Myrmekite in graphic granite and in vein perthite.

(With Plates VI and VII.)

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1. INTRODUCTION.

THIS paper describes the occurrence of myrmekite in a graphic quartz-microcline-rock from the mica-bearing pegmatites of Kodarma, Bihar, India. The myrmekite has grown out from the quartz-microcline junctions into the potash-felspar with the appearance of having replaced the latter. The two are in optical and crystallographic continuity and, owing to the large 'single crystal' character of the microcline, definitely oriented sections can readily be prepared. A detailed study of these sections shows that the myrmekite has been formed by the segregation and coalescence of microperthitic albite formerly held in solid solution in the potash-felspar. Successive stages in this process of segregation can be observed.

These sections also provide evidence of the paragenetic relationship between the quartz rods, the vein perthite,[1] and the body microcline. This is supplemented by additional evidence from graphic granites and vein perthites obtained from other localities.

2. KODARMA GRAPHIC GRANITE.

(a) *Megascopic characters.*

This rock was obtained from a road-cutting near the Ramchance mica mine, Kodarma. At the time of collecting the specimens, the newly made cutting exposed a cross-section of at least 40 feet of pegmatite which consisted almost entirely of quartz and microcline in graphic intergrowth. As is usual with these graphic intergrowths the whole of the microcline apparently consisted of one crystal. The texture varies in size from two or three inches across individual bands down to several to the inch. Where unweathered the microcline of this graphic rock is colourless and translucent to nearly clear, cleavage fragments up to $\frac{1}{8}$ inch being glass clear when viewed along the *b* and *c* directions, but turbid along the *a*-axis. The quartz rods are clear and moderately free from inclusions.

When a specimen of this rock is ground and polished parallel to the (001) direction of the microcline, the felspar portion shows an uneven pearly or satiny schiller. This unevenness becomes very marked when the polished surface is

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[1] Throughout this paper Andersen's term 'vein' perthite has been used when referring to the coarser variety of perthitic albite lamellae found in pegmatitic microcline. This term appears to have received general acceptance amongst petrographers, although, as Alling has pointed out, it may at times lead to confusion. His alternative term 'band' perthite, is not strictly descriptive of these lamellae, since they are usually lenticular in form and often arranged in echelon.

viewed by point-source oblique illumination, as may be seen from text-fig. 1, the bright and shaded portions being microcline, the quartz rods being shown in black. The puckered or 'rucked up' appearance of the microcline surface is due to a local distortion of the basal and perthite planes. This distortion is more pronounced near the contact with the quartz rods.

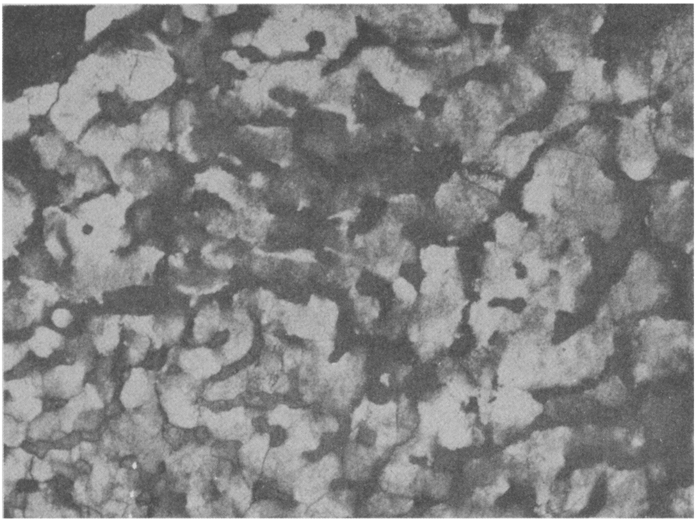

FIG. 1. Graphic granite, Kodarma, India, ground and polished on (001), viewed by oblique illumination. Shows internal distortion of perthite and basal planes of the microcline. Natural size.

(*b*) *Description of microscope sections.*

As the myrmekite intergrowths in these pegmatitic microclines, together with the vein perthite, are believed by the writer to have been derived mainly from microperthitic albite by a process of segregation and coalescence, the evidence for this segregation, as seen in sections, will be given in some detail before describing the myrmekite bodies.

Sections on (001).—In ordinary light, sections on (001) of the microcline portion of the graphic rock show fine evenly distributed microperthitic lamellae with occasional larger units of vein perthite. The microperthite is finer in size than in many microclines, but much coarser than in the microperthitic orthoclases, the length and breadth being about 0·05 to 0·1 mm. and 0·005 to 0·01 mm. respectively. The vein perthite ranges up to about 0·1 mm. in breadth and several millimetres in length. The finer lamellae lie mainly along the trace of (100); the directions taken by the larger lenses are more irregular, often branching off from (100) into prism traces.

In the neighbourhood of the coarser vein perthite the finer lamellae tend to be scarce or absent, but here and there, occasional smaller lamellae divert towards the larger units, rivulet fashion. This coalescence is more pronounced near the ends of the larger lenses, and can be better observed under polarized light with the albite lamellae in extinction and the nicols slightly uncrossed to subdue the microcline twinning and show up the perthite. A photograph taken with this setting is shown in pl. VI, fig. 1. The stream-like diversion of the finer lamellae towards larger individuals is fairly evident. This segregation appears to have been very sensitive to the influence of slight local movement in the felspar and to the presence of foreign inclusions. The effect of such inclusions can be seen in pl. VI, fig. 2, which shows three quartz blebs (one to the left of the photograph, one centre, and a very small one below centre) and a mica lath on the left, all of which have acted as nuclei for coalescence of the microperthite. Another feature common to these two sections, seen also in microclines from other localities, is the development of a much coarser type of microcline twin blading around the coarser perthite lenses, with a preponderance of the albite over the pericline twinning. This may be due to the coarser albite blades having imposed a larger type of twinning on the common lattice framework of the adjacent microcline, or in part to the absence of fine microperthite in these areas having allowed greater freedom for the microcline to form uninterrupted twin blades.

Sections on (010).—Sections on (010) show the usual longitudinal microperthitic lamellae typical of many microclines, running in a direction approximately 73° to the basal cleavage as in microperthitic orthoclase. The length of the individual lamellae is about 0·1 mm. and the thickness about 0·01 mm. These dimensions are several times larger than the microperthite commonly seen in orthoclase and the definition is much sharper, indicating a more complete separation from the potash-felspar component.

Here and there one sees coarser bands of vein perthite up to several millimetres in length and 0·1 mm. in thickness. These larger lamellae tend to run obliquely across the finer microperthite, in a direction roughly 64° to the trace of the basal cleavage. Many of them show incomplete segregation, and their formation can be progressively traced from the coalescence of a few microperthitic individuals, their segregation into a 'swarm', and the coalescence of these into vein perthite. The swarms of smaller aggregates usually show a crude echelon arrangement (pl. VI, fig. 3).

Sections containing myrmekite.—In sections on (010) across the quartz-microcline junctions, the quartz cuts clean across the perthite texture with no change in size or amount of perthite near the contact, and with no evidence of selective action on either of the two perthite components. Occasionally, however, the vein perthite may continue as a band or layer of albitic material along the junction. Sometimes these films are found along one side only of a quartz rod, or round a promontory, suggesting that they may have filled in cracks or cavities formed at the junction by a slight relative movement of the two components. The films are in crystallographic and optical continuity with the adjacent vein albite lamellae and extinguish with them. A section on (010) through one of these boundary films, is shown in pl. VI, fig. 5, with the microcline in extinction. The darker 'core' of the film of albite is due to the slightly lower extinction-angle of the central portion, which is a little more anorthitic than the rest. The quartz rod, seen in the lower half of the picture contains two islands of microcline, oriented differently from the main microcline and from each other. These will be referred to later in the text.

In places these boundary films broaden out, when the central core becomes larger and still more anorthitic, and small rods of quartz make their appearance. Occasionally these boundary films or segregations thicken out into true myrmekite 'warts' or protuberances, with convex surfaces turned towards the microcline, and with a core of more anorthitic plagioclases containing the characteristic vermicular quartz of ordinary myrmekite. A number of myrmekite blebs which have grown out in this way along a quartz-microcline junction are shown in pl. VI, fig. 6. The section is cut parallel to the (010) direction of the microcline and viewed with the quartz rod and the vein perthite in extinction, the myrmekitic quartz and the body microcline being in illumination. The myrmekite has the 'warty' appearance and texture common to these intergrowths, with convex surface turned towards the microcline. It will be noted that the myrmekite blebs have a dark outer rim which is in extinction with the vein perthite and that the two join up and blend together in places. They have the same composition and have evidently been formed at the same time. Their extinction-angle is 16° relative to the basal cleavage of the microcline, corresponding to the composition $Ab_{94}An_6$. That of the myrmekitic core is 6°, corresponding to $Ab_{77}An_{23}$. As would be expected from this difference in composition the myrmekitic quartz is almost confined to the more anorthitic cores. It will be observed that the change from albitic rim to anorthitic core is very sharp.

The progressive development of vein perthite by coalescence from microperthite, and of myrmekite through boundary film albite, indicates that both these forms of plagioclase were derived from microperthite, and thence originally from solid solution in the potash-felspar.

A few sections of the microcline of this graphic rock show crush or 'mush' zones in which myrmekite has developed. One such crush zone, lying between the ends of two graphic quartz rods, is seen in pl. VII, fig. 8, in (001) section between crossed nicols. Only one of the quartz rods is shown—to the left of the photograph. The zone contains a few myrmekite blebs associated with a number of hypidiomorphic microcline crystals. These have a random orientation relative to the main microcline crystal and are bordered in places by a rim of albite. They are more pellucid and less perthitic than the main microcline crystal, indicating that they have formed later and at a lower temperature, yet within the exsolution temperature range.

Another interesting (010) section of a crush or 'mush' zone is shown in pl. VII, fig. 7, with the body microcline in partial extinction. A portion of the main microcline crystal embayed in a graphic quartz rod—shown in the upper part of the photograph—has been torn away and twisted through an angle of about 30°, as can be seen from the relative perthite directions in the two parts. The 'mush' zone between them contains myrmekite together with small albite and microcline crystals. The strongly perthitic character of the embayed microcline fragment shows that it was formed at or near the same temperature as the main microcline. The absence of sharp fracture lines between the two portions indicates that when the relative movement occurred the quartz rod was more or less rigid and the body microcline in a semi-plastic or 'mushy' condition. The curvature of the perthite bands towards the crush zone also lends support to this view. The 'rucking up' of the microcline in this Kodarma rock referred to on p. 80 and shown in text-fig 1, also suggests a greater rigidity of the quartz rods than the microcline during the consolidation period.

3. SIMILAR TEXTURES IN PEGMATITIC MICROCLINES FROM OTHER AREAS.

While it is possible that the structures described in these Kodarma graphic specimens, namely coalescence of microperthite into vein perthite and the formation of myrmekite blebs, may have been influenced in part by relative local movement between the graphic quartz rods and body microcline, similar features have been observed in pegmatitic microclines from other areas without accompanying evidence of local movement.

Incipient coalescence of the microperthite can be seen in the section of dental microcline from Quebec shown in pl. VI, fig. 4. Here coalescence has been encouraged by the presence of small mica inclusions. This segregation or coalescence is often accompanied by other evidence of the close genetic relationship between the two forms of perthite, as, for example, the depletion or impoverishment in microperthite of the areas immediately surrounding the larger perthite lenses. Pl. VII, fig. 9, shows a (010) section of microcline from a pegmatite near Asansol, Bengal, in which the vein perthite lenses, arranged in echelon, have robbed the surrounding areas of fine microperthite.

Another feature sometimes seen is the 'patterning' or regular distribution of the finer lamellae in relation to the coarse, as is shown in pl. VII, fig. 10, which represents a (010) section of a microcline from the Nellore mica-pegmatites, Madras. This feature is usually associated with an irregular arrangement of the vein perthite and may indicate local movement during consolidation.

Microperthitic impoverishment, or depletion, near the coarser albite lenses has been recorded by Maurice (1940, p. 166) in pegmatitic microcline from Spruce Pine, North Carolina. His view is that the larger perthite or 'veinlets' have been formed by recrystallization of the albite squeezed from the nearby microperthite lamellae.

In the writer's opinion many of the excellent photographs figured by Andersen (1928, pls. I and II) show this coalescence of the microperthite, with consequent depletion near the larger vein perthite. Another example figured by Goldich and Kinser (1939, p. 418) shows, in a section of pegmatitic microcline from Granite Mountain, Texas, coarse vein perthite, fine 'patterned' microperthite, and short rods of coarse perthite in echelon with depleted areas between.

Microcline perthite sometimes shows incipient myrmekite within the vein perthite lenses, especially when the felspar is higher in lime than usual. A section of microcline perthite on (010) from a pegmatite near Burakur, Bengal, shows this feature (pl. VII, fig. 11). The single broad band of vein perthite is seen to contain darker, more anorthitic cores, within which a few bright rods of myrmekitic quartz occur. All the vein perthite in this microcline shows this feature in a greater or less degree. The extinction of the outer shell relative to the basal cleavage, is 18°, corresponding to $Ab_{97}An_3$. That of the core averages 9–10°, corresponding to $Ab_{88}An_{12}$.

Andersen (1928, pp. 155–162) also noted more anorthitic cores in many of the vein perthites examined by him and of one specimen he remarked 'a characteristic of this specimen as of many others, is that the veins always contain fairly regularly arranged bodies of quartz running along the central part of the vein'. Barth (1928, pp. 424–428) has described in some detail incipient myrmekite textures in vein perthites of pegmatitic microcline from primitive rocks in southern Norway, very similar to the one shown on pl. VII, fig. 11. He measured the extinction-angles of the shell and the core in 18 specimens, 16 of which averaged $Ab_{95.4}An_{4.6}$ for the shell, and $Ab_{87}An_{13}$ for the core. He observed that the composition of the shell was the same as that of the microperthitic albite lamellae, and he suggested that both the fine and the coarse perthite had been formed by exsolution, the lime-felspar separating first—with some of the soda—at a higher temperature, followed at a lower temperature by the bulk of the soda-felspar which had deposited as shells round the earlier lime-soda-felspar or separately in the body microcline as microperthite. Shibata (1933) has figured true wart-like myrmekite in a peculiar pegmatitic microcline-perthite from Ishikawa.

4. Origin of these Textures.

In the foregoing pages, three well-known rock textures, namely graphic quartz-microcline, vein and microperthite, and myrmekite, have been described in association in the same pegmatite rock, and observations and deductions have been made in regard to their origin. Each of these textures has, in the past, formed the subject of investigation and research by petrographers and a considerable volume of somewhat controversial literature is now available in regard to them. In order to discuss the relevance of the observations made in these pages to the various theories which have been put forward to account for the formation of these various textures, a brief résumé will be made of the literature dealing with each type.

(a) *Graphic granite.*

Because of the resemblance to many artificial eutectic crystallizations and the relatively constant ratio of quartz to felspar, these graphic intergrowths were early ascribed to simultaneous crystallization of the eutectic kind by Vogt (1904). Mäkinen (1917) measured the ratio of quartz to felspar in a number of graphic granites of Finland and found a limited free-quartz range of 23–32 %. Holmes (1919, p. 77) carried out field measurements on a number of graphic granite exposures in Mozambique and obtained a quartz range of 24–28 %. In both these cases the results were believed to support the direct crystallization theory. Eskola (1928), examining the rapakivi rocks from the Gulf of Bothnia, found micrographic quartz-felspar growths around orthoclase cores. One of his figures shows them growing out perpendicularly from each face of an idiomorphic felspar crystal, proving in this case an origin by simultaneous crystallization. Fersman (1929) examined the relative orientation of the quartz rods and the felspar and found a definite relation between them. He also noted that in some cases the quartz rods were of the 'high' temperature kind, in others the 'low'. His conclusions were that the texture had been produced by simultaneous crystallization of the quartz and felspar. Vogt (1931, p. 125) in a later discussion of granites and granite-pegmatites, suggested that graphic granite had been formed by simultaneous crystallization from a 'cotectic' magma, at a late stage in the consolidation of the pegmatite. He assumed the composition of the cotectic magma to be the same as that of the graphic granite, plus a third component consisting of $SiO_2.nH_2O$, and a small amount of other mineralizers. Vogt again emphasized that these intergrowths fell within narrow limits of composition, both as regards the quartz-felspar ratio and the ratio of potash- to soda-felspar, the latter being about the same as that in ordinary pegmatitic microclines.

Other investigators have questioned the limited range of composition ascribed to these graphic granites and have expressed the opinion that many, if not all of them, may have been formed by the replacement of potash- or potash-soda-felspar by silica. Schaller (1925, pp. 274–276) suggested that the original pegmatite rock possibly consisted of orthoclase and that this had been successively replaced by soda and by silica-bearing solutions. He observed (1927) that the quartz rods of the graphic structures cut across the perthite lamellae and submitted this as evidence that the quartz had been introduced after the formation of the perthite. Vogt (1931, p. 136), however, suggested that as the perthite lamellae had been formed by exsolution, they had *naturally stopped* at the quartz rods, hence the appearance of their being 'cut across' by the latter. Landes (1932) discussing the origin of the graphic granite of Baringer Hill, Texas, referred to Vogt's observations and pointed out that in the Baringer Hill pegmatite the quartz rods cut across 'vein' perthite which, according to Andersen (1928) and Alling (1932), is a product of replacement and not of exsolution. Hence he concluded that the graphic quartz must have been introduced by replacement at a still later stage than the vein perthite. In support of this view he instanced the occurrence of 'islands' of microcline within the quartz rods, having the same orientation as the main microcline crystal. Hess (1933, pp. 451–452) referring to the Minor Keith pegmatites near Auburn, Maine, remarked: 'the production of graphic granite from a perthitic feldspar dike by the introduction of quartz from quartz veins is almost diagrammatically shown'. Wahlstrom (1939) examined the relative orientation of the quartz rods and the microcline in a number of graphic granites and obtained results at variance with those of Fersman. He also questioned whether these structures had a limited range of composition and concluded that they had been formed, in the main, by replacement and not by simultaneous crystallization. Switzer (1938, 1939) and Mitchell (1941) may be mentioned as recent investigators who have favoured the idea of simultaneous crystallization for these graphic granites. Uspensky (1943) described a peculiar radiating type of graphic granite in a pegmatite of Transbaikal, which displayed a rhythmic broadening and narrowing of the quartz rods, and which he believed had been produced by simultaneous crystallization. In an earlier paper (1938, pp. 105–106) the writer refers to these graphic granite textures, citing five Indian samples with a limited compositional range, and concludes that the constituents have crystallized simultaneously.

The arguments for and against simultaneous crystallization on the one hand and replacement on the other, have thus centred round:

(1) *Quartz-felspar ratio.*—A few workers have questioned the limited compositional range, but the great majority of those who have examined the quantitative relationship between the quartz and the microcline have concluded that the compositional range is a comparatively narrow one—far too narrow to be explained by replacement.

A feature sometimes met with in these graphic quartz-microcline structures, which has a bearing on this compositional range, is the local impoverishment of the surrounding area by a larger quartz rod or 'ichthyoglypt'. Text-fig. 2 shows a hand-specimen of graphic quartz-microcline with a central larger rod which has evidently robbed the surrounding area of free silica. Another specimen with finer-grained graphic structure is shown in text-fig. 3; the relatively larger rods are seen to be surrounded by areas devoid of quartz. This feature of impoverishment, already discussed in relation to the perthites, is more common in the latter, probably owing to the greater mobility of the alkali ion than the silicon-oxygen group. Similar impoverishment or depletion of the surrounding areas in food supply by larger individuals is a common feature of metallic alloys, and can be produced almost at will either by direct crystallization or by exsolution from the solid state. *Where such impoverishment occurs in these rock textures, it provides* strong evidence of simultaneous crystallization rather than replacement.

FIG. 2. Graphic granite, Jointora, Bihar, India. Ground on (100), showing local impoverishment in quartz. × 2·5.

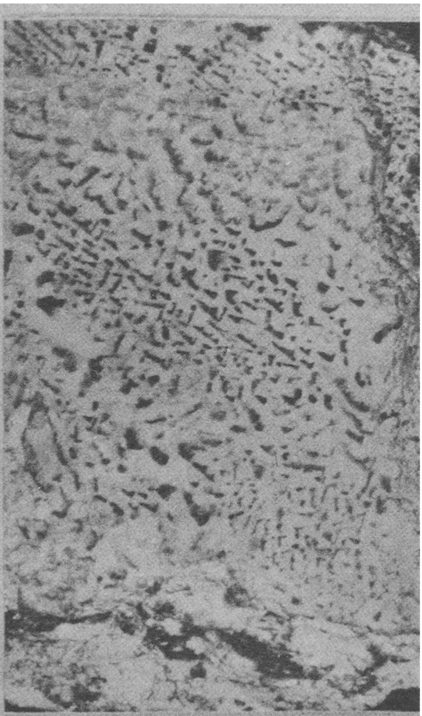

FIG. 3. Fine-grained graphic granite from Miask, Urals. Ground on (100), mainly. Shows local impoverishment in quartz. × 2.

(2) *Crystallographic relationship.*—Whether such a relationship exists between the quartz rods and the microcline is still an open question which may yet be solved by X-ray analysis. Oriented intergrowths like the one figured by Eskola (1928, pl. I, fig. 3) or the coarser rhythmic intergrowths described and figured by Uspensky (1943, p. 439) would, however, be difficult to explain by replacement.

(3) *Relationship of quartz to the perthite.*—The 'cutting across' of the perthite by the quartz, put forward by Schaller as evidence of replacement, appears to the

writer to be of doubtful value. One would expect such invading silica-bearing solutions to have dissolved away more of one perthite component than the other, if they were already in existence when the silica was introduced, yet there is no evidence at all of selective action. This is all the more remarkable when it is remembered that the silica-enrichment phase is assumed to have followed replacement of potash- by soda-felspar to produce vein perthite. Equally remarkable—if they are replacements—is the manner in which the silica-bearing solutions have avoided earlier perthite replacement directions and other 'lines of weakness' in the felspar.

The Kodarma specimens described in the foregoing pages, provide direct evidence that the appearance of 'cutting across' by the quartz rods of the perthite does not necessarily imply a later origin for the quartz. In the same section—as in pl. VI, fig. 5—one can observe the quartz cutting clean across the perthite, whilst a short distance away a layer of albite lies along the quartz rod boundary. These albitic layers have most obviously been deposited against the quartz, and if they and the vein perthite are of the same age, the quartz must antedate both. This view is also supported by the occasional presence, in graphic-granite sections, of vein perthite partially enveloping or wrapping round the end of a quartz rod. The two sections figured by Wahlstrom (1939, p. 691) show this phenomenon.

In other specimens, where the graphic structures are sufficiently small for several parallel quartz rods to be observed in the same section, the true relationship is seen to be one of perthite growing out from the quartz rods, not of the quartz cutting the perthite. This is shown in pl. VII, fig. 12, which represents a section of fine-grained graphic granite from the Urals, cut along the basal plane and seen under crossed nicols with the body microcline in the 'neutral' position. The vertical white bands are quartz rods; the nearly horizontal torch-like blades are vein albite. It is very evident that the latter have, in the main, grown out from the quartz rods and not been cut across by them. Another feature met with in these graphic structures and which suggests simultaneous crystallization, is the sudden change in size or direction of the quartz rod 'ichthyoglypts' within the same microcline crystal, as can be seen in text-figs. 4 (*a*), (*b*), and (*c*), which show three views of a specimen of quartz-amazonite graphic rock from the Urals. The microcline is one untwinned crystal, and from an uneven surface within the crystal—lying near an orthodome—the quartz rods have grown out in two directions and sizes. The fine white striations nearly perpendicular to the trace of (001) in the upper portion of fig. 4 (*a*) represent vein perthite.

The 'rucking up' of the microcline described on p. 80 and illustrated by text-fig. 1, also suggests that the consolidation of the body microcline took place after that of the quartz rods. So also does the torn fragment of microcline embayed in a quartz rod referred to on p. 82 and shown in pl. VII, fig. 7. Landes's suggestion, already mentioned, that 'islands' or patches of microcline, lying within the quartz rods and oriented with the main microcline crystal, represent replacement residues loses its value if it can be shown that these 'islands' often have 'random' orientation. Of the many such inclusions observed by the writer in the Kodarma graphic granite probably less than half show parallel orientation. The two seen in the lower part of pl. VI, fig. 5, both have 'random' orientation. With 'islands' of random orientation the evidence is definitely against replacement; with those showing parallel orientation one is never certain that the

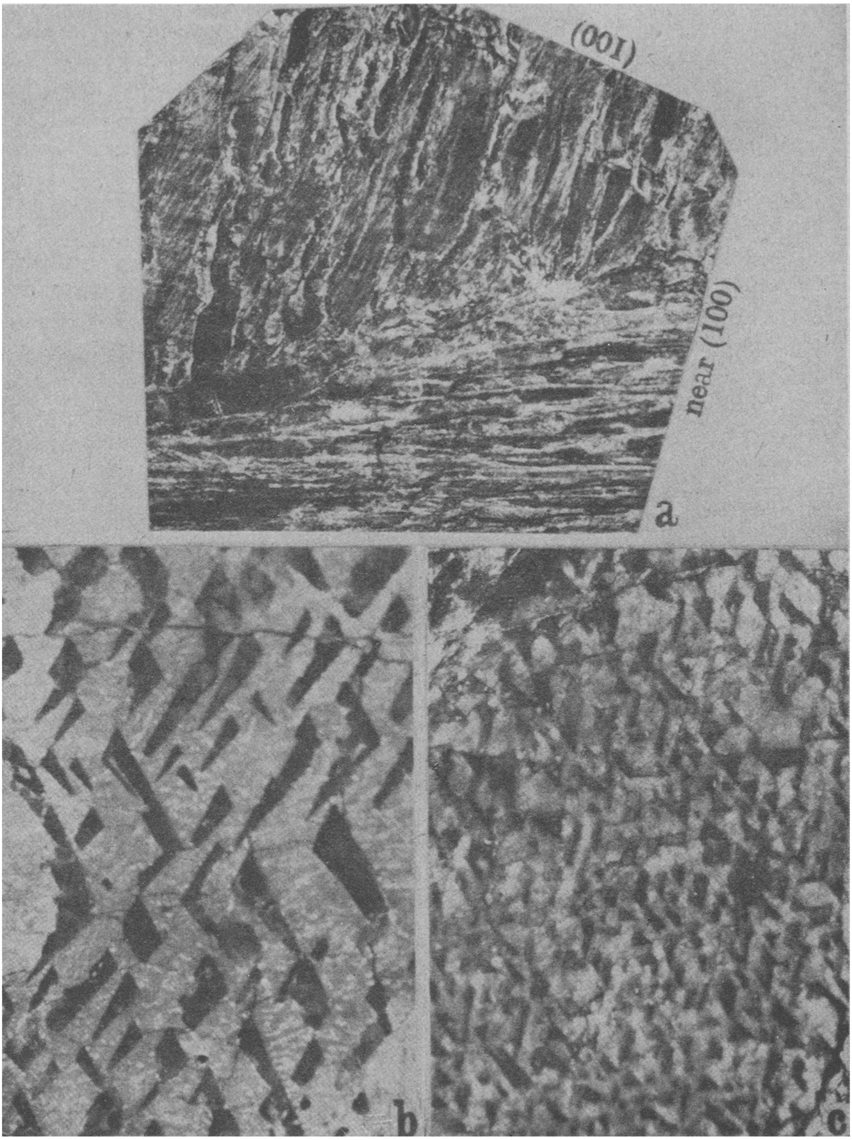

Fig. 4. Graphic quartz and amazonite from Miask, Urals. (*a*) Roughly cleaved on (010). Shows two directions and sizes of quartz rods in the same microcline crystal. The fine striations in the upper part are vein perthite. × ⅔. (*b*) Ground on (001). × 1·5. (*c*) Ground on surface near (100). × 1·5.

separation of the inclusion from the body microcline is absolute, or only apparently so, due to the particular direction of the section.

(*b*) *Vein perthite and microperthite.*

It is now generally agreed that the microperthite commonly found in potash-soda-orthoclase and to a lesser degree in microcline has been formed, as originally suggested by Vogt (1906), by an 'unmixing' of the potash- and the soda-felspar to which process Alling (1921, p. 222) gave the name 'exsolution'. The writer has shown (1930, 1937) that these microperthitic lamellae can be taken into solution by heating and brought out again on slow cooling at temperatures far below the melting-point of the felspar. X-ray investigations by Taylor and others (1934) have provided an explanation of these changes based on the migration of the alkali ions within a relatively rigid SiO_4AlO_4 tetrahedral framework.

Microperthite is best developed in the orthoclase felspars; in the microclines, the coarser form, vein perthite, usually predominates. Andersen (1928) has explained the formation of this coarser type of perthite on the assumption that shrinkage cracks were developed along certain directions in the felspar, whilst cooling from its formation temperature (near 850° C.) down to the quartz inversion temperature of 575° C. Soda-bearing solutions had then entered these cracks and formed vein perthite. In a previous issue of this magazine (1938, pp. 106–107) the writer has expressed the opinion that much of the evidence available in regard to these potash-soda-felspars is at variance with Andersen's shrinkage crack theory. The additional information supplied by these Kodarma and other Indian specimens lends further support to this view. They show that the vein perthite has been formed by a process of exsolution and coalescence while the felspar was probably in a semi-plastic state. In this condition the formation of shrinkage cracks would not be possible. Moreover, these microclines have probably been formed not very appreciably above the lower limit of Andersen's temperature range. On the other hand, the microperthitic orthoclases formed in all probability nearer the upper limit of this range are signally devoid of vein perthite.

It is possible that the differential contraction of orthoclase felspar with falling temperature may have had an effect on the *microperthitic* separation or exsolution, in the *opposite* manner to that suggested by Andersen. X-ray investigations indicate that the greater expansion and contraction along the a-axis with change of temperature is caused by a concertina-like extension or closing up of the linked tetrahedral chains of the felspar framework along this direction. Such a closing up of the chains with falling temperature would have the effect of internal compression rather than tension in that direction, and the separation of the microperthitic albite lamellae perpendicular to this direction would be analogous to the orientation of mineral plates or films in a slate or schist, perpendicular to the direction of pressure.

Schaller (1925, p. 276) suggested that the physical changes resulting from the inversion of orthoclase to microcline in pegmatites, may have facilitated the entrance of albitizing solutions. An accurate comparison of the densities of these two felspars is difficult, owing to the heterogeneous character of most microclines, but from a number of analyses and density determinations made by the writer, together with similar determinations made by Jayaraman (1940) on microclines, I estimate that the difference in density between orthoclase and microcline—of the same chemical composition—is in the order of 0·004, with microcline the heavier. This corresponds to a difference in volume of about 0·16 % which is only about one-quarter of the volume change caused by the exsolution of 25–30 % of microperthitic albite (Spencer, 1937, p. 470) and only about one-tenth the total volume change on slowly cooling such a felspar from 750° C. to 450° C. (Kôzu, 1925). Hence, even if such an inversion has taken place fairly rapidly, it could not have had any pronounced effect on the physical conditions within the cooling felspar. It is more probable that the principal effect would be to reduce the solid solubility of the soda- in the potash-felspar.

Vogt appears to have regarded both vein perthite and microperthite as products of exsolution and Barth (1928) regarded the Norwegian perthites in this light. Shaub (1929, p. 76) has also suggested that the vein type of perthite may have been formed by exsolution. The modern concept of microperthitic exsolution as representing a metallic ion, and not a complex molecular translation within the solid crystal, lends itself to the suggestion that these larger lamellae may have been formed in this way. Nevertheless the fact, already emphasized, that the potash-soda-orthoclases, formed at higher temperatures than the microclines, contain only fine microperthite does indicate that these ionic segregations in the solid felspar produce only the fine variety of perthite.

What then are the conditions under which the pegmatitic microclines, with their varied types of vein and microperthite, have been formed? Heat-treatment experiments by the writer (1937, p. 473) on the microperthitic orthoclases have shown that up to 30 % of soda component can be taken into solid solution, by heating for relatively short periods to about 750° C., and brought out again by slow cooling to 400–450° C. This 'main exsolution temperature range' is considerably below the formation temperatures of the orthoclase felspars. On the other hand, field and other evidence indicates that the microclines have probably crystallized somewhere between 500° C. and 700° C., which temperatures fall within the above exsolution range. *In the writer's opinion it is this overlap of the crystallizing temperatures into the 'main exsolution temperature range' which has given rise to the differences in texture and character between the microclines and the orthoclases.*

Let us assume potash-soda-felspar to be crystallizing from a pegmatitic magma, at a temperature of say 700° C., saturated with soda component at that temperature (25–30 % soda component), and with the magma rich in water and other mineralizers. If, due to rapid cooling or the sudden loss of liquefying mineralizers, solidification is rapid, a felspar approaching orthoclase in character would be formed, with fine and fairly regular microperthite, fine woolly cross-hatch twinning —so fine as to be nearly invisible—and devoid of vein perthite. Microclines of this type are not uncommon, and have occasionally been obtained by the writer from narrow bands of pegmatite where field evidence of rapid cooling is found. They are often richer in soda than those containing vein perthite.

The texture of a microcline formed under the above conditions, would be modified if the crystallizing period was prolonged, or if, after solidification, the felspar had been subjected through the exsolution temperature range to the soaking action of residual magmatic liquids held within the pegmatite. By such means the formation of larger perthite individuals by coalescence would be induced, leaving the adjacent areas impoverished in microperthite.

Very slow cooling in the presence of mineralizers would allow additional factors to come into play. Exsolution would accompany crystallization and the local strains set up thereby in the crystallizing lattice framework would encourage inversion to the microcline form, causing increased exsolution. The falling temperature would also reduce the solubility for soda in the magma and in the crystallizing felspar and the excess would tend to crystallize independently within the felspar meshwork as coarser vein perthite less regular in type than that formed by coalescence. Magmas crystallizing at lower temperatures would produce microclines lower in soda and with less perthite.

This brief attempt to explain the origin of the various microcline textures, formed in ordinary granite-pegmatites by direct crystallization from a more or less 'closed' magmatic system, takes into consideration the fact that by far the greater majority of these microclines contain no more—and often no less—soda component than one would expect from equilibrium conditions at their probable formation temperatures. Thus the introduction of soda, by way of albitization or replacement from without, is quite unnecessary to account either for the composition, or for the different perthite textures found in these microclines.

I would here emphasize, however, that the foregoing observations regarding replacement in pegmatites, refer only to the ordinary or simple granite-pegmatites in which microcline and quartz are the principal constituents, muscovite and free plagioclase, &c., being present only in subordinate amounts. The complex pegmatites, on the other hand, are usually richer in plagioclase and often show indubitable evidence of replacement by soda-bearing solutions in the form of relics or remnants of older pegmatitic material partly or wholly enclosed within the invading felspar. Owing to their economic importance as repositories of many rare or valuable minerals these complex pegmatites have received much more attention from the mining geologist and mineralogist than the simple granite-pegmatites. Nevertheless, this should not blind one to the fact that they represent only a very small fraction of the total volume of pegmatitic material, and conclusions drawn from them, in regard to replacement, cannot be applied in a general way to ordinary pegmatites, without checks as to their validity. Even the complex pegmatites have occasionally been referred to a direct crystallization origin. For example Shaub (1940) examined a number of the lithium-bearing pegmatites of Maine and expressed the opinion that their texture and mineral assemblage could be best explained by direct crystallization from a closed magmatic system. Maurice (1940) has attributed the origin of the mica-bearing oligoclase-pegmatites of the Spruce Pine district, North Carolina, mainly to direct crystallization.

(c) *Myrmekite.*

Few microscopic rock intergrowths have received so much attention, or been the subject of so much controversy, as the wart-like assemblages of plagioclase and vermicular quartz to which Sederholm (1897) gave the name 'myrmekite'. These intergrowths are found in granites, granite-gneisses, charnockites, syenites, and in most deep-seated rocks in which potash-soda-felspar plays a prominent role.

Becke (1908), who made the first systematic examination of myrmekite, showed that it consisted of quartz and plagioclase felspar, the proportion of quartz to felspar increasing with the basicity of the plagioclase. He also observed that the basicity of the myrmekitic plagioclase increased with that of the primary plagioclase of the rock. He found that in most cases the myrmekite grew out from a central core or kernel of quartz-free plagioclase invasively into adjacent orthoclase or microcline, the convex surface of the myrmekite projecting into the potash-felspar. He suggested that these facts could be best explained on the assumption that the potassium of the orthoclase or microcline had been replaced by sodium and calcium. The sodium would be exchanged atom for atom with the potassium yielding an equivalent of albite; but, with calcium, anorthite would be formed in place of potash-felspar, and this would release the equivalent of four molecules of silica, hence the quartz of the myrmekite, the more basic the plagioclase the greater the quantity of quartz. He further suggested that the potash set free by this transformation might have given rise to the secondary muscovite commonly found in rocks rich in myrmekite.

Schwantke (1909) discussing the role of the lime-felspar held in solid solution in potash-soda-felspar, found that most of the then available analyses showed an excess of silica over that required by the felspars, and a deficiency of total felspars from 100 %. By recasting the lime-felspar as $Ca(AlSi_3O_8)_2$—analogous to orthoclase and albite—in place of anorthite $CaAl_2Si_2O_8$, he found that for the majority of the analyses the discrepancy largely disappeared. He pointed out that if the lime was really present in solid solution in this higher silicate form, it would account for the quartz in the myrmekitic intergrowths. The lime-felspar would, on separation from solid solution, revert to the anorthite form, setting free the equivalent of four molecules of silica. Schwantke appears to have abandoned his hypothesis because 'the observations on perthitic felspars do not show a release of free silica during exsolution', but he concluded 'However, the observed facts and possibilities merit careful study. Above all, with new analyses on pure suitable material, the role of Ca in the potash-felspars could be more accurately determined.'

Petrologists who have suggested a direct crystallization origin for myrmekite, on the lines of micropegmatite formation, include Petrascheck (1904), Tschirwinsky (1911), Sustschinsky (1912), and Svitalsky (1913). Luczizky (1912) considered myrmekite to be of secondary origin, but suggested that its formation was closely bound up with the alteration and dissolution of primary isomorphous mixtures of potash-sodium-lime-felspars.

Eskola (1914, pp. 27–28) discussing the myrmekite occurrences in the microcline-granites of south-west Finland referred to the frequent occurrence of myrmekite with rectilinear boundaries against the microcline. These idiomorphic forms occurred associated with ordinary curved myrmekite, having been formed later than the rectilinear variety. Eskola agreed with Becke that myrmekite had been formed towards the end of the period of rock consolidation, but suggested that the idiomorphic form originated earlier during the process of consolidation.

Sedcrholm (1916) made an extensive survey of the literature on myrmekite and myrmekite-like intergrowths, adding his own detailed observations on myrmekite in rocks from Fenno-Scandia. He considered that these intergrowths 'cannot be regarded as primary in the strictest sense of the word since they have crystallized within the borders of another mineral, replacing its substance'.

He stated, however, that in many cases the structures were formed 'before the final consolidation of all the mineral constituents of the magma in question. The greatest part of the magma itself had crystallized, but solutions and gases, derived from the neighbourhood or from more distant parts of the same rock masses, still circulated within them.' With Becke, he concluded that myrmekite has been produced by the replacement of the potash in orthoclase or microcline by soda and lime from late-stage magmatic solutions, silica being set free by the lime in the process. For changes of this nature in direct continuation of the consolidation of the rock magma, Sederholm proposed the term 'deuteric'.

Myrmekite intergrowths examined by the writer, in British granites and in granites and charnockites of Indian origin, show, in general, a convex surface 'invasive' into the potash-felspar, as described by Becke and Sederholm. In some cases, however, more particularly in the Indian charnockites rich in myrmekite, the tendency towards rectilinear outlines described by Eskola is observed. In these rocks also, blebs of myrmekite totally enclosed in microcline or orthoclase are not at all uncommon. The potash-felspar is sometimes orthoclase, sometimes microcline and is almost invariably perthitic.

If we examine the evidence put forward by Becke, Sederholm, and others for the view that these intergrowths have been formed by secondary replacement—a view which has been accepted and used by many petrographers as evidence of albitization in these rocks—we find that it rests almost entirely on the appearance of 'invasion' which the myrmekite assemblage presents towards the potash-felspar. Other features including type of intergrowth, relation of amount of quartz to the basicity of the plagioclase felspar, and the decrease of basicity towards the outside of the intergrowths, can be as readily explained by direct crystallization or other methods of formation, while the tendency to rectilinear outlines sometimes seen in these structures suggests (as intimated by Eskola) direct crystallization rather than replacement. Where the myrmekite occurs totally enclosed in potash-felspar—or in plagioclase as instanced by Sederholm—the replacement theory needs to assume connecting channels for the invading solutions, or a reconstitution of the enclosing felspar, for which there is often little or no evidence.

Perhaps the strongest objection to the replacement explanation of these intergrowths, in other words to albitization, lies in the strictly limited size of these structures and the limited amount of local 'replacement' which they represent. As Sederholm has pointed out, these myrmekite structures never exceed about a millimetre in diameter yet they usually occur scattered fairly evenly through very large rock masses, without completely 'replacing' the potash-felspar present, even in the small localized area of a hand-specimen. This itself points to a *very* local source for the 'invading' plagioclase and to a 'closed system'. Sederholm (1916, p. 136) gives one instance of a porphyritic granite in which the amount of myrmekite is as high as 15 %. A granite of this type would probably contain, originally, as much as 50 % potash-soda-felspar, so that even with 15 % of myrmekite there would still be more than half the potash-soda-felspar 'unreplaced'.

Is it possible then that this 'invasive' character of the myrmekite into the potash- or potash-soda-felspar is only apparent and that it does not truly represent 'replacement' by solutions rich in soda and lime from outside sources. The pegmatitic myrmekites described in the earlier part of this paper, show that true wart-like myrmekite can be formed, along with vein perthite, by a process of exsolution, coalescence, and segregation, from material held at one time in solid solution within the crystallizing potash-felspar, or in part liquid within its interstices. Moreover, the quartz of the myrmekite has also undoubtedly come from the same local source as the plagioclase, and as the amount of quartz varies directly with the basicity of the plagioclase, we are driven to the conclusion that there may be some truth in Schwantke's hypothesis of a high silica-lime-felspar for that portion held in solid solution in potash-felspar. The transformation of this silicate $Ca(AlSi_3O_8)_2$ to anorthite $CaAl_2Si_2O_8$, on exsolution, would provide the quartz of the myrmekite.

Do recent analyses of potash-soda-felspar throw any more light on this problem than they did when Schwantke made his observations? Most analyses examined by the writer show a definite excess of silica and a deficiency of total felspars when the anorthite formula is used in felspar calculations. The felspar deficiency is often hidden in published analyses by the practice—of which the writer has himself been guilty—of recasting the results to 100 %. The discrepancies are not regularly proportional to the lime contents, but they tend to disappear in lime-free potash-soda-felspars. Usually the relatively low lime contents of these felspars, together with possible errors of analysis, render a comparison between the two formulae inconclusive, but it can be said that in most cases the high silica formula would agree with the ultimate analysis at least as well as the anorthite formula. It is conceivable that both forms may be present in potash-soda-felspar.

X-ray interpretations of potash-soda-felspar structures also involve the part played by the lime-felspar held in solid solution. Are the calcium ions interchangeable with sodium and potassium ions in a relatively rigid SiO_4AlO_4 tetrahedral framework with the same monoclinic setting and environment, or does each calcium ion have the unique triclinic setting of anorthite? In the latter case one would expect less freedom to segregate within the framework. Perthite separations show that the lime-felspar has segregated with the soda-felspar in the early stages of exsolution. Hence the probability that it exists in the homogeneous potash-soda-felspar mainly in the high silica form.

The decreasing basicity from core to rim of myrmekite intergrowths, difficult to explain by the replacement theory, is readily understood if the lime-felspar has been derived by exsolution from the potash-felspar. Its early separation in relatively greater portion than the albite would leave the later-formed plagioclase richer in soda.

Another feature, observed by Becke and other workers, is the more acid character of the plagioclase of the myrmekite, than the primary plagioclase of the rock. This again would follow from the relatively lower solubility of lime than of soda in the potash-felspar. The microcline-pegmatites show a similar relationship between the perthitic plagioclase of the microcline and the primary plagioclase of the pegmatite. This may be illustrated by the Kodarma and the Burakur microclines, both of which occur associated with primary pegmatitic oligoclase. Samples of these and of the microcline were analysed with the following results.

	Kodarma graphic microcline with myrmekite.	Kodarma oligoclase.	Burakur microcline with myrmekitic vein perthite.	Burakur oligoclase.
SiO_2	64·56	66·52	64·46	63·2
Al_2O_3	19·25	21·27	18·90	22·84
Fe_2O_3	0·35	0·19	0·22	0·32
MgO	trace	trace	trace	trace
CaO	0·22	1·95	0·27	3·36
Na_2O	1·88	9·76	2·10	8·24
K_2O	13·32	0·74	13·63	0·88
Ign. loss	0·36	0·20	0·20	0·70
	99·94	100·63	99·78	99·54
Ab	15·84	82·5	17·75	69·7
An	1·10	9·75	1·35	16·8
Or	75·72	3·2	80·56	2·6
Mica	4·0	2·2	—	5·0

In the Kodarma microcline the An : Ab ratio is 7 : 93 and in the oligoclase 10·5 to 89·5. In the Burakur microcline the An : Ab ratio is again 7 : 93, but in the corresponding oligoclase it is 19·5 to 80·5. Shibata also found a similar relationship in the Ishikawa pegmatite referred to on page 84. For the myrmekite-bearing microcline-perthite the An : Ab ratio is 8 : 92, in the vein perthite lamellae it is 14 : 86, and in the primary plagioclase 30 : 70. The high An : Ab ratio in the last corresponds with an unusually high soda-lime content in the microcline (37 %). The microcline is also unusual in containing blue schillerized orthoclase-like patches with reduced optic axial angle. All these features point to a relatively high formation temperature.

The low An : Ab ratios of most pegmatitic microclines—due to the low temperature of formation—would account for the scarcity of myrmekite in them as compared with deep-seated rocks formed within the exsolution temperature range. In the above myrmekitic microclines the An : Ab ratio of 7 : 93 is not high, yet it appears to be higher than the normal value. Andersen's 28 microcline analyses all show a distinctly lower ratio, and although he reported anorthitic cores in the vein perthite—with quartz in some cases—none was described as myrmekitic. Jarayaman (1940) gives 9 microcline and 2 primary plagioclase analyses from Nellore pegmatites all with An : Ab ratios not exceeding 4 : 96. No anorthitic cores or myrmekite were reported by him.

Many deep-seated rocks, as for example the soda-syenites, are rich in potash-soda-felspar with a fairly high An : Ab ratio, yet contain no myrmekite. This could be explained by a scarcity of mineralizing solutions in the crystallizing magma. Such relatively dry magmas would become solid well above the main exsolution temperature range, and true microperthites devoid of myrmekite would be formed in the same way that high-temperature pegmatites give rise to microperthitic felspars devoid of vein perthite. It is significant that in both these cases the potash-soda-felspar is orthoclase.

Water and other mineralizers would lower the crystallization temperature until it fell within the exsolution range. The conditions would then favour coalescence of the soda-lime component separating by exsolution from the potash-felspar. Such segregations might form myrmekite intergrowths within the crystallizing potash-soda-felspar or alternatively collect into blebs, finally to crystallize out from solution as myrmekite. The coarser perthites of plutonic rocks, which have sometimes been regarded as products of albitization, could also be explained in a like manner by exsolution and coalescence. Thus the 'injection' perthite of Colony (1923) and the 'deuteric' and other plutonic perthites figured by Alling (1938) would belong to this type. In many respects they resemble vein perthite.

5. SUMMARY AND CONCLUSIONS.

The view, that myrmekite, the coarser perthite of plutonic rocks, and the vein perthite of pegmatitic microcline, are not the result of albitization or replacement by solutions from without, but of exsolution and rearrangement, under special conditions, of material formerly held in solid solution in the potash-felspar, appears to the writer to agree with the known facts better than any of the various replacement theories. It avoids the *deus ex machina* of invading soda-lime bearing solutions, brought in to act always selectively, and yet only partially—on the potash-felspar. It also conforms with the experimental evidence that potash-felspar crystallizing out from a magma in which soda and lime are present will hold in solid solution an amount of plagioclase corresponding to its formation temperature (e.g. 25–30 % at 750° C.); which plagioclase must of necessity separate from the potash-felspar as microperthite, or in the coarser form of vein perthite (or myrmekite), by the time the rock temperature has fallen to 400° C. Evidence has also been provided that graphic granite is a product of direct crystallization and not of replacement.

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EXPLANATION OF PLATES VI AND VII.

All the figures shown on the two plates represent sections—wholly or in part—of graphic or pegmatite microcline cut parallel to (001) or (010). Sections on (001) are shown with the *a*-axis approximately vertical, those on (010) with the *c*-axis approximately vertical. All, except the first two, are shown with the nicols crossed. Figs. 1 and 2 are seen with the nicols about 10° uncrossed and the perthite in extinction to subdue the microcline twinning and show up the perthite.

FIG. 1. Section on (001) of microcline from the Kodarma graphic granite. To show coalescence of microperthite into vein perthite. Note the coarser microcline twin-lamellae near the coarser perthite. ×21.

FIG. 2. Another (001) section of the same microcline with same microscope setting. Shows coalescence of the microperthite towards quartz and mica inclusions. Note the same broader twinning near the coarser perthite. ×24.

FIG. 3. Section of the same microcline cut parallel to (010) and with the microcline in extinction. Shows coalescence of microperthite albite lamellae into larger units with an echelon tendency. ×21.

FIG. 4. Section on (010) of dental microcline, Quebec, with microcline in extinction. Shows incipient coalescence of microperthitic albite lamellae into coarser units, especially near the small mica inclusions. ×21.

FIG. 5. Section on (010) across a quartz-microcline junction, in the Kodarma graphic granite, with the microcline in extinction. Shows segregation of the perthitic albite along the quartz-microcline contact. The quartz rod contains two inclusions of microcline with 'random' orientation, one in conjunction with a mica lath which is in extinction. ×24.

FIG. 6. Another (010) section across a quartz-microcline junction in the same rock. Shows segregation of the perthite material into myrmekite along the quartz-microcline junction. The perthite albite and the quartz rod are seen in extinction, the microcline and the myrmekitic wormy quartz being illuminated. Note how the myrmekite 'grows out' from the quartz rod into the body microcline; also the blending of the vein perthite with the outer myrmekite rims and their common extinction. ×21.

FIG. 7. Another (010) section across a quartz-microcline junction in the Kodarma graphic granite. Shows an embayed portion of the main microcline which has been torn away and twisted through an angle of about 30° with no rupture of the quartz rod. The mush zone between the two portions of microcline contains small microcline and albite grains, and myrmekite. ×21.

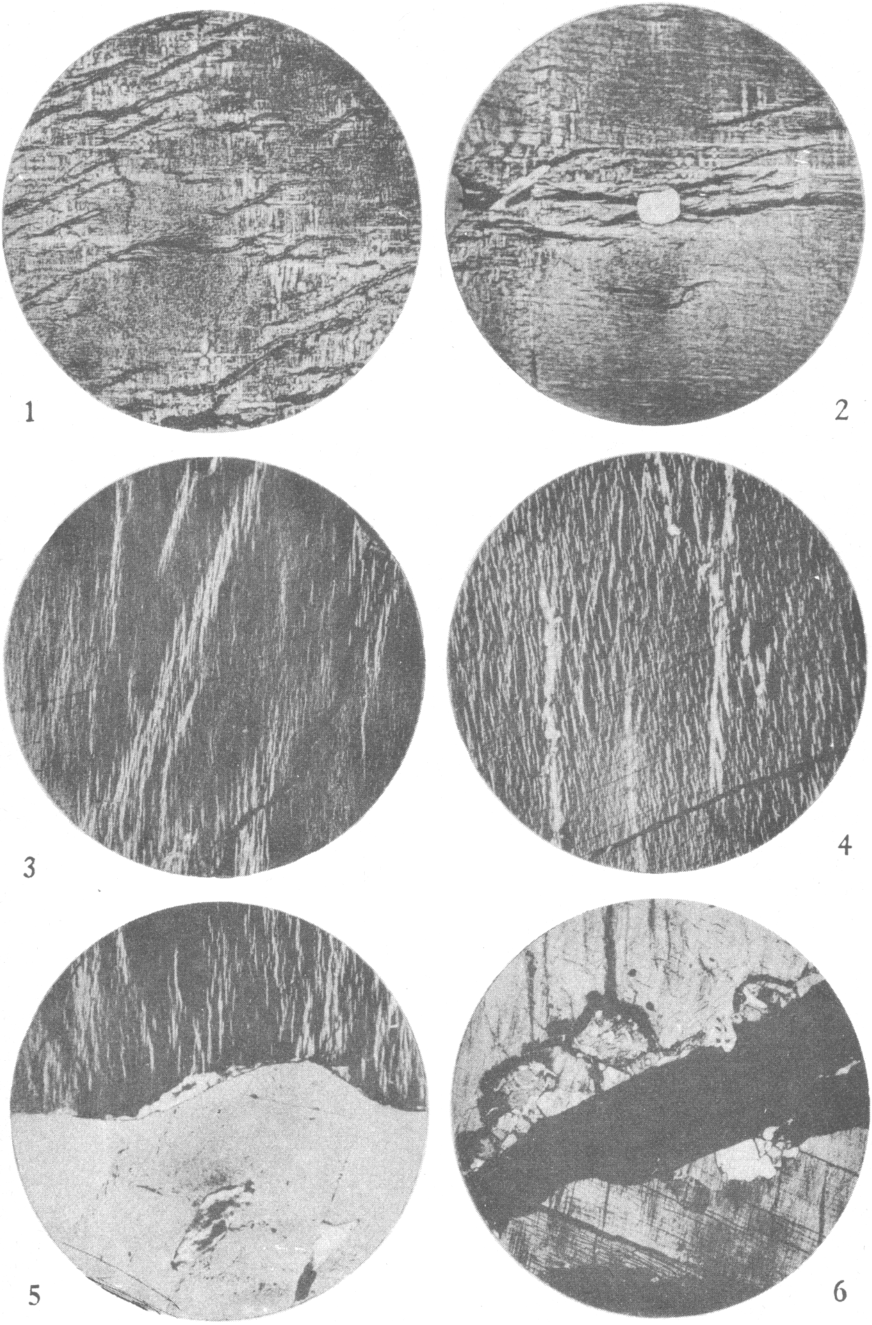
FIG. 8. Section on (001) across a crush zone between the ends of two quartz rods, Kodarma graphic granite. One of the rods can be seen to the left of the photograph. The crush zone contains small hypidiomorphic microcline crystals with 'random' orientation, and some myrmekite. ×21.

FIG. 9. Section on (010) of pegmatitic microcline from Asansol, Bengal, with microcline in extinction. Shows vein perthite lenses in echelon surrounded by dark areas depleted of microperthite. ×28.

FIG. 10. Section on (010) of pegmatitic microcline from Nellore, Madras, with microcline in extinction. Shows 'patterning' of the microperthite in relation to the vein perthite and some dark areas of 'impoverishment'. ×28.

FIG. 11. Section on (010) of pegmatitic microcline from Burakur, Bengal, with microcline in extinction. Shows vein perthite containing more anorthitic centres of a myrmekitic character. These are seen as darker patches owing to lower extinction. Note the wormy quartz within them. ×24.

FIG. 12. Section on (001) of fine-grained graphic granite from Miask, Urals. Shows quartz rods (vertical) and vein perthite (horizontal) both illuminated, the microcline being near extinction. Note how the torch-like vein perthite grows out from the quartz rods. ×14.



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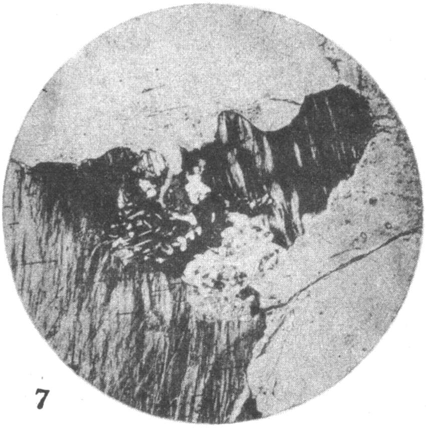
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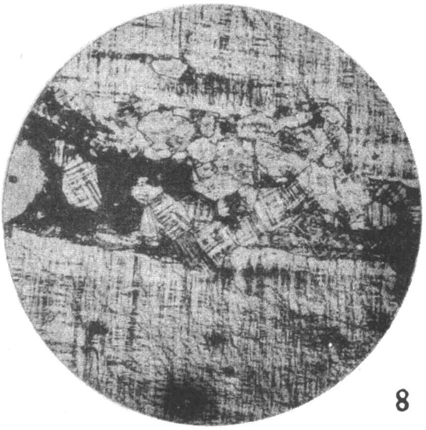
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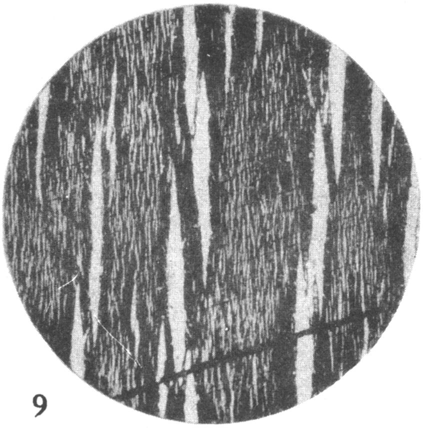
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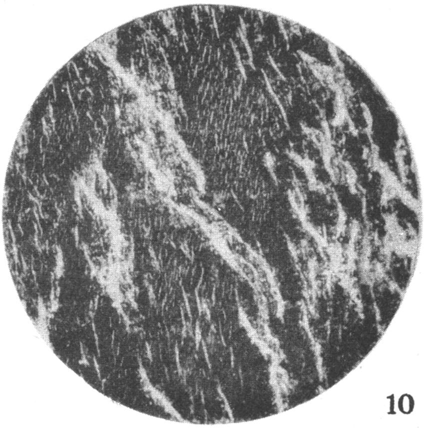
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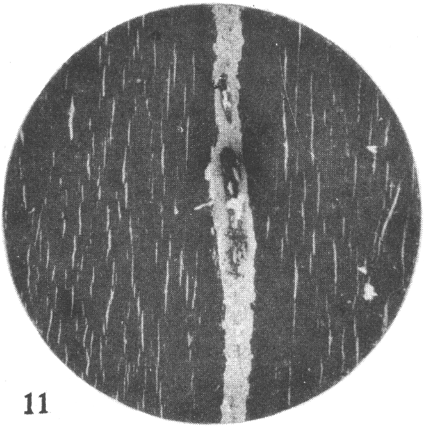
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