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Journal of Structural Geology 26 (2004) 1465–1481

JOURNAL OF STRUCTURAL GEOLOGY

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The significance of microgranitoid enclave shapes and orientations

Scott R. Paterson[a,*], Geoffrey S. Pignotta[a], Ron H. Vernon[a,b]

[a]*Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089-0740, USA*

[b]*Department of Earth and Planetary Sciences and GEMOC, Macquarie University, Sydney, NSW 2109, Australia*

Received 18 January 2003; received in revised form 14 July 2003; accepted 25 August 2003

Available online 17 April 2004

Abstract

Enclaves are often incorrectly used to measure magmatic strains in plutons. We emphasize that microgranitoid enclaves are not like other ellipsoidal markers used to determine strain for the following reasons. (1) Adjacent enclaves may form at different times and different places and initially have non-spherical shapes with axial ratios up to 2.7. (2) The final shapes and orientations of enclaves are a complex function of (a) initial shape and temperature of enclaves, (b) subtle changes in composition, melt percents, volatiles, grain sizes, and thus temporally variable viscosity contrasts between the enclave and magma, (c) a competition between strain and interfacial energies, and (d) deformation path, which may include internal strain and rigid rotations caused by magma flow during ascent, convection, expansion, chamber boundary processes, and tectonism. (3) Enclaves spend much of their time in magma as relatively rigid objects, and thus rigidly rotate and potentially break apart, rather than strain at matrix strain rates. (4) In some instances, enclaves do not record or track finite strain. Because of the above, final enclave populations are heterogeneous, and the use of single enclaves or enclave populations as strain markers violates many assumptions needed to complete strain analyses. On the other hand, a comparison of the preserved characteristics of igneous layering, mineral fabrics, and carefully evaluated enclave fabrics, including internal mineral alignment in enclaves, may provide qualitative data on the changing magnitude and kinematics of magmatic strains.

Keywords: Expanding plutons; Rf/ϕ analyses; Granites; Igneous enclaves; Magmatic foliations; Microgranitoid enclaves; Strain analyses

1. Introduction

Microgranitoid enclaves or 'mafic inclusions', typically formed by mingling of two magmas (Vernon, 1983; Frost and Mahood, 1987), are common in many plutons (Fig. 1). Their wide distribution and common ellipsoidal shapes, as well as the lack of other suitable markers in plutons, make them a natural target for use as strain markers. Williams and Tobisch (1994) explored some of the challenges of using enclaves to determine solid-state strains. However, enclaves are also used to quantify magmatic strains, which are often assumed to occur during emplacement (Holder, 1979; Courrioux, 1987; Hutton, 1988; Ramsay, 1989; John and Blundy, 1993). Even though the use of enclaves as magmatic strain markers has been challenged (Paterson and Vernon, 1995; Paterson et al., 1998), they continue to be used routinely (e.g. Molyneux and Hutton, 2000; Vassallo and Wilson, 2002). Given that the quantitative results of such studies are used to evaluate a wide variety of magma ascent and emplacement mechanisms, and sometimes the nature of syn-emplacement tectonism, we feel that further evaluation of this issue is important.

In this paper we emphasize that microgranitoid enclaves are not like other ellipsoidal markers used to determine strain (e.g. conglomerates or volcanic breccia), and thus careful evaluation of enclave data sets is needed prior to using them in any quantitative manner. We suggest that the following need to be addressed if geologists want to obtain meaningful results from enclave shapes and orientations, or their spatial distribution: (1) the initial characteristics of single enclaves and enclave populations and temporal and spatial variation of enclave formation; (2) enclave rheology and enclave/host magma viscosity contrasts; (3) whether enclaves track finite strain, particularly in situations where multiple magmatic fabrics exist; and (4) the final variability in shapes and orientations of enclave populations. We begin by reviewing the assumptions made to successfully complete strain analysis using spherical or ellipsoidal markers in all rock types. We then examine each of the

* Corresponding author. Tel.: +1-213-740-6103; fax: +1-213-740-8801.
E-mail address: paterson@usc.edu (S.R. Paterson).

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doi:10.1016/j.jsg.2003.08.013

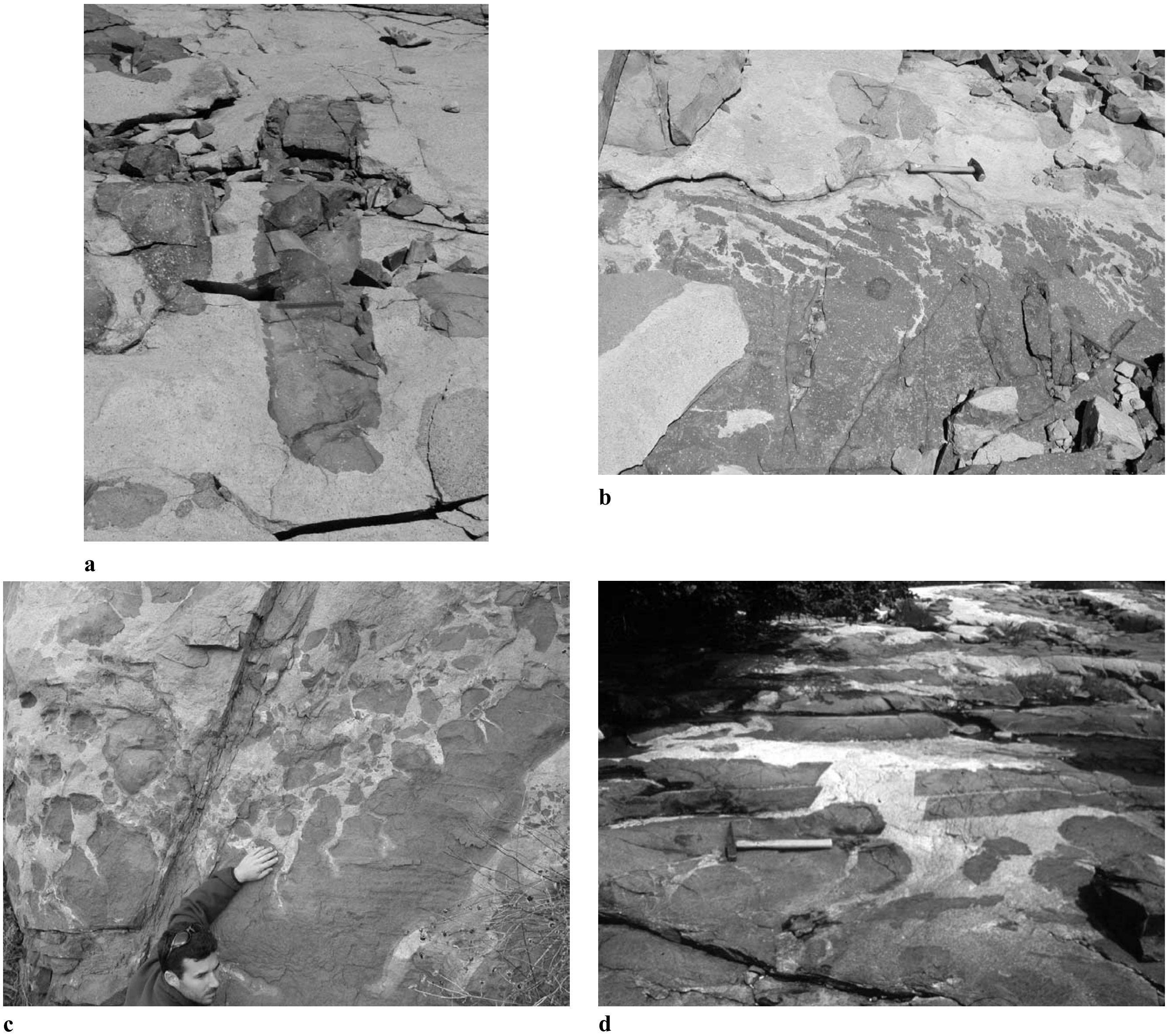


Fig. 1. Field photos showing characteristics of enclave formation. (a) Disrupted mafic dike with crenulate margin in the granitic Post Peak pluton, central Sierra Nevada, California. Dike width ~50 cm. (b) Close-up of another dike margin in the Post Peak pluton, showing disaggregation of dike and formation of enclaves. Note that some enclaves have large length/width ratios. Hammer for scale. (c) Margin of mafic dike in the Guadalupe Igneous Complex, Sierra Nevada, California, displaying disaggregation of dike and formation of enclaves. (d) Mafic sheets in Cadillac Mountain pluton, Maine showing disaggregation of sheets and formation of enclaves. See Wiebe (1994, 1996) for detailed discussion of this photo.

above issues and provide natural examples in which individual enclaves or enclave populations do not track all or part of the strain history. We conclude by considering possible approaches and resulting type(s) of information accessible from the qualitative evaluation of markers, including enclaves, in plutons.

2. Review of strain analyses

Our intent is to evaluate whether or not single enclaves or enclave populations are useful strain markers. While doing so, it is important to keep in mind the conditions that must be met in order to successfully determine strain from any set of objects. We find it useful to consider assumptions required to determine strains in other rock types, such as conglomerates or lapilli tuffs, and then evaluate the extent to which using enclaves to measure magmatic strains in plutonic rocks may or may not be the same. We focus on the three most common techniques used to measure strains from enclaves: (1) means of single enclaves (Lisle, 1977; Hutton, 1982), (2) Rf/ϕ techniques, which use the shapes and orientations of ellipsoidal markers (e.g. Shimamoto and Ikeda, 1976; Miller and Oertel, 1979; Wheeler, 1986), and (3) Fry analyses, which use the center-to-center distances between objects (e.g. Hanna and Fry, 1979; Erslev, 1988).

Assumptions required to apply the above techniques include the following. (1) Strain is homogeneous over the scale of individual analyses. (2) Markers are passive, or, alternatively, are part of a marker-supported population (Gay, 1968), or else a means of correcting for differences in marker versus matrix viscosities is applied (Gay, 1968; Freeman, 1987). (3) Initial marker shapes and orientations or the characteristics of initial marker populations are known or assumed. If averaged means of single markers or populations of markers are used, all markers are assumed to be initially spherical. If the Rf/ϕ technique is used, an initial assumption of evenly distributed shapes and orientations of markers is made (Lisle, 1985). To apply Fry analyses it is assumed that statistical averages of initial center-to-center distances are the same in all directions or that any departure from this is known (Hanna and Fry, 1979). (4) Single markers do not have irregular shapes in three dimensions (e.g. Srogi and Lutz, 1988) and can be approximated by an ellipsoid, and tensor averages of populations of marker orientations and shapes can also be represented by an ellipsoid (Wheeler, 1986; De Paor et al., 1988). (5) If populations of markers are analyzed, all markers are assumed to be the same age and to have shared the same strain history. (6) Sufficient markers are used to statistically characterize the population of markers at the scale of analyses. (7) Data are collected at a scale for which principal planes of strain exist (Treagus and Lisle, 1997). For application of Fry analyses, the following additional assumptions are made. (8) True centers of each object are used, or normalizing techniques are applied to correct for use of apparent centers (Erslev, 1988; Dunne et al., 1990). (9) Marker populations are clustered or anticlustered, the degree of clustering/anticlustering controlling the quality of results (Hanna and Fry, 1979; Crespi, 1986).

Some of these assumptions (e.g. numbers 2 and 3) remain problematic for any type of strain analysis. Moreover, below we argue that several of these assumptions, such as the characteristics of initial markers or marker populations, marker/matrix viscosity contrasts, and the temporal relationship between markers, are even more problematic when microgranitoid enclaves are used to measure magmatic strains.

3. Temporal and spatial variation in the formation of enclaves and enclave populations

Microgranitoid enclaves (igneous enclaves, 'mafic enclaves') are very common in granites (Phillips, 1880; Harker and Marr, 1891; Harker, 1904, 1909; Pabst, 1928; Blake et al., 1965; Wiebe, 1968, 1973, 1974, 1994, 1996; Didier, 1973; Fershtater and Borodina, 1977; Blake, 1981; Hibbard, 1981; Reid et al., 1983; Vernon, 1983, 1984, 1986, 1990, 1991, 1996; Vernon et al., 1988; Didier and Barbarin, 1991). They are generally felsic to intermediate in chemical composition (rarely mafic), are rounded, scalloped or lenticular in shape, and are finer-grained and typically more mafic than the host granite. They have igneous microstructures, commonly with euhedral phenocrysts, oscillatory-zoned plagioclase, and mineral alignment reflecting magmatic strain. Some show chilled margins against the host granite. These features indicate that the enclaves were originally magma globules that strained and quenched to finer-grained solid enclaves in the host magma (e.g. Walker and Skelhorn, 1966; Blake, 1981; Reid et al., 1983; Vernon, 1983, 1984; Vernon et al., 1988). Microgranitoid enclaves also occur in compositionally equivalent volcanic rocks (Wilcox, 1966; Bacon and Metz, 1984; Vernon, 1990, 1991), where their commonly partly glassy groundmass confirms that they were magma globules in the parent granitic magma (Vernon, 1983, 1991).

Microgranitoid enclaves typically show microstructural evidence that before their parent magma globules were incorporated into the host magma (*undergoing magma mingling*), they underwent *magma mixing*, in a setting where the mafic magma was more abundant than the felsic magma (Vernon, 1983, 1986, 1990, 1991). The evidence in enclaves includes: (1) quartz xenocrysts, commonly with mafic rims, forming 'ocelli' or mantled xenocrysts, (2) K-feldspar megacrysts identical to those in the host, which are commonly, though not necessarily, corroded and/or rimmed with plagioclase, and (3) corrosion, overgrowths and sharp zoning discontinuities (compositional spikes) in plagioclase (e.g. King, 1964; Wiebe, 1968; Hibbard, 1981). These features reflect compositional instability of minerals mixed into the more mafic magma from the felsic magma. Thus, the magma that gives rise to the enclaves generally appears to be of hybrid origin.

Some mixing may occur locally in the host granite before the enclaves solidify (e.g. Frost and Mahood, 1987; Vernon, 1990; Wiebe, 1994, 1996; Wiebe and Collins, 1998), but the local proportion of mafic to felsic magma needs to be high enough to keep the more mafic magma sufficiently fluid for mixing to occur. Generally, the enclaves are too small and isolated for this process to occur, except perhaps in the very margins of some enclaves. Thus, the mixing mostly occurs outside the present host magma chamber, presumably in deeper magma bodies that break up on encountering the main magma body to form the microgranitoid enclaves that become dispersed in the host magma.

In the above situations, enclaves may have a complex history prior to arriving in the final chamber where they are preserved. Furthermore, there is no a priori reason why individual enclaves should form as initial spheres and several reasons why they probably should not. Two models of initial formation of microgranitoid enclaves are: (1) dikes intrude into magma chambers and break apart (Fig. 1a–c) (Frost and Mahood, 1987; Smith, 2000), and (2) injected mafic sheets form along chamber floors (Vernon, 1983; Wiebe, 1994, 1996; Wiebe and Collins, 1998) and their margins break apart and mingle (Fig. 1d). In both models, the more mafic bodies are sheet-like and break apart by either boudinage (Foster and Hyndman, 1990; Williams and Tobisch, 1994) or mechanical instabilities (Rayleigh-Taylor) driven by buoyancy, thermal, or chemical gradients (Fig. 1b and c) (Marsh, 1981; McBirney, 1993; Bergantz, 2000; Smith, 2000). The first process requires flow of the host magma and results in rectangular pieces that may become ellipsoidal with time (Fig. 1) (Foster and Hyndman, 1990). The second process results in irregular blobs with variable wavelengths that migrate away from mafic margins in static magmas or along more complex paths in flowing magmas (Fig. 1). Once magma batches are separate from the parent layers, their evolving shapes reflect a competition between interfacial energy, which drives blobs towards spherical shapes, and coupling with the flowing magma, which tends to strain and potentially break apart enclaves (Williams and Tobisch, 1994).

To evaluate initial shapes, we have completed 10 two-dimensional analyses of shapes and orientations of enclaves forming at the margins of dikes (e.g. Fig. 1b and c). The ratios of long/short axes range from 1.1 to >2.7, and long axes are typically at high angles to the dike walls. Thus, we contend that microgranitoid enclaves rarely begin as perfectly spherical objects and may not form in magma that is necessarily static. We also emphasize that different enclaves may form at different times (from different dikes or injected sheets, or as instabilities form at different times/rates), a point to which we return to below. These observations call into question the appropriateness of using the shapes and orientations of single enclaves to determine strains.

If we ignore the processes by which enclaves form, one might imagine a situation in which a population of enclaves comes into existence and then subsequently shares the same strain history. We would then need to know the shapes and orientations of the undeformed enclaves or make one of the following assumptions about the population: (1) all enclaves were initially spherical; (2) enclave ratios and orientations are evenly distributed; or (3) center-to-center distances are initially the same in all directions. If knowledge about the initial population characteristics is available, we could estimate the strain experienced by the population using Fry or Rf/ϕ techniques. This assumes that enclaves are not added after the population begins to strain, that enclaves do not continue to break apart during straining, and that all enclaves behave the same way throughout the strain history (discussed further in sections below).

To our knowledge, only indirect data exist for evaluating the characteristics of initial enclave populations, largely because ALL preserved enclave populations have been deformed during transport to their preserved site. However, one approach used by others is to assume that enclaves in the center of plutons are in 'low strain sites' and thus represent unstrained populations (e.g. Holder, 1979; Hutton, 1988; Ramsay, 1989; Molyneux and Hutton, 2000). This is a puzzling assumption to us, because it would require that the enclaves all originated at these localities, or that they were transported to these localities without being deformed during transport. In the above hypotheses for the formation of enclaves, initial formation never takes place in the centers of chambers, since neither mafic dikes (Frost and Mahood, 1987) nor sheets (Wiebe, 1994, 1996) typically reach the crystal-poor centers of magma chambers. In contrast, if enclaves were transported by any form of magma flow, they probably would rotate and/or change shape (Williams and Tobisch, 1994). For example, Cruden (1990) discussed the evolving shapes and orientations of passive markers during convection, and concluded that even passive markers at the centers of plutons should show moderate to high axial ratios and constrictional shapes.

However unlikely we find the assumption that undeformed enclave populations form at exposed pluton centers, it is nevertheless informative to examine data collected on individual enclaves in these locations. Fig. 2 summarizes data collected in this setting by Fowler and Paterson (1997), Hrouda et al. (1999) and John and Blundy (1993). All enclaves are statistically not spherical, and show a range in long/short ratios from 1.3 to 14 and a wide range in three-dimensional shapes. Again this scatter invalidates the use of single enclaves to determine strain. Nor does it support the interpretation that these enclave populations formed in these sites without strain.

Our two-dimensional enclave ratios of 1.1–2.7 and the above three-dimensional X/Z ratios of 1.3–14 may not seem large. However, it is important to remember that finite strains are multiplicative, and so ignoring these initial

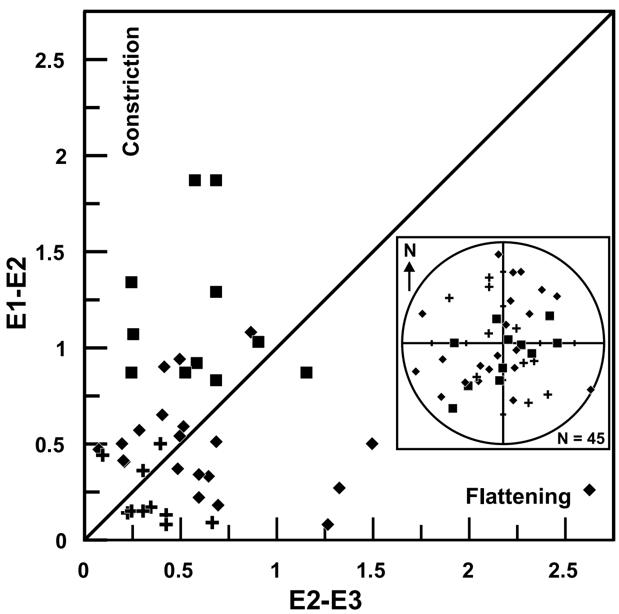


Fig. 2. Flinn plot of enclave strain data from 'low strain' sites in magma chambers. Squares—Hrouda et al. (1999); Diamonds—John and Blundy (1993); Crosses—Fowler and Paterson (1997). Note that ratios vary up to 2.5, and fabric ellipsoid shapes range from constrictional to flattening. Inset shows orientations of the long axis of the enclave fabric ellipsoid plotted on a lower hemisphere equal-area stereonet (symbols are the same as for Flinn plot). Note the variability in orientation both between and within datasets.

deviations from sphericity can introduce huge errors (Seymour and Boulter, 1979; Holst, 1982; Paterson and Hao, 1994). For example, if we start with an initial ratio of 2.0 and coaxially superimpose a strain with a ratio of 5.0, the final enclave shape or tensor averaged enclave population would give a 'strain' of 10, which is double the correct value.

In summary, the initial formation of enclaves and enclave populations involves processes that do not result in perfectly spherical enclaves, or homogeneous enclave population characteristics. This invalidates the use of single enclaves as strain markers and makes the use of enclave populations of doubtful validity. It would be useful for others using enclaves for measuring strains to provide a thorough appraisal of initial enclave characteristics and the potential errors introduced by these characteristics (e.g. Tobisch and Williams, 1998).

4. Effects of enclave rheology and viscosity contrasts

The amount of strain recorded by any object in part depends on its effective viscosity and on its transient viscosity contrast with the surrounding matrix. In strain analyses using other markers, it is assumed that all markers essentially have the same effective viscosity and the same rheologic history during deformation. Otherwise different markers would record different amounts of internal strain and undergo different amounts of rotation during deformation, resulting in a complex population of final marker shapes and orientations. This is probably true for most populations, but the assumption has always been that it is a minor effect in many instances.

In comparison with other clastic markers, which may have viscosities that vary by a few orders of magnitude (Gay, 1968; Freeman, 1987), microgranitoid enclaves are again unique for two reasons: (a) small changes in factors, such as composition (Shaw, 1965; Bottinga and Weill, 1972), temperature (Williams and Tobisch, 1994), the size and percent of crystals (Komar, 1972) and percent of volatiles (Scaillet et al., 1998, 2000), may have a huge effect on their effective viscosities (Fig. 3), and (b) a single enclave potentially changes its effective viscosity by >10 orders of magnitude during crystallization and cooling (Figs. 3 and 4). Moreover, since the magma surrounding these enclaves also undergoes a large change in viscosity during cooling (up to 16 orders of magnitude), enclaves may have very complex rheological histories (Fig. 4). Below we examine potential effects of variable viscosities and viscosity contrasts of enclaves on strain analyses.

Enclave populations are commonly compositionally and microstructurally heterogeneous, and show both field and microstructural evidence of variable behavior during magma deformation (Fig. 5). Compositional and micro-structural differences in enclaves have been emphasized in previous studies of enclave swarms (Tobisch et al., 1997).

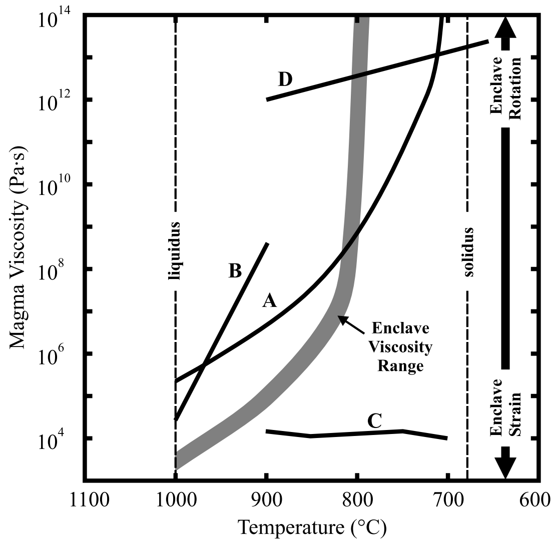


Fig. 3. Enclave viscosity plot combining data from different sources. Line A and 'Enclave Viscosity Range' are from Hrouda et al. (1999) for a granodiorite host. Line B is from Williams and Tobisch (1994) for a 65 wt% SiO_2 host. Line C is from Scaillet et al. (1998) for wet (3.5–7 wt% H_2O) granite. Line D is from Rutter and Neumann (1995) for dry Westerly granite. Note the strong viscosity dependence on both temperature and H_2O content.

One useful means of determining the degree to which enclaves in heterogeneous populations internally strain during deformation of the surrounding magma is to compare the alignment of magmatic minerals in the enclaves with the orientation of the long axes of enclaves, and to magmatic fabrics in the matrix surrounding the enclaves. A wide variety of potential relationships exist (Figs. 6 and 7). For example, enclaves may have no mineral alignment, may be elongate and record different fabrics from those in the matrix, may have fabrics parallel to matrix fabrics, or may be elongate with internal fabrics not necessarily parallel to their principal axes (Fig. 6). We have examined enclave fabrics in three plutons in the Sierra Nevada, namely the Mitchell Peak and Jackass Lakes plutons and the Tuolumne Intrusive Suite. In all three plutons, adjacent enclaves show remarkably different degrees of internal mineral alignment, ranging from examples where all minerals in the enclave are aligned parallel to both the enclave long axes and to magmatic foliation in the matrix (Figs. 6 and 7), to examples where internal minerals show no alignment, even though the enclave is elliptical and a magmatic foliation occurs in the surrounding matrix (Figs. 5 and 7). These observations indicate that nearby enclaves record different amounts of internal strain, and thus rarely behave as passive markers.

Field data also provide spectacular examples of the existence of enclave/matrix viscosity contrasts (Fig. 8). Such marker/matrix viscosity contrasts are easily recognized where compositional layering (Fig. 8a) or the matrix foliation (Fig. 8b and c) is deflected around the enclave, where indentation or deflection of one enclave by another occurs (Fig. 8b and c), where internal microstructures

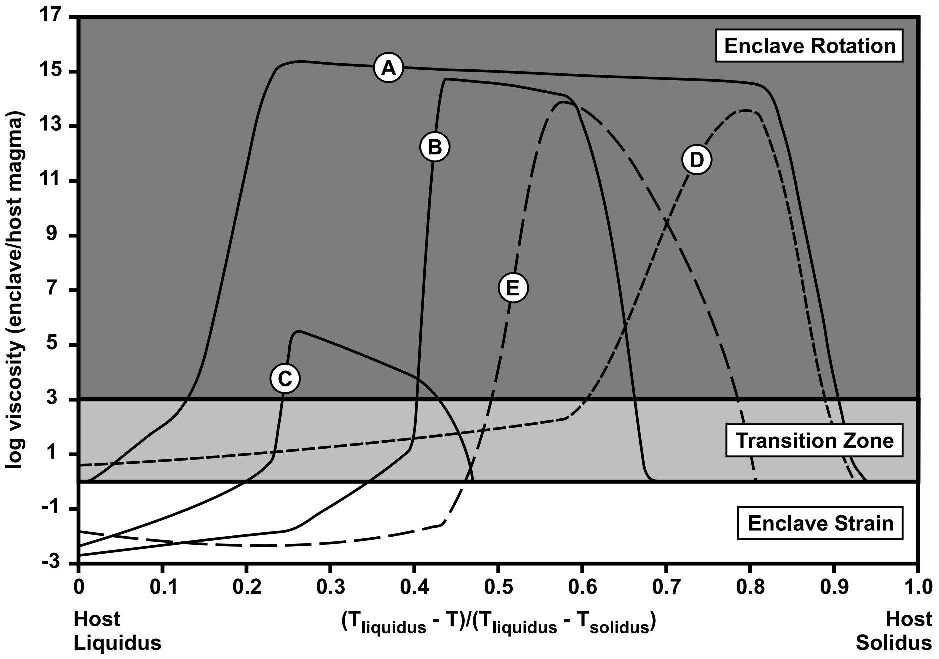


Fig. 4. Enclave versus host magma viscosity ratio curves, modified from Scaillet et al. (2000). (A) Basalt enclave in rhyolite host magma with 4.5 wt% H_2O; (B) basalt enclave in dacite host magma with 4 wt% H_2O; (C) basalt enclave in andesite host magma with 4 wt% H_2O; (D) dacite enclave in rhyolite host magma with 4 wt% H_2O; (E) andesite enclave in dacite host magma with 4 wt% H_2O.

indicate that the enclave did not share the same strain history as the matrix (Figs. 6 and 7), or where the enclave underwent markedly different behavior from that of its matrix, such as enclave boudinage (Fig. 8d–f), development of irregular margins (Fig. 8e), and development of 'fish-tail' patterns (Fig. 8f). Such enclaves violate the assumption of passive markers and so should not be used for calculating strains, particularly if they are not part of an enclave-supported population.

Published modeling can predict all of the above processes and strongly supports the notion that microgranitoid enclaves have a large viscosity contrast with matrix magmas throughout much of their hypersolidus history. Williams and Tobisch (1994) used liquid drop theory to model gabbro magma globule behavior in more felsic melt with a different viscosity. They showed that both composition and temperature have profound effects on how much strain each enclave records (Figs. 3 and 4). Williams and Tobisch (1994) argued that most magma globules flow internally (change shape) only at relatively high temperatures and low viscosity contrasts. As temperatures are lowered or viscosity contrasts increased, microgranitoid enclaves increasingly behave as rigid objects. Scaillet et al. (2000) expanded these studies, investigating the effect of both host magma-enclave composition and water content on viscosity. Effective viscosity of magmas, even at the same temperature, can be remarkably different. For example, water content strongly influences effective viscosity (Figs. 3 and 4), lowering it by several orders of magnitude (Scaillet et al., 1997, 2000). They also concluded that enclaves should not record strain through much of the crystallization history of the granitoid host—in fact only at high temperatures and later near the host solidus, when the viscosity ratio between enclave and host are similar enough for enclaves to record strain (Fig. 4). Both of these studies concluded that over a wide range of temperatures and enclave compositions, the enclaves do not strain internally, but instead rotate as rigid objects.

Given that enclaves throughout much of their magmatic history may act as rigid objects, it is important to evaluate the rotational histories of such objects and ask whether the preferred orientation of such markers (rather than their shapes) might provide quantitative information about strain. However, recent studies indicate that rigid markers with aspect ratios >1.5 typically have non-periodic rotation trajectories, producing heterogeneous and asymmetric instantaneous and finite strain patterns (Ildefonse et al., 1992, 1997; Arbaret et al., 1996, 2001). These types of histories for enclaves are supported by our field observations (Figs. 5c and d, 7, 8c, g and h and 9a and c). Although enclave long axes typically show a degree of preferred orientation, we consistently find individual enclave long axes at high angles to the predominant enclave orientation and to mineral foliations in the surrounding matrix (Figs. 5c and d and 9a).

We are aware of two processes that might lessen the above effects. (1) A small amount of residual melt may occur in the enclave if the temperature of the matrix magma remains above the enclave solidus (Vernon, 1984), and (2) melt may migrate into the enclave and, if abundant enough to form interconnected films, may weaken the enclave sufficiently to allow internal strain. Although some internal

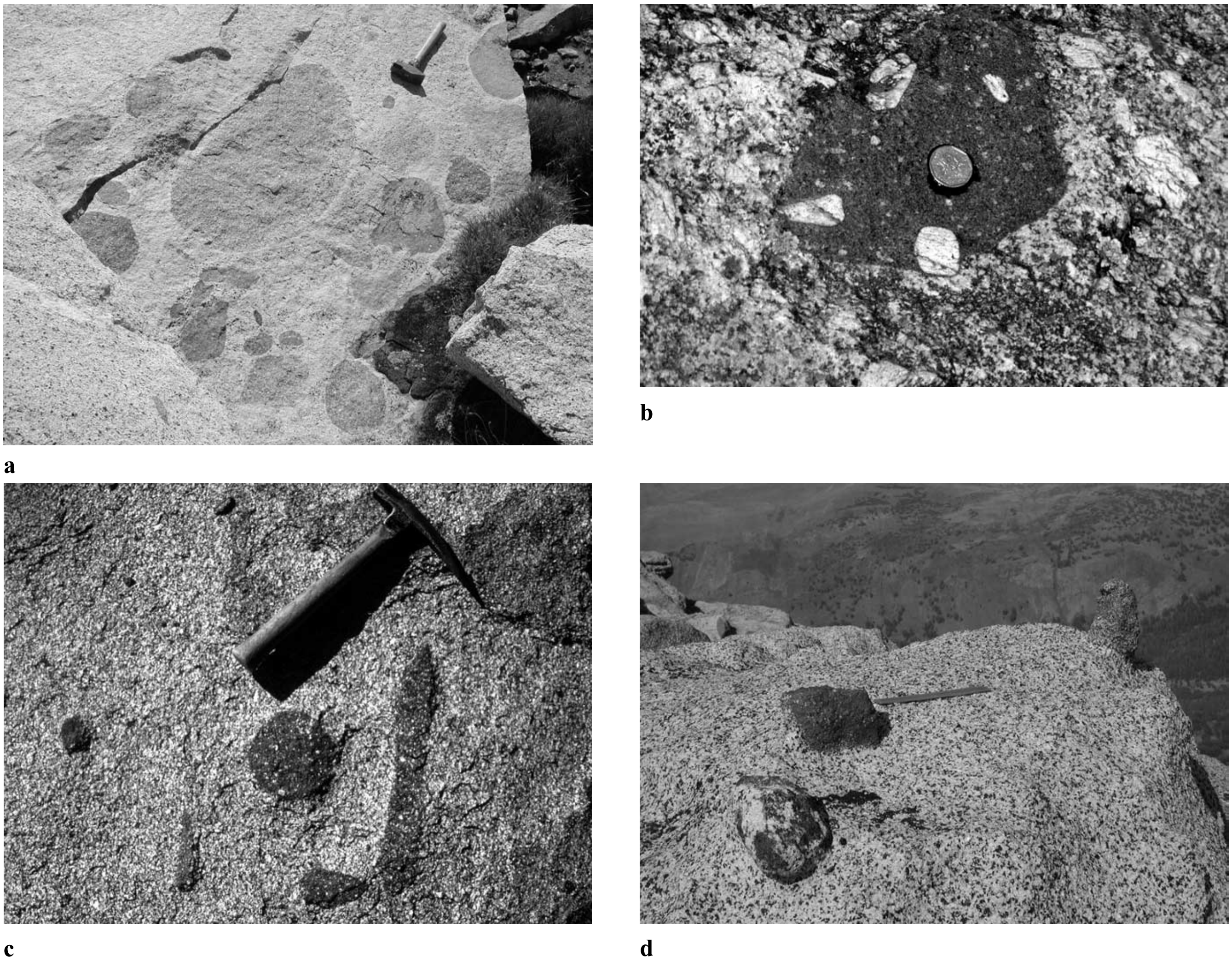


Fig. 5. Field photos showing variability in enclave characteristics. (a) Mixed enclave swarm in the Tuolumne Intrusive Suite showing four distinct textural/compositional enclave types; hammer for scale. (b) Enclave with large K-feldspar megacrysts, suggesting magma mixing incorporating megacrysts from host magma, although timing of mixing uncertain. From the Mount Lozère batholith, Massif Central, France. French coin for scale. (c) Microstructurally and compositionally similar enclaves in the Dinkey Creek pluton, Sierra Nevada. Tobisch et al. (1997) interpreted these to reflect very irregular enclaves attached in the third dimension, which would indicate that they are not good recorders of magmatic strain. Alternatively, they are separate enclaves that have recorded different amounts of strain and then rigidly rotated to their present orientations. (d) 3D view of enclaves in Kuna Crest phase of Tuolumne Intrusive Suite. Note the different shapes and orientation of enclaves, which also show small microstructural differences difficult to see in photo. 15 cm ruler for scale.

strain may occur in either instance, the enclave viscosity typically would remain higher than the matrix viscosity and thus would not record the same magnitude of strain as the surrounding magma.

In summary, because of their highly variable effective viscosities and potentially large enclave/matrix viscosity contrasts, enclaves do not meet the assumption of passive markers. This again invalidates techniques relying on measurements of single enclaves. Moreover, given the ample field evidence of heterogeneity in enclave compositions and internal fabrics, as well as theoretical results predicting that each enclave may undergo a unique deformation history, it is also questionable to treat them as a homogeneous population and/or to apply a single marker/matrix 'viscosity' correction to each enclave or enclave population. This makes the application of Fry and Rf/ϕ techniques problematic as well.

5. Tracking strain and multiple magmatic fabrics in plutons

There is a large and contentious body of literature on whether markers and associated foliations should maintain parallelism with the *XY* plane of finite strain, based on both theoretical (e.g. Bayly, 1974; Ghosh, 1982; Treagus and Hobbs, 1985) and practical grounds (Williams, 1977; Means, 1981; Siddans, 1983). If enclaves behave as perfectly passive markers, the *XY* principal planes of ellipsoidal enclaves should track the *XY* plane of finite strain in the matrix. Above we have argued that enclaves are

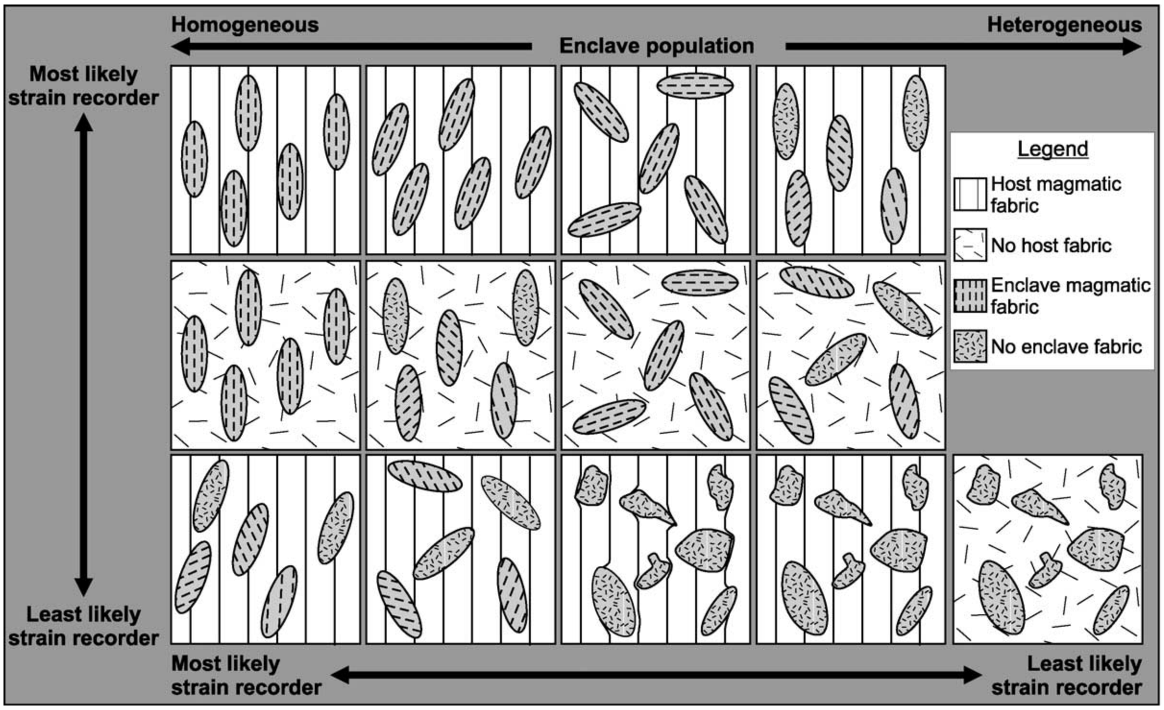


Fig. 6. Cartoon showing the range of possible relationships between enclave shapes, internal magmatic mineral fabrics in enclaves, and magmatic mineral fabrics in the host granite. Although it is impossible to do so completely, the examples have been arranged to emphasize relationships most likely to result from simultaneous strain of enclaves and matrix (top left) to those indicating that enclaves were rigid objects during final matrix strain. Note, however, that even the most likely could have formed by high temperature strain of enclaves (to form enclave shape and internal mineral alignment) and subsequent rigid rotation parallel to the matrix foliation.

not passive markers. But even so, if enclaves continue to strain, then at moderate to high strains we would expect enclave *XY* planes, on average, to be subparallel to the matrix foliation, if both continue to record finite strain. Thus, one means of testing the use of enclaves as strain markers is to examine their geometric relationship to other features that record finite strain.

Besides enclaves, we are aware of three other features in plutons that potentially record magmatic strain: (1) internal layering, (2) dikes, and (3) magmatic mineral fabrics. The challenge is that each of these features, including enclaves, probably record different increments of the strain experienced by the magma. The most widely used feature is magmatic mineral fabric. Unfortunately, an increasing number of studies have concluded that magmatic foliations and lineations are easily reset and only record the final increments of strain as crystal-rich mushes approach their solidus (Benn and Allard, 1989; Ildefonse et al., 1997; Paterson et al., 1998). A further complication arises when two magmatic fabrics with different orientations form in a single pluton, implying that neither fabric records the complete strain history (Blumenfeld and Bouchez, 1988; Schulmann et al., 1997; Paterson et al., 1998). In spite of these complexities, we find it informative to examine the relationship between enclaves and magmatic fabrics (Figs. 6, 7 and 10).

In the plutons we have examined, some individual enclaves with large axial ratios commonly have their principal planes at high angles to foliations defined by magmatic mineral alignment (Fig. 7) and to foliations defined by nearby enclave populations (Fig. 10). This again indicates that single enclave shapes and orientations do not necessarily reflect the strain ellipsoid, and instead behave as rigid tumbling objects during at least part of their history (Williams and Tobisch, 1994; Ildefonse et al., 1997; Scaillet et al., 1997, 2000).

We have also observed several places where more than one magmatic foliation occurs in a pluton (Figs. 7 and 10). For example, in the Tuolumne Intrusive Suite, Sierra Nevada, we have mapped two foliations defined by aligned magmatic minerals, one ~N–S that is typically parallel to internal contacts, and one WNW–ESE that cuts across internal contacts (see also Bateman, 1992). These two mineral fabrics are associated with constrictional finite fabric ellipsoids with steeply plunging long axes defined in the field by a magmatic lineation. Enclaves are widespread, and may be parallel to either fabric. In some locations, enclave shapes mimic the constrictional mineral fabrics, but in other locations they do not (Figs. 5d and 10a and b). Fig. 10a shows enclaves with oblate shapes aligned parallel to the ~N–S foliation, but at high angles to the WNW–ESE mineral foliation. Mineral alignments in the enclaves are parallel to the host magmatic foliation, not to the long axes of the enclaves. Also note that the thin end of one enclave has been rotated ~70° and smeared out along the WNW–ESE foliation defined by the magmatic mineral alignment

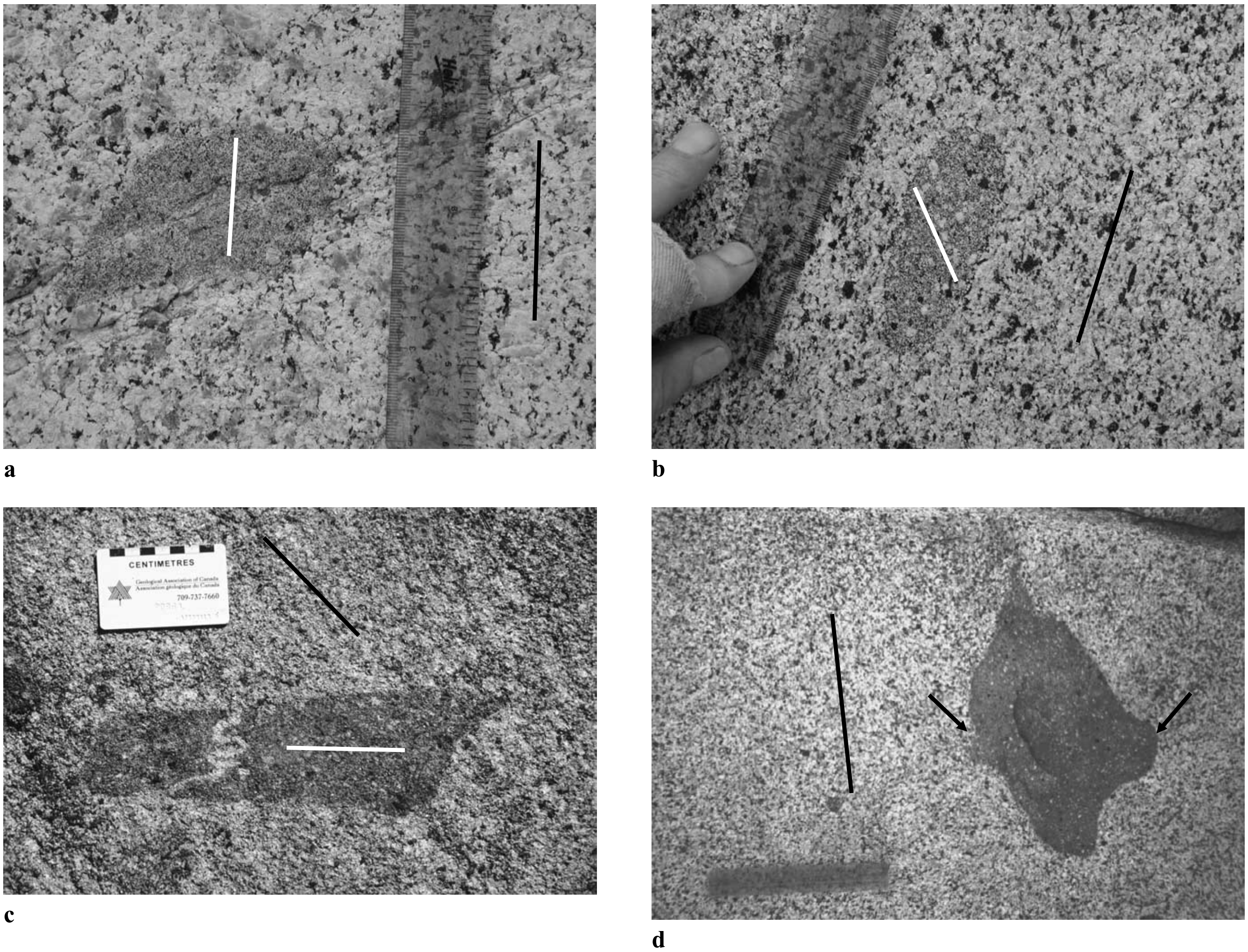


Fig. 7. Field photos showing variable relationships between enclave shapes, enclave mineral fabrics and matrix mineral fabrics. All magmatic foliations in host parallel to black lines. All mineral fabrics in enclave parallel to white lines. (a) Internal and external mineral fabrics parallel, but both at a high angle to enclave long axis. From Tuolumne Intrusive Suite. Centimeters on left side of ruler, ~14 cm visible. (b) Enclave long axis parallel to matrix mineral fabric, with enclave mineral fabric at high angle to both. From Tuolumne Intrusive Suite. Centimeters on right side of ruler, ~14 cm visible. (c) Angular enclave from Mitchell pluton, southern Sierra Nevada, California, preserving folded vein of melt from the host magma. Internal fabric parallel to axial plane of fold and parallel to enclave long axis, but at high angles to matrix foliation. 9 cm ruler for scale. (d) 'Double-pronged' enclave from the Green Lakes pluton, central Sierra Nevada, California. E–W prongs marked with black arrows; N–S prongs parallel to matrix foliation. The E–W prongs parallel to a second magmatic foliation developed domainally in this pluton. 15 cm ruler for scale.

(Fig. 10a). We have found similar examples elsewhere in the Tuolumne Intrusive Suite (Fig. 10b) and in the nearby Soldier Lake (Fig. 10c) and Jackass Lakes plutons (Fig. 10d).

Our interpretation of the above examples is that enclave long axes formed parallel to slightly older magmatic fabrics and then were rheologically 'locked in' during formation of younger magmatic fabrics. We suggest that this 'locking in' of enclaves occurred because it was rheologically difficult for the large enclaves to rotate and 'sweep out' a large volume of host dominated by crystal-rich mush. In contrast, individual magmatic minerals, presumably bound by melt films and small melt pockets, could continue to rotate parallel to a new foliation and do so with relatively little strain. In any case, the above are clear examples of elongated and aligned enclaves that do not track the younger magmatic foliation, nor record the finite strains.

Another interesting example in plutons with two magmatic fabrics is the presence of 'double-pronged' enclaves (Fig. 7d), that is enclaves with two pairs of protrusions from an otherwise elliptically shaped enclave, or locally four sharp corners of non-elliptical enclaves, one pair parallel to one magmatic foliation and the other pair parallel to the second magmatic foliation. Particularly, the protrusions suggest that local extension of the enclave occurred at some time parallel to each magmatic foliation. However, these 'double-pronged' enclave shapes typically occur in sections perpendicular to well developed magmatic lineations associated with constrictional fabrics, which suggests that shortening should be occurring in the directions of the protrusions. We discuss these enclaves

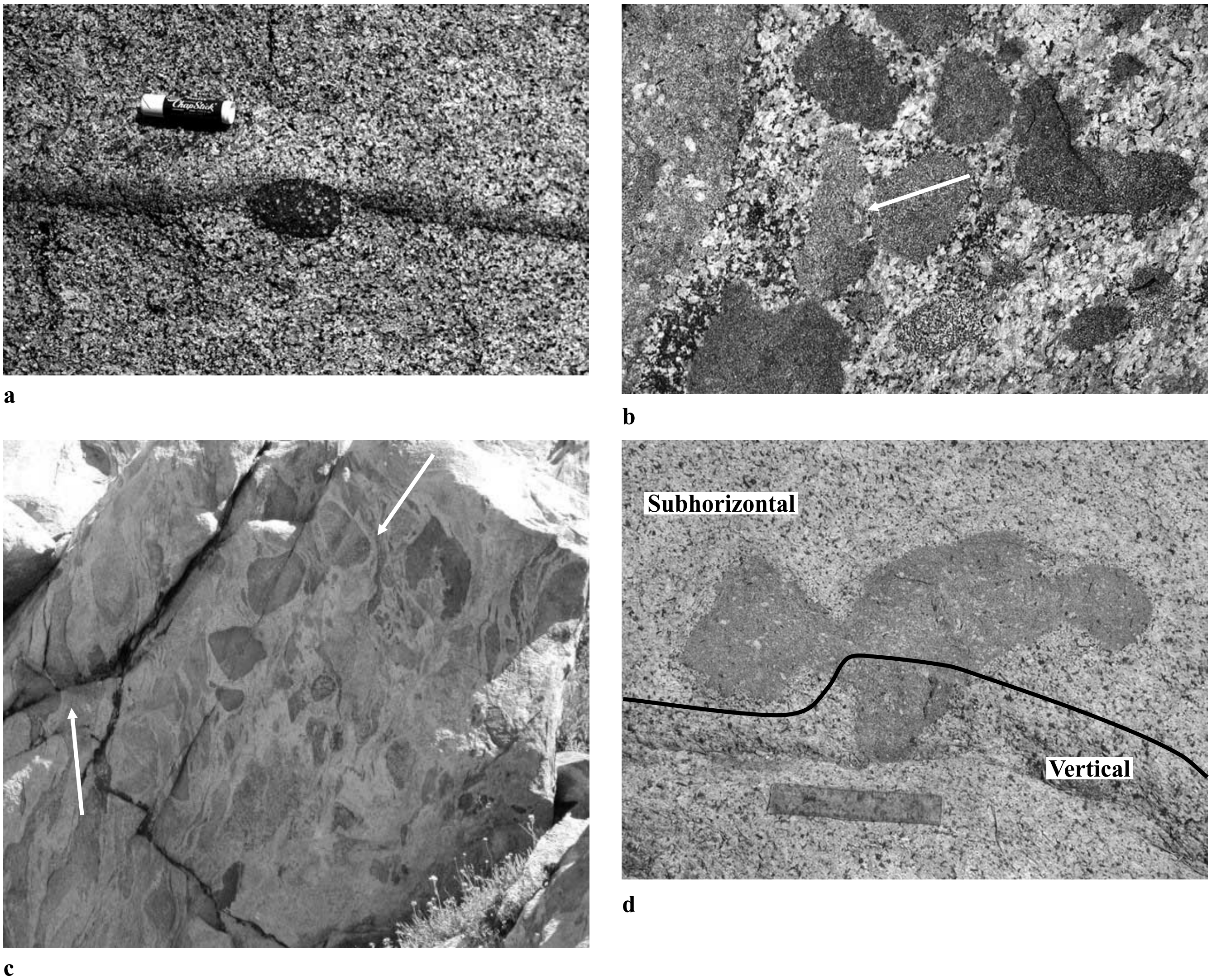


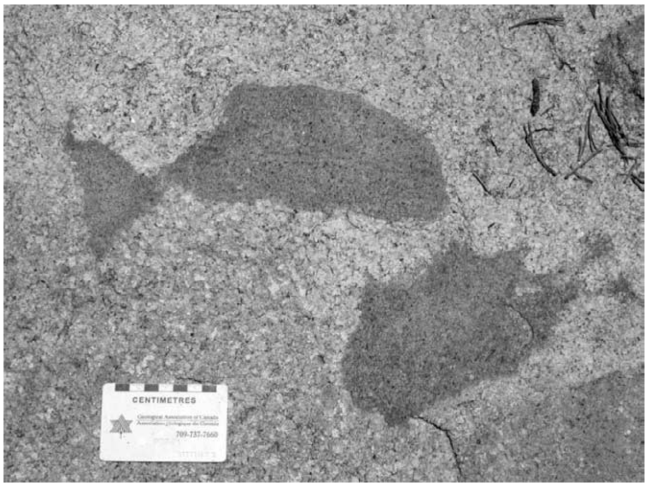
Fig. 8. Field photos showing variable enclave behavior due to viscosity contrasts with matrix. (a) Enclave in Dinkey Creek pluton, Sierra Nevada indenting schlieren layering. (b) Enclaves in Tuolumne Intrusive Suite, showing one enclave indenting another near white arrow. Base of photo ~1 m. (c) Enclave swarm in Jackass Lakes pluton showing enclaves near white arrows bending around other enclaves. Base of photo ~2 m. (d) 3D view of enclave boudinage in Kuna Crest phase of the Tuolumne Intrusive Suite. Moderate boudinage is shown in the subhorizontal face, whereas the vertical face shows stretching parallel to the magmatic mineral lineation, forming rods. 15 cm ruler for scale. (e) Enclave 'fish' in Jackass Lakes pluton, central Sierra Nevada. Ruler = 9 cm. (f) 'Fish-tail' boudinage of enclave in Half Dome phase of the Tuolumne Intrusive Suite. 15 cm ruler for scale. (g) Adjacent enclaves from Ardara pluton, Ireland showing different axial ratios, and 'core-tail' structure formed by tip streaming in lower enclave. (h) Boudinage of enclave with long tails (one tail is below white arrow) connecting up enclaves. Also note other enclaves at angles to boudinaged enclave. From Half Dome phase of Tuolumne Intrusive Suite. 9 cm ruler for scale.

more fully elsewhere (Paterson et al., in review). But for the purposes of this paper they are clear examples of non-elliptical enclaves that do not record the constrictional finite strain recorded by the surrounding matrix.

In summary, we have found many examples of individual enclaves that do not have their principal planes even subparallel to principal planes of strain defined by the host magma minerals, of 'double-pronged' enclaves with non-elliptical shapes, and of enclave populations overprinted at high angles by fabrics defined by magmatic crystals. In all of these situations, the enclaves cannot have tracked the finite strain.

6. Evaluation of final enclave populations

The observations presented above indicate that the use of single enclaves to measure magmatic strain is inappropriate. In this section we focus on the use of enclave populations. Studies often use the change in population characteristics (sometimes based on many single enclave analyses and less commonly based on Rf/ϕ analyses of multiple enclaves) to make inferences about chamber expansion (John and Blundy, 1993; Paterson and Vernon, 1995; Molyneux and Hutton, 2000; Oyhantcabal et al., 2001), flow during convection (McBirney, 1993), and flow of lavas (Ventura,



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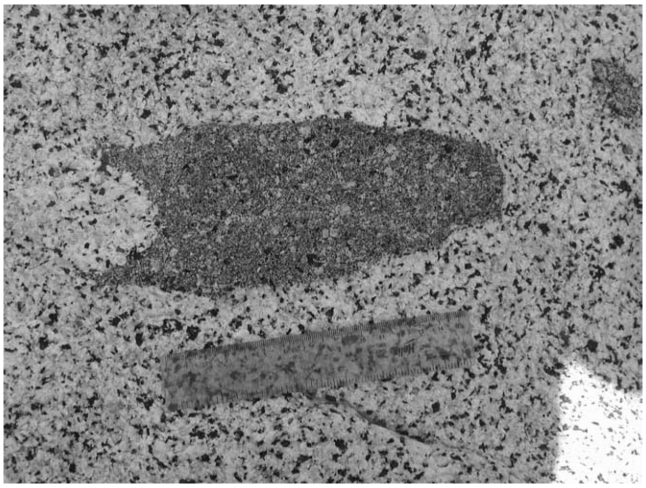

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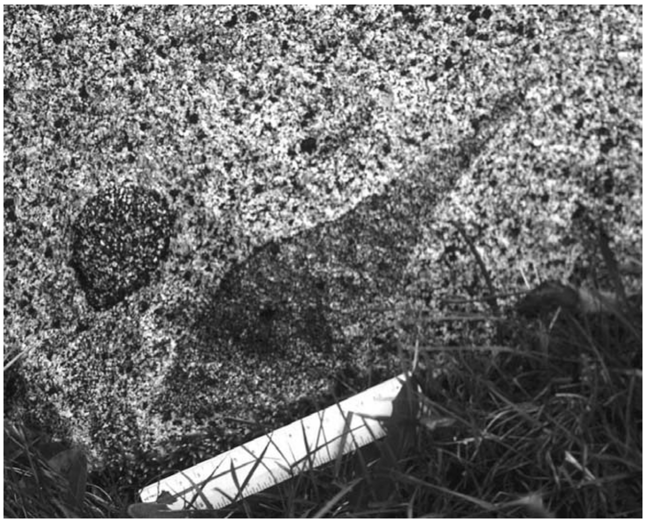

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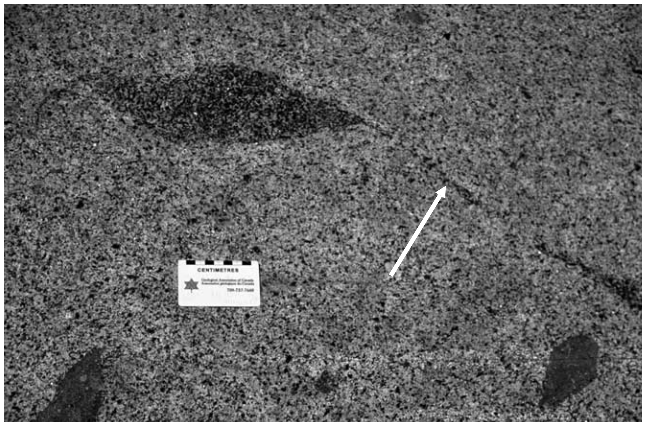

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Fig. 8 (*continued*)

2001). Below we examine data from one of these studies, in order to exemplify issues about the analyses of enclave populations.

One of the most extensively studied plutons with enclaves in the world is the Ardara pluton, Ireland (Pitcher and Berger, 1972; Holder, 1979; Sanderson and Meneilly, 1981; Vernon and Paterson, 1993). Several recent data sets have been added to previous data sets published on the Ardara pluton. Molyneux and Hutton (2000) published a structural study of the aureole and analyses of internal fabrics including enclaves and Siegesmund and Becker (2000) published a new AMS study of fabrics within the pluton. These multiple studies make this an ideal example in which to examine the use of enclave populations. We focus on Molyneux and Hutton's analysis of deformed microgranitoid enclaves based on averages of geometric means of single enclaves. In their model, enclave strain increases from a central 'low strain' region of magma injection towards the high strain margin of the pluton. Using these data, it was estimated by the authors that over 85% of the space needed during chamber construction was created by radial expansion.

Given the issues raised in previous sections regarding the use of single enclaves, the original population characteristics of enclaves, the process by which enclaves arrive at plutons centers, and the likely high viscosity contrasts between enclaves and matrix, it is tempting to immediately discard Molyneux and Hutton's enclave analyses. Certainly analyses of single enclaves to estimate strain violates several assumptions needed for all existing strain techniques. However, we think it is a useful exercise to further examine the characteristics of their enclave data set in this pluton in order to raise issues about how all enclave data sets have been evaluated by many different research groups.

If all enclaves in the Ardara pluton formed at the same time and were initially spherical, and if magmatic strains did

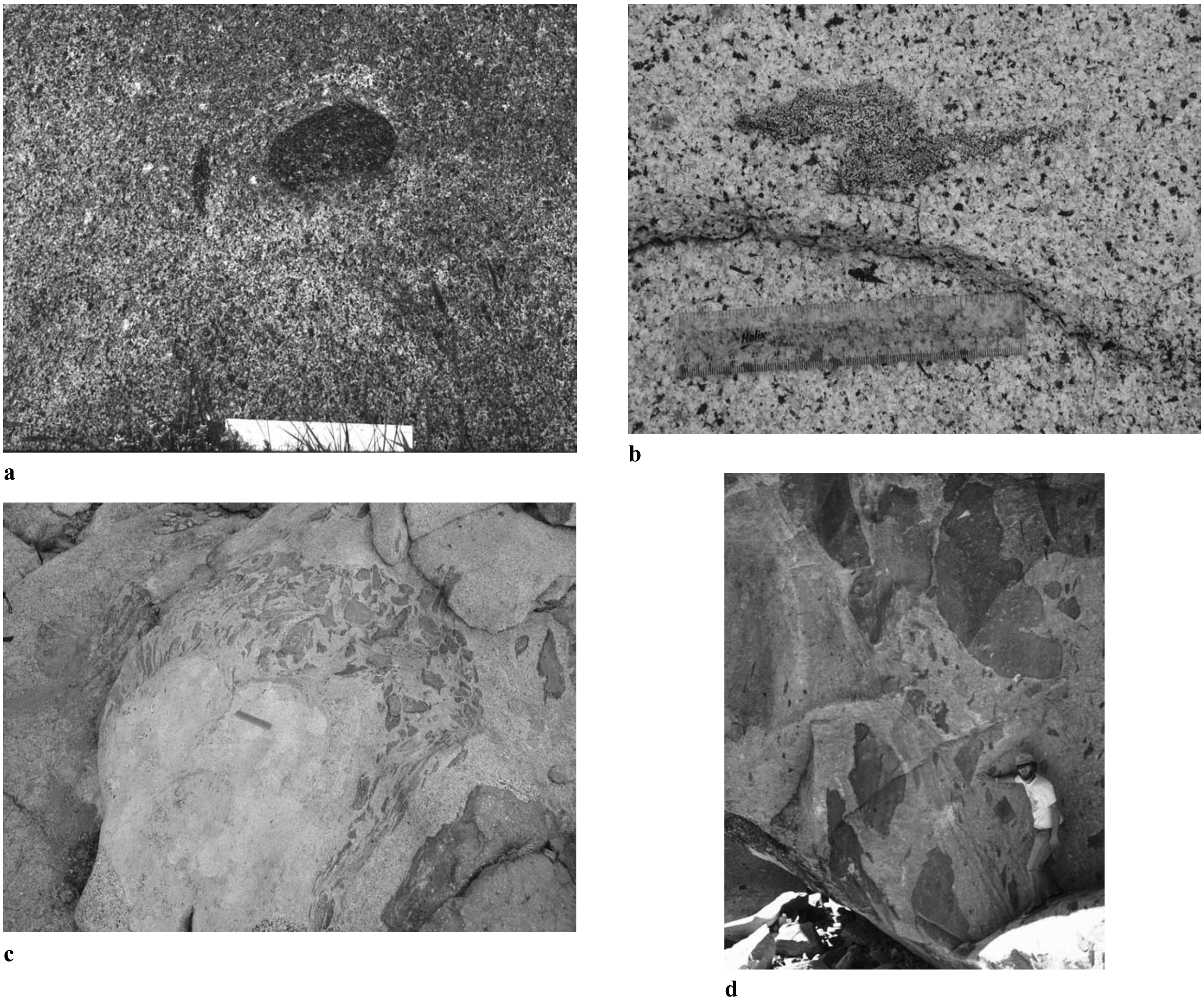

Fig. 9. Field photos showing complex enclave shapes and/or enclave population patterns due to heterogeneous strain. (a) Two microstructurally similar enclaves that have remarkably different ratios and long axis orientations in the margin of the Ardara pluton, Ireland (see Vernon and Paterson (1993) for detailed description). 15 cm ruler for scale. (b) Folded (magmatic) enclave in the Half Dome phase of the Tuolumne Intrusive Suite, central Sierra Nevada. 15 cm ruler for scale. (c) Complex strain patterns reflected by enclave shapes and orientations around a buoyantly rising pulse of granitic magma in the Half Dome phase of the Tuolumne Intrusive Suite, central Sierra Nevada. 15 cm ruler for scale. (d) Large and complexly shaped enclaves in and along a magmatic shear zone exposed near El Portal, central Sierra California. Person for scale.

increase towards the pluton margin (which can occur not only by chamber expansion, but by internal convection, stress alignment in crystallizing mush zones, or strain refraction across the magma-host contact), then the enclave ratios should increase linearly towards the margin of the pluton. Examination of Molyneux and Hutton's (2000) enclave axial ratios versus distance from the center of the pluton (Fig. 11) does not show a linear increase, but instead shows an impressive increase in *scatter* towards the margin. In fact, the outermost 2.5 km of the pluton record nearly the entire range (from core to margin) of observed strain. We have used a program Data Thief II (http://www.nikhef.nl/keeshu/datathief/) and recalculated a best fit line to Molyneux and Hutton's data (Fig. 11). Although our line is only slightly different from their calculated line, it has an R^2 value equal to 0.2, indicating a general lack of any statistically valid trend in their data. Instead their data are intriguing in that they require that strains become remarkably heterogeneous as the pluton margin is approached, or that the initial enclave population was heterogeneous. In fact, our reevaluation of Molyneux and Hutton's data (Fig. 11) suggests that even their 'lowest strain' enclaves had a scatter of ratios from 1.5 to 2.5 and thus were not spherical. These 'initial' ratios provide one explanation for the range of maximum and minimum values of final ratios at high strains (Lisle, 1985). Alternatively, if one assumes that these enclaves started out with axial ratios close to 1.0, some mechanism, such as enclave boudinage or

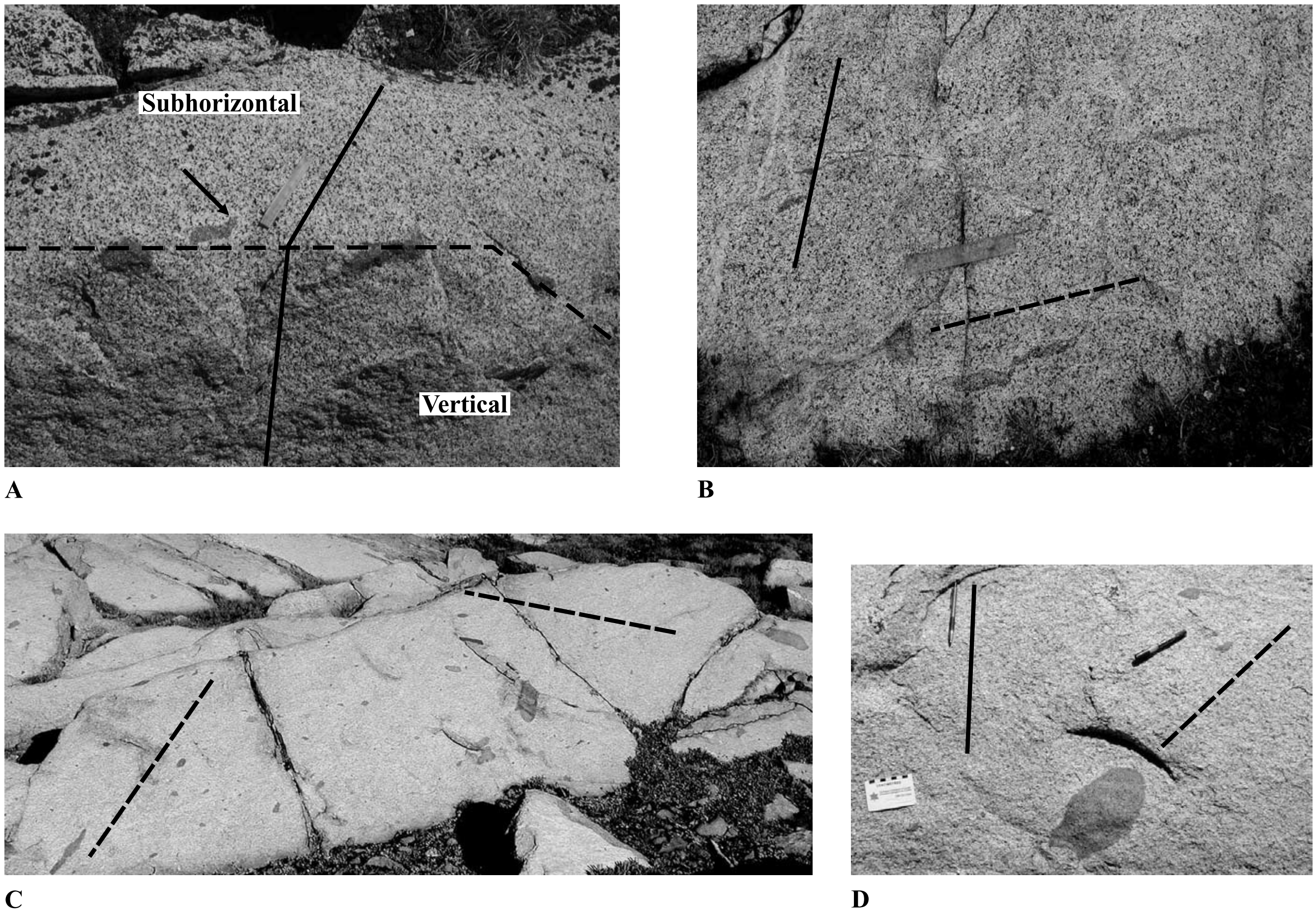

Fig. 10. Field photos showing examples in plutons of two magmatic fabrics parallel to solid and dashed lines. (a) Enclave alignment (dashed line) overprinted by magmatic mineral alignment in both enclaves and matrix (solid line) in Kuna Crest phase of the Tuolumne Intrusive Suite. Enclave fabric is parallel to N–S striking internal boundaries. Mineral alignment parallel to WNW striking chamber-wide magmatic foliation. Note how one enclave tip (below black arrow) has been smeared out along new mineral foliation. 15 cm ruler for scale. (b) Enclave alignment (dashed line) at angle to mineral alignment (solid line) in Kuna Crest phase of Tuolumne Intrusive Suite. Enclaves aligned parallel to N–S striking internal boundaries. Mineral alignment parallel to WNW striking chamber wide foliation. 15 cm rule for scale. (c) Two different enclave alignments at approximately 90° in the Soldier Lake pluton, central Sierra Nevada. Enclave long axes are statistically parallel to one or the other, and only rarely have orientations in between. Magmatic minerals form steeply plunging constrictional fabrics. 15 cm ruler for scale. (d) Enclave alignment (dashed line) at angle to magmatic mineral alignment (solid line) in Jackass Lakes pluton. 9 cm ruler for scale.

differential strain rates of enclaves, is needed to introduce the scatter into final ratios seen near the pluton margin. Both of these interpretations invalidate the use of single enclaves or means of enclave populations to calculate strains.

Another observation used in the Ardara pluton and by other researchers to argue that microgranitoid enclaves record the strain associated with magmatic foliations is enclave parallelism with these foliations. This may not be a meaningful argument. If microgranitoid enclaves acquire their shapes early in the magmatic history (e.g. Williams and Tobisch, 1994) and subsequently behave as rigid objects (Scaillet et al., 1997, 2000), they may follow tumbling paths and become statistically aligned parallel to fabrics, but with a few long axes statistically at high angles to the foliation. They may also break apart during boudinage, or late in the crystallization history accumulate some strains but at slower strain rates, resulting in long axes statistically aligned parallel to matrix foliations, but with heterogeneous axial ratios. This is exactly what we see in the margin of the Ardara pluton (Vernon and Paterson, 1993), namely good alignment of enclaves, but with some examples of enclaves with long axes at high angles to magmatic fabrics (Fig. 9a), evidence of enclave viscosity contrasts (Fig. 8g), and increasingly heterogeneous axial ratios as the margin is approached (Fig. 11).

In spite of the above concerns, we agree that the scatter of axial ratios does increase towards the margin of the Ardara pluton, as well as in many other elliptically shaped plutons, indicating that the largest enclave axial ratios commonly do increase towards pluton margins. We note that this increase in heterogeneity is also seen in Molyneux and Hutton's Fry analyses data using crystals and in the AMS data of Siegesmund and Becker (2000). This pattern implies that some additional heterogeneous, magmatic strain occurred due to expansion, internal convection, or other margin related processes (e.g. Paterson et al., 1998). The questions remain of how much strain is required and about which process(es) contributed to this strain.

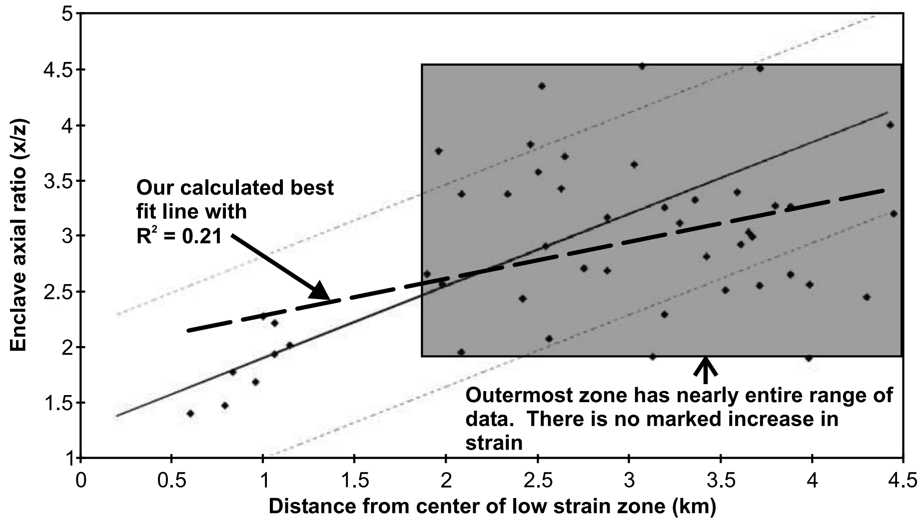

Fig. 11. Re-evaluation of strain data acquired from mafic enclaves presented in Molyneux and Hutton (2000), illustrating an increase in scatter of strain towards the pluton margin. This patterns support a complex strain history for the Ardara pluton rather than simple, linear strain increase from center to margin. It also requires heterogeneity in original enclave shapes.

7. Summary and conclusions

In order to fully understand the significance of magmatic fabric intensities and fabric patterns in plutons, it is important to search for and apply quantitative approaches. We thus support the continued evaluation of enclave ratios and orientations, particularly if combined with careful studies of their internal fabrics. But at the present time we question the appropriateness of using these data as a measure of finite strain. The use of single enclaves is particularly unjustified. Unfortunately, the evidence we have summarized above indicates that even populations of carefully selected enclaves cannot be treated as populations of normal strain markers. Unlike other marker populations, such as conglomerates or volcanic clasts, enclaves undergo huge variations in effective viscosity, may break apart during their history, spend much of their magmatic residence time with significantly greater effective viscosities than their host, and do not necessarily form at the same time or place. The need for large populations (since the use of single enclaves is inappropriate) increases the likelihood that spatial heterogeneity and marker/matrix viscosity ratios would introduce greater errors in final analyses.

Furthermore, our field studies agree with theoretical (Williams and Tobisch, 1994) and experimental (e.g. Scaillet et al., 2000) studies, which conclude that the shapes and orientations of enclaves are complex functions of (1) shape and temperature of enclaves during formation, (2) subtle changes in composition, melt percents, volatiles, grain sizes, and thus temporally variable viscosity contrasts between the enclave and magma, (3) a competition between strain and interfacial energies, and (4) deformation path, which may include rigid rotations and internal strain caused by magma flow during ascent, convection, expansion, chamber boundary processes, and tectonism. We suggest that most of the time magma globules change shape (strain) while the magma globules are still hot and well above their solidus, and subsequently act as increasingly rigid objects during much of their magmatic history (e.g. Scaillet et al., 1997, 2000). Thus, many microgranitoid enclaves rotate or follow irregular tumbling paths (Ghosh and Ramberg, 1976; Ildefonse et al., 1997) and undergo little internal strain during much of their displacement history. This rotation develops a degree of preferred orientation parallel to foliations as the host magma becomes increasingly viscous, although exceptions occur because of irregular tumbling. It is also possible that small amounts of melt may reside in enclaves if the host magma temperatures remain hot enough or if melt from the matrix migrates into and sufficiently weakens the enclaves, so that some strain may occur throughout enclave displacement histories, but at slower rates than the surrounding magma is straining. In addition, as the host magma nears its solidus, increased coupling and lower viscosity ratio between enclave and host crystal mushes may allow some late submagmatic strain to occur in the enclave. An example of the latter process is the rotation and smearing out of the enclave tip in Fig. 10a.

The above observations indicate that Rf/ϕ techniques are also inappropriate for evaluating magmatic strain from enclaves, since the use of enclaves violates several of the assumptions needed to apply these techniques. We suggest that techniques based on measuring the statistical preferred orientations of rigidly rotating objects (e.g. Ildefonse et al., 1997) may be more robust, although in detail one must also violate the assumptions needed to apply these techniques as well.

We believe that accurately measuring strains in magmas will always be problematic, because so much of the strain is accommodated by flow of melt, which then crystallizes and preserves little information about this strain. However, one promising line of inquiry in our own studies is the recognition that igneous layering, enclaves, and mineral fabrics may record different increments of coupled strain/-displacement histories in magma chambers. A comparison of strain/displacement from the three types of markers may not ever provide accurate values of strain, but potentially provides information about the timing and kinematics of strain/displacement histories and semi-quantitative information about the changing magnitudes of strain/displacements.

We speculate that the most useful approach may be to evaluate the deflection and change in thickness of early-formed igneous layering, since these features potentially record both strain and rigid rotations/translations. However, we recognize that even the use of layering is challenging, because layer thicknesses may vary during formation and subsequently undergo compaction and removal of melts (geometrically equivalent to volume loss by pressure solution or dewatering in other rock types) and that the cause(s) and timing of layer deflections are commonly poorly constrained. Even so, a comparison of layer behavior with enclave and mineral fabrics may prove useful. The earliest formed layers should record the most complete record of strain/displacement. Then, if a more realistic approach to evaluating enclaves is used, it may provide some information about high temperature strains (enclave shapes) and subsequent rotations (preferred orientations). Mineral fabrics (including AMS data) record composite and typically even smaller increments of late strain that occur as the chamber approaches its solidus. Late layering or dikes may also record these late strains, as well as late displacements. Thus a comparison of data obtained from these different markers has the potential for evaluating changing displacement/strain histories in chambers.

For example, in several Sierran plutons, we are presently examining the changes in cut-off angles between schlieren layers in troughs (equivalent to cut-off angles in cross-bedding in sandstones) to evaluate strain after trough formation. We are also examining the relationship between the shapes of schlieren tubes (e.g. Weinberg et al., 2001) and crosscutting magmatic mineral fabrics. In addition, late aplitic to pegmatitic dikes in these same plutons locally define gentle to open magmatic folds with mineral fabrics parallel to their axial planes. If these are treated as buckle folds, two-dimensional strains in profile sections range from 0 to 26% shortening and typically record much less strain than analyses of shapes of enclaves statistically parallel to the axial planar mineral foliations. The comparisons of these different data sets are providing a glimpse into both the evolving displacement fields of melts and strain resulting from these displacements.

The patterns of displacement defined by displaced layering and strain gradients (rather than absolute values) defined by mineral or enclave fabrics provide important information about the evolution of magma chambers. Potential end-member patterns and means of evaluating these gradients are discussed in Paterson et al. (1998). But we believe that these patterns commonly are much more complex than typically recognized (e.g. the Molyneux and Hutton data). Our evaluation of enclave data suggests that this complexity may preserve important information on the processes that form these fabrics, and thus should be the focus of future studies, rather than de-emphasized through questionable statistical averaging.

Acknowledgements

SRP and GP acknowledge the support of NSF grant EAR-0073943. RHV acknowledges the support of a Macquarie University Research Grant. We thank Richard Lisle for a review of the manuscript and Richard Norris for editorial assistance.

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