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Mafic–felsic magma mixing limited by reactive processes: A case study of biotite-rich rinds on mafic enclaves

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ABSTRACT

Mafic enclaves in felsic plutons are often used to argue that intermediate magmas are formed by mafic–felsic magma mixing, but the extent and nature of mixing remains unclear. Here, we examine biotite-rich rinds on mafic enclaves from the Cretaceous Bernasconi Hills Pluton in the Peninsular Ranges Batholith of southern California to gain insight into magma mixing processes. Rinds differ from the enclave interior and the host monzogranite in being more fine-grained and more mafic and potassic. Rinds are also 2–5 times more enriched in rare earth elements than the host monzogranite and up to 3 times more enriched than enclave interiors. These observations indicate that the rinds were not generated by isochemical quenching, binary mixing between enclave and host monzogranite, or in-situ magmatic differentiation. Instead, rinds appear to have been formed by chemical reaction between the solidified enclave and a hydrous K-rich residual melt or fluid formed after progressive crystallization and cooling of the host magma body, transforming amphibole in the enclave into biotite-rich rinds. Field observations show snapshots of biotite-rich rinds being eroded away and new rinds simultaneously forming on freshly eroded surfaces of enclaves, consistent with rinds being formed by chemical reaction instead of as quenching products. Deformation of enclaves is accommodated primarily by ductile attenuation of the thin rind while the enclave as a whole tends to rotate as a rigid body with minimal internal deformation other than localized brittle failure. A comparison of the aspect ratios and cross-sectional areas of mafic bodies in the pluton shows that those with high aspect ratios (indicating greater accumulated strain) are systematically more biotite-rich and have smaller cross-sectional areas than those with lower aspect ratios, which are amphibole-rich. These relationships not only confirm that biotite-rich lithologies are more deformable but also indicate that the high aspect ratio biotite-rich bodies (also known as schlieren) derive from small parent bodies, consistent with a derivation from eroding enclave rinds rather than from the enclave itself. Finally, geochemical and thermodynamic modeling indicates that the biotite-rich rinds formed when the host felsic magma had cooled to a low melt fraction state ($F = 0.15$–0.3; 700–760 °C), suggesting that such reactions occur late in the lifespan of a magma body. Thus, mafic–felsic mixing may not be an efficient process for making intermediate magmas unless the magma body can reside at this low temperature range long enough to permit rind formation and subsequent deformation.

1. Introduction

Mafic enclaves are ubiquitous in felsic plutons, and their presence has been interpreted as evidence of mixing between mafic and felsic magmas (Pabst, 1928; Walker and Skelhorn, 1966; Reid et al., 1983; Vernon, 1984; Furman and Spera, 1985; Didier, 1987; Frost and Mahood, 1987; Vernon, 1990; Wiebe et al., 1997; Ratajeski et al., 2001; Barbarin, 2005). The abundance of enclave-bearing plutons has motivated the hypothesis that mixing may be an important mechanism by which intermediate magmas, like andesites, form (Eichelberger, 1975; Reid et al., 1983; Frost and Mahood, 1987; Ratajeski et al., 2001). Although many studies have demonstrated that geochemical mixing trends exist between enclave and granitoid end-members, the exact processes by which mixing occurs remain unclear (Frost and Mahood, 1987; Zorpi et al., 1989; Sisson et al., 1996; Ratajeski et al., 2001; Eichelberger et al., 2006; Reubi and Blundy, 2009). A common feature of enclaves is that they are finer-grained than their host pluton and often have dark, fine-grained margins. This has led to the interpretation that enclaves are chilled upon contact with felsic magma and that these

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fine-grained margins represent quench rinds (Wager and Bailey, 1953; Chapman, 1962; Blake et al., 1965; Walker and Skelhorn, 1966; Furman and Spera, 1985; Vernon, 1990; Wiebe et al., 1997; Barbarin, 2005). Such a scenario is expected given that mafic magmas have higher liquidus and solidus temperatures than silicic magmas and therefore should freeze if intruded into a silicic magma host. However, freezing of mafic magmas would result in a high viscosity contrast between the solidified enclaves and the partially molten host magma, thereby inhibiting deformation of enclaves and mechanical mixing (Frost and Mahood, 1987; Paterson et al., 2004). Mixing might only be efficient in basalt-dominated systems as the basaltic host would provide sufficient heat to completely melt felsic material, but the reverse, that is, mixing of mafic enclaves incorporated into felsic-dominated systems, is more difficult. How do we reconcile the rheological difficulties of mafic–felsic mixing with the apparent evidence for mixing based on the presence of mafic enclaves and associated schlieren?

Here we examine enclaves from the Cretaceous Bernasconi Hills Pluton in the northern Penninsular Ranges of southern California. At this locality, rinds on mafic enclaves are chemically distinct from both the host rock and enclave core and therefore cannot represent isochemical quench rinds. We demonstrate that these rinds are K and biotite-rich and exhibit highly enriched REE patterns compared to enclave interiors and host rock. This implies that the rinds may instead represent reaction products between the enclave and interstitial liquids within the host magma body. We propose that these biotite-rich rinds form by reaction between hydrous residual liquids or fluids and the solidifying mafic enclave during the late stages of pluton crystallization. We further show that these rinds are rheologically weak and hence become preferentially deformed relative to their parent enclave, resulting in their delamination or erosion from the enclave and the formation of biotite-rich schlieren. We propose that enclave deformation and the formation of schlieren is thus limited by the generation of biotite-rich reaction rinds. Therefore, magma mixing, in at least some felsic systems, may be limited by chemical reaction between enclaves and interstitial melt.

2. Geologic background

The Peninsular Ranges Batholith (PRB) intruded during the mid to late Cretaceous and is the southernmost intrusion in the chain of North American Mesozoic batholiths spanning from Alaska to Baja California. The PRB has been divided into western and eastern zones based upon regional variations in lithology, geochemistry and age of individual plutons as well as metamorphic grade of surrounding wallrock (Gastil, 1975; Gromet and Silver, 1987; Gastil et al., 1988; Todd et al., 1988; Kistler et al., 2003; Wetmore et al., 2003; Lee et al., 2007). This boundary between western and eastern zones is inferred to represent a tectonic suture between accreted island arc terranes and the Paleozoic North American continental margin, respectively (Gastil, 1975; Todd et al., 1988; Kistler et al., 2003; Wetmore et al., 2003; Lee et al., 2007). In the northern PRB the boundary runs roughly north–south until the Agua Blanca Fault in Baja California, where it trends southeast until the terminus of the range (Gastil et al., 1988; Wetmore et al., 2003; Lee et al., 2007).

This study focuses on the Bernasconi Hills Pluton, which lies west of the suture in the northern PRB, Riverside County, California. The southern margin of the pluton is truncated by the adjacent ∼90 Ma Lakeview Mountains Pluton (Morton, 1969, 2003; Mason and Cohen, 1990) indicating that it is older than 90 Ma, but the exact age is unknown. It is composed mainly of monzogranite, granodiorite and tonalite, however small bodies of diorite are also observed within the pluton. Our study area lies along a ∼200 m segment (33.839°N, 117.168°W) exposed by recent quarrying in the southern portion of the pluton. Quarrying has provided fresh outcrop exposure and a clear view of mafic enclave–host rock relations within the interior of the pluton.

3. Analytical methods

Mafic enclaves and the adjacent host granitoid were collected from the quarried section of the Bernasconi Hills Pluton. Enclaves were selected on the basis of being relatively unweathered and having a sufficiently thick rind for geochemical analysis. Each enclave was separated into host rock, rind and enclave interior subsamples with a saw. Whole rock geochemistry samples were crushed to a fine powder in a tungsten carbide mill and fused with a lithium tetraborate–lithium metaborate mix. Major oxide compositions were determined by X-ray fluorescence spectrometry (XRF) at California State University, Fresno (see Busby et al., 2008). Trace element concentrations were determined at Rice University by laser ablation-ICP-MS (LA-ICP-MS) with a ThermoFinnigan Element 2 equipped with a New Wave 213 nm laser ablation system for the same fused glass disks used in XRF analyses. External standards used for LA-ICP-MS analysis were United States Geological Survey basaltic (BHVO2g and BCR2g) and National Institute of Standards synthetic silica-rich glasses (NIST612). Laser ablation was conducted with a fluence of 20 J/cm^2, 10 Hz frequency, and 55 μm spot size. Prior to measurement, the instrument was tuned by controlling the sample gas (Ar) to achieve a sensitivity of 250,000 cps on 15 ppm La in BHVO2g in low mass resolution ($m/\Delta m \sim 300$). Raw data were converted to concentrations using an in-house data reduction program (http://www.ruf.rice.edu/~ctlee/Laser-RAWDATA-TEMPLATE.xls) that removed background signal intensities and elemental fractionation with external standards. Signal intensities were normalized to an internal standard (^{25}Mg), and time-resolved intervals were integrated.

4. Field observations

4.1. Granitoid rocks

The Bernasconi Hills Pluton is mainly composed of biotite–hornblende–monzogranite and granodiorite with lesser amounts of tonalite. At outcrop scale (∼5 m) the pluton has a uniform appearance except where enclaves, schlieren and biotite–amphibole selvages are present. Diorite is also present as a large body near the middle of the quarried section of the pluton. The diorite weathers dark gray and superficially resembles mafic enclaves, but is distinguished by its coarse-grained texture and more heavily weathered appearance.

4.2. Enclaves

Mafic enclaves occur as gray to blackish blobs throughout the Bernasconi Hills Pluton and range in size from a few centimeters to a meter in longest dimension. Enclaves show varying degrees of attenuation as shown in Fig. 1. Enclave size and shape vary on the scale of a few centimeters in some parts of the pluton and these variations are most pronounced where there is a large enclave density such as in enclave swarms. The range of enclave shapes indicate that multiple stages in the strain history of a typical enclave are preserved within the pluton, giving a continuous view of how physical interaction between enclaves and the host magma progresses with respect to the enclave.

Almost all enclaves are mantled by thin (0.2–2 cm thick) rinds, which differ from the amphibole-rich enclave interiors by being darker in coloration, finer-grained, and biotite-rich. In many cases, the biotite-rich rinds appear to delaminate, erode or shear off from