Determining relative magma and host rock xenolith rheology during magmatic fabric formation in plutons: Examples from the middle and upper crust

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ABSTRACT

Field observations, structural analysis, and analytical calculations are utilized to evaluate the strength of intermediate magmas during crystallization in a regional strain field. Two plutons are examined, the subvolcanic 98 Ma old Jackass Lakes pluton, central Sierra Nevada, California, and the voluminous middle crustal 442 Ma old Andalshatten pluton, central Norway. The Andalshatten example contains millimeter- to kilometer-scale xenoliths that display evidence for synmagmatic deformation, including fold reactivation and boudinage, after being isolated in the magma. Fabrics within the pluton adjacent to the xenoliths are usually magmatic, with only local, discontinuous zones of crystal-plastic deformation <1 m from the xenolith contact. Examination of particularly well exposed mafic metavolcanic xenoliths in the Jackass Lakes pluton indicates that all were strained prior to incorporation and then separated from the remaining host rock by brittle cracking. Once isolated from the host rocks, some of these xenoliths were intruded by veins fed by the in situ draining of melt and magma from the surrounding crystal mush zone. The xenoliths continued to deform ductilely at presumably fast strain rates. Axial-planar magmatic foliations within folded granodioritic dikes within xenoliths are parallel to magmatic foliations throughout the Jackass Lakes pluton and metamorphic foliations within the host rocks, indicating that the xenolith deformation occurred within the regional 98 Ma old strain field that affected the pluton.

The behavior of these xenoliths suggests that late in the crystallization history, magmas in both middle crustal and subvolcanic settings behaved as a high-strength crystall-melt mush capable of transmitting deviatoric stresses, which drove both elastic and plastic deformation in the enclosed xenoliths. Simultaneously, intercrystalline melt, and in some cases magma, was drained from the host intrusions into the xenoliths. Rheological modeling based on geochemical data yields an effective viscosity of a crystal-free melt of ~10^4 Pa s and increased to ~10^7 Pa s as cooling proceeded to 758 °C and crystal content approached 40% for the Jackass Lakes pluton. Such viscosities are too low to impart or transmit deformation into the xenoliths. The preservation of xenoliths in both plutons is compatible with higher crystallinities and/or magma yield strengths as an explanation to arrest the xenoliths in their final position and allow deformation. Estimated effective viscosities considering magma yield strength and measured density variables (melt and solid) are ~10^13 Pa s.

INTRODUCTION

The strength of magmas as they crystallize remains poorly constrained in natural environments. However, the rheological transitions that occur during crystallization (and melting) must play a pivotal role in the mechanical evolution of the lithosphere, the segregation and migration of magma, and the eventual solidification and thus emplacement of igneous bodies. In this article we explore how magma-xenolith relations in plutons may provide information on the viscosity of partially molten systems and the strength of magmas as they crystallize. Many experimental and theoretical investigations have demonstrated the complexity and difficulty in quantifying the rheology of magmas because of their multiphase nature across a range of temperatures, pressures, ambient deviatoric stresses, and fluid compositions and/or concentrations (e.g., Arzi, 1978; Van der Molen and Paterson, 1979; Mc Birney, 1993; Lejeune and Richet, 1995; Rutter and Neumann, 1995; Barboza

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and Bergantz, 1998; Renner et al., 2000; Rosenberg, 2001; Petford, 2003). Our approach is to utilize field relations, structural analysis, and geochemistry to place constraints on the rheology of magmas during xenolith incorporation and deformation in shallow crustal and middle crustal environments. Our results may bear on the efficacy of magma emplacement processes such as diking and stoping, as well as provide constraints on magma viscosity at high crystal fractions.

In this paper we use the term xenolith to describe any body of rock that is foreign to and entirely surrounded by the host igneous rock in contact with the xenolith. This may include stope blocks from the roof, walls, or floor of the magma chamber, cognate xenoliths (autoliths) derived from earlier crystallized portions of the magma system, and screens (kilometric-scale xenoliths, sometimes referred to as pendants), or raft trains of xenoliths (e.g., Pitcher, 1970). We differentiate xenoliths from mafic magmatic enclaves or microgranitoid enclaves (e.g., Düder and Barbarin, 1991). Xenocrysts are defined as mineral fragments that are encapsulated in the host igneous rock and have no direct chemical relationship with the host magma. The study of such xenoliths may provide information about magma compositional changes due to assimilation (e.g., Barnes et al., 2004), the paleohorizonal at the time of final chamber construction, timing of formation of structures in plutons, kinematics of magma flow, and the rheology of magmas at the time of xenolith capture (e.g., Paterson and Miller, 1998). Xenoliths also may preserve examples of the complex interactions that occur along chamber margins, including the interplay of processes such as host rock melting (McLeod et al., 1998), thermal cracking (Clarke et al., 1998), high-temperature creep (Langdon, 1985), the initiation of dikes (Rubin, 1993a, 1993b), and magma fractionation and crystallization along boundaries (Mahood and Cornejo, 1992; McNulty et al., 1987; McBurney, 1993).

Two pluton-host rock systems are examined that preserve abundant well-exposed xenolith-magma interactions. The 98 Ma old Jackass Lakes pluton, Sierra Nevada, is a subvolcanic pluton that intruded its own volcanic ejecta and minor metasedimentary rocks and contains numerous xenoliths at scales ranging from millimeters to kilometers (Nordgulen et al., 1992; Anderson et al., 2007). Examination of xenoliths in both plutons indicates that they were all pervasively deformed during magmatic fabric formation. While this ductile deformation was ongoing, the xenoliths were brittlely cracked, sometimes injected by melts and magmas from the surrounding magma, and in some cases these veins were boudinaged and/or folded at relatively fast strain rates.

The above observations are interpreted to indicate that late in the crystallization history of both plutons, the magma behaved as a high-strength crystal-melt mush capable of transmitting deviatoric stresses, which drove both elastic and plastic deformation in the xenoliths, while intercrystalline melt drained from the host magma into the xenoliths. Furthermore, comparison of structures in the host pluton and in the xenoliths indicates that the strength of the crystal-melt mush during magmatic fabric formation was equal to or greater than that of the metasomatic xenoliths in the Jackass Lakes pluton.

Migmatic foliations and lineations in both plutons are interpreted to reflect regional strain. Thus, both plutons preserve evidence for the orientation of the regional strain field during magmatic emplacement.

XENOLITHS IN THE JACKASS LAKES PLUTON, CENTRAL SIERRA NEVADA, CALIFORNIA

The Jackass Lakes pluton (Fig. 1) in map view is an ~13 x 17 km rectangular body that intruded slightly older metavolcanic and plutonic pendants and screens (Peck, 1980; McNulty et al., 1996). McNulty et al. (1996) analyzed two samples of the granodiorite for U-Pb zircon geochronology, and reported a concordant age of 98.5 ± 0.3 Ma (old from a population of zircons from the northeast portion of the pluton and a discordant age of 97.1 ± 0.7 Ma old from the southwest portion. The pluton is truncated to the south by the ca. 90 Ma old Mount Givens pluton (McNulty et al., 2000) and to the north by the 95 ± 2 Ma old Red Devil Lake pluton (Tobisch et al., 1995). Aluminum-in-hornblende geobarometric calculations yield anomalously high (~400 MPa) pressures of crystallization (i.e., 13–15 km depths; Ague and Brimhall, 1988). Geologic reconstructions of the overlying ca. 98–101 Ma old Minarets caldera (Fiske and Tobisch, 1978, 1994), the presence of miarolitic cavities, and the observation that the pluton intruded its own volcanic ejecta and subvolcanic plutonic rocks point to a subvolcanic emplacement depth for the pluton (Peck, 1980; Stern et al., 1981; Fiske and Tobisch, 1978; 1994; Coyne et al., 2004; Wolak, 2004; Krueger, 2005).

The composition of the Jackass Lakes pluton can be variable down to the meter scale, and includes diorite, quartz diorite, biotite ± hornblende granodiorite, granite, leucogranite, and additional hybrid phases (McNulty et al., 1996; Coyne et al., 2004). Generally these various phases form north-northwest-trending, steeply dipping sheet-like bodies ranging in width from meters to kilometers with variable contacts ranging from gradational to locally sharp. However, the central and western portions of the pluton contain distinct compositional units several kilometers in width with quite variable shapes, although generally elongate in the northeast direction. Mafic microgranitoid enclave swarms of dioritic composition as wide as 50 m occur in the more felsic units and are often northwest trending. Textures vary considerably, from aphanitic to coarse grained, and from equigranular to porphyritic.

Numerous metavolcanic and metasedimentary xenoliths occur throughout the Jackass Lakes pluton and vary from kilometer-scale screens to millimeter-scale xenoliths (Figs. 1 and 2). The largest screens resemble lithologies exposed in the Minarets caldera sequence to the east (Fig. 1) and include both metavolcanic and metasedimentary rocks. Some pendants are also intruded by a porphyritic leucogranite with miarolitic cavities called the Post Peak phase, which probably is a slightly earlier, subvolcanic leucogranoitc phase of the Jackass Lakes pluton (Peck, 1980). Individual xenoliths and/or raft trains of xenoliths are particularly common near the large pendants, but occur throughout the pluton with variable sizes (meters to several hundred meters) and rock types (metavolcanic, leucogranite, and metasedimentary; Wolak, 2004).

Migmatic foliations in the Jackass Lakes pluton strike north to northwest, dip steeply, and are subparallel to elongate host-rock screens within the pluton (Figs. 1, and 2). Magmatic lineations typically plunge steeply to shallowly north within the foliation plane. Magmatic lineations in the western quarter of the pluton are shallowly north plunging (Krueger, 2005). McNulty et al. (1996) interpreted the magmatic fabric in the Jackass Lakes pluton to reflect kinematics of magma flow during chamber construction. Wiebe (1999, 2000) suggested that Jackass Lakes pluton formed by episodic input of mafic and felsic sheets that accumulated on a subhorizontal (10°–30°) chamber floor and were subsequently tilted to their present steep dips. Magmatic fabrics in this model reflect compaction in cumulate piles below layers and local flow during convection above mafic sheets. However, magmatic foliations cut across compositional boundaries and are subparallel to regional structural trends in the xenoliths and host rocks (see following; Peck, 1980; McNulty et al., 1996). Therefore, in contrast to the previous interpretations...
noted above (e.g., Wiebe, 1999, 2000), we suggest that this fabric reflects regional strain imprinted on the still hypersolidus magma 97–98 Ma ago (see also Krueger, 2005).

In the following sections, different xenolith suites are characterized in terms of the magmatic structures surrounding the xenoliths and internal structures within the xenoliths.

**Descriptions of Xenoliths**

**Black Beauty Xenolith**

The metavolcanic xenolith described here, informally named the Black Beauty xenolith, is andesitic in composition and is located ~100 m from the margin of the nearest exposure of the pluton roof called the Post Peak pendant (Figs. 1 and 2). The xenolith is 45 × 25 m with a long dimension that strikes ~N25°W and is exposed on a glacially polished subhorizontal surface. The xenolith is metamorphosed and contains a well-developed foliation oriented ~N35°W/83°NE defined by aligned phenocrysts of plagioclase and hornblende and fine-grained biotite and quartz (Fig. 3A). Metamorphic foliations in the xenolith are subparallel to foliations in the nearby Post Peak pendant. Around the xenolith magmatic foliation (N5°W/84°NE) and lineation (70° at S30°E) occur in the host granodiorite and are well defined by the alignment of magmatic biotite ± hornblende ± feldspar and flattened mafic microgranitoid enclaves (Fig. 2D). Little to no deflection of this foliation occurs as the xenolith is approached at the two ends of the xenolith; i.e., in regions where the foliation and xenolith margins are at high angles (Fig. 2). Local deflections at the meter scale occur along other portions of the xenolith margins. Both field and microstructural observations (Figs. 3B–3D) indicate that this foliation is entirely magmatic, using criteria outlined in Paterson et al. (1998).

**Xenolith Margins**

At the meter to centimeter scale the margins of the Black Beauty xenolith are defined by straight to undulating segments connected by lobate to angular corners where margins abruptly change directions (Fig. 4). Undulating and lobate margins tend to have amplitudes and wavelengths of centimeter to decimeter dimensions. Straight margin segments in both the larger xenolith and smaller pieces usually have cutoff angles between metamorphic foliations in the xenolith and the xenolith contact of 10° or more, indicating that xenolith internal anisotropy did not control fracture formation. Exceptions to the development of planar margins occur at the centimeter scale in locations where the overall xenolith margins strike at high angles to the magmatic foliation, i.e., at the ends of elongate north-northwest–trending xenoliths. In the Black Beauty example, the margins become concave with respect to the granodiorite, with centimeter scale V-shaped cusps of host rock at the magma-xenolith interface pointing outward toward the host granodiorite and subparallel to the magmatic foliation (Figs. 4A, 4B). Between these cusps, lobate margins of the granodiorite are concave toward the xenolith. Such cuspatelobate patterns may form between two materials with different effective viscosities, with the material forming the cusps having the lower viscosity (e.g., Fletcher, 1982; Smith, 2000). The occurrence of these margins only on the sides of the xenolith at high angles to the granodiorite magmatic foliation and subparallelism...
Figure 2. (A) Location of Black Beauty xenolith with respect to host rocks. Kj—Jackass Lakes pluton; Kr—Red Devil Lake pluton (ca. 95 Ma old; McNulty et al., 1996); Km—Cretaceous metavolcanic rocks. The red contact separates the Jackass Lakes pluton from the metavolcanic rocks of the Post Peak pendant shown in Figure 1. (B) Geologic map of the xenolith and surrounding rocks. (C) Outcrop photograph displaying variation in orientations of foliations and xenolith long axis. (D) Lower-hemisphere stereonet displaying orientations of structures in and around the xenolith. Xenolith in A and C is approximately 45 m long.
between the cusps and magmatic foliation suggest that these margins and the magmatic foliation formed at the same time during east-northeast–west-southwest contraction.

**Dikes and Veins in Xenoliths**

Granodioritic dikes and quartzofeldspathic veins of various sizes intrude virtually all of the xenoliths observed within the Jackass Lakes pluton. The Black Beauty xenolith displays structures associated with these dikes and veins that bear on magma-xenolith rheology. Millimeter- to centimeter-thick veins and dikes intrude the xenolith and taper to thin tips (Figs. 4B–4D). In some cases these veins can be traced continuously across the xenolith-granodiorite contact and into the granodiorite, where they become indistinguishable from the surrounding groundmass (Figs. 4B–4D). Vein tips taper to <1 mm in width and typically die out in preserved fractures that extend for short distances in front of the vein tip. It is not possible to determine whether these fractures were preexisting or formed during vein formation. However, fractures with no vein material exist in the xenolith. In no case are dikes or veins observed to be truncated at the xenolith-granodiorite contact, indicating that dikes and veins must have formed once the xenolith was stationary and could not move within the magma.

Veins range from strongly deformed to late, crosscutting, relatively undeformed examples and are divided into three sets (Figs. 5 and 6). For the deformed veins, the type of deformation is largely a function of the vein orientation relative to the xenolith foliation. Those striking at low angles to the foliation (set 1) display boudinage (Fig. 5B), whereas those striking at high angles are folded (sets 2 and 3; Fig. 5C). Field observations (Figs. 3–5) and microstructural observations (Fig. 3D) indicate that the veins underwent little to no subsolidus crystal-plastic deformation (beyond minor dislocation glide in quartz and feldspar).

One granodioritic dike is unusually thick and shows several features not seen in other veins within the xenolith. (Figs. 5A and 6). This dike is no longer planar and shows both fold patterns and lobate margins (Figs. 6A, 6B). It is by far the thickest dike in the xenolith and has walls that are subperpendicular to the xenolith

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Figure 3. (A) Photomicrograph of metamorphic foliation in the metavolcanic xenolith shown in Figures 2A–2C; also shown are granitic veins. (B) Magmatic foliation, defined by aligned igneous minerals and enclaves in the Jackass Lakes pluton. This outcrop is a short distance from xenolith in Figure 2. (C) Folded and locally sheared schlieren layers and granodiorite several hundred meters south of examined xenolith in Figure 2. (D) Photomicrograph of magmatic foliation in the Jackass Lakes granodiorite; white line in upper right depicts average orientation of foliation in rock. The main foliation shown in D is axial planer to folds in C. Ruler in top center of C is 6 cm long.
stretching direction. The vein is coarser grained, and muscovite and biotite locally form comb layering where crystals nucleated on and grew perpendicular to the margin (Fig. 6C), indicating that any deformation in this vein occurred in the magmatic state. This dike has curving margins that, over several wavelengths, form cusped-lobate patterns similar to those seen along the main xenolith margin (cf. Figs. 4 and 6). Here also the andesitic xenolith forms cusps perpendicular to the xenolith-vein margin, suggesting that it had a lower effective viscosity during folding of the vein. Locally foliation in the xenolith is deflected around fold hinges or lobate protrusions, indicating that the xenolith was ductile and flowing during magmatic deformation of the vein.

**Snake Xenolith**

Mapping throughout the Jackass Lakes pluton reveals similar xenolith-magma relationships. In another example, a large (50 m × 55 m) andesitic xenolith crops out along the eastern margin of the Sing Peak pendant (Figs. 1 and 7). The xenolith contains a northwest-trending, steeply east dipping metamorphic foliation that is subparallel to a well-developed magmatic foliation within the host granodiorite. Contact relations display similar geometries as the Black Beauty xenolith: discordant hypersolidus foliations in the granodioritic host occur at the ends of the xenolith, whereas concordant fabrics occur along the sides (Fig. 7A). Large-scale mapping (1:300) reveals a meter-wide granodioritic dike that can be traced continually from the southern to northern edge of the xenolith and into the host granodiorite (Figs. 7A, 7B). This dike is folded about axial planes that are subparallel to the metamorphic foliation in the xenolith and magmatic foliation within the granodioritic host (Figs. 7C–7F). Schlieren layering within the dike is folded. The dike contains an axial

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**Figure 4. Field photos of xenolith margins.** (A) Sharp margin between xenolith (dark color) and granodiorite (light color) showing ~60° jog in margin. (B) Cuspate-lobate pattern at ends of xenolith. Black and white arrows in A and B point toward concave granodiorite-xenolith contacts where cusps of the meta-andesite point into the granodiorite. Three veins of late melt extend into the xenolith, are continuous across the xenolith margin, and have no subsolidus deformation. The largest vein (blue arrow) extends a short distance into the granodiorite before merging into the granodiorite matrix. (C) Close-up of ~90° step along xenolith margin with both straight and slightly curved margins. More felsic magma (lighter-colored material) accumulated along margin and a thin vein intruded into xenolith at inner step (arrow). (D) Vein of late melt extending into xenolith. Note that vein is continuous across xenolith margin. Orange ruler in all images is 15 cm long.
Figure 5. Photos of granodiorite and granite veins in meta-andesitic xenolith. (A) Best-exposed portion of xenolith and contact with granodiorite showing three vein sets. Set 1 is subparallel to metamorphic foliation in the xenolith; set 2 is subperpendicular to the foliation; set 3 is at high angles to foliation and typically defined by thicker dikes. Single veins can abruptly change orientation from one set to the next. Crosscutting relationships are complex, but typically suggest that set 1 formed before set 2, followed by set 3. (B) Boudinaged vein set 1; note rectangular shapes and lack of change in thickness of most boudins. (C) Close-up of folded vein (set 2); 5 cm of ruler for scale. (D) Folded and boudinaged veins showing estimates of extension and shortening in subhorizontal plane, i.e., at high angles to mineral lineation. Orange scale in A and B is 15 cm long.
planar, magmatic foliation defined by subhedral plagioclase laths and amphibole crystals that is subparallel to the metamorphic foliation within the xenolith and magmatic foliation within the host granodiorite. In addition, centimeter-scale elongate xenoliths of andesitic composition occur within the dike and share the axial planar orientation (Fig. 7D).

**XENOLITHS IN THE ANDALSHATTEN PLUTON**

The Andalshatten pluton, central Norway, is a large (~630 km²) elongate intrusive complex with exposed dimensions of 18 × 35 km (Fig. 8). The pluton consists of a large K-feldspar mega-cryrstic granodiorite unit with lesser tonalite, diorite, and leucogranite. Nordgulen et al. (1993) published a U-Pb zircon age of 447 ± 8 Ma. More recent chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) dating on two samples from the granodiorite phase yields ages of 442.66 ± 0.18 Ma and 442.86 ± 0.20 Ma old (Anderson et al., 2007). The Andalshatten pluton is rich in xenoliths of all lithologies observed in the host rocks and at centimeter to kilometer scales.

Regional mapping (Nordgulen et al., 1992; Anderson et al., 2007) has demonstrated that magmatic fabrics in the Andalshatten pluton cut across compositional boundaries at the map scale. We interpret this relationship to indicate that the magmatic fabrics formed late in the crystallization history of the Andalshatten pluton. Ongoing structural work along the north and eastern margin of the pluton indicates a penetrative crystal-plastic overprint that is interpreted to reflect ca. 442 Ma ago regional deformation. Therefore, we view the magmatic fabrics within the Andalshatten pluton as the hypersolidus record of this deformation.

**Descriptions of Xenoliths**

The following descriptions are from a suite of xenoliths and screens ranging in size from several to tens of meters in length exposed near the western contact of the pluton (Fig. 9). In contrast to the Jackass Lakes pluton, xenoliths and screens within the Andalshatten pluton show more evidence for ductile modification of contacts and internal strain.

A spectacular example of symmagmatic deformation of a screen occurs along shoreline exposures near the southwest margin of the pluton (Fig. 9). At this locality, termed the “taffy” screen, an ~100-m-long, elongate screen of folded calc-silicate rock was intruded by north-trending sheets of coarse-grained granodiorite and shows evidence for boudinage in the granodioritic magma. The contacts of the screen dip steeply to shallowly east and broadly define an S shape in map view (Fig. 9B). The screen contains sets of upright, tight to isoclinal folds defined by transposed layers of calc-silicate and metaarkosic rocks. A spaced axial planar cleavage is well developed in the folds. Both the axial planar cleavage and the limbs of the folds mimmic the S shape of the screen. At the neck of the boudin, point P in Figure 9A, the interlimb angles of the folds approach 0° and the axial planar cleavage becomes penetrative with lithons that decrease in width to <2 cm.

**Xenolith Margins**

The contacts of the taffy screen are variable in terms of the relative concordance and shape with respect to internal structure within the screen. At the meter scale, undulating, lobate
Figure 7. (A) Geologic map of large metavolcanic xenolith (Km—Cretaceous metavolcanic) within the Stanford Lakes xenolith field, located in the southwestern Jackass Lakes pluton (Kj; see Fig. 1). Universal Transverse Mercator projection, NAD 1972 Zone 11. Arrow in A denotes area of folded dike show in B–D. (B) Photo of xenolith. (C) Drawing of B. Note the granodiorite dike that intrudes the xenolith and is folded about an axial plane parallel to magmatic fabrics in the Kj. (D) Hypersolidus foliations in the dike and metamorphic foliations in the enclosing xenoliths are subparallel parallel to the pencil. (E) Lower-hemisphere stereonet displaying poles to magmatic foliations. (F) Lower-hemisphere stereonet displaying poles to metamorphic foliations.
contacts with amplitudes and wavelengths of as much as tens of centimeters can be followed that display a transition from obliquely discordant to concordant (Fig. 9). The maximum length of straight and planar contacts is ~1 m. Where lobate contacts with granodiorite bow into the screen, the layering is attenuated at the apex of the lobe (Fig. 9C). Locally, the layering is truncated along the inflection points of lobes (Fig. 9C) forming a bedding cutoff, analogous to cutoff angles between strata and faults in brittle fault systems (e.g., Boyer and Elliot, 1982). At the lobe apex, bedding, although attenuated, is usually concordant to the contact.

**Dikes and Sills in Xenoliths**

Dikes and sills of granodiorite and leucogranite intrude most of the larger xenoliths and virtually all of the screens. The taffy screen contains two examples that bear on the nature of synmagmatic deformation of metasedimentary xenoliths. In Figure 10 a granodioritic dike intrudes the eastern margin of the screen at a very shallow angle with respect to layering. The dike continues for several meters obliquely into the screen where it tapers to a pointed end in the eastern limb of a tight syncline. An en echelon vein of granodiorite is observed 20 cm west of this dike that cuts the axial planar cleavage in the core of the syncline (Fig. 10A). The

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**Figure 8. Simplified geologic map of the Andalshatten pluton and Helgeland Nappe Complex.** The Andalshatten pluton intrudes rocks of all the major nappes within the Helgeland Nappe Complex. Note that screens and xenoliths within the Andalshatten contain lithologies that are apparently observed along strike in the host rocks.
Figure 9. (A) North-looking perspective of the taffy screen (see text). Note the attenuation of the screen at point P. White arrow shows perspective of view in Figure 10. Black arrows denote contacts that are impinged by the granodiorite. (B) Geologic map of the taffy screen and other nearby xenoliths. (C) Detail of contact between xenolith and granodiorite. White arrow denotes concordance, whereas black arrows denote cutoffs between layering and xenolith-granodiorite contact. Marker layers (bedding) x and y display progressive attenuation before they are truncated at the contact.
The dike is boudinaged in the screen along a flattening plane that is subparallel with the axial planar cleavage contained within the screen (Fig. 10A). Cutoffs between the dike and layering are consistently <15°.

In contrast to the boudinaged dike, Figures 10B and 10C display a composite granodioritic and/or leucogranitic sill that intruded parallel to layering within the calc-silicate rock. Bedding is folded about the same axes shown in Figure 9. The sill, therefore, has a folded geometry but contains no evidence of strain associated with folding. In contrast to the examples from the Jackass Lakes pluton (e.g., Fig. 7), there is no preserved axial planar magmatic foliation within the sill. However, within the sill, panels of calc-silicate rock 2–3 cm wide and as much as 1 m long are entrained and in some cases tightly to isoclinally folded about chaotically oriented fold axes (Fig. 10C).

Figure 10. Detail view of internal strain and diking in the taffy screen in Figure 9. (A) Oblique view to south of the east margin of the taffy screen displaying the tightly folded syncline, transposed bedding, and boudinaged granodioritic dikes that emanated from the host magma (bottom and left side of the image). Layering-contact cutoffs are <10°. Crystal-plastic fabrics within the granodiorite are localized to within a few centimeters to meters of the screen contact. Note how scale changes with perspective. (B) Folded composite granodioritic-leucogranitic sill that intruded previously folded calc-silicate rocks. (C) Lower limb of folded granodioritic dike in B displaying panels of calc-silicate rock that are folded about randomly oriented axes (black arrow). Coin is ~15 mm in diameter.
DISCUSSION

Xenolith Formation, Incorporation, and Strain

Both the subvolcanic Jackass Lakes pluton and the middle crustal Andalshatten pluton are littered with pieces of host rock ranging in size from meter-scale to kilometer-scale xenoliths. In some cases it is possible to establish that xenoliths have been detached from screens or the host rocks and moved through the magma prior to being trapped at their present location. In other cases, xenoliths appear to have been translated away from the host by an invading dike, but do not appear to have been considerably rotated. Whether most xenoliths or screens have remained in situ cannot be constrained because magma emplacement must move either the host rock contact or the screen (or both) during intrusion.

In both plutons, xenoliths and screens have variably discordant margins, or cutoffs, defined by planar fractures that typically cut across any structure in the xenolith (e.g., Figs. 2, 4, 7, 8, and 10). Such bedding and/or layering contact cutoff angles provide information about initiation of xenolith incorporation as well as subsequent xenolith deformation within the magma. These planar contacts were deformed to various extents after the xenolith was incorporated into the magma, resulting in tightened cutoff angles, folding, and boudinage (e.g., Fig. 9). In the following sections we examine how xenoliths may be used to evaluate magma-xenolith rheology and strain fields in plutons.

The folding and boudinage of veins (Fig. 5), thickening and formation of cuspatelobate margins of some veins (e.g., Fig. 4), and the deflection of foliations in the xenoliths around vein margins all indicate that the xenoliths underwent additional ductile strain during vein formation. The late crosscutting undeformed veins establish that this ductile deformation ceased before final crystallization of the Jackass Lakes pluton. The presence of a single foliation in all of the xenoliths examined and the orientation of this foliation parallel to the direction of vein extension and perpendicular to vein shortening (indicated by vein boudinage and folding, respectively) imply that this preexisting foliation was reactivated during the in situ ductile deformation of the xenoliths and the formation of the magmatic foliation in the Jackass Lakes pluton. This conclusion is supported by the axial planar, hypersolidus foliation observed in folded dikes (e.g., Fig. 7).

In the Black Beauty xenolith we have estimated the magnitude of strain associated with this synmagmatic pulse of ductile deformation by using the folded and boudinaged veins. These veins occur on subhorizontal faces that are subperpendicular to the steeply plunging lineation in this region and therefore reflect the YZ plane of the strain ellipsoid. Because the thickness of the vein boudins does not vary along veins, and because they show no signs of necking or other internal strain, we treat the boudins as solid rectangles formed by brittle cracking and then rigidly translated during extension. Therefore, we can use their original and deformed lengths to calculate the amount of shortening perpendicular to the foliation plane (Fig. 5D; Ferguson, 1981). We have also treated the folded veins as ptygmatic folds and used their deformed and undeformed lengths to calculate the amount of shortening perpendicular to the foliation plane (Fig. 5D). Our measurements indicate that the most deformed veins record ~31% extension and 49% shortening in the horizontal surface. We have no quantitative information about strain in the vertical direction in this xenolith. These values for strain are interpreted to reflect the minimum strain that affected the xenoliths and magma during folding and boudinage of the granodioritic veins and dikes prior to final cracking and intrusion of the late crosscutting dikes.

Figure 11 depicts a schematic characterization of xenolith-magma deformation as observed in both the Jackass Lakes and Andalshatten examples. Deformation within the xenolith is kinematically compatible with regional deformation associated with fabric development in the host magma. At the point of fabric formation in the system, we envision that the rheology of the xenolith and magma are similar. Given the apparent fast rate at which dikes in the Jackass Lakes pluton may have cooled, the xenoliths likely continued to deform ductilely at presumably fast strain rates so as to maintain the magmatic foliation within the dikes. Albertz et al. (2005), on the basis of thermal modeling and field observations in shallow crustal settings, suggested that strain rates may approach $10^{-2}$ s$^{-1}$ in order to preserve magmatic fabrics within the axial planes of folded granodioritic dikes. Regardless of the absolute rate of deformation, axial planar magmatic fabrics in the folded granodiorite dikes that are parallel to metamorphic fabrics in the xenoliths imply relatively fast strain rates in the pluton–host rock system.
Rheology of the Magma–Host Rock–Xenolith System

Several observations suggest that the granodioritic magma in both the subvolcanic Jackass Lakes chamber and the middle crustal Andalshatten chamber was as strong as or stronger than the andesitic and calc-silicate xenoliths, respectively, while the xenoliths were internally deforming. The pytgomery folding and boudination of veins (e.g., Figs. 5 and 7) and xenoliths (e.g., Fig. 9), the presence of cuspatelobate margins (Fig. 4), and the thin V-shaped cusps all suggest that the magma effective viscosity approached and in some cases exceeded the xenolith viscosity in both plutons. One consequence of these observations is that if the xenoliths are internally shortening and elongating during fabric formation within the magma, then the magma must have been capable of transmitting deviatoric stresses to the xenoliths. This implies that the magmas in both cases were non-Newtonian, crystal-rich mushes with significant strength and that the strength of the xenoliths must be equal to or less than the magma. We also note that the magmatic fabrics in the Jackass Lakes pluton are not strongly deformed around xenoliths, again suggesting that xenoliths were not stronger than the magma.

Structural relations in the Jackass Lakes pluton–host rock system can be used to constrain relative magma viscosities at the time of fabric formation. For example, the degree of deflection of magmatic foliations along the margins of xenoliths may provide information about the viscosity ratio between the crystallizing magma and xenoliths (Paterson and Miller, 1998). Undefined magmatic foliations and subparallel metamorphic foliations in xenoliths in the Jackass Lakes pluton suggest a very low viscosity ratio. That is, where xenoliths and their internal foliations are parallel to the magmatic fabric, and where granodiorite dikes in xenoliths are folded about axial planes that are parallel to the magmatic fabrics, then the viscosity of the crystallizing magma was similar to that of host rock xenoliths. Assuming that individual xenoliths were entirely surrounded by granodioritic magma, the magma viscosity must have been high enough to trap xenoliths (i.e., higher than the most dense block), yet still had sufficient melt present to allow a magmatic foliation to form during regional tectonism and after incorporation of some of the xenoliths.

Granodioritic melt viscosities during ascent, emplacement, and fabric formation are dependent on a number of factors, including composition, pressure, temperature, volatile content, and crystallinity (e.g., Mc Birney, 1993; Scaillet et al., 1997; Bachmann and Bergantz, 2004). To estimate magma viscosities over a range of conditions in the Jackass Lakes pluton, we analyzed five samples of granodiorite from the Jackass Lakes pluton for major and trace elements (Wolak, 2004). These data were then used as input in the programs MELTS (Ghiorso and Sack, 1995) and PELE (Boudreau, 1999) to model effective magma viscosities. Although originally developed for simulating melt evolution in basaltic magmas, these programs may also be used to determine silicic melt parameters at low crystal proportions (<40% crystals). Unfortunately, the programs cannot account for hydrous mafic phases, and are thus less reliable as crystallization proceeds. However, these results provide minimum estimates of the viscosity of the crystal-melt mush and therefore provide a minimum estimate of the strength of the magma.

The shallow emplacement depth, temperature (~900–800 °C), and compositions are well constrained for the pluton (Fiske and Tobisch, 1994; McNulty et al., 1996; Coyne et al., 2004; Wolak, 2004; Krueger, 2005). Although less well constrained in our study, volatile contents are probably between 3 and 8 wt% H2O (Scaillet et al., 1997; Bachmann and Bergantz, 2003). For granodioritic melts with 3 wt% H2O, a liquidus of ~983 °C was calculated. The effective viscosity of a crystal-free melt of this composition was ~1010 Pa s and increased to ~1012 Pa s as cooling proceeded to 758 °C and crystal content approached 40%. Increasing the H2O content to 6 wt% lowered the effective viscosities to ~1010–1012 Pa s and yielded a liquidus temperature of 872 °C. This is compatible with Scaillet et al. (1997) and other studies, which predict that higher volatile contents will result in lower magma viscosities. In addition, our values agree with Coyne et al. (2004), who suggested an estimated solidus of ~670 °C.

Modeled densities of the magma described above ranged from 2230–2410 kg/m3, much lower than our average measured density for metavolcanic xenoliths of 2640 kg/m3 (Wolak, 2004). These data indicate that host rock xenoliths in the Jackass Lakes pluton were negatively buoyant and should have sunk steadily through the crystal-poor magma, assuming xenolith incorporation at crystallinities <40%. Assuming an average block radius of 1 m, the densities given above, granodioritic magma viscosities of 1010–1012 Pa s, and using Stokes’ settling laws for static, Newtonian melts, settling rates of 4.0 × 10−4 to 1.5 × 10−4 m/s (~5 m/a) are predicted for our metavolcanic xenoliths. To achieve slower settling rates (e.g., <10 cm/ka) requires significantly higher viscosities in order to trap xenoliths and allow a magmatic foliation to form after incorporation of the xenolith into the magma. For example, a magma viscosity on the order of 1013 Pa s due to increased crystallinity yields a settling velocity of ~2.13 cm/ka. Therefore, we suggest that the Jackass Lakes magma must have been crystal rich (>50% crystals) at the time of xenolith capture and thus at temperatures approaching the solidus. This conclusion agrees with: (1) the conclusions of Scaillet et al. (1997) and Bachmann and Bergantz (2004), who suggested that the greatest increase in viscosity, due to crystal content, occurs at temperatures nearing the solidus; and (2) previous workers who have estimated magma viscosities ranging from 1010 to 1016 Pa s in crystal-rich mushes during fabric formation in granodioritic to gabbroic compositions (Nicolas and Ildefonse, 1996; Paterson and Miller, 1998; Yoshinobu and Hirth, 2002).

Settling rate estimates for a Newtonian liquid, as described above, are well established for a wide range of conditions (Mc Birney, 1993, and others) but are probably not realistic for a magma. Sparks et al. (1977) suggested that magmas may behave as granular materials with some yield strength, i.e., viscoplastic or Bingham behavior. One effect of an increase in yield strength would be to capture xenoliths at lower magma viscosities. Figure 12 is reproduced from Sparks et al. (1977) and plots the maximum diameter of spheres at excess densities of 300, 500, and 700 kg/m3 with respect to the enclosing magmas as functions of yield strength. Given excess densities of 200–400 kg/m3 for metavolcanic xenoliths (diameter 1 m) in the Jackass Lakes pluton, we estimate that yield strengths needed to trap blocks range from ~250 to 500 N/m2. Like Paterson and Miller (1998), we note that our yield strength estimates are much higher than those measured by Sparks et al. (1977), and therefore require a crystal-rich magma (>50% crystals). Therefore, we contend that higher crystal fractions are required in order to explain the observations from the Jackass Lakes pluton. We note that such Bingham behavior would reduce melt viscosities needed to trap blocks by one to two orders of magnitude (Sparks et al., 1977; Paterson and Miller, 1998).

We summarize the following steps regarding changing magma viscosities, incorporation of host rock xenoliths, and formation of magmatic fabrics in the granodiorite of Jackass Lakes. (1) Xenoliths removed from the margins of the growing magma chamber, whatever via stoping or diking, during the final stages of emplacement must have been incorporated into a crystal-rich magmatic mush with viscosities ranging in excess of 1013 Pa s, or possibly 1–2 orders of magnitude lower if the magma had some yield strength. (2) The granodioritic mush retained enough melt to allow reorientation of framework grains after xenolith capture, thereby erasing most evidence for xenolith incorporation. (3) The viscosities and densities of the magma–host rock–xenolith system were very similar at the
Implications for Fabric Formation in the Jackass Lakes Pluton

One important conclusion is that the preserved magmatic fabric (i.e., foliation and lineation) in the Jackass Lakes pluton (and the Andalsahatten pluton) formed at the same time as the xenoliths were internally deforming. We base this conclusion on the following observations: (1) the subparallelism between the magmatic foliation and/or lineation and metamorphic foliations and/or lineation contained in the xenoliths; (2) subparallelism between these structures and axial planes defined by magmatic foliations within folded granodioritic dikes and veins; (3) lack of significant deflection of the magmatic foliation around the xenoliths; and (4) synchronous pluton fabric formation and vein and/or dike deformation. Given the above, the general characteristics of the xenoliths and Jackass Lakes pluton veins (Figs. 6–9), and the map pattern of the Jackass Lakes pluton fabric (Fig. 1), we summarize the following.

1. The preserved Jackass Lakes pluton fabric formed under a deviatoric stress very late in the crystallization history of the chamber.
2. The amount of strain recorded by the deformed veins in the xenoliths is certainly sufficient enough to form the relatively weak fabric in the Jackass Lakes pluton, implying that the preserved Jackass Lakes pluton fabric may have formed within a short duration and during rapid strain rates.
3. The overprinting of internal intrusive contacts by the fabric and local discordance between the north-south–striking Jackass Lakes pluton fabric and chamber margin indicate that the Jackass Lakes pluton fabric formed after chamber construction, and thus reflects regional strain of an existing chamber and not emplacement-related deformation. If the Jackass Lakes pluton is a subcaldera chamber, then this implies that following caldera collapse (represented by the numerous pendants and xenoliths in the chamber), regional tectonic stresses dominated over any stresses related to the evolution of the magmatic-volcanic system.

CONCLUSIONS

Field observations, structural analysis, and modeled crystallization histories based on major element data may be used to place constraints on the effective viscosity of the magmas in the presence of xenoliths during fabric formation. We summarize our conclusions as follows.

1. The subvolcanic Jackass Lakes pluton, central Sierra Nevada, California, and the middle crustal Andalsahatten pluton, Norway, contain numerous centimeter- to kilometer-scale xenoliths that display evidence for postincorporation, synmagmatic deformation.

2. Late in the cooling history, the crystal-melt mush of both plutons behaved as high-strength materials capable of transmitting deviatoric stresses to the xenoliths, which drove both elastic and crystal plastic deformation in the xenoliths.

3. During synmagmatic deformation melts drained into the xenoliths from the surrounding crystal-rich magma.

4. Estimates of magma viscosity at the time of xenolith capture are in the range of $10^{13}$ Pa s for the Jackass Lakes pluton, suggesting a crystal-rich mush in which realignment of grains to form a magmatic foliation was still possible.

We conclude that magma-xenolith systems may share similar viscosities during near solidus crystallization. In addition, evidence from the Jackass Lakes pluton supports the notion that deformation of the magma-xenolith system may reflect the regional strain field ca. 97–98 Ma ago. This study documents the potential of utilizing detailed field observations of xenolith and igneous structures in plutons to better understand magma rheologies and paleostrain fields in arcs. An interesting future study would include examination of fabric geometry in different plutons with different ages in the same arc system to attempt to track the changing strain field through time.

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