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A CONTRIBUTION TO THE GENEALOGY OF INCLUSIONS

by E. J. GÜBELIN, Ph.D., C.G. F.G.A.

QUITE apart from the tendency to take the subject of inclusions out of the sphere of imperfections and accentuating their aesthetic value, particular emphasis was hitherto put on the description of the phenomenological appearance in order to set forth their diagnostic and practical importance. Under this aspect a classification of inclusions was established which agreed best with their importance as a means of identification, and occasional discussion of the genesis of inclusions was only interwoven for the purpose of incidentally shedding light on the origin of gemstones themselves.

A new phase may now begin by concentrating more intensified research on the formation of the inclusions themselves, and some important steps have already been taken. The problem offers enormous difficulties and various explanations as well as experiments which were considered to reveal the truth had subsequently to be given up. It may, therefore, be comprehensible that in spite of the great number of studies on inclusions, the question of the formation of inclusions and the morphology of the phenomena have, with a few exceptions, been hitherto neglected. Thus the morphology of inclusions, which is an essential factor for diagnosing gemstones, will in future be increased to a valuable extent by the genealogy of inclusions.

Under the aspect of the genetic characteristics of all types of inclusions—solid, liquid and gaseous—which might be united in a system, one could divide them into two main classes :—

(a) Primary Inclusions,
and (b) Secondary Inclusions.

Both classes may again be sub-divided into two groups :—

Primary Inclusions into (aa) Autogenetic Inclusions,
(ab) Xenogenetic Inclusions.
Secondary Inclusions into (ba) Healing Fissures
(Secondary Liquid Inclusions),
(bb) Inclusions formed by exsolution.

(aa) Autogenetic Inclusions

Autogenetic inclusions are such formations as originate from the mother liquor, e.g. glass (Fig. 1) or magma for pyrogenetic minerals, and are caused by peculiarities of the crystal growth, especially through skeleton-like (Fig. 2), step-like (Fig. 3), " druse "-like development ; therefore they are always related to real crystal faces, and the so-called " phantoms " (Fig. 4) form a typical example of this kind. All such marks of inhomogeneous, disturbed or irregular process of formation can hardly be considered true inclusions but may much more adequately be called "inhomogeneities." They are usually affected by the conditions of growth and are consequently either irregular or subjected to the law of periodicity. It has been found that inclusions arrange themselves on the faces which have a stronger bond, i.e., the greater speed of growth, and primary inclusions are never found outside these faces and directions. Hence primary inclusions never form intersecting planes or feathers ; yet, since they follow crystal faces, they may meet at angles and create the impression of crossing. These inclusions either occur on faces of the growing crystal or in a plane which was developed as a trace of the movement of an edge, or in a row or string (Fig. 5) upon which (acting as a rail of the movement) the crystal point had moved along. Thanks to the complete wetting of the crystal face with mother liquor, the autogenetic inhomogeneities either reveal the shape of an exact replica of the crystal, or they

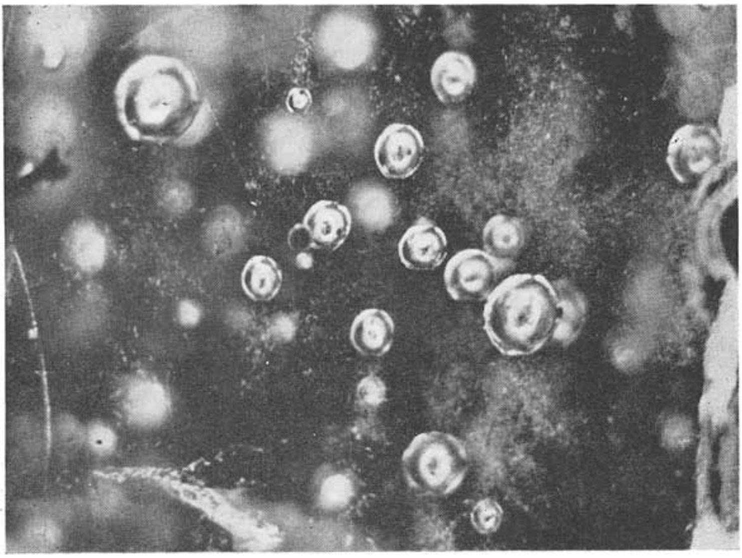

Fig. 1. Glass " bubbles " in peridot. 80 ×.

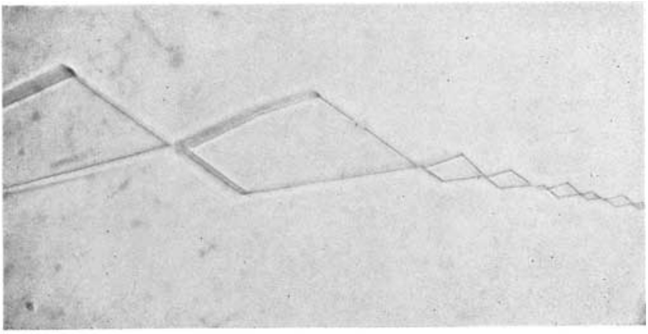

Fig. 2. Autogenetic inhomogeneity as a result of skeleton growth in topaz (Lit. 3). (Photo by K. Schlossmacher.)

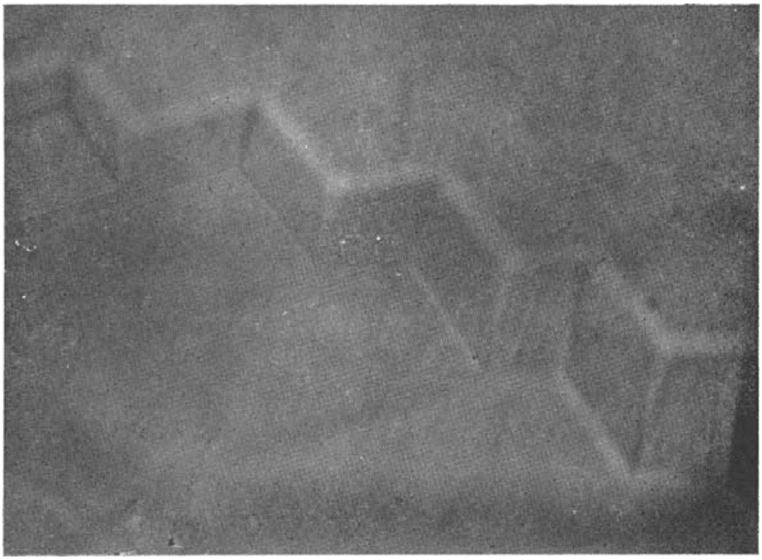

Fig. 3. Step-like markings as a result of irregular growth. (Lit. 6.) Photo by R. Webster.

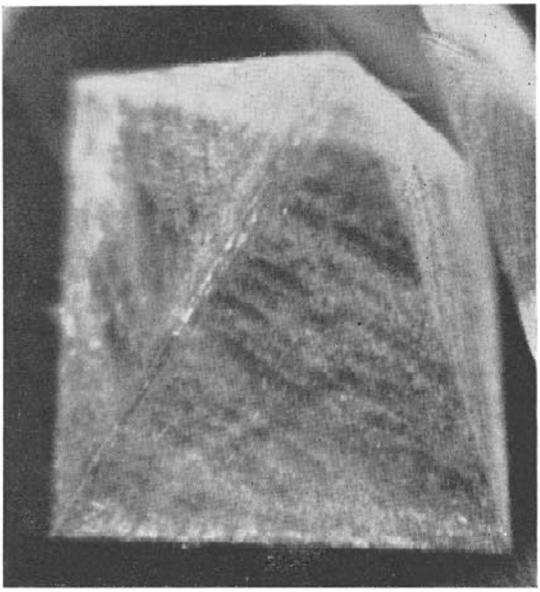

Fig. 4. Octahedral phantom in diamond. 80 ×.

form an accessory sculpture of the face as it was at the moment of being embedded (Fig. 6). In cross-sections one can see the well-known picture of zonal arrangement (Fig. 7), or radial orientation (trace of the edges) (Fig. 8).

(ab) XENOGENETIC INCLUSIONS

Xenogenetic inclusions are any foreign substances enclosed in a mineral regardless of their phase of matter at the moment of being trapped, i.e., solid, liquid or gaseous. Contrary to many autogenetic inclusions, xenogenetic inclusions are true enclosures (inclusions)—foreign substances enclosed in the host mineral. If a foreign matter happened to drop, or rest, or grow on a face of a crystal in *statu nascendi*, it was mechanically enclosed (Fig. 9) and if foreign inclusions densely cover crystal faces, sometimes even in succession, conclusions may readily be derived about the host crystal's habit at previous stages (Fig. 10). Here xenogenetic inclusions have some similarity to the " phantom " formed by autogenetic inclusions. Xenogenetic liquid inclusions are also formed by drops of foreign liquid which did not mix with the mother liquor. Since they did not at all or only partially wet the surface of the growing crystal, they assumed the shape of a drop, which usually became slightly deformed after the growth direction of the growing host. Such slightly deformed drops may often be encountered in quartz (Fig. 11), Ceylon sapphire (Fig. 12), emerald and other minerals, and in the laboratory they can readily be caused in alum crystals by adding olive oil to the aluminous solution. Since the formation of primary inclusions stands in direct relation to the phases of growth of the host crystal, autogenetic and xenogenetic inclusions prefer to arrange themselves according to crystallographic directions. They are normally found in zonal orientation.

(ba) SECONDARY LIQUID INCLUSIONS

The difficulty of explaining the appearance of certain liquid inclusions through primary formation leads to the idea of secondary liquid inclusions. Considering the powerful strain of mechanical pressure on account of geotectonic upheaval, it is not far fetched to assume that in the course of such disturbances crystals fractured along irregular directions, or were affected by some shifting force developing planes and fissures of translation, and that liquid could infiltrate into the cavities of the damaged crystal along fine fissures,

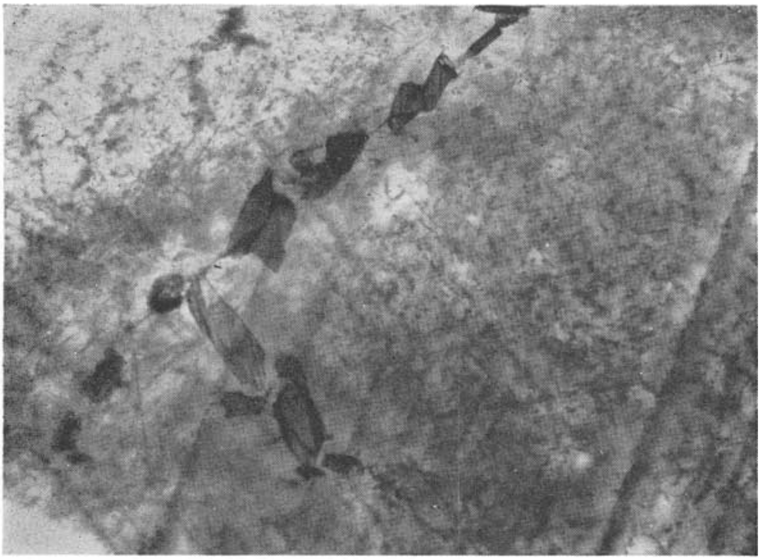

Fig. 5. Sphene crystals tracing crystallographic directions in spinel. 75 ×.

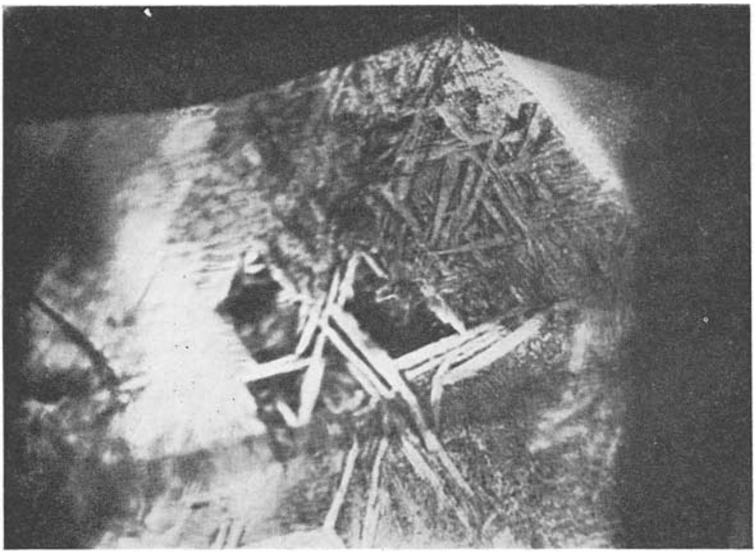

Fig. 6. Sublimation of alien matter on previous crystal face of a ruby. 75 ×.

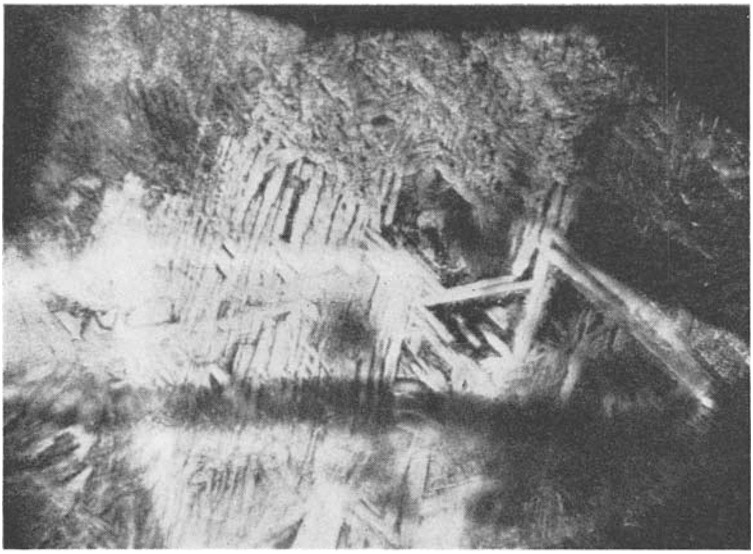

Fig. 6a. Sublimation of alien matter on previous crystal face of a ruby. 75 ×.

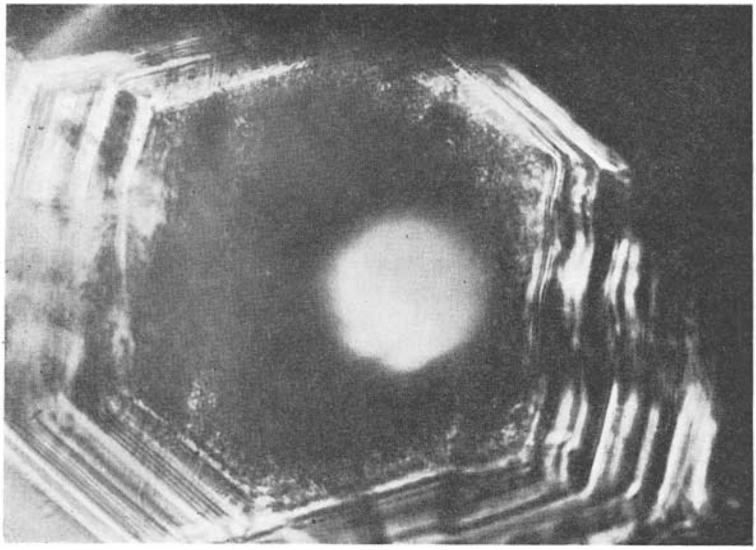

Fig. 7. Strongly marked zonal structure in ruby. 25 ×.

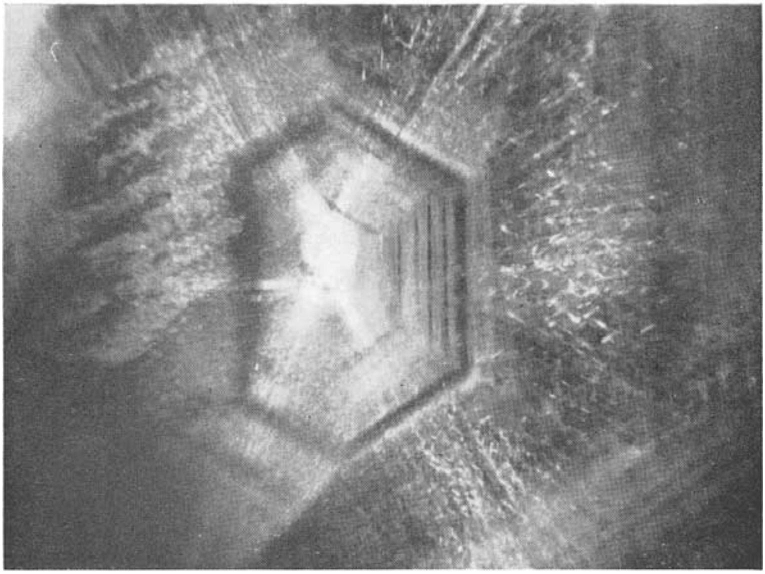

Fig. 8. Zonal structure with radial sub-structure of rutile needles in a sapphire. 15 ×.

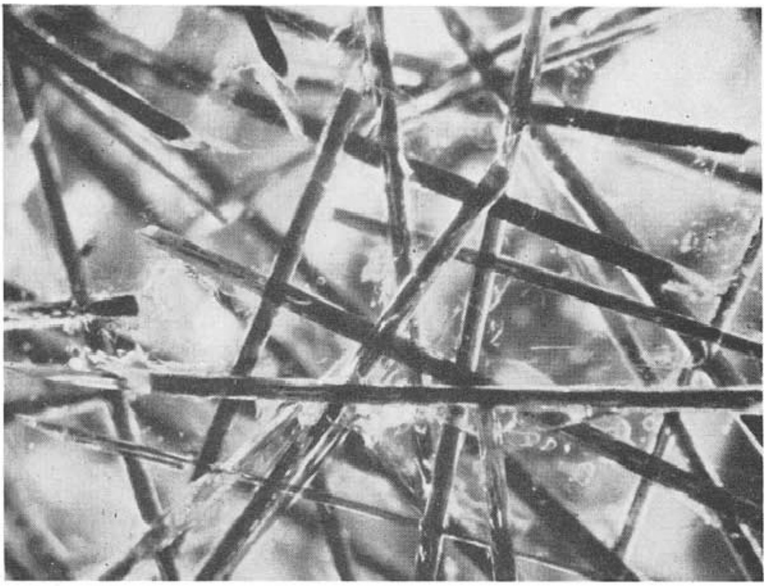

Fig. 9. Tourmaline rod-crystals in quartz. 20 ×

which later on closed up in growing and then healed up. Cracks resulting from change of temperature, contraction, or alteration may have caused the same defect. The whole procedure can only be imagined if it happened as long as the mineral was still in direct contact with its mother liquor, which contained and supplied the remedial ingredients necessary and responsible for the process of closing up. These healing fissures have always special characteristics and display the very typical pattern of liquid inclusions. They traverse the mineral along irregular directions, rarely following crystallographic orientation, and very often intersecting each other (contrary to primary liquid inclusions, which never cross each other). Under the microscope these " feathers " appear to consist of minute liquid drops, all more or less densely arranged in one compact form and of most fanciful shapes. Their geometrical outlines vary in accordance with their location within the fissure and also according to the host crystal which imposes directional growth power on the formation of these inclusions, e.g. in isometric crystals following the contours of the principal faces (Fig. 13), in orthorhombic crystals forming rectangular shapes or lozenges, in hexagonal gems manifesting the main crystallographic directions (Fig. 14), etc. In the narrower part of the wedge-like fissure they are particularly affected by crystallographic influence (Fig. 15), whereas towards the open end of the crack the droplets may change into irregular (Fig. 16), distorted, hose-like, twisted and most bizarre shapes (Fig. 17). The fissures, easily recognizable by the enclosed liquid drops, frequently come to an abrupt end within the crystal along a convex or irregular line (Fig. 18). Here the liquid inclusions are very tiny, increasing in size towards the surface, and they may attain remarkable dimensions sometimes, yet in all cases they are extremely flat.

George Laemmlein (Lit. 1) was successful in carrying out several ingenious experiments in that he partly split crystals of rock salt and nitre (Saltpetre) by pressing the sharp point of a knife against the surface, thus producing an artificial crack. He then allowed solutions of NaCl and KNO_4, respectively, to soak into the fissure which, because of capillary power, filled immediately. After a short while he could observe how dendritic crystals started to grow from the innermost edge of the fissure and how the orientating influence of crystallographic power exerted itself on the dendritic crystals (Fig. 19) and forced them to grow along the directions of

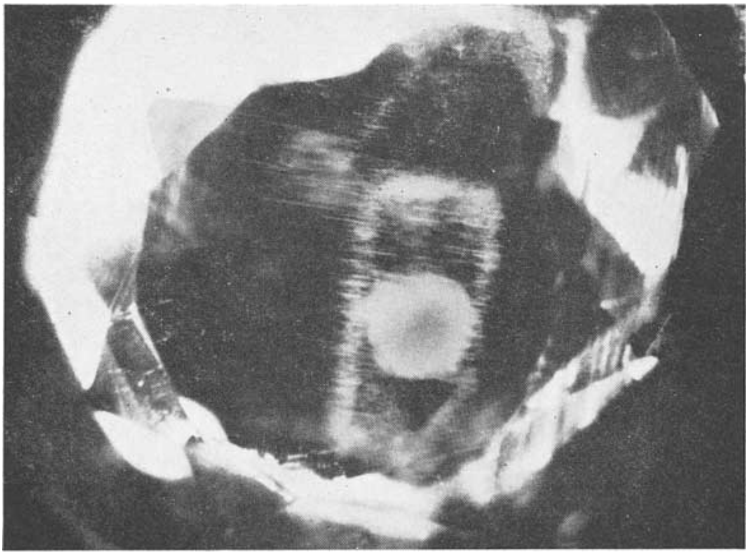

Fig. 10. " Phantom "-like arrangement of " silk " marking previous phase of growth of ruby crystal. 25 ×.

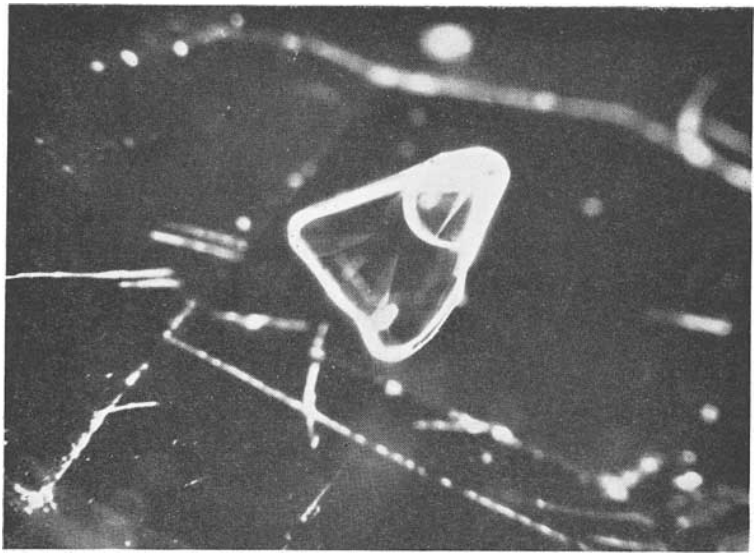

Fig. 11. Cavity filled with liquid and libella in amethyst. 15 ×.

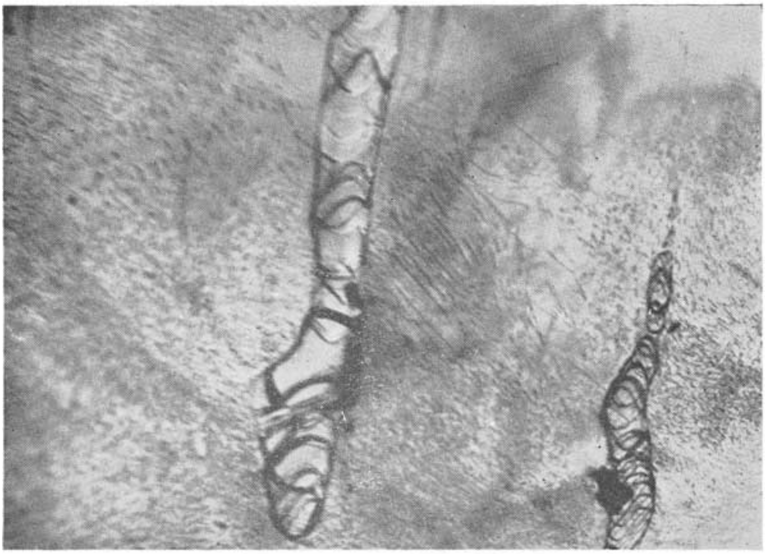

Fig. 12. Stocking-shaped liquid inclusions of primary origin in sapphire from Ceylon. 30×.

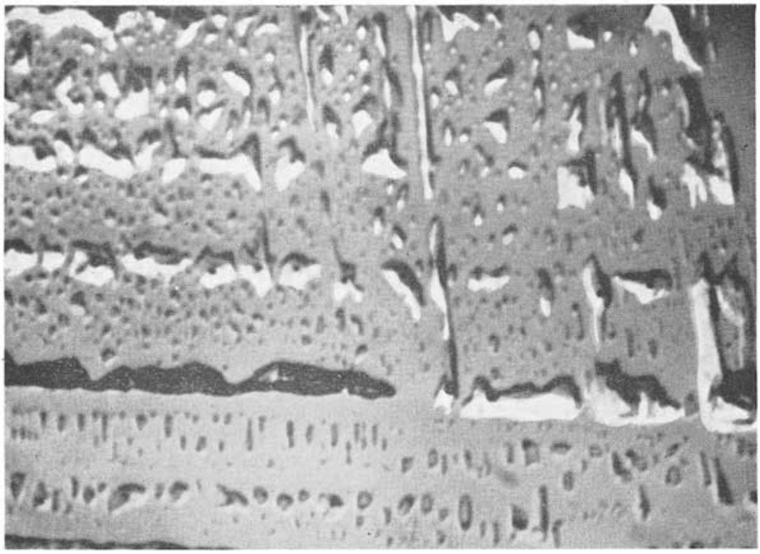

Fig. 13. Fluorspar : healed fissure, liquid drops being affected by directional crystallographic power. 75×.

main growth of the host crystal (octahedron and principal rhombohedron respectively). This is easy to understand if we consider that the growth of the dendritic crystals takes its course within the walls of a homogeneous substance and begins where these walls are closest together. Branches of crystals developed in directions of first, second and third rank and met at last, leaving residual drops of the healing solution (artificial mother liquor) between themselves. In accordance with the conditions and depending on the quantity of healing material, the droplets were smaller or larger, sparsely or more densely distributed. It proved especially instructive to observe that these liquid residuals of enclosed mother liquor did not immediately assume a definite shape, but altered their form continuously in an attempt to decrease their surface energy with unchanged volume. Long channels, large films and hose-like drops revealed a tendency to shrink into numerous small, compact, negative crystals of cubic, octahedral or rhombohedral shape respectively, thus assuming the stable form of liquid inclusions. Many of the inclusions created by this process of healing showed convex contours (modelled by growth) at the beginning, which altered in the course of the distribution of the material into liquid inclusions with concave relief (modelled by dissolution). After a few days the healing process was completed. Comparison between the artificially healed fissures and the natural ones showed entire conformity and led to the conviction that similar healing processes on a much more gigantic scale must occur in all mineral deposits which have undergone mechanical disturbances. Experiments similar to those described were also performed with alum crystals, which disclosed a novelty in that in crystals already containing layers of feathers of primary liquid inclusions the fractures paralleled those layers, so that the layer of secondary inclusions was superimposed upon the layer of primary inclusions. Similar occurrences may also be often met with in natural gems (Fig. 20).

Through these experiments and the observations they rendered possible the intrinsic character of the mechanism of the formation of secondary liquid inclusions and their virtue have been recognized, while their characteristic patterns may be described as follows :—

1. Coincidence of layers of secondary liquid inclusions with fractures, cleavage cracks, translation cracks and contraction cracks simultaneously traversing the elements of crystal growth, such

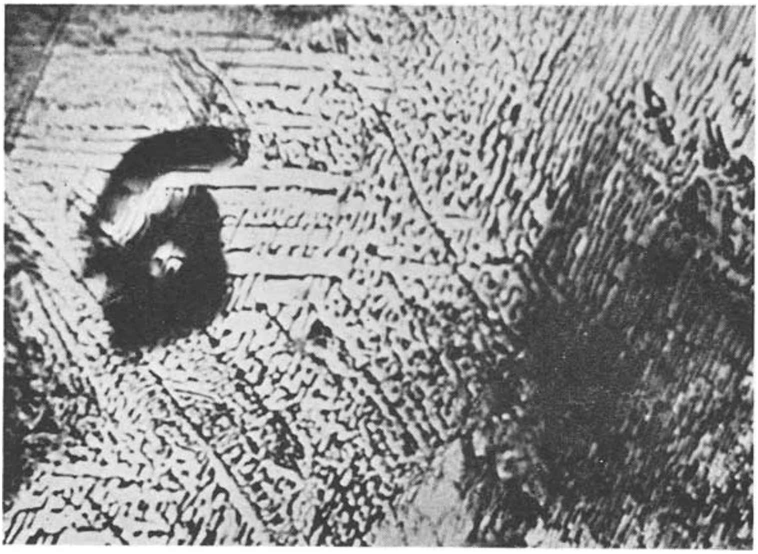

Fig. 14. Ruby : healed fissure, the liquid drops of which are oriented according to crystallographic directions. 40 ×.

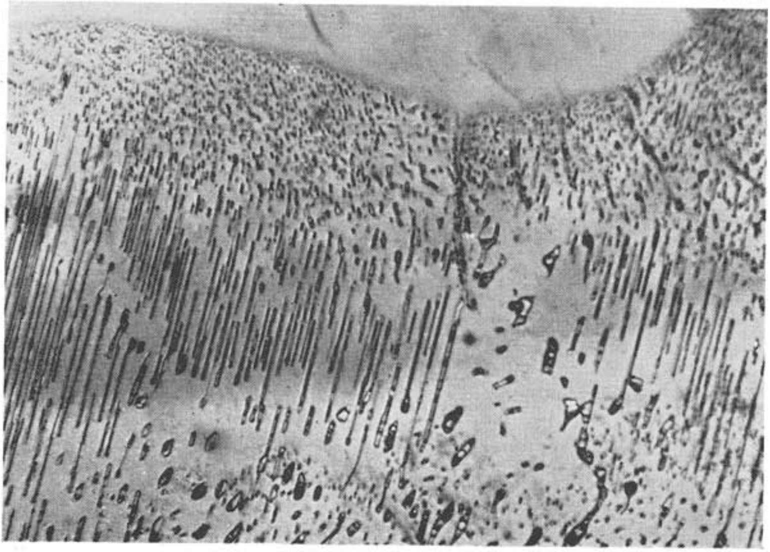

Fig. 15. Healed fissure in Burma sapphire. 75 ×.

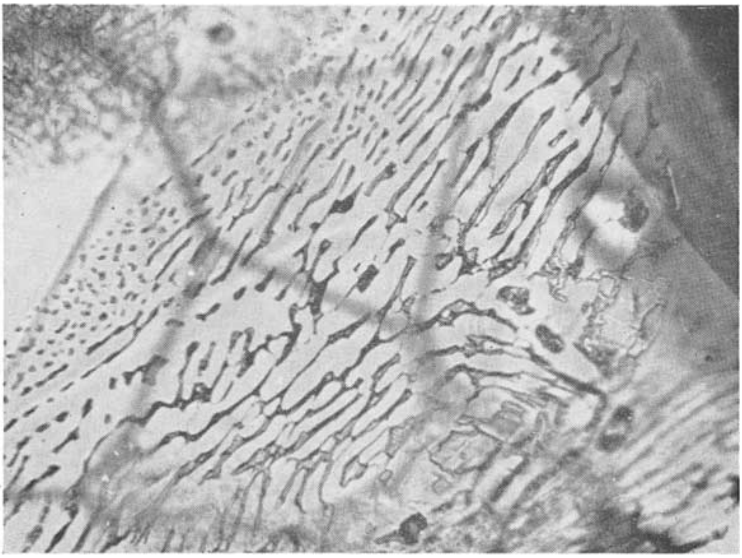

Fig. 16. Healed fissure with irregular liquid drops in Burma ruby. 50 ×.

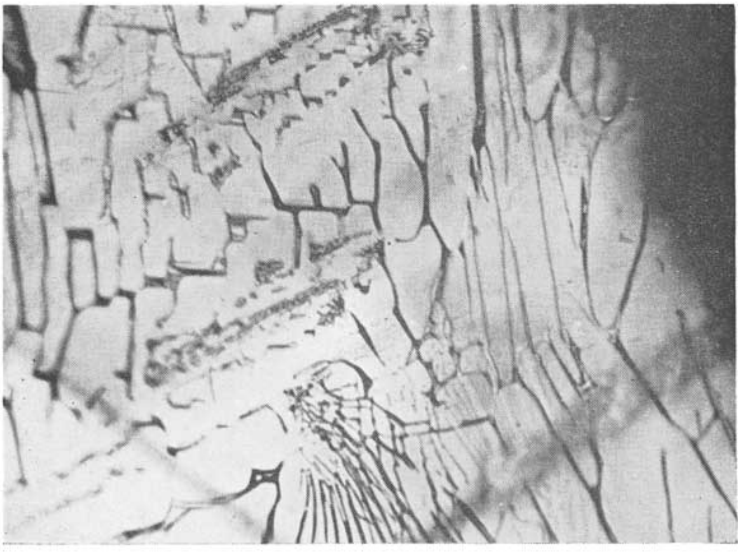

Fig. 17. **Irregular shapes of residual liquid drops in healed fissure in sapphire. 75 ×.**

as zonal colouring and zonal arrangement of primary inclusions, polysynthetic lamellae, etc. (Fig. 21).

2. Layers of secondary liquid inclusions are not only flat (cleavage, translation and contraction planes), but may also be curved, corrugated or conchoidal fractures (Fig. 22).
3. The healing fissures may run parallel to a layer of primary inclusions and through the process of healing the secondary inclusions are superimposed on the primary ones (Fig. 23).
4. Layers of secondary liquid inclusions must not necessarily traverse the whole crystal but may end within the host (Fig. 24). Such healed up fissures are usually wedge-shaped and the dimensions of the liquid inclusions increase from the interior towards the external opening of the fissure (Fig. 15).
5. With regard to their extent, secondary liquid inclusions may attain considerable dimensions, while their thickness is limited by the walls of the crack and in most cases is film thin (Fig. 25).

For all the past years whenever I studied inclusions in gemstones I tried to find the individual characteristics described above in order to separate the inclusions into those of primary and secondary origin. It was thus noticed that secondary inclusions—healed and unhealed ones—may occur in any gemstone ; especially in those of hydrothermal formation and those partly in relation with pneumatolytical processes.

We may now examine some typical primary and secondary inclusions (healing fissures) in gemstones :—

Diamond. In diamond the primary inclusions are much more common than secondary inclusions. Phantom-like clouds (Fig. 26) and marks of growth-phases (Fig. 27) are autogenetic inhomogeneities ; enclosed diamonds and trapped fragments of matrix are also of autogenetic origin, while all those numerous well-known foreign enclosures, such as zircon, graphite, garnet, olivine, quartz and hematite, are xenogenetic (Fig. 28). Among the thousands of diamonds I have tested, I have never found any with definite secondary liquid inclusions, although a great many of them contained cleavage (Fig. 29), or fracture cracks, or fissures by tension or contraction (Fig. 30), many of which were certainly of secondary origin, yet all these flaws appeared to be dry and unhealed. The fact that diamonds are devoid of secondary liquid inclusions may offer a valuable contribution towards an explanation of the genesis

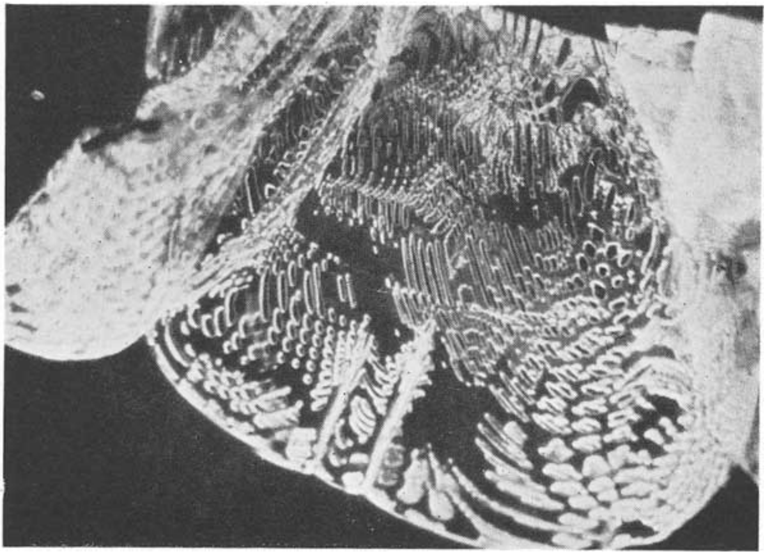

Fig. 18. Healed fissure with individual drops in green beryl. 40 ×.

Fig. 19. Solar pattern of re-crystallization centres in healed fissures in Burma sapphire. 75 ×.

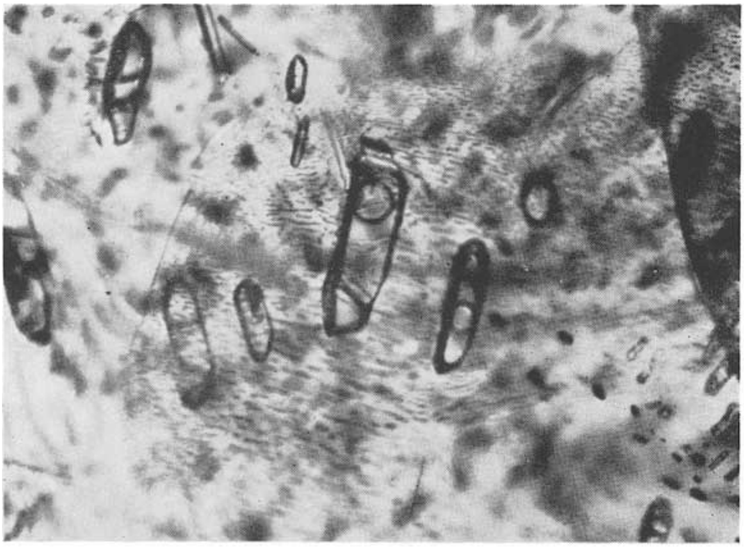

Fig. 20. Primary autogenetic liquid enclosures overlying secondary liquid inclusion in ruby from Ceylon. 125 ×.

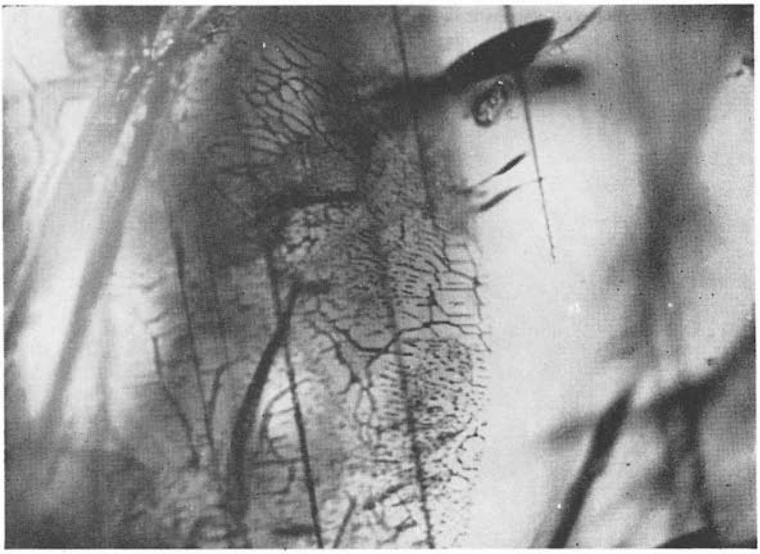

Fig. 21. Network of residual liquid drops of a healed fissure traversing several twin lamellae in Siam ruby. 75 ×.

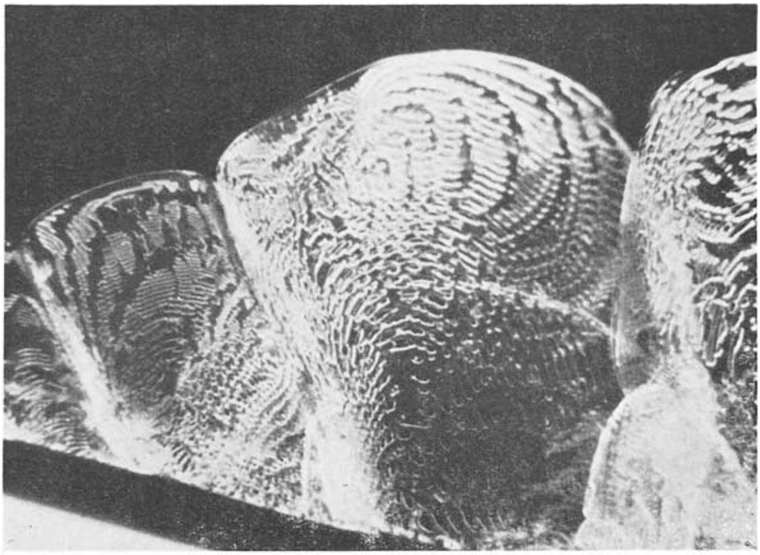

Fig. 22. Succession of various conchoidal healed cracks in green beryl. 30 ×.

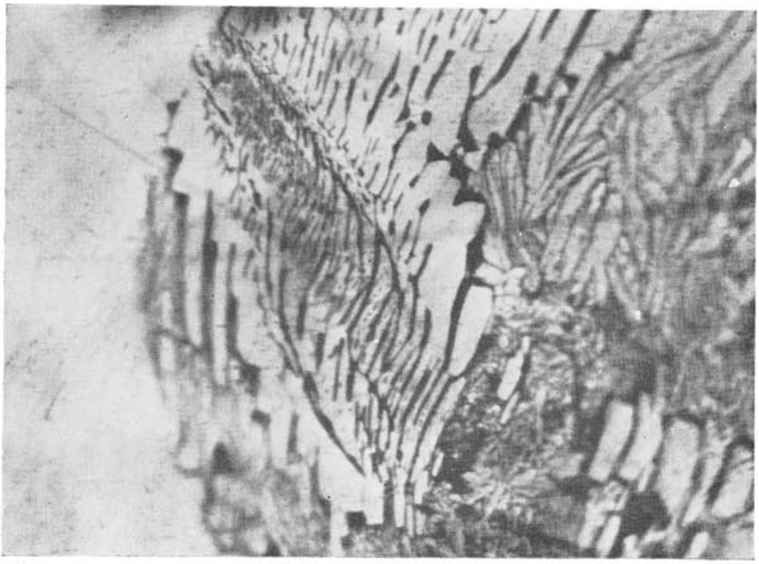

Fig. 22a. Curved and corrugated liquid feather in a Ceylon sapphire. 75 ×.

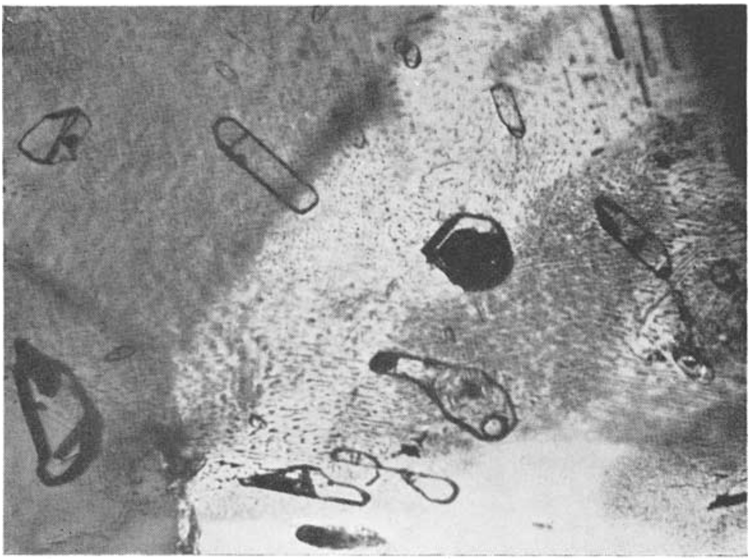

Fig. 23. Primary liquid drops overlying secondary liquid inclusion. 75 ×.

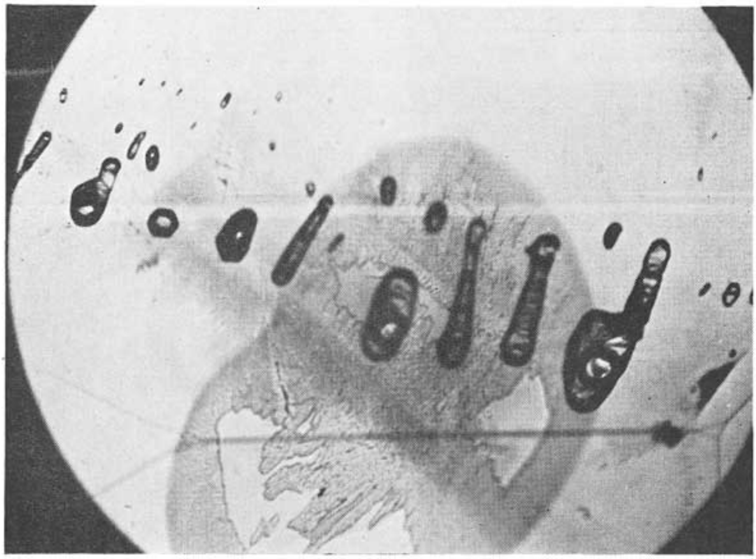

Fig. 23a. Primary liquid drops overlying secondary liquid inclusion. 75 ×.

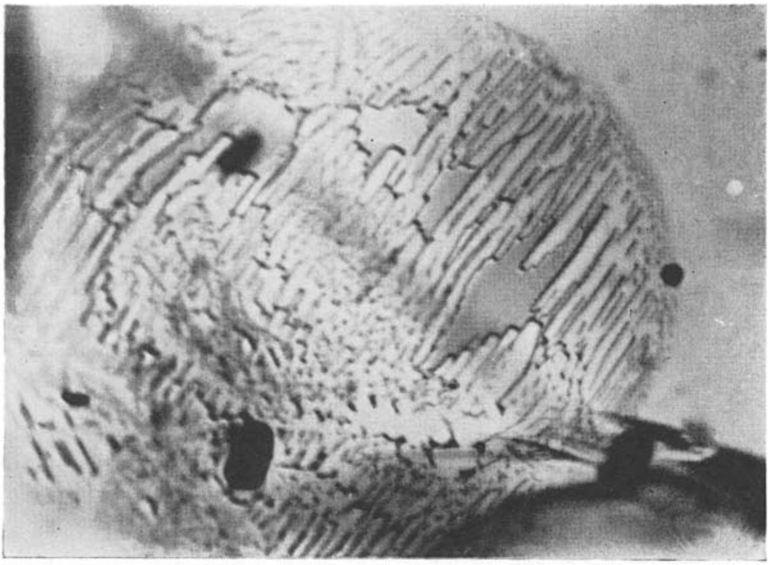

Fig. 24. Healed crack with circular circumference in Ceylon ruby. 125 ×.

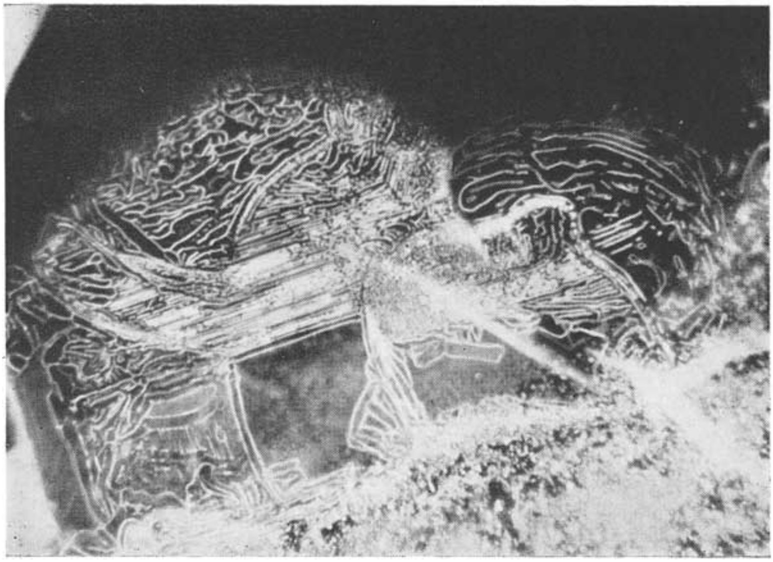

Fig. 25. Extremely thin healed fissure in zircon from Mongka. 80 ×.

of diamond, indicating that the diamond had been formed way down in the " sima " before it was lifted up by the kimberlite magma into the earth's crust, where it was often broken when the blue and yellow ground solidified, or that the diamond was formed in that gaseous carbon crystallized by avoiding the liquid phase (pneumatolytic genesis).

Corundum. With respect to inclusions corundum grants a profusion of interesting material. All genetic kinds of inclusions may frequently be found within one and the same stone. Zonal structure, phantoms, negative crystals filled with mother liquor and opaque grains of corundum such as in Siam rubies and Montana sapphires are autogenetic inclusions (Fig. 31). Xenogenetic inclusions are represented by the great number of foreign minerals, such as zircon, spinel, garnet, ores, rutile, etc. Those well-known liquid feathers which seem to occur at random and often intersect primary inclusions are in most cases healing fissures clearly marked by the residual drops of mother liquor trapped within the healed portions (Fig. 32). They characterize themselves by all the aforementioned features. Healing fissures usually run in irregular directions (Fig. 33), but may, however, sometimes parallel crystallographic orientations (Fig. 34), such as the basis or parting planes, and sometimes traverse same (Fig. 35), or they may be found lying across one lamella which was broken during its growth, subsequently healed and then acted as a seed of a polysynthetically twinned corundum crystal (Fig. 36), and occasionally their shape may portray the hexagonal habit of the host (Fig. 37). Whether the secondary liquid inclusions, that is, the cracks into which the mother liquor subsequently infused, occurred as a result of mechanical strain or in the course of a crystallographic alteration (altering from the α modification into the γ modification) will have to be investigated by further studies, the results of which may give the answer to an unsolved genetic problem about corundum.

Beryl. Many of the heretofore described inclusions in emerald, which often designate the host gem's nature or source, such as pyrite in El Chivor emerald, calcite, coaly substance or parisite in Muzo emerald, actinolite in Ural emerald, tremolite in Habach emerald, are primary inclusions of xenogenetic origin.

In beryl from all deposits, secondary liquid inclusions are found in great quantities and all observations made hitherto have shown that, in general, healing fissures lie parallel to the basal plane or to

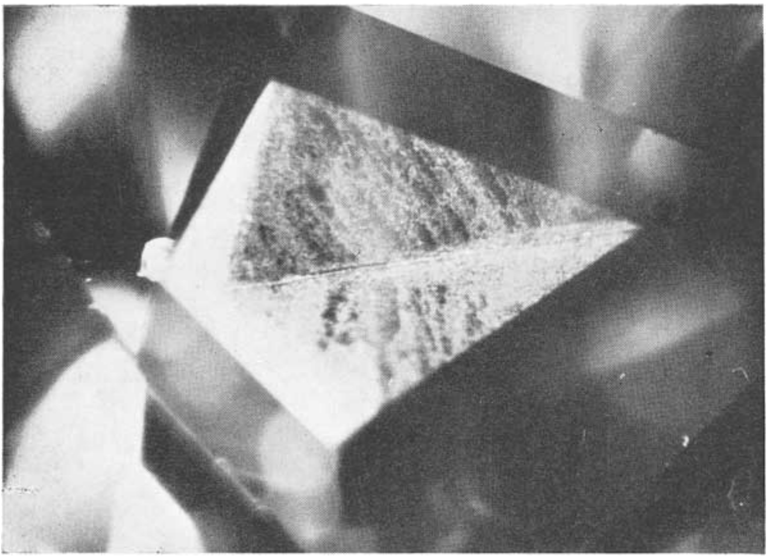

Fig. 26. Autogenetic inhomogeneity forming a " phantom " in a diamond. 20 × .

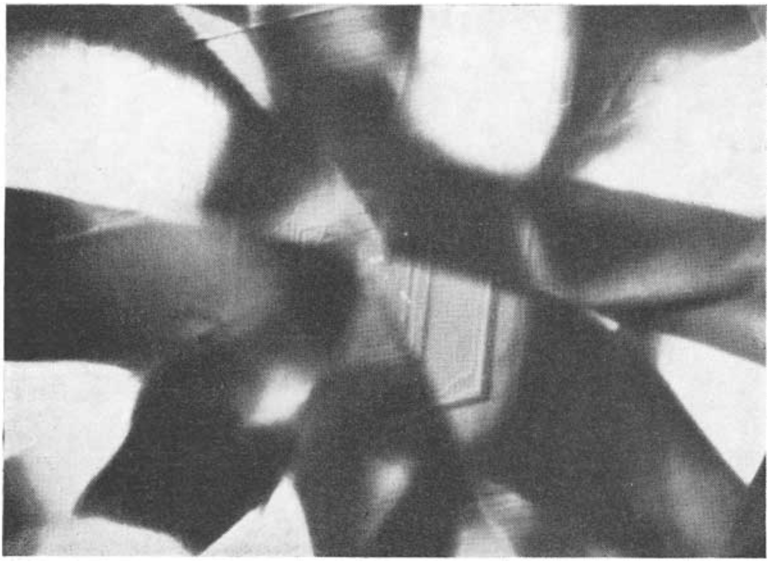

Fig. 27. **Marks of growth phases in a diamond. 40 × .**

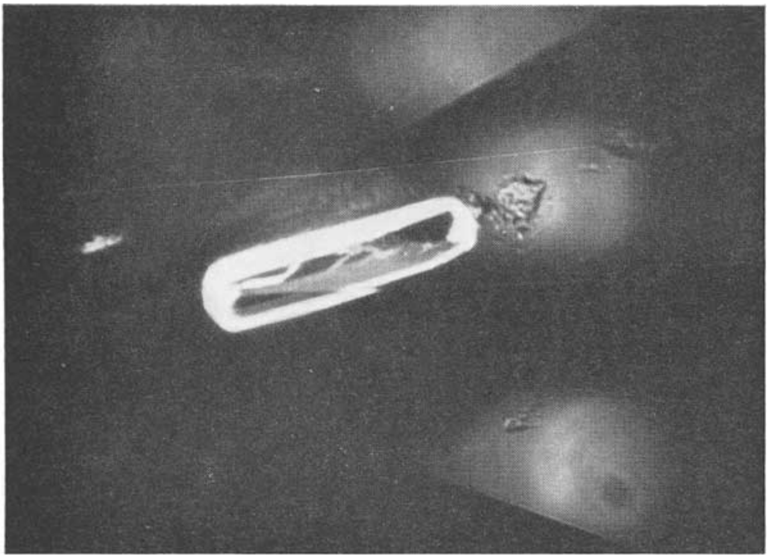

Fig. 28. Euhedral olivine-crystal in a diamond. 120 ×.

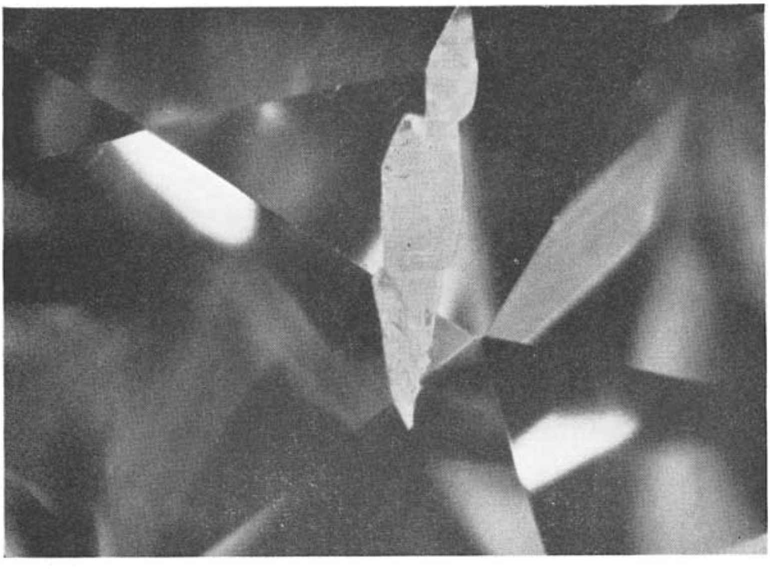

Fig. 29. Cleavage crack in a brilliant-cut diamond. 40 ×.

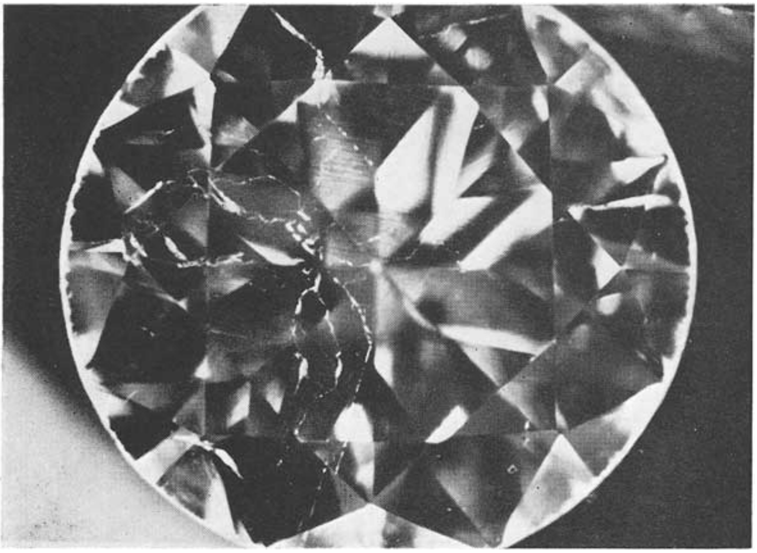

Fig. 30. Cracks by tension or contraction in a brilliant-cut diamond. 20 ×.

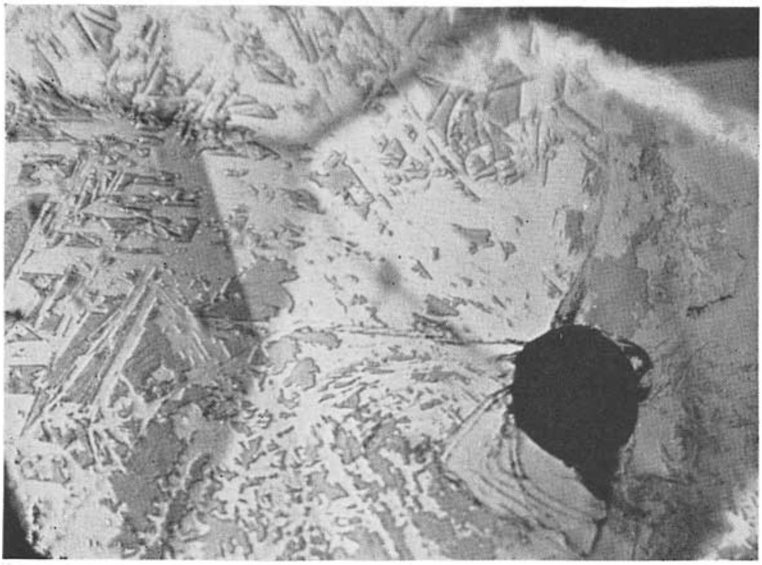

Fig. 31. Opaque crystal of primary origin with crystallization halo. 75 ×.

the prism $(10\bar{1}0)$, but may also be found to form accidental undulating planes. Healing fissures parallel to the basis may betray themselves by the tell-tale pattern of the liquid drops which often fill part of the stone's centre only and do not extend into the homogeneous coat which wrapped the broken core after it had become healed (Fig. 38). This proves that in the course of crystal formation we may conclude that some mechanical forces must have caused fractures and, while the beryl formation ceased, the cracks filled with healing substance out of the mother liquor ; the outer coat, however, grew afterwards without further disturbance. This phenomenon is frequently met with in emeralds from Habachtal.

But there is a further type of secondary liquid inclusion which contains a libella and almost always a well-shaped cubic crystal, or slightly distorted crystal, of NaCl (rock salt)—the well-known three-phase inclusions in emerald from Colombia (Fig. 39). Their form is most individual and distinctly different from other secondary liquid inclusions and so also is their content.

Though they seem to prefer orientation parallel to the prism, they are very frequently assembled in irregularly curved or undulatory layers. Comparison with the comma-like two-phase inclusions in Indian emerald reveals most beautifully the well-defined distinction between primary autogenetic and secondary liquid inclusions (Fig. 40 and Fig. 41). Such a remarkable difference in the character of the arrangement, shape and content of the two types of inclusions could never be explained by simultaneous formation with regard to the growing phases of the host minerals. It is interesting to know that exactly the same type of secondary three-phase inclusion is also found in fluorspar from South Africa and in quartz from various sources. Contrary to the primary inhomogeneities (negative crystals that are evenly developed in all directions) these secondary liquid inclusions predominantly spread in the plane of development (healed fissure), while their expansion perpendicular to this plane is confined by the walls of the fissure, that is, mostly extremely thin.

In aquamarines healed cracks are generally found to lie either parallel to the basal plane or the prism, but both differ entirely in character. While those parallel to the basis are made visible by the typical character of the droplet pattern (Fig. 42), those following

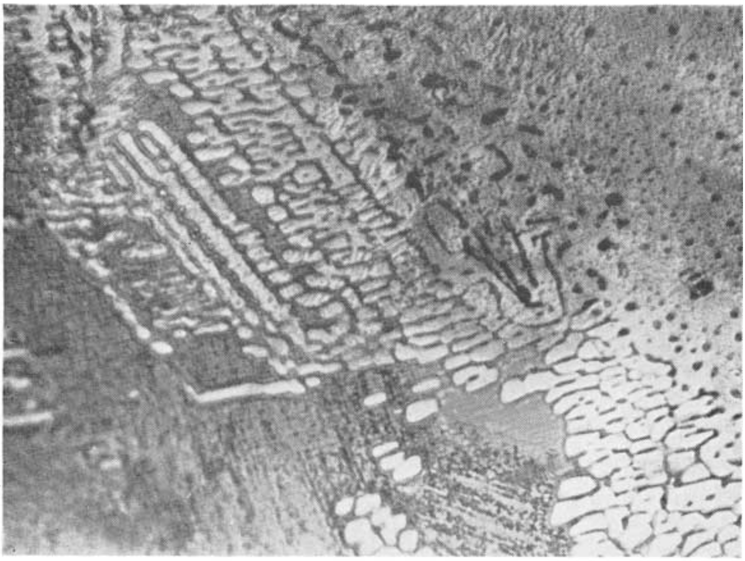

Fig. 32. Interesting pattern of a healed fissure in a Siam sapphire. 125 ×.

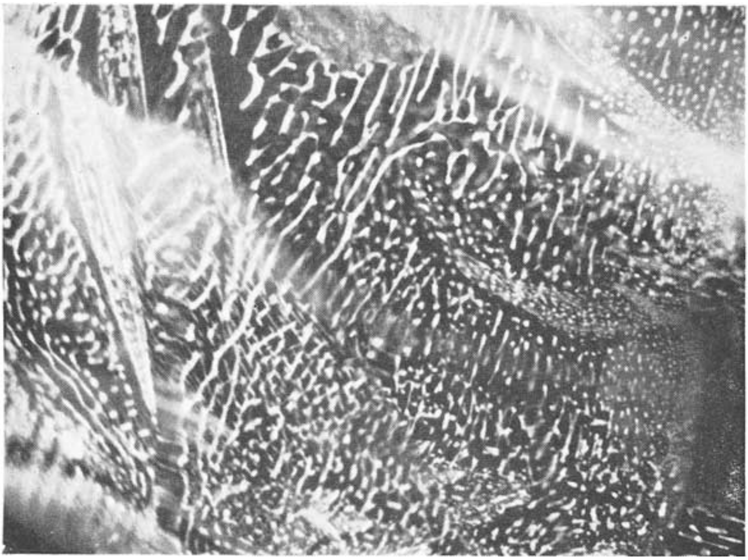

Fig. 33. Various healing fissures of typical design running in different directions in a sapphire. 40 ×.

the prism consist of extended parallel liquid filled tubes. With the latter it would be rather difficult to distinguish them from the very similar type of primary autogenetic liquid filled straight capillaries which were formed by the skeleton growth of aquamarines (Fig. 43), were it not for the tell-tale pattern of healed fissures consisting of long, extended yet interrupted, irregularly shaped tubes surrounded by a collar of tiny liquid drops in the thinner part of the wedging fissure from where the remedial action began (Fig. 44).

Quartz. Quartzes from many different sources, particularly those from the Alps and from Russian deposits, are pregnant with a treasury of secondary liquid inclusions worthy of investigation. Primary liquid enclosures are mainly confined to cairngorm, smoky quartz, amethyst and rock crystals from Carrara, Brazil, and Herkeimer, N.Y., and usually consist of euhedral negative crystals occurring singly or in masses and are of the autogenetic type (Fig. 45). They are filled with liquid usually confirmed by a libella and sometimes washing round some ore crystals. Another type of rather frequent primary inclusions in quartz is formed by glass drops. I have mentioned these two types of primary inclusions in quartz because they occur very often in relation with secondary inclusions. Quartz offers the most classical examples of "phantoms," which often depict a complete *curriculum vitae* through all the phases of growth by an unbroken succession of " phantoms " from the minutest embryo up to the fully grown finished crystal. Undulating veils of intersecting and overlapping secondary liquid inclusions with myriads of drops traverse these gems giving lively evidence of the manifold phases of turmoil they must have gone through.

As stated above, the three-phase inclusion containing a cubic crystal of rock-salt is also one of the striking types of healing features in quartz.

Apart from these healed fissures there is still another type of secondary inclusion or rather a secondary inhomogeneity, which is the result of some shifting actions causing cracks of translation, which if they did not fill with healing liquid remained dry and appear as those intriguing cracks with " tiger-stripes " (Fig. 46). In A. E. Fersman's opinion (Lit. 2) cracks and fractures in pyrogenetic quartz were not caused by mechanical strain but rather on account of crystallographic alteration which was an inversion of

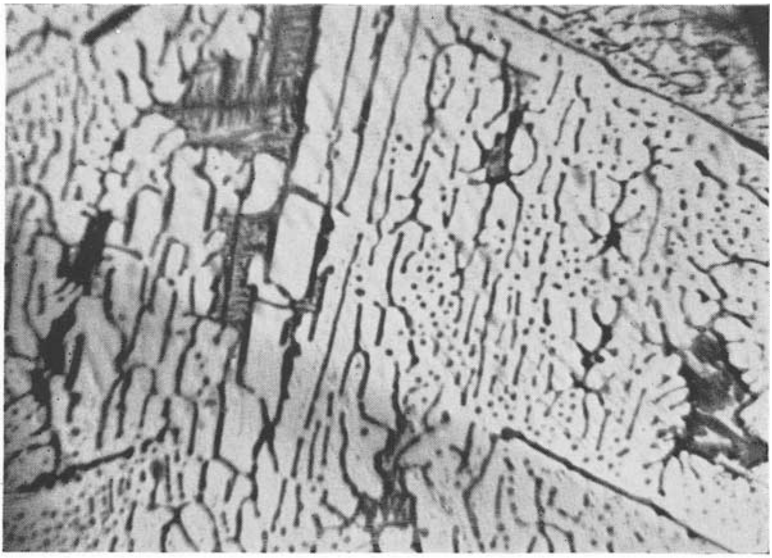

Fig. 34. The individual drops of this healed crack in a sapphire are strongly influenced by the directional crystallographic power of the host. 120 ×.

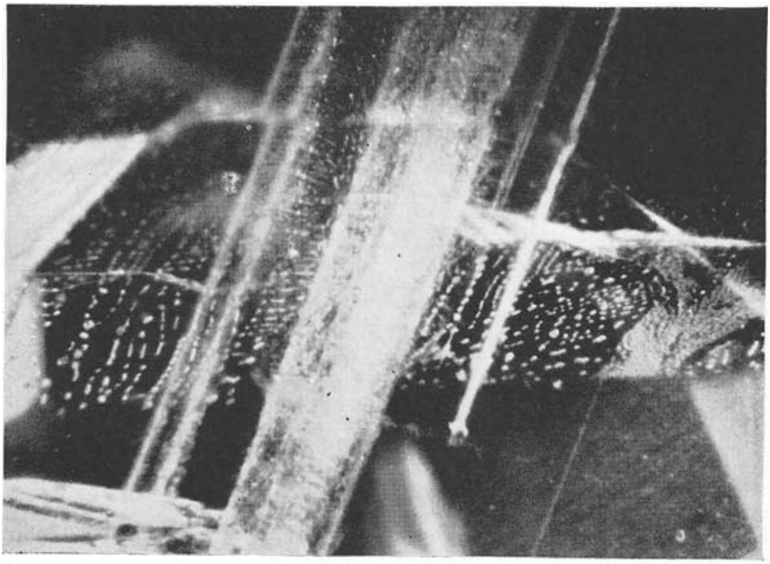

Fig. 35. Healed fissure traversing polysynthetic twin lamella in a sapphire. 40 ×.

the hexagonal α-quartz into the trigonal modification of β-quartz caused by continuous sinking of the temperature of the magma down to 575°C. The fissures of translation and the fractures run parallel to one prism and rarely along the rhombohedron. If in the course of postvolcanic processes a hydrothermal phase follows, the permeating solutions will infuse the previously formed dry fissures and heal them up. Through this process β-quartz will precipitate.

Topaz. In topaz just as in the gems dealt with before, inclusions are of primary and secondary origin and may be clearly distinguished. Among the primary autogenetic inclusions we know the typical negative crystals (Fig. 47) occurring individually or arranged in planes and recently we were informed about interesting growth marks in topaz manifesting irregular faces of growth (Lit. 3) (Fig. 2). Hornblende blades, asbestos fibres, hematite and many other foreign minerals are xenogenetic inclusions. Secondary inclusions are often bound to the various types of cracks as well as to planes which are weakened by primary inclusions. Consequently, secondary liquid inclusions may occur in flat, curved or wavy planes, or in layers superimposed upon primary inclusions. Sometimes a primary cavity may have become filled with liquid of secondary origin, or large primary inclusions may be embedded in a thin film of secondary inclusions spread over the same plane and following the direction of the basal cleavage (Fig. 48 and Fig. 49).

Fluorite. Fluorspar offers the most characteristic example of secondary liquid inclusions (healed fissures) strongly affected by directional crystallographic power. Residual liquid drops are usually extended according to crystallographic directions (orientations) and groups of parallel liquid inclusions follow either octahedral or cubic directions, often intersecting each other (Fig. 50). In other specimens a multiple dendritic pattern manifests healed fissures such as depicted in Fig. 51. They seem to have exerted a much more powerful healing effect on the damaged fluorspar than a third type of secondary liquid inclusions—the so-called three-phase inclusions containing liquid, a gas-bubble (libella) and a cube of NaCl (Fig. 52).

Primary autogenetic inhomogeneities are formed by those negative cubic bisphenoids filled with liquid, which are so specific a mark of this gemstone. Primary xenogenetic inclusions may also consist of various internally paragenetic minerals.

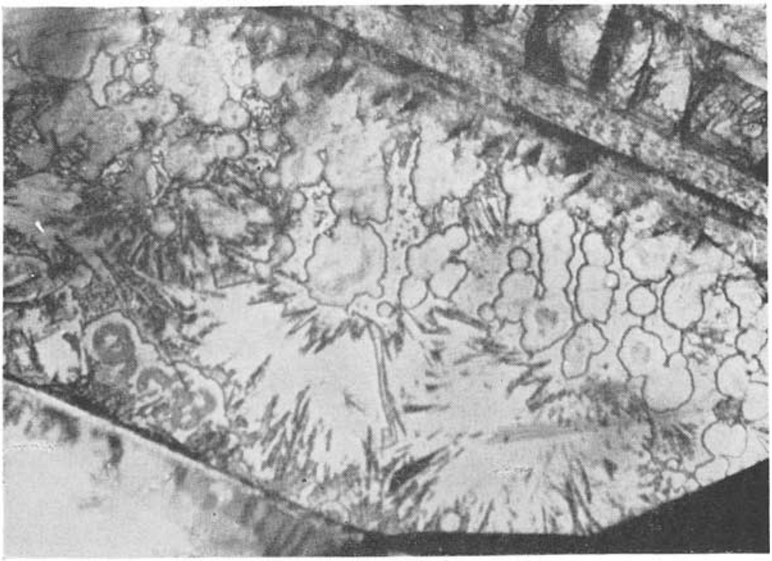

Fig. 36. Healed fissure limited to one twin lamella in a sapphire. 120 ×.

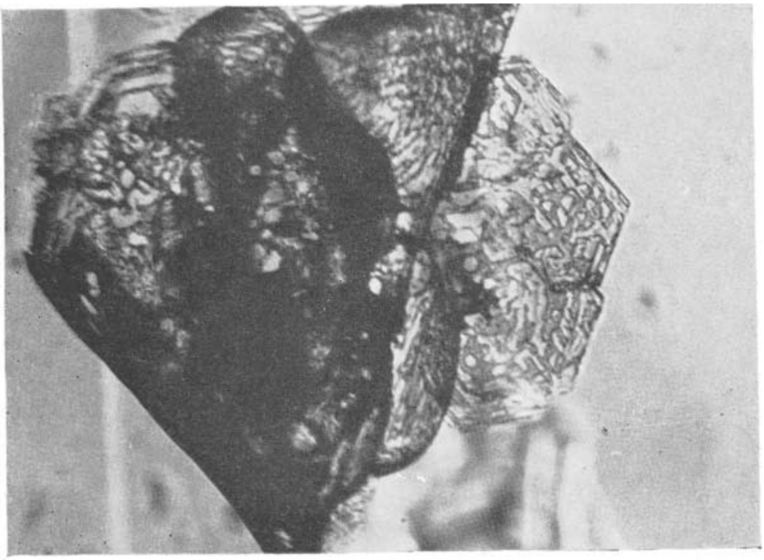

Fig. 37. Multifold healed crack with hexagonal outlines in a Montana sapphire. 120 ×.

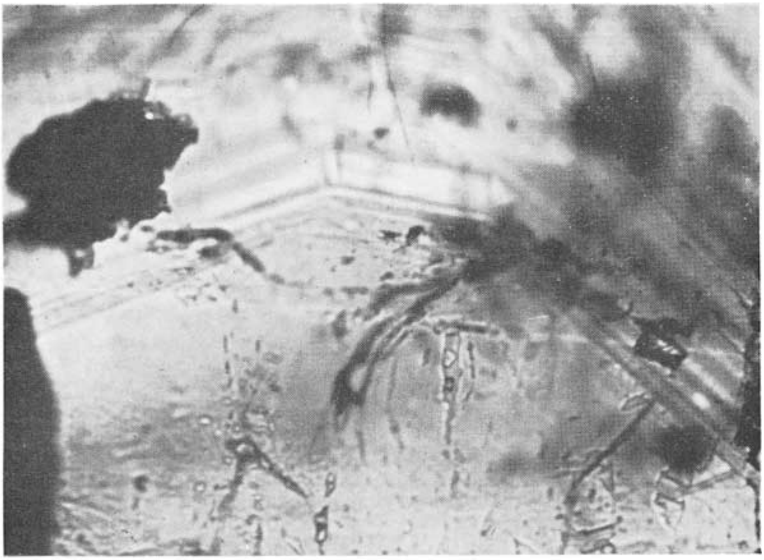

Fig. 38. Emerald with healed crack parallel to basis enclosed by homogeneous coat which is of a later phase. 40 ×.

Fig. 39. Secondary liquid inclusions of the three-phase type parallel to one prism in an emerald from Colombia. 40 ×.

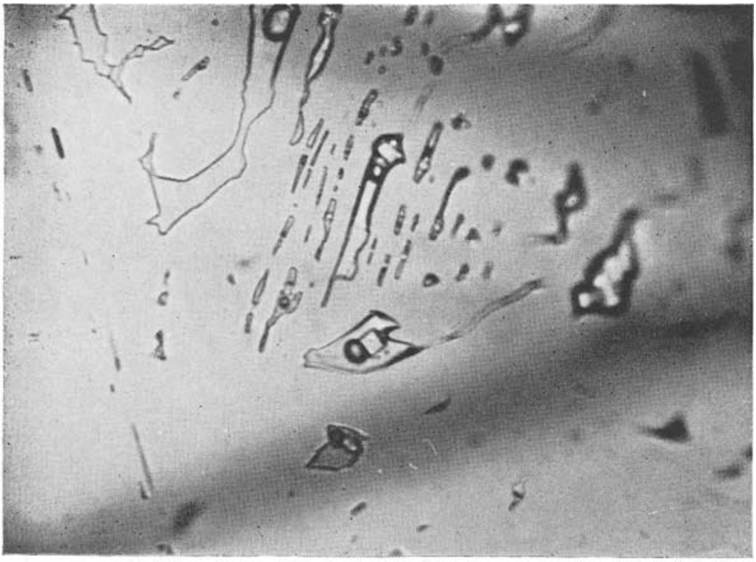

Fig. 40. Secondary liquid inclusions with a cube of NaCl, being residual drops in a healed fissure in emerald from Colombia. 120 ×.

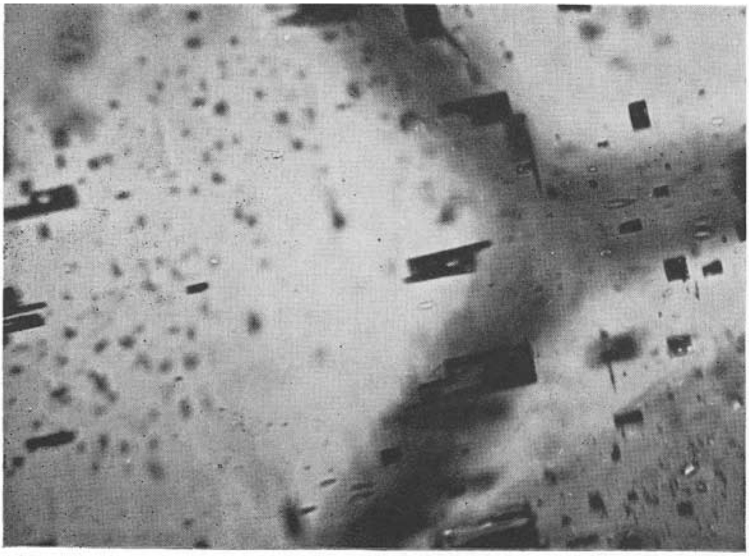

Fig. 41. Primary liquid inclusions of the two-phase type characteristic of Indian emerald. 75 ×

(bb) INCLUSIONS FORMED BY EXSOLUTION

It was extremely difficult to understand the occurrence and genesis of some solid inclusions, which always consisted of foreign microlites usually very densely filling the host gem, until the synthesis of star corundum densely permeated with rutile needles shed light on the problem. It then became known, and was understood, that their formation was due to an " un-mixing " of one component at lowered temperature of a mixed crystal that had been homogeneous at high temperature.

For the sake of those readers who may not be sufficiently acquainted with the theory of isomorphism in modern mineralogy, a brief explanation of the process and definition of the theory is given.

We know that several gemstones belong to the so-called isomorphous series and isomorphism is obvious in all those cases in which elements can easily form with each other isomorphous, mixed crystals in all proportions of mixing, such as albite and anorthite in plagioclase, forsterite and fayalite in olivine, enstatite and hypersthene in orthorhombic pyroxenes, etc. This relationship is thus expressed that in chemical stoichiometric compounds the replaceable atoms, called " diadochic " atoms, are put in parenthesis and separated by a comma, e.g., olivine mixtures $(Mg,Fe)_2SiO_4$, spinel group $(Mg,Fe)Al_2O_4$, etc.

If the isomorphism is less pronounced, then interruptions (miscibility gaps) occur in the isomorphous mixture series, and only a smaller and variable part of one component may be replaced by the other one. The grossular members $[Ca_3Al_2(SiO_4)_3]$ and almandine members $[Fe_3Al_2(SiO_4)_3]$ of the garnet family offer a good example in that the compounds of Mg,Fe″ and Mn″ on one hand and of Al and Fe‴ on the other hand are unlimitedly mixable.

A further group, however, does not seem to permit the least isomorphous mixture. For instance, NaCl and KCl crystallize isometric holohedral, they cleave isometrically, yet they do not mix at all at room temperature, because the radii of Na(·98Å) and K(1·34Å) differ too much. If the chemical compounds are complex, mixtures may readily occur even with relatively great differences of dimensions (mass-isomorphism). Thus in apatite Cl (radius 1·81) and F (radius 1·33) may replace each other.

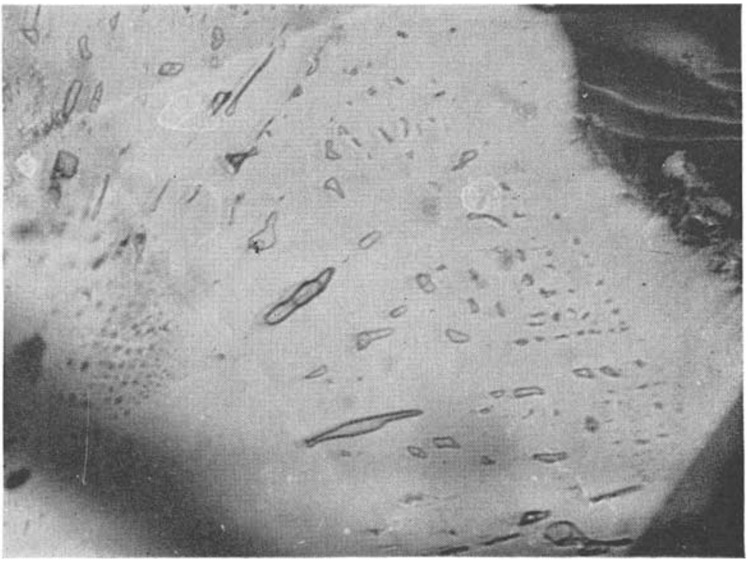

Fig. 42. Secondary liquid drops parallel to basis in aquamarine. 75 ×.

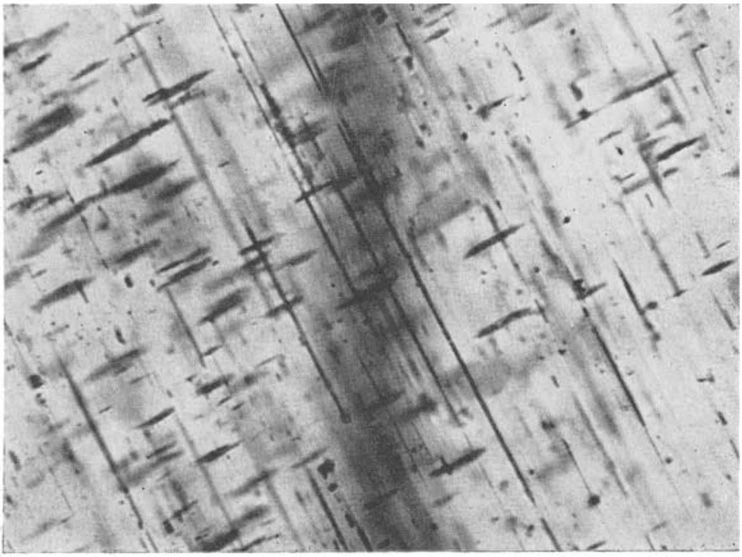

Fig. 43. Primary liquid-filled tubes running parallel to the c-axis in aquamarine. 75 ×.

Minerals of similar development and of different chemical composition are mutually isomorphous if their formulae are analogous both as to the total number of atoms and to the number of positive and negative ions.

The unit cells must be nearly identical and the positive as well as the negative ions within the cells must occupy analogous positions.

The identity of the elements comprises conformity of their radii as well as of their polarizing properties within certain limits. Complete isomorphism therefore postulates that the crystals with " diadochic " atoms belong to the same class of symmetry and even to the same space group. We thus see that in a certain type of crystal structure, particles of the same co-ordinative behaviour and similar space requirements can substitute for one another. This behaviour is called diadochic. This substitution may, under certain conditions of formation, take place either to a limited or unlimited extent.

In the above, only the isomorphism of elements with identical valency has been considered, but it happens very often that elements of different valency substitute for one another, this being made possible by their having similar space requirements and the same co-ordinative properties. Since the structure must remain unchanged, the deficiency or excess of valency produced by such a substitution must be compensated by substitutions producing the reverse effect. This is called coupled atomic substitution.

Pressure and temperature affect the length of the radii of ions and the polarizing properties, the latter being more strongly influenced by temperature. (Generally the degree of isomorphism increases with rising temperature.) There are many examples of substances which mix more readily at high temperature than at low. As mentioned above NaCl and KCl do not mix at all at room temperature, yet readily form mixed crystals near their melting point. Diopside $CaMg(SiO_3)_2$ for instance and clino-enstatite $MgSiO_3$ do not mix in rocks, which solidified at relatively low temperature, yet mix readily and unrestrictedly if they crystallize from dry fusions. Such conditions of isomorphism have been observed with many minerals. The constituents mix together and melt into mixed crystals at high temperatures, but they refuse so to react at low temperature. In this case, as in many others, mixed crystals which formed at high temperature separate from

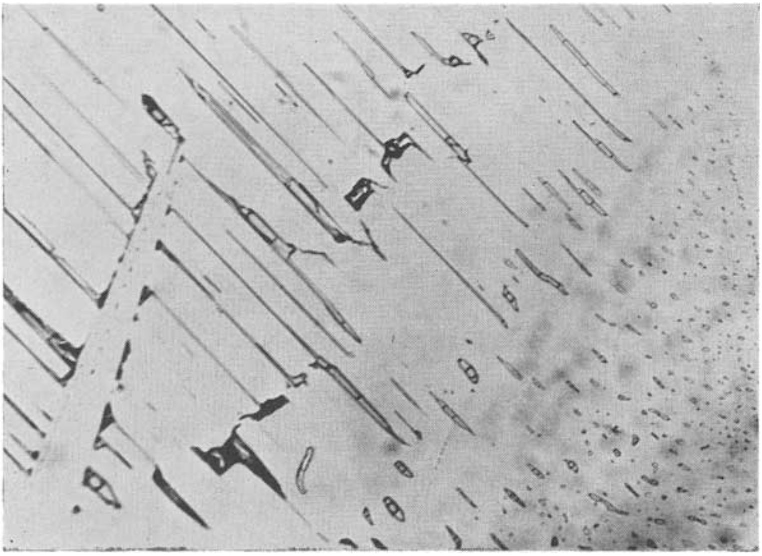

Fig. 44. Secondary inclusions parallel to one prism. The healing action began in the region of the tiniest droplets. The directional power of the growing crystal is well marked by the elongation of the liquid inclusions. 75 ×.

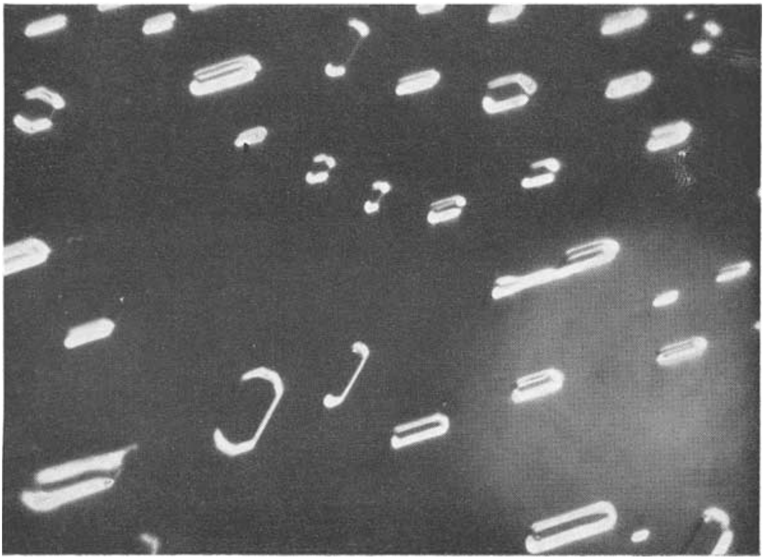

Fig. 45. Negative crystals in an amethyst. 80 ×.

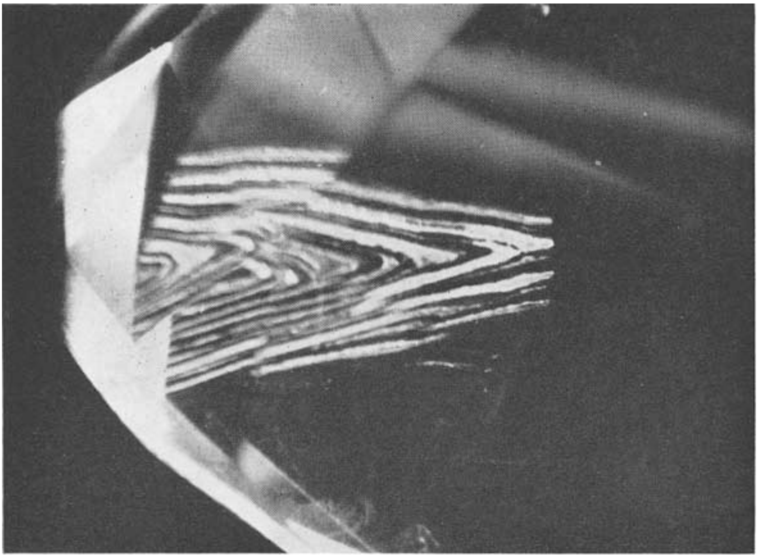

Fig. 46. Translation crack marked by " tiger stripes " in a citrine. 20 ×.

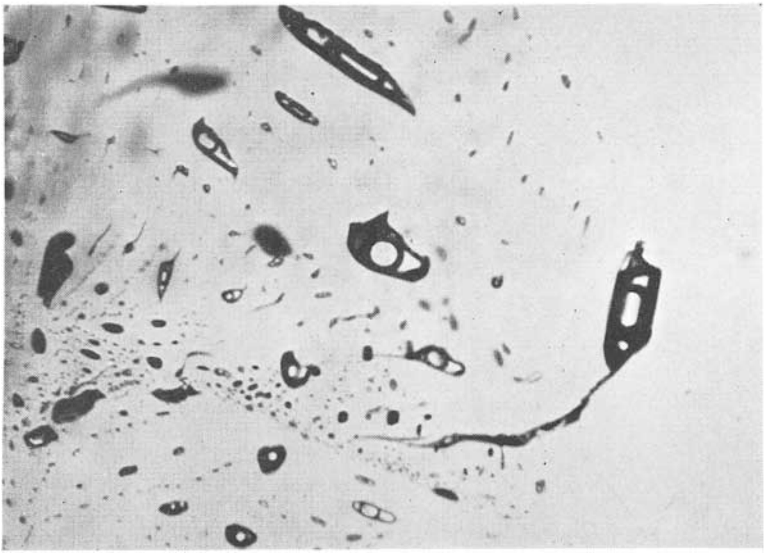

Fig. 47. Negative crystals being of primary origin in a topaz. 30 ×.

each other in the solid state, because cooling causes elements, which are no longer able to substitute for the main atoms, to leave the mixed structure and form another new species within the originally homogeneous mixed crystal, i.e., they un-mix at lower temperatures. This process of separation is called exsolution. The mixture crystal of NaCl and KCl fused together at high temperature becomes labile at room temperature and un-mixes, turning into a turbid porcelain-like product. In silicates formed at high temperatures some Ti is often found to have replaced other elements (e.g. Mg, Fe, Al) having kz 6 in respect to O (see footnote*). At low temperatures it often forms TiO_2 by un-mixing. Crystallizations of rutile needles are then to be found in the originally homogeneous mineral (e.g. almandine). Similarly, some silicates in which Al has kz 4 in respect to O tend, on cooling, to separate in the form of hematite (Fe_2O_3) (e.g. peristerite, scapolite).

The application of this particular peculiarity of isomorphism with interruptions of mixture leading to exsolution made possible the synthesis of star corundum by the Linde Air Corporation and Wiedes Carbid Werke and the " un-mixing " of corundum microlites in synthetic spinel (Fig. 53) by W. F. Eppler. The latter and the author have been carrying out some work of research, investigating properties in natural gemstones with the aim of creating a better understanding of the relationship between certain intermixed compounds in these gems and their inclusions. These studies are not yet terminated, but will be published as soon as definite conclusions are possible.

Since the shedding out of the excessive constituent which had been primarily incorporated in the melt, from which the mixture crystal was formed, occurred in the course of the subsequent process of cooling off, the inclusions formed thereby may also be classed as secondary inclusions. The size of the un-mixed microlites is usually minute but their number is legion, hence they are often responsible for a certain turbidity or certain optical phenomena such as spangled glitter, aventurescence, asterism, play of iridescent colours or complete alteration of colour. The emigration of the excess component, however, does not always take place over vast areas within the host-component, but covers sometimes small patches only (Fig. 54) Since the dimensions (the radii of the ions) and

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* kz symbolizes co-ordination number of ions, e.g., SiO_2 or SiO_4 in which the kz of Si in respect to O is 2 or 4.

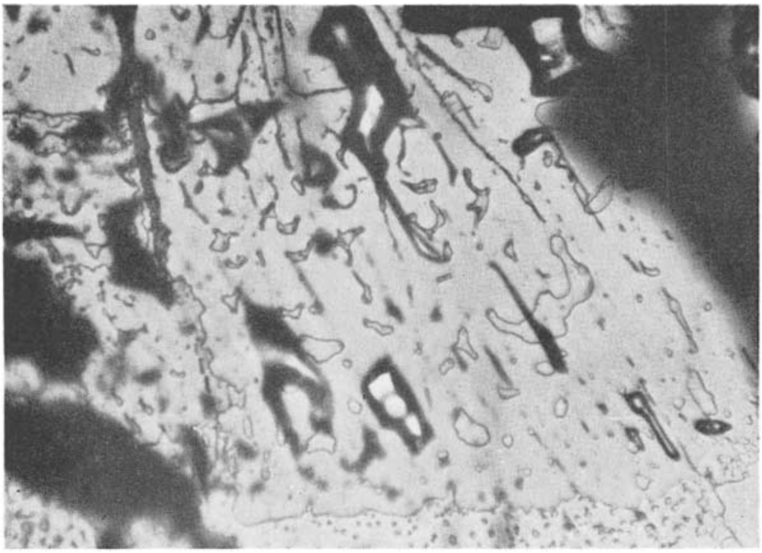

Fig. 48. Primary and secondary liquid inclusions in a topaz. 75 ×.

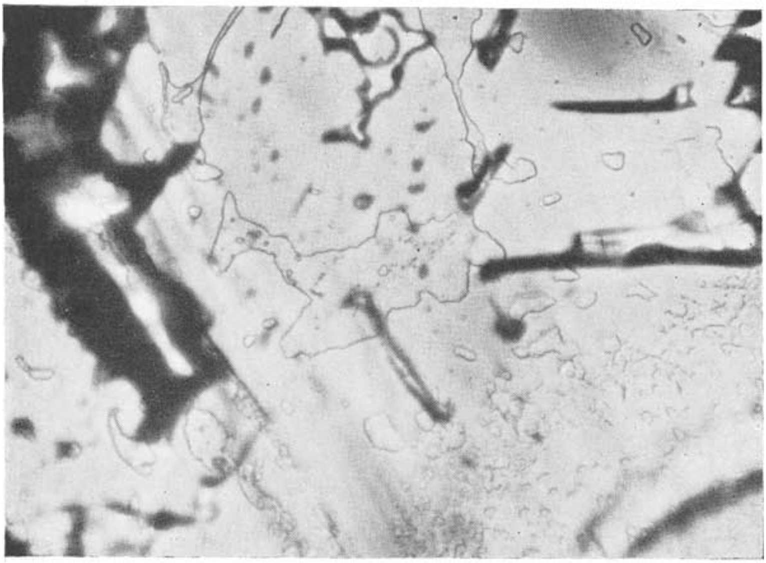

Fig. 49. Healed fissure with very flat residual drops in a topaz. 120 ×.

the distances (space requirements of the ions) of the constituent elements are the fundamental law of isomorphism, the solid inclusions formed by exsolution parallel themselves according to the crystallographic directions.

From the mineralogical point of view the feldspar family is the most important group of reciprocal isomorphism and exsolution. The examples are extraordinarily numerous, so that their products by exsolution expressly received the name of perthite. The spangled effect of aventurine feldspar (sunstone) is due to platy goethite crystals, and the often greenish-black metallic appearance of peristerite is caused by platelets of hematite ; the origin of both types of inclusions is due to an un-mixing of an originally homogeneous feldspar that contained some iron oxide in solid solution. Separation of components within labradorite is also responsible for its play of iridescence. The subtle bluish adularescence of the moonstones from Ceylon is partly due to un-mixed albite molecules. In moonstone—a very pure variety of orthoclase—the grade of milky haziness depends on the portion of expelled albite (Na), and exsolution is often impossible either on account of lack of sufficient intermixed albite or because of very quick cooling off. Slow cooling off favours exsolution, while sudden chilling prevents this and forms a clearly transparent mixture crystal. The waterclear moonstones from Burma were either chilled off very quickly or they did not contain the albite molecules necessary for perthitic exsolution.

For the gemmologist corundum forms the most valuable example of a gemstone being greatly affected by the results of exsolution. By far the majority of the well-known acicular rutile crystals owe their existence to this process of internal separation from the alumina component of the original mixture. Under certain circumstances certain crystallographic planes may be favoured by heavier concentration, and thus twinned rutile needles may un-mix in sagenite pattern. It is then not always easy to distinguish the origin of rutile needles either from exsolution or from sagenite-like adsorption. The latter forms flat layers which may repeat while the former usually distributes the inclusions all through the host, playing an important role as the cause of asterism, although concentration along zones may often be preferred. Another constituent readily mixing and un-mixing with corundum is ilmenite, which also is a frequent inclusion in corundum.

There exists such intimate correlation of isomorphism between

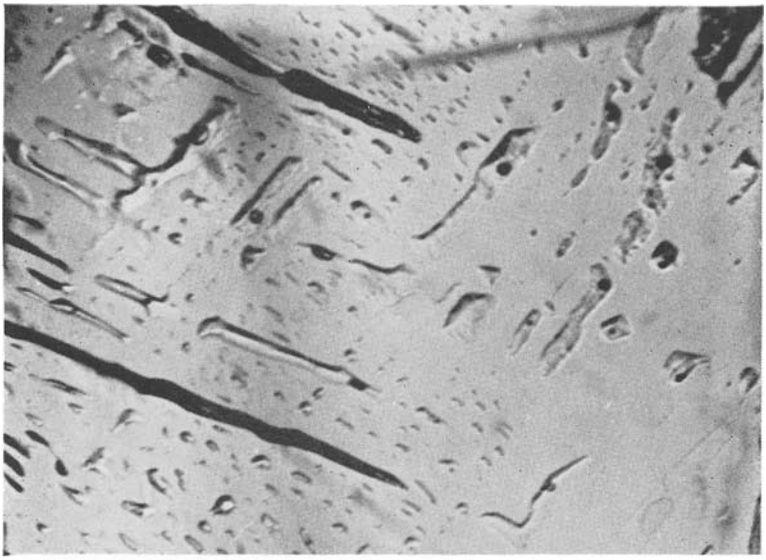

Fig. 50. Fluorspar. The residual liquid drops of this healed fissure reveal directional crystallographic power. 75 ×.

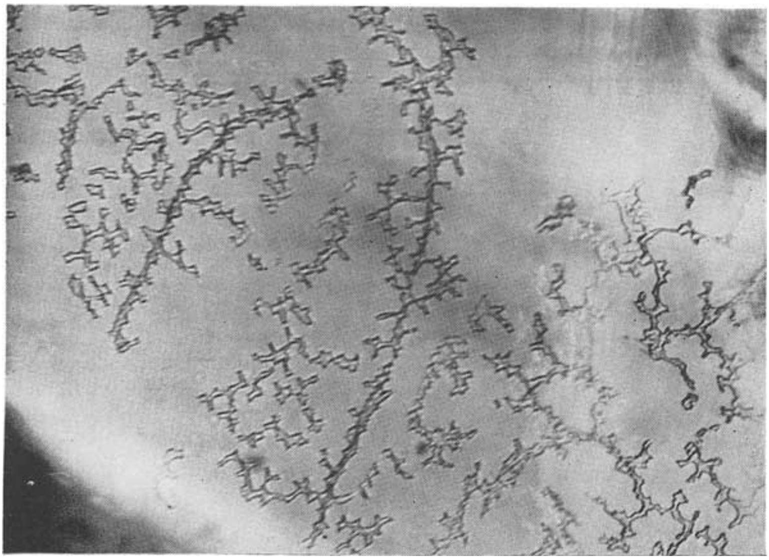

Fig. 51. Almost completely healed fissure with but a few residual dentritic liquid inclusions in fluorspar. 125 ×.

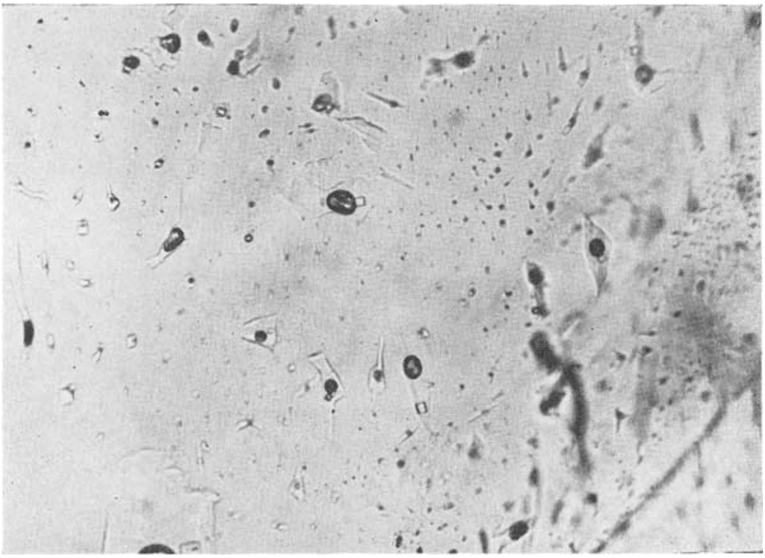

Fig. 52. Fluorspar. Secondary liquid inclusions of the three-phase type with a cubic rock-salt crystal and a libella. 75 ×.

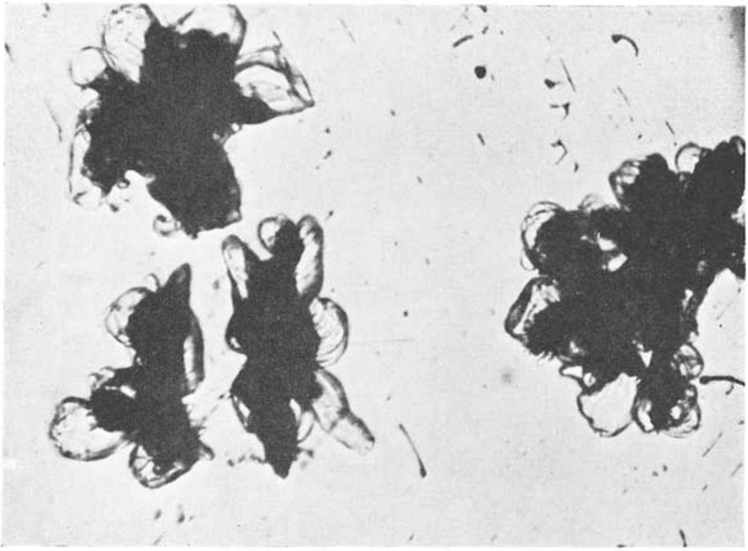

Fig. 53. Clusters of corundum crystals caused through exsolution in a synthetic spinel. 75 ×.

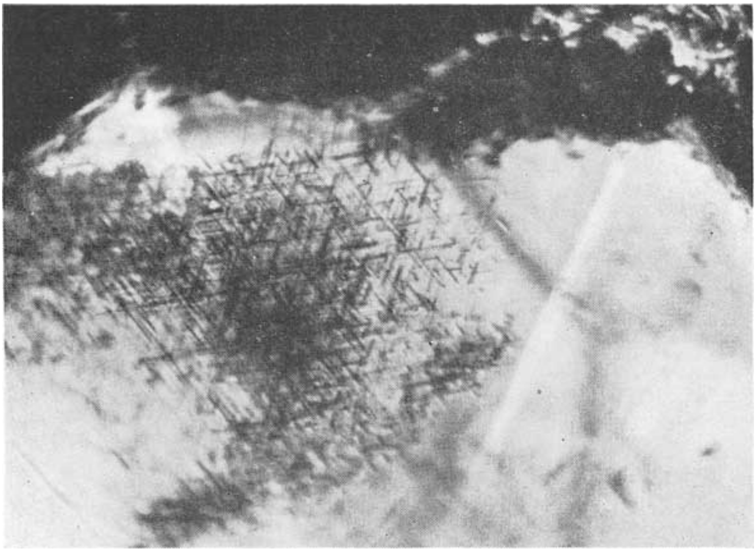

Fig. 54. One of those characteristic patches of rutile needles in a Burma ruby. 75 ×.

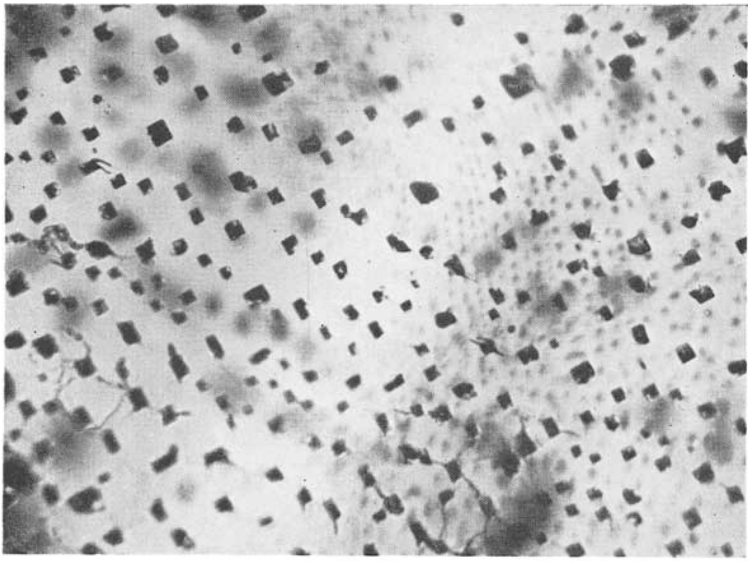

Fig. 55. Uncountable magnetite octahedra formed by un-mixing of one of the diadochic elements in spinel. 50 ×.

the members of the spinel-magnetite group that not only all grades of reciprocal isomorphism but also of exsolution take place, the manifestation of which is manifold. The black tell-tale octahedral (Fig. 55) microlites distributed in small groups, or over wide planes in spinel, are magnetite crystals " exuded " by exsolution. These spinels seem to have had abundant time for cooling off slowly in order to allow the separation of the phases. To the same cause of origin have also to be ascribed those myriads of minute, acicular, sphene crystals (Fig. 56) which often cause asterism in spinels. Their phenomenological appearance differs very distinctly from those sphene wedges (Fig. 57) which grew in sagenite-like arrangement on previous crystal faces and became thus entrapped in the spinel, being primary xenogenetic inclusions. However, under certain circumstances large sphene crystals may sometimes un-mix along definite crystallographic directions and then cover certain privileged crystal planes manifesting also a sagenite-like pattern.

A characteristic result of exsolution consists in the dense repletion of cordierite with goethite (lepidocrocite) platelets (Fig. 58) recently described by R. K. Mitchell (Lit. 4), while the white, blotty agglomerates of opaque white crystals also observed in iolite by E. H. Rutland (Lit. 5) are rather the result of alteration into pinite or mica by the introduction of alkaline.

The bronzy colour and metallic iridescence of bronzite is due to ilmenite tablets that completely fill the body of the host crystal, thanks to subsequent separation of phases of an originally homogeneous mixture crystal.

In many peridots, which to the naked eye appear somewhat hazy or brownish, the uncountable numbers of ultra-tiny fayalite crystals (Fig. 59) are also the characteristic result of exsolution, i.e. they are secondary solid inclusions which owe their presence to the slow cooling off and the separation of the constituent rich in iron from a previously isomorphous and homogeneous mixture crystal.

The whirl-like appearance of hessonite (Fig. 60), which belongs to an isomorphous series of garnets (andradite and uvarovite) that may mix unrestrictedly, is an indication of the internal strain and initial dilapidation in the smallest areas as a result of incomplete exsolution. Through quick cooling off (temperature that sank too quickly) the separation of phases microscopically visible was inhibited although in view of the equal proportion of both ions the chemical conditions ought to have exacted exsolution.

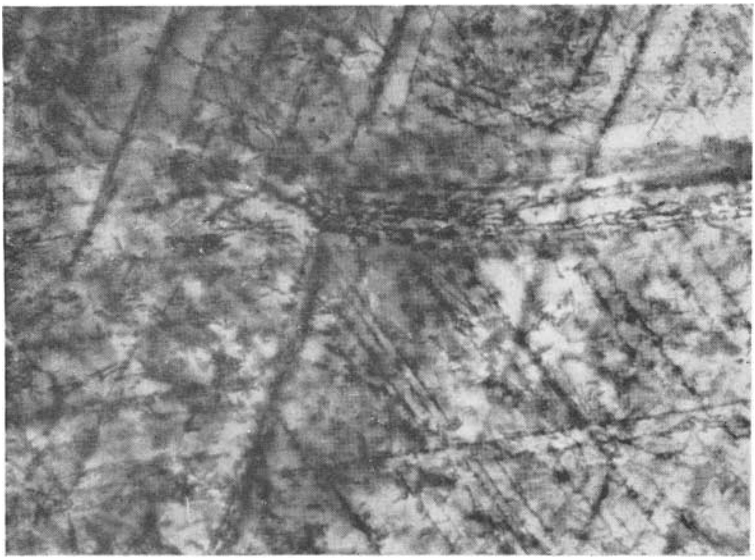

Fig. 56. Star spinel : dense and partly oriented repletion of tiny sphene needles caused by exsolution. 75 ×.

Fig. 57. Sagenite-like deposition of sphene crystals on a previous crystal face in a star spinel. 75 ×.

Fig. 58. Myriads of tiny platelets of lepidocrocite in a cordierite from Ceylon. 125 ×.

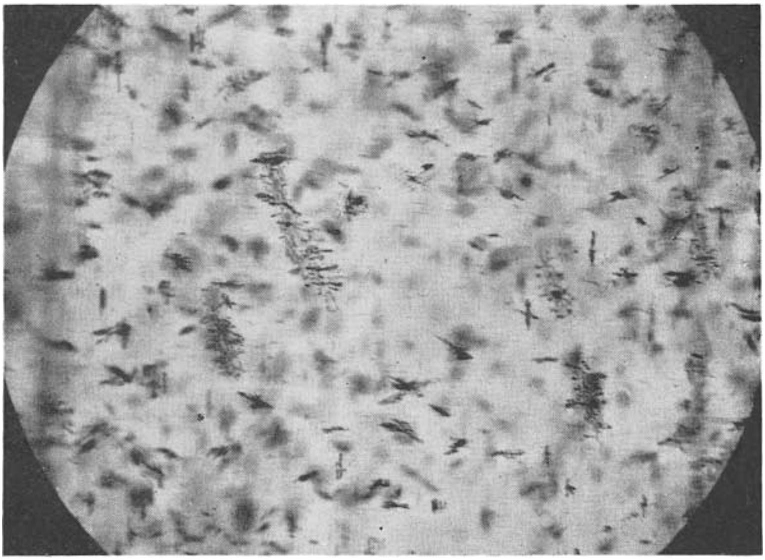

Fig. 59. Through the action of exsolution legion of microscopic fayalite crystals were formed within a peridot. 50 ×.

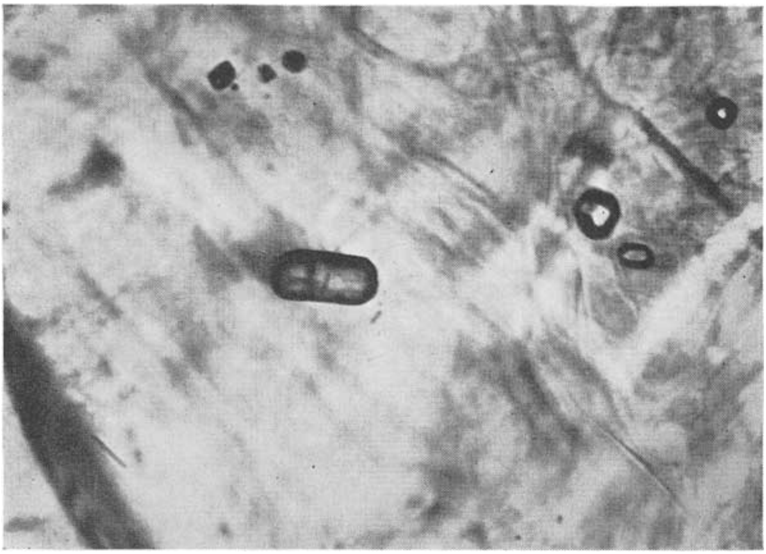

Fig. 60. Typical swirl-marks in hessonite as a result of incomplete un-mixing. 75 ×.

As can be seen from the above explanations, a new classification for gemstone inclusions has been established, distinguishing between primary and secondary inclusions. Primary inclusions can be divided into autogenetic and xenogenetic inclusions and examples are mentioned. The secondary inclusions are those which were formed during a secondary phase, or after completion of the crystal growth. Most liquid secondary inclusions are healing fissures which are either completely or partly healed cracks, or were still in the state of healing when the gem was extracted from the mother earth. Solid secondary inclusions are frequently formed by the process of exsolution, which has also been briefly explained. Further studies must confirm the correctness of this classification and it is hoped that future investigations will yield increasing and valuable knowledge on the genesis of inclusions and their hosts.

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Lit. 4. R. K. Mitchell. "*Bloodshot*" *Iolite,* in The Gemmologist 1955, p. 110.

Lit. 5. E. H. Rutland. *Inclusions in Iolite* (Letter to the Editor), in The Gemmologist, 1953, p. 51.

Lit. 6. R. Webster. *Inclusions in Yellow Chrysoberyl,* in Gems and Gemology, Fall 1953, p. 343.

ASSOCIATION NOTICES

GIFTS TO THE ASSOCIATION

The Council of the Association acknowledges with gratitude the following gifts : from Mr. A. J. Breebaart, F.G.A., of Nijmegen, Netherlands, a cabochon cut synthetic spinel with the appearance of moonstone ; *Das Reich der gesteine*, by Karl Kruger (anonymously) ; and from Mr. R. Webster, Encyclopedia of Gems by H. E. Briggs, Introductory Gemology, by V. Hinton and the donor, and a specimen of Aragonite (var. Flosferri) from the Organ Mts., New Mexico.

PRESENTATION OF AWARDS

The presentation of the awards gained in the 1956 examinations in gemmology took place at Goldsmiths' Hall, Foster Lane, London, E.C.2, on 3rd October. The Chairman of the Association, Mr. F. H. Knowles-Brown, presided and welcomed members and their friends. He specially welcomed Mr. Malcolm Stevenson of Adelaide, Australia. Mr. Stevenson was a Fellow of the Association and had been active in the formation of the Gemmological Association of Australia in 1947, and was now President of the South Australian Branch of that organization.

Mr. B. W. Anderson presented the prizes to the successful candidates and asked Mr. Stevenson to accept the Tully Medal on behalf of Mr. Percy George Marks, of Sydney, Australia. It was the first occasion that the Association's highest award had been won by an Australian.

Mr. Stevenson, in accepting the award, spoke briefly of the work of the Australian Association and said that he would convey greetings to the members of his organization from the British gemmologists.

The Vice-Chairman, Mr. Norman Harper, thanked Mr. Anderson for presenting the awards.

Afterwards members and visitors inspected an exhibition of silver work that had been arranged in an adjacent room by the Worshipful Company of Goldsmiths.

A list of successful candidates was given in the October, 1956, issue of the *Journal* (Vol. 5, No. 8).

MIDLANDS BRANCH

The fourth annual general meeting of the Midlands Branch of the Association was held on 4th October, 1956, at the Auctioneers' and Estate Agents' Institute, Birmingham.

Mr. Trevor Solomon was elected to serve as Chairman for a fifth year and Mr. A. E. Shipton was re-elected as Secretary. The following were elected to the Committee : Miss J. Rice, Miss E. Padbury, Mr. D. King, Mr. B. Leng, Mr. W. Bowen.

A presentation was made to Mr. Norman Harper by the students of the Branch, on the occasion of his resignation as senior lecturer in gemmology at the Birmingham Jewellers' School.

TALKS BY MEMBERS

King, R. F.: " Fakes and Mistakes," to Nottingham Business and Professional Women's Association, 12th December, 1956.

Melrose, R. A. : " Diamonds and Diamond Cutting," Durham Rotary Club, 26th September, 1956 ; " Colour and Gem Stones," Newcastle-upon-Tyne Inner Wheel, 1st October, 1956 ; " The Story of Diamonds," Houghton-le-Spring Rotary Club, 3rd October, 1956.

Warren, Kathleen G. : " Gemstones," to Baptist Women's Fellowship, Bromley, 12th October, 1956.

Webb, Malcolm H. : " Gems," to Rochester Church Women's Guild, 6th November, 1956,

MEMBERS' MEETINGS

A meeting of members will be held at Saint Dunstan's House, London, E.C.2, on Friday, 1st February, 1957, at 6.45 p.m., for an " Any Questions " evening.

The twenty-seventh Annual General Meeting of the Association will be held at Goldsmiths' Hall, Foster Lane, London, E.C.2, on Friday, 15th March, 1957, at 6.30 p.m.

The President of the Association, Sir Lawrence Bragg, F.R.S., has kindly consented to give the Herbert Smith Memorial Lecture at the Royal Institution on Wednesday, 3rd April, 1957. Sir Lawrence will be speaking about the atomic patterns of gemstones and other minerals.

BRITISH MUSEUM (NATURAL HISTORY)

Lectures in the MINERAL GALLERY on Saturdays at 3 p.m.

Jan.	26th	Gemstones made by man	Dr. G. F. Claringbull
Feb.	2nd	Minerals in everyday life	Mr. P. G. Embrey
	9th	Compressed rocks	Dr. G. H. Francis
	16th	Meteorites III : Glass meteorites	Dr. M. H. Hey
	23rd	What are crystals ?	Dr. A. A. Moss
Mar.	2nd	How to take care of minerals	Miss J. M. Sweet
	9th	Radioactivity of the deep-sea...	Dr. J. D. H. Wiseman
	16th	Diamond and graphite	Dr. A. A. Moss
	23rd	Magnetic minerals and rock magnetism	Dr. G. F. Claringbull
	30th	How crystals grow	Mr. P. G. Embrey
Apr.	6th	Baked rocks	Dr. G. H. Francis
	13th	Meteorite craters	Dr. M. H. Hey
	20th	Mineral fakes	Miss J. M. Sweet
	27th	The structure of silicate minerals	Dr. A. A. Moss

THIS PROGRAMME IS SUBJECT TO ALTERATION

COUNCIL MEETING

At a meeting of the Council of the Association held at Saint Dunstan's House, Carey Lane, London, E.C.2, on 30th October, 1956, the following were elected to membership :

FELLOWSHIP

Anderson, Arne T., Tonsberg, Norway.
Batt, Keith M., Torquay
Bochatay, Albano, Geneva, Switzerland
Bohe, Edward R., San Diego, U.S.A.
Bone, William G., London
Boyd, James G., Cambusland, Scotland
Brewer, George P. R., Aldershot
Chiles, Sylvia D. M., Warlingham
Downing, Richard A., London
Ebbestad, Jens C., Oslo, Norway
Felin, Juul, Oslo, Norway
Ferguson, William F., Alexandria, Scotland
Fortune, Kenneth W., London
Gordon, Davina B., Ruislip
Grounds, Walter J., Birmingham
Harris, John S., Glasgow
Hewitt, Frederick E. J., Ormskirk
Hopewell, Ronald C., Grays
Hoskyns, Kenneth, Birmingham
Kirk, Ronald M., Rutherglen
Lewis, Emily C., London
McGuigan, Alix (Mrs.), Bearsden
Oftedahl, Christoffer, Stabekk, Norway
Peplow, Sarah A., Stourbridge
Pollard, Frederick D., London
Selwood, Brian L., Watford
Sidaway, John T., Torquay
Toms, Brian G., Plymouth
Tye, Leslie H., Bromley

FELLOWSHIP (TRANSFERRED FROM ORDINARY AND PROBATIONARY MEMBERSHIP)

Banks, Kenneth A., Manchester
Bates, Michael A., Croydon
Breeze, Michael D. G., Leicester
Brooks, Beatrice B., Bristol
Burley, Walter R., London
Clifford, Edwin W., Cassington
Gam-Dede, Markson A., New York, U.S.A.

FELLOWSHIP (TRANSFERRED FROM ORDINARY AND PROBATIONARY MEMBERSHIP) *(contd.)*

Jeffreys, Roy E. H., London
Leiper, Hugh, Austin, U.S.A.
Hodgson, Edwin S., Darlington
Longbottom, William, Hull
Marks, Percy G., Sydney, Australia
Mason, Cyril T., London
Mendis, Clement S., Colombo, Ceylon
Messenger, Shirley J., St. Albans
Molyneux, Frank, London
Morgan-Smith, John, London
Muir, William A., Wilmslow
Muscat, Bernhard, Johannesburg, S.A.
Padbury, Edna P., Birmingham
Peters, Brian L., Camberley
Phillips, William H. M., Ross-on-Wye
Schoo, Johan J., Arnhem, Holland
Sherrard, Julian S., London
Smith, Cora A., Grays
Smyth, John C., Baltimore, U.S.A.
Vainer, Milos, London

LIFE FELLOWSHIP

van Loo, Jan. (D.1950), Utrecht, Holland

ORDINARY MEMBERSHIP

Abhyankar, Jagannath S., Bombay, India
Assenmacher, Jean, Bulawayo, S. Rhodesia
Bick, Louis, Montreal, Canada
Boermans, Lambertus T. M., Venlo, Holland
Fleming, John Alan, Auckland, New Zealand
Forrest, H. Ian, London
Gardner, Malcolm, London
Halstead, Dwight, Dallas, Texas, U.S.A.
Hayman, Harry M., Vancouver, Canada
Jones, Gwilym M., Colwyn Bay
Kind, Dora (Mrs.), Newcastle
McBurry, John W., Washington, U.S.A.
Max, Sidney, London
Mohamed, Syed, London

ORDINARY MEMBERSHIP (*contd.*)

Radford, Edward T., Harrogate
Ronaldson, Robert G., London
Seneviratne, Dayatissa, London
Smith, Clifford J., Birmingham
Solman, Barbara (Mrs.),
Worcester Park
Stanoyev, William N., Regina, Canada

PROBATIONARY MEMBERSHIP

Horton, Anthony, London
Hatcher, June Ann, Birmingham

CONVERSAZIONE AND EXHIBITION

Well over 200 members and their friends attended a Conversazione, held at Goldsmiths' Hall on 28th November, 1956.

It was a most successful evening and in addition to demonstrations a small exhibition had been arranged. A central feature showed literature, minerals, gems and instruments associated with the gemmological organizations in Australia, Brazil, Germany, Great Britain, Norway, Switzerland and the United States of America.

Mr. B. W. Anderson demonstrated the immersion contact of gemstones by using the comparative refractive index of stones in a fluid of known refractive index. Another impressive demonstration was arranged by Messrs. H. Lee and D. Hill who showed samples of the materials used by nature in the formation of minerals. A skilful synthesis of what happened in nature was demonstrated alongside. A display of apparatus and photographs telling of the synthesizing of quartz, rutile, corundum and spinel was arranged by the Research Laboratories of the General Electric Company Limited. Some twenty minerals were displayed under ultra-violet light and visitors were invited to identify the specimens and their provenance.

Around the hall were show cases of various rough and cut gems and gem minerals and a display of photographs from some of the larger exhibitions arranged by the Association. Of interest, too, was a Bill of Lading, dated 1756, for the shipment of corals to Fort St. George, and the oil portrait painting of the late Dr. G. F. Herbert Smith.

The Council of the Association is indebted to many people for the success of the evening and, apart from those who kindly arranged demonstrations and displays, acknowledges the help given by Messrs. Rayner & Keeler, Ltd., Drewell & Bradshaw, Ltd., W. Stern, E. H. Rutland, B. Silver, A. E. Farn, Mrs. T. H. Bevis-Smith and the Gemological Institute of America. The Council is specially grateful to Miss E. Ruff, Mr. T. H. Bevis-Smith and Mr. R. Webster, who comprised a Committee which arranged the whole programme and staged most of the exhibits, and to the Wardens of the Worshipful Company of Goldsmiths for kindly placing the Livery Hall and other rooms at the disposal of the Association.


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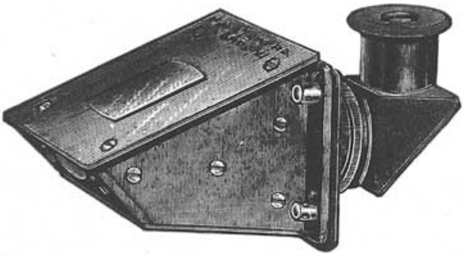

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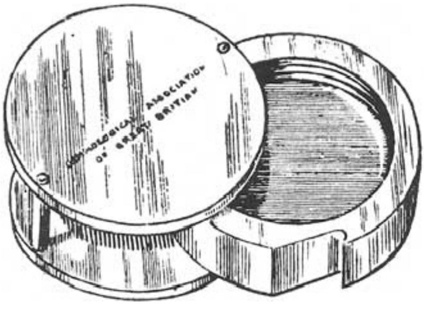

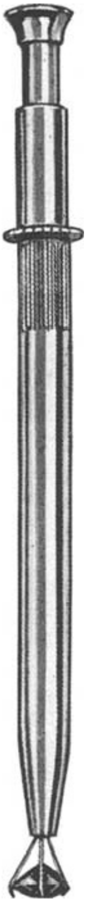

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