# *A contribution to the study of luxullianite.*

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LUXULLIANITE is well known, at least by name, in this country, and indeed it enjoys an international reputation among petrologists. Its general characters have been described by Bonney[1] and Sir John Flett,[2] while reference to the type is to be found in most standard text-books on petrology. It is, however, a rock of outstanding interest and deserves fuller description and illustration than have yet been accorded it.

The preparation by Mr. A. V. Weatherhead of a large set of thin sections for teaching purposes has given the writer an opportunity of making a more detailed examination of the micropetrology of the rock, with special reference to the manner of the replacement of the several original components. The particular specimen described was collected by Prof. W. T. Gordon from a loose boulder near Luxullian in Cornwall. It contains rather fewer porphyritic felspars than normally, and these are light pink to cream in colour.

The rock is regarded as the product of the arrested pneumatolytic modification, by boric emanations, of a porphyritic alkali-granite of normal West of England type. The three essential components are microperthitic felspar, tourmaline, and quartz, with apatite of two types, zircon, and a little rather dubious topaz accompanying them as accessories. The individual minerals are described first. The second part is an analysis of the various processes involved in the 'pneumatolysis' of the rock.

## COMPONENT MINERALS.

*Felspar.*—This is the only essential mineral that is wholly pre-pneumatolytic. It occurs as large, pink, corroded phenocrysts, often twinned on the Carlsbad law. In thin section it is difficult to find a patch free from cloudy decomposition products, but the microperthitic structure can still be seen as a small-scale general blotchiness, rather than clearly defined areas of albite in orthoclase. That some corrosion has occurred is obvious from the shapes of the relics that have survived, and the interest lies in the manner of the replacement. The inward limit of penetration by the reactive agents is invariably an intricately sutured boundary (figs. 1 and 2), usually obvious enough in plane polarized light by reason of the cloudiness of the felspar, contrasting with the clearness of the quartz; but sometimes it is invisible, as the quartz, which fills great embayments in the felspars, is as densely charged with inclusions as the latter. The inclusions in this case have been merely by-passed. Elsewhere, by a curious contrast, the felspar has been cleared of impurities in advance of the invading silica. Penetration has been most successful along cleavages, and the outlines of the embayments are in detail

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[1] T. G. Bonney, Min. Mag., 1877, vol. 1, p. 215.

[2] J. S. Flett, in The geology of the country around Bodmin and St. Austell. Mem. Geol. Surv. England and Wales, Sheet 347, 1909, p. 66.

controlled by the latter, giving a complex, geometrical type of 'coastline'. The original, pre-corrosion boundaries of the felspars are less easy to see; but surrounding some of the relics are zones of minute inclusions lying in the invasive quartz mosaic, quite independent of the shapes of the component grains of quartz, but evidently related to the felspar (fig. 1). These shadow-boundaries show the one-time euhedrism of the phenocrysts, and such marginal replacement is the first stage in the elimination of the felspar. At a later stage the latter is reduced to an archipelago of islets in optical parallelism, set in a sea of quartz (fig. 3). Finally, only concentrations of undigested impurities survive.

*Quartz.*—It has not proved practicable to distinguish between the primary and the pneumatolytic quartz, though some grains show the characteristic arcuate lines of minute gaseous and fluid inclusions—these may well be original—while that which has demonstrably replaced felspar is clearly pneumatolytic. The mineral shows differences in habit, proving it to have originated at different times, under varying conditions. A noteworthy feature of many of the sections is the large number of perfectly euhedral prisms occurring, sometimes in the tourmaline 'felt' described below, and sometimes in quartz with a different optical orientation and of later growth (figs. 4 and 9 respectively). Such crystals as those shown in fig. 4 are important as demonstrating the fact that some of the quartz preceded the secondary tourmaline; but some of it is definitely post-tourmaline, proving that the period of quartz formation overlapped that of tourmaline at both ends of the time-scale.

FIG. 1.

FIG. 2.

FIG. 1. A much-corroded microperthite crystal, invaded by quartz mosaic. Original boundaries outlined by minute inclusions. Sections of two conical segments of tourmaline radial aggregate attached to later growths of euhedral, zoned tourmaline (top right, vertical section; bottom right, slightly skewed horizontal section). ×20.

FIG. 2. Microperthite, top left and bottom right, corroded and replaced by quartz mosiac showing pseudochalcedonic structure. The boundaries of the individual grains in heavy outlines, and of the bladed segments shown by lighter lines. Imperfect stellate aggregates of tourmaline in the quartz. ×20.

The nature of the quartz mosaic may be judged from figs. 1, 2, and 9, in which the boundaries of the individual grains, as seen between crossed nicols, have been inserted. Once again it may be noted that, even in the mosaic, straight edges between adjacent grains are very common. Certain long, tenuous crystals occur in veins of special significance, considered below.

Although their exact nature remains in doubt, reference may be made to certain 'chloritic patches' which have exerted some control over the crystallization of the quartz. These are polygonal in shape, surrounded by quartz, there being as many grains as there are sides to the polygons, the boundaries of the grains running off symmetrically from the corners. Concentric with the sides of the chloritic areas are narrow bands of minute inclusions giving a ghost-crystal effect (fig. 3).

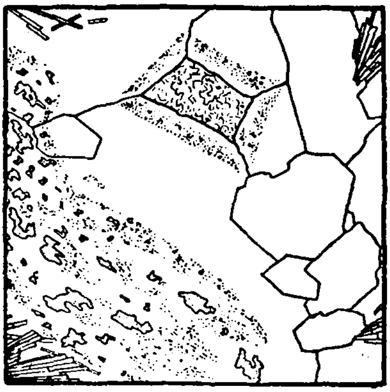

FIG. 3.

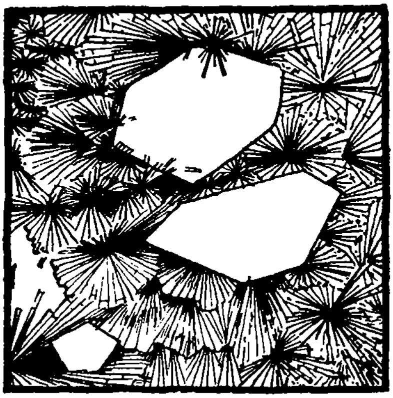

FIG. 4.

FIG. 3. Detail of quartz mosaic showing subhedral grains, some with zones of minute inclusions concentrically disposed about 'chloritic areas'. In the lower left-hand corner an archipelago of optically alined islets of microperthite in quartz, representing the penultimate stage in elimination of felspar. ×22.

FIG. 4. Detail of tourmaline 'felt' of closely packed radial aggregates containing earlier euhedral quartz crystals. ×22.

The quartz which has demonstrably replaced felspar shows one curious phenomenon between crossed nicols. The larger grains of the mosaic are themselves in part minutely composite, being segmented, or, in extreme cases, minutely bladed in a manner reminiscent of some forms of chalcedony. The boundaries of the pseudochalcedonic areas are quite independent of those of the larger grains affected, but are obviously related to the quartz-felspar boundaries (fig. 2). This suggests that the phenomenon is due to strains set up at these boundaries, probably during cooling, and is related to the intimate interlocking of the two minerals hereabouts.

*Tourmaline.*—As noted by earlier writers, the rock contains tourmaline of two generations, distinguished by differences in crystal habit and optical characters. The earlier type occurs as relatively large crystals or irregular masses mainly yellow in thin section: the later type consists of delicate green prisms. The yellow tourmaline forms relatively massive hexagonal or trigonal prisms often much embayed by corrosion, and is therefore judged to be primary. The ends of the prisms have often suffered most, and basal sections occur consisting of optically parallel, isolated, and quite shapeless masses, bearing no relation whatever to the shape of the original prism (fig. 5). Strong colour-zoning is exhibited by the primary tourmaline according to the following scheme:

| Core. | Outer zone. | Thin margin. |
|---|---|---|
| $\epsilon$...very pale buff, nearly colourless | pale buff | darker buff |
| $\omega$...very pale yellow | dull orange | light indigo |

Absorption is, of course, much less for $\epsilon$ than for $\omega$. A birefringence of 0·032 measured with the Berek compensator indicates a composition near schorlite (Winchell).

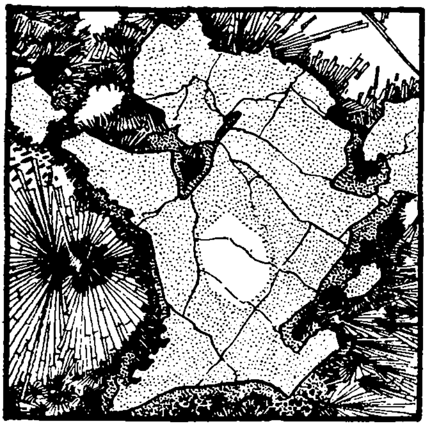

FIG. 5.

FIG. 6.

FIG. 5. Much-corroded primary tourmaline with solid reaction border passing out into radial aggregate. × 18.

FIG. 6. A typical field showing abrupt termination of tourmaline prisms against ghost-boundaries; two generations of apatite, one pre-pneumatolytic, with dark cores (top left, vertical sections; top right, basal section). × 18.

Bonney believed that the original granite contained biotite as an essential component, and that replacement followed the order:—biotite into yellow tourmaline, and the latter into green tourmaline; but in none of the present set of slides has any trace of biotite been found. Brammall[1] has already described certain facies of the Dartmoor granite in which tourmaline has taken over a primary role, and this appears to be the case in luxullianite.

*The green pneumatolytic tourmaline* is the mineral that has made the rock famous. It forms perhaps the most beautiful radial aggregates ('stellate aggregates' of Sir John Flett) occurring in any British rock. They have been referred to as spherulites; but comparison with true spherulites in acid lavas shows many points of difference and the term is not applicable. In spherulitic obsidian or pitchstone the component fibres, whether cristobalite or sanidine or both, developed about isolated centres with the same speed of growth and stopped at the same instant of time. The result is perfect, or nearly perfect, solid spheres. These tourmaline aggregates, on the other hand, are rarely spherical, and except

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[1] A. Brammall and H. F. Harwood, Min. Mag., 1925, vol. 20, p. 319.

when in the 'tourmaline felt' described below, are not solid. The dispersed nature of the individual needles is best shown in sections remote from a centre of growth, in which case a scattered constellation of small, euhedral, basal sections is seen embedded in an irregular quartz mosaic (fig. 6, top right-hand corner).

Although so minute, each crystal is a highly euhedral prism, displaying its polar symmetry by colour changes from almost black at the nuclear end, through brown and green to colourless at the distal end. The basal sections are perfectly hexagonal (not trigonal); they are strongly zoned with almost black centres bordered by bluish-green. Concentric with the centres of many of the denser aggregates are uniform, brown rings, of an almost constant radius (fig. 7). It is somewhat a mystery why, at the same stage of growth, some thousands of growing crystals should instantaneously change colour. This feature might have developed after the growth of the crystals had ceased; but it is much more likely to be an effect of a slight alteration in the physical conditions during crystallization.

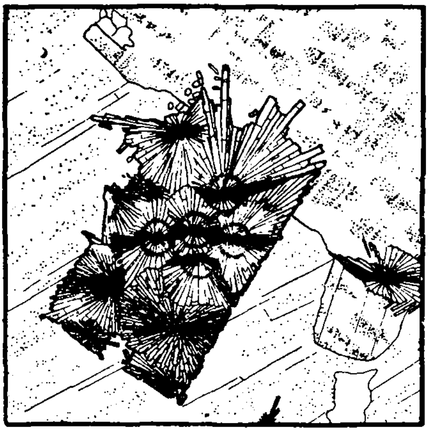

FIG. 7.

FIG. 8.

FIG. 7. Pseudomorph, probably after primary tourmaline, completely embedded in microperthite, and consisting solely of secondary sub-spherulitic tourmaline. ×20.

FIG. 8. Vertical sections of primary tourmaline prisms, zoned and surrounded by outgrowths of secondary, green tourmaline. Sections across two parallel disks of radial tourmaline-aggregate (bottom right). ×20.

The stellate aggregates are most delicate indicators of the conditions obtaining during their formation. Very few of them are symmetrical or even approximately spherical, and the individual needles vary immensely in length in different directions within one aggregate. There are four probable reasons for the wide shape-variations observed:

(1) Local differences in viscosity and irregular supply of material from which the growing prisms were drawing their substance, account for some of the 'deformities'.

(2) In those examples varying from much-flattened spheroids to mere disks, dynamic stress was probably the controlling factor. It may be noted in this connexion that several neighbouring aggregates often show a parallel maximum elongation. Some part of the observed variation in shape is due to the different

orientation of these bodies in the slides. An extreme case is that of a cross-section of a disk-like form, which consists of a single line of crystals varying in azimuth from basal sections at the centre to prismatic ones at either end (fig. 8).

(3) There remain many tourmaline aggregates which cannot be explained in these ways, however. Some of them appear to be conical in form, of fan-shaped section therefore—such radial clusters have grown on the sides of early formed crystals of felspar for example; but others are seen embedded in uniform quartz mosaic, and are less easy to explain. These are considered below.

FIG. 9.

FIG. 10.

FIG. 9. Quartz mosaic containing haphazard acicular tourmalines marking positions of crystal faces of earlier stage. Boundaries of quartz grains inserted to show the complete lack of relationship between the former and the tourmaline: the V-shaped zone of inclusions (bottom centre) passes centrally through a large quartz grain. ×20.

FIG. 10. The effect of mechanical shattering accompanied by injection of fluid silica carrying a little boron, &c. Note the very fine late outgrowths of tourmaline growing from margins of quartz-filled channels and from xenoliths broken away from radial aggregates of tourmaline. Primary tourmaline (top left) surrounded by parallel fibrous form, and that by tourmaline felt. ×20.

(4) Another extraordinary feature of the aggregates is the frequent abrupt termination of the component prisms along straight lines, that surely represent pre-existing crystal faces (figs. 6 and 9). Between crossed nicols, however, these straight lines are entirely unrelated to the existing boundaries of the quartz grains in the mosaic. There are two possible explanations: either these ghost-boundaries represent crystal faces of minerals which have been pneumatolysed out of existence (e.g., felspar replaced by quartz); or they mark the position of euhedral pre-tourmaline quartz crystals. The latter, being first in the field, set the limits to the growth of the tourmaline. After the formation of this tourmaline, the interstices were infilled with a secondary outgrowth, in optical continuity with the original quartz. Thus the once-euhedral faces were destroyed, though the earlier structure is faithfully indicated by the tourmaline.

The relation between the primary, yellow tourmaline and the green pneumatolytic forms is of considerable interest. The significant facts are as follows:

(1) The greatest concentration of stellate aggregates is invariably found round

much-corroded relics of primary tourmaline (figs. 8 and 5). The latter was evidently unstable under the new conditions and suffered corrosion.

(2) The corrosion embayments are now occupied by fibrous green tourmaline, all the fibres being parallel and in optical alinement with the corroded nucleus (fig. 10). Less frequently the parallel fibres are perpendicular to the $c$-axis of the nucleus, though these may well be outgrowths from, rather than replacements of, the primary crystal (fig. 8).

(3) This parallel habit gives place outwards to a zone of dense, fibrous brushes forming a solid felt of sub-spherulitic tourmaline (figs. 10, 5, and 4).

(4) Implanted on this felt are outwardly directed radial aggregates of much stouter prisms, penetrating freely into quartz mosaic.

The above sequence (1) to (4) is so clearly displayed about a number of corroded yellow nuclei, some of which are reduced to mere shapeless shreds, that it is reasonable to envisage the further step involving the complete elimination of the primary by the secondary tourmaline. Much of the latter has originated in this manner. Pseudomorphs of rectangular shape, still perfect in form, though consisting solely of sub-spherulitic tourmaline occur, sometimes embedded in felspar (fig. 7). They contain no trace of the original mineral, and the shape is not diagnostic; but there is little doubt that these were prisms of primary tourmaline, completely altered at a stage when felspar had hardly been attacked.

As to the significance of the facts (1) to (4), the tourmaline of parallel fibrous habit was still under the control of the original lattice, and the change was textural rather than compositional, though a slight atomic reshuffle was involved, the absorption formula for $\omega$ changing from light buff (for the primary nucleus) to deep bluish-green (for the secondary type). The felt of radial brushes is also exclusively tourmaline, but resulted from greater atomic mobility, and represents an attempt to develop an independent crystal habit. The coarser stellate aggregates growing freely into quartz mosaic developed under conditions of maximum atomic mobility, in 'channels' between 'islands' of disappearing felspar and primary tourmaline.

It may be noted that the felt sometimes contains considerable numbers of short, stout, perfectly hexagonal, dark-cored prisms of a different order of magnitude altogether from the fibres building the aggregate in which they are embedded. There is no doubt that these developed from the felt by recrystallization under the general urge of the pneumatolytic conditions: nothing more than a slight structural change is involved: but it gives yet another generation of tourmaline crystals of distinctive habit.

*The accessory minerals* shed little light on the process of pneumatolysis. Apatite occurs sporadically as large, often rather irregular prisms, sometimes corroded and with fine solution channels parallel to the $c$-axis. These short prisms contain dusky cores, and in basal sections they may be almost black throughout (fig. 6, top, left and right). Other smaller clear, doubly-terminated prisms evidently belong to a later generation, suggesting that the cored crystals are pre-pneumatolytic.

## SUMMARY OF THE 'PNEUMATOLYTIC' CHANGES.

The above account refers to the mineralogical and textural changes developed in a very small portion of an Armorican granite placed in the path of mineralizers rich in borofluoric flux, concentrated in and escaping from the granitic magma.

Of the original minerals, quartz, felspar, and tourmaline, the second and third proved unstable under these conditions. The felspar was attacked for the soda and alumina, essential for the growth of the new tourmaline; while the yellow tourmaline, after a period of corrosion, served as nuclei about which radially disposed acicular tourmaline crystallized.

The question naturally arises as to the extent to which the rock was actually liquefied during pneumatolysis. The new tourmaline has not crystallized freely in and about the felspar, while the structure of the latter has been sometimes retained. This suggests that the conversion of the microperthite into quartz mosaic with a very little microlithic tourmaline was effected largely by molecular diffusion. It was a two-way diffusion, silica and boron moving in across the felspar boundaries, and alumina, potash, and soda moving out in the opposite direction. The main lines of attack by the pneumatolysing agents are shown by the channels referred to above, within which delicately acicular crystals of tourmaline, of relatively great length, developed freely in all directions: they were clearly growing in a fluid environment, which later 'set' as quartz mosaic containing fluid and gaseous inclusions in abundance. But such local molecular diffusion and liquefaction do not seem suitable vehicles for the large-scale transfer of pneumatolytic material through any thickness of granite, and there is evidence of another process, which may well be important. This is mechanical shattering and all the phenomena of stoping on an extensive, though microscopic, scale. The shattering has affected all the primary minerals, and allowed the invasion of siliceous fluid under pressure to wedge off micro-xenoliths, forming anastomosing veins. The displaced sides of the channels so produced could sometimes be fitted together again with jig-saw precision (fig. 10); but in many other instances the veins are ill-defined. Wholesale breaking up of some of the stellate aggregates has produced innumerable pieces, ranging from conical segments to short sections of two or three contiguous prisms, scattered in all directions in the quartz mosaic. This was the third cause of irregularity in the shape of the tourmaline aggregates, referred to above.

The material which was intruded during this period of shattering was very largely silica, but with a small amount of potential tourmaline, which crystallized in the form of short, very fine needles, growing in optical alinement into the channels from the torn ends of the larger tourmalines, or as a fine outgrowth from the fractured xenoliths of stellate aggregate. In addition, some of the channels are margined by a haphazard mesh of fine microlithic tourmalines, looking like stranded flotsam. The quartz in the channels shows none of the normal vein-quartz structure, but occurs as very long crystals—one crystal may completely fill a vein—and there is no observable difference between the quartz in the veins and that outside in the ordinary mosaic.

The fact that the largest tourmaline aggregates have been involved in this shattering shows that the mechanism continued beyond the phase of maximum fluidity. The effects of arrested stoping are clearly shown at this late stage in the cooling of the rock. Similar but earlier episodes of shattering will have had their effects obliterated by the greater fluidity and fluxing of that time. The process may well be an important factor in this type of pneumatolysis.

The amount of replacement of the primary minerals in this rock has been great: indeed it has locally been so thorough that the evidence of change is circumstantial only. To-day, when the igneous origin of many so-called igneous rocks is being called in question, and when so much is claimed for mineralizing agents in rock genesis, it is useful to look again at an instance where the evidence of replacement is beyond question by reason of the many relics of its past history that remain decipherable.

### *Acknowledgements.*

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