

QUARTZ AND FELDSPAR MICROSTRUCTURES IN METAMORPHIC ROCKS

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ABSTRACT

The shapes of quartz and feldspar grains in metamorphic rocks are among the most reliable criteria for determining parental rock-types. Rational faces and elongate crystals of feldspar, especially with oscillatory zoning, indicate an igneous precursor, and residual faces and embayments in quartz indicate a volcanic precursor. Simple twinning in K-feldspar indicates a magmatic origin, and aligned crystals of feldspar indicate magmatic flow. Quartz and plagioclase inclusions are useful for distinguishing between phenocrysts and porphyroblasts of K-feldspar in metamorphic terranes. K-feldspar phenocrysts are characterized by zonally arranged inclusions, whereas K-feldspar porphyroblasts are characterized by spherical inclusions of quartz and plagioclase, either at random or arranged in trails that reflect an overgrown foliation. Inclusions of quartz and feldspar tend to be spherical in metamorphic porphyroblasts (*e.g.*, staurolite), even where the boundary between the porphyroblast and quartz or feldspar in the matrix is a rational face, which may be due to absence of fluid along the host-inclusion boundary, compared with its accumulation along the advancing porphyroblast-matrix boundary. The following microstructural criteria, preserved best in less deformed migmatites, indicate anatectic leucosome. (1) Crystal faces of K-feldspar or plagioclase may occur against quartz. (2) Inclusion trails are absent, in contrast to grains of the same minerals in the mesosome. (3) Overgrowths free of inclusion trails may occur on minerals with inclusion trails (*e.g.*, K-feldspar, cordierite). (4) Simple twinning may occur in K-feldspar, which appears to be diagnostic of crystallization of K-feldspar in a melt, rather than in the solid state.

Keywords: crystal faces, feldspar, inclusions, leucosome, metamorphism, microstructures, migmatites, quartz.

SOMMAIRE

La morphologie des cristaux de quartz et de feldspath des roches métamorphiques offre des critères parmi les plus fiables pour déterminer la nature du précurseur. Les faces rationnelles et les cristaux allongés de feldspaths, et en particulier ceux qui font preuve de zonation oscillatoire, indiquent un précurseur igné. De plus, la présence de faces résiduelles et de "doigts de gants" dans le quartz indique un précurseur volcanique. Le développement d'une macle simple dans le feldspath potassique indique une origine magmatique, et un alignement de cristaux de feldspath évoque une origine par flux magmatique. Les inclusions de quartz et de plagioclase sont utiles pour établir la distinction entre phénocristaux et porphyroblastes de feldspath potassique dans les socles métamorphiques. Les phénocristaux de feldspath potassique contiennent des inclusions disposées en zones, tandis que les porphyroblastes de feldspath potassique contiennent des inclusions sphériques de quartz et de plagioclase, disposées aléatoirement ou en traînées qui témoignent des restes d'un plan de foliation antécédent. Les inclusions de quartz et de feldspath ont tendance à être sphériques dans les porphyroblastes typiques (*e.g.*, staurolite), même où l'interface entre l'hôte et les inclusions de quartz ou feldspath de la matrice est une face rationnelle; ceci pourrait signaler l'absence d'une phase fluide le long de l'interface hôte-inclusion, et son accumulation le long de l'interface porphyroblaste-matrice à mesure que celle-ci avance. Les indices microstructuraux suivants, préservés dans les migmatites les moins déformées, indiquent la présence d'un leucosome anatectique. (1) Les cristaux de feldspath potassique ou de plagioclase peuvent développer des faces en contact avec le quartz. (2) Les traînées d'inclusions sont absentes, en contraste avec les cristaux des mêmes minéraux dans le mésosome. (3) On peut rencontrer, sur des minéraux (par exemple, feldspath potassique, cordiérite) ayant des traînées d'inclusions, des surcroissances sans de telles traînées. (4) Des macles simples peuvent apparaître dans le feldspath potassique, ce qui semble caractériser une croissance dans un bain fondu, plutôt qu'à l'état solide.

(Traduit par la Rédaction)

Mots-clés: faces des cristaux, feldspath, inclusions, leucosome, métamorphisme, microstructures, migmatites, quartz.

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INTRODUCTION

This paper is about the interpretation of microstructures involving quartz and feldspar in metamorphic rocks, namely: (1) using quartz and feldspar microstructures to determine parent (precursor) rock-types, (2) using shapes of quartz and feldspar inclusions as indicators of the presence or absence of fluid on grain boundaries, and (3) using quartz and feldspar microstructures to determine the anatectic origin of leucosomes in migmatites. Though quartz and feldspar are often viewed as relatively unimportant minerals in many metamorphic reactions, they can be very useful in microstructural studies.

USING QUARTZ AND FELDSPAR MICROSTRUCTURES TO DETERMINE PARENTAL ROCK-TYPES

The shapes of quartz and feldspar grains in metamorphic rocks are among the most reliable criteria for determining parental rock-types, with implications not only for metamorphic history, but also for models of mineral-resource exploration in metamorphic terranes.

For example, features indicative of igneous feldspar include: (1) rational crystal faces, though they are not particularly common in coarse-grained, intrusive igneous rocks, even in plagioclase; (2) elongate crystals or

grains (Figs. 1, 2), where twins are parallel to the elongation; (3) residual crystal faces and embayments in quartz (Fig. 3), indicating a volcanic precursor (*e.g.*, Vernon 1986a, Williams & Burr 1994); (4) aligned, elongate crystals of feldspar (Fig. 4), indicating magmatic flow (Paterson *et al.* 1989); (5) simple twinning in K-feldspar (Vernon 1986b); (6) complex and oscillatory zoning (Vernon 1976), and (6) zoning truncated by grain boundaries (*e.g.*, Vernon *et al.* 1987). Metamorphic K-feldspar and plagioclase grains tend to be equant and polygonal (*e.g.*, Kretz 1966, Vernon 1968), and compositional zoning of metamorphic origin follows the metamorphic grain boundaries, rather than being truncated by them.

Quartz and plagioclase inclusions are useful for distinguishing phenocrysts and porphyroblasts of K-feldspar in metamorphic terranes, and hence for determining parental rock-types. K-feldspar phenocrysts are characterized by zonally arranged inclusions (Fig. 5), especially of well-formed plagioclase crystals (*e.g.*, Vernon 1986b), whereas K-feldspar porphyroblasts are characterized by spherical quartz and plagioclase inclusions, either at random or arranged in trails reflecting an overgrown foliation (*e.g.*, Vernon 1968), as shown in Figure 6.

Though deformation and recrystallization tend to obliterate these igneous features, many can be at least partly preserved, even at granulite-facies conditions

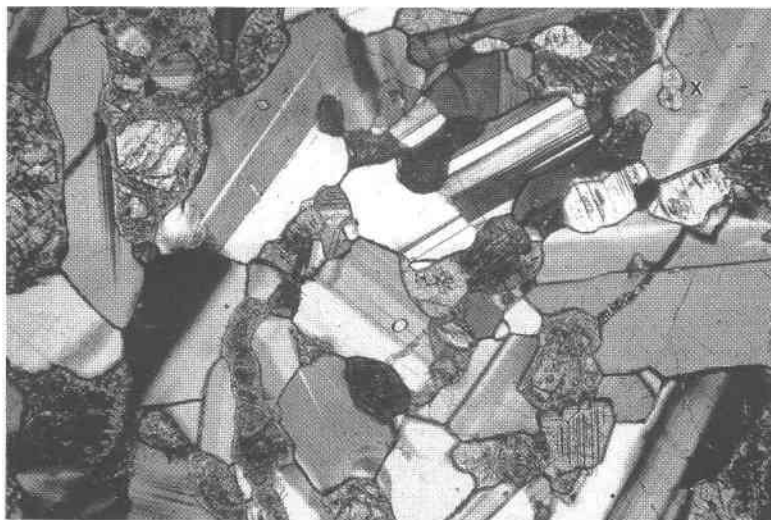


FIG. 1. Norite with some elongate grains of plagioclase, but also with many predominantly equant polygonal aggregates of plagioclase, clinopyroxene and orthopyroxene (partly replaced by fine-grained aggregates of secondary amphibole), suggesting adjustment of grain boundaries in the solid state, possibly during slow cooling. Inclusions of pyroxene in plagioclase and *vice versa* have relatively spherical (*i.e.*, well-adjusted) shapes. A "double inclusion" (X) of clinopyroxene in plagioclase (top right) shows plagioclase *versus* clinopyroxene-clinopyroxene dihedral angles, indicating a strong tendency toward minimization of interfacial energies by solid-state adjustment. Crossed polars; base of photo 6 mm.

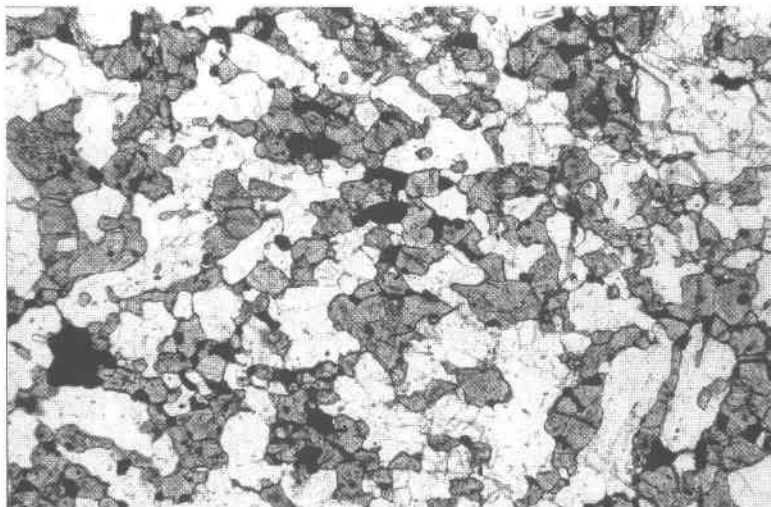


FIG. 2. Metagabbro with predominantly equant, polygonal grains, but also with several elongate grains of plagioclase inherited from the original igneous microstructure; Giles Complex, central Australia. Plane-polarized light; base of photo 3.5 mm.



FIG. 3. Embayed phenocryst of quartz in amphibolite-facies metarhyolite, Picuris Range, New Mexico. Crossed polars; base of photo 3 mm.

(Fig. 2), especially in zones of relatively low accumulation of strain. Even in mylonite zones, rational crystal faces may be preserved in large, strong grains (porphyroclasts) of K-feldspar (Vernon 1986b, Vernon & Williams 1988), as shown in Figures 7, 8 and 9; that these are residual phenocrysts and not porphyroblasts is commonly shown by evidence of deformation, such as microcline twinning and marginal recrystallization (Vernon 1990), as shown in Figure 10, as well as by preservation of simple twinning (Fig. 10) and zonally

arranged inclusions (Figs. 7, 8, 9), as discussed by Vernon (1986b).

QUARTZ AND FELDSPAR MICROSTRUCTURES AS INDICATORS OF FLUID ON GRAIN BOUNDARIES

Microstructural relationships of quartz and feldspar can provide evidence of the presence or absence of fluid on grain boundaries during metamorphism. Minerals with a relatively anisotropic structure, such as sheet silicates, hornblende and sillimanite, tend to develop crystal faces against quartz and feldspar in metamorphic rocks (e.g., Kretz 1966, Vernon 1968, 1976). In effect, the crystal faces show no tendency to adjust their shapes to the presence of quartz and feldspar boundaries (Fig. 11a). The result is a "rational-impingement" triple junction (Vernon 1968, 1976), in which the quartz – quartz or quartz – feldspar interface impinges on the very low-energy (and hence relatively stable) crystal face without causing it to adjust to their presence, as opposed to an "adjustment" triple junction (Fig. 11b).

Boundaries between sheet silicates and quartz or feldspar

Sheet silicates develop rational crystal faces between their (001) planes and quartz or feldspar. Voll (1960) regarded quartz – (001) mica interfaces as being of infinitely high energy, relative to random quartz – quartz interfaces, which follows from the usual considerations of interfacial energy along triple junctions in solid aggregates. However, in view of the ubiquitous occurrence of straight quartz – (001) mica interfaces in metamor-

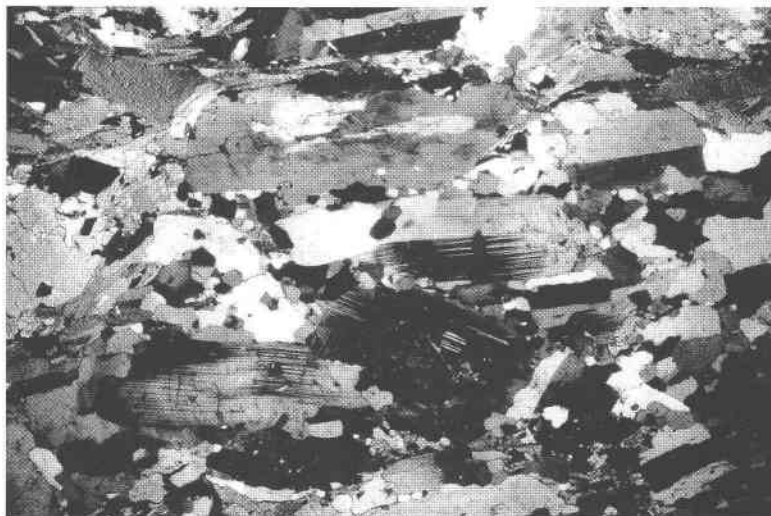


FIG. 4. Magmatic flow-induced foliation (indicated by subparallel, elongate crystals of plagioclase without or recrystallization or severe internal deformation) in a granodiorite that has undergone some solid-state deformation (indicated by recrystallized quartz). The only internal deformation in the plagioclase is mechanical twinning and minor bending of a few crystals, which can be attributed to the later solid-state deformation of the rock. Cascade Range, Washington. Crossed polars; base of photo 6.3 mm.

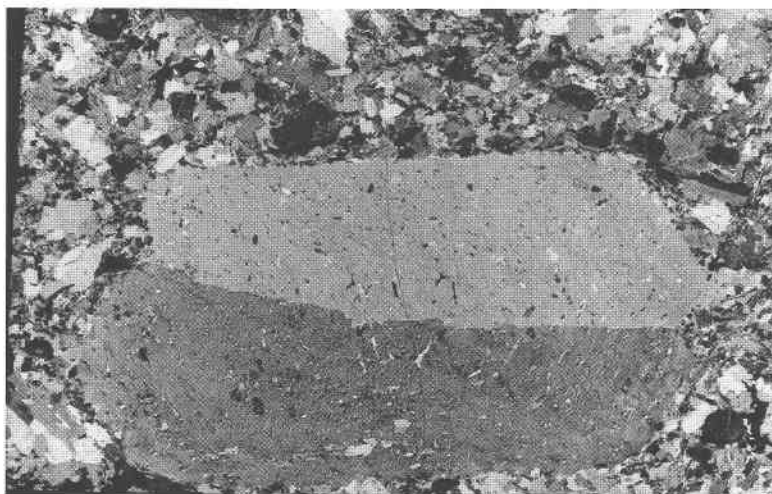


FIG. 5. K-feldspar phenocryst (megacryst) with crystal faces, simple twinning and zonally arranged inclusions (especially of plagioclase) in the Wuuluman Granite near Wellington, New South Wales, Australia. Crossed polars; base of photo 4.9 cm.

phic rocks of all grades, they are more reasonably regarded as being of relatively low energy. If the interfacial free energy varies considerably with crystallographic orientation of one or both minerals involved (as with sheet silicates), the theory of Herring (Kretz

1966, p. 88–89) shows that the interfacial energies can be balanced, even though the straight interface is regarded as being of low energy. From this viewpoint, the total interfacial free energy at the “rational impingement” triple junction between (001) biotite and two

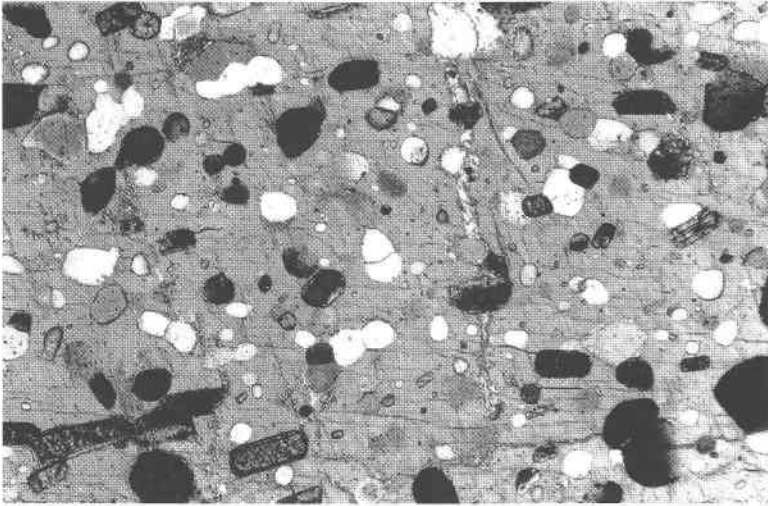


FIG. 6. Part of a K-feldspar porphyroblast in a high-grade metapelite rock from Broken Hill, New South Wales, Australia, showing random inclusions of quartz, which are predominantly spherical, and biotite, which tend to be elongate with round terminations in sections approximately perpendicular to (001) and spherical in sections approximately parallel to (001). Crossed polars; base of photo 4 mm. From Vernon (1968, p. 12).

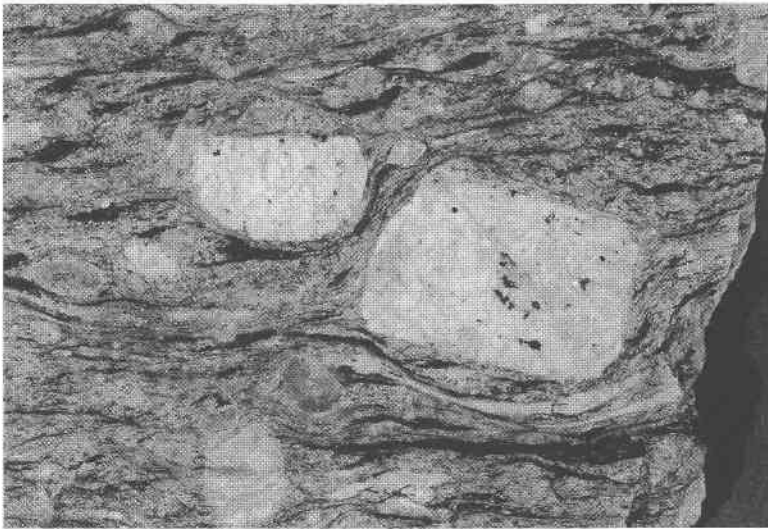


FIG. 7. K-feldspar phenocryst with crystal faces and zonally arranged inclusions of quartz, plagioclase and opaque grains (right) in deformed granitic rock in a mylonite zone, Wongwibinda area, New South Wales, Australia. Base of photo 6.5 cm.

grains of quartz shown in Figure 11a is lower than that in the hypothetical "adjustment" triple junction shown in Figure 11b. "Rational impingement" junctions also apply to (001) biotite – biotite interfaces (Fig. 11c), as in the typical "decussate" microstructure of mica (*e.g.*,

Vernon 1968, 1976).

Assuming that the quartz – (001) biotite interface has a very low energy in this specific orientation, any change toward the situation shown in Figure 11b, even a slight change, would markedly increase the energy of the inter-

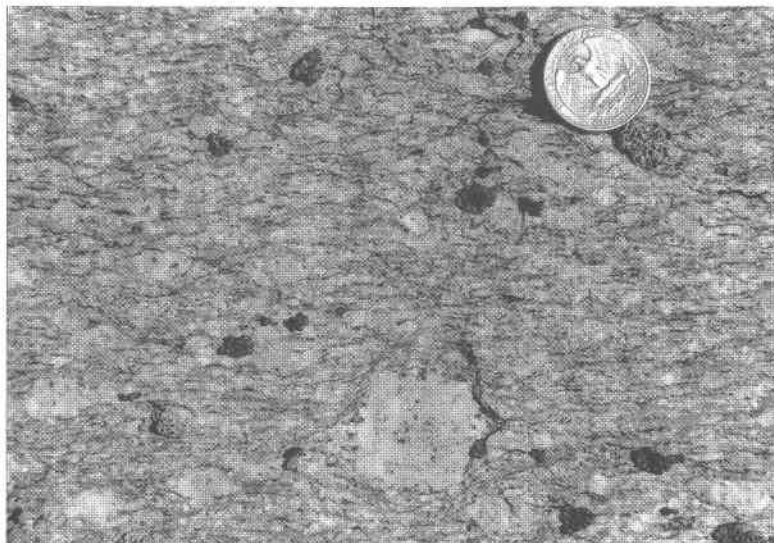


FIG. 8. Euhedral phenocryst of K-feldspar with zonally arranged inclusions in strongly deformed granitic rock in a mylonite zone, Papoose Flat, Inyo Mountains, California.

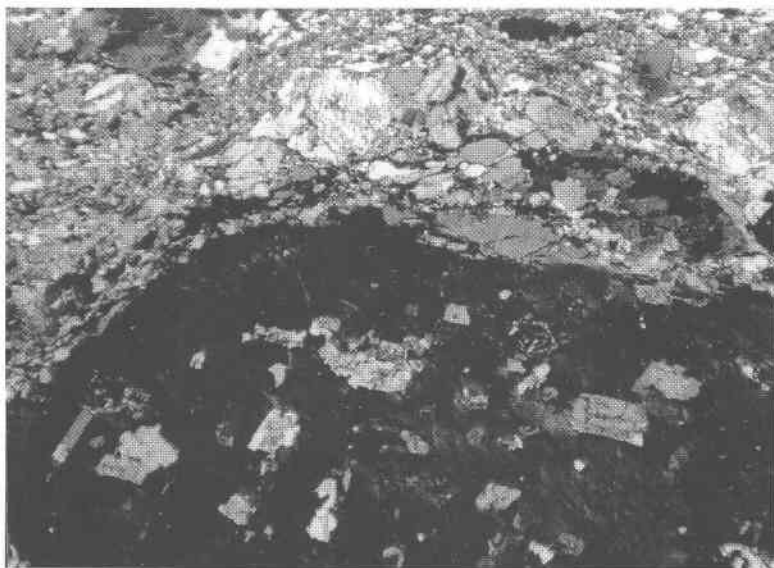


FIG. 9. Similar rock to that shown in Figure 6, showing zonally arranged, euhedral inclusions of plagioclase preserved in a K-feldspar phenocryst (at extinction) in a granitic mylonite, Papoose Flat, Inyo Mountains, California. Though deformed, especially at its margins, the phenocryst has been strong enough to resist the deformation, most of which occurred in the former groundmass of the granite. Crosses polars; base of photo 10 mm.

face. In other words, the energy of the interface reduces abruptly when the interface is exactly parallel to (001) from relatively high values at all other orientations. As

a confirmation of this, interfaces between quartz and biotite oblique to (001) form adjustment boundaries, as shown in Figure 12.

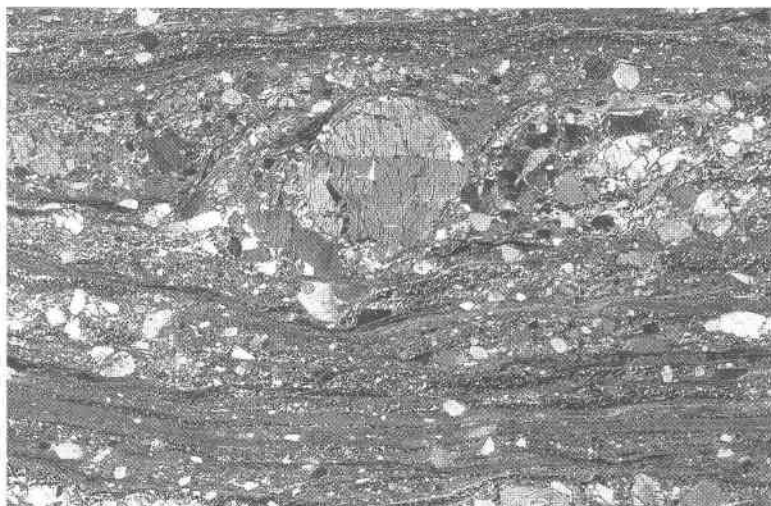


FIG. 10. Strongly deformed granite mylonite from the Wyangala Batholith, New South Wales, Australia. K-feldspar phenocrysts have resisted the deformation more than the former groundmass, but have been fractured and marginally recrystallized. Despite this, a simple twin is preserved in the K-feldspar porphyroblast in the center. Crossed polars; base of photo 5 cm.

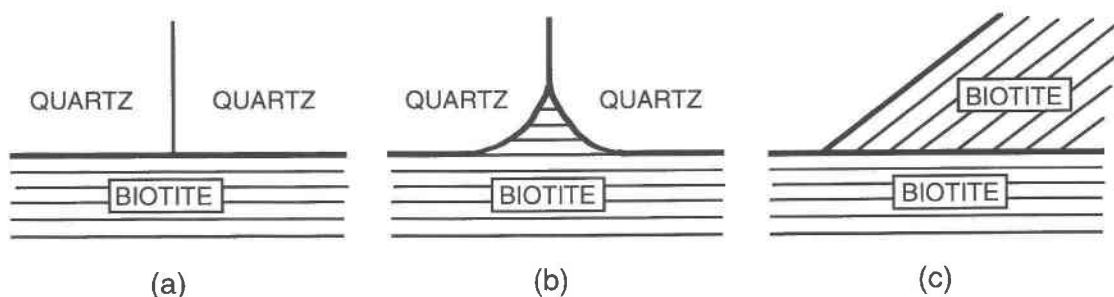


FIG. 11. a) Commonly observed "rational-impingement" triple junction between two random grains of quartz and a grain of biotite with (001) planes (shown diagrammatically by parallel lines) perpendicular to the plane of the drawing. b) Hypothetical "adjustment" triple junction with a mica *versus* quartz-quartz dihedral angle of less than 180° . c) Impingement of one biotite grain on the (001) plane of another, the (001) planes of both being shown diagrammatically by parallel lines.

The number of atomic bonds of a sheet silicate directed obliquely to (001) that are available for linking to available bonds from a neighboring mineral is very small, whereas consideration of the atomic structure of quartz (Bragg 1937) shows that many bonds would be available from quartz, regardless of its crystallographic orientation or the orientation of the interface. Therefore, a relatively high proportion of unsaturated bonds should occur at the quartz-(001) sheet silicate interface. These bonds could be satisfied by the adsorption of impurities, especially hydroxyl, leading to a water-rich film at the interface. This should also apply to the impingement of a grain of a sheet silicate with (001) oblique to the

(001) plane of another sheet silicate grain (Fig. 11c). The curved, irrational, adjustment boundaries between quartz or feldspar and biotite oblique to (001) shown in Fig. 12 presumably were dry because abundant bonds from both the biotite and the tectosilicates are available.

Boundaries between hornblende and quartz or feldspar

Despite a general tendency to develop rational crystal faces against quartz and feldspar (Fig. 13), elongate sections of hornblende may develop adjustment boundaries under some circumstances (Fig. 14), which is the

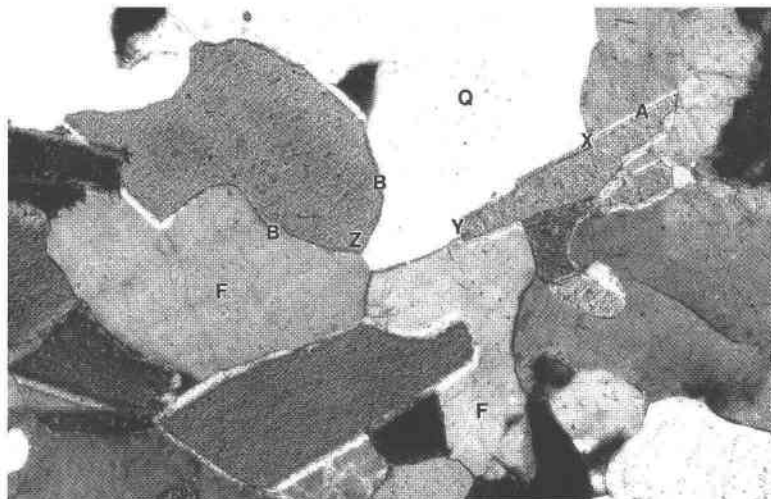


FIG. 12. Contrasts between rational, planar (001) biotite – quartz boundaries (labeled A) and curved boundaries between biotite very oblique to (001) – quartz boundaries (labeled B). Quartz (Q) – quartz, feldspar (F) – feldspar and quartz – feldspar boundaries meet biotite (001) boundaries at very high angles, approaching or attaining 90° (labeled X) or are attached to corners of biotite grains (labeled Y), if viewed at high angles to (001), or make triple junctions with definite biotite *versus* Q – Q or biotite *versus* Q – F dihedral angles (labeled Z), if viewed at low angles to (001). Granulite-facies felsic gneiss, Sri Lanka. Crossed polars; base of photo 1.75 mm.

usual situation where all minerals involved have relatively three-dimensional structures with bonding broadly similar in all directions (*e.g.*, quartz and feldspar), as shown in Figure 15. The hornblende interface against quartz and plagioclase shown in Figure 14 may have acted as an adjustment boundary because the rock was dry (apart from the hydroxyl in the hornblende structure), which is in accord with its occurrence in a granulite-facies terrane.

Shapes of quartz and feldspar inclusions

An even more striking contrast is provided by inclusion shapes in many metamorphic porphyroblasts. Quartz and feldspar inclusions tend to be spherical or at least have curved corners in a wide variety of metamorphic minerals (*e.g.*, Kretz 1966, Vernon 1968, 1976). This is generally interpreted as a tendency to minimize interfacial energy by minimizing the interface area, which applies especially where both inclusion and host have relatively uniform atomic structures, such as quartz inclusions in feldspar (*e.g.*, Kretz 1966, Vernon 1968, 1976). However, inclusions of quartz tend to be spherical even where the boundary between the porphyroblast (*e.g.*, staurolite) and quartz in the matrix is a straight crystal face (Fig. 16). The reason crystal faces generally are not developed against the inclusions may be connected with the absence of fluid along the host-in-

clusion boundary, compared with its accumulation along the advancing porphyroblast–matrix boundary. Fluid may diffuse from grain boundaries in the matrix to the main porphyroblast boundary as grains of quartz are gradually overgrown and included during growth of both inclusions and porphyroblast (Vernon 1977). This leaves the porphyroblast–inclusion boundary dry, so that it adjusts as a normal dry grain-boundary. In fact, Sunagawa *et al.* (1974) and Tomura *et al.* (1979) have suggested that the development of crystal faces in metamorphic rocks may require fluid accumulation.

Films of fluid around porphyroblasts?

The inferred presence of fluid implies that the only interfacial free energy relationships to have effect would be those between the solid porphyroblast and the fluid, not between solid and solid. Effectively, the porphyroblast grows in a fluid, and so tends to develop crystal faces. The postulated fluid films involve a “chicken-and-egg” argument, inasmuch as the presence of a crystal face attracts fluid, and the presence of fluid permits the development of a crystal face.

Most porphyroblasts and residual phenocrysts of plagioclase and K-feldspar (Fig. 15) in strongly recrystallized metamorphic rocks have high-energy, irrational boundaries, presumably because any section through them tends to have many bonds available for linking to

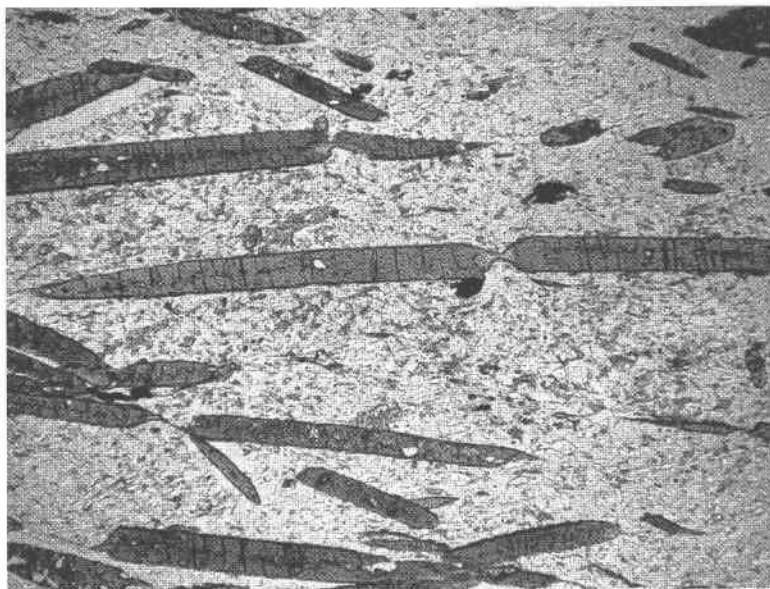


FIG. 13. Hornblende porphyroblasts with rational (low-energy) crystal faces against quartz and feldspar in the matrix. Amphibolite-facies "Garbenschiefer", Sweden. Plane-polarized light; base of photo 6 mm.

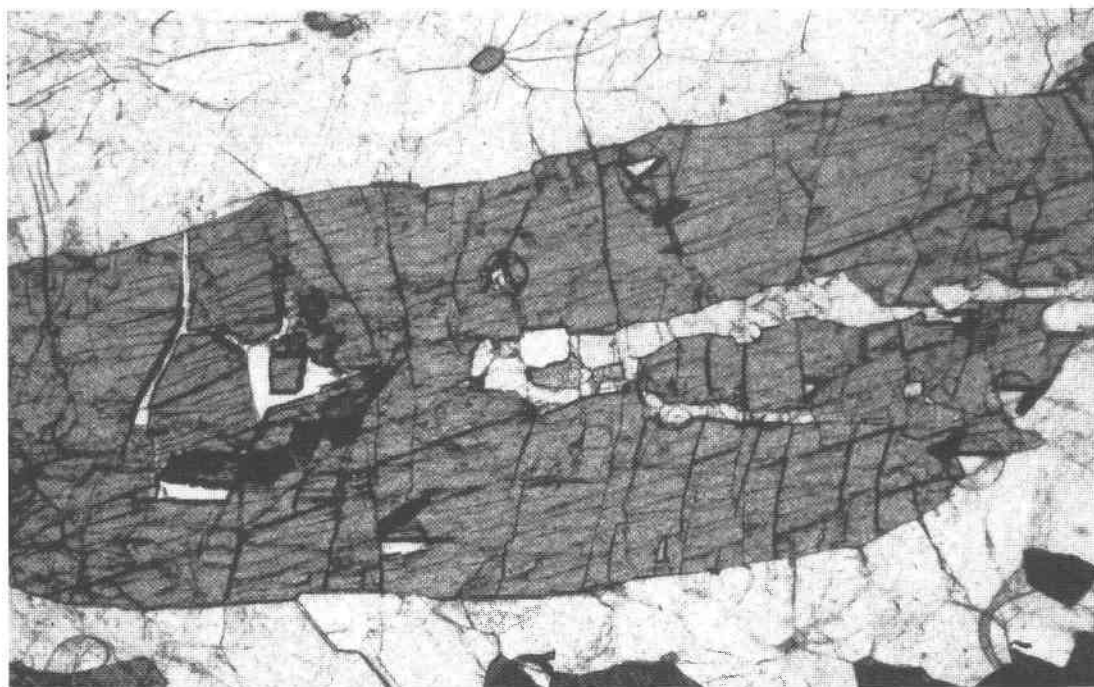


FIG. 14. Plagioclase-quartz, quartz-quartz and plagioclase-plagioclase boundaries meet hornblende-quartz and hornblende-plagioclase boundaries at triple junctions, implying solid-solid adjustment during granulite-facies metamorphism. This is in marked contrast to situations in which hornblende has crystal faces, as in Figure 13. Mud Rock Tank, Arunta Block, central Australia. Plane-polarized light; base of photo 4 mm.

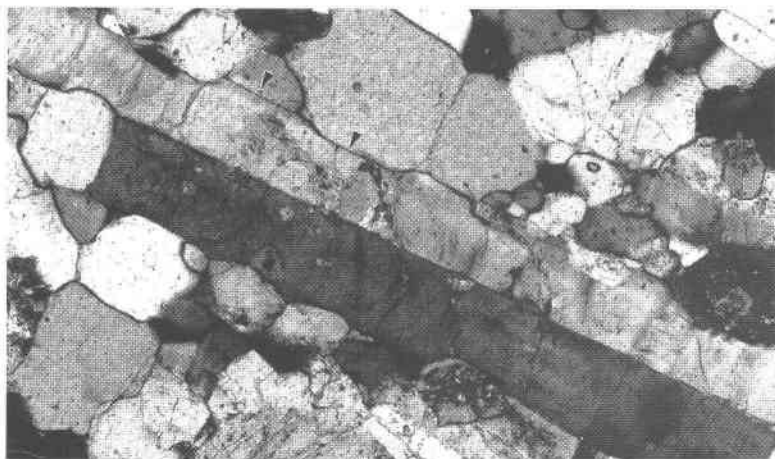


FIG. 15. Scalloped edge of former K-feldspar (now microcline) phenocryst with simple twinning against recrystallized quartz and feldspar in a hornfels at Kentucky, New South Wales, Australia. Dihedral angles formed where the microcline meets two matrix grains reflect a strong tendency toward the attainment of minimum interfacial energies during recrystallization. Though small, local, planar or almost planar boundaries are present in microcline (arrows), their variable distance from the twin boundary indicates that they have moved, and so they cannot be interpreted as residual parts of a former crystal face. Crossed polars; base of photo 1.75 mm.

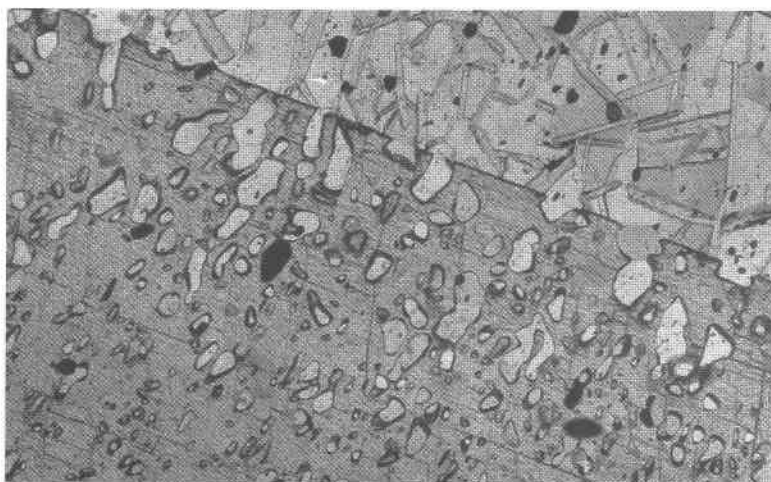


FIG. 16. Staurolite porphyroblast in a mica-quartz-staurolite schist, showing planar, rational (low-energy) boundaries against quartz grains in the matrix. In contrast, included and partly included quartz grains and aggregates have curved, irrational (high-energy) quartz-staurolite boundaries. Partly crossed polars; base of photo 2 mm.

adjacent minerals and few bonds free for collection of hydroxyl. The rare idioblastic or partly idioblastic examples (assuming that their origin as porphyroblasts rather than residual phenocrysts can be verified) may have accumulated enough fluid for faces to develop.

If H_2O is present as a continuous film around idioblastic porphyroblasts, the potential weakening effect would be limited by the isolation of the porphyroblasts. If films of fluid were present on all grain boundaries, the rock should be very weak, owing to reduction in

effective stress. This suggests that the H_2O escaping from sites of dehydration reactions is mainly present as bubbles (White & White 1981) in local, transient over-pressured openings (tensile cracks) inside grains and along general high-energy boundaries (Etheridge *et al.* 1983), or in rational crystal-face boundaries, as discussed previously.

This discussion has implied that available fluid may tend to concentrate on rational crystal faces, regardless of deformation. However, potential weakness of bonds across these interfaces could cause them to open preferentially and accept H_2O during deformation (Etheridge *et al.* 1983, p. 212–213).

USING QUARTZ AND FELDSPAR MICROSTRUCTURES TO DETERMINE THE ANATECTIC ORIGIN OF LEUCOSOMES IN MIGMATITES

Quartz and feldspar microstructures can be useful for distinguishing between anatectic leucosome and quartz-feldspar aggregates formed in the solid state in relatively weakly deformed and relatively rapidly cooled rocks, using the following criteria. (1) Crystal faces of K-feldspar or plagioclase may occur against quartz (Fig. 17), as discussed by Kenah & Hollister (1983) and Vernon & Collins (1988). (2) Inclusion trails are absent, in contrast to grains of the same minerals in the mesosome (*e.g.*, Brown 1998, Fig. 6b). (3) Overgrowths free of inclusion trails may occur on minerals with inclusion trails, such as K-feldspar (Fig. 18). (4) Simple twinning

may occur in K-feldspar, which appears to be diagnostic of crystallization of K-feldspar in a melt, rather than in the solid state (*e.g.*, Vernon 1986b); however, this may not apply to K-feldspar in leucosomes if it grows on pre-existing metamorphic K-feldspar (Fig. 18). These criteria may be applicable even to leucosomes formed in the early stages of melting, as in the Cooma complex, southeastern Australia (work in progress).

These microstructural features are less likely to be preserved in leucosomes formed during slow cooling and in leucosomes that have been extensively deformed and recrystallized. In the Cooma Complex, euhedral shapes of K-feldspar crystals observed in weakly deformed leucosomes are preserved even where the quartz has been strongly recrystallized in zones of deformation. However, intense deformation and recrystallization of K-feldspar can occur in some mylonites, in which euhedral shapes may or may not be preserved. This also applies to simple twinning, though complete recrystallization of original phenocrysts would be needed to remove it.

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FIG. 17. Leucosome in migmatite in a low-pressure, high-temperature terrane, Snowy Mountains, southeastern Australia, showing crystal faces of plagioclase (P) against quartz (Q), microcline (M) against quartz, and plagioclase against microcline. The leucosome is not sufficiently deformed to obliterate the igneous grain-shapes, though some evidence of deformation is indicated by the presence of microcline twinning and myrmekite. Crossed polars; base of photo 1.75 mm.

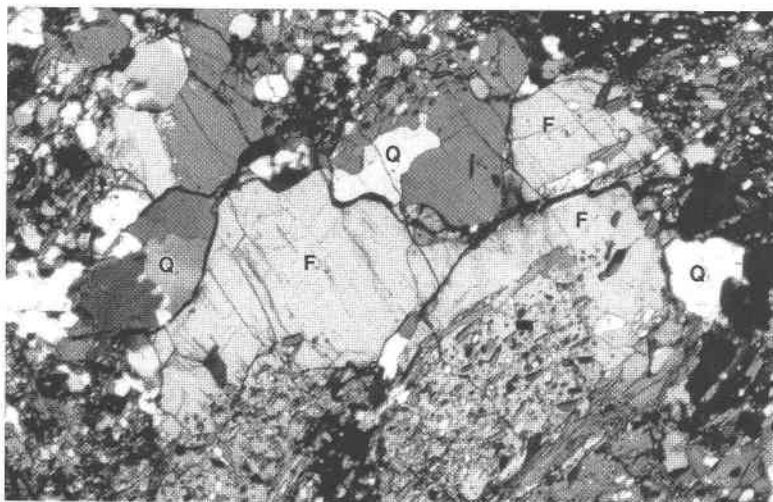


FIG. 18. Leucosome patch in migmatite in a low-pressure, high-temperature terrane, Cooma Complex, southeastern Australia, containing recrystallized quartz (Q) and abundant K-feldspar (F), much of which shows an inclusion-rich (metamorphic) core and inclusion-free (magmatic) rim. Crossed polars; base of photo 4.4 mm.

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