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Exsolution during metamorphism with particular reference to feldspar solid solutions

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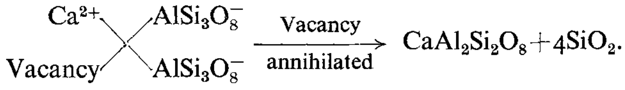
SUMMARY. In the aureole of the syn-orogenic Hasvik Gabbro a variety of exsolution phenomena developed during the contact metamorphism. These exsolution phenomena have similar textures to those produced during the age-hardening of metal alloys. In feldspars the exsolution precipitates are closely related to the pattern of excesses over and deficiencies from the formula requirements, particularly in terms of SiO_2 and Al_2O_3. The exsolution products are dependent upon both the temperatures of ageing and the details of the mineral chemistry. Evidence supporting an exsolution theory of origin for myrmekite is provided, and it is shown that precipitation from heterotype feldspar solid solutions during metamorphism may in fact be a complex process involving a number of precipitate phases.

The nucleation of sillimanite as a precipitate phase is discussed and it is shown how sillimanite develops at a number of distinctive sites within feldspar and garnet. From the textural relations of sillimanite precipitates and their host minerals a control exerted by the thermal stress configuration over the nucleation of precipitate phases is suggested. It is argued that the thermal stresses exerted across grain boundaries and within minerals during metamorphism may have considerable relevance to the interpretation of textures in metamorphic rocks.

IN recent years increasing attention has been paid to the textures of metamorphic rocks, particularly in the unravelling of crystallization sequences in metamorphic rocks during orogenic deformation (Zwart, 1961; Sturt and Harris, 1961; Johnson, 1963; and Rast, 1965). Emphasis has also been placed on the features of grain-boundaries and exsolution phenomena in metamorphic rocks, and many analogies have been made with the textures produced during the working and recrystallization of metal alloys (De Vore, 1959; Voll, 1960; Flinn, 1965; and Rast 1965). Many of the gross features of exsolution, produced during the protracted cooling of igneous and metamorphic rocks, have long been understood, e.g. the perthitic and antiperthitic structures of feldspars and exsolution lamellae in minerals such as pyroxene; Carstens (1967*a*), for example, discusses the textures displayed by antiperthites from South Norwegian anorthosites, and demonstrates how they exhibit continuous and discontinuous precipitation. Carstens indicates how the textures of these feldspars are identical with those produced during the unmixing of metal alloys (Aaronson, 1962; Christian, 1965). Less well known are textures in metamorphic rocks analogous to those produced by the precipitation of minor constituents from solid solutions during the age-hardening of metals (Geisler, 1953; McLean, 1957). One common example is the included lamellae of ilmenite and spinel in the pyroxenes of many basic igneous rocks, these inclusions being oriented in directions controlled by the pyroxene lattice. Moore (1968) also describes rutile inclusions in the pyroxenes of the Giles Complex, Central Australia, which appear to be the result of exsolution of excess constituents during protracted cooling. Other examples of precipitates include rutile needles in quartz, and Mellis (1965) discusses a variety in garnets.

In recent papers Hubbard (1967) and Carstens (1967*a*) re-present the theory of an exsolution origin for myrmekite. The essential basis of this theory is that many feldspars contain an excess of SiO_2 above that demanded by formula requirements, a feature first pointed out by Schwancte (1909). Schwancte showed that the available analyses of alkali feldspar had in fact an excess of SiO_2, but if the Ca^{2+} was considered as being incorporated into the alkali feldspar lattice as $Ca(AlSi_3O_8)_2$ instead of being present as anorthite the discrepancy largely disappears. Hubbard (1967) maintains that if the Ca^{2+} was held in this form the reversion to anorthite on exsolution of the plagioclase from the alkali feldspar solid solution would release the necessary quartz for the formation of myrmekite:



$$\begin{matrix} Ca^{2+} & & AlSi_3O_8^- \\ & \times & \\ \text{Vacancy} & & AlSi_3O_8^- \end{matrix} \xrightarrow[\text{annihilated}]{\text{Vacancy}} CaAl_2Si_2O_8+4SiO_2.$$

Hubbard shows that there is indeed a direct link between the development of many myrmekites and the exsolution of the plagioclase components from alkali feldspar solid solutions during the formation of perthite (see also Spencer, 1945; Voll, 1960; and Phillips, 1964).

A common origin for intergranular albite and the albite component of perthites has been convincingly argued by a number of authors (Tuttle and Bowen, 1958; Voll, 1960; and Ramberg, 1962). Hubbard (1967) claims that a number of predictions can be made of the sites for precipitation of quartz and albite and states that these accord well with the observed occurrences, the method of exsolution being viewed as similar to precipitation in slow-cooled metal alloys. An account of the course of precipitation during the age-hardening of metal alloys is given by Geisler (1953), who demonstrates that this is in fact a two-stage process beginning with the sub-microscopic clustering of solute atoms along planes within the lattice to form domains coherent with this lattice. As the aggregation of the solute continues, however, a stage is reached where the strain becomes too great for the retention of the enlarged domains as coherent zones in the lattice, and they break away to form distinct particles with their own crystal structure and definite interfaces. Hubbard (1967) shows how this principle can be applied to the ternary feldspar system, which in fact is not strictly ternary for heterotype solid solutions.

During the course of the investigation of the contact metamorphic aureole about the syn-regional metamorphic Hasvik Gabbro (Sturt, 1969) on the island of Söröy in Northern Norway, the author has observed a variety of exsolution phenomena both within the metamorphic minerals and at their grain boundaries. These features are most markedly developed in relation to the alkali and plagioclase feldspars. Progressive changes can be observed in perthitic and antiperthitic exsolution textures, and the character of these intergrowths is observed to change in relation to the temperature gradient towards the gabbro contact, becoming increasingly microperthitic. Precipitation of intergranular plagioclase has occurred between alkali feldspar and a number of other minerals. Abundant myrmekitic quartz is developed in the plagioclase abutting on to alkali feldspar, in the grain boundary plagioclase, and within the plagioclase components of patch, vein, hair, and film perthites. This myrmekite is considered to have a predominantly exsolution origin and is often associated with fine-grained sillimanite, for which an exsolution origin is also adduced. The sillimanite may occur alone as a precipitate within feldspar or with corundum or more rarely with spinel. The possible exsolution origin of corundum in the syenitic rocks of the Söröy region is considered, and certain general conclusions regarding the degree of silica saturation of feldspars in alkaline rocks are drawn.

The study of the textures in the Hasvik hornfelses indicates that the country rocks were undergoing almandine amphibolite facies metamorphism at the time of emplacement of the gabbro, conditions of regional metamorphism that indeed were maintained long after the thermal effects of the intrusion had been dissipated (Sturt, 1969). Owing to the fact that the thermal gradient of the gabbro was superimposed upon the regional almandine amphibolite facies conditions, it is apparent that during the contact metamorphism very high temperatures were reached within the aureole. At the time of gabbro emplacement biotite, quartz, feldspar, garnet, and locally kyanite and staurolite were crystallizing within the metasedimentary country rocks. In the inner parts of the aureole many of these minerals underwent conversion into various high-temperature breakdown products, e.g. sillimanite after kyanite; spinel+sillimanite after staurolite; sillimanite+magnetite and sillimanite+magnetite+biotite after garnet. After the emplacement of the gabbro the temperatures in the contact aureole gradually declined to those of the regional amphibolite facies field, which resulted in a partial redevelopment of minerals such as garnet, kyanite, and biotite at the expense of the higher-temperature contact assemblages.

GRAIN BOUNDARY RELATIONS AND OTHER SMALL-SCALE TEXTURAL PHENOMENA IN THE HASVIK HORNFELSES

The feldspars

The main features of perthitic exsolution within the feldspars of the Hasvik aureole have been mentioned and a correlation suggested between the perthite types and the temperatures developed during the contact metamorphism. It is not proposed, however, to discuss the details of the perthite structure but to consider other exsolution phenomena occurring in association with these feldspars.

On passing from the country metasediments into the aureole of the gabbro a progressive increase in the occurrence of myrmekitic intergrowths is apparent. The myrmekite typically occurs at alkali-feldspar/plagioclase grain-boundaries, with the characteristic rods and blebs of quartz contained in the plagioclase making contact with the alkali feldspar (fig. 1A). The plagioclase containing the myrmekitic quartz usually forms wart-like outgrowths, which develop across the grain-boundary and replace part of the volume of the alkali-feldspar. Proceeding inwards through the aureole the grain-boundary textures become more complex and the next stage is seen in the formation of granular plagioclase at the boundaries of alkali feldspar grains (fig. 1B). This plagioclase generally forms a polygonal grain mozaic with good 120° triple junctions, and the phenomenon of 'swapped rims' (Voll, 1960) is of frequent occurrence. Grain-boundary plagioclase is more abundant in the inner parts of the aureole and located not only at boundaries between alkali feldspar grains, but also of alkali feldspar with plagioclase, quartz, hypersthene, biotite, garnet, and even iron ore grains (fig. 2). Evidently the plagioclase component of the alkali feldspar solid solution has unmixed along virtually any convenient grain interface.

In the outer parts of the aureole the intergranular plagioclase often contains rods and blebs of myrmekitic quartz and the plagioclase components of the large bordering patch perthites are also frequently myrmekitic (figs. 1A, 2). Further into the aureole, myrmekite is present in the plagioclase components of vein and hair perthites; and eventually in the innermost parts small quartz blebs and rods are often scattered amongst the plagioclase films of film perthites. The present study thus indicates a progressive appearance of myrmekitic quartz–plagioclase intergrowths at grain boundaries and within the plagioclase components of the different types of perthite structures, controlled by the temperature gradient towards the gabbro contact.

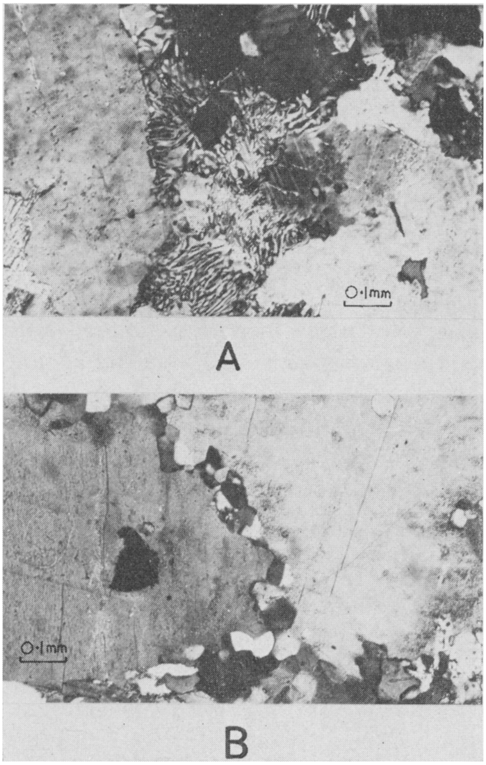


FIG. 1. A, Myrmekite in plagioclase in contact with K-feldspars. B, Intergranular plagioclase precipitate at mesoperthite grain-boundaries.

On passing into the aureole an almost ubiquitous association of minute needles and rods of sillimanite with the previously described phenomena at feldspar grain-boundaries is apparent. Sillimanite occurs at six types of site:

Alkali feldspar grain-boundaries. Here the sillimanite occurs typically in the intergranular plagioclase associated with myrmekitic quartz, although in some instances only sillimanite is present. The thin elongate sillimanite rods often project from the intergranular plagioclase grains into the bordering alkali-feldspar (figs. 2, 3A, B). Sillimanite of similar habit also occurs in the grain-boundary plagioclase between alkali feldspar with plagioclase, quartz, hypersthene, garnet, biotite, and iron ore grains (figs. 2, 3D). Sillimanite is not present in the grain-boundary plagioclase in the outer part of the aureole where myrmekite is the sole precipitate phase, and the incidence of sillimanite at such sites progressively increases towards the gabbro contact. Where swapped-rims are well-developed at alkali-feldspar grain boundaries, the sillimanite is concentrated along the line of the

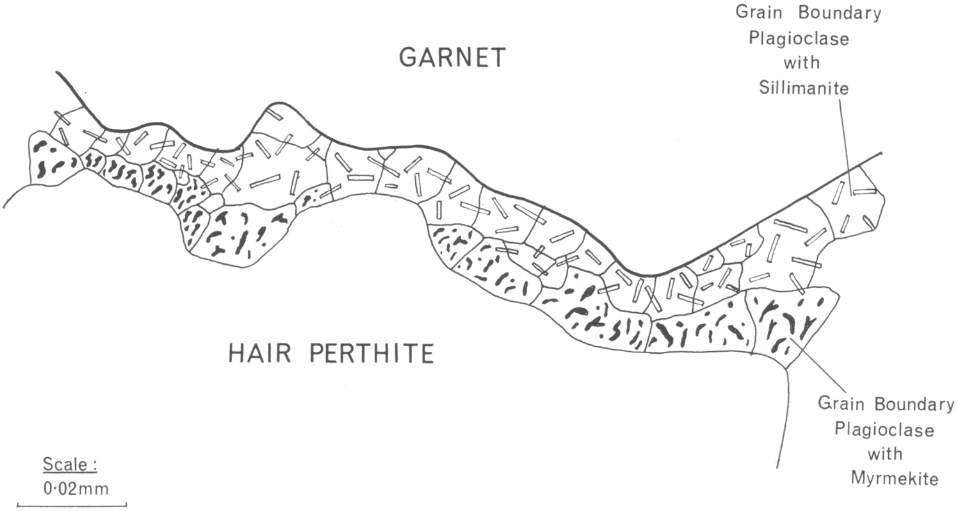


FIG. 2. Granular plagioclase precipitate at mesoperthite/garnet grain boundary, containing myrmekite quartz next to perthite and sillimanite next to garnet.

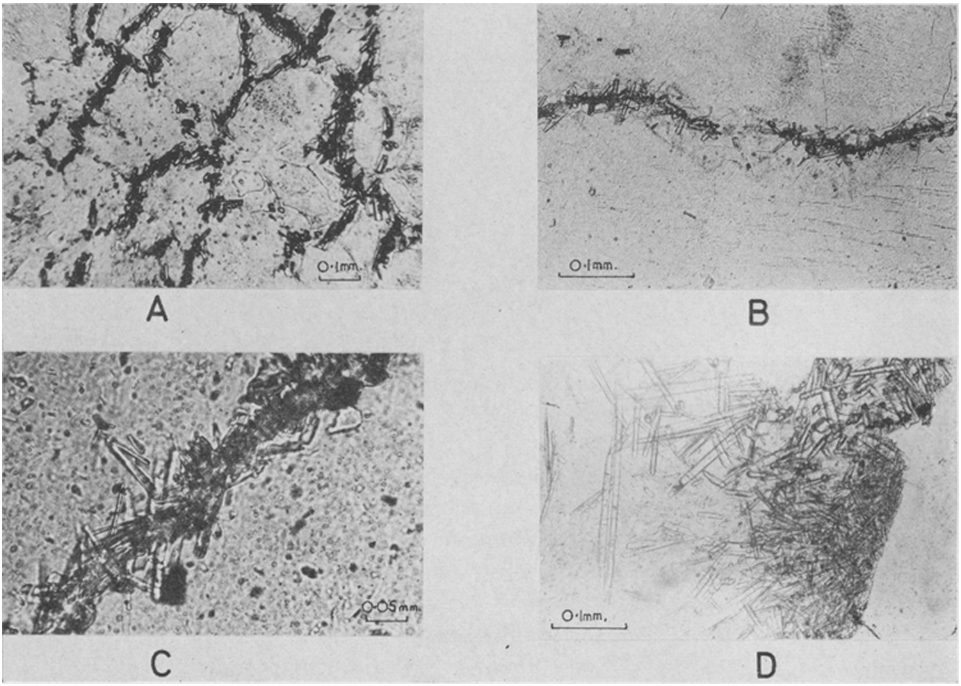


FIG. 3. A, Sillimanite needles in grain boundary plagioclase precipitate. B, Sillimanite concentrated near old grain boundary of mesoperthite grains, within swapped rim plagioclase precipitate. C, Sillimanite needles at boundary between two plagioclase grains. D, Sillimanite in plagioclase against quartz (on right-hand side).

old contact, and has apparently been overgrown by the swapped-rim plagioclase, implying an early precipitation of sillimanite at the grain margins prior to the development of the swapped-rim plagioclase (fig. 3A, B).

Feldspar/garnet grain-boundaries with no intervening feldspar precipitate. The sillimanite at these sites tends to grow in the feldspar as dense sheaves of thin rods and fibres, whose elongation generally makes a high angle with the grain-boundary (fig. 4A, B). Growth of sillimanite is particularly prominent where a convex surface of garnet lobes into the plagioclase feldspar, and the sillimanite has the appearance of a 'beard' about the garnet lobe (fig. 4A). The zone of dense sillimanite nucleation is relatively narrow against the garnet crystals.

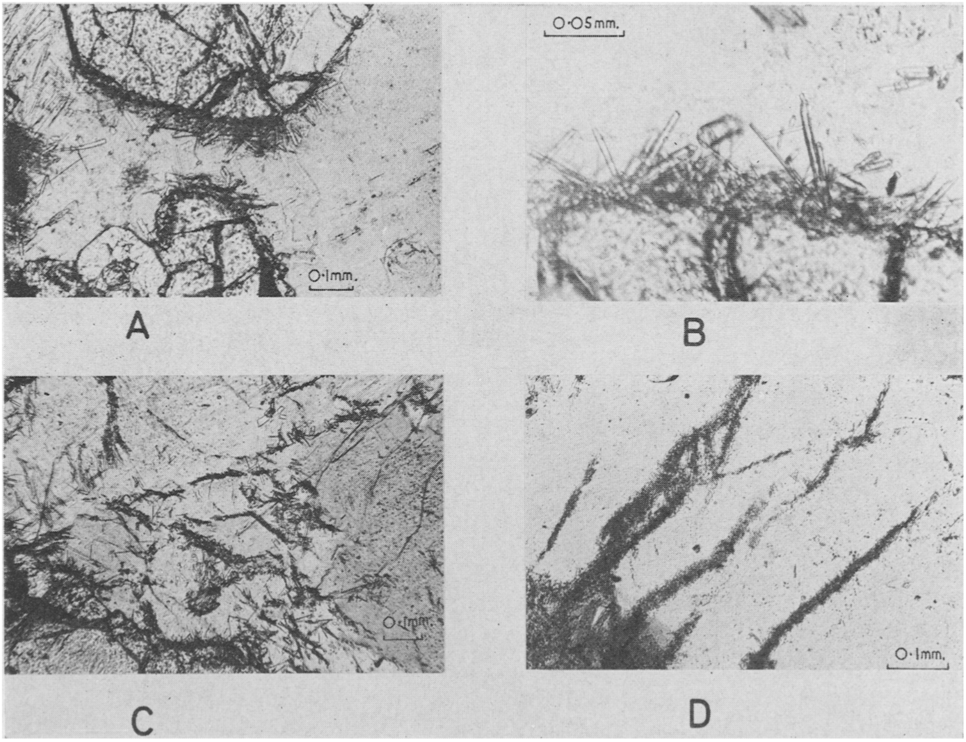


Fig. 4. A; Sillimanite in feldspar at garnet/feldspar grain boundary. B, Sillimanite at garnet/feldspar grain boundary. C and D, Sillimanite sealing cracks in feldspar.

A similar growth of sillimanite is observed at feldspar/quartz grain-boundaries, where the sillimanite in the feldspar often forms dense aggregates (fig. 3D).

Plagioclase/plagioclase feldspar grain-boundaries. At these sites the sillimanite has the typical form of 'primary grain-boundary precipitates' (Geisler, 1953), and forms dense sheaves of needles, which project into the feldspar on either side of the grain interface (fig. 3C). Where an occasional rim of K-feldspar intervenes between the plagioclase grains small needles of sillimanite occur with the rim.

Within the perthite structure. The presence of myrmekitic quartz within the plagioclase constituents of the different varieties of perthite has been discussed. In the inner parts of the Hasvik aureole this is frequently accompanied by the development of thin rods and plates of sillimanite, which often project into the alkali-feldspar host. In the innermost parts of the contact zone the precipitate in the plagioclase is often entirely sillimanite, and in rare instances this may be accompanied by small rods and blebs of corundum and occasionally spinel. Sillimanite is found to be associated with all perthite varieties.

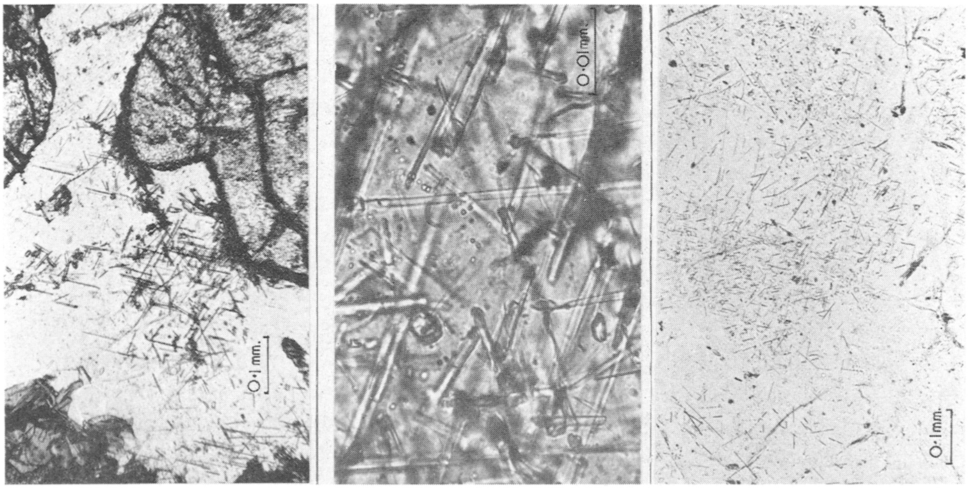


FIG. 5. A (left), Sillimanite with Widmanstätten-like pattern in feldspar. B (middle), Sillimanite with Widmanstätten-like pattern in feldspar; note also small grains of corundum (oil immersion). C (right), Rutile needles with Widmanstätten-like pattern in quartz.

Internal growth within the feldspars. Here the orientation of the sillimanite needles is apparently controlled by directions in the plagioclase lattice; such growth of sillimanite occurs only in the inner parts of the aureole. The small needles (up to 0·02 mm long) are orientated parallel to (010), (110), and (001), which presumably are the most suitably orientated planes in the feldspar. The arrangement of the sillimanite needles within the feldspar (fig. 5A and B) appears to be analogous to the Widmanstätten figure, which is developed in 'aged' metal solid solutions (Geisler, 1953; McLean, 1957; Doan, 1958). Occasionally small blebs of corundum and rarely spinel occur in association with the sillimanite. When sillimanite precipitation in the feldspar was particularly dense it appears that certain of the sillimanite sites were favoured for continued growth and some recrystallization of the sillimanite precipitate occurred. It is of considerable interest in this context that Carstens (1967*a*) has described antiperthites from Norwegian anorthosites, with the rod-shaped K-feldspar plates having the Widmanstätten arrangement within the plagioclase host.

Strain zones in the feldspars. Close to the gabbro contact, where the feldspars have been subjected to considerable strains, sillimanite is often observed to have grown at strain-controlled sites. This is also evident further from the contact where feldspars are practically surrounded by garnet or quartz grains or both. Cracks are developed in such feldspars, sometimes of fairly regular form, which traverse several grains, and at other times as irregular splintery fractures, which are usually confined to a single grain. The cracks in the feldspars are invariably healed by the growth of sheaves of sillimanite needles projecting into the feldspar on either side of the crack (fig. 4C, D). In other examples abundant sillimanite growth occurs at the boundaries between marked strain shadow zones. The sillimanites found at these sites appear to transgress the lattice-orientated variety. In some examples small rounded blebs of corundum and spinel occur in association with sillimanite.

Other minerals

Pyroxene. Exsolution features are quite commonly developed within the pyroxenes of both the gabbro and the hornfelses, both in terms of 'schiller' and of lamellae of one pyroxene phase in another. Schiller inclusions of ilmenite and spinel and more occasionally rutile and sphene occur in pyroxenes of the hornfelses and the gabbro. The elongated plates of these inclusions are frequently arranged parallel to crystallographic planes in the host-pyroxenes to form Widmanstätten-like figures. Examples of schiller inclusions of ilmenite and spinel in pyroxenes are widely cited in the literature, though rutile has but recently been described as an exsolution precipitate (Moore, 1968). The presence of sphene in the schiller would appear to be the result of the subsequent amphibolite facies regional metamorphism, indeed rutile and ilmenite inclusions showing various stages in the conversion to sphene are to be observed (cf. Stumpfl and Sturt, 1964).

Quartz. In the inner parts of the aureole quartz often contains minute elongate needles of rutile, orientated within the quartz in a Widmanstätten-like pattern (fig. 5C). This would appear to be the result of the unmixing of excess TiO_2 as rutile during slow cooling. It is of interest to note that the quartz of the hornfelses often has a greyish-blue colour, which according to Deer, Howie, and Zussman (1963) is typical of granulite facies terrains. They further point out that this colour is probably due to the presence of included rutile needles.

Biotite. In the hornfelses biotite often contains conspicuous lobate and vermicular inclusions of quartz, which have the appearance of biotite–quartz symplectites (fig. 6). The incidence of such textures is observed to increase towards the gabbro contact. The intergrowths

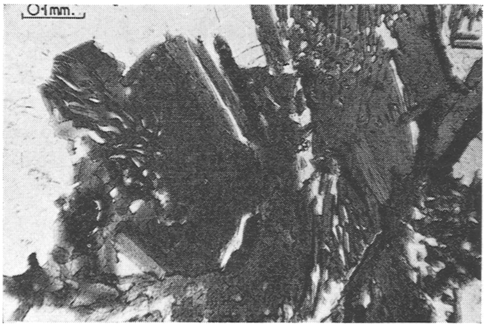


FIG. 6. Biotite with lobate and vermicular quartz inclusions.

are very similar to those described as 'mica-myrmekites' by Sederholm (1916). It is apparent that some of these intergrowths originate *via* the reaction Hypersthene+K-feldspar → Biotite+Quartz. In other examples it appears that the mica/quartz intergrowths result from the recrystallization of biotite present prior to the onset of contact metamorphism and that the quartz blebs have been precipitated during the slow cooling of the hornfelses.

Garnet. It has been mentioned previously that garnets within the inner parts of the hornfelses are variably converted to a number of high-temperature breakdown products, in which sillimanite is prominent. In the initial stages of breakdown the garnet characteristically contains delicate needles of sillimanite parallel to rhombdodecahedral planes. This early nucleation of sillimanite controlled by the garnet lattice appears to represent an essential prerequisite to the formation of high-temperature breakdown products except in those rare instances where spinel is prominent in the high-temperature assemblage. An inspection of a number of garnet analyses from regionally metamorphosed pelitic schists (Sturt, 1962) shows that many of these contain an excess of both SiO_2 and Al_2O_3 above their formula requirements, indicating that the constituents of Al_2SiO_5 may be held in excess solid solution in the garnets, and at high temperatures precipitation in the form of sillimanite is possible.

DISCUSSION OF THE FELDSPAR TEXTURES AND PRECIPITATION IN FELDSPARS

Many of the small-scale textural phenomena of the feldspars and also of other minerals in the Hasvik Hornfelses find close analogies in the descriptions of products of exsolution precipitation from metal solid solutions. Detailed descriptions of the characteristic features of such precipitates are given by Geisler (1953), McLean (1957), and Doan (1958).

Myrmekite and sillimanite. A general review of the theory for the exsolution origin of myrmekite has already been given. The case for an excess of SiO_2 in naturally occurring feldspars, above that required to satisfy their formula requirements, has recently received experimental verification through the work of Carman and Tuttle (1967). These authors demonstrate that when sanidines, carefully hand-picked and checked for purity, were treated at 500 °C and 10 000 bars in sealed gold tubes and in the presence of 10 % water, two feldspar phases and quartz were produced (exsolved) from the sanidine solid solution. The experiments indicated that the amount of 'unmixed quartz' was of the order of 2 % by weight, and they conclude that this represents just a part of the total excess SiO_2, as the ageing temperature used was only 500 °C. Further experimental verification of the solution of silica at high temperatures in alkali feldspar has recently been given by Morse (1969). Phillips and Ransom (1968, 1969) maintain that a proportionality exists between the composition of plagioclase in myrmekitic intergrowths and the amount of associated quartz, and demonstrate how this supports the exsolution theory. In a recent paper Widenfalk (1969) made an extensive study of myrmekitic intergrowths using electron-microprobe analytical techniques, and concludes that myrmekite has an exsolution origin and that excesses in SiO_2 in the feldspars are enhanced by diffusion of alkalis and lime out of the feldspars. Thus it would appear that the general proposition of Schwancte of an exsolution origin of myrmekite based on an excess of SiO_2 in the feldspar solid solution is on a firm basis.

In the case of the Hasvik Hornfelses, in addition to myrmekitic quartz, sillimanite and more rarely corundum and spinel appear to have been formed as precipitates. The next stage is thus to inquire whether similar conditions pertain in relation to an Al_2O_3 excess in feldspars. In a short note Perry (1966) states that the feldspar analyses presented in Deer, Howie, and Zussman (1963) show excesses and deficiencies in both SiO_2 and Al_2O_3 above what could be expected in terms of analytical errors. Accordingly the alkali feldspar and plagioclase feldspar analyses (with the exception of bytownite/anorthite) presented by Deer, Howie, and Zussman plus additional analyses from later sources (Carmichael, 1963; Heier, 1966; Wright, 1967; Perchuk *et al.*, 1968) have been recalculated. The analyses were recast generally in terms of three main end-members (albite, anorthite, and orthoclase) though where BaO and SrO determinations were given they were recast to five end-members. The results show (fig. 7) that Schwancte and Hubbard are correct in their general proposition of a silica excess in feldspars, and 67·8 % of the feldspar analyses show an SiO_2 excess while 28·4 % have in fact a deficiency in SiO_2. This perhaps surprising percentage with an SiO_2 deficiency is best explained in that the analyses considered by Schwancte included practically none of feldspars from alkaline rocks. Of the recalculated analyses, no less than 41 (or 78·8 %) of the 52 feldspars showing an SiO_2 deficiency are from alkaline rocks, and 35 of these also contain feldspathoids. Only five feldspars from rocks containing coexisting feldspars and feldspathoids proved to have an excess of SiO_2. This observation is in accord with the fact that myrmekite is extremely rare in alkaline rocks, and to the author's knowledge has never been reported in feldspathoidal varieties.

On inspection of fig. 7 it is apparent that excesses of Al_2O_3 above that necessary to satisfy the formula requirements of the feldspars are even more common than excesses of SiO_2.[1] Of the analyses recast 78·7 % have an excess of Al_2O_3 and only 5 a deficiency. Thus, excluding those from the alkaline rocks, the recasting of a large and representative sample of feldspar analyses shows that excesses of both SiO_2 and Al_2O_3 above the formula considerations are common in feldspars. It has recently been demonstrated experimentally that anorthite may contain an excess of Al_2O_3 in solid solution (Bhatty *et al.*, 1970).

Hence, given the appropriate physical conditions, exsolution of both Al_2O_3 and SiO_2 could occur from heterotype feldspar solid solutions. It appears from the systematic study of the feldspars in the Hasvik hornfelses that SiO_2 is more readily precipitated at lower temperatures as myrmekitic quartz than Al_2O_3 and SiO_2 together as sillimanite (Al_2SiO_5). The latter precipitate becomes progressively more abundant in the inner parts of the aureole and is developed at an increasing variety of sites. In the higher-grade hornfelses the sillimanite may be accompanied by corundum and spinel.

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[1] It is realized, however, that excesses and deficiencies in SiO_2 and Al_2O_3 are partly the result of analytical errors and that these are liable to be most serious in the case of Al_2O_3 (Fairbairn, 1953).

Watson (1948) has given an account of sillimanite developed from feldspars in the migmatites of Kildonan, Sutherland, Scotland, and considers that the sillimanite formed as the result of metasomatic activity during the late stages in the evolution of the migmatite complex. The sillimanite present as fibrolite in these migmatites typically occurs at or near the grain boundaries of the feldspars. Watson postulates that the formation of the fibrolite is a consequence of the diffusion of alkalis out of the feldspars, along the grain boundaries. A rather similar explanation is given by Kingery (1964) for the formation of mullite in the feldspars of fired feldspar–kaolinite mixtures. Sillimanite habits similar to those described by Watson have been found by the author from a number of migmatite localities on Söröy, and it is probable that grain-boundary alkali diffusion was an important process. Many textures also exist in these migmatites, and indeed in those of Kildonan (thin-sections kindly lent by Dr. Watson), that find analogies to primary precipitate textures in metal alloys. Thus it is reasonable to assume that, if such a process of grain-boundary diffusion of alkalis was operative, the state of the feldspar solid solution would be in a constant state of change enhancing

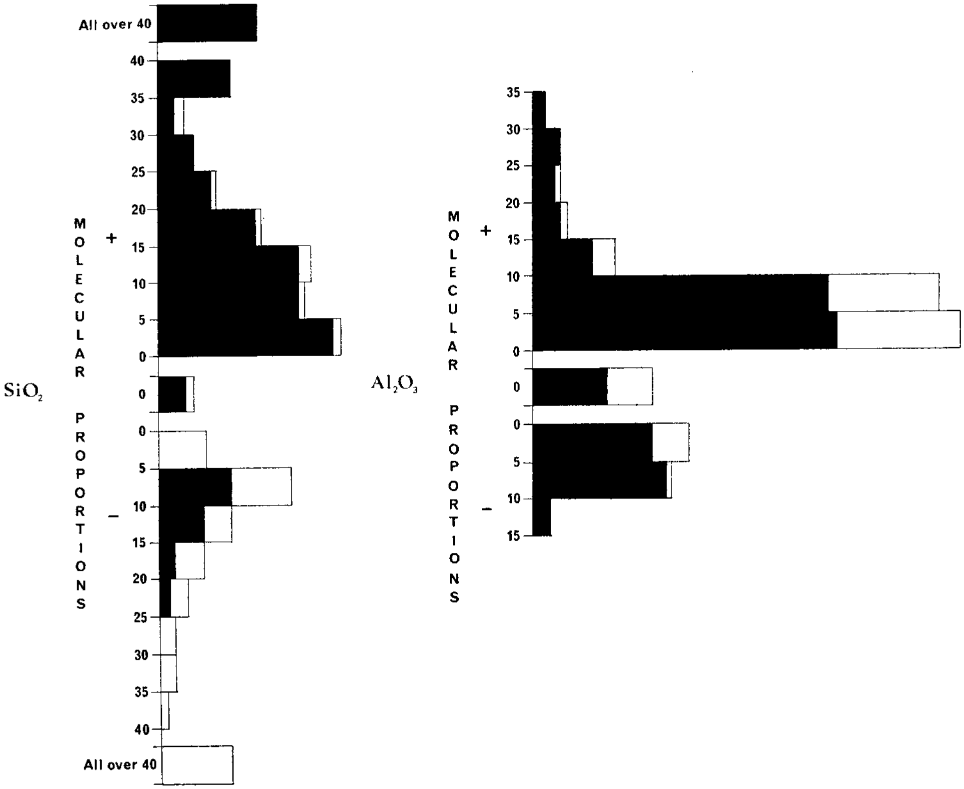

FIG. 7. Recalculation of 183 feldspar analyses showing excesses and deficiencies in SiO_2 and Al_2O_3 expressed in molecular proportions. Feldspar from alkaline rocks shown by blank areas.

the possibilities for the precipitation of sillimanite. This would be pertinent in relation to the Hasvik Hornfelses, as any diffusion of alkalis or lime out of the feldspars would change the compositional balance in the direction of increasing excesses in Al_2O_3 and SiO_2.

Corundum. The presence of corundum as a possible precipitate phase with sillimanite in feldspars implies that if the SiO_2 excess is insufficient to satisfy all the excess Al_2O_3 in the form of sillimanite, then under appropriate conditions the precipitation of corundum will result. Thus in the feldspars of rocks containing feldspathoids, corundum would be expected to be the only significant precipitate phase. The author has investigated this possibility in relation to the miaskitic nepheline syenites of Söröy (Sturt and Ramsay, 1965) and Stjernöy (Heier, 1961, 1966), which have suffered the effects of subsequent regional metamorphism.

In the nepheline syenite gneisses of Söröy a variety of textural relationships between feldspar and corundum were observed, the principal features being: The corundum occurs as quite large grains (up to 0·1 mm diameter) at the triple junctions of plagioclase/plagioclase grain boundaries in a well-marked annealed metamorphic fabric. The triple grain junctions make good 120° angles; the corundum is observed to replace part of the volume of the plagioclase (fig. 8). Or the corundum occurs as small grains, often elongate along feldspar/feldspar grain boundaries. Or the corundum forms a droplet texture in the plagioclase, and has a rather similar appearance to myrmekite; small infrequent droplets of green spinel and needles of rutile are occasionally found in association with the corundum.

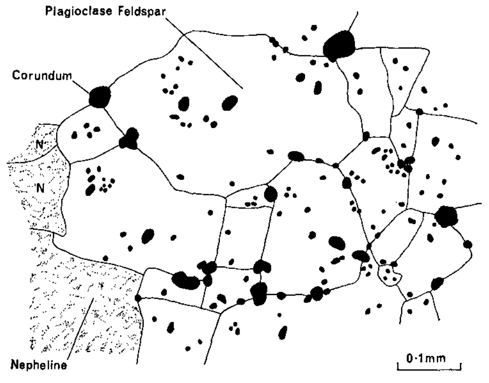

FIG. 8. Textural relations of plagioclase and corundum in Nepheline Syenite Gneiss, Breivikbotn, Söröy (SB170A).

In some examples (fig. 8) all of these types of feldspar/corundum textures occur in association, and the fabrics are closely similar to those developed in aged metal alloys as figured by Geisler (1953) and Doan (1958). It is thus considered that the corundum has formed as the result of the exsolution of a minor phase (Al_2O_3) from the feldspar solid solution during metamorphism. In one example (SB 480) of a nepheline-free perthositic syenite, where corundum has the typical textures described above in relation to perthitic and antiperthitic feldspars, some of the feldspars also contain sillimanite needles with orientations controlled by the feldspar lattice, and as sheaves of needles at the feldspar grain boundaries. Again rare blebs of green spinel are detected in the feldspars.

The metamorphosed nepheline syenite pluton of Lillebugt, Stjernöy is mainly composed of hair- and vein-perthite and nepheline with subordinate mafics (Heier, 1961). The metamorphism causes the precipitation of intergranular plagioclase at the perthite/perthite grain boundaries, showing swapped rims (Ramsay and Sturt, 1970). Minute grains of corundum may occur as small blebs in this plagioclase giving a texture analogous to that of the myrmekite developed in plagioclase precipitates of the Hasvik Hornfelses. The nepheline syenite is traversed by occasional syn-metamorphic shear zones, and these possess strongly annealed fabrics with nepheline, albite/oligoclase, and microcline occurring as separate phases. The annealed mosaic has well-developed triple grain intersections at approximately 120°, and at these junctions small granules of corundum often occur and obviously replace part of the feldspar. Corundum granules, often elongate, are present at grain boundaries and minute droplets of corundum occur within the feldspars. The presence of separate albite/oligoclase and microcline phases in the shear zones implies a virtually complete unmixing of the microperthitic feldspars of the nepheline syenite as the result of the deformation and the succeeding annealing recrystallization. This is in agreement with Chayes's (1952) argument for a more complete unmixing of feldspar solid solutions in zones of strong deformation. Comparable unmixing of feldspar solid solutions has been described by Floor (1966) from strongly deformed aegirine–riebeckite gneisses from Spain.

The possibility of a general deficiency of silica in the feldspars of alkaline rocks also allows for the prediction of exsolution of nepheline from alkali feldspars. Indeed since this paper was first written an example has been given of the unmixing of nepheline from alkali feldspars in larvikites from Southern Norway (Widenfalk, 1970). It is of interest in this connection that exsolution of albite/oligoclase occurs within nephelines from nepheline syenite pegmatites on Söröy and Seiland. This implies possible presence of excess SiO_2 in many nephelines allowing for the unmixing of a stable feldspar phase.

FORMATION OF SILLIMANITE IN FELDSPAR AND GARNET AND POSSIBLE THERMAL STRESS CONSIDERATIONS

The precipitation of sillimanite in both feldspar and garnet in the Hasvik Hornfelses has been described earlier. Certain anomalies, however, exist in these relationships that appear to be a consequence of the local mineralogical environment. This is most obvious in the case of sillimanite precipitation from garnet. Where the garnet is surrounded by feldspar, mica, etc., in the inner parts of the aureole, it is commonly observed to have been converted into a variety of high-temperature breakdown products. On the other hand, when a garnet crystal is surrounded by quartz such an alteration is the exception. The differences would appear to result from the local environment around the individual garnet grain, and the physical properties of the various mineral phases may have a considerable influence at these elevated temperatures. Indeed the location of sillimanite nucleation at certain sites may possibly be influenced by the level of thermal stress set up in the minerals during the contact metamorphism. In such a consideration, factors such as the volume coefficients of the thermal expansion and the densities of the mineral phases and the ΔV of the reactions involved must be taken into account. In a discussion of the nucleation of sillimanite in feldspar and garnet it is thus pertinent to discuss the textural arrangements of these minerals in terms of the possible thermal strains set up during the contact metamorphism.

In this discussion it is perhaps helpful to start with a hypothetical situation where three mineral phases X, Y, Z occur. These have different molar volumes, densities, and coefficients of volume thermal expansion. X and Z are taken to represent two contrasting phases in the rock (coefficient of volume thermal expansion $X > Z$, and Y is formed as a precipitate from both of these phases (densities $X > Y > Z$). If we now consider the thermal stress configuration shown in fig. 9, A and B, it is possible to see that when, at elevated temperatures, Z is surrounded by X it will be under compression and a volume reduction is favoured; conversely, when X is surrounded by Z it can undergo a volume expansion owing to the fact that the volume coefficient of thermal expansion of X is greater than that of Z. If it is assumed that both the mineral solid solutions X and Z contain the components of Y in excess, then precipitation of Y from X and Z could occur if the thermal stresses were appropriate. Y would be precipitated from X because it is a phase of lower density and X is able to expand at the expense of Z, while Y can be precipitated from Z because Z is under compression and Y is a phase of higher density than Z. Thus when X precipitates Y the ΔV of the reaction has a positive sign, whereas when Z precipitates Y the ΔV of the reaction will have a negative sign. If a fourth mineral phase W occurs, which has a higher coefficient of volume thermal expansion than X, and where Y does not form a precipitate phase in W, then the situation of W relative to X and Z is shown in fig. 9, C and D. It is obvious that both X and Z will be under compression. With mineral Z the precipitation of phase Y can proceed, as the thermodynamic requirements of the precipitation reaction will be maintained. However, for X to precipitate Y there must be a positive value of ΔV, and this is impossible owing to the thermal stress configuration where X is seen to be under compression (fig. 9C).

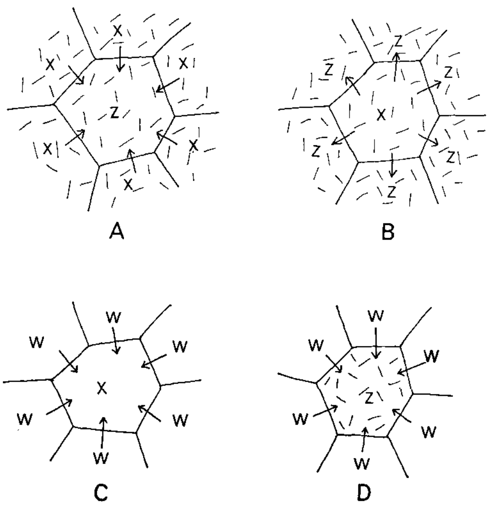

FIG. 9. Thermal strains and nucleation of precipitate phase Y (shown by short dashes). Coefficients of volume thermal expansion $W > X > Z$; densities $X > Y > Z$.

It has been noted above that sillimanite nucleates within the feldspar, often as dense sheaves against the garnet boundary, and that the nucleation and growth of sillimanite needles is particularly dense where a convex surface of garnet lobes into the feldspar. In this situation the nucleation of the sillimanite is aided by the thermal strains within the feldspar. The coefficient of volume thermal expansion of plagioclase expressed as a percentage expansion of volume at 800 °C is 1·10 for plagioclase of composition

An_{95} and 1·32 for plagioclase of composition An_{45} (Clark, 1966). For garnet of pure almandine composition the figure is 1·906, though it is probably higher for the solid solutions under consideration. Thus in the case of garnet surrounding plagioclase the garnet is expanding at the expense of the feldspar, and the latter mineral is subjected to compressive strains at the high temperatures developed. This is similar to the situation in glazed ceramic materials where the glaze has a lower thermal expansion coefficient than the body (Kingery, 1964, p. 624), and the glaze is subjected to compressive stresses as the glaze–body composite is cooled. As a consequence the nucleation of a phase of higher density, i.e. sillimanite, is facilitated from the heterotype feldspar solid solution. This is particularly well illustrated where sillimanite is densely nucleated about a convex lobe of garnet protruding into feldspar (fig. 3A). The strains, consequent upon the thermal stresses, are expressed in terms of brittle deformation by the formation of abundant cracks in the feldspars healed by sillimanite growth. However, much of the thermal stress relaxation probably occurs by plastic deformation involving dislocation gliding, as indicated by the occurrence of sillimanite in Widmanstätten patterns. This would naturally imply that the density of dislocations increases towards the grain boundaries and this would be an important factor in determining the dense nucleation of precipitate phases at such sites. The fact that dislocations are preferred nucleation sites may be of some significance in explaining why the nucleation of new phases is dependent upon the thermal stress field.

It has been shown earlier that the components of Al_2SiO_5 are often held in excess solid solution within the garnets of regionally metamorphosed schists, and that sillimanite apparently forms by precipitation from garnet. This can be explained by a similar line of reasoning to that used for the sillimanite precipitates in feldspar, in that the sillimanite is a phase of lower density than garnet and may thus be precipitated from an expanded garnet lattice. The sillimanite in garnet, however, mainly forms as the result of a series of high-temperature breakdown reactions during the contact metamorphism, e.g.:

$$\underset{\text{Garnet}}{Fe_3Al_2(SiO_4)_3} \rightarrow \underset{\text{Sillimanite}}{Al_2SiO_5} + \underset{\text{Magnetite}}{Fe_3O_4} + \underset{\text{Quartz}}{SiO_2}$$

$$\underset{\text{Garnet}}{3Fe_3Al_2(SiO_4)_3} + 2K^+ + 2H_2O \rightarrow \underset{\text{Sillimanite}}{2Al_2SiO_5} + \underset{\text{Biotite}}{2KFe_3(AlSi_3O_{10})(OH)_2} + \underset{\text{Magnetite}}{Fe_3O_4} + \underset{\text{Quartz}}{SiO_2}$$

These reactions both have positive values of $\Delta V/V$ %. The breakdown of garnet to such high-temperature products will be unimpeded in an environment of minerals with lower coefficients of volume thermal expansion. However, it can be observed in all the thin-sections examined that when garnet is surrounded by quartz it rarely shows precipitation of sillimanite or the development of high-temperature breakdown products. This is a possible consequence of the coefficient of volume thermal expansion of quartz being 4·43 % at 800 °C as compared with a value of 1·90 % for almandine garnet. The garnet will thus be under compression, and reactions such as those outlined above will be inhibited.

This discussion illustrates an important point in that even if the general physical conditions of metamorphism have reached a level at which a specific reaction may be expected to occur, e.g. garnet breakdown, that reaction will only be initiated if the local thermal stress configuration is favourable. Furthermore it is to be expected that the reaction can take place in some parts of the rock and be inhibited in others depending upon the stress conditions across the grain boundaries. An example which illustrates this principle is seen in fig. 10, where the formation of high-temperature breakdown products after garnet appears to be conditioned by the thermal strain configuration set up within the garnet grain as a consequence of the different minerals making contact with it. This shows the delicate control exercised by thermal stresses, and that differential strains may be set up within a single mineral lattice.

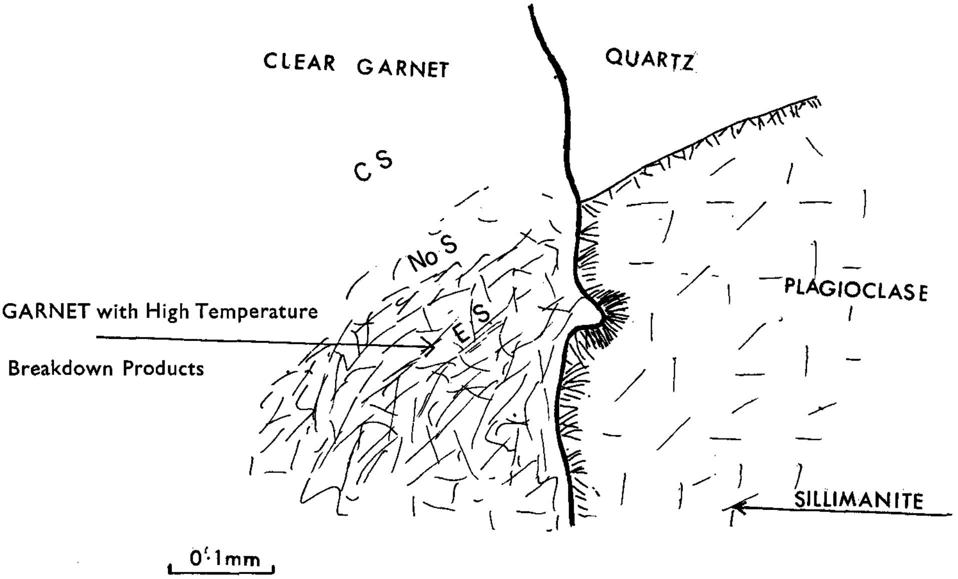

FIG. 10. Nucleation of sillimanite in plagioclase, and formation of high-temperature breakdown products in garnet. Thermal strains in garnet: CS = compressive strain; NoS = no strain or minimal strain; ES = expansional strain.

CONCLUSIONS

Under *suitable* conditions of metamorphism, exsolution and recrystallization takes place in mineral solid solutions in a manner analogous to that occurring in age-hardened metal alloys. In the case of heterotype feldspar solid solutions the type of precipitate mineral phase, i.e. quartz, sillimanite, corundum, spinel, etc., is dependent upon the detailed composition of the host feldspar in terms of excesses over or deficiencies from the formula requirements of the feldspar. This is illustrated in the case of the feldspars from alkaline rocks where corundum appears as a precipitate phase, contrasting markedly with the occurrence of myrmekite in feldspars that had an excess of SiO_2.

It also appears that the nucleation of new mineral phases is in part dependent upon the local thermal stress fields developed during metamorphism. The work indicates that although the boundary conditions for the initiation of a metamorphic reaction may be exceeded in general terms, if the local thermal stress configuration is of the wrong type the reaction may be inhibited. It is concluded that such considerations of the thermal stresses produced across grain-boundaries and within minerals may have considerable importance in the interpretation of the textures in metamorphic rocks.

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