Barnett. In those early days mineralogists, with a few honourable exceptions, regarded the infant science with aloof distaste, and it is only since the jewellers have lifted themselves up by their own shoe-strings (so to speak) that mineralogists have as a body developed an interest in the subject. In any case, even if one holds the view implicit in Mr. Pearl's article, that jewellers are in general an ignorant lot whose amateur gropings in gemmology require external guidance, it is arguable that the tutelage of the physicist is likely to be more profitable than that of the mineralogist. Certainly the work and teaching of a physicist and chemist, Mr. B. W. Anderson, have been so outstanding in gemmology that his name alone serves to confirm this in no uncertain fashion.

The cavalier dismissal of research into the mythology of gemstones as " nonsense " is oddly discordant with Mr. Pearl's general thesis. We agree with him in having but a lukewarm enthusiasm for this facet of gemmology, but consider nevertheless that it is an integral and valuable department of that subject.

Yours sincerely,

THOROLD JONES.
E. J. BURBAGE.

26, Wolseley Gardens, W.4.

Dear Sir,

I regret that my article should have tended in any way to provoke an unfavourable reply from Messrs. Thorold Jones and E. J. Burbage, whose purposes in advancing the field of gemmology are fundamentally the same as my own. I had hoped that instead it would lead to a re-orientation and broadening of our viewpoints and a furthering of the interests of gemmologists the world over.

The term " untechnical knowledge " should not offend anyone except those who make a pretence to information and training they do not possess, an error not committed by those who are formally associated with the Gemmological Association of Great Britain. We all have an untechnical knowledge of every subject except our own specialty. Most jewellers, even to-day, even in Britain, have an untechnical knowledge of gems. Messrs. Jones and Burbage belong to a distinguished minority.

Everyone, I believe, who cares to exert himself can become a capable gemmologist, be he jeweller, mineralogist, chemist, or poet. It is, however, the mineralogist—because of his required basic training in physics, chemistry, and geology—who happens to be in the best position, through no fault of his own, to qualify as a gemmologist. Your correspondents were not justified in interpreting my statement as a slur upon the worthy members of the jewellery trade. There should be no occasion for any hard feelings in this matter ; I apologize sincerely for any that may have arisen.

The last criticism is likewise the result of a misunderstanding, a confusion of words. I defined gemmology as the *science of gems,* hence the superstitions, folk-lore, and old wives' tales are not a part of it. They are indeed entertaining and interesting nonsense (so is "Alice in Wonderland ") —but they are not gemmology. As I said originally, if we can spend time on such things, we should consider also the many minerals and rocks that deserve a place in gemmology even if they are not sold in the jewellery stores. This is part of the broadening horizon.

Yours sincerely,

RICHARD M. PEARL.

Colorado College.

FINE CUT OF SYNTHETIC RUTILE

Dear Sir,

I should greatly appreciate if you could publish the following note on Mr. G. G. Waite's " Approaches to the Fine Cut of Synthetic Rutile " (this Journal, Vol. II, No. 2, April, 1949, pages 35 to 44).

Mr. Waite's suggestions are based on practical investigations of synthetic rutile. My suggestions for a suitable fashioning of synthetic rutile had been made from optical considerations and calculations. For conventional reasons the brilliant-cut was adopted, and I concluded with the words: " It will be interesting to see to what extent these values will prove satisfactory in practice."

The quesion will easily find its objective answer as soon as synthetic rutile, cut according to calculated values, can be compared with the cut now in vogue, as well as that suggested by Mr. Waite. " Reflectograms," which I myself cannot at present provide yet, would greatly facilitate such a comparison.

As for the Jubilee-cut of synthetic rutile, optical theory appears to indicate some alterations of the angles suggested by Mr. Waite ; his values are set out below together with the revision:—

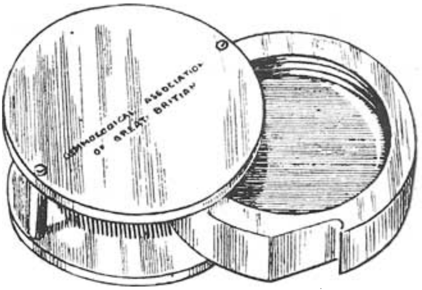
TABLE

SUGGESTION FOR THE JUBILEE-CUT OF SYNTHETIC RUTILE
(angles of facets with the girdle plane)

	Mr. Waite's values	**Suggestion for improved new values**
Main pavilions	40°	45.0°
Point	35°	41.3°
Main crown	30°	23.0°
Star	10°	9.0°

Yours sincerely,

Freyung v. W., Germany. W. F. EPPLER.



GEMMOLOGICAL ASSOCIATION OF GREAT BRITAIN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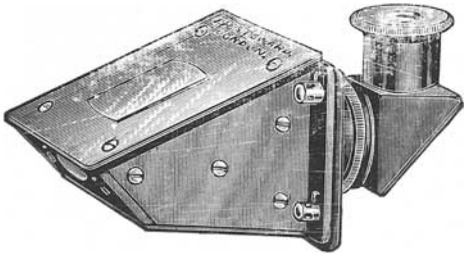
LONDON



Vol. II
No. 6
April, 1950

CONTENTS

ASSOCIATION NOTICES :—

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