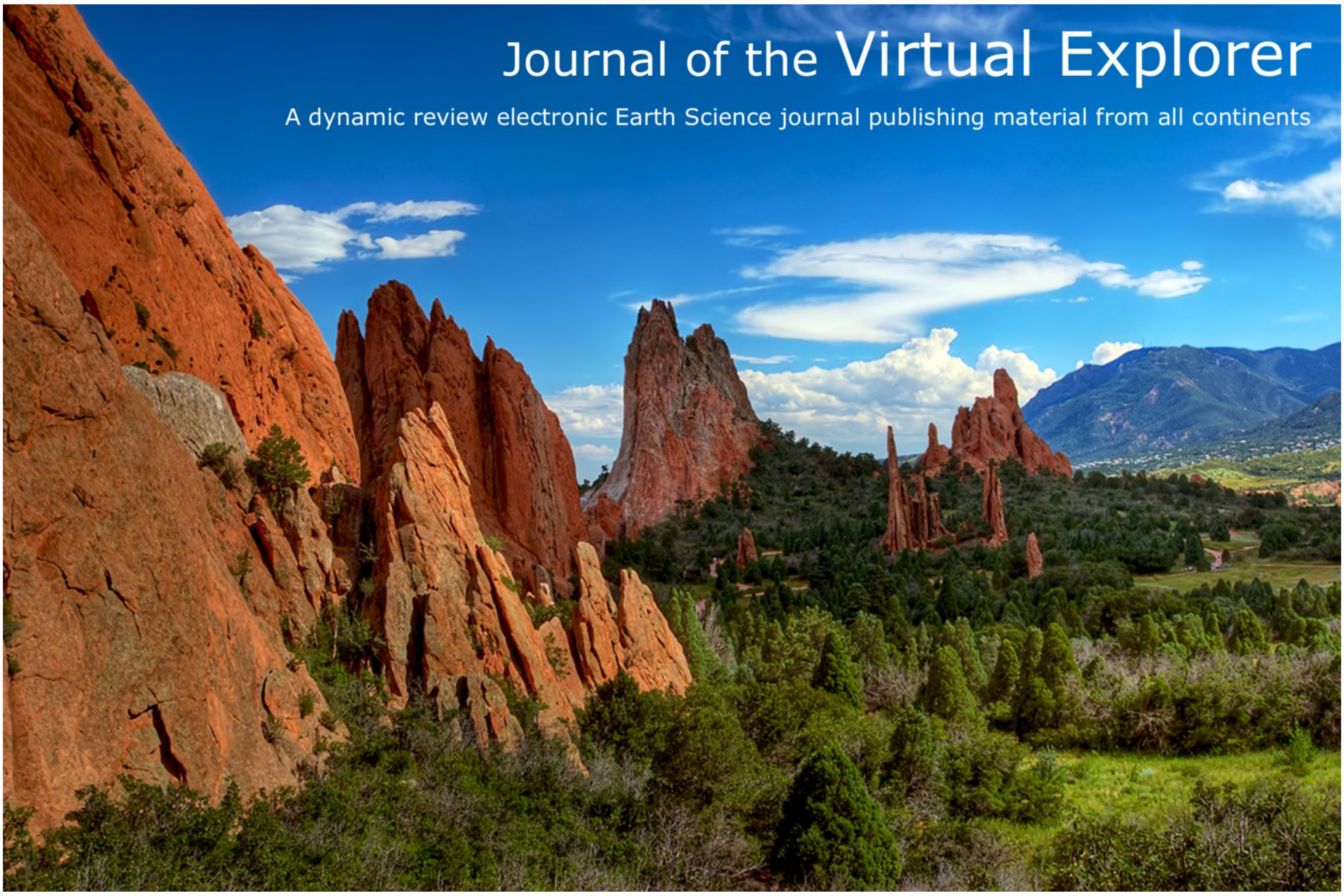

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Granites Really Are Magmatic: Using Microstructural Evidence to Refute Some Obstinate Hypotheses

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Abstract: Microstructural evidence can be used to distinguish between magmatic and solid-state features in granitoids, as well as to interpret most of the crystallization and post-crystallization history, though generally it can give little or no information about the earliest stages of crystallization or the order of nucleation of minerals. Structural evidence is critical for the evaluation of the following three, persistently promoted hypotheses, namely: (1) granitoids typically contain solid restite, (2) K-feldspar megacrysts form after most or all crystallization of granitic magma, and (3) granitoids change their grain shapes appreciably during slow cooling and so are effectively metamorphic rocks. Microstructural evidence questioning hypothesis (1) includes: a lack of convincing evidence for a restitic origin of xenocrysts and xenoliths; the igneous nature of microgranitoid enclaves; restite-poor feeder dykes; the tendency for solids to separate from liquid during flow; the tendency of restite to melt during ascent; and evidence for magmatic crystallization in many minerals in granitoids, especially oscillatory zoning, which reflects growth in liquid from the earliest stages. Microstructural evidence refuting hypothesis (2) includes: quenched felsic rocks with euhedral K-feldspar megacrysts surrounded by an abundant fine-grained groundmass; widespread structural evidence of crystal movement, flow alignment and physical accumulation in granitic magmas; and evidence of mixing of megacrysts in hybrid mafic magma, implying the presence of megacrysts in liquid. Microstructural evidence refuting hypothesis (3) includes: preservation of euhedral crystal shapes, especially for quartz and feldspar; common preservation of oscillatory zoning without major truncations by grain boundaries; preservation of graphic intergrowths; euhedral, rather than rounded inclusion shapes; and arrangement of inclusions in crystallographic zones in the host crystals, rather than at random or in inclusion trails. Thus, microstructural evidence confirms that most granitoid minerals crystallize in liquid, even crystals (‘antecrysts’) that grow elsewhere and become entrained in the host granitoid, and that: (1) solid restite is generally absent or difficult to recognize, (2) K-feldspar megacrysts crystallize as normal phenocrysts, and (3) granitoids generally do not undergo major changes in grain shapes during slow cooling.

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Introduction

This paper is concerned with the interpretation of granitoid microstructures, especially microstructural evidence that granitoids crystallize from liquids, and that their grain shapes do not change appreciably during cooling, in the absence of deformation and metamorphism. The paper is prompted by persistent assertions that (1) granitoids contain abundant solid material (restite) from the source, (2) K-feldspar megacrysts grow very late, in largely or completely crystallized rock, and (3) granitoids undergo essentially metamorphic changes as they cool. I present microstructural evidence to argue against these three hypotheses. For an explanation of my use of the term 'microstructure' (= 'texture' for many petrologists), see Vernon [2004, p. 7].

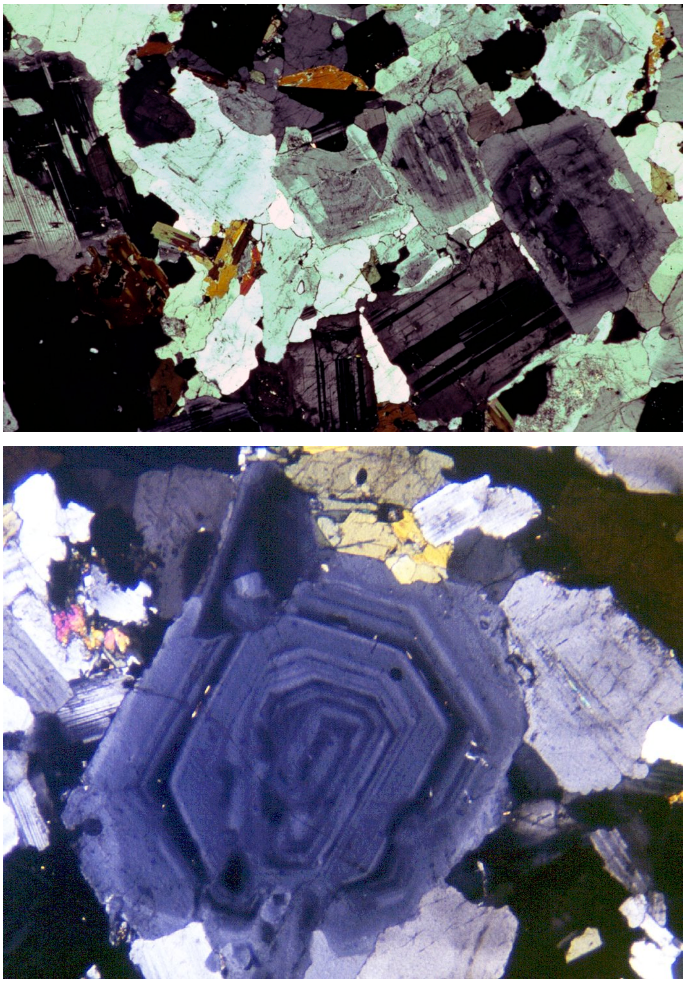
Though some geochemists appear to regard chemical data as being more reliable than structural evidence, considerations of both fundamental properties of solids, structure and chemical composition, are important for making genetic interpretations. A problem with a whole-rock chemical analysis, used alone, is that it averages grain-scale chemical variations, just as a whole-rock isotopic composition averages the isotopic compositions of all the minerals in a rock, which can have very different magmatic histories [e.g., Davidson *et al.*, 2007]. For example, crystals can grow in other parts of a magma chamber or another magma body, after which they can be mixed with crystals formed in situ, thereby becoming ‘antecrysts’. Fortunately, accurate in situ chemical and isotopic analyses of parts of single mineral grains are now possible, so that chemical evidence can be directly linked to individual mineral grains and their microstructural relationships. This combination of chemical and microstructural approaches is proving to be very powerful in the inference of rock-forming processes [e.g., Davidson *et al.*, 1988, 2007; Charlier *et al.*, 2005; Jerram and Davidson, 2007]. Just as limitations of whole-rock chemical analysis need to be acknowledged, so do limitations of structural interpretation, before applying it to specific problems.

Limitations of microstructural interpretation

Some petrologists have suggested that granitoid microstructures should not be used for petrogenetic interpretations because they are unreliable. This reservation has been clearly expressed by Means and Park [1994, p. 323], who wrote: “in plutonic igneous rocks …, it is not even entirely clear which textural features are produced during magmatic crystallization and which represent later, solid-state adjustments. On the contrary, I contend that it is generally possible to make such a distinction, except for minor irregularities at the margins of some grains (Figure 1), which could be due either to impingement of two minerals with weakly anisotropic crystal structures or to minor grain-boundary adjustment after impingement. Detailed evidence for distinguishing between magmatic and solid-state microstructures has been presented by Vernon (1999, 2000, 2004) and Vernon and Paterson (2008c), and will be further discussed in the evaluation of hypothesis 3.

Early stages of crystallization: A limitation of microstructural interpretation is that a rock’s structure is the end-product of a possibly complex history (as is a rock’s chemical analysis), the early stages of which may not be well preserved [e.g., Means and Park, 1994; Johnson and Glazner, 2010]. Inferences about early crystallization processes in magmas have been made from observations of (a) synkinematic crystallization experiments using analogue compounds and (b) glassy volcanic rocks. However, such observations can be misleading for the interpretation of granitoid microstructures. For example, low-temperature, synkinematic, analogue experiments by Means and Park [1994] revealed several processes that could conceivably occur in magmas, such as coarsening of graphic intergrowths to form independent crystals. Graphic intergrowths occur in some high-level granitoids, but evidence of coarsening to form independent grains is not observed. Solid-state adjustment of symplectites, forming globular to polygonal grains, occurs in some metamorphic rocks [e.g., Vernon, 2004, pp. 256-261; figure 4.65]; however, this situation is rarely, if ever, duplicated in granitoid plutons, because it would have to involve early undercooling to form the intergrowth, followed by prolonged heating to coarsen the aggregate. In contrast, the entire crystallization history of most granitic magma in plutons is likely occur at relatively small degrees of undercooling, owing to slow cooling rates, leading to relatively high proportions of crystal faces and euhedral zoning patterns in the resulting granitoids (Figure 1). The contrasting effects of strong undercooling are well shown by rapidly cooled pegmatites and granophyres, which are characterized by graphic intergrowths [London, 1996, 2005, 2008; Vernon, 2004, figure 3.55; pp. 115-119]. Some high-level granites show normal quartz and feldspar phenocrysts merging into graphic intergrowths, owing to a change in conditions from slow to rapid cooling, with a consequent increase in the degree of undercooling.

Figure 1. Grain shapes and oscillatory zoning in granodiorite



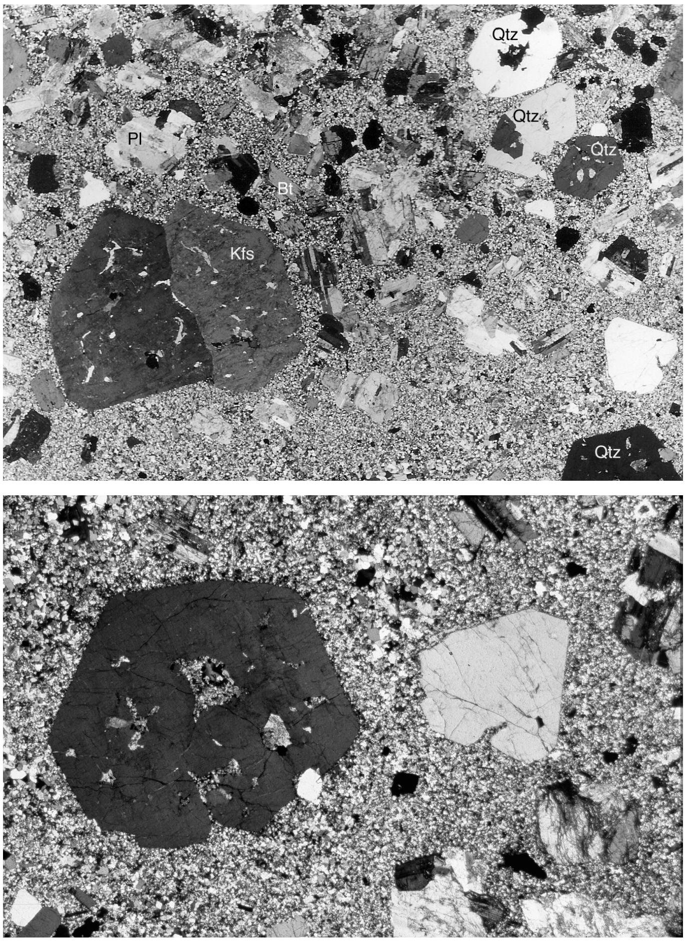
(A) Granodiorite, Tenaya Lake, Sierra Nevada Batholith, California, USA, showing plagioclase with complete oscillatory zoning patterns, indicating that solid-state grain-shape changes during cooling were negligible. Some plagioclase boundaries against quartz and other plagioclase grains (for example, at the right of the image) are planar and appear to be crystal faces, reflecting unimpeded growth in liquid. In contrast, other plagioclase/plagioclase and plagioclase/quartz boundaries are irregular, reflecting mutual interference during simultaneous growth, minor subsolidus grain-boundary adjustment, or both. The hornblende crystal at the top of the image has crystal faces against quartz, reflecting unimpeded growth in a liquid, and also shows a simple twin, which probably indicates growth from a twinned nucleus. Crossed polars; base of photo 4.5 mm.

(B) Oscillatory growth zoning in plagioclase in tonalite, San José pluton, Baja California, México. The zoning developed through the whole growing history of the crystal, and the pattern reveals successive stages in the crystal's shape. The crystal boundaries are partly euhedral and partly indented, owing to impingement with adjacent grains during growth or minor deformation. Crossed polars; base of photo 2 mm. From Vernon (2004, fig. 3.45).

Similarly, inferences made from observations of phenocryst-free glassy volcanic rocks need not be relevant for coarse-grained compositional equivalents, because the volcanic rocks represent very rapid crystallization at conditions of strong undercooling that are unrealistic for magmas at depth. On the other hand, rapidly cooled rocks that previously had undergone some crystallization at low degrees of undercooling do preserve a 'snapshot' of the mineral assemblage and microstructure at the instant of chilling (Figures 2, 3), and so are relevant to the interpretation of granitoid early crystallization history (see evaluation of hypothesis 2).

Johnson and Glazner [2010] wrote: "only by textural coarsening can coarse-grained plutonic textures form from finer-grained equivalents." This statement appears to assume that coarse-grained plutonic rocks initially consist of fine-grained crystal aggregates that coarsen by solid-state grain growth. On the contrary, crystallization in most granitic magmas probably initiates as scattered independent crystals, owing to low nucleation rates at small degrees of undercooling [e.g., Vernon, 2004, pp. 46-54; figures 3.2, 3.6], after which the small crystals could simply grow larger while new ones nucleate. This situation is illustrated by Figures 2 and 3, which show many separate crystals, with or without some glomeroporphyritic aggregates, at a relatively early stages of crystallization. As part of this process, a crystal dissolution/coarsening process ('Ostwald ripening') could apply to the very early stages of crystallization, when interfacial free energy differences between minute particles can drive diffusion and so contribute to the formation of viable nuclei by eliminating smaller particles that are close enough for diffusion to be effective [e.g., Vernon, 2004, pp. 51-52].

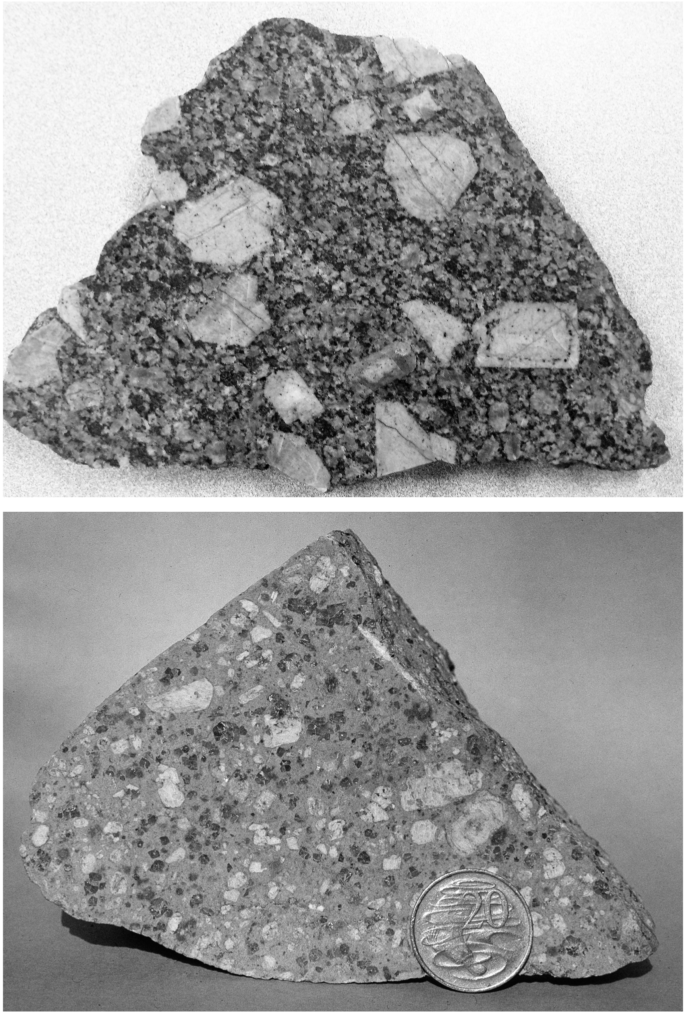
Figure 2. Unimpeded growth of K-feldspar megacryst in liquid



(A) Porphyritic microgranodiorite, Yetholme, New South Wales, Australia, showing a twinned megacryst of K-feldspar (Kfs), together with much smaller phenocrysts of plagioclase (Pl), quartz (Qtz) and biotite (Bt), all set in a very fine-grained quartz-feldspar groundmass. All phenocrysts show a high proportion of crystal faces, owing to free growth in liquid. Rapid cooling has preserved evidence of growth of the K-feldspar megacrysts in liquid. The K-feldspar grew relatively rapidly from few nuclei. Glomeroporphyritic aggregates (especially of plagioclase) are more common in crystal-rich parts of the rock, which is consistent with fortuitous impingement, but does not exclude heterogeneous nucleation. The quartz phenocrysts have embayments, cross-sections of which appear as rounded to irregular patches (pseudo-inclusions) of groundmass. Crossed polars; base of photo 29 mm. Photo by Bill D'Arcy.

(B) Same rock as in (A), showing independent euhedral phenocrysts of quartz and plagioclase in an abundant fine-grained groundmass. Crossed polars; base of photo 13 mm. Photo by Bill D'Arcy.

Figure 3. Separate euhedral phenocrysts



(A) Separate, euhedral megacrysts of K-feldspar in a granitoid, suggesting independent (possibly homogeneous) nucleation in abundant liquid. Some of the megacrysts show oscillatory zoning or crystallographically arranged zones of inclusions. Sawn slab; base of photo 25 cm.

(B) Predominantly separate euhedral phenocrysts of plagioclase and quartz in a dacite. Sawn slab; coin diameter 2.8 cm.

Jerram *et al.* [2003] reviewed the evidence for crystal clustering in igneous rocks, implying that this is a basic process in the development of magmatic rock structure, involving either heterogeneous nucleation or fortuitous coalescence. Clustering is an inevitable result of crystal accumulation by either mechanical processes or removal of interstitial liquid [e.g., Vernon & Collins, 2011]. For example, relatively coarse-grained (glomeroporphyritic) aggregates or 'clots', generally interpreted as being of cumulate origin, are common in calc-alkaline volcanic rocks [e.g., Flood *et al.*, 1977; Garcia & Jacobson, 1979; Scarfe & Fujii, 1987; Renzulli & Santi, 1997; Gençalioğlu Kuşcu & Floyd, 2001]. The aggregates appear to represent precipitates of a parental magma, generally at an earlier stage of development than that represented by the phenocrysts of the host magma.

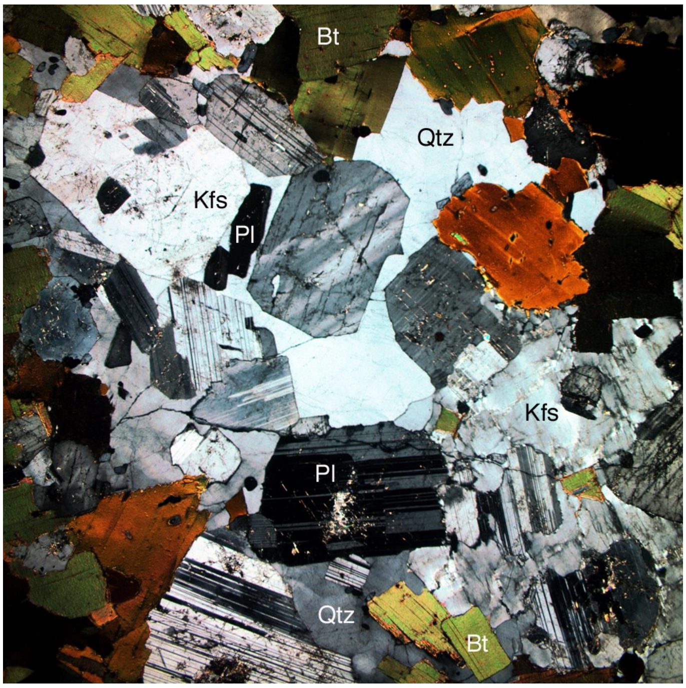
Jerram *et al.* [2003, p. 2049] stated, without explanation, that "in more slowly cooled intrusive bodies, clustering would be expected to occur very early in the crystallization history of the magma, although it may occur over longer time-scales because of slower growth rates in the plutonic environment." However, the situation represented by Figures 2 and 3 suggests that clustering is relatively uncommon in the early stages of crystallization in slowly cooled felsic magmas. Instead, crystals generally appear mainly to have nucleated separately, though local clustering can occur. This situation is shown by many felsic and intermediate, porphyritic, shallow intrusive and volcanic rocks (non-pyroclastic), which are characterized by mainly dispersed, euhedral phenocrysts [e.g., Vernon, 2004, figures 3.5, 3.7, 3.8, 3.9, 3.13; McDonnell *et al.*, 2004, figure 2]. For example, O'Donnell and Hogan [2004] and Hogan and O'Donnell [2008] described a rhyolite dyke carrying euhedral to subhedral phenocrysts of quartz (25%) and perthitic K-feldspar (75%) in a fine-grained quartz-feldspar groundmass, most of the phenocrysts being independent, some occurring in glomeroporphyritc aggregates. Moreover, studies of over 6000 zircon crystals and over 3000 quartz crystals in felsic pumice (reflecting instantaneous conditions in the granitic parent magma) have revealed only two zircon aggregates and five quartz aggregates, confirming that independent crystallization of these minerals in felsic melts is typical [Bindeman, 2003, p. 367]. In view of this situation, most of the clustering in granitoids is probably due to fortuitous impingement, rather than heterogeneous nucleation, and so would be favoured by higher crystal concentrations. Mock & Jerram [2005, p. 1538] suggested that the relatively high yield strength of felsic liquids could allow phenocrysts to be suspended without interconnection at higher proportions of crystals than more mafic liquids. Under conditions of slow cooling in plutons, crystal aggregates are formed by liquid movement, causing fortuitous impingement of grown crystals, forming chain structures [see Vernon, 2004, pp. 109-115 for a summary] or igneous cumulates, including both cumulates formed by physical accumulation and cumulates formed by removal of interstitial liquid [e.g., Vernon and Collins, 2011].

Most published examples of clustered nucleation occur in strongly undercooled rocks, such as basalts and komatiites [e.g., Kirkpatrick, 1977, 1981; Jerram and Cheadle, 2000; Jerram *et al.*, 2003], for which nucleation is forced to occur heterogeneously [e.g., Vernon, 2004, figures 3.4, 3.50]. Hersum and Marsh [2007, p. 250, figure 3] suggested that aggregated small crystals in basaltic lava lakes grow into larger ones by consuming still smaller crystals, in a process of grain-boundary migration, by which grains with lower total surface free energy (normally the larger crystals) survive and grow. Hersum and Marsh [2007] wrote that "the process may also continue, given the proper opportunities, at high crystallinities where quenching is uncommon" and that "the kinetics of this process of grain annexation, which is, in effect, a form of high-temperature annealing, are so rapid that little evidence of such growth is left in the final rock record." Mock and Jerram [2005, p. 1537] also emphasized "crystal growth by annexation of small crystals into large ones (after abutment of crystals) by grain boundary diffusion, producing optically continuous large crystals."

However, there is no clear evidence connecting this inferred behaviour in lava lakes, where cooling is rapid at large degrees of undercooling (leading to heterogeneous nucleation and crystal clustering), with crystallization of coarse-grained gabbros, where temperatures would be higher for longer periods, undercooling would be minimal, and consequently nucleation rates would be relatively low, resulting in fewer, more widely separated nuclei that would grow into larger independent crystals in liquid. Grain-shape modification could occur only after impingement of these large crystals, evidence of which is found in some gabbros, anorthosites and peridotites (see section dealing with hypothesis 3). However, evidence of such modification is generally absent from granitoids, as shown in Figures 1 and 4 (see section dealing with hypothesis 3).

Another argument against the grain-boundary migration coarsening process proposed by Hersum and Marsh [2007] and Johnson and Glazner [2010] is that the abundance of crystals with oscillatory growth zoning extending right to the centre in granitoids (Figures 1, 2, 5, 6) eliminates the possibility of grain coarsening by grain-boundary movement after very small crystals have developed. Although such zoning patterns can be disrupted by changes in magmatic conditions, they typically outline former crystal growth surfaces [e.g., Wiebe, 1968], reflecting crystallization in liquid. The growth zones generally show no evidence of major partial removal at crystal edges by migrating grain boundaries after solidification, except for uncommon examples of contact melting [e.g., Vernon *et al.*, 2004; Vernon, 2004, pp. 462-463], as discussed later.

Figure 4. Crystal faces and local poikilitic structure

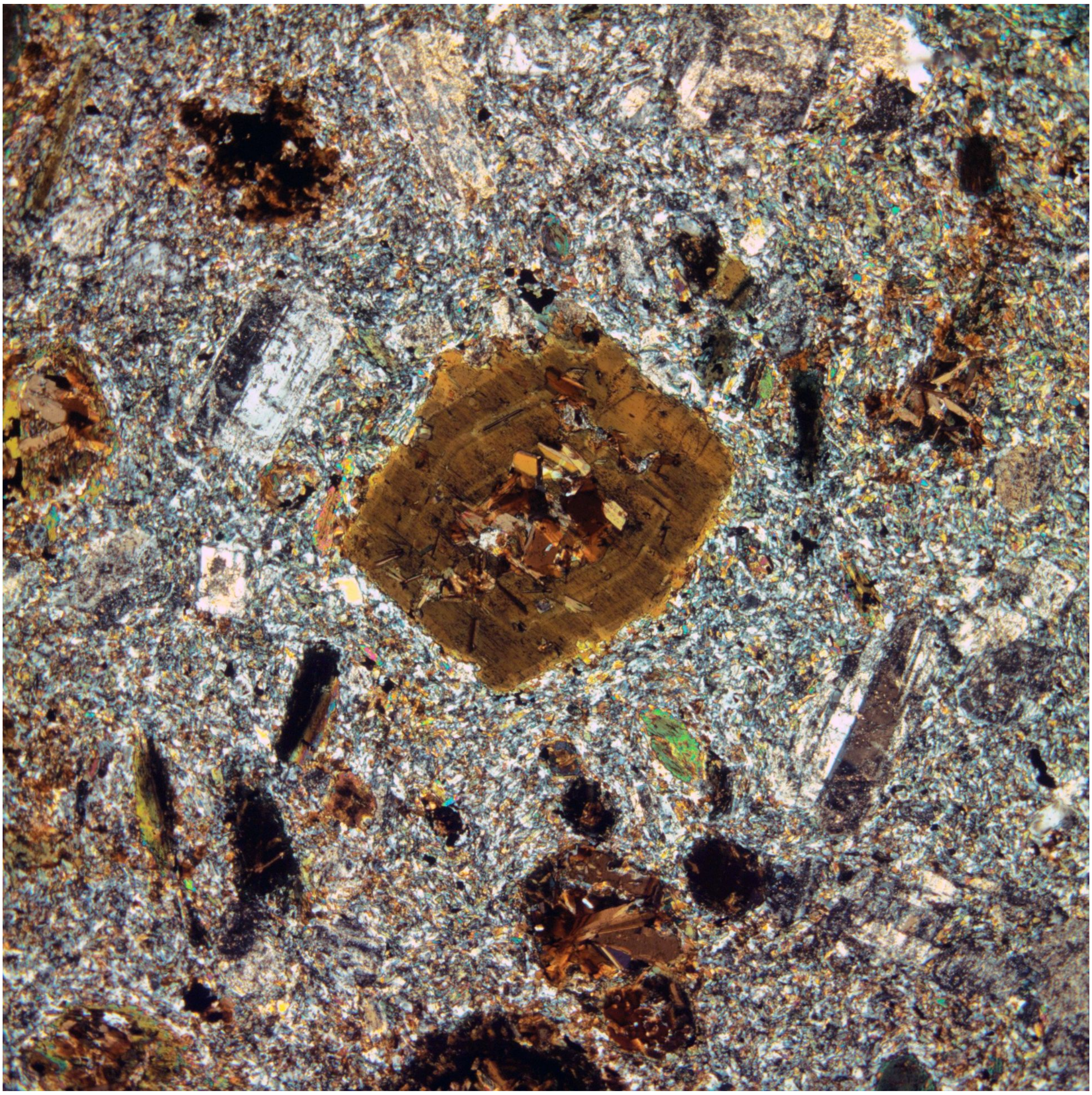


Plagioclase (Pl) and biotite (Bt) with crystal faces against quartz (Qtz) and K-feldspar (Kfs), as well as local poikilitc microstructure consisting of small crystals of plagioclase enclosed in quartz and K-feldspar, Kameruka Granodiorite, Bega Batholith, south-eastern Australia. A possible interpretation is that the small plagioclase crystals represent relatively late crystals that grew in interstitial liquid at the same time as more rapid growth from fewer nuclei of quartz and K-feldspar. Crossed polars; base of photo 7 mm.

The concept of grain coarsening conceivably could be used to explain relatively small inclusions, compared with the sizes of other grains of the same mineral in some granitoids (Figure 4), by implying that originally all crystals of the included minerals are small (when some of them are incorporated in the host crystal), after which the non-included crystals grow at the expense of others that dissolve. However, this process ("Ostwald ripening") is limited by diffusion rates [e.g., Carlson, 1999, 2000] and grainsize. For surface free energy to dominate the volume chemical free energy to the extent that it drives dissolution, the particles must be very small, in the micrometre or smaller size range (Jackson, 1967; Martin and Doherty, 1976; Baronnet, 1982; Lasaga, 1988, p. 150; Vernon, 2004, p. 52). Therefore, the process would only apply in the every early (post-nucleation) stages. Experiments have shown that Ostwald ripening is negligible for millimetre-size quartz crystals in rhyolitic magma [Cabane *et al.*, 2001] and this has been confirmed by CSD studies of quartz crystals in rhyolitic pumice [Bindeman, 2003, p. 369]. The alternative idea, that the coarsening of non-included grains occurs in the solid state (grain growth) is theoretically viable, but should result in metamorphic-like aggregates, which are generally not observed in granitoids (see section dealing with hypothesis 3).

In view of these considerations, a preferable explanation of inclusions that are smaller than surrounding grains of the same mineral is that the inclusions represent crystals that nucleate in interstitial liquid during the later stages of growth of the larger crystals, as nucleation rates begin to increase and growth rates decrease. Theoretically, large and small crystals should coexist, because the crystallization of liquids involves continuous nucleation and growth [Hersum and Marsh, 2007, p. 248]. So, even if a magma is held at small degrees of undercooling for most of its cooling history, the last remaining liquid would be expected to nucleate new crystals, with the result that some smaller crystals should always be present. However, they would probably be scattered sparsely through an otherwise coarse-grained aggregate, and so could be hard to detect. On the other hand, detailed CSD analysis of many quartz and zircon crystals in rhyolitic pumice (representing magma practically instantaneously extracted from a felsic pluton) by Bindeman [2003] shows a deficiency of smallest crystals, which suggests that nucleation in slowly cooling felsic magmas does not occur homogeneously, but occurs by forming layers on existing crystals. This could apply to feldspar as well [Bindeman, 2003]. On the other hand, similar under representation of small sizes in quartz and feldspar CSD curves for a rhyolite dyke have been attributed to resorption during ascent decompression by O'Donnell and Hogan [2004] and Hogan and O'Donnell [2008]. The relative uniform dispersal of phenocrysts in many felsic rocks (Figures 2, 3) is consistent with homogeneous nucleation for the formation of the intial crystals, on which later growth can occur, though clear evidence of the initial nucleation process is unavailable. The large grains of poikilitic quartz and K-feldspar illustrated in Figure 4 could have grown at the same time as the fine-grained plagioclase inclusions, but from few nuclei. This interpretation, if correct, emphasizes the complications caused by variations in nucleation rate between different minerals in granitoids (see section on order of crystallization, below).

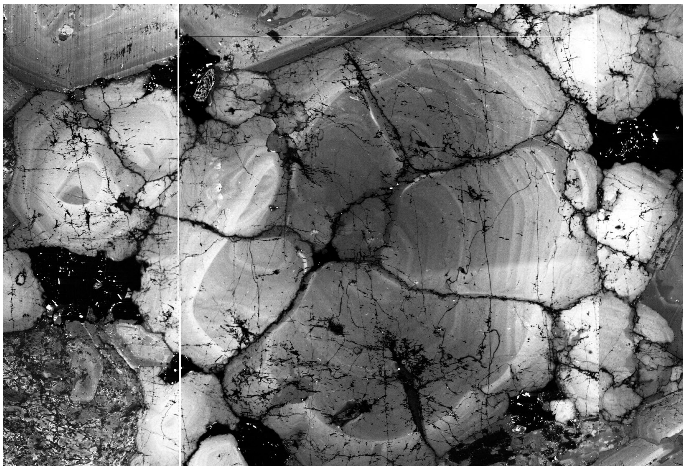
Figure 5. Early crystallization 'snapshot'



Porphyritic microgranodiorite dyke, Hartley, New South Wales, Australia, showing evidence of the earlier stages of crystallization, in the form of isolated, euhedral plagioclase and brown hornblende phenocrysts with oscillatory zoning patterns that reflect the growth histories of the crystals. Much of the hornblende has been replaced by aggregates of biotite, inferred to be of subsolidus origin. The central hornblende phenocryst shows abunbdant oscillatory zoning and only minor replacement by late biotite flakes. Crossed polars; base of photo 7 mm.

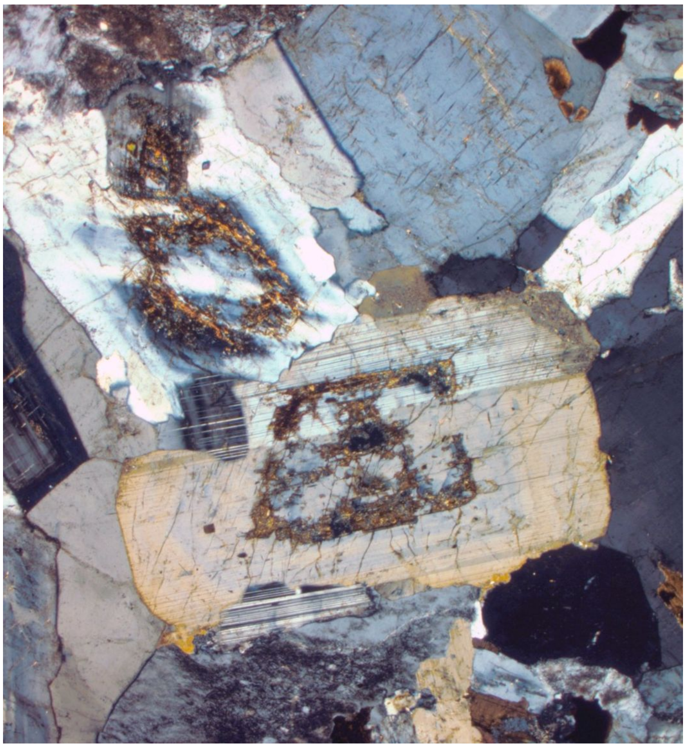
Spasmodic events: Intermittent re-heating episodes, commonly associated with magma mixing and/or convection, are responsible for zoning discontinuities and mantled crystals, which are common in granitoids and equivalent volcanic rocks [e.g., Wiebe, 1968; Davidson *et al.*, 1988, 2007, Charlier *et al.*, 2005; Jerram and Davidson, 2007], as well as coexistence of crystals with different zoning patterns [e.g., Collins *et al.,* 2006; Vernon and Paterson, 2008a]. Mechanical accumulation of crystals and/or passive accumulation through loss of interstitial liquid are also prominent processes in granitic magmas [e.g., Paterson *et al.*, 2005; Collins *et al.*, 2006; Vernon and Paterson, 2008a]. Spasmodic re-heating of crystals in response to mafic magma replenishments and/or convection can cause dissolution of small crystals and transfer of dissolved components to nearby larger crystals [e.g., Higgins and Roberge, 2003]. However, though all these processes enrich and complicate the crystallization history, they do not alter the overall magmatic nature of granitoids.

Figure 6. Oscillatory zoning in quartz



Aggregate of quartz phenocrysts in the Vinalhaven pluton, Maine, USA, showing euhedral concentric oscillatory Ti zoning revealed by SEM cathodoluminescence, reflecting former growth habits. The zoning in the outer part of the largest crystal has been truncated and rimmed by new brighter zones richer in Ti, the truncation having been caused by dissolution in response to replenishment by more mafic magma. The dissolution was followed by precipitation of Ti-enriched quartz from the heated felsic magma (Wiebe *et al.*, 2007). Mosaic of cathodoluminescence images; largest quartz crystal 4.2 mm across. Photo by Bob Wiebe.

Figure 7. Contact melting



Irregular interface, consistent with contact melting, between two zoned plagioclase grains, each of which has a complete core (outlined by preferentially altered zones), reflecting a period of independent growth in liquid before impingement. Wards Mistake Adamellite, New England Batholith, New South Wales, Australia. Crossed polars; base of photo 3.7 mm.

Order of crystallization: A problem that generally cannot be solved by microstructural evidence, is the inference of an order of nucleation of minerals in granitoids, as argued by Flood and Vernon [1988] and Vernon [1996, 2004], who showed that inclusion and moulding relationships are unreliable, and that the only structures reliably indicating an order of nucleation are mantles or corona structures formed by discontinuous reactions, such as hornblende rims on pyroxene (Figure 8). An additional complication is suggested by the analogue experiments of Means and Park [1994], which revealed migration of grain boundaries during cooling. Means and Park [1994, p. 326] emphasized that if melt-present grain- and phase-boundary migration are important, caution must be exercised when “classically” interpreting the order of crystallization from microstructural observations. As an example of “classically” interpreted orders of crystallization, they cited Flood and Vernon [1988], which was unfortunate, because Flood and Vernon

[1988] took great pains to point out that the classical approach is invalid, and that moulding and impingement relationships should not be used to make inferences about an order of crystallization. This warning was re-emphasized by Vernon [2004, pp. 102-108].

Figure 8. Discontinuous reaction relationship

Relic of pyroxene mantled and partly replaced by hornblende (a discontinuous magmatic reaction relationship) in granodiorite, Uralla, New South Wales, Australia. This is one of the few microstructural relationships indicative of an order of nucleation. Crossed polars; base of photo 4.4 mm.

General inference: The foregoing discussion indicates that the main limitations to microstructural interpretation are that (1) evidence of the earliest stages of crystallization is generally not available, and (2) microstructural evidence should not be used to infer an order of nucleation, except for corona structures. However, provided these limitations are kept in mind, microstructural evidence can be applied to petrogenetic problems of granitoids, for example, problems posed by the following three hypotheses.

Hypothesis 1 (granites typically contain solid restite)

Some petrologists have contended that granitic magmas are rarely entirely liquid, but instead are mixtures of minimum or near-minimum temperature ('haplogranitic') liquid, together with the unmelted remainder of the source-rock (solid 'restite'), which is transported from the source to the emplacement level [e.g., Chappell and White, 1974, 1976, 1991; Chappell, 1984, 2004; White and Chappell, 1977, 1988; Griffin *et al.*, 1978; Hine *et al.*, 1978; Chappell *et al.*, 1987, 1993, 2000; Wyborn *et al.*, 1981; Chappell and Wyborn, 2004]. According to this hypothesis, the solid restite contains most of the calcic and mafic components of the resulting granitoids and equivalent felsic volcanic rocks. The 'solid restite hypothesis' encounters the following seven main problems.

(1) *Problem of biotite and hornblende:* In its simplest form, the solid restite hypothesis regards biotite and hornblende crystals in granitoids as being transported from the source, which implies (a) relatively low-temperature melting, in order to preserve the biotite and hornblende, and (b) externally derived water to produce the liquid, because internal water is retained in the biotite and hornblende. However, field and petrological evidence in many migmatite complexes, as well as experimental evidence, indicate that incongruent melting of biotite and hornblende is the main process responsible for the formation of crustal granitic magmas, producing hydrous liquid and anhydrous or weakly hydrous ('peritectic') solids, such as pyroxene, garnet or cordierite. This destruction of source biotite and hornblende necessitates that all or most of the biotite and hornblende in granitoids is magmatic, unless it can be shown that they form by replacement of anhydrous restite crystals without the restite chemical components dissolving in the liquid and re-precipitating as new crystals, which would be magmatic.

(2) *Lack of convincing microstrructural evidence in inferred restite crystals and aggregates:* Sillimanite inclusions in cordierite in some S-type granites have been cited as indicators of restite [e.g., White and Chappell, 1977], but they can also be explained by an accidental xenocrystic origin for the cordierite [e.g., Vernon, 2007]. Moreover, inclusions of magmatic sillimanite occur in cordierite and muscovite phenocrysts in some peraluminous dacites [Zeck, 1972; Roycroft, 1991; Büttner, 2005]. The solid restite hypothesis contends that the upper amphibolite facies metasedimentary enclaves in many S-type granitoids are restite, but they could be accidental xenoliths from an amphibolite facies terrane above the granulite facies source terrane [e.g., Vernon, 2007].

Corroded, unzoned cores conceivably could represent transported solids that were partly dissolved in the magma in the source rocks or during ascent. Examples of crystals with cores and mantles in granitoids are (i) mantled quartz and feldspar xenocrysts ('antecrysts') resulting from magma mixing, (ii) rapakivi structure, which commonly results from magma mixing or pressure change, (iii) orthopyroxene mantled by biotite, clinopyroxene partly replaced by hornblende, and garnet partly replaced by cordierite ± biotite, the cores of which could all represent magmatic precipitates, restite or xenocrysts (see below); and (iv) calcic plagioclase cores in some granitoids, which have been inferred to be transported restite [e.g., Chappell *et al.*, 1987], but which also can be explained as products of fractional crystallization with variation of $a_{(H2O)}$ [Allen, 2001]. None of these types of core necessitates explanation by transport from the source, which emphasizes the general lack of *convincing* microstructural evidence for restite crystals in granitoids.

As noted above, rims of biotite on orthopyroxene or hornblende on clinopyroxene (Figure 8) may or may not represent partly replaced restite, it being difficult to distinguish between phenocrystic, xenocrystic and restitic origins of the pyroxene. However, even if replaced restite is inferred, it is generally difficult to determine whether the original grain was replaced in the solid state, retaining its former shape, or whether it was dissolved in the melt and the new mineral magmatically precipitated on the dissolving grain. Stevens et al. [2007] inferred that peritectic garnet grains were carried up rapidly from source metapelites in peraluminous granitic magmas responsible for the Cape Granite Suite, South Africa. As a result of abrupt decrease in pressure, the garnet broke down to lower-pressure minerals, such as cordierite ± orthopyroxene, releasing the components of these minerals into the liquid, from which they precipitated as magmatic minerals. Villaros *et al.* [2009] suggested that peritectic garnet from the source underwent coupled dissolution and re-precipitation during ascent and cooling of leucogranite magma. Villaros *et al.* [2009] inferred that the garnet crystals retained their original shapes through this process, which implies that the silicate liquid thoroughly penetrated the crystals, dissolving them and simultaneously precipitating new garnet, as proposed by Putnis [2002, p. 695] for reactions between plagioclase crystals and silicate liquid. However, it is difficult to eliminate the possibility of dissolution and independent crystallization of new magmatic crystals, in view of the lack of primary inclusions and the common subhedral shapes of the garnet crystals in these rocks. Similarly, despite the presentation of abundant detailed evidence of the entrainment of peritectic garnet in leucogranitic magma by Taylor and Stevens [2010], the garnet grains show evidence of (1) precipitation of compositionally identical garnet as inclusion-free rims on inferred restite cores, and (2) grain "amalgamation" or "fusion", which presumably involves some dissolution and re-precipitation, and (3) increasing magmatic character (e.g., euhedral shape) of the garnet with increasing degree of segregation of magma from the source. These processes tend to blur the structural distinction between incorporated solid restite (even if compositionally modified) and magmatic precipitation of dissolved restite components.

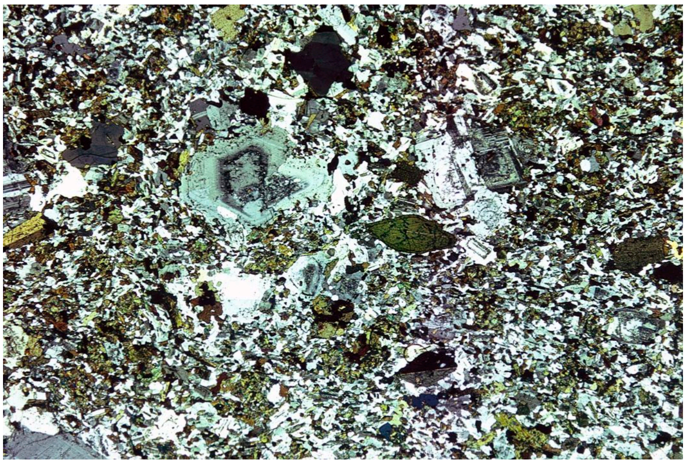
Cordierite with oscillatory zoning in some granitoids [Erdmann *et al.*, 2009] and peraluminous felsic volcanic rocks [Zeck, 1972] is consistent with magmatic precipitation of dissolved components of former restite, resister (unreactive material in the source rock) or xenocrystic cordierite and/or other aluminous minerals.

(3) *Microgranitoid enclaves are igneous:* Microgranitoid enclaves ('mafic enclaves') in granitoids have been interpreted as restite or modified restite. [e.g., Chappell, 1996, p. 467]. However, the porphyritic and fine-grained igneous microstructures of microgranitoid enclaves (Figures 9, 10, 11, 12) are inconsistent with a restite origin. Characteristic igneous features of microgranitoid enclaves [e.g., Vernon, 1983, 1984, 1990, 1991, 2004, 2007] include euhedral plagioclase phenocrysts with oscillatory zoning, abundant zoned plagioclase laths, magmatic flow foliations marked by aligned plagioclase laths, interstitial quartz or K-feldspar in a poikilitic relationship with plagioclase and/or biotite, highly elongate orthopyroxene crystals, thin platy biotite crystals, acicular apatite and ilmenite, and skeletal zircon, as well as features characteristic of magma mixing, such as mantled quartz and feldspar xenocrysts [e.g., Vernon, 2007], as shown in Figures 11 and 13. The microstructures of the enclaves are similar to those of many dykes (Figures 14, 15), which are unquestionably igneous, as noted by Harker and Marr [1891]. Moreover, identical enclaves occur in metaluminous and peraluminous volcanic rocks (Figure 16), some of these enclaves being glassy, which confirms that they were originally magma globules, not restite [e.g., Vernon, 1983, 1984, 1991, 2004]. In addition, miaroles filled with euhedral feldspar crystals projecting inwards into quartz [Vernon, 1991, figure 11], as shown in Figure 17, are clear evidence of the escape of gas from magma prior to solidification of the enclave [e.g., Vernon, 1983, p. 98; 1991, pp. 289-290].

Figure 9. Igneous microstructure of microgranitoid enclave

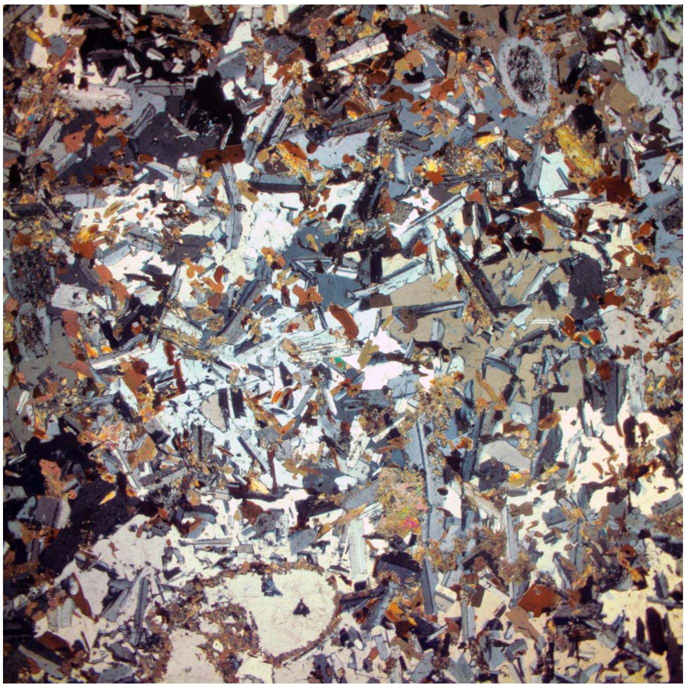
Microtonalite enclave in the Sierra Nevada Batholith, California, USA, consisting of phenocrysts of zoned plagioclase in a groundmass of elongate plagioclase, hornblende and biotite with interstitial quartz. Crossed polars; base of photo 7 mm.

Figure 10. Plagioclase and hornblende phenocrysts in microgranitoid enclave



Microgranodiorite enclave, Moonbi Supersuite, New England Batholith, New South Wales, Australia, consisting of euhedral phenocrysts of hornblende and zoned plagioclase, in a fine-grained groundmass of plagioclase laths, biotite, hornblende and quartz. The plagioclase laths locally show a magmatic flow alignment. Crossed polars; base of photo 8.4 mm.

Figure 11. Poikilitic structure in microgranitoid enclave

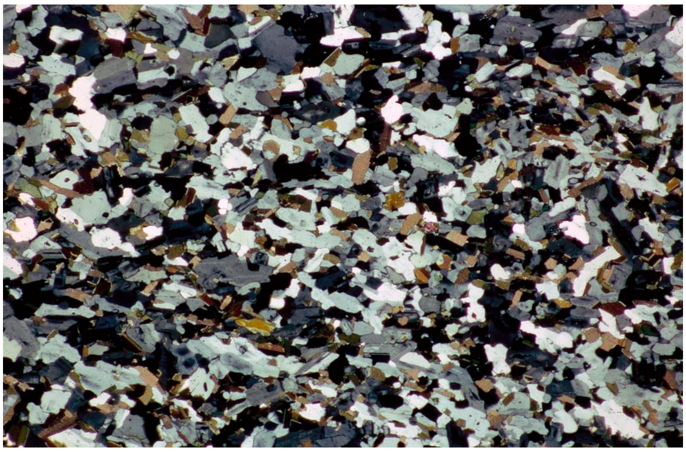


Peraluminous microtonalite enclave, Cowra Granodiorite New South Wales, Australia, with an igneous microstructure, consisting mainly of plagioclase, biotite and orthopyroxene (mostly altered to hydrothermal fine-grained amphibole aggregates), with interstitial quartz, which has a poikilitic relationship with the other minerals. Also shown (bottom) is a quartz xenocryst ("ocellus") with a rim of fine-grained orthopyroxene (later altered), reflecting magma mixing. Crossed polars; base of photo 7 mm.

The magmatic nature of microgranitoid enclaves is also confirmed by K-feldspar megacrystic xenocrysts with overgrowths containing random, small inclusions of groundmass minerals, adjacent to aligned, larger crystals in the enclave groundmass (Vernon, 1990, fig. 6a), showing that minerals in the groundmass continued to grow, and the enclave magma underwent magmatic flow, after crystallization of the overgrowths.

In an attempt to account for the igneous microstructures, Chen *et al.* [1989], Chappell and White [1991], White *et al.* [1991] and White *et al.* [1999] speculated that these putative "restite" enclaves contained a small amount of melt, which somehow converted a metamorphic into an igneous-looking microstructure, which White *et al.* [1991] called "pseudo-doleritic." The mechanisms of this questionable transformation were not explained. Crystallization of magma is a simpler and more probable interpretation, even for peraluminous orthopyroxene-biotite microtonalite enclaves in peraluminous granitoids, such as the Cowra Granodiorite, New South Wales, Australia, which show all the igneous features listed above [e.g., Vernon, 2007].

Figure 12. Magmatic flow structure in microgranitoid enclave



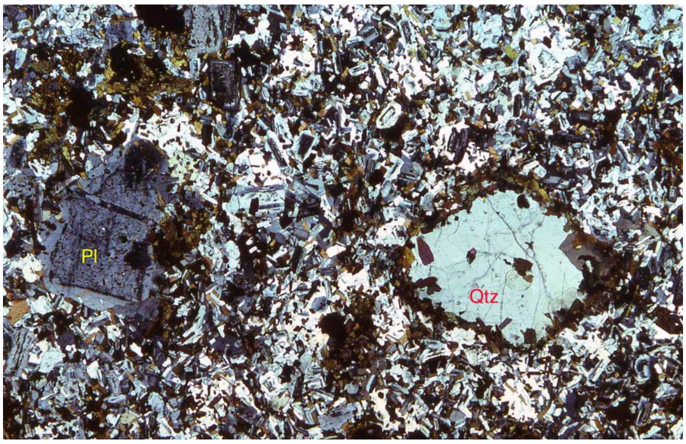
Microgranodiorite enclave, Tioga Pass, Sierra Nevada Batholith, California, USA, consisting mainly of plagioclase, quartz, biotite and hornblende. Many of the biotite grains show {001} crystal faces, and some plagioclase grains also show crystal faces. Most plagioclase/plagioclase and plagioclase/quartz interfaces are indented, owing probably to mutual impingement, though possibly in response to minor deformation. The elongate biotite and plagioclase grains show a moderate to strong alignment, reflecting magmatic flow. Crossed polars; base of photo 3.3 mm.

Waight *et al.* [2001] and Nicholls *et al.* [2001] showed that peraluminous microgranitoid enclaves in Lachlan Fold Belt (SE Australia) peraluminous granitoids have isotopic compositions (initial $^{87}Sr/^{86}Sr$ and ε_{Nd}) that are generally more primitive than, or similar to, those of the host granitoid, and that the high CaO contents and relatively high ε_{Nd} of the enclaves are not found in either the Palaeozoic Lachlan Fold Belt turbidites or the metapsammitic-pelitic enclaves in Lachlan Fold Belt granitoids. The isotopic variability, lower initial $^{87}Sr/^{86}Sr$ and higher ε_{Nd} of the enclaves, compared with the host granitoid, are probably the result of equilibration of the enclave magma with an initially isotopically more primitive magma [Waight *et al.*, 2001], presumably during magma mixing at depth, before the resulting hybrid magma entered the granitoid pluton and disaggregated into enclaves.

(4) *Crystal-poor felsic feeder dykes:* Good evidence of the absence of restite in granitoid magmas is provided by crystal-free or crystal-poor felsic feeder dykes that enter and become dispersed into a granitoid pluton, as in the Kameruka pluton of the Bega Batholith, south-eastern New South Wales, Australia [Collins *et al.*, 2006].

(5) *Separation of crystals and liquid:* When a small amount of silicate liquid ("melt") is formed, it tends to escape from the source rock [e.g., Bons, 2007; Bons *et al.*, 2004, 2008], leaving most of the solid material behind. Moreover, solids tend to separate from liquids during flow [e.g., Petford and Koenders, 1998]. Therefore, if both crystals and liquid move as a mass (forming a "diatexite"), crystals tend to separate and form layer concentrations or "schlieren" [Sawyer, 1998; Milord and Sawyer, 2003] that tend to coalesce and be left behind [e.g., Vernon, 2007, p. 171; Vernon and Clarke, 2008, pp. 182-184]. This separation commonly occurs close to the source [e.g., Sawyer, 1996, 1998; Sawyer *et al.*, 1999].

Figure 13. Evidence of magma mixing in enclave



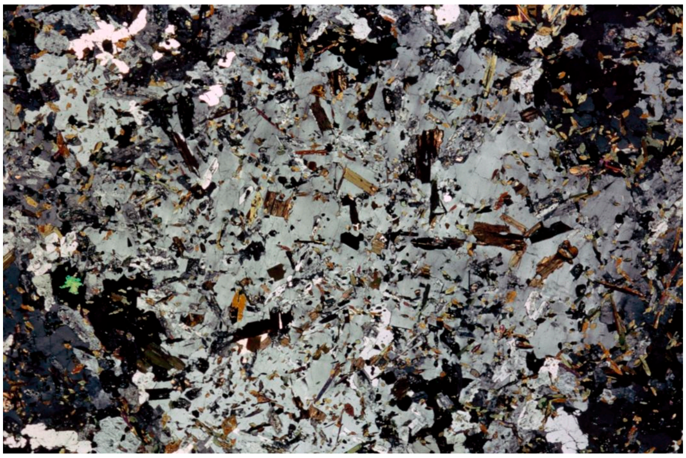
Microgranodiorite enclave, Moonbi Supersuite, New England Batholith, New South Wales, Australia, containing a phenocryst of plagioclase (Pl) with a corroded core and a mantled xenocryst ("ocellus") of quartz (Qtz), reflecting magma mixing, in a groundmass with elongate laths of zoned plagioclase, hornblende, biotite and interstitial quartz. The mantle on the quartz xenocryst consists of hornblende. Crossed polars; base of photo 8.4 mm.

(6) *Restite melting during ascent:* Another problem with the solid restite hypothesis is the suggestion of Clemens *et al.* [1997] and Annen *et al.* [2006, p. 528] that crystals can melt during ascent of felsic magma, owing to the shallower slopes of P-T mineral stability curves, compared with the steep slopes of magma ascent

paths. If so, many or most restite crystals should be removed from felsic magmas by the time they reach temporary storage chambers or final emplacement levels.

(7) *Evidence of crystal growth in liquid:* The main problem with the solid restite hypothesis is that granitoid minerals mostly show evidence of having crystallized in liquid, namely (a) euhedral crystal shapes, (b) euhedral inclusions arranged zonally (crystallographically) in the host mineral, and (c) zoning patterns (especially oscillatory zoning) reflecting euhedral growth.

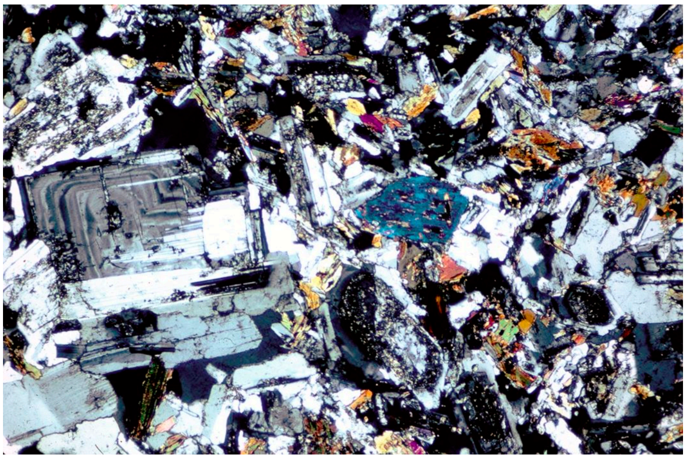
Figure 14. Dyke microstructure with K-feldspar oikocryst



Large poikilitic crystal (oikocryst) of K-feldspar, with numerous, small, predominantly euhedral inclusions of plagioclase, biotite and hornblende, in a synplutonic microgranitoid dyke, Tenaya Lake, Yosemite National Park, California, USA. Though the K-feldspar in this rock grew from few nuclei and developed large grains, the proportion of crystallized other minerals was too large to permit the K-feldspar to grow as a euhedral crystal. This situation is in contrast to that shown in Figure 2, in which the proportion of already crystallized material was low enough and scattered enough for K-feldspar to form large independent crystals by free growth in liquid. Crossed polars; base of photo 8 mm.

(a) Euhedral crystals of quartz and feldspar result from growth in a liquid, for example in felsic volcanic rocks [e.g., Vernon, 1999, 2004]. They are common in porphyritic micrograniroids (Figures 2, 3, 4, 15) and some granitoids (Figure 18), but are rare in metamorphic rocks, except as igneous relics [Vernon, 1986b, 1999, 2004; Vernon and Clarke, 2008, pp. 336-345]. Because fluid along grain boundaries appears to be necessary for the development of euhedral crystals in metamorphic rocks, as discussed by Vernon [2004, pp. 213-216], a reasonable inference is that the absence of crystal faces in metamorphic quartz and feldspar reflects fluid-absent growth in the solid state. In igneous rocks, crystal faces for quartz and feldspar indicate growth in a liquid, and absence of crystal faces is consistent with impingement and interference with other minerals during growth and/or adjustment of boundaries after impingement (Figure 1). Crystal faces for other minerals in granitoids, such as hornblende (Figures 1, 3), biotite (Figure 4), sphene and cordierite, are also consistent with magmatic crystallization.

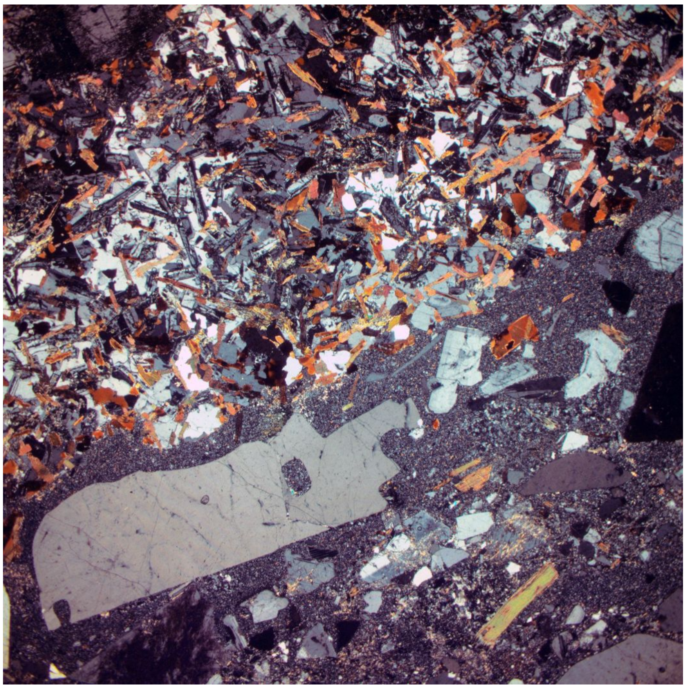
Figure 15. Dyke microstructure



Dyke of porphyritic microgranodiorite, south of Yea, Victoria, Australia, consisting of euhedral plagioclase phenocrysts with oscillatory zoning, in a groundmass of zoned plagioclase laths, hornblende, biotite and interstitial quartz. Crossed polars; base of photo 4 mm.

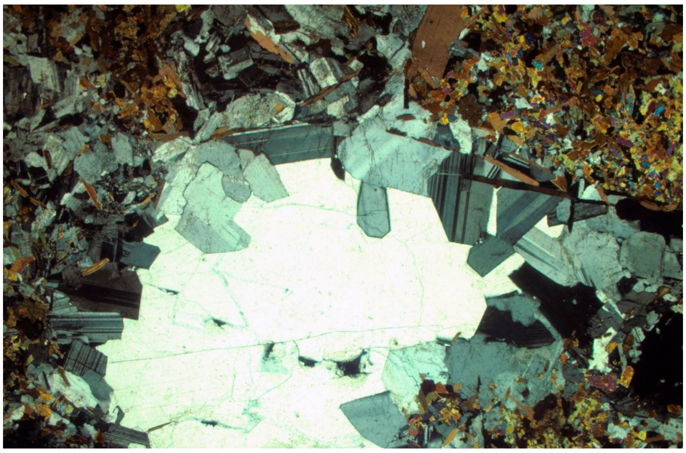
(b) Zonally arranged mineral inclusions, delineating former euhedral growth surfaces in the host mineral, occur in plagioclase and K-feldspar in some granitoids. Such inclusions are especially common in K-feldspar megacrysts (Figure 18), the inclusions consisting of zoned plagioclase, biotite, hornblende, quartz, apatite, zircon or sphene, as reviewed by Vernon [1986a, pp. 12-15]. Most of the inclusions are arranged in crystallographically controlled zones in the K-feldspar, in such a way that the {001} cleavage in biotite, (010) twin planes in plagioclase, and the longer axes of plagioclase, biotite, hornblende and sphene inclusions are parallel or approximately parallel to the nearest margin, and therefore to former growth faces of the K-feldspar host crystal, as discussed by Hibbard [1965, p. 248], Vance [1969, pp. 19, 21] and Smith [1974, pp. 276-277]. The included minerals are not similarly oriented in the groundmass, indicating they are arranged in this way as a result of incorporation in the megacryst, presumably by rotation to alignment against the K-feldspar growth surfaces. The fact that plagioclase inclusions in K-feldspar have complete zoning patterns indicates that the plagioclase crystals existed independently in the liquid before incorporation, rather than nucleating on the surface of the growing megacryst [Vance, 1969, pp. 19, 21; Vernon, 1986a, p. 14]. Rarely, shells of zonally (crystallographically) arranged inclusions occur in quartz phenocrysts [e.g., Haapala, 1997, p. 1646]. In contrast to this situation, inclusion patterns in metamorphic feldspar are random or delineate 'inclusion trails' unrelated to the crystal structure of the host mineral. Therefore, random inclusions or inclusion trails should also occur in any restite or peritectic feldspar grains in granitoids, but these features are typically not observed. In any event, grains with such features would be difficult to identify as restite or xenocrysts [e.g., Vernon, 2007].

Figure 16. Microgranitoid enclave in dacite



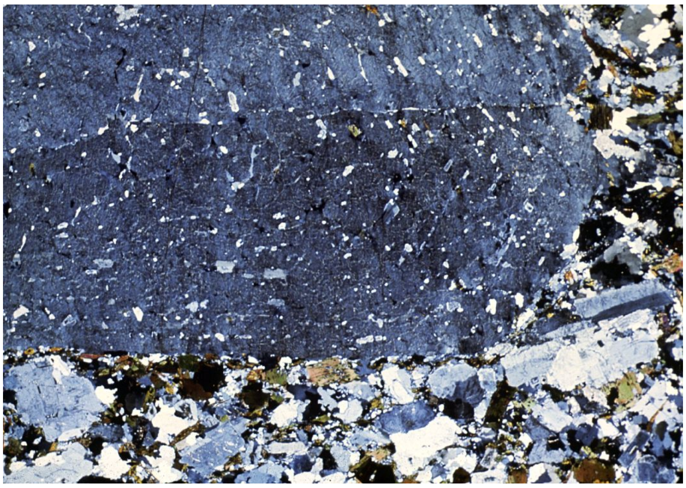
Microgranitoid (microtonalite) enclave (top-left half of photo) in dacitic ignimbrite consisting of phenocrystic fragments of embayed quartz, zoned plagioclase and biotite, Violet Town Volcanics, Victoria, Australia. The enclave has an igneous microstructure, with elongate grains of plagioclase and biotite and interstitial, poikilitic quartz. Crossed polars; base of photo 7 mm.

Figure 17. Miarole in microgranitoid enclave



Miarole (miarolitic cavity) characterized by euhedral plagioclase crystals projecting into quartz. The former cavity was formed by escape of gas from the hybrid enclave magma, followed by cooling sufficiently rapid to avoid collapse of the bubble, permitting later quartz to crystallize. Crossed polars; base of photo 7 mm.

Figure 18. Crystallographically arranged inclusions in K-feldspar



Part of a euhedral megacryst of K-feldspar with zonally arranged inclusions of plagioclase, in the Wuluuman Granite, Wellington, New South Wales, Australia. Parallel to the rows of inclusions are faint darker and lighter bands that represent oscillatory zoning. Crossed polars, base of photo 22 mm. Photo by Bill D'Arcy. From Vernon (2004, figure 3.12).

(c) Oscillatory zoning in granitoid minerals is a strong indicator of magmatic growth, because it is invariably inferred to result from growth in liquid [e.g., Vance, 1962; Boone, 1962; Boesen, 1964; Hibbard, 1965, p. 253; Bottinga *et al.*, 1966; Wiebe, 1968; Boyd and Smith, 1971; Zeck, 1972; Gibb, 1973; Smith, 1974, pp. 212-214;

Downes, 1974; Sibley *et al.*, 1976; Haase *et al.*, 1980; Mehnert and Büsch, 1981; Barton *et al.*, 1982; Eriksson, 1985; Clark *et al.*, 1986; Roycroft, 1989, 1991; Halden and Hawthorne, 1993; Jones and Papike, 1993; Shore and Fowler, 1996; Hattori and Sato, 1996; Fowler *et al.*, 2002; Bachmann and Dungan, 2002; Dempster *et al.*, 2003; Vernon, 2004, pp. 140-146, 262-268; Erdmann *et al.*, 2005, 2009, p. 497; Sato *et al.*, 2005; Féménias *et al.*, 2006; Wiebe *et al.*, 2007, p. 449; Tsune and Toramaru, 2007; Burger *et al.*, 2009; Dziggel *et al.*, 2009].

Figure 19. Oscillatory zoning in K-feldspar megacryst

Megacryst of K-feldspar with prominent oscillatory zoning and simple twinning in the Walcha Road pluton, New England Batholith, near Walcha, New South Wales, Australia. Crossed polars; base of photo 7 mm. Photo by Bill D'Arcy.

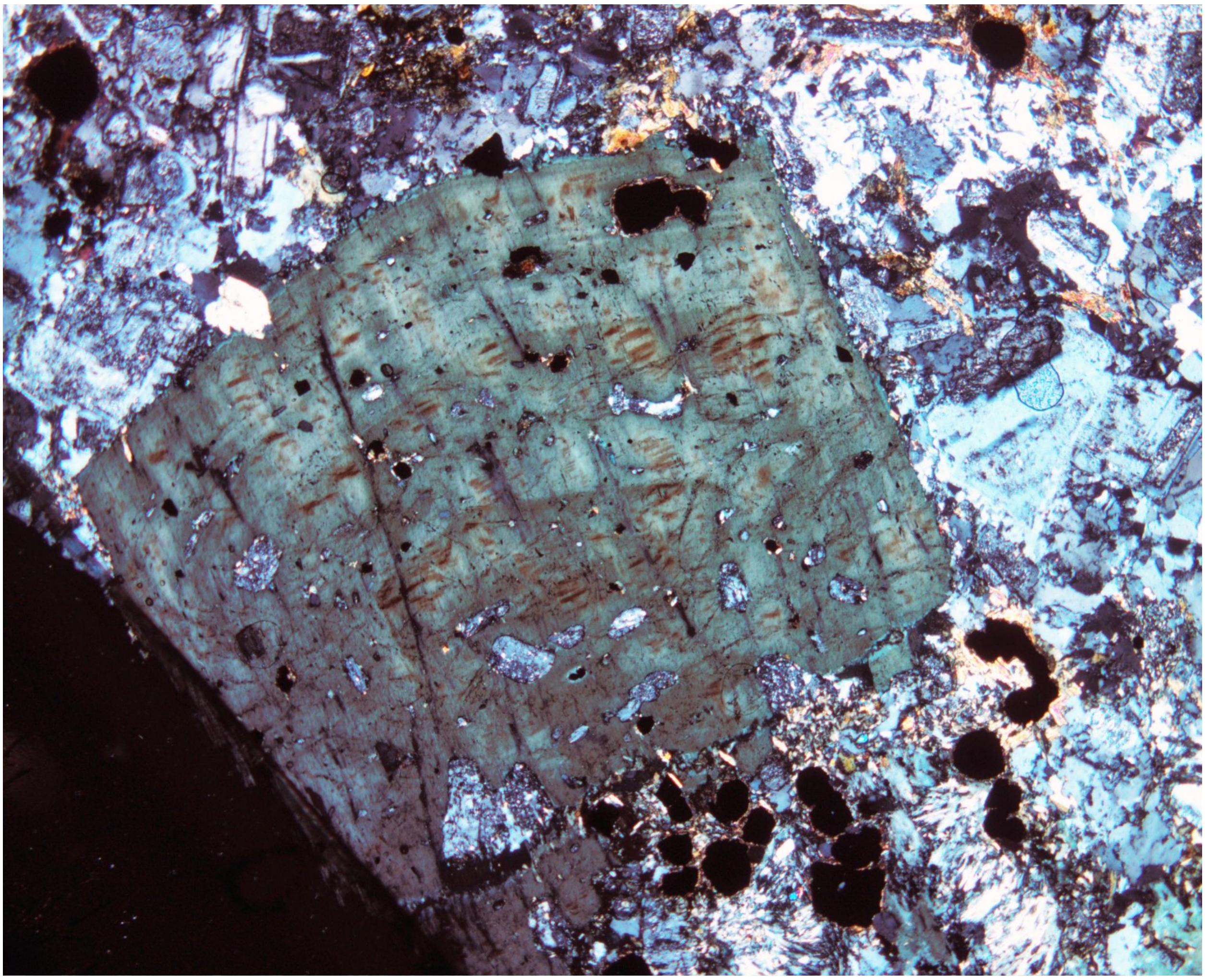
In granitoids, oscillatory zoning occurs in plagioclase (Figures 1, 5), K-feldspar (Figures 18, 19) quartz (Figure 6), hornblende (Figure 20), cordierite [Erdmann *et al.*, 2009, fig. 9d], sphene, zircon, apatite [Dempster *et al.*, 2003] and allanite [e.g., Shaw & Flood, 2009, fig. 2b], as revealed by optical and/or scanning electron microscope (SEM) techniques. Oscillatory zoning is especially common in plagioclase [e.g., Vance, 1962; Hibbard, 1965; Bottinga *et al.*, 1966; Wiebe, 1968; Smith, 1974; Sibley *et al.*, 1976; Haase *et al.*, 1980; Vernon, 2004; Tsune and Toramaru, 2007] and K-feldspar [Oen, 1960; Boone, 1962; Bateman *et al.*, 1963, p. D15; Vaniman, 1978; McTaggart, 1979; Michael, 1981; Phillips *et al.*, 1981, p. 362; Mehnert and Büsch, 1981; Brigham, 1984; Vernon, 1986a] in granitoids. Oscillatory zoning in quartz in high-level granitoids (Figure 6) has been revealed by cathodoluminescence [e.g., D'Lemos *et al.*, 1997; Seyedolali *et al.*, 1997; Watt *et al.*, 1997; Müller *et al.*, 2000, 2002a, 2002b, 2005; Peppard *et al.*, 2001; Wiebe *et al.*, 2007; Larsen *et al.*, 2009], but whether or not it commonly occurs in deeper granitoids is uncertain.

Oscillatory zoning in euhedral hornblende phenocrysts in dacite (derived from granodioritic magma) of the Fish Canyon Tuff, Colorado, USA, has been described and illustrated by Bachmann and Dungan [2002], and oscillatory zoning in euhedral hornblende phenocrysts in dacite of the Unzen Volcano, Japan, has been described and illustrated by Sato *et al.* [2005, figure 1, pp. 340-341], the zoning showing corrosion breaks that correspond to similar discontinuities in oscillatory zoning in plagioclase phenocrysts, caused by magma mixing. Oscillatory zoning also occurs in euhedral hornblende phenocrysts in andesite erupted at the Soufrière Hills Volcano, Montserrat [Rutherford and Devine, 2003, figures 1c, 1d], an andesite dyke, Motru Dyke Swarm, Romania [Féménias *et al.*, 2006] and a porphyritic microgranodiorite dyke from Hartley, New South Wales, Australia (Figure 3). All these zoned hornblende crystals crystallized from felsic to intermediate magma at depth, before volcanic eruption or dyke emplacement, and so indicate that oscillatory zoned hornblende can form in the plutonic environment, at least at relatively high crustal levels. A detailed search for oscillatory zoning in hornblende in a range of granitoid plutons is needed, to determine the extent of its development.

Oscillatory zoning occurs in muscovite in some peraluminous granites [Roycroft, 1989, 1991], but does not appear to have been previously reported in biotite. However, SEM images of Ba oscillatory zoning in biotite in the Half Dome Granodiorite, Tuolumne Batholith, California, USA, have been obtained by Joachim Krause [personal communication], and so zoned biotite in granitoids is worth further investigation.

Oscillatory zoning in granitoids is strong evidence that granitic minerals crystallize from liquid, because the zoning preserves former euhedral shapes developed as the crystal grows, constituting a 'growth stratigraphy' [Wiebe, 1968]. The regular oscillatory pattern can be locally interrupted and truncated by resorption events, after which oscillatory growth resumes [e.g., Shore and Fowler, 1996; Roycroft, 1991]. The zoning patterns can record elimination of fastest growing faces, temporary faces, temporary face widening, and disruption to patterns caused by inclusions [e.g., Roycroft, 1991, figure 2], indicating that the zoning is a primary growth feature, not one formed by subsolidus alteration processes.

Figure 20. Oscillatory zoning in hornblende



Oscillatory zoning in hornblende in the Ravenswood Granodiorite, north Queensland, Australia. Crossed polars; base of photo 3.5 mm.

The euhedral oscillatory zoning patterns commonly extend right to the centre of the crystal (Figures 1, 5, 6), reflecting crystallization from a liquid for the crystal's entire growth history, except for late overgrowths that interpenetrate with neighbouring minerals (Figures 1, 5), and therefore rule out a restite origin. In contrast, oscillatory zoning in metamorphic minerals is uncommon, apart from occurrences in skarns and hydrothermal veins [e.g., Shore and Fowler, 1996, p. 1117]. Oscillatory zoning in metamorphic garnet has been reported, as summarized by Vernon [2004, pp. 265-266], but is typically less sharply defined than in igneous minerals, and is generally attributed to open-system growth conditions involving changes in fluid composition [Jamtveit, 1991; Jamtveit and Andersen, 1992; Jamtveit *et al.*, 1993; Boundy *et al.*, 2002; Clechenko and Valley, 2003; Dziggel *et al.*, 2009]. Moreover, the zoning patterns typically reflect successive crystal faces developed during growth [e.g., Schumacher *et al.*, 1999; Vernon, 2004, pp. 263-265], indicating growth in at least a small amount of fluid [e.g., Kingery, 1960; Budworth, 1970; Sunagawa, 1974, 1977; Sunagawa *et al.*, 1974; Tomura *et al.*, 1979; Urai, 1983a, 1983b; Urai *et al.*, 1986; Rakovan and Jaszczak, 2000; Vernon, 2004, pp. 213-216, 263].

The well defined oscillatory zoning that is common in metamorphic grossular-andradite garnet invariably reflects growth in fluid-filled open cavities [Vernon, 2004, p. 263], as illustrated by Clechenko and Valley [2003, figs 2c, 2d], Intayot *et al.* [2007, p. 69, figures 2, 3] and Dziggel *et al.* [2009, fig. 6]. Oscillatory zoning in prehnite and clinopyroxene precipitated from hydrothermal fluids in cavities has been observed by Yardley *et al.* [1991], and is well known in many other minerals that crystallize in open spaces from fluids [Shore and Fowler, 1996, table 1]. All these examples show a 'growth stratigraphy' [e.g., Wiebe, 1968] outlined by former crystal faces preserved in the zoning patterns.

Generally, metamorphism and hydrothermal alteration remove pre-existing oscillatory zoning. For example, Long and Luth [1986] noted that hydrothermally altered parts of the Puntiagudo granite porphyry, New Mexico, USA, contain homogenized Ba in formerly zoned K-feldspar megacrysts. Therefore, it is reasonable to infer that any putative restite in granitoids would not show oscillatory zoning. The contrast between replacement and primary magmatic hornblende is well shown by Fe and Al X-ray maps produced by Joachim Krause (personal communication); the replacement hornblende is unzoned, whereas the outer magmatically precipitated hornblende shows an oscillatory zoning pattern.

General inference about restite in granitoids: The implication of the foregoing discussion of predominantly microstructural evidence is that most minerals in granitoids crystallize from liquid, rather than being solids inherited from source rocks. Most fragmental foreign grains are difficult or impossible to distinguish on microstructural grounds, and so could be xenocrysts, restite (including peritectic minerals) or their modified equivalents.

However, absence of microstructural evidence of solid restite in granitoids does not preclude the presence of potential or former restite chemical components dissolved in the liquid. For example, restite components could enter the liquid if solid restite crystals were dissolved during ascent [e.g., Annen *et al.*, 2006, p. 532], or if they reacted with the liquid to produce new minerals or compositional variants of the original minerals. When such components are dissolved, they end up in magmatic crystals, and so cannot be identified as such. Higher-temperature components (which would otherwise occur in restite) also could enter the liquid in the source, owing to relatively high melting temperatures, so that different magma batches in a collection zone could contain different proportions of higher-temperature components, depending on the local melting temperature in those parts of the source region from which the batches were extracted, while remaining entirely magmatic. High-temperature melting would be especially likely in 'deep hot zones', which is where many large granitic magma batches are probably generated [e.g., Annen *et al.*, 2006, 2008; Vernon, 2007].

The main conclusion is that most minerals in granitoids crystallize from liquid, regardless of how their chemical components enter the liquid, and that unambiguous solid restite or peritectic grains and aggregates from the source are uncommon, apart from modified garnet grains in some peraluminous granitoids and inherited zircon crystals or cores.

Hypothesis 2 (megacrysts grow after all or most crystallization)

A recent paper by Johnson and Glazner [2010] marks a return to an old idea, that K-feldspar megacrysts form late in granitoids — too late for enough free liquid to be available for them to grow large and for any movement and concentration of megacrysts to occur. The mechanism ('thermal recycling') proposed by Johnson and Glazer [2010] is that the K-feldspar megacrysts grow very late, after dissolution of smaller already crystallized K-feldspar grains, in response to multiple episodes of reheating and fluid fluxing caused by arrivals of later magma batches. They wrote that "coarsening may occur during thermal fluctuations with small amounts of melt remaining, during small-degree partial remelting, or in the presence of a fluid phase."

Johnson and Glazner [2010] and Glazner and Boudreau [2010, p. 327] have asserted that K-feldspar megacrysts are "almost universally interpreted as early-forming crystals". On the contrary, Vernon [1986, p. 52] and Vernon and Paterson [2008b] have emphasized that experiments indicate that K-feldspar nucleates *late* in the sequence of mineral appearances, referring to the experimental results of Piwinskii [1968], Piwinskii and Wyllie [1968], Whitney [1975] and Clemens and Wall [1981]. However, the important point is that the magma can have 60-70% liquid when the K-feldspar crystallizes— sufficient for it to grow large crystals capable of moving into flow alignment and forming physical accumulations [Clemens and Wall, 1981, p. 116; Winkler and Schultes, 1982, pp. 560-561]. In contrast, the assertion of Johnson and Glazner [2010] that insufficient liquid is available for growth and movement of megacrysts does not agree with the experimental results. Hypothesis 2 encounters the following ten problems.

(1) *Abundance of liquid when megacrysts grow:* The availability of abundant liquid is verified by the excellent evidence of unimpeded growth of a K-feldspar megacryst shown in Figure 2, which depicts a porphyritic rock that was chilled (forming a fine-grained quartzofeldspathic groundmass), containing large, euhedral K-feldspar megacrysts surrounded by former liquid, as well as much smaller euhedral phenocrysts of plagioclase, quartz and biotite. The rapid cooling has preserved evidence of unimpeded growth of K-feldspar in liquid, either later than or at the same time as plagioclase, biotite and quartz. The K-feldspar grew relatively rapidly from few nuclei and had plenty of space in which to grow freely and so develop crystal faces. This rock shows unequivocally that K-feldspar megacrysts can grow in liquid as normal euhedral phenocrysts. Other illustrations of rapidly cooled felsic rocks with independent K-feldspar megacrysts separated by abundant groundmass have been presented by Vernon [2004, figure 3.13] and McDonnell *et al.* [2004, figure 2]. In contrast, Figure 14 shows a large oikocryst of K-feldspar, with numerous, small, predominantly euhedral inclusions of plagioclase, biotite and hornblende, in a synplutonic microgranitoid dyke. Though the K-feldspar in this rock also grew from few nuclei and developed very large grains, the proportion of already crystallized minerals evidently was too large to permit the K-feldspar to grow as a euhedral megacryst.

Figure 21. Mixing of K-feldspar megacrysts into mafic replenishment

Outcrop view of arrested mixing and dispersal of K-feldspar megacrysts from porphyritic granitoid cumulate into overlying mafic sheet, Cadillac Mountain pluton, Mount Desert Island, Maine, USA. Knife 9 cm long.

(2) *Space problem for late growth:* The hypothesis of Johnson and Glazner [2010] encounters the same problem that its authors ascribe to the normal phenocryst hypothesis, namely that space has to be provided for the megacrysts, which would be especially difficult where most of the crystallization of the rock has already occurred. The authors do not explain how sufficient room could be made for the development of megacrysts if only small amounts of melt were present, or how the scattered pockets of liquid produced by the putative melting of small K-feldspar crystals coalesce to form pools large enough to accommodate megacrysts. The deficiency of small K-feldspar crystals in the presence of large ones,

observed by Johnson and Glazner [2010], can be explained by megacryst growth as normal phenocrysts. It is much easier to make space where 60 to 70% of the liquid is available, and so it is more reasonable to accept that K-feldspar megacrysts grow as normal phenocrysts, and that sufficient liquid remains for them to undergo some movement and physical accumulation in granitic magmas.

(3) *Overgrowths on megacrysts:* Once nucleated, K-feldspar megacrysts grow rapidly, compared with growth rates of the other minerals present, as indicated by their size. Fenn [1977] and Swanson [1977] observed experimental growth rates (several millimetres in several days) that are fast enough to produce, in a reasonable time, feldspar crystals as large as any found in granitoids. Evidently enough time is available for megacrysts to reach large sizes before space restrictions force the megacrysts to grow in an interstitial manner, commonly forming crystallographically continuous off-shoots (overgrowths) from the rims of the megacrysts between adjacent grains. These overgrowths are consistent with continued magmatic growth after euhedral megacrystic growth ceased, the overgrowths being impeded mainly by simultaneously crystallizing quartz and feldspar grains [Anderson, 1934; Bateman *et al.*, 1963, p. D16; Exley and Stone, 1964, pp. 135, 159; Booth, 1968, p. 1036: Emmermann, 1969, p. 292: Wilshire, 1969, p. 243; Higgins and Kawachi, 1977, p. 275; Kawachi and Sato, 1978; Vernon, 1986a, p. 5; Higgins, 1999; Vernon and Paterson, 2008]. However, Johnson and Glazner [2010] regarded these interstitial ‘tendrils’ as “remnant pathways by which interstitial K-feldspar migrated toward the megacrysts.” This speculation cannot explain how each independently originating ‘tendril’ (joining others only where they reach the edge of the megacryst) could acquire the same crystallographic orientation.

(4) *Sizes of inclusions in megacrysts:* The sizes of inclusions in K-feldspar megacrysts are usually inferred to reflect the sizes of crystals of the included minerals at the time the megacrysts incorporated them [Kerrick 1969; Mehnert and Büsch, 1981; Vernon, 1986; Vernon and Paterson, 2008a]. This interpretation is confirmed by the small crystals of plagioclase, quartz and biotite in the groundmass around the megacryst in Figure 2. However, Johnson and Glazner [2010] suggested that the inclusions are small because any larger crystals would accumulate (presumably by being pushed aside) at the edges of the growing megacryst — an intuitive idea that is unsupported by microstructural evidence. The common presence of euhedral plagioclase inclusions with normal zoning indicates that the plagioclase crystals were growing independently in the liquid before being incorporated in the K-feldspar megacrysts. As Swanson [1977, figure 3b] found experimentally for a granodioritic composition, the growth rate of plagioclase is much lower than that of alkali feldspar at the degree of undercooling at which alkali feldspar reaches its maximum growth rate. Therefore, a growing megacryst has a good chance of encountering and enclosing plagioclase grains much smaller than itself. In contrast, K-feldspar inclusions in plagioclase are rare, as they are generally too large, though small inclusions of K-feldspar in plagioclase phenocrysts have been described [e.g., Boone, 1962, figure 4].

(5) *Megacrysts involved in magma mixing:* Another problem with the Johnson and Glazner [2010] hypothesis is the common incorporation of K-feldspar megacrysts into mafic magma replenishments in granitic magma chambers [e.g., Vernon, 1983, 1984, 1986, 1990, 1991; Reid *et al.*, 1983; Wiebe, 1993, 1994, 1996; Wiebe *et al.*, 2002; Collins *et al.*, 2006], as shown in Figures 21, 22, 23 and 24. This situation requires that the megacrysts exist independently in enough liquid to mix with the more mafic magma, which would be very difficult or impossible if the megacrysts formed late in largely solid rock.

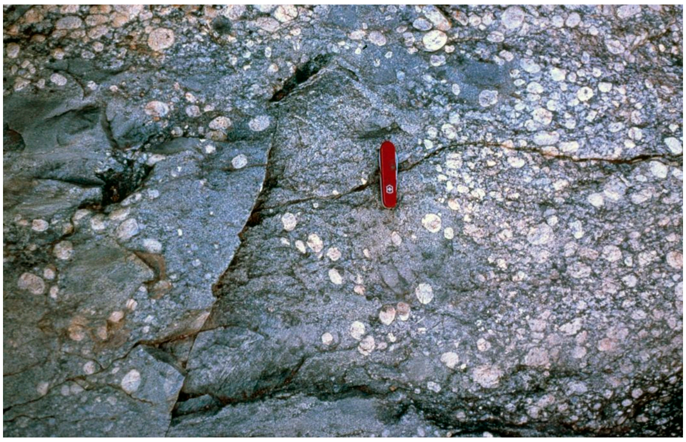
Figure 22. K-feldspar megacrysts in microgranitoid enclave

Microgranitoid enclave with megacrysts of K-feldspar derived from the host magma, Bungulla Adamellite, northern New England Batholith, New South Wales, Australia. Knife 9 cm long.

Figure 23. Microgranitoid enclave with megacrysts

Microgranitoid enclave with abundant megacrysts of K-feldspar derived from the host magma, Wuluuman pluton, Wellington, New South Wales, Australia.

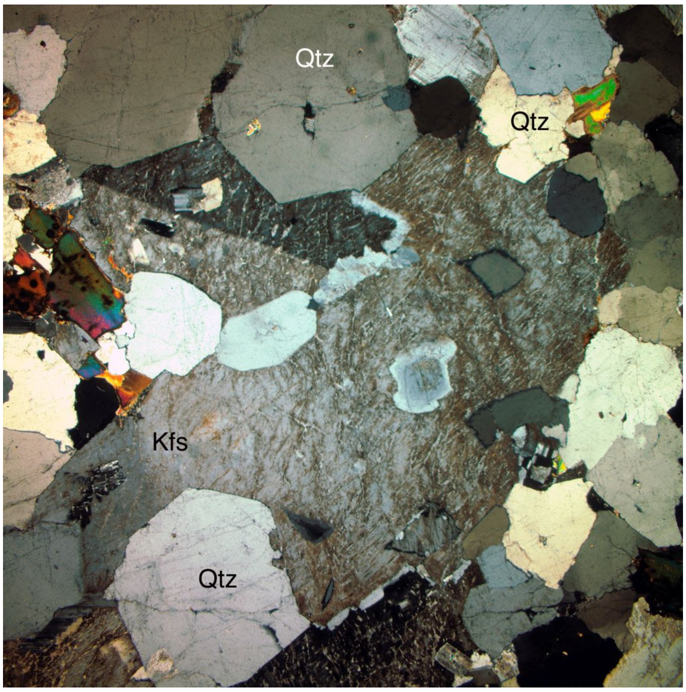
Figure 24. Megacrysts mixed into enclave magma



K-feldspar megacrysts (some with plagioclase rims, forming rapakivi stucture) from the surrounding megacrystic granitoid variably dispersed through more mafic magma, Yundurbulu Batholith, Mount Stafford, central Australia. Knife 9 cm long.

(6) *Supposed 'idiomorphic tendency' of K-feldspar, but not quartz:* Johnson and Glazner (2010) stated that "selective coarsening of K-feldspar relative to other phases is governed by the idiomorphic tendencies of K-feldspar …. In contrast, quartz also crystallizes late but rarely forms euhedral crystals in granites, presumably because it is less idiomorphic." On the contrary, both quartz and K-feldspar develop crystal faces when growing in liquid, as is well known from felsic volcanic rocks, porphyritic microgranitoids (Figures 2, 3, 15) and some granitoids (Figures 18, 25). Euhedral growth of both K-feldspar and quartz is confirmed by euhedral oscillatory zoning patterns (Figures 6, 18, 19), though external boundaries of these minerals in granitoids are commonly anhedral (Figures 6, 19), owing to impingement with adjacent growing grains or minor grain-boundary migration during weak deformation.

Figure 25. Early euhedral quartz



Euhedral crystals of quartz (Qtz) projecting into K-feldspar (Kfs) in granite. Crossed polars; base of photo 7 mm.

(7) *K-feldspar concentrations in granitoids:* Concentrations of euhedral K-feldspar megacrysts in granitoids [Gilbert, 1906; Cloos, 1936; Phillips, 1968, p. 180; Wilshire, 1969, p. 244; Wahrhaftig, 1979; Barrière, 1981; Vernon, 1986, pp. 7-8; Abbott, 1989; Reid *et al.*, 1993; Tobisch *et al.*, 1997; Clarke and Clarke, 1998; Weinberg *et al.*, 2001; Paterson *et al.*, 2005; Vernon and Paterson, 2008a], as shown in Figures 26 and 27, are usually ascribed to physical accumulation. The common magmatic flow alignment of megacrysts [e.g, Gilbert, 1906; Vernon, 1986a; Clarke and Clarke, 1998; Paterson *et al.*, 2005; Vernon and Peterson, 2008a] indicates that the megacrysts are able to rotate in liquid without deforming plastically. The alternative explanation of Higgins [1999] and Johnson and Glazner [2010] for K-feldspar

megacryst concentrations is that solution and regrowth of K-feldspar are concentrated at selected places. However, as noted by Vernon [2004, pp. 64-65], this hypothesis fails to explain why (a) only K-feldspar was precipitated, without quartz, plagioclase and biotite (with which the inferred percolating felsic liquid should also have been saturated), and (b) the concentrated K-feldspar megacrysts typically do not interpenetrate, even where in contact, but tend to remain as separate solids in the concentrating process, whereas simultaneous growth would be expected to produce moulding of one crystal around another. Mechanical concentration is a simpler explanation, which avoids remelting and/or K metasomatism to concentrate the K-feldspar.

Figure 26. Megacryst accumulation

Patch rich in euhedral K-feldspar megacrysts, Cathedral Peak pluton, Tuolumne Batholith, California, USA. The distribution appears to be the result of accumulation, not in situ growth, because the proportion of K-feldspar is much higher than in the bulk of the pluton and is too high for a local magma composition. Knife 9 cm long.

Figure 27. K-feldspar-rich granitoid cumulate

Megacrystic granitoid inferred to have become enriched in megacrysts by physical accumulation, removal of liquid, or both. The strong alignment of the megacrysts reflects magmatic flow, probably involving rotation of the crystals during compaction. United States quarter dollar for scale.

(8) *Rarity of megacrysts in felsic volcanic rocks:* Johnson and Glazner [2010] claimed that because K-feldspar phenocrysts commonly do not occur in dacitic volcanic rocks, they cannot move and accumulate in clusters in magma chambers. However, intuitive assertion is a poor substitute for evidence, and the presence of trough structures with graded layers, as well as local megacryst-rich intrusions [e.g., Weinberg *et al.*, 2001; Paterson *et al.*, 2005; Vernon and Paterson, 2008a] should not be ignored. Many granitoids show evidence of crystal accumulation, by mechanical movement of crystals or crystal aggregates [Paterson *et al.*, 2005; Vernon and Paterson, 2008a], removal of liquid [McMurry, 2001; Vernon and Collins, 2011], or both. Some megacryst-rich accumulations could occur by extraction of the residual liquid commonly inferred to be responsible for many felsic volcanic and tuffaceous rocks. An example is the Bodocó quartz-monzonite pluton, Brazil, which shows no isotopic variation, but considerable modal variation, including K-feldspar megacryst enrichment, which can be attributed to in situ crystal accumulation consequent on loss of interstitial felsic liquid [McMurry, 2001]. The common inability of megacryst-rich magmas to erupt as such to the surface could reflect loss of interstitial liquid or a relatively low volatile content of the magma, even at the

stage when megacrysts are mobile, and so need have no bearing on the previous ability or inability of megacrysts to move, relative to liquid, in plutons.

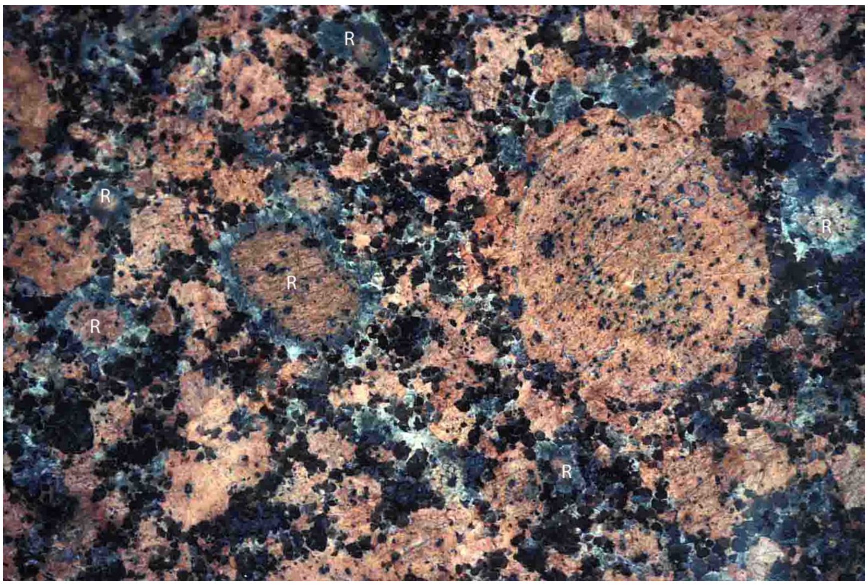
(9) *Consequence of repeated replenishment:* Johnson and Glazner [2010] asserted that “granitic plutons are emplaced incrementally and … megacrystic textures are evidence of such an emplacement process” (that is, ‘thermal recycling’ occurs as a result of replenishment), but that “some compositionally indistinguishable granitic plutons contain K-feldspar megacrysts whereas others do not.” These statements combined raise a problem for the Johnson and Glazner [2010] hypothesis, because the repeated replenishment the authors infer to be responsible for the formation of all granitoid plutons, should cause ‘thermal recycling’ and hence growth of megacrysts in all of them.

(10) *Rapakivi structure and K-feldspar antecrysts:* K-feldspar megacrysts with plagioclase rims (‘rapakivi structure’) dispersed through non-mantled megacrysts (Figures 28, 29) imply that crystals that previously had reacted with liquid (because of changed P-T-X_{H2O} conditions or magma mixing) were derived from another magma or a different part of the same magma, and then mixed with non-reacted crystals precipitated from the host magma. Though foreign, such ‘antecrysts’ are nevertheless magmatic. Moreover, because of their evidence of reaction and replacement and/or mantling, these crystals grew early enough for magmatic reaction or later mixing to occur.

Figure 28. Rapakivi antecrysts

Rapakivi granite, southern Finland, showing K-feldspar megacrysts with light-coloured plagioclase rims (antecrysts) dispersed through non-mantled megacrysts. Despite the presence of lichen on the outcrop, the contrast between mantled and non-mantled megacrysts is clearly shown.

Figure 29. Antecrysts in rapakivi granite



Sawn slab of rapakivi granite, southern Finland, showing K-feldspar megacrysts (R) showing grey plagioclase rims (antecrysts), labelled “R”, dispersed through non-mantled megacrysts. Base of photo c. 30 cm.

General inference about late K-feldspar in granitoids: The foregoing discussion confirms that, though K-feldspar typically nucleates late in the crystallization history, it generally has plenty of liquid volume in which to develop large crystals, which consequently can move, relative to liquid, as witnessed by numerous examples of flow-aligned megacrysts and megacryst-rich cumulates.

Hypothesis 3 (granites are effectively metamorphic rocks)

Many petrologists have assumed, generally without presenting evidence, that extensive subsolidus grain-shape changes occur as granitoids cool [e.g., Spencer, 1937; Drescher-Kaden, 1948; Augustithis, 1973; Pitcher, 1979; Hughes, 1982, p. 162; Hibbard, 1995, p. 228; Pitcher, 1997 p. 69; Bindeman, 2003, p. 367; Bachmann *et al.*, 2007, p. 7; Kemp *et al.*, 2008, p. 337]. For example, Tuttle [1952] and Tuttle and Bowen [1958] speculated that independent grains of K-feldspar and plagioclase in some granitoids are formed by extreme solid-state exsolution from a single feldspar, and Luth [1976, p. 336] stated that “most granitic rocks exhibit textural and mineralogical features which are less related to the ultimate magmatic origin and early history than to subsequent sub-solidus recrystallization.” O’Brient [1986, p. 608] referred to “complete subsolidus recrystallization that affects all but the shallowest and most rapidly quenched intrusions” and asserted that “plutonic rocks only indirectly preserve primary magmatic features.” Bartley *et al.* [2004] and Coleman *et al.* [2005] suggested that recrystallization (by which they presumably implied grain growth, rather than strain-induced recrystallization) in granitoids can obscure or even obliterate major structures, such as internal contacts in plutons. Similarly, Glazner and Bartley [2006] stated (also without presenting evidence) that “recrystallization is a well-established mechanism for rearranging crystal boundaries and obliterating contacts between lithologically identical rocks” in granitic intrusions. In addition, Coleman *et al.* [2005, p. 18] stated that the structures shown by K-feldspar in the Tuolumne Batholith, California, USA, “are not clearly igneous … and have been significantly modified by late-stage processes,” again without presenting evidence.

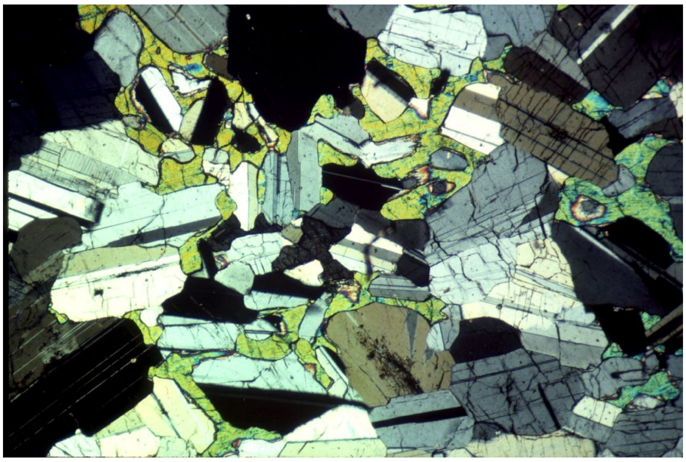
Perhaps the broadest assertions of this kind have been made by Coleman *et al.* [2005, p. 1], who stated that “thermal models indicate that slow incremental growth can maintain much of a pluton at temperatures corresponding to the amphibolite facies of metamorphism for extended time periods” promoting “subsolidus textural modification that is likely to further obscure any primary intrusive contacts between intrusive increments,” and McBirney [2009, p. 4], who wrote that “the textures of most coarse-grained igneous rocks are essentially metamorphic… As they cool, the minerals pass through a range of conditions in which a metamorphic petrologist would normally expect there to be conspicuous changes, including both compositional and textural re-equilibration of the kind seen in other rocks under comparable conditions.”

The foregoing assertions about grain-shape changes during slow cooling in granitoids evidently spring from the inferred long cooling times of large felsic plutons, leading to understandable speculations that they must therefore change their microstructures to resemble high-grade metamorphic rocks. However, Vernon and Paterson [2008c] presented detailed structural evidence that extensive grain-shape changes typically do not occur in cooling granitoids, in the absence of tectonic deformation or metamorphism, though minor grain-boundary adjustments can occur locally, and intragranular changes (such as exsolution and deuteric alteration) are common. Hypothesis 3 encounters the following four main problems.

(1) *Contrast with mafic rocks:* Grain-shape adjustments evidently do occur in mafic-ultramafic cumulate rocks that cool slowly from very high temperatures, because many such rocks have grain shapes indicative of solid-state grain-boundary adjustment [e.g., Voll, 1960; Weedon, 1965; Vernon, 1970, 1976, 2004, pp. 224-229; Hulbert and von Gruenenwaldt, 1985; Reynolds, 1985; Mathison, 1987; Hunter, 1987, 1996; Higgins, 1991, 1998; Waters & Boudreau, 1996; Duchesne, 1999; Holness, 2005, 2010; Holness *et al.*, 2005; O’Driscoll *et al.*, 2010], as shown in Figures 30, 31, 32, 33 and 34. Vernon [1970, 2004] found that some gabbros and ultramafic cumulates are essentially polygonal aggregates (Figure 34, 35) that resemble granulite facies metamorphic aggregates (Figure 36), except that they commonly preserve some residual elongate igneous shapes without crystal faces (Figure 37). On the other hand, many gabbros preserve abundant elongate plagioclase crystal shapes and euhedral plagioclase inclusions in pyroxene, and hence have an overall igneous appearance (Figures 38, 39). Vernon [1970] found that dihedral angles in some mafic/ultramafic cumulates are similar to those in typical

granulite facies compositional equivalents, but Holness [2005 and this volume] and Holness *et al.* [2005] measured variable dihedral angles in aggregates in some individual oikocrysts, suggesting that equilibration of interfacial angles and change of igneous microstructure are limited, compared with aggregates of the same minerals in granulite facies metamorphic rocks. Evidently, mafic and ultramafic plutonic rocks are capable of undergoing extensive subsolidus grain-boundary changes in the absence of imposed metamorphism and deformation, but minimum-energy grain and inclusion shapes are not always achieved.

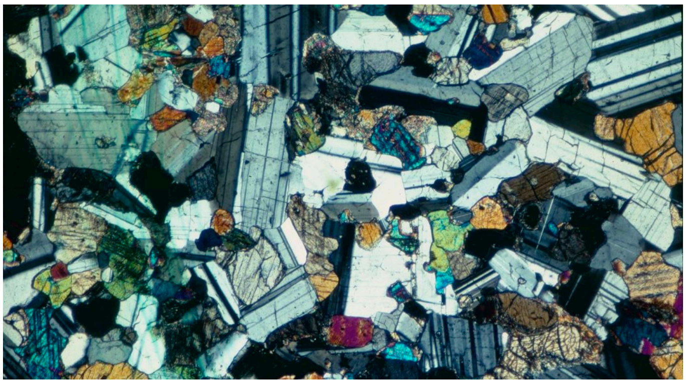
Figure 30. Subsolidus grain-shape adjustment in gabbro



Gabbro from the Bushveld mafic-ultramafic igneous complex, South Africa, showing moderately aligned, elongate grains of twinned plagioclase, with clinopyroxene containing inclusions of plagioclase in ophitic to subophitic intergrowths. The inclusions of plagioclase are smaller than the plagioclase grains outside the clinopyroxene, reflecting the shorter growth period of the included plagioclase. The rounded corners of the plagioclase inclusions, together with the clinopyroxene versus plagioclase/plagioclase dihedral angles indicate that solid-state adjustment of grain boundaries occurred during slow cooling. Crossed polars; base of photo 4.4 mm. From Vernon (2004, figure 3.46).

Adcumulates typically have polygonal grain shapes (Figures 33, 34, 35, 37), whereas non-cumulate ophitic gabbros commonly show weak or no evidence of grain-shape changes with cooling (Figure 39). This difference could be due to the tendency for 'sintering' to occur in cumulate aggregates in liquid (leading to polygonal grain shapes), whereas simultaneously crystallizing plagioclase and pyroxene in ophitic gabbros and dolerites produce liquid-free intergrowths that would not show sintering tendencies.

Figure 31. Subsolidus changes in gabbro



Gabbro, Days Creek, New England, New South Wales, Australia, with abundance of curved, irrational grain boundaries, polygonal grain shapes, and dihedral angles between plagioclase and pyroxene, though retaining many elongate plagioclase shapes reflecting a magmatic origin. Crossed polars; base of photo 4.4 mm.

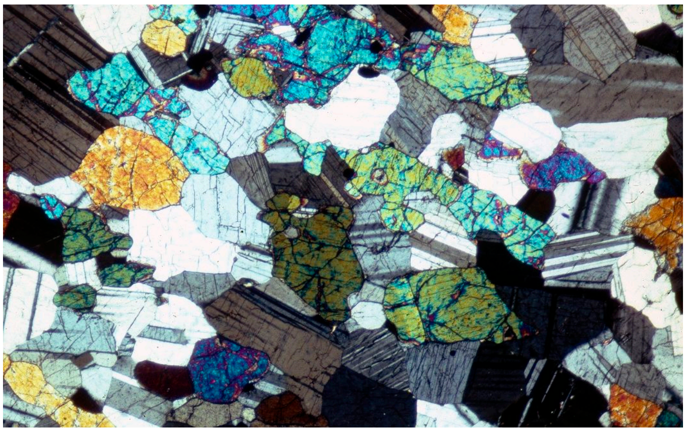
Figure 32. Polygonal grain shapes in gabbro

Gabbro dominated by polygonal grain shapes, rounded inclusion shapes, and curved grain boundaries, reflecting extensive subsolidus grain-shape adjustment. Plane-polarized light; base of photo c. 2 mm.

Hotter intrusions and deeper, more slowly cooled intrusions would be expected to undergo the most extensive grain-shape changes during cooling (Marian Holness, personal communication), other factors (such as deformation) being uninvolved. However, the gabbro illustrated in Figure 31 shows almost no residual crystal faces, though many of the plagioclase grains are elongate, reflecting approximate original shapes and sizes.

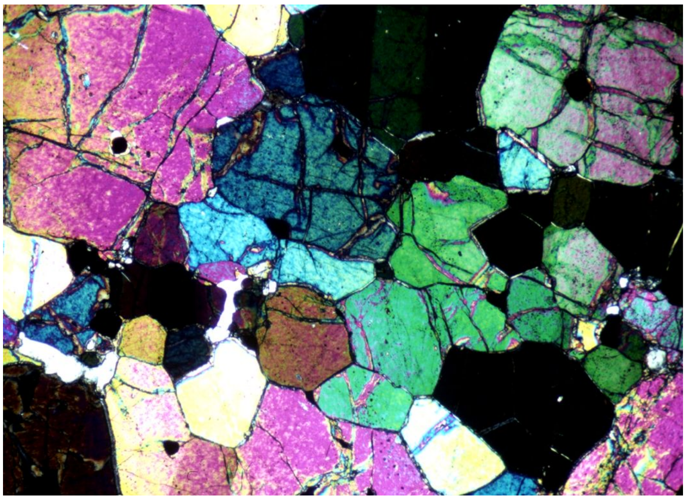
The intrusion is small, occurs in low-grade rocks, and does not appear to have been metamorphosed or deformed. The reasons for the grain-shape changes in this rock are unclear, but could be connected with an original cumulate origin, which promoted some high-temperature 'sintering'.

Figure 33. Polygonal grain shapes in troctolite



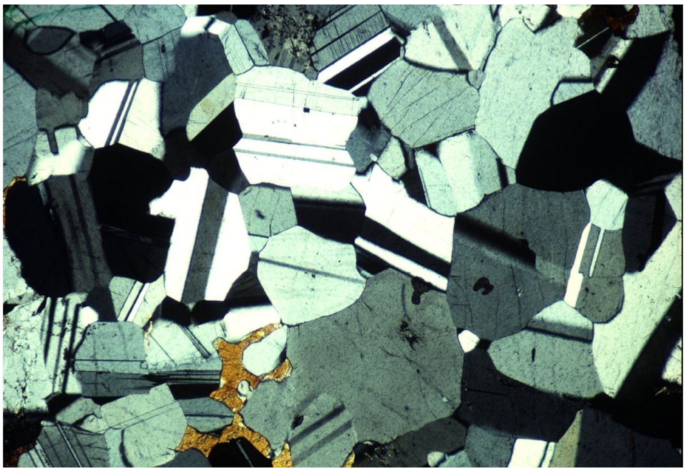
Troctolite, Rhum layered igneous complex, Scotland, dominated by polygonal olivine and plagioclase grain shapes formed by grain-boundary movement during slow cooling from high temperature. Crossed polars; base of photo 4.4 mm.

Figure 34. Polygonal olivine in dunite



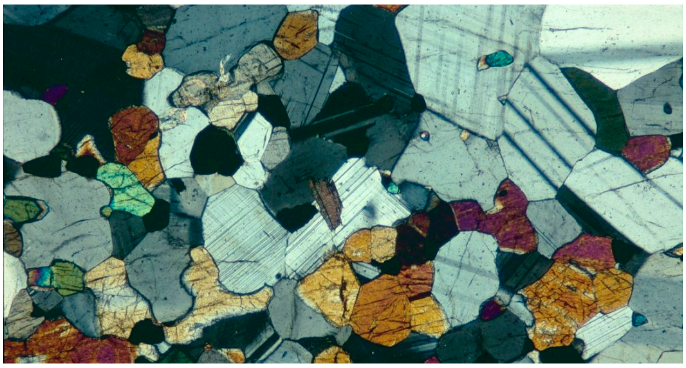
Ultramafic cumulate (dunite) showing polygonal olivine grain shapes formed by grain-boundary movement during slow cooling from high temperature, Rhum layered igneous complex, Scotland. Crossed polars; base of photo 4.4 mm.

Figure 35. Polygonal plagioclase in anorthosite



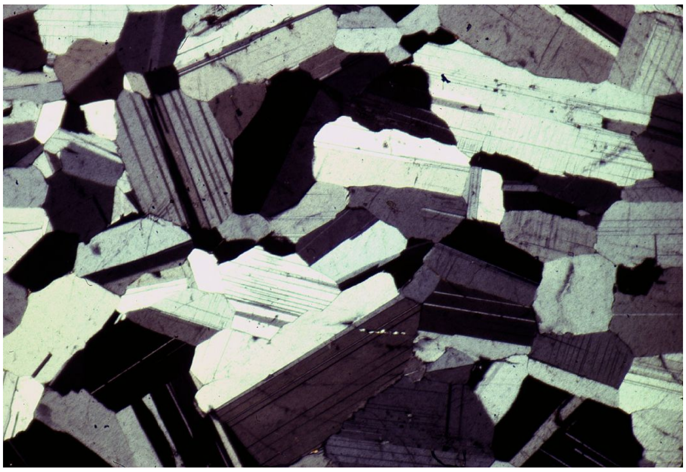
Polygonal aggregate of calcic plagioclase in an anorthosite cumulate from the Bushveld Complex, South Africa. Crossed polars; base of photo 4.4 mm. From Vernon (2004, figure 4.41A).

Figure 36. Granulite facies mafic microstructure



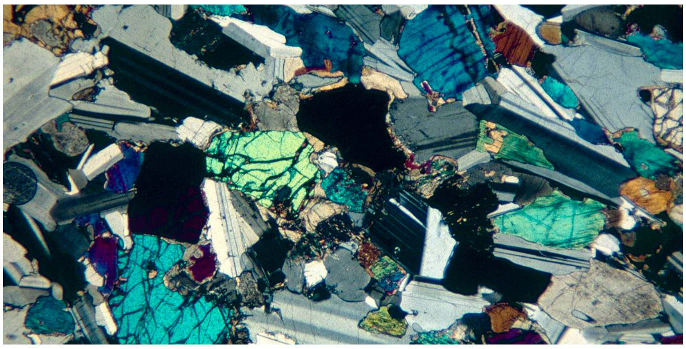
Polygonal grain shapes of plagioclase and pyroxene that are typical of the microstructure of granulite facies mafic metamorphic rocks. Crossed polars; base of photo 4 mm.

Figure 37. Anorthosite with residual elongate grain shapes



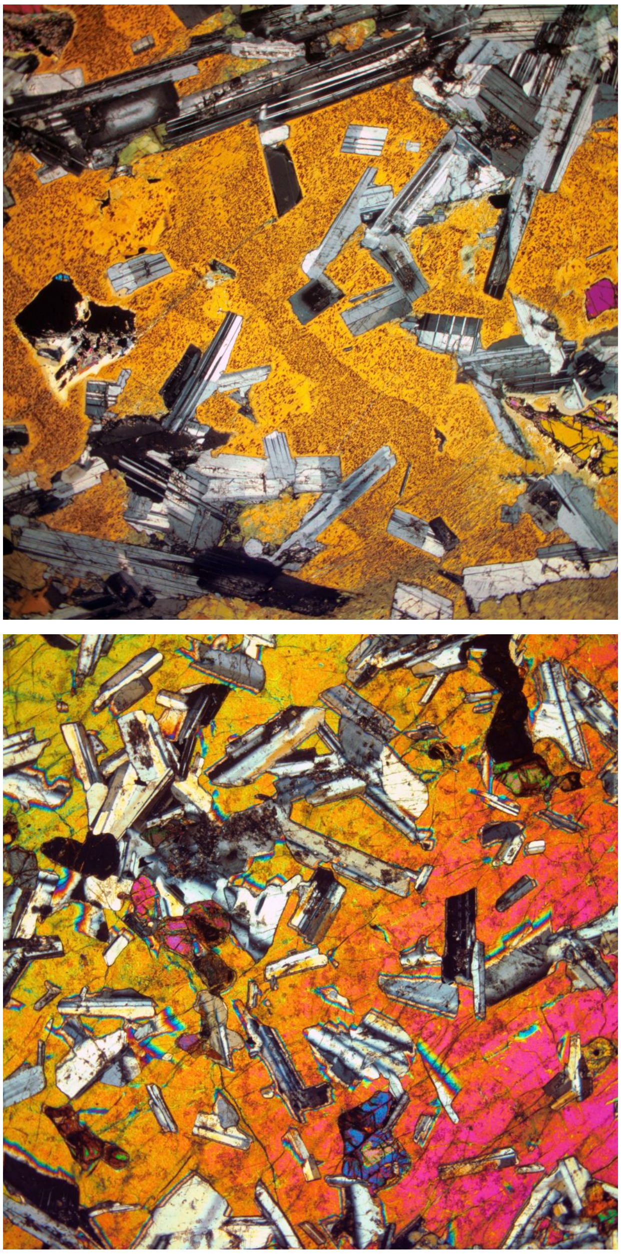
Polygonal aggregate of calcic plagioclase, in a section perpendicular to that shown in Figure 35. Despite the solid-state grain-boundary adjustment, elongate magmatic grain shapes aligned by magmatic flow have been preserved. Crossed polars; base of photo 4.4 mm. From Vernon (2004, figure 4.41B).

Figure 38. Gabbro microstructure



Gabbro consisting of olivine, pyroxene and elongate plagioclase grains. The elongate plagioclase grains reflect a magmatic origin, compared with the typically polygonal grains of high-grade metamorphic rocks (Figure 36), but most grain boundaries are irrational, reflecting subsolidus adjustments Crossed polars; base of photo 4 mm.

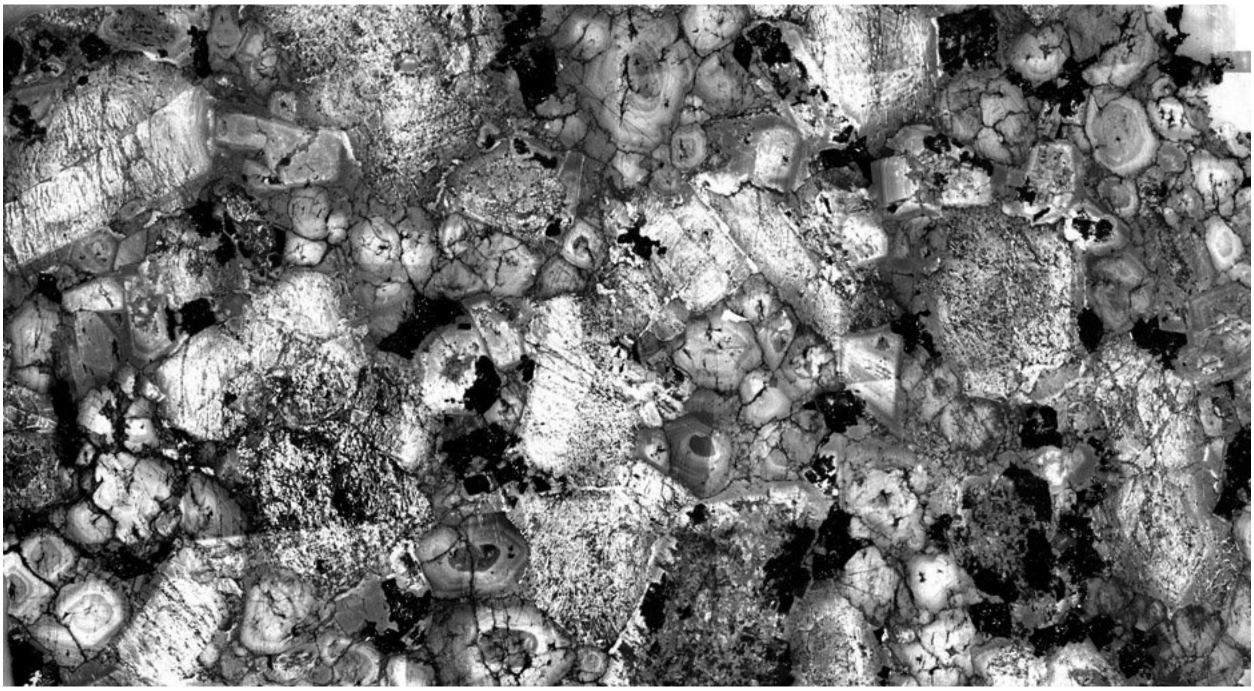
Figure 39. Ophitic structure very well preserved in gabbro



(A) Large grain of clinopyroxene with inclusions of elongate plagioclase grains, forming an ophitic microstructure in gabbro. The rounded corners of some of the plagioclase inclusions suggest minor solid-state adjustment during slow cooling, but most inclusions are euhedral and the overall igneous microstructure is retained. Crossed polars; base of photo 7 mm.

(B) Similar situation to that shown in (A), but with more rounding of plagioclase corners, suggesting a higher degree of solid-state adjustment during cooling, but still with preservation of the igneous structure. Crossed polars; base of photo 3.5 mm.

Figure 40. Oscillatory zoning in quartz and feldspar



Quartz grains with euhedral concentric oscillatory Ti zoning, revealed by SEM cathodoluminescence, reflecting former crystal growth habits, Vinalhaven pluton, Maine, USA. Some of the zoning patterns indicate rounded former shapes suggesting repeated dissolution, followed by euhedral regrowth. Oscillatory zoning is also present in the plagioclase and K-feldspar (poorly polished). The zoning patterns in all three minerals are evidence of magmatic crystallization. Base of photo 40 mm. Photo by Bob Wiebe.

In contrast to the behaviour of hotter mafic rocks, microstructural evidence (discussed below) indicates that major grain-shape changes during cooling do not occur in most granitoids, in the absence of tectonic deformation. As McBirney [2009, p. 4] wrote: "the story of plutonic rocks does not end with precipitation of a stable mass of cotectic minerals", because of the abundant evidence of subsolidus intragranular changes (e.g., exsolution in alkali feldspar) and deuteric alteration in granitoids, but these processes typically do not involve major grain-shape changes [Vernon and Paterson, 2008c], even for granitoids in which subsolidus intragranular changes are prominent [e.g., Haapala, 1997]. The contrast between the behaviour of granitoid cumulates and mafic-ultramafic cumulates is probably due mainly to the lower solidus temperatures and hence smaller cooling temperature ranges of granitoids.

(2) *Preservation of oscillatory zoning:* The putative grain shape changes during cooling would be most likely to occur by high-temperature recrystallization, involving the formation of smaller new grains or the modification and rearrangement of existing grains by grain-boundary 'sweeping' during grain boundary migration recrystallization ('fast grain boundary migration'), which is most effective at high temperatures, especially if water is present [e.g., Vernon, 2004, pp. 338-342; Vernon and Clarke, 2008, p. 273]. Vernon and Paterson [2008c] emphasized that oscillatory zoning would be truncated or even removed by grain-boundary 'sweeping'. On the contrary, oscillatory and other zoning patterns are typically well preserved in granitoids, and are not appreciably truncated by grain boundaries (Figures 1, 5, 6), except for uncommon examples of 'contact melting' resulting from impingement at the magmatic stage (Figure 7) and internal pattern truncations resulting from corrosion in response to magma mixing during crystal growth (Figure 6). Some granitoids are characterized by complete oscillatory zoning patterns in all three felsic minerals, quartz, plagioclase and K-feldspar [e.g., Wiebe *et al.*, 2004], as shown in Figure 40, and, as mentioned previously, oscillatory zoning can also occur in a wide range of common granitic minerals, such as zircon, allanite, sphene, apatite, cordierite, hornblende and biotite.

Figure 41. Micrographic intergrowth

Graphic intergrowth (granophyric variety) of quartz and alkali feldspar in granite, Tallong, New South Wales, Australia. Preservation of this structure, without any tendency to produce rounded or polygonal grain shapes testifies to a lack of solid-state grain-boundary adjustment during cooling. Crossed polars; base of photo 7 mm.

(3) *Preservation of other igneous microstructures:* Characteristic magmatic features, such as elongate, euhedral to subhedral feldspar or quartz grains, euhedral plagioclase inclusions in quartz and K-feldspar, and graphic intergrowths in some higher-level granitoids are uncommon in metamorphic rocks of equivalent composition, in which solid-state recrystallization/neocrystallization processes dominate [Vernon & Paterson, 2008c]. In particular, graphic intergrowths (Figure 41), with relatively high-energy grain-boundary configurations, in many high-level granitoids show no evidence of recrystallization to form the polygonal aggregates typically produced where such intergrowths are recrystallized [e.g., Vernon, 2004, pp. 256-257, fig. 4.65].

(4) *Contrast with metamorphic microstructures:* Vernon and Paterson [2008c] emphasized that the shapes of grains and included grains in granitoids typically do not resemble those of medium- to high-grade metamorphic rocks. For example, inclusions of plagioclase in granitoid minerals are typically euhedral, and can be arranged in crystallographic zones in the host mineral (Figure 18), whereas inclusions of plagioclase in metamorphic minerals are commonly rounded and either random or arranged in trails [e.g., Vernon, 1999, 2004]. The contrast with high-grade metamorphic rocks is due partly to the lack of driving forces for recrystallization, owing to the chemical compatibility of the granitoid mineral assemblage, and especially the absence of sufficient solid-state deformation to promote recrystallization [Vernon and Paterson, 2008c].

I emphasize that the foregoing discussion refers to preservation of primary granitoid microstructures during slow cooling in the absence of solid-state deformation or metamorphism, which can induce recrystallization, involving processes such as grain-boundary migration and the formation of new grains [e.g., Vernon, 2000a; 2004; Vernon and Clarke, 2008; Vernon *et al.*, 2010].

Conclusions

Granitoid microstructures are consistent with crystallization in liquid, even if the crystallization occurred elsewhere before final positioning of the crystal, as with antecrysts. Structural evidence indicates that: (1) solid restite is generally absent, (2) K-feldspar megacrysts crystallize as normal phenocrysts with sufficient room in which to grow, rotate into foliations, move into new locations and concentrate passively, and (3) granitoids generally do not undergo major changes in grain shapes during slow cooling.

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