Tabular spessartine crystals in muscovite.

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DURING the course of a survey of the mineral deposits of the area immediately south of the Murchison Range in the NE. Transvaal, a visit was paid to the Union mica mine, one of the only two producing mica mines in South Africa. Interest very soon centred round the occurrence of flattened garnet inclusions in a large number of the mica sheets inspected in the trimming hut. A description has been given by A. L. Hall[2] of the nature of the occurrence of the muscovite, while the geology of the area surrounding the mine is shown in a general way on his map. However, no mention was made of platy garnet crystals; and the Union mine is shown on the map as the Premier mica mines, a name by which it was then known. It is situated on the farm Inyoko (or Inyoka) (24° 8′ 25″ S., 30° 50′ 49″ E.) on the western slopes of a ridge overlooking the Sandspruit valley, and lies only two miles from Mica Siding on the Selati Railway, though best approached from Gravelotte by road, a distance about 22 miles.

The mica, which occurs as large books in coarse pegmatite injecting the Old Granite, is won by means of a complicated system of tunnels, winzes, drives, and chambers, and in fact the mine has followed the sporadic occurrence of books and shoots of muscovite down to 160 feet. When seen by the fitful light of a torch reflected from the myriad glistening sheets of mica studding the walls and lying as fine waste on the floor, these chambers seem veritable Aladdin's caves. It is noticeable that the larger books of mica are invariably associated with the more felspathic pegmatites.

The pegmatites consist essentially of quartz and white felspar usually segregated into patches several inches or even feet across and rarely in graphic intergrowth. The most extraordinary feature is that all the

[1] With permission of the Hon. the Minister of Mines, Union of South Africa.
[2] A. L. Hall, Mica in the eastern Transvaal. Mem. Geol. Survey, South Africa, 1920, no. 13. [Min. Abstr. 1-270.]

felspar appears to be albite. Some of it certainly does not show albite twinning under the microscope in thin sections, but every sample crushed for examination revealed a certain amount of fine polysynthetic twinning and the optical properties agree with albite containing only a few per cent. of the anorthite molecule. This albite occurs as cleaved masses up to several inches across showing well-defined twinning macroscopically, but also in sub-parallel aggregates and somewhat radiating masses of presumed later origin. While it seems reasonable to regard this latter as of secondary origin, however, it is difficult to see how the large individuals can be regarded as anything but primary. The more intimate associations fail to give any definite clue as to replacement, but it should be noted that no microcline or orthoclase was actually observed which might have represented original unreplaced felspar. The identity of the felspar as albite was established by A. L. Hall by chemical analysis, but he does not appear to have stressed the peculiar fact that microcline, the common felspar of pegmatites, is either absent or very subordinate.

Other minerals which are common in the pegmatites and occur in the specimens examined are muscovite and garnet, while apatite occurs but rarely. Muscovite is common throughout the pegmatites and is usually of a greenish or more rarely brownish tint. Rough tests gave the following figures: sp. gr. 2·9, β 1·595, 2V 40°, which are characteristic of ordinary muscovite, so that no further work was done on it. The garnet crystals are described separately, and the only other mineral was a pale blue apatite. This from its refractive index is fluor-apatite, and occurs as columnar masses enclosing quartz and apparently replacing albite. It is of interest that A. L. Hall mentions apatite enclosed in garnet.

The garnet occurs in two fairly distinct ways which may be conveniently referred to as rounded and flattened respectively. The rounded type occurs only at the margin of the mica books. That portion or those specimens which occur just within the mica are invariably idiomorphic crystals up to 2 cm. diameter consisting of the icositetrahedron modified by the rhombic-dodecahedron; while those just outside the mica and thus within the pegmatite are generally in the form of irregular masses, sometimes weighing several pounds and completely lacking in crystal facets. These rounded forms are usually of a deep reddish-brown colour and practically opaque in the hand-specimen except for the smaller idiomorphic specimens. They are, moreover, largely altered to a limonitic product. Tested chemically they are found to contain a high percentage of manganese.

The flattened garnets, on the other hand, occur exclusively within the mica books, the plane of flattening being invariably parallel to the cleavage-plane of the mica. They appear to be limited in their distribution to certain layers within the mica and are more prevalent towards the outer fringes of the books. In addition, they are more frequently encountered in the larger books. In thickness they vary from 0·1 to 15 mm., being on the average 1–2 mm., while in diameter they range from that of a pin's head up to 2 cm. The flattest garnet encountered was 12 mm. in diameter and only 0·25 mm. in thickness. According to Mr. F. Burch, a former manager of the mine, they are thicker on the average in the 'edge-waste' of the books than within the larger leaves. They vary in colour from a pale brownish-pink to a deep ruby-red.

These flattened garnets occur sometimes as isolated crystals and sometimes in strings, in which case they tend to be nearer to the outer margin of the books. Such strings of garnet (figs. 1 and 3) consist usually of tiny crystals up to 2 mm. across and 0·3 mm. in thickness. They are found in a feathery type of muscovite in which the large plates are divided up into areas, each characterized by a sort of fluting or foliation parallel to the rays of the pressure-figure of the mica respectively. Now each of these foliated areas contains only strings of garnet crystals perpendicular to this foliation, and thus the strings are arranged parallel to the traces of the unit prism and clinopinakoid, or, in other words, parallel to the rays of the percussion-figure (fig. 4). The strings are spaced irregularly, and parallel to them are also other lines of disturbance without the presence of garnets. Within the strings the tiny crystals are themselves spaced at irregular intervals, but generally the larger the crystals the greater the space between them. Occasionally such strings penetrate a considerable thickness of the mica book, the garnets then lying in a plane roughly perpendicular to the mica cleavage.

Thirty crystals, both of the isolated type and of those in the strings, were detached and examined carefully on the two-circle goniometer, being mounted on the large face; but before removal the trace of the optic axial plane of the muscovite was ruled on one of the large faces of each crystal. They sometimes possess a fairly regular six-sided outline (fig. 2) and may be distinctly elongated parallel to a pair of these edges, but generally possess a somewhat rounded or polygonal outline. They also occur in parallel growths and in groups of two or three irregularly associated. The large face rarely gives a good image owing to appreciable convexity, and it frequently carries a pattern of growth-pits which, however, proved useless for orientation purposes. The edges of the tablet are usually modified by half a dozen or so recognizable faces, but the rest of the margin is usually indistinct and fluted. In spite of this, however, a number of reflections were obtained on the goniometer from ill-defined faces. These showed that the crystals are nearly always tabular near a face of the rhombic-dodecahedron and that other reflec-

FIG. 1. FIG. 2.

FIG. 1. Rows of garnet crystals in muscovite arranged perpendicular to fluting. $\times \frac{1}{2}$.

FIG. 2. Typical garnet crystals enclosed in muscovite. $\times 3$.

tions all belong to either the rhombic-dodecahedron or the icositetrahedron (211). Faces of the former usually give the better reflections, while the latter tend to be striated parallel to their intersection with the former.

Where a dodecahedral face is located at anything over $\rho = 5°$ or so, it appears distinctly as a sort of vicinal face modifying the large face and recognizable in the hand-specimen. In this case the large face gives a number of images, both isolated and in strings, and of varying degrees of definition within a radius of 5°, corresponding to various vicinal faces and zones of faces. In those cases where the pole of the plane of flattening departs appreciably from that of a dodecahedral face it is found to lie roughly on one of the principal zones passing through a dodecahedral face, but in only one case did it lie between the dodecahedron and cube. The poles were plotted on a gnomonic projection on a (110) plane as shown in the diagram (fig. 5), only those falling outside the 3° radius

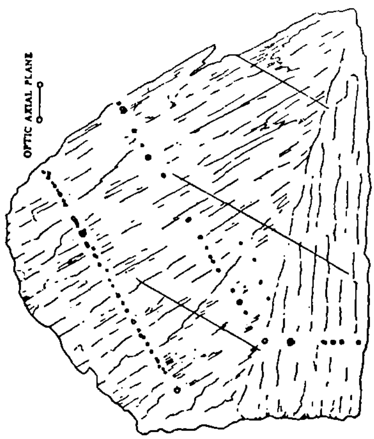

FIG. 3.

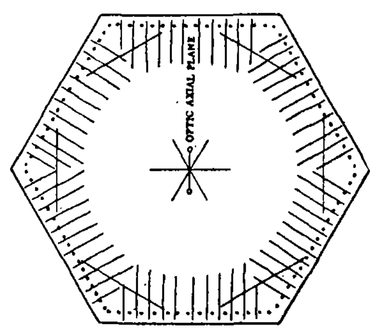

FIG. 4.

FIG. 3. Rows of garnet crystals in muscovite arranged perpendicular to fluting. *Straight lines are planes of parting. Sketch of the plate, a portion of which is shown* in fig. 1.

FIG. 4. Diagram to illustrate the orientation of rows of garnet crystals with respect to the fluting, planes of parting, percussion-figure, and optic axial plane of the muscovite.

being indicated; 18 poles out of the 30 thus fell within 3° of a dodecahedral face. It will be noticed that flattening does not occur anywhere near a cubic face.

With regard to the orientation of the garnet individuals relative to the trace of the optic axial plane of the muscovite, very little can be stated. There is, however, a strong tendency for the optic axial plane to lie parallel to either the longer or the shorter diagonals of the dodecahedral face on which flattening occurs, while other cases occur where it lies definitely parallel or perpendicular to a side of the face. The results of the goniometric measurements show conclusively that there is no common orientation.

A few of the thicker crystals possess marked parting-planes parallel to faces of the rhombic-dodecahedron, especially developed parallel to the large face of flattening. The specific gravity determined in Clerici solution was found to vary slightly, being about 4·10. The pale brown crystals have a slightly lower figure than the deeper-coloured ones. Under the microscope, the crystals are mostly quite isotropic and their refractive index is about 1·805–1·810, but no variation was observed. A few of the crystals show well-defined colour zoning, the inner zones being polygonal but not necessarily of the same shape as the crystal outline.

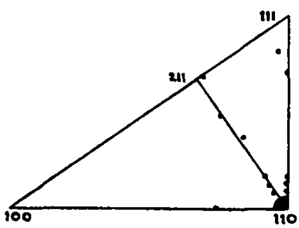

FIG. 5. Gnomonic projection showing orientations of the plane of flattening of 30 garnet crystals. The large dot around (110) represents 18 of them.

A clear reddish tabular crystal weighing 0·3 gram was crushed and a rough analysis was made of the iron and manganese. The iron was determined by titration with titanous chloride and the manganese colorimetrically after oxidation with sodium bismuthate, giving total iron (as FeO) 16 % and MnO 24 %, which correspond to $Alm_{40}Sp_{60}$. A number of other crystals were tested with the sodium carbonate bead and found to be rich in manganese, so that all the garnets are assumed to consist predominantly of the spessartine molecule.

The garnet crystals are in general not situated on the surface of the muscovite books but are very definitely enclosed deep within them. They have, however, influenced the adjacent cleavage-layers and leave a slight hollow where the immediate layers have been in contact with the crystals, an effect which is noticed through a different thickness of mica in different cases. The mica layers in a continuous plane with the crystal tablet stop abruptly against the edge of the tablet usually without modification except for the existence of a system of radial cracks in the mica presumably due to pressure, like expansion cracks commonly found round olivine crystals altered to serpentine. The pressure exerted by the garnet on the surrounding muscovite is not regarded necessarily as an effect of the original cystallization of the garnet, but may possibly be due to subsequent alteration of the garnet crystals caused through oxidation of ferrous iron. The garnet crystals themselves, especially the larger ones, are commonly riddled with cracks as though they had been under strain.

In 'Ore deposits of the Western States' (p. 144 et seq.),[1] W. T. Schaller

[1] Amer. Inst. Mining and Metall. Engineers, Lindgren volume, 1933. [M.A. 6–3.]

states that irrespective of whether the original pyrogenic rock of the pegmatites consisted essentially of potash-felspar or of graphic granite or both, the outstanding fact of pegmatitic development is that the aggregates of albite, micas, garnets, and many other minerals are formed by later hydrothermal replacement processes acting on and replacing the first formed potash-felspar rock. As stated previously, it would appear that the parent rock in the present case was essentially albite-quartz-pegmatite, though some of the albite is almost certainly secondary. Of the other minerals, Schaller gives the following order: albite, muscovite, and the general group including tourmaline, garnet, and beryl. Where the garnet occurs in the albite or micropegmatite, the appearance of the garnet and its mode of occurrence suggest that it was formed at the expense of the felspar, but where the garnet occurs in muscovite, the case for replacement and a later age for the garnet is not so clear. It is difficult to imagine, perhaps, some of the larger garnets up to 2 cm. across developing in a book of muscovite by replacement, but such a process may nevertheless be possible.

The principal features of the garnet are the habit of the flattened crystals and the arrangement in strings. In Dana's 'System of Mineralogy' (6th ed., 1892, p. 619) appears the following statement: 'Muscovite often encloses flattened crystals of garnet, tourmaline, also quartz in thin plates between the sheets; further, not infrequently magnetite in dendrite-like forms following in part the directions of the percussion figure, also those of the pressure figure.' It might be added that white chalcedony occurs in films up to 8 mm. thick, interleaved with the mica now described, and is associated with films and even small crystals of quartz. The thicker films consist sometimes of alternating bands of dull white chalcedony and clear quartz and resemble extremely flattened agates in structure. These, however, appear to be almost entirely confined to the upper 40 feet of the workings and are therefore limited to the zone of oxidation. They show that on weathering the muscovite has become invaded by siliceous solutions.

Even under stress conditions garnet crystals usually have an equidimensional development, thrusting aside other minerals by their power of crystallization in such rocks as garnetiferous mica-schist, and consequently there seems to be no doubt that the tabular habit is due not to mechanical forces, but to some influence of the muscovite on the molecular aggregation of the garnet crystals. Dr. R. Brauns in his book 'The Mineral Kingdom'[1] writes: 'Enclosures of other minerals in musco-

[1] English translation by L. J. Spencer, 1912, p. 331.

vite are frequent and are of special interest. Growing along with the mica between its planes of lamination these foreign minerals have been constrained to take a thin, flattened form. Thus crystals of garnet, which are so characteristically rounded or grain-like in form, when found embedded in sheets of mica have the form of thin plates with an almost circular outline. . . . That mica is capable of exerting some influence over the crystallization of other substances is shown by the following simple experiment. An aqueous solution of potassium iodide when allowed to crystallize on a glass plate produces a crop of thick cubes. If, on the other hand, the solution is crystallized on a clean, fresh cleavage sheet of mica, the crystals of potassium iodide take the form of flattened octahedra; and not only this, but the tiny crystals are all regularly oriented in the same direction on the sheet of mica, one of their triangular edges being parallel to the optic axial plane of the mica.' From these considerations it seems certain that in our case the muscovite is not merely moulded on earlier formed garnet crystals, but that already crystallized muscovite has influenced the habit of the garnets. This, of course, will explain why the flattened crystals are found within the mica books, while the rounded type is found only at the margin where the crystal structure of the muscovite has had no influence on their habit.

In two recent papers in the 'American Mineralogist'[1] there are described oriented inclusions of tourmaline, magnetite, and haematite in muscovite; and the authors incidentally referred to flattened garnet crystals, though without any details. In the case of magnetite the flattening is perpendicular to a threefold axis, and the authors showed that a close similarity exists between the spacing of the oxygen atoms parallel to the basal plane of muscovite and those of an octahedral plane of magnetite. In the case of garnet the crystals are flattened parallel to a rhombic-dodecahedral face and not an octahedral face. From data kindly supplied by the Royal Institution, the arrangement of the oxygen atoms in this plane has been plotted, but no appreciable amount of coincidence with those of the basal plane of muscovite could be recognized. The silicon atoms were also plotted, in both cases with similar negative results. In the cases mentioned here, where the trace of the optic axial plane of the muscovite is parallel to one of the diagonals of the dodecahedral face of flattening of the garnet, the plane of symmetry of the muscovite corresponds to a plane of symmetry of the

[1] C. Frondel, 1936, vol. 21, p. 777; C. Frondel and G. E. Ashby, 1937, vol. 22, p. 104. [M.A. 6–517, 518.]

garnet, but apart from these two directions at right angles there are no other coincidences among planes of low indices.

The existence of strings of garnets in lines parallel to what would presumably during growth be the equatorial faces of a crystal of muscovite suggests further that they have developed along growth-planes, and thus simultaneously with the muscovite. On the other hand, growth-planes are likely to be, and definitely are, planes of weakness, and it is possible that hydrothermal solutions could have followed such lines and introduced the material of the garnets subsequently.

Evidence has already been given to show that the development of garnet within the muscovite led to strains being developed in the mica, but the layers of muscovite are far from being entirely bent round the inclusions 'augen'-fashion. In fact, the muscovite appears to be only slightly disturbed in contact with the edges of the garnet tablets. Small rhomb-shaped highly birefringent strips of muscovite sometimes occur within the books near the garnet crystals and at first it was thought that they were fractured pieces which had been introduced subsequently, but in one or two cases these fragments were embedded in a ferruginous matrix.

In two cases of very flat crystals there is a narrow green zone along part of the margin of what appeared to be the garnet crystal, while the surrounding muscovite was also a little deeper green than the rest. This green marginal zone in the garnet was found to be soft and when the powder was examined under the microscope it was seen to consist of massive mica with an optic axial angle somewhat smaller than the ordinary muscovite, but similar in other respects and showing aggregate polarization. The garnet portion consists of a parallel growth of crystals passing into isolated crystals in the green marginal matrix, themselves arranged in parallel positions. This kind of crystalline habit does not seem to support any suggestion that garnet crystals have been produced by replacement within the large muscovite plates. Moreover, the occurrence of euhedral zoned garnet crystals within the muscovite is surely not reconcilable with a replacement origin so far as replacing muscovite is concerned.

In conclusion, then, garnet inclusions flattened more or less parallel to the rhombic-dodecahedron occur in muscovite books parallel to the mica cleavage without any other well-defined orientation of the crystals themselves, but sometimes occurring in rows parallel to growth-planes of the muscovite. The evidence indicates that the mica cannot have developed round these garnets, and that probably the crystallization of garnet and muscovite was more or less simultaneous, the partially crystallized mica influencing the habit of the garnet inclusion by molecular forces.

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