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A review of criteria for the identification of magmatic and tectonic foliations in granitoids

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Abstract—Foliations in granitoids can form by magmatic flow, 'submagmatic flow', high-temperature solid-state deformation and moderate- to low-temperature solid-state deformation. A review of previous work suggests that no single criterion can consistently distinguish foliations in granitoids formed by flow during ascent, diapiric emplacement and expansion, emplacement during regional deformation, or regional deformation post-dating emplacement. However, a magmatic origin is favoured for foliations defined by the alignment of igneous, commonly euhedral minerals, particularly where the foliation is parallel to internal or external pluton contacts. Foliations formed during expansion or 'ballooning' of diapirs may be strictly magmatic in origin, although some studies suggest that solid-state deformation also may occur. If so, we would hope to find evidence of deformation of crystal–melt systems, and that the solid-state deformation occurred at high temperatures. The inference of syntectonic foliations is most convincing where magmatic and high-temperature solid-state foliations are subparallel, these foliations are continuous with regionally developed foliations in the wall rocks, synkinematic porphyroblasts are present in the wallrocks, and igneous minerals have the same age as metamorphic minerals associated with the regional cleavage. A strictly tectonic origin for foliations in granitoids is favoured when the foliation is defined by metamorphic minerals, no alignment of igneous minerals occurs, the foliation is locally at high angles to pluton–wallrock contacts, and the foliation is continuous with a regionally developed cleavage.

INTRODUCTION

A LONGSTANDING controversy exists over what criteria are useful for distinguishing foliations formed by magmatic flow in granitoids from those formed by tectonic processes. In contrast to Berger & Pitcher (1970) and Castro (1987), we believe that this distinction is critical for understanding the timing and means of emplacement of plutons, which in turn influence ihterpretations of the age and significance of structures and metamorphism in the surrounding country rock. However, we agree with Berger & Pitcher (1970) and Castro (1987) that many structures in plutons are formed by flow of crystals plus liquid and that a clearer definition of 'magmatic flow' is needed. We define 'magmatic flow' as deformation by displacement of melt, with consequent rigid-body rotation of crystals, without sufficient interference between crystals to cause plastic deformation (i.e. suspension-like behavior). The critical proportion of melt needed for the formation of throughgoing melt-filled fractures appears to be around 30 volume per cent (Arzi 1978, van der Molen & Paterson 1979), but may increase to around 50 volume per cent under some circumstances (Vernon *et al.* in press).

A continuum likely exists between magmatic and solid-state processes operating during the development of foliations in granitoids. For the purposes of this paper, we divide this continuum into four types: magmatic flow (suspension-like behavior), 'submagmatic' flow (flow with less than the critical amount of melt for suspension-like behavior), high-temperature solid-state flow (subsolidus plastic deformation), and moderate- to low-temperature solid-state flow. We will first examine criteria for recognizing foliations formed by the two end-member processes of magmatic and solid-state flow. We will then examine criteria put forth in support of two intermediate stages, that of deformation of crystal–melt systems with less than 30% melt (e.g. van der Molen & Paterson 1979, Hibbard 1987) and that of high-temperature solid-state deformation (e.g. Gapais & Barbarin 1986).

Publications on the emplacement of plutons infer that foliations in granitoids may develop by (1) flow during ascent, (2) diapiric emplacement and expansion (ballooning), (3) emplacement during regional deformation, (4) regional deformation post-dating emplacement, or (5) combinations of the above. Which processes or combinations of processes operate to form foliations during the emplacement of plutons are in some doubt. For example, do margin-parallel foliations in plutons emplaced by diapirism and ballooning largely reflect solid-state deformation (Holder 1981, Bateman 1985) or magmatic flow with or without small tectonic overprints (Marre 1986, Paterson in press)? And do both magmatic and solid-state processes operate during the emplacement of syntectonic plutons? Therefore, it is important to determine what criteria are useful for distinguishing foliations formed by magmatic and tectonic processes operating during different methods of emplacement. To address such questions, structural and metamorphic observations both within and adjacent to plutons must be combined with criteria for recognizing magmatic and solid-state flow in granitoids.

IDENTIFICATION OF FOLIATIONS FORMED BY MAGMATIC AND SOLID-STATE PROCESSES

Microstructural and mesostructural evidence of magmatic flow

(1) The main criterion of magmatic flow is the preferred orientation of primary igneous minerals that show no evidence of plastic deformation or recrystallization, either of the aligned crystals or of interstitial minerals (e.g. Balk 1937, Oertel 1955, Reesor 1958, Berger & Pitcher 1970, Johnson & Pollard 1973, Bateman *et al.* 1983, Shelley 1985, Vernon *et al.* 1988), as shown in Fig. 1. For this to happen, enough melt must be present during deformation for crystals to rotate without significant interference with neighbouring minerals. This criterion is strongest where the oriented mineral is euhedral K-feldspar or plagioclase (Figs. 1a & b), because feldspars generally do not grow as euhedral crystals in unmelted metamorphic rocks (e.g. Vernon 1968, 1976, 1986), and so an appeal cannot be made to solid-state growth to explain the alignment or crystal shapes. An igneous origin is particularly favored if the aligned feldspar crystals show igneous microstructures (e.g. 'synneusis', oscillatory zoning), are unbroken, and are not separated by recrystallized aggregates.

Biotite and hornblende may be aligned in both magmatic and solid-state foliations, and so are less reliable. If they occur as aligned, independent, euhedral grains, a magmatic interpretation is preferred, particularly where the crystals are surrounded by a groundmass of minerals with igneous microstructures (Figs. 1b & c). Magmatic foliations defined by aligned hornblende (Fig. 1c) or biotite are common in tonalites and diorites (e.g. Bateman *et al.* 1963, 1983). However, aligned independent crystals of hornblende or biotite also occur in metamorphic foliations, even in the most strongly deformed and neocrystallized mylonites (Bell & Etheridge 1973). Conversely, if the aligned biotite or hornblende are in aggregates, the foliation is more likely to be metamorphic, although these minerals also occur, less commonly, as aggregates in non-deformed granitoids.

(2) Aligned crystals surrounded by anhedral, non-deformed quartz grains or non-aligned, anhedral aggregates of quartz, imply magmatic alignment of the crystals. This is because quartz or quartz aggregates do not have a strong shape preferred orientation in non-deformed granitoids. Also, quartz undergoes plastic deformation and consequent elongation more readily (for any given P, T, fluids, etc.) than other minerals in granitoids, so that it is a sensitive indicator of solid-state flow (e.g. Vauchez 1980, Marre 1986).

(3) Imbrication or 'tiling' of crystals (Den Tex 1969) implies non-coaxial magmatic flow, involving rotation of crystals in a viscous fluid. Imbrication of K-feldspar crystals has been described by Blumenfeld (1983). Closely related to this phenomenon is the curvature of lines of feldspar crystals in granitic veins, owing to drag against the walls during magmatic flow (Blanchard *et al.* 1979).

(4) Measurements of magnetic anisotropy have revealed alignment of magnetite in non-deformed granitoids. The plane containing the maximum and intermediate axes of magnetic anisotropy are parallel to magmatic flow foliations, indicating that such measurements can be used to define magmatic fabrics (Balsley & Buddington 1960, Guillet *et al.* 1983, Rathore & Kafafy 1986). However, alignment of magnetic minerals may also develop during deformation (Hrouda & Janak 1976, Guillet *et al.* 1983), so it is important to show that the magnetic minerals have not been thermally reset or deformed in the solid-state.

(5) Preferred alignment of elongate microgranitoid enclaves (Fig. 1d), which we interpret as incompletely solidified magma globules (Vernon 1983, 1984), indicates magmatic flow if the enclaves show no evidence of plastic deformation or recrystallization (e.g. Pabst 1928, Reesor 1958, Bateman *et al.* 1983, Vernon 1983, Marre 1986, Vernon *et al.* 1988). The patterns of preferred orientation of the minerals in the enclave commonly are similar to or even stronger than those in the enclosing magmatically foliated granitoid (Pabst 1928, Hurlbut 1935, Marre 1986). Alignment of xenoliths, i.e. fragments of solid rock, may also occur during magmatic flow (Balk 1937), and older foliations, which may or may not be parallel to the magmatic foliation, can be preserved in the xenoliths.

(6) Magmatic flow foliations and elongate microgranitoid enclaves are deflected around large metasedimentary xenoliths (Hurlbut 1935). Magmatic flow foliations are sometimes deflected around microgranitoid enclaves (e.g. Sen 1956), although the deflection is usually slight (e.g. Marre 1986).

(7) Schlieren layering (e.g. Balk 1937, Pabst 1928, Bateman *et al.* 1963, Moore & Lockwood 1973, Wilshire 1969, Reid & Hamilton 1987) is a clear indicator of magmatic flow, in the absence of evidence of plastic deformation of the minerals involved. However, it must be shown that the layering is due to flow sorting (e.g. Bateman *et al.* 1963, Wilshire 1969, Barriere 1981, Irvine 1987) rather than gravitational sorting (e.g. Sorensen & Larsen 1987, Clark & Clarke in review), which does not directly reflect the direction of magma flow (Wager & Brown 1967, Barriere 1981). Comb layering (e.g. Moore & Lockwood 1973), layering formed by aplitic and pegmatitic segregations during crystallization (e.g. Duke *et al.* in review), and layering formed by *in situ* rhythmic supersaturation (e.g. Parsons & Becker 1987, Sorensen & Larsen 1987) are excluded from this criterion.

(8) When the flow layering is parallel to the walls of the intrusion, phenocrysts and enclaves may be scarce at the contact, but abundant a few feet inside the granitoid (Reesor 1958). This is likely due to the Bagnold effect (Barriere 1981), which causes crystals in flowing magma to move away from walls.

Microstructural and mesostructural evidence of solid-state flow

(1) The mineral grains show microscopic evidence of plastic deformation (e.g. undulatory extinction, kinking

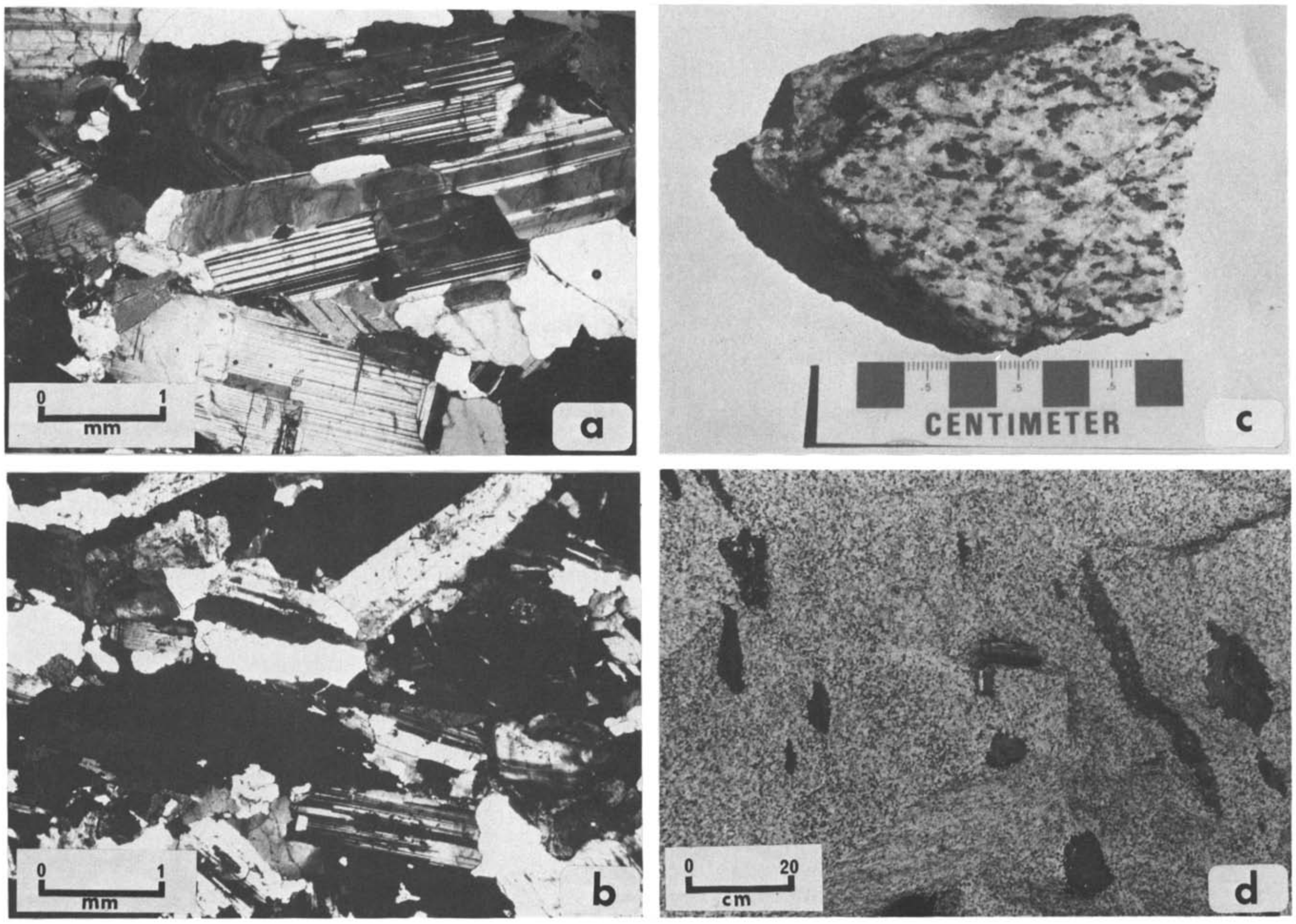


Fig. 1. Magmatic foliations defined by: (a) feldspar alignment, Bass Lake tonalite, Sierra Nevada, California (crossed nicols); (b) plagioclase alignment surrounded by weakly deformed but equidimensional aggregates of quartz (crossed nicols); (c) hornblende alignment, the Bass Lake tonalite, Sierra Nevada, California; (d) alignment of microgranitoid enclaves, from a granitoid near El Portal, California. Note how plagioclase twins in (a) and (b) are parallel to long dimension of crystals.

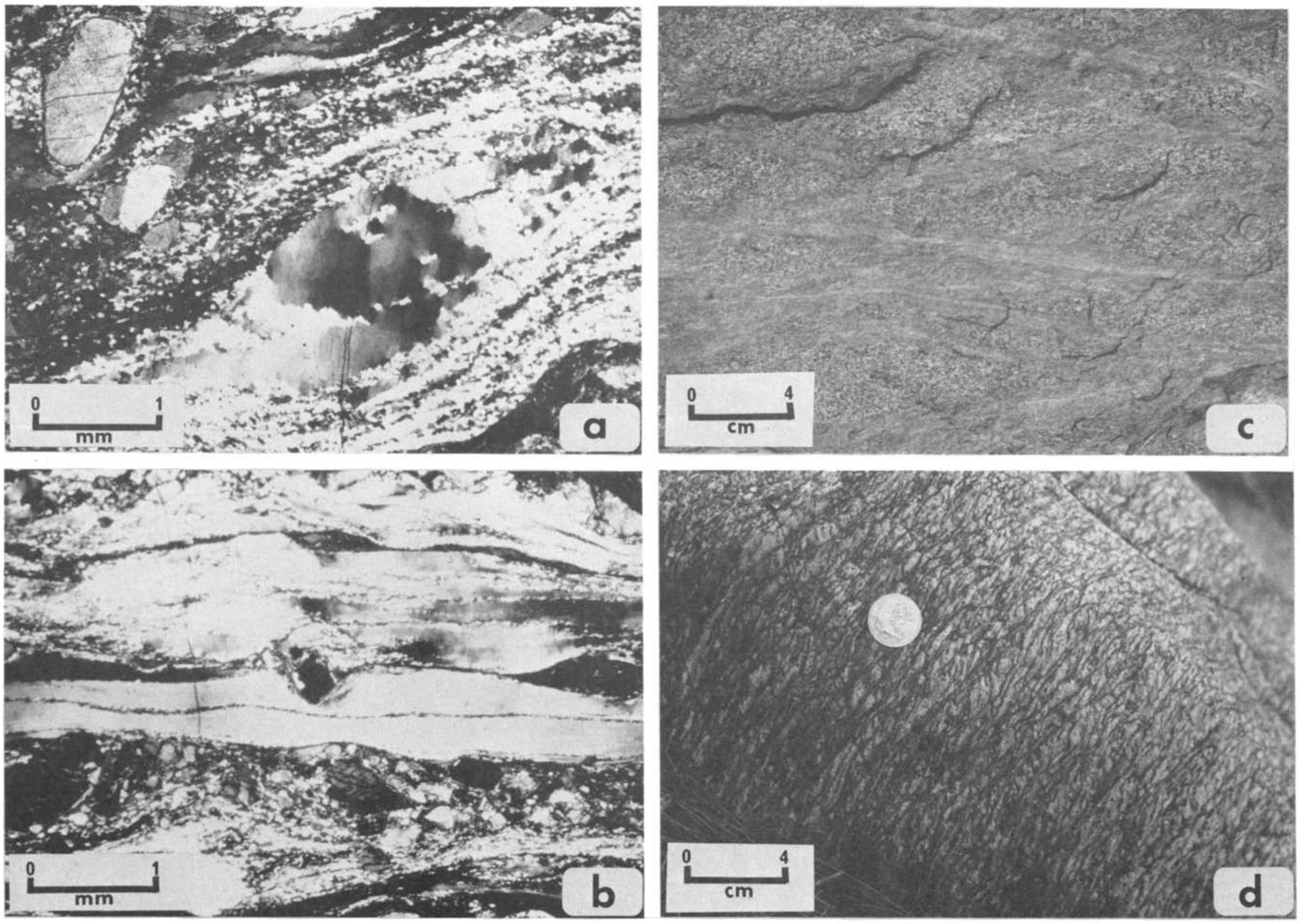


Fig. 2. Solid-state foliations defined by: (a) recrystallized aggregates of quartz and biotite surrounding deformed residual phenocrysts of quartz and plagioclase; (b) long aggregates of quartz in mylonite zones, Wyangala batholith, Australia; (c) mylonite zones anastomosing around foliated pods of less deformed tonalite in the Santa Cruz Mountain pluton, California (base of photo approximately 20 cm); (d) *S–C* surfaces, Wologorong batholith, Australia.

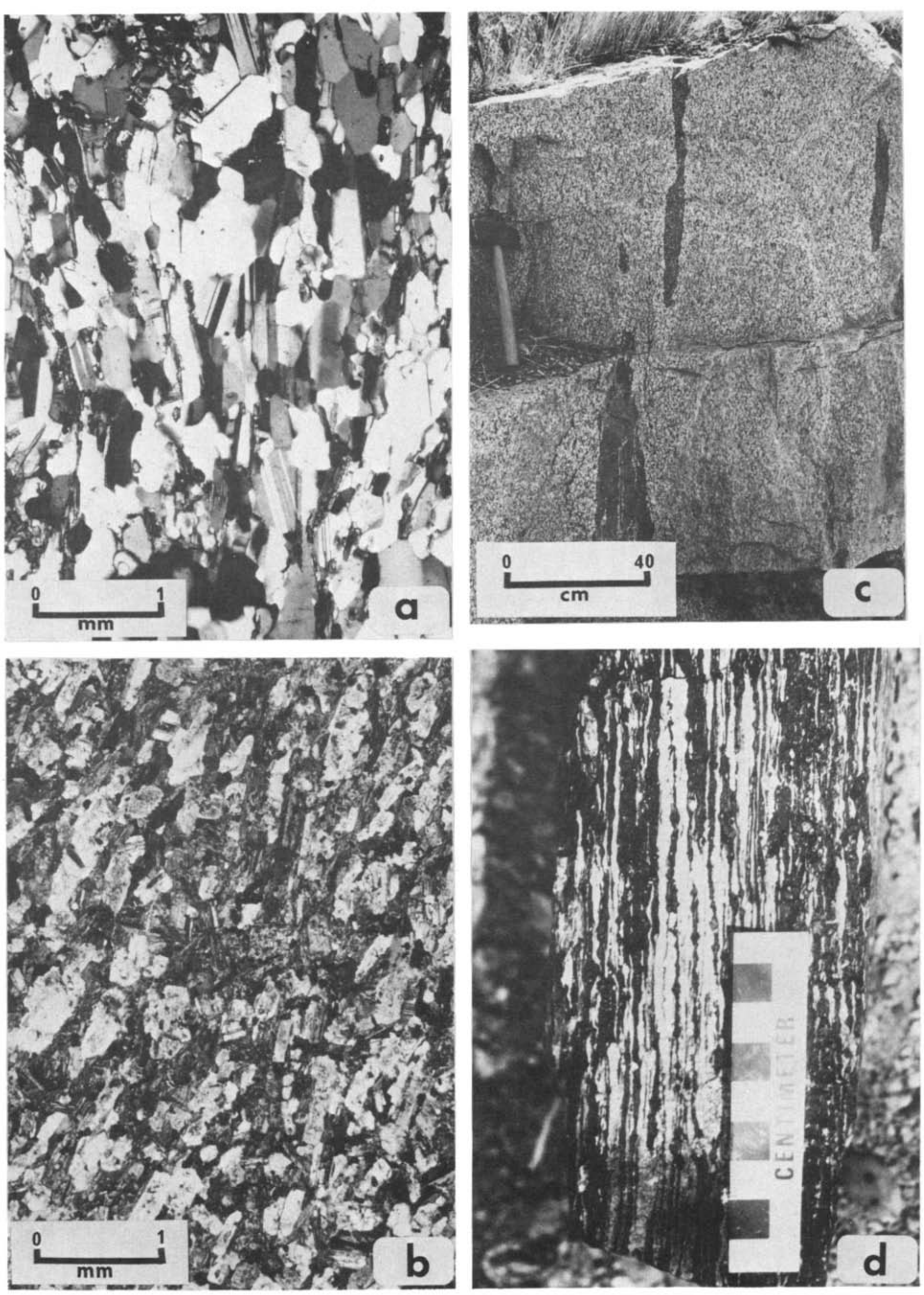
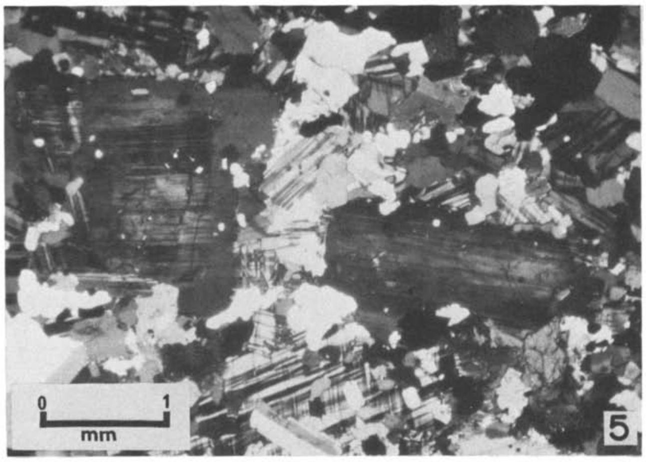
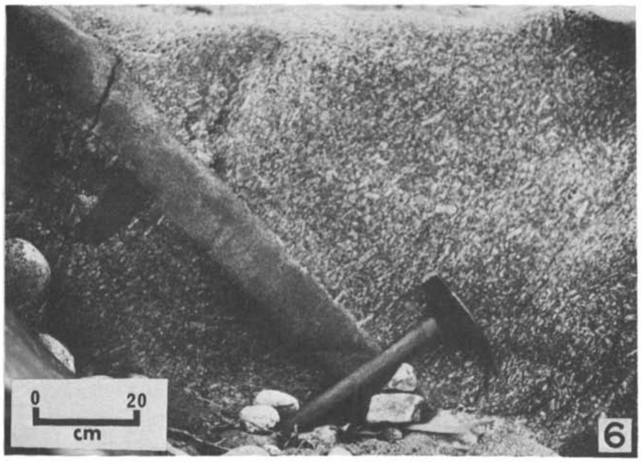
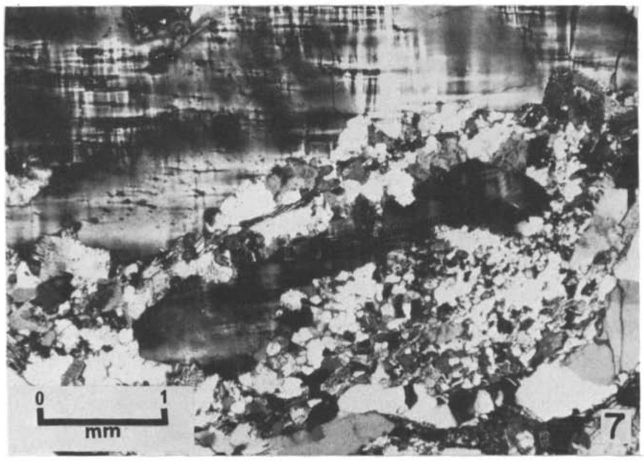


Fig. 3. Magmatic and/or superimposed solid-state foliations. (a) Foliation defined by aligned twins in anhedral plagioclase from the Hornitos pluton, Sierra Nevada, California (crossed nicols). We suggest that the aligned twins represent a magmatic alignment, whereas recrystallization of plagioclase margins and hornblende is associated with development of a high-temperature solid-state foliation. (b) Microstructure of elongate microgranitoid enclave (Fig. 3c), showing elongate laths of plagioclase, recrystallized hornblende aggregates and aligned flakes of recrystallized biotite (crossed nicols). (c) Elongate microgranitoid enclaves in foliated granitoid about 4 miles east of Three Rivers, Sierra Nevada, California. Although largely magmatically deformed, these enclaves show microscopic evidence of superimposed solid-state deformation, as shown in (b). (d) Ribbons of recrystallized plagioclase (white layers) and pyroxene–hornblende aggregates (dark layers) indicating a relatively high-temperature, solid-state deformation. Western margin Guadalupe igneous complex, Sierra Nevada, California.







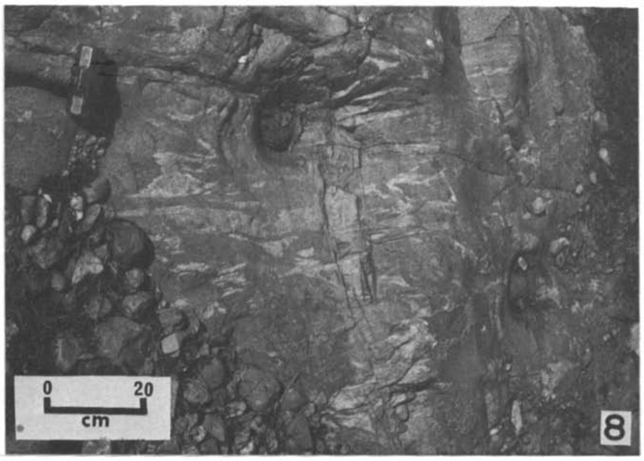


Fig. 5. Photomicrograph of weakly aligned feldspars in the Ardara granite, Ireland (crossed nicols). Note the recrystallization of quartz and biotite, but the lack of any strong preferred orientation of these recrystallized aggregates.

Fig. 6. Foliation in the margin of the Cannibal Creek granite defined by the alignment of euhedral feldspars and microgranitoid enclaves. Note how the enclave and feldspars are cut by a synplutonic dike. Although a small amount of recrystallization occurs in this pluton, we suggest that this foliation formed largely by magmatic flow with a small tectonic overprint (Paterson in press).

Fig. 7. Photomicrograph of microstructures in deformed granitoids from the western margin of the Papoose Flat pluton (crossed nicols). Note the deformed microcline surrounded by aggregates of recrystallized quartz, feldspar, biotite and muscovite, and local myrmekite.

Fig. 8. Compositional heterogeneity in the Hornitos pluton, Sierra Nevada, California. Several different magmatic phases occur in this pluton and form lensoid-shaped enclaves or sill-like sheets, both of which are parallel to magmatic and solid-state foliations.

in feldspar and mica), recovery such as subgrain structures in quartz and recrystallization to finer-grained aggregates (e.g. of quartz, feldspar, or mica), as shown in Figs 2(a) & (b). The new aggregates may be monomineralic in the case of recrystallization *sensu stricto*, or polymineralic if metamorphic reactions are involved (neocrystallization), as commonly happens (e.g. Vernon *et al.* 1983, Urai *et al.* 1986).

(2) The combination of grain size reduction and elongation of these finer-grained aggregates leads to the formation of folia, such as 'ribbons' of recrystallized quartz (Fig. 2b), lenticular aggregates of muscovite, aggregates of new biotite, muscovite and sphene which neocrystallized from deformed biotite, and lenses of recrystallized myrmekite (e.g. Vauchez 1980, Bateman *et al.* 1983, Vernon *et al.* 1983, Simpson 1985). The result is commonly a lenticular compositional layering controlled by the tendency of old grains to recrystallize or neocrystallize, rather than for new grains to develop randomly (e.g. Vernon 1974, Vernon *et al.* 1983), although random nucleation of new grains may occur in mylonites at high strain (e.g. Bell & Etheridge 1973). The lenticular layering may resemble layering produced by extreme magmatic elongation of microgranitoid enclaves (Vernon *et al.* 1988). However, the microstructural criteria already discussed should enable a distinction to be made.

(3) Strong minerals, such as feldspar and hornblende, fracture and undergo boudinage, typically with recrystallized quartz and mica filling fractures and boudin necks (Vernon *et al.* 1983, Simpson 1985).

(4) Orthoclase usually inverts to microcline during solid-state deformation (Eggleton & Buseck 1980).

(5) The foliation commonly passes through enclaves, whether xenoliths or microgranitoid enclaves, because both enclave and granitoid, being solid at the time of deformation, have similar viscosities. However, some refraction may occur if the enclaves and host have very different compositions and textures.

(6) Aplite veins may be folded, with the foliation parallel to the axial planes of the folds (e.g. Phillips 1956, Hobbs 1966). However, caution must be used because early aplitic veins may also be folded and foliated by magmatic flow of the host granitoid (Berger & Pitcher 1970).

(7) Strain is commonly very heterogeneous and mylonitic zones may develop (Choukroune & Gapais 1983, Vernon *et al.* 1983). Moreover, solid-state (gneissic) foliations generally anastomose (Fig. 2c) and are more lenticular and less continuous than most magmatic (schlieren) layering. At lower temperatures (e.g. greenschist-facies conditions) feldspars tend to fracture, whereas all minerals more readily recrystallize at higher metamorphic grades (Simpson 1985). Mylonite zones in deformed granitoids may or may not show evidence of cataclastic zones (e.g. Simpson 1985).

(8) In granitoids two foliations may occur, either as conjugate sets (Choukroune & Gapais 1983) or as '*S–C*' planes (Fig. 2d; see also Berthé *et al.* 1979, Choukroune & Gapais 1983, Vernon *et al.* 1983, Lister & Snoke 1984). In either situation, the two foliations subtend smaller angles with increasing strain.

(9) Evidence of solution of crystals may be associated with the development of solid-state foliations (Kerrich *et al.* 1980, Burg & Ponce de Leon 1985).

SUPERIMPOSITION OF SOLID-STATE FLOW ON MAGMATIC FLOW

Many plutonic rocks show evidence of the superimposition of solid-state deformation on a magmatic foliation (Fig. 3). Such rocks have aligned igneous minerals, especially euhedral feldspar, and yet show evidence of recrystallization, which involves the formation and/or movement of high-angle grain boundaries (Figs. 3a & b). If feldspar crystal faces are preserved, a magmatic component of flow may be inferred with some confidence, but where recrystallization has involved grain-boundary movement to the extent that igneous grain margins are largely obliterated, recognition of a magmatic component may be difficult or impossible. Where plagioclase grains retain a dimensional preferred elongation, a magmatic component of flow may be inferred, provided albite-law or carlsbad-law twin interfaces are parallel to the direction of elongation (Fig. 3a). This implies that the elongation is more likely to be due to original crystal shape (only the crystal margins and surrounding matrix have recrystallized), rather than to extension in response to plastic deformation which generally produces granoblastic aggregates. However, the possibility of elongation of metamorphic plagioclase due to growth along a previous foliation must be kept in mind.

Microstructural criteria for a transition from magmatic to solid-state flow

Many people have suggested that magmatic flow may pass continuously into solid-state flow, for example, as the crystallized margin of a diapiric pluton is deformed by ballooning of the still magmatic interior, in response to either buoyancy forces (e.g. Holder 1981, Ramsay 1981, Bateman 1985) or tectonic shortening (Castro 1987). Other examples are where granite veins or sheets are emplaced into a deforming metamorphic succession (Blumenfeld 1983, Blumenfeld & Bouchez 1988) and where granitoids are inferred to have intruded active shear zones (Hanmer & Vigneresse 1980, Anderson & Rowley 1981, Hutton 1982, Guineberteau *et al.* 1987). Microstructural criteria that conceivably could be used as evidence of deformation during the transition from magmatic to solid-state flow include the following, each of which we will evaluate:

(a) *c*-slip (i.e. slip parallel to quartz *c*-axes to create basal subgrains) in quartz, which occurs only at high temperatures, around 650–750°C in hydrous conditions, and so indicates plastic deformation at temperatures near the granite solidus (Blumenfeld *et al.* 1986, Gapais & Barbarin 1986, Mainprice *et al.* 1986);

(b) recrystallization of feldspars (Fig. 3d), which appears to require temperatures above 450°C at natural strain rates (Voll 1976, Tullis 1983);

(c) albite exsolution lamellae in recrystallized alkali feldspar, which indicate that recrystallization occurred at temperatures above the alkali feldspar solvus (Vernon *et al.* 1983);

(d) a change from relatively homogeneous deformation (Fig. 3) involving rapid movement of grain boundaries at high temperatures ('migration recrystallization') to heterogeneous deformation (Fig. 2c) involving *a*-slip in quartz and grain size reduction ('rotation crystallization'; i.e. dynamic recrystallization involving rotation of subgrains to produce new grains) at lower temperatures (Gapais & Barbarin 1986);

(e) '*S–C*' foliation relationships indicating the same sense of shear as the inferred magmatic imbrication of feldspar crystals in the same rock (Blumenfeld 1983, Blumenfeld & Bouchez 1988); and

(f) presence of late magmatic minerals in 'pressure-shadow' positions, implying transfer of small amounts of melt during the deformation of granite with less than the critical amount of melt for magmatic flow, as defined in this paper (Gapais & Barbarin 1986, Hibbard 1987).

Evaluation of criteria. Criteria (a) and (c) indicate that deformation took place at temperatures near the solidus, although O'Hara & Gromet (1985) suggest that *c*-slip in quartz may occur at somewhat lower temperatures. In any case, it needs to be determined whether the deformation and recrystallization occurred during cooling from magmatic temperatures or during later heating (Vernon *et al.* 1983). The observations of Gapais & Barbarin (1986) that in a weakly deformed granitoid, the larger the quartz grain the closer its *c*-axis is to the local extension direction, and that the angle between the *c*-axis and the local extension direction increases with decreasing size of recrystallized grains, strongly suggest a continuum between high-temperature *c*-slip, producing basal subgrains, and lower-temperature *a*-slip, producing prismatic subgrains, in quartz. Alternatively, the large grains could grow from a solution in an elongate direction parallel to their *c*-axis. Either case is consistent with continuous deformation from late- or sub-magmatic temperatures to temperatures well below the solidus.

Although feldspar recrystallization (criterion b) requires relatively high temperature, it can occur well below the granite solidus, and so is not a useful criterion on its own.

As noted by Gapais & Barbarin (1986), criteria (d) and (e) are also consistent with a gradation from late-magmatic to solid-state flow. Especially indicative is the evidence of continuous change from abundant grain-boundary migration (indicating high temperature) in relatively equant grains and aggregates of quartz in weakly deformed granitoids, compared with evidence of abundant nucleation of new grains in strongly deformed granitoids, coupled with the change in *c*-axis orientation discussed previously.

The suggestion of Hibbard (1987) that deformation of granitoids by 'submagmatic' flow (criterion f) may leave

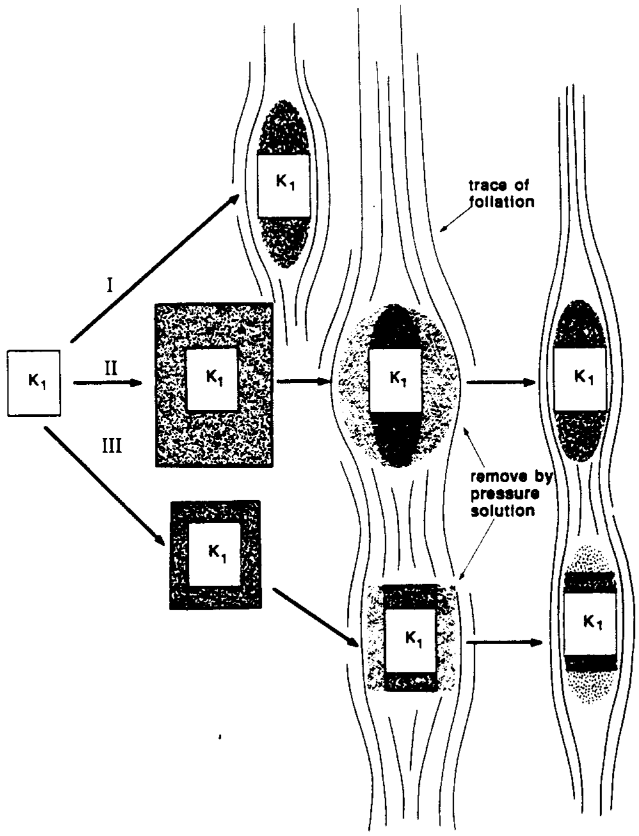


Fig. 4. Diagram of different means of developing Hibbard's (1987) 'strain shadows'. Option I shows K-feldspar overgrowths developed by movement of melt into pressure shadow regions (e.g. Hibbard 1987). Option II shows how a similar K-feldspar and overgrowth pattern can develop by removal of the K-feldspar rim by solution processes. Option III shows how smaller K-feldspar rims may be preserved in pressure shadows even after some solution transfer.

an imprint on the microstructure requires some detailed comment, as reliable criteria of this situation would be very valuable indicators of a possible continuum between magmatic and solid-state flow in plutons. One criterion suggested by Hibbard (1987) is the occurrence of late-magmatic overgrowths of plagioclase or K-feldspar in 'pressure-shadow' positions (Case I in Fig. 4). However, this also could be produced by truncation during removal of formerly complete overgrowths (Case II in Fig. 4). Therefore, it is necessary to examine relatively undeformed parts of the same granitoid to determine the thickness of magmatic overgrowths, if any, so that they can be compared with those in the deformed zones (Cases II and III in Fig. 4). It must be shown that a greater thickness of overgrowths developed in 'pressure-shadow' regions, and that the thickness of overgrowths is not a result of selective removal (Fig. 4). However, even then magmatic precipitation is not necessarily indicated, as Simpson & Wintsch (in press) have inferred that K-feldspar occurring in fractures in, and 'tails' against plagioclase porphyroclasts precipitated from aqueous solutions.

Criterion (f) also involves the common presence of myrmekite in deformed granitoids, which Hibbard (1987) has inferred to be due to crystallization of water-saturated magma in response to 'micro pressure-quenching' during deformation. This interpretation is based on the suggestion of Hibbard (1979) that all myrmekite in granitoids is due to crystallization from water-saturated melt in response to pressure-quenching, as opposed to more conventional hypotheses involving replacement of K-feldspar in the solid state. However, myrmekite has been produced in granitoids that were deformed well after solidification without developing a melt. Vernon *et al.* (1983), Simpson (1985) and Simpson & Wintsch (in press) suggested that the presence of myrmekite and recrystallized quartz–feldspar aggregates usually indicate solid-state deformation, rather than the presence of a melt.

Hibbard (1987) also stated that myrmekite occurs mainly in 'pressure-shadow' areas, rather than in zones normal to the local direction of maximum shortening, suggesting migration of magma to low-strain zones. Observations of Vernon *et al.* (1983), Simpson (1985) and La Tour (1987) do not support this contention. In many deformed granitoids, myrmekite lobes commonly pass continuously into polygonal areas of plagioclase and quartz, via intermediate stages, in which some of the quartz remains as blebs. Hibbard (1987) referred to these aggregates as 'microaplite', inferring that they crystallized from a melt. However, as noted by Hibbard (1987), they can also be interpreted as being due to progressive recrystallization of myrmekite (Vernon *et al.* 1983, Simpson 1985, Moore 1987), which is consistent with the common observation that these aggregates pass laterally into folia (e.g. Vernon *et al.* 1983).

Although some of the foregoing criteria probably indicate deformation at or close to granite-solidus temperatures, they do not necessarily indicate a transition from magmatic to solid-state deformation, unless transfer of a liquid can be shown unequivocally. This is because later metamorphism of granitoids under amphibolite facies conditions or higher can produce the same effect (Simpson & Wintsch in press). However, if the high-temperature deformation is confined to the granitoid and its environs, solid-state deformation during or immediately after emplacement would be favored.

CHARACTERISTICS OF FOLIATIONS FORMED DURING DIFFERENT STYLES OF EMPLACEMENT

Plutons emplaced by magmatic flow

Numerous plutons show magmatic foliations or appear isotropic, although we suspect that weak foliations commonly are present in isotropically-appearing granitoids, indicating that these plutons are emplaced entirely by magmatic flow. It is particularly important to examine the nature of such foliations before considering fabrics formed in other settings, so that we can recognize situations where foliations in granitoids were formed by the superimposition of magmatic and solid-state processes.

As noted above, magmatic foliations are most easily recognized where defined by the alignment of igneous crystals, microgranitoid enclaves, or xenoliths, particularly where these objects are surrounded by a groundmass of minerals with igneous microstructures. More subtle foliations have been defined in isotropic-appearing granitoids using the statistical alignment of feldspar (Balk 1937, Marre 1986, R. H. Flood & S. E. Shaw personal communication 1987), or magnetic anisotropy (Guillet *et al.* 1983, Rathore & Kafafy 1986).

Magmatic foliations are usually parallel to the margins of intrusions (Balk 1937, Reesor 1958, Bateman *et al.* 1963, Pitcher & Berger 1972, Raciot *et al.* 1984) and therefore are sometimes used to infer the three-dimensional shapes of such bodies. However, magmatic foliations also outline lobes within plutons (e.g. Balk 1937, Buddington 1959, Barriere 1981, Krouskopf 1985, Frost & Mahood 1987), and may form at angles to both internal and external pluton contacts (e.g. Balk 1937, Berger & Pitcher 1970, Pitcher & Berger 1972, Whitney & Wenner 1980, Krouskopf 1985, Courrioux 1987). The intensity of development of magmatic foliations (defined by the degree of preferred orientation of minerals or elongation of enclaves) commonly increases towards the external margin of the pluton (Pabst 1928, Bateman *et al.* 1963, Pitcher & Berger 1972, Raciot *et al.* 1984, Castro 1986, Marre 1986, Frost & Mahood 1987, Vernon *et al.* in press), but can show more complex variations (Buddington 1959, Pitcher & Berger 1972, Courrioux 1987).

Marre (1986) inferred that 60–70% shortening (assuming that the igneous minerals and enclaves were initially random) was involved with the production of magmatic foliations near the margin of the Querigut complex, France, and microgranitoid enclaves even more intensely flattened during magmatic flow have been described by Vernon *et al.* (1988) in the Moruya Batholith, Australia. The degree of elongation of microgranitoid enclaves correlates visually with the degree of preferred orientation of minerals defining the magmatic foliation in the host granitoid (Pabst 1928, Hutton 1982, Vernon 1983, Marre 1986, Vernon *et al.* 1988).

Patterns of foliations in adjacent wallrocks can also vary considerably. Where magmatic foliations increase in intensity near the margins of plutons, foliations in the country rock are commonly rotated into parallelism with the margin (Reesor 1958, Buddington 1959, Bateman *et al.* 1963, Raciot *et al.* 1984, Castro 1986). When magmatic foliations are weakly developed, foliations in the country rock may or may not be deflected near the plutons (Buddington 1959, Bateman *et al.* 1963, Pitcher & Berger 1972).

We emphasize that granitoids emplaced strictly by magmatic flow can rotate foliations in the wall rocks parallel to the pluton margin, produce folds in the wall rocks, develop *magmatic* foliations that increase in intensity towards external contacts, and have flattened enclaves indicative of greater than 60% shortening near these margins. These observations are important, because similar features have been used to infer development of a foliation during *solid-state* deformation accompanying ballooning.

Plutons emplaced as expanding or 'ballooning' diapirs

Many authors have suggested that during final emplacement, diapirs can expand or 'balloon' and that during this expansion, a foliation is developed in the already solidified outer portion of the pluton (Ramsay 1975, Sylvester *et al.* 1978, Holder 1981, Bateman 1985, Mahood 1985, Courrioux 1987). If so, foliations in the outer, solidified granitoid should form by solid-state processes near emplacement temperatures, and overprint older magmatic foliations where present, whereas largely magmatic foliations would be expected in the inner portion of the body.

Evaluation of criteria. Criteria used by previous authors in support of ballooning during emplacement of diapirs include the following: (a) concentric zoning of the pluton, (b) development of foliations in the aureole parallel to the pluton margin, (c) synkinematic growth of porphyroblasts in the aureole, (d) foliations in the pluton that are parallel to foliations in the aureole, and that increase in intensity towards the pluton margin, (e) evidence that final emplacement took place by bulk heterogeneous flattening (e.g. lack of stretching lineations or presence of 'millipede' structures, as described by Bell & Rubenach 1980), (f) folding of aplitic dikes originating from the core of the pluton with foliations in external portions of the pluton parallel to the axial planes, and (g) solid-state deformation associated with the foliations in the outer portions of the granitoid (Ramsay 1975, Sylvester *et al.* 1978, Holder 1981, Bateman 1985, Courrioux 1987).

Criteria (a) – (e) are compatible with diapiric emplacement, but cannot be used in support of solid-state ballooning; identical features also develop around plutons emplaced by magmatic flow (see foregoing section), or during later deformation (van den Eeckhout *et al.* 1986, Paterson & Tobisch in press). Criterion (f) is useful if the veins or dikes are clearly related to inner, younger portions of the pluton, and if it can be shown that the dikes intruded an already solidified margin. The use of criterion (g) is controversial; in our opinion, there is some question about how much, if any, solid-state deformation takes place during the emplacement of 'ballooning' plutons.

One possible alternative to the model of solid-state ballooning, is that expansion of plutons does occur during final emplacement, but by magmatic flow (e.g. Paterson in press). After emplacement, regional deformation, possibly intensified near the intrusion because of the increase in heat and fluids (e.g. Berger & Pitcher 1970, Rubenach & Bell in press), caused solid-state deformation in the pluton. Because of the coarse-grained nature of plutonic rocks and the common presence of pre-existing magmatic foliation, metamorphic minerals will tend to grow parallel to this foliation at low strains.

If the application of criteria for recognizing magmatic foliations indicates that a magmatic foliation existed in the outer portions of a granitoid prior to solid-state deformation, further doubt is cast on ballooning as the cause of the solid-state deformation. One means of evaluating the significance of the solid-state deformation is to examine the relationship between the intensity of foliation development and the accompanying solid-state microstructures. Specifically, if the shapes of microgranitoid enclaves in such bodies indicate values of *solid-state* shortening varying from 0% near the pluton center to 60% or greater (e.g. Holder 1981, Bateman 1985), we presume that solid-state microstructures would be widespread and gneissic to mylonitic foliations common throughout the outer portions of these granitoids. We would also expect to see discontinuities in the intensity of the development of foliations and solid-state microstructures across any internal contacts marking the border of 'younger magmatic pulses' (e.g. Courrioux 1987).

Solid-state foliations in ballooning plutons. The Ardara granodiorite, Ireland (Akaad 1956, Holder 1979), and Cannibal Creek granite, Australia (Bateman 1985), two granitoids commonly noted as examples of ballooning plutons, exemplify the problems noted above. These plutons are compositionally zoned, have foliations that increase in intensity and microgranitoid enclaves that are increasingly flattened towards the pluton margin, and have microstructures indicative of solid-state deformation. However, both plutons were emplaced prior to significant deformation of the wall rocks (Holder 1979, Bateman 1985). Could the later deformation be the cause of the solid-state textures in these plutons?

In thin sections examined from the Ardara and Cannibal Creek granitoids, the amount of solid-state deformation is not intense (e.g. Fig. 5). In the margins of both plutons, euhedral feldspar crystals (along with large, isolated biotite crystals in the Cannibal Creek granite) are aligned parallel to the foliation, indicating a magmatic origin (Fig. 6). Some recrystallization of mica and quartz has occurred, but penetrative gneissic foliations are not common, and mylonites are rare. Widespread development of microstructures in the margins of these plutons that would be compatible with greater than 60% solid-state shortening (as suggested by Holder 1979 and Bateman 1985) have not been described by these authors or others, nor observed by the present authors during a brief examination of these granitoids. Therefore, we suggest that the foliations in these two plutons largely formed in the magmatic state and were overprinted by mildly to moderately intense regional deformation. If true, this would imply that little or no solid-state deformation took place during emplacement and change interpretations about the relative timing of pluton emplacement and regional deformation in the wallrocks.

The nature of the solid-state deformation in other granitoids such as the Papoose Flat quartz monzonite, California (Sylvester *et al.* 1978), and Ward Mountain tonalite, California (Bateman *et al.* 1983), is more difficult to explain by deformation after emplacement. Sylvester *et al.* (1978) suggested that intense foliations formed in one margin of the Papoose Flat quartz monzonite during sideways expansion of the pluton and thinning of the country rock by up to 90%. No magmatic foliations were noted in the pluton and no regional post-emplacement deformation was recognized in the country rock. The foliation in the deformed margin of this granitoid is defined by a matrix of aligned recrystallized quartz and biotite anastomosing around microcline megacrysts (Fig. 7).

Bateman *et al.* (1983) reported extensive development of a solid-state foliation in the Bass Lake (formerly Blue Canyon) tonalite, western Sierra Nevada, California, that was inferred to have been caused by the emplacement of the Ward Mountain leucotonalite. The foliation in the Bass Lake tonalite varies from a magmatic foliation defined by aligned, euhedral plagioclase, hornblende, and biotite (Figs. 1a & c), to a gneissic layering near the Ward Mountain granitoid defined by discontinuous bands of light- and dark-colored finer-grained minerals (Bateman *et al.* 1983). A solid-state foliation is present everywhere in the Ward Mountain leucotonalite, but increases in intensity near the margins. The close spatial association of the domain in which the solid-state foliation is developed and the eastern contact of the Ward Mountain pluton led Bateman *et al.* (1983) to suggest that this foliation was formed by the uplift and stretching of the Bass Lake tonalite during emplacement of the Ward Mountain leucotonalite.

In summary, we suggest that foliations in some plutons inferred to be emplaced by 'ballooning' form by the alignment of crystals during magmatic flow and are subsequently overprinted by post-emplacement regional deformation. However, the observations of Sylvester *et al.* (1978) and Bateman *et al.* (1983) are consistent with the suggestion that foliations form during emplacement by solid-state deformation. If so, evidence of high-temperature subsolidus deformation, or deformation of magmas by 'submagmatic flow' should occur in these bodies.

Plutons emplaced during regional deformation

Plutons inferred to have been emplaced during regional deformation presumably should have foliations formed by processes ranging from magmatic flow to solid-state deformation. By definition, these granitoids are overprinted by tectonic foliations, making it difficult to always ascertain the nature of earlier foliations and the exact timing of emplacement. Criteria put forth by previous authors in support of syntectonic emplacement include the following: (a) continuity of foliations and lineations developed within wallrocks and granitoids; (b) presence of cleavage triple points (CTPs) near the two 'ends' of forcefully emplaced syntectonic plutons; (c) a continuum between magmatic and high-temperature solid-state processes during the development of foliations in granitoids; (d) synkinematic growth of porphyroblasts and a gradation between metamorphic assemblages occurring near granitoids and regionally developed assemblages; (e) elongate pluton shapes and geometries of structures that indicate emplacement in active fault zones; and (f) mutual cross-cutting relationships between granitic apophyses and folds with the development of axial planar foliations in both the plutons and country rock (Milnes *et al.* 1977, Anderson & Rowley 1981, Brun & Pons 1981, Hutton 1982, Soula 1982, Cooper & Bruck 1983, Dimroth *et al.* 1986, Hollister & Crawford 1986, Guineberteau *et al.* 1987).

All these features can be associated with granitoids emplaced by other methods, and thus should not be used individually. For example, synkinematic porphyroblasts can occur around post-tectonic intrusions that deform their country rock (Vernon 1988), cleavage patterns and CTPs can be remarkably similar around pre-, syn- and post-tectonic granitoids (Paterson & Tobisch in press), and solid-state foliations might form during emplacement of post-tectonic plutons (Sylvester *et al.* 1978, Courrioux 1987).

We suggest that the strongest evidence for syntectonic emplacement is where (1) a pluton shows parallel or subparallel magmatic and high-temperature solid-state foliations, (2) the solid-state foliation is continuous with a regionally developed foliation in the wallrocks, and (3) porphyroblasts in the contact aureole are synkinematic with respect to this foliation. We believe it is particularly important to show that the solid-state foliation in the pluton developed during and not after emplacement by obtaining evidence for high-temperature solid-state deformation or of deformation of granitoids by 'submagmatic flow'.

A close correlation apparently exists between the occurrence and geometry of some syntectonic intrusions and ductile shear zones (e.g. Anderson & Rowley 1981, Brun & Pons 1981, Hutton 1982, Soula 1982, Dimroth *et al.* 1986, Hollister & Crawford 1986, Le Fort *et al.* 1986, Guineberteau *et al.* 1987 and others). Plutons in this setting tend to be tabular or elliptical, with the long axis of the intrusion parallel to the fault zone. In the most convincing examples of intrusion emplaced in active shear zones, both magmatic and high-temperature solid-state foliations are present in the intrusion and are roughly parallel to one another (e.g. Guineberteau *et al.* 1986, Marre 1986, Blumenfeld & Bouchez 1988). Rather than being concentrically zoned, these plutons are commonly compositionally heterogeneous over short distances (Strong & Hanmer 1981, Hutton 1982, Raciot *et al.* 1984, Guineberteau *et al.* 1986, Marre 1986).

An excellent example of such a granitoid examined by the authors occurs in the Bear Mountains fault zone in the Foothills Terrane, central Sierra Nevada, California (Vernon *et al.* 1988), and is inferred by us to have been emplaced during active motion of this fault zone. The pluton is compositionally heterogeneous over distances of less than 1 m with rock types ranging from gabbro to granite (Fig. 8). The different rock types form lenticular zones or sill-like sheets that are parallel to a well-developed magmatic foliation defined by aligned plagioclase and hornblende (Fig. 3a). The magmatic foliation is parallel to a tectonic foliation present in both the country rock and pluton, and both foliations are deformed by large and small folds. U/Pb zircon ages (Paterson *et al.* 1987) and $^{40}Ar/^{39}Ar$ ages of hornblende and biotite (E. Geary personal communication 1988), indicate that deformation and metamorphism along the fault were synchronous with pluton emplacement.

CHARACTERISTICS OF TECTONIC FOLIATIONS IN PLUTONS

In an earlier section, we suggested microstructural criteria for discrimination between magmatic and solid-state foliations. We now consider the field characteristics indicative of the development of solid-state foliations in granitoids resulting from regional tectonic processes, that is, excluding solid-state deformation due to emplacement. The most unambiguous field criterion is where the orientation of the foliation in the granitoid behaves independently of pluton boundaries and maintains a strike parallel to the strike of the regional foliation in the wall rock. Patterns of tectonic foliation within plutons can vary considerably. The simplest example is one in which the foliation orientation in the granitoid is constant and shows little or no deflection at the wallrock–pluton interface (e.g. Pitcher & Berger 1972, Castro 1986, Tobisch *et al.* in press). More complex patterns characterized by folding or overprinting of foliations are especially pronounced in plutons affected by repeated regional deformation (e.g. Page & Bell 1986), or those affected by domains of ductile shear (e.g. Berthé *et al.* 1979, Choukroune & Gapais 1983, Vernon *et al.* 1983, Guineberteau *et al.* 1987).

Two factors important in controlling the development and distribution of tectonic foliations in plutons are mineral proportions and the existence of early-formed foliations. The presence or absence of quartz and mica and their distribution appears to strongly influence how easily tectonic foliations form in granitoid rocks. Vernon and Flood (1988) have shown that quartz/mica-rich granitoids in the Lachlan fold belt, Australia (usually S-type), have undergone ductile deformation and foliation development to a greater degree than quartz/mica-poor granitoids (usually I-types) of similar age in that belt. The latter granitoids tend to be non-foliated.

This compositional control of deformation is also seen in the Foothills Terrane, west-central Sierra Nevada, California, where tonalitic plutons intruded a volcano–sedimentary sequence prior to regional deformation (Tobisch *et al.* in press). Of this suite of granitoids, an older (146 Ma) hornblende diorite body with essentially no quartz or mica is in contact with a younger (137 Ma) pluton with abundant quartz, two micas and garnet. A well-developed solid-state foliation passes through the *younger* pluton and is undeflected, whereas the older hornblende diorite is non-foliated and only weakly recrystallized. Such examples underline the dangers of using the presence or absence of tectonic foliation in granitoids to judge their time of emplacement relative to cleavage generation.

Early-formed tectonic surfaces also influence whether or not the entire pluton develops a tectonic foliation. For example, the Santa Cruz Mountain pluton in the Foothills terrane, Sierra Nevada (Tobisch *et al.* in press), shows widespread development of a gneissic foliation and zones of mylonite. However, discrete areas of granitoid have remained weakly- or non-foliated, despite the common occurrence of quartz and biotite. A very similar case has been reported by Choukroune & Gapais (1983). Once ductile strain increases in discrete zones, fluid activity and associated strain-softening mechanisms in these zones will promote continued deformation there, rather than initiate deformation in non-foliated domains (White *et al.* 1980, Passchier 1982, Vernon *et al.* 1983). Tectonic foliations in granitoids, therefore, are likely to be heterogeneous in intensity of development (Choukroune & Gapais 1983, Castro 1986).

The use of strain measurements to distinguish foliations of regional tectonic origin from those of magmatic flow or emplacement is of dubious value. As mentioned earlier, strong foliations and lineations may form from magmatic flow (Bateman *et al.* 1963, Pitcher & Berger 1972, Marre 1986, Vernon *et al.* 1988). Both the shapes of enclaves (Vernon *et al.* 1988) and the distribution of magmatic minerals, such as K-feldspar or quartz, from which strains have been determined in granitoids, are affected by magmatic flow. In granitoids that have undergone strong solid-state deformation, the magmatic component of the strain may go undetected, introducing considerable error in the interpretation of the strain measurements.

Regional deformation in many orogenic belts occurs at temperatures well below that of emplacement temperatures of plutons. If the mineral assemblages defining a foliation in the granitoid indicate low- to moderate-temperatures, a tectonic origin is supported.

SUMMARY AND CONCLUSIONS

We believe that the distinction between foliations formed by magmatic and solid-state processes, as well as the distinction between foliations formed during different mechanisms of granitoid emplacement, are vital to an understanding of both timing relationships and behavior of plutons during and after emplacement. Ideally, studies aimed at understanding the nature and timing of foliations in plutons should incorporate the following: (a) an examination of microstructures in the pluton; (b) an examination of patterns of foliations in the pluton and surrounding wallrocks; (c) studies of cleavage–porphyroblast relationships in the wallrocks; and (d) determination of radiometric ages of both magmatic and metamorphic minerals.

No single criterion can consistently distinguish different types of foliations in granitoids, and even the application of multiple criteria is sometimes inconclusive. However, a magmatic origin is favored for foliations defined by the alignment of igneous, commonly euhedral minerals, particularly where the foliation is parallel to internal or external pluton contacts.

Foliations formed during expansion or 'ballooning' of diapirs may be strictly magmatic in origin, although some studies suggest that solid-state deformation also occurs. If so, we would hope to find evidence of deformation of crystal–melt systems with less than 30% melt, and/or that the solid-state deformation occurred at high temperatures and not during later metamorphic events. Foliations formed during syntectonic emplacement of plutons are difficult to recognize, because similar features can form by a combination of emplacement and post-emplacement processes. However, the inference of syntectonic foliations is most convincing where magmatic and high-temperature solid-state foliations are subparallel, these foliations are continuous with regionally developed foliations in the wall rocks, synkinematic porphyroblasts are present in the wallrocks, and igneous minerals in the pluton have the same age as metamorphic minerals associated with the regional cleavage. A strictly tectonic origin for foliations is particularly favored when the foliation is defined by metamorphic minerals, no alignment of igneous minerals occurs, the foliation is locally at high angles to pluton–wallrock contacts, and the foliation is continuous with a regional cleavage.

These criteria represent 'end-member' cases, and some plutons will have foliations formed by a combination of processes under changing conditions. However, it is equally important to attempt to establish the relative importance and timing of each of these processes, in order to interpret timing relations correctly and emplacement mechanisms. For example, we have suggested that the solid-state deformation in some 'ballooning' plutons may be associated with post-emplacement deformation. If correct, this interpretation implies that the plutons were emplaced by magmatic flow, and that significant regional(?) deformation took place after emplacement. Another example concerns the recognition of magmatic foliations in plutons unequivocally overprinted by solid-state deformation. We believe that magmatic foliations are more common than presently assumed, and that after small to moderate amounts of solid-state deformation, these foliations may superficially resemble tectonic foliations. However, interpreting such foliations as entirely tectonic in origin would imply an incorrect intensity of solid-state deformation in the pluton, imply that magmatic foliations did not form during emplacement, and, therefore, be misleading in regards to the timing and means of granitoid emplacement.

The range of possible behavior of pretectonic intrusions also needs further consideration. These plutons may or may not develop foliations during subsequent deformation, and may have cleavage patterns superficially similar to syn- or post-tectonic granitoids (e.g. Oliver & Wall 1987, Paterson *et al.* 1987, Vernon & Flood 1988, Paterson & Tobisch in press). A better understanding is needed of the factors that control the development of foliations in such bodies, as well as criteria for recognizing these granitoids, since pluton ages are increasingly used to date regional deformation and metamorphism.

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