ORIGIN OF MAFIC ENCLAVES AND THEIR FELDSPAR PHENOCRYSTs IN THE EL CAPITAN GRANITE, YOSEMITE NATIONAL PARK, CALIFORNIA

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ABSTRACT

KAYLA R. IRELAND: Origin of mafic enclaves and their feldspar phenocrysts in the El Capitan Granite, Yosemite National Park, California
(Under the direction of Dr. Allen F. Glazner)

The El Capitan Granite of Yosemite Valley contains abundant mafic enclaves and is adjacent to a large, roughly coeval mafic complex known as the diorite of the Rockslides (DOTR) that has been suggested as an enclave source. However, Na₂O and MnO lie above a simple mixing line between the two, precluding mixing as a complete explanation for their bulk compositions. The mafic enclaves also contain large plagioclase crystals similar in size to those in the host El Capitan Granite, yet their compositions are distinct from those in the El Capitan Granite and DOTR. Inclusions of Mn-rich ilmenite distinct to the mafic enclaves are also observed within the plagioclase. These data indicate enclaves did not result from mixing of the El Capitan Granite and mafic rocks of the DOTR, but most likely arose from andesitic magmas that are not otherwise found in the Sierra Nevada batholith.
ACKNOWLEDGEMENTS

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Finally, thank you to my friends, family and neighbors for their love and daily support throughout this process.
Nothing exists except atoms and empty space; everything else is opinion.

-Democritus
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INTRODUCTION

Formation of intermediate composition igneous rock is an important process because the continental crust is largely composed of such rocks, yet magmatic input from the mantle is largely mafic (Thomas and Smith 1932; Rudnick and Fountain 1994; Taylor and McLennan 1995). However, the mechanisms by which intermediate rocks are generated remain unknown. Magma mixing, the process by which two initially chemically distinct magmas completely homogenize, is one possible mechanism for their formation, yet the processes that facilitate mixing are still under scrutiny. The principal problem is that contrasts in physical properties such as melting temperature, density, and viscosity between mafic and felsic magmas should inhibit mixing (Frost and Mahood 1987; Wiebe and Collins 1998).

The El Capitan Granite of Yosemite Valley, California and its associated mafic rocks are interpreted to preserve the mingled relations of interacting magmas (Reid et al. 1983; Ratajeski et al. 2001). Mafic pods, enclaves, and schlieren are locally abundant in the El Capitan Granite and are easily observed in the excellent exposures present in Yosemite Valley as well as at the summit of El Capitan itself (Ratajeski 1999). Not only does the El Capitan Granite contain examples of mafic bodies enclosed within a felsic host, but the mafic rocks also contain unusually large plagioclase feldspar crystals, up to 1 cm in size. These feldspars are common in mafic magmatic enclaves and have incited a variety of origin hypotheses (Harker 1904; Grantham 1926; Thomas and Smith 1932; Piwinski 1968; Didier 1973; Presnall and Bateman 1973; Bateman 1995; Baxter and
Feely 2002: Johnson and Barnes 2006). Are these plagioclase crystals xenocrysts from a more felsic magma that were stirred into the mafic end member, or did they develop within the mafic magma as a product of recrystallization due to hybridization or diffusion? Either option presents complexities, as it is uncommon for feldspars this large to form within mafic magma, yet the density and viscosity differences of the end member magmas make physical mixing between the two difficult.

If the large plagioclase crystals originated from a felsic magma, they may reveal signs of chemical disequilibria with their host rock such as reaction rims or zoning. In this case, melt and other smaller crystals would also be brought into the new magma along with the plagioclase crystals, affecting the composition of the enclaves. If the crystals originated in the mafic end-member, however, they would exhibit chemical equilibria with the mafic melt, indicating that there are instead complex chemical and mineralogical processes occurring within the mafic magma itself. Geochemical study of these plagioclase crystals, as well as investigation of the origin of their host mafic enclaves, will lead to a deeper understanding of the extent to which magmas are able to interact and the chemical processes taking place in large magmatic systems.
GEOLOGIC SETTING

The intrusive suite of Yosemite Valley (ISYV; Bateman 1992) is a group of plutonic rocks located within the west-central section of the Sierra Nevada batholith, which formed during arc magmatism in the Cretaceous (Stern et al. 1981; Chen and Moore 1982). The ISYV consists of two main felsic rock units, the El Capitan and Taft Granites, and a mafic complex known as the diorite of the Rockslides (Fig. 1). Attempts to obtain a precise U-Pb zircon age for the El Capitan Granite are complicated by possible lead loss and inheritance (Ratajeski et al. 2001; Ingalls unpublished). Stern et al. (1981) report two concordant U-Pb zircon ages of 102 and 103 Ma for the El Capitan Granite, but with large errors. A more recent study by Ratajeski et al. (2001), using improvements in the U-Pb zircon technique, acquired discordant U-Pb zircon ages in the range of 102-105 Ma. Further efforts to date sections of the El Capitan Granite by Ingalls (unpublished) using U-Pb zircon methods resulted in a concordant ages of 105.41 ± 0.26 for the westernmost section and 103.8 at the base of El Capitan.

The El Capitan Granite is a porphyritic, leucocratic biotite granite (Bateman 1992), and hosts mafic intrusive rocks ranging from gabbro to diorite (Ratajeski et al. 2001). The adjacent mafic intrusive complex diorite of the Rockslides (DOTR) is composed of a variety of rock types including biotite hornblende gabbro and diorite, leucocratic hornblende-biotite diorite and tonalite (Nelson 2006). Field and petrologic observations (Reid et al. 1983; Ratajeski et al. 2001; Nelson 2006) and U-Pb zircon ages (103 Ma; Stern et al. 1981; Ratajeski et al. 2001) indicate that emplacement of the DOTR
Fig. 1  Geologic map of the western portion of Yosemite Valley, Yosemite National Park. Modified from Huber, Bateman, and Wahrhaftig (1989) and Ratajeski (1999). Sampling locations at El Capitan and the Cookie Slide are indicated by the numbers 1 and 2 respectively. The DOTR mafic complex is denoted by the number 3.
was coeval with the El Capitan Granite. The DOTR is therefore often interpreted as a possible source for the isolated mafic enclaves and pods, as well as mafic dikes, within the granite (Reid et al. 1983; Ratajeski et al. 2001). However, geochemical data on the DOTR and North America wall diorites of El Capitan reveal that processes other than simple mixing may be occurring between these two end-members, and other sources may need to be considered for the smaller mafic rocks within the El Capitan Granite (Ratajeski 1999; Nelson 2006).

Exposures created during a large rockslide at Cookie Cliff reveal the relationships of the granite and its synplutonic mafic rocks. This rockslide of El Capitan Granite, termed the Cookie Slide, occurred in 1982 when a portion of Cookie Cliff collapsed and fell across El Portal Road and into the Merced River (Wieczorek et al. 1992; Glazner and Stock 2010). The origin of the mafic enclaves observed here and of their plagioclase crystals are the focus of this study, as well as determining if either provides evidence of mechanical mixing of magmas occurring within the ISYV.
BACKGROUND

Magma mingling

Magma mingling occurs when end-member magmas interact yet remain distinct due to physical and chemical contrasts. Differences in composition, crystallization temperature, viscosity, water content, and relative volume of interacting magmas hinder their ability to homogenize and lead to mingling instead of pure mixing (Shaw 1963; Huppert et al. 1982; Huppert et al. 1983; Huppert et al. 1984; Sparks and Marshall 1985; Turner and Campbell 1986; Frost and Mahood 1987; Fernandez and Barbarin 1991; Sisson and Grove 1993; Bateman 1995). Generally, the viscosities of mafic magmas are one to four orders of magnitude lower than a more silicic magma at the same temperature (Fernandez and Barbarin 1991). Also, the difference in melting temperature between mafic and felsic magmas is great enough such that when a mafic magma is cool enough to have completely crystallized, a more felsic magma may still be molten (Huppert et al. 1982; Sparks and Marshall 1985; Frost and Mahood 1987; Fernandez and Barbarin 1991; Bateman 1995).

If sufficient time is available for chemical diffusion and shearing, and a high proportion of the mafic fraction is present, homogenization of magmas can occur (Huppert et al. 1982; Huppert et al. 1983; Sparks and Marshall 1985; Turner and Campbell 1986). Experimental models indicate that a larger proportion of the mafic component allows for thermal equilibration between two magmas and permits mixing,
whereas a relatively small amount quickly under-cools and mingling takes place (Sparks and Marshall 1985; Bacon 1986; Fernandez and Barbarin 1991).

**Mafic enclaves**

The apparent igneous textures of mafic enclaves in silicic volcanic rocks led to the interpretation that these features represent mingling of two compositionally distinct magmas (Eichelberger 1980; Heiken and Eichelberger 1980; Bacon and Metz 1984; Bacon 1986; Clynne 1999). Chilled margins, along with concentric zonation in crystal sizes indicate that these enclaves are blobs of mafic magma undercooled within a more silicic host (Heiken and Eichelberger 1980; Bacon 1986), and contrasting phenocryst compositions and equilibration temperatures, vesicles, and interstitial glass within enclaves indicate that they are not simply immiscible segregations (Bacon, 1986).

The presence of similar characteristics in plutonic enclaves has led to analogous interpretations for these environments (Reid et al. 1983; Vernon 1983; Cantagrel et al. 1984; Vernon 1984; Sparks and Marshall 1985; Frost and Mahood 1987; Dorais et al. 1990; Elburg and Nicholls 1995). Characteristics such as plastic deformation, fine-grained igneous textures, and chilled margins support a magmatic formation for these mafic seclusions as well (Didier 1973; Frost and Mahood 1987; Barbarin and Didier 1991). Enclaves of this type are termed mafic microgranular enclaves (Didier 1973) and are often interpreted to be indications of earlier mixing at depth, as many are of intermediate-composition (Cantagrel et al. 1984; Bacon 1986; Sparks and Marshall 1986; Fernandez and Barbarin 1991). Examples of enclaves seeming to represent cumulates of early-formed minerals (Gagny 1978; Dodge and Kistler 1990) or restites (Piwinskii 1968;
Chappell 1978; Chappell et al. 1987; Chen et al. 1990) exist, but are rare in both volcanic and plutonic rocks.

Mafic dikes and enclave-choked dikes present within the El Capitan Granite, as well as the adjacent mafic complex the DOTR (Ratajeski 1999) indicate that the mafic enclaves observed in this rock are most likely also magmatic in origin, and did not result from heating and recrystallization of xenolithic material.

**Plagioclase**

The large plagioclase crystals frequently observed in mafic enclaves have been interpreted to have several possible origins:

1) xenocrysts from a more felsic host rock that were incorporated into the enclaves by physical mixing (Harker 1904; Thomas and Smith 1932; Cantagrel et al. 1984; Bateman 1995; Johnson and Barnes 2006)

2) phenocrysts of the mafic enclaves that grew due to thermal and elemental diffusion with their granitic host rock (Grantham 1926; Nockolds 1932; Reynolds 1946; Didier 1973).

3) relict phenocrysts of restitic material (represented by the mafic enclaves) left over from partial melting of crustal material (Piwinski 1968; Presnall and Bateman 1973).

Plagioclase crystals interpreted as xenocrysts exhibit disequilibrium textures such as resorption and rims of differing compositions from their cores (Harker 1904; Thomas
and Smith 1932; Bateman 1995; Johnson and Barnes 2006). The presence of xenocrysts indicates that magma mixing has occurred in the formation of large granitoid bodies (Thomas and Smith 1932; Baxter and Feely 2002). Yet in order to mechanically transport the plagioclase crystals, mafic enclaves would need to be semi-fluid or plastic within the also fluid felsic magma, and still able to retain their shape and resist mixing (Harker 1904; Thomas and Smith 1932). The phenocryst hypothesis attributes the growth of these crystals to chemical exchange or assimilation of the enclaves with the surrounding more felsic host (Nockolds 1932; Reynolds 1946; Didier 1973). This process, termed metasomatic granitization (Didier 1973) leads to coarsening of the crystals in the enclaves and a texture and mineralogy that approaches that of the host (Nockolds 1932).

Relict phenocryst hypotheses are the least explored, and have been used to explain plagioclase phenocrysts that are anomalously sodic (Piwinskii 1968).

Feldspar crystals are also commonly believed to preserve the crystallization histories of the magmatic systems in which they are found (Hibbard 1981; Anderson 1984; Davidson et al. 1990; Słaby and Götze 2004). Chemical zoning records the magmatic environment present during their formation, and because interdiffusion of CaAl and NaSi in plagioclase is extremely slow, these compositional bands can be retained through subsequent diffusive reequilibration (Grove et al. 1984; Morse 1984; Liu and Yund 1992). Therefore it is expected that if changes in environment occur, such as would result from mechanical mixing of plagioclase crystals into a new magma, the resulting disequilibria conditions would be recorded in the textures of the crystals themselves. However, changes in plagioclase composition have been shown to occur after crystallization, such as through reaction with hydrous melt (Lundstrom et al. 2005).
Such experiments indicate that rapid elemental exchange can occur into the cores of plagioclase crystals as a result of diffusion-reaction, overprinting previous compositions. Inclusions of other minerals within feldspars are also useful as indicators of magma mixing as they may record differing magmatic environments throughout the growth of the minerals (Davidson et al. 1990; Tepley et al. 1999; Gagnevin et al. 2005).
METHODS

Sample collection

Samples were collected from the base and summit of El Capitan and from the Cookie Slide in Yosemite National Park, California (Fig. 1). The Cookie Slide exposure provided exceptionally fresh, broken pieces from the interior of the outcrop at Cookie Cliff. Samples collected included mafic enclaves as well as the portions of host El Capitan Granite directly surrounding them. Portions of the granite away from enclaves were also collected. Enclaves with unusually large (~1 cm) plagioclase crystals, as well as samples representing a large range of textures, were collected for later analysis. Detailed descriptions of the enclaves included the nature of the enclave/granite contacts, abundance of plagioclase crystals in the enclaves, presence of quartz ocelli (rounded quartz crystals mantled by hornblende), and the general enclave texture (Table 1).
### Table 1 Descriptions of mafic enclaves within the El Capitan Granite

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Large plagioclase</th>
<th>Quartz ocelli</th>
<th>Type of boundary</th>
<th>Other features</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECB717-4</td>
<td>rare</td>
<td>no</td>
<td>sharp</td>
<td></td>
</tr>
<tr>
<td>ECB718-1</td>
<td>abundant</td>
<td>yes</td>
<td>sharp</td>
<td></td>
</tr>
<tr>
<td>CS719-1</td>
<td>abundant</td>
<td>no</td>
<td>sharp</td>
<td></td>
</tr>
<tr>
<td>CS719-2</td>
<td>rare</td>
<td>yes</td>
<td>sharp</td>
<td></td>
</tr>
<tr>
<td>CS719-3</td>
<td>rare</td>
<td>yes</td>
<td>sharp</td>
<td>intermediate band</td>
</tr>
<tr>
<td>CS719-4</td>
<td>rare</td>
<td>yes</td>
<td>sharp</td>
<td></td>
</tr>
<tr>
<td>CS719-11</td>
<td>abundant</td>
<td>no</td>
<td>gradational</td>
<td></td>
</tr>
<tr>
<td>CS720-1</td>
<td>rare</td>
<td>yes</td>
<td>sharp</td>
<td></td>
</tr>
<tr>
<td>CS720-3</td>
<td>abundant</td>
<td>yes</td>
<td>sharp</td>
<td></td>
</tr>
<tr>
<td>CS720-4</td>
<td>abundant</td>
<td>yes</td>
<td>sharp</td>
<td></td>
</tr>
<tr>
<td>CS722-1</td>
<td>rare</td>
<td>no</td>
<td>NA</td>
<td>abundant titanite</td>
</tr>
<tr>
<td>CS720-7</td>
<td>rare</td>
<td>no</td>
<td>sharp</td>
<td>small (~6 cm)</td>
</tr>
</tbody>
</table>
Whole-rock major- and trace-element geochemistry

Whole-rock analyses of the enclaves and the surrounding granite were performed using wavelength-dispersive x-ray fluorescence (XRF) at the University of North Carolina at Chapel Hill. Major elements were determined by mixing powdered sample in a 1:9 ratio with either pure lithium tetraborate or a 33% lithium tetraborate /66% lithium metaborate flux and fusing the mixture. Standards used for calibration were AGV-1, G-2, GSP-2, MAG-1, QLO-1, STM-1 and W-2 USGS reference materials. Trace element analyses were also performed with XRF using pressed powder disks using standards AGV-1, G-2, MAG-1, QLO-1, STM-1 and SDC-1.

Transects from the El Capitan Granite into the mafic enclaves were also prepared to investigate compositional profiles through the contact zones of the two rock types. Slabs were cut perpendicular to the enclave/granite boundary and extended several centimeters into both the surrounding granite and the mafic enclaves. The slabs were then cut into 1 cm sections parallel to the enclave/granite contact for analysis (Fig. 2).
Fig. 2  Slabs from which two of the enclave/granite transects were cut.  

a  Sample CS719-3 with intermediate composition segment D.  

b  Sample CS720-1, containing a visually observable felsic halo (segments F and G)
Electron microprobe

Mineral analyses for the enclaves and the enclosing El Capitan Granite were performed using the JEOL JXA-8530F field-emission electron microprobe at the Southeastern North Carolina Regional Microanalytical and Imaging Center (SENCR-MIC) at Fayetteville State University. Minerals were analyzed at an accelerating voltage of 15 kV using a 10 nA probe current with a spot size of 2 µm to reduce volatilization. Matrix corrections were performed using the ZAF correction scheme. Plagioclase analyses were obtained from multiple crystals in each enclave, and from several thin sections of the El Capitan Granite and DOTR. For most large plagioclase crystals, the core and rim were analyzed separately. Traverses or line scans across the grain were performed on several large plagioclase crystals in order to discern compositional zoning.

Mineral imaging was performed on the JEOL JXA-8530F field-emission electron microprobe at Fayetteville State University and a Leica 440 scanning electron microscope at the University of North Carolina at Chapel Hill. Backscattered-electron images and X-ray maps were created using an accelerating voltage of 15-10 kV and a beam current of 10 nA.

Mineral staining

Slabs from 3 samples were cut perpendicular to the enclave/granite boundary and polished to remove saw marks. The cut faces were soaked in 29M hydrofluoric acid for ~1 minute, and then rinsed in distilled water. The slabs were immersed in a 20% amaranth solution for ~5 seconds to apply a reddish-purple stain to the plagioclase crystals. K-feldspar was stained yellow by immersing the slabs in 50% sodium
cobaltinitrite solution for ~10 seconds. The slabs were rinsed in water baths after each stain.
RESULTS

Enclave descriptions

Mafic enclaves in the El Capitan Granite are ellipsoidal to slightly angular and range in size from 6 cm to ~1 meter in the longest direction (Fig. 3a-c). Rare small sigmoidal enclaves locally occur (Fig. 3d). Contacts with the host granite are typically sharp but the enclaves lack fine-grained boundaries that would imply a chilled margin. Coarse-grained enclaves with diffuse boundaries are less abundant. Enclaves are composed of diorite and contain mainly hornblende, biotite, plagioclase and quartz. Accessory minerals include titanite, apatite, zircon, iron-oxides and Mn-rich ilmenite. Enclaves are generally porphyritic with large plagioclase (0.5 - 1cm) and quartz crystals. Many of the enclaves contain quartz ocelli (Fig. 3f).

A leucocratic halo approximately 2 cm thick locally occurs within the granite adjacent to the enclaves (Fig. 3e-f). Sample CS719-3 differs from the other enclaves in that it also contains a light gray band up to 1 cm thick between the enclave and the leucocratic halo. This gray band is similar in crystal size to the enclave, but more felsic in composition (Fig. 2a). At some points this intermediate band becomes particularly quartz-rich at the enclave boundary (Fig. 4).
Fig. 3 Characteristic mafic enclaves of the El Capitan Granite at the Cookie Slide. 

a Elongate mafic enclaves within a fresh boulder of the host granite. 
b Small swarm of rounded mafic enclaves. 
c Elongate mafic enclave with abundant large plagioclase crystals. 
d Small (~10cm) sigmoidal enclave. 
e Mafic enclave with sparse large plagioclase crystals (denoted by arrows) and a visible felsic halo. 
f Mafic enclave with felsic halo and quartz ocellus.
Fig. 4 Examples of the types of enclave/granite boundaries. CS720-1 has a characteristic sharp boundary with a thick felsic halo adjacent to the enclave (outlined by the yellow dashed line) and sparse plagioclase phenocrysts. The boundary of CS719-11 is diffuse, and lacks any felsic halo. It also contains an abundance of plagioclase phenocrysts. CS719-3 has a sharp boundary but no visible felsic halo. Instead it contains a thin rim of mostly quartz at the edge of the mafic enclave. ECB718-1 has a defined boundary that is distorted by the abundant plagioclase phenocrysts present within the enclave.
Whole-rock major- and trace-element geochemistry

Eleven mafic enclaves from this study, as well as three from Ratajeski, 1999, were analyzed for whole-rock geochemistry (Table 2). All mafic enclaves contain between 56 and 65 wt% SiO₂. The enclave analyses plot between analyses of El Capitan Granite and DOTR samples from this study, Ratajeski (1999) and Nelson (2006) for most elements, but their MnO and Na₂O contents lie above a simple mixing line (Fig. 5). The enclaves also deviate from the trends observed in rocks from the general Sierra Nevada batholith compiled by Bateman (1984) for these two components.

The felsic halos surrounding the mafic enclaves are depleted in K₂O and enriched in Na₂O relative to the El Capitan Granite and other rocks of the Sierra Nevada batholith (Fig. 5). One of these halo analyses, from sample CS719-11, is compositionally similar to the mafic enclaves. This sample is from an enclave that has a gradational contact with the granite and appears to lack this more felsic region between itself and the El Capitan Granite. Detailed analysis of the 1 cm transects through the halos and their adjacent granite and mafic enclave reveals a more complex geochemical relation. A decrease in SiO₂ and increases in TiO₂, Al₂O₃, Fe₂O₃, MnO, MgO, K₂O, and P₂O₅ are observed in the portion of the enclaves directly adjacent to the granite. A corresponding depletion in these oxides, and increase in SiO₂, appears in the leucocratic halo on the granite side of the contact (Fig. 6). Plots of the transects also reveal subsequent increases (or a decrease, in the case of SiO₂) further into the granite outside of the halo. The compositions of the granite within this section generally differ from the range exhibited by the general El Capitan Granite samples. The return to El Capitan Granite composition is only observed for transect CS720-7, in which the enclave is relatively small (6 cm across) and transects
<table>
<thead>
<tr>
<th>Sample</th>
<th>CS719-1</th>
<th>CS719-2</th>
<th>CS719-3</th>
<th>CS719-4</th>
<th>CS719-11</th>
<th>CS720-1</th>
<th>CS720-3</th>
<th>CS720-4</th>
<th>CS722-1</th>
<th>ECB717-4</th>
<th>ECB718-1</th>
</tr>
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<tbody>
<tr>
<td>SiO$_2$ (wt%)</td>
<td>58.17</td>
<td>55.45</td>
<td>58.08</td>
<td>58.06</td>
<td>61.44</td>
<td>59.42</td>
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<td>62.33</td>
</tr>
<tr>
<td>TiO$_2$</td>
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<td>0.92</td>
<td>0.89</td>
<td>0.81</td>
<td>0.67</td>
<td>0.84</td>
<td>0.58</td>
<td>0.65</td>
<td>0.94</td>
<td>0.75</td>
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<tr>
<td>Al$_2$O$_3$</td>
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<td>17.34</td>
<td>17.29</td>
<td>17.63</td>
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| Ba (ppm) | 392     | 845     | 671     | 745     | 1153    | 358     | 893      | 836      | N.D.    |
| Co        | 3       | 3       | 4       | 6       | 13      | 0       | 2        | 2        | N.D.    |
| Cr        | 45      | 66      | 43      | 16      | 74      | 24      | 52       | 68       | N.D.    |
| Ni        | 7       | 5       | 5       | 5       | 1       | 10      | 6        | 7        | N.D.    |
| Rb        | 77      | 90      | 78      | 87      | 118     | 57      | 148      | 75       | N.D.    |
| Sc        | 10      | 11      | 11      | 10      | 12      | 10      | 10       | 10       | N.D.    |
| Sr        | 384     | 468     | 492     | 361     | 422     | 344     | 287      | 392      | N.D.    |
| V         | 23      | 34      | 41      | 41      | 73      | 4       | 26       | 20       | N.D.    |
| Y         | 31      | 38      | 29      | 29      | 49      | 26      | 40       | 28       | N.D.    |
| Zr        | 189     | 253     | 264     | 249     | 448     | 103     | 162      | 155      | N.D.    |
Fig. 5 Harker diagrams for the El Capitan Granite, the DOTR, mafic enclaves, and felsic halos rimming the mafic enclaves compared to other rocks of the Sierra Nevada batholith from Bateman, 1984.
Fig. 6  Plots of composition vs. distance for the 1 cm traverses through the enclave/granite contact zone. Top scale in each plot is for sample CS720-7 and the bottom is for samples CS719-3 and CS720-1. On both scales 0 cm is the last transect on the granite side of the contact and 1 cm is the first transect on the enclave side. Dashed line indicates the enclave/granite contact.
could be obtained further into the granite.

Trace-element data were collected for comparison of the mafic enclaves to the El Capitan Granite as well as their felsic halos. Sc, Sr, and V show consistent decreases with increasing SiO$_2$ for the El Capitan Granite, DOTR, and mafic enclaves (Fig. 7) while other trace-elements have similar compositional ranges for three rock types (Ba, Y, Zr). However, the trace-element contents of the mafic enclaves often do not lie on a mixing line between the El Capitan Granite and the DOTR. Unlike to the major-element trends, trace-element contents of the felsic halos are often more similar to those of the mafic enclaves than the El Capitan Granite.
Fig. 7  Plots of trace elements vs. SiO$_2$ for the El Capitan Granite, the DOTR, mafic enclaves, and felsic halos surrounding the mafic enclaves. Trace element compositions of the felsic halos are generally similar to those of the mafic enclaves, except in the case of V and Zr, where they are more similar to the El Capitan Granite, and Y, in which they appear generally enriched compared to all other rock types.
Plagioclase in enclaves

Two forms of plagioclase phenocrysts exist in the enclaves of the El Capitan Granite. Plagioclase crystals are euhedral to subhedral and lack distinct internal subdivisions, such as between rim and core, in enclaves with abundant crystals larger than \( \sim 0.5 \) cm (e.g., sample CS719-11, Fig. 4). X-ray images reveal that these crystals generally have oscillatory or patchy zoning (Fig. 8). Rim-to-center traverses across large crystals indicate a fair amount of oscillatory zoning, but again do not show consistent chemical variations between rims and cores (Fig. 9). Mineral inclusions are sparse but uniform in distribution and include hornblende, apatite, and K-feldspar.

Enclaves having sharp contacts with the granite contain sparse plagioclase crystals with distinct rims and cores (e.g., sample CS720-1, Fig. 4). Cores are rounded euhedral crystals and are mantled by a thin zone of plagioclase more anorthite-rich than both the interior core and the rim (Fig. 10a-d). This zone is easily detectable in backscattered-electron images as a light band \( \sim 100 \) µm wide (Fig. 11a-b). The rims of these plagioclase crystals are subhedral to anhedral and are commonly intergrown with adjacent crystals (Fig. 10d). Small mineral inclusions of hornblende, biotite, K-feldspar, apatite, and Mn-rich ilmenite are abundant in the cores but sparse in the rims.

Groundmass plagioclase crystals of the enclaves exhibit similar morphology to the larger crystals of their relative enclaves, including the anorthite-rich bands (Fig. 11c-d).

Plagioclase crystals within the mafic enclaves are fairly sodic. Large plagioclase crystals have compositions of \( \sim \text{An}_{16} \) to \( \text{An}_{42} \), with two crystal analyses having An numbers over 50. Compositions of the groundmass plagioclase range from \( \text{An}_{22} \) to \( \text{An}_{43} \), with two having An numbers over 58. When a core and rim could be distinguished for a
Fig. 8  Backscattered-electron image (left) and Ca x-ray map (right) of enclave sample CS719-11. The yellow line denotes the boundary of a large (~6 mm) plagioclase crystal. Lighter shades of blue indicate a higher abundance of calcium within the crystal and reveal patchy compositional zoning near the outer edge. Microprobe spot analyses also indicate a wide range in anorthite content (An$_{21}$ to An$_{40}$) within this single crystal. Similar variations in composition, indicated by the range in color, are exhibited by the surrounding groundmass plagioclase. Black areas within the crystal on the x-ray image are inclusions of quartz and biotite.
Fig. 9 Traverses of one small and two large oscillatory zoned plagioclase crystals in sample CS719-11 lacking the resorbed core and anorthitic rim. Large variations in An content are observed within each of these samples, particularly in plot c. Vertical lines indicate approximate center for each crystal. All points along the linear traverses were hand selected to avoid inclusions within the plagioclase crystals.
Fig. 10 Photographs of large plagioclase and quartz crystals in mafic enclaves of the El Capitan Granite. **a - d** Plagioclase crystals from samples CS719-1, CS720-1, and ECB718-1, enclaves which all have sharp enclave/granite contacts. Crystals have rounded cores surrounded by a thin anorthitic rim. In **d** intergrowth of the rim with surrounding crystals is easily observed. **e - f** Rounded quartz grains surrounded by hornblende and biotite. *All photographs taken under cross-polarized light.*
Fig. 11 Backscattered-electron images of enclave plagioclase crystals exhibiting anorthite-rich bands. 

**a** Small crystal with rounded core and an anhedral rim intergrown with the surrounding crystals. Inclusions within this crystal include biotite, quartz and K-feldspar. 

**b** End of large plagioclase crystal with rounded core and a fairly subhedral rim containing abundant inclusions of biotite, quartz, Mn-rich ilmenite, hornblende and K-feldspar. 

**c** Enclave groundmass plagioclase crystals containing anorthite-rich bands, indicated by red arrows. These bands often surround a slightly mottled area within the groundmass plagioclase. 

**d** Close-up of a groundmass plagioclase crystal, its anorthite-rich band, indicated by red arrows, directly surrounds a slightly mottled core.
single plagioclase crystal, analyses of both were performed. However, no compositional difference between the two is observed (Fig. 12). The only variation noted was in the more calcic bands surrounding resorbed cores, which often have higher anorthite contents than the main population of plagioclase crystals (An$_{23-60}$).

Plagioclase phenocrysts of the El Capitan Granite range from An$_{12-27}$, while those from DOTR exist in two populations. The more sodic population of DOTR plagioclase crystal analyses (An$_{32-62}$) represents the rims and the more calcic population (An$_{74-90}$), their cores (Nelson, 2006). However, cores of plagioclase crystals from DOTR samples analyzed in this study had compositions of An$_{40-62}$, corresponding to the compositions of the rims determined by Nelson (2006). Plagioclase crystals in the felsic halos have a slightly higher An content than those in the general El Capitan Granite (Fig. 13). Their compositions (An$_{23-33}$) are similar to those of the plagioclase crystals in the mafic enclaves.
Fig. 12 Plot of plagioclase Or vs. An compositions for rim, core and anorthite-rich bands of large enclave plagioclase crystals. An compositions of the rims and cores exhibit the same main population of ~An20-35. The anorthite-rich bands within the large plagioclase crystals exhibit greater variation in An content.
Fig. 13 Plots of plagioclase Or vs. An composition by host rock and crystal type. An compositions of the El Capitan Granite, the DOTR, and mafic enclaves define separate populations, though their ranges overlap slightly. An compositions for the large plagioclase crystals of the enclaves and the groundmass plagioclase exhibit a similar range. The compositions of plagioclase crystals within the felsic halos are also similar to those of the mafic enclaves. DOTR data include analyses from this study and Nelson, 2006.
**Biotite, K-feldspar and Fe-oxide compositions**

Biotites in the mafic enclaves are compositionally similar to that of the El Capitan Granite (Fig. 14). All biotite crystals analyzed are Fe-rich and plot closest to the siderophyllite end-member. However, biotites of the El Capitan all have a nearly constant Fe/(Fe+Mg) ratio (~0.64) while those in the mafic enclaves have a much broader range (0.52-0.66). Compositions of biotite inclusions within the large enclave plagioclase crystals are also similar to both, yet also have a larger Fe/(Fe+Mg) compositional range than the El Capitan Granite (0.59-0.66).

All K-feldspar present in the mafic enclaves exists as inclusions in larger plagioclase crystals and have compositions of Or73-99, whereas K-feldspar crystals in the El Capitan Granite occur as phenocrysts up to 1 cm in size and have compositions of Or86-96.

Crystals of ilmenite occur as subhedral inclusions in the groundmass of the enclaves as well as inclusions within large plagioclase crystals (Fig. 15). The ilmenite crystals within the mafic enclaves are Mn-rich and contain from 10 to 21 mole percent pyrophanite (MnTiO$_3$). Samples of the DOTR also contain subhedral crystals of ilmenite with 3 to 4 mole percent pyrophanite (Table 3). Ilmenites from both rock types contain almost no Mg, and plot in two distinct groups along the pyrophanite-ilmenite series solid solution (Fig 16). Ilmenites of the mafic enclaves and those of the DOTR also plot in two discrete groups on the ilmenite-hematite-pyrophanite ternary. The El Capitan Granite lacks these Mn-rich ilmenites entirely.
Fig. 14  Classification of biotites in the El Capitan Granite, mafic enclaves, and inclusions within large plagioclase crystals in the mafic enclaves (after Deer et al. 1992). Biotite crystals in the El Capitan Granite are compositionally similar to those in the enclaves, however the enclave biotites and biotite inclusions have a slightly larger range in Fe content.
Fig. 15 Backscattered-electron images of Mn-rich ilmenite crystals (*bright white*) within the mafic enclaves. **a** Large ilmenite inclusion within the core of a large plagioclase crystal. **b** Several small ilmenite inclusions within one large plagioclase crystal, designated by yellow boxes. **c** Ilmenite crystal in groundmass of a mafic enclave. **d** Several ilmenite crystals within mafic enclave groundmass.
**Table 3** Representative ilmenite compositions determined by electron microprobe

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<td>MgO</td>
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<td>0.02</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
<td>0.05</td>
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</tr>
<tr>
<td>CaO</td>
<td>N.D.</td>
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<td>0.12</td>
<td>0.00</td>
<td>N.D.</td>
<td>0.04</td>
<td>0.02</td>
<td>0.10</td>
<td>0.03</td>
</tr>
<tr>
<td><strong>Total</strong></td>
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<td>99.24</td>
<td>97.51</td>
<td>98.79</td>
<td>100.99</td>
<td>100.73</td>
<td>101.39</td>
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<td>Geikielite (mol%)</td>
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<td>0.06</td>
<td>0.05</td>
<td>0.00</td>
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<td>0.12</td>
<td>0.18</td>
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<tr>
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<tr>
<td>Pyrophanite</td>
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<td>11.77</td>
<td>15.44</td>
<td>4.33</td>
<td>3.33</td>
<td>4.48</td>
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Fig. 16  Ternary plot of ilmenite analyses from the mafic enclaves and the DOTR plotted on the ilmenite-hematite-pyrophanite ternary. Each tick mark represents 10 mol%. Ilmenites in the mafic enclaves plot in a distinct group from those in DOTR rocks, containing more manganese and less titanium.
**Plagioclase and K-feldspar staining**

Feldspar staining of the enclave/granite contacts reveals enrichment in quartz and depletion in mafic minerals and K-feldspar within the felsic halo (Fig. 17). For sample CS720-1, which has the most visible felsic halo, quartz crystals within this region are larger than those in the host granite (up to 1 cm). Their size and abundance both decrease ~3 cm from the contact with the enclave. In this sample, smaller quartz crystals occur in the felsic halo directly astride the sharp contact with the enclave. In the other stained samples, with less visible or smaller halos, an increase in grain size was not observed.

Mineral abundance calculations were also performed after Le Maitre (1982) for the three enclave/granite transects using measured mineral compositions and the whole rock geochemical analyses. Calculations were performed using unweighted least squares by the equation

\[
R = w_{Qtz}Qtz + w_{Pl}Pl + w_{Ksp}Ksp + w_{Bt}Bt + w_{Hbl}Hbl + w_{Ti}Ti
\]

where R is the whole rock composition expressed as a vector, \( w_i \) is the weight fraction of mineral, and Qtz, Pl, etc. are mineral compositions. These calculations support the visual observations supplied by slab staining, indicating an increase in quartz and decrease in K-feldspar within the felsic halos. They also reveal a complementary increase in biotite and decrease in quartz abundance within the outermost several centimeters of the enclave (Fig. 18).
Fig. 17 Photographs of stained slabs cut through enclave/granite boundaries. Plagioclase stains red and K-felspar stains yellow, while quartz remains white. Sample CS720-1 had the most visible felsic halo before staining and sharpest enclave boundary. All samples indicate a decrease in K-feldspar near the enclave, however sample CS720-1 exhibits an increase in grain size within the halo while CS719-3 and CS719-1 show no change or a decrease in grain size near the enclave.
Fig. 18 Plots of the calculated mineral abundances for the enclave/granite transects. Each lettered segment represents a 1 cm wide transect. Gray dotted line indicates the enclave boundary, with CS719-3 also having an intermediate-composition band between the enclave and the granite. These transects indicate an increase in quartz and plagioclase in the segments corresponding to the felsic halos and an increase in biotite within the outer rim of the mafic enclaves.
DISCUSSION

Origin of the leucocratic halos

Along with the visually prominent felsic halos, geochemical analyses reveal the presence of a corresponding more mafic rim directly inside the enclaves. Felsic halos lacking K-feldspar and ferromagnesian minerals are often observed rimming mafic enclaves (Didier 1973; Barbarin 1991; Barbarin and Didier 1991; Bussy 1991; Orsini et al. 1991; Tobisch et al. 1997; Johnson and Barnes 2006) but few also note this darker margin within the enclaves that is poor in silica and enriched in the components of biotite (Bussy 1991; Le Fort 1991).

Earlier studies suggest that the felsic halos simply represent transfer and enrichment of alkalis (Bacon 1986; Orsini et al. 1991); however the first several centimeters on either side of the enclave/granite contact of the rocks studied here reveal that other elements are diffusing across this boundary as well. The most marked differences observed in the transects are the relative increase in SiO$_2$ within the halos and increase in K$_2$O within the enclaves. These elemental variations coincide with an abundance of quartz crystals in the leucocratic halos and an increase in biotite directly inside the enclaves.

K$_2$O, MgO, Fe$_2$O$_3$, and Al$_2$O$_3$ are also shown to diffuse out of the granite and into the more mafic enclaves (Fig. 6). This elemental exchange leads to the observed increase of biotite within the outer rim of the enclaves as well as the depletion of the surrounding granitic melt in ferromagnesian minerals. Similarly, the diffusion of SiO$_2$ and Na$_2$O into
the granite produces the observed abundance of crystallizing quartz and plagioclase within the felsic halos and lack of quartz, hornblende and K-feldspar directly inside the enclaves.

*Origin of large plagioclase crystals in the mafic enclaves*

The compositional profiles of the El Capitan Granite plagioclase and the crystals in the mafic enclaves overlap slightly, yet their differences in range are significant enough to suggest separate sources. Plagioclase crystals within the mafic enclaves also have different compositional ranges from those in DOTR rocks, again indicating separate magmatic sources (Fig. 13). Also, the similarity in composition of both the cores and rims of the large plagioclase crystals as well as the groundmass plagioclase of the enclaves suggests that both formed in the same magma and under the same pressure and temperature conditions (Nockolds 1932; Didier 1973).

Both large plagioclase crystals and groundmass plagioclase in the enclaves exhibit the same textures, as the thin anorthite-rich sections of the larger crystals are reproduced in the groundmass as small bands or cores (Figs. 8, 11). Therefore these anorthitic bands likely result from a change in environment affecting the enclaves and do not represent physical transport of the large plagioclase crystals from a magma of differing composition. These textures could reflect an increase in temperature or $PH_2O$ during initial crystallization of the crystals (Morse and Nolan, 1984; Watson and Jurewicz 1984; Housh and Luhr 1991; Van der Laan and Wyllie 1993; Couch et al. 2003) or be products of later diffusion-reaction (Lundstrom 2005), both processes occurring within the mafic enclaves and not indicating physical mixing.
Mn-rich ilmenite also exists within the groundmass of the enclaves and as inclusions within the cores of the large plagioclase crystals; however, this mineral is absent in the El Capitan Granite and is of a different composition when found in the DOTR samples. Its presence is strong evidence that the cores of these plagioclase crystals must have crystallized within the enclaves. Inclusions of hornblende, which is rare in the El Capitan Granite, also contradict this rock as the source of the large crystals.

The albitic composition of these plagioclase crystals may result from a particularly sodic original magma, or conversely, the composition of the plagioclase phenocrysts could result from diffusion of sodium into the partially crystalline mafic enclaves after emplacement in the El Capitan Granite. In the later model, the magma from which the enclaves were sourced may have had a high modal abundance plagioclase that was originally more calcic. After emplacement as enclaves into partially crystalline El Capitan Granite, the attempts of both magmas to reach phase-equilibria would cause diffusion of sodium into the enclaves and result in enclave plagioclase approaching the more sodic composition of those in the El Capitan Granite (Nockolds 1932; Reynolds 1946; Didier 1973; Lundstrom 2005).

As recent studies indicate that cores of plagioclase crystals may be in communication with their surrounding melt (Lundstrom et al. 2005; Lundstrom and Tepley 2006) this process could conceivably affect the composition of the entire crystal, and not simply newly crystallizing rims. The diffusion-reaction process is also shown to occur at much faster rates than solid-state diffusion (Lundstrom et al. 2005). In this case, the anorthitic bands could be relicts of the crystal rims remaining in Ca-Na exchange equilibrium with the melt as the cores changed in composition (Lundstrom et al. 2005).
Chemical exchange with the granite could also result in the patchy zoning observed in some of these enclave plagioclase crystals (Dider 1973).

This diffusion-reaction process may be similar to hypothesized metasomatic granitization, in which grain size within enclaves increases and phenocrysts of plagioclase form due to thermal and chemical equilibration between the enclave and granite (Nockolds 1932; Reynolds 1946; Didier 1973). Feldspathic enclaves throughout the Sierra Nevada batholith exhibit similar morphologies and are interpreted to have formed through this process (Pabst 1928; Barbarin 1990; Sylvester 2011), indicating that perhaps elemental diffusion plays an important part in enclave development throughout the Sierra Nevada batholith.

However, transects of the enclave boundaries seem to indicate that Na$_2$O is diffusing out of the enclaves, as the felsic halos are enriched in sodium relative to the surrounding El Capitan Granite (Fig. 5). This direction of exchange would then indicate that the albitic nature of the large plagioclase crystals and groundmass plagioclase is due to an initial abundance of sodium in the original enclave magma.

Origin of mafic enclaves

Mafic enclaves in the El Capitan Granite are too silicic to have formed from the same parent magma as the DOTR without significant modification. Major- and trace-element data also indicate that the enclaves could not result from simple mixing of the more felsic El Capitan Granite and the DOTR. Although most major elements fit a simple mixing model for the two, the Na$_2$O and MnO contents of the enclaves sit far above a mixing line between these two end-members.
Major-element concentrations of the felsic halos indicate that diffusion of alkalis occurred between the mafic enclaves and their hosts as previously hypothesized (Bacon 1986; Orsini et al. 1991), but that other elements are diffusing as well. The halos, which represent the sections of granite closest to the enclaves, have similar major-element concentrations to the El Capitan Granite for most elements but are distinctly more similar to the enclaves in K$_2$O and Na$_2$O composition (Fig. 5). This suggests that perhaps the highly mobile alkalis were able to diffuse between the enclaves and nearby granite more quickly than the other less mobile elements (Watson 1976; Van der Laan and Wyllie 1993).

Mineralogic abundance calculations also indicate that the compositions of the enclaves may indeed be altered by chemical interaction with the host, and that the surrounding granite is affected as well. This work reveals that the length scale of the interaction with the granite could be quite large. Figure 6 reveals that up to ~7 cm away from an enclave, the granite may still be altered from its original composition. Therefore, further work at larger scales could indicate significant elemental interaction between the enclaves and granite that affects the composition of not only the mafic bodies, but the host as well.

The present composition of the mafic enclaves could thus represent 1) significant alteration due to elemental diffusion across the enclave/granite boundaries, or 2) the original composition of the enclave source magma, if this diffusion affects only the outer several centimeters of the enclaves.
Method 1: elemental diffusion

Rather than representing magma mixing processes, the compositions of mafic enclaves may reflect elemental diffusion with the host rock (Van der Laan and Wyllie 1993; Watson 1984). Diffusion of sodium into the mafic enclaves may then be the source of their enrichment, as it is a highly mobile element (Watson 1976). Though studies on melts demonstrate that sodium tends to diffuse from a mafic magma into more silicic one, and that diffusion may even occur “uphill” into a magma that has a higher Na$_2$O concentration (Watson 1976; Ryerson and Hess 1978; Watson 1982; Van der Laan and Wyllie 1993), diffusion effects between partially crystalline magmas are more difficult to predict.

If the El Capitan Granite and mafic enclaves are both sufficiently crystalline at the time they began interacting with one another, the behavior of sodium may be driven by the attempts of the magmas to reach equilibrium by having equal phase compositions in the enclave and granite (Reynolds 1946; Didier 1973; Lundstrom 2005). In this case, the particularly sodic nature of the plagioclase phenocrysts, and consequently the enclaves, could result from diffusion of sodium into the partially crystalline mafic enclaves after emplacement in the El Capitan Granite, as discussed in the previous section. This process would require Ca-Na exchange within the plagioclase crystals of the enclaves to attain phase-equilibria with their new host (Lundstrom et al. 2005; Lundstrom and Teply 2006). The overlap in compositions of biotite as well as plagioclase between the enclaves and El Capitan Granite could also indicate attempts of the enclaves to reach phase-equilibria with the surrounding granite.

Subsequently, the enclaves could be sourced from a mixture of DOTR magma and the El Capitan Granite but the original mineral and whole-rock compositions have
since been altered by elemental diffusion after emplacement. If this is indeed the case, more probe data for minerals in all DOTR rock types, as well as analysis of enclaves based on their proximity to the DOTR outcrop would be useful for determining if these enclaves are sourced from this magmatic body and are simply approaching phase equilibrium with their new host El Capitan Granite.

**Method 2: Na-rich magma**

Conversely, the original magma from which the mafic enclaves formed may have originally been particularly sodic. As previously stated, the depletion in K₂O and enrichment in Na₂O of the halos relative to the granite appear to indicate movement of potassium into the enclaves and diffusion of sodium into the granite, indicating that elemental diffusion occurring between them and the El Capitan Granite is not responsible for the observed Na-enrichment.

Although rocks compositionally similar to these mafic enclaves are scarce in the Sierra Nevada batholith, similar enrichments in Na₂O are observed in some continental arc-rocks. One such example is the Cascade arc Medicine Lake volcanic field in northern California, which exhibits Na₂O enrichments for magmas with 55-65 wt% SiO₂, similar to the enclaves from the El Capitan Granite (Baker et al. 1991; Donnelly-Nolan 2008). The compositions of other rock types found within the ISYV mirror the trend observed in the Medicine Lake volcanic rocks for other elements as well (Fig. 19). Though rocks exhibiting this sodium enrichment appear to be common in the volcanic rocks produced at continental-arcs (Fig. 20) large bodies of this rock type are not observed in the Sierra Nevada batholith.
Fig. 19 Harker diagrams of ISYV rocks from this study and the Medicine Lake volcanic field. Mafic enclaves from the El Capitan Granite that fit poorly to the trend of Sierran data indicate good correlation to the distribution of rock types from this continental-arc volcano, especially in Na$_2$O and MnO content.
Fig. 20 $\text{Na}_2\text{O}$ vs. $\text{SiO}_2$ plots for the Central American Volcanic Arc of western Mexico, Parinacota volcano on the Chile/Bolivia border (central Andean volcanic zone), and Tatara volcano in Chile (southern Andean volcanic zone). Each of these shows an arc in $\text{Na}_2\text{O}$ content around 55-70 wt% $\text{SiO}_2$, similar to the enclaves of the ISYV. Gray outlines indicate general range in composition for the Sierra Nevada batholith. Data from the GEOROC Central American volcanic arc and Andean arc precompiled datasets.
The rarity of these rocks in a plutonic setting may be due to extensive mixing of magmas, which would produce a more linear trend of compositions for the entire batholith (Frost and Mahood 1987; Saleeby 1987; Bateman 1988; Bateman 1995; Ratajeski 1999; Wenner 2004). The small relicts of this and other high-sodium magmas may then be preserved only in scattered mafic enclaves of the Sierra Nevada batholith, their small abundances restricting mixing with host granitoids (Saleeby 1987; Frost and Mahood 1987; Van der Laan and Wyllie 1993). The scarcity of this rock type could also be due to a lack of deeper exposures in most of the Sierra Nevada batholith (Evernden and Kistler 1970; Wiebe 1996; Saleeby et al. 2007). Influx of a more mafic magma beneath the El Capitan Granite would create a convective transfer of heat across their interface (Huppert et al. 1982; Turner and Campbell 1986), allowing mingling between the magmas at their boundary. Thus if a larger source mass of these intermediate composition rocks exists, it likely lies unexposed deeper in the batholith (Huppert et al. 1982; Sparks and Marshall 1986; Turner and Campbell 1986; Snyder and Tait 1995).
CONCLUSIONS

Mafic enclaves of the El Capitan Granite do not represent simple mixing of this unit with magmas of the DOTR. Particularly, enclaves exhibit enrichments in sodium and manganese that could not be explained by this process alone. Elemental diffusion is shown to have occurred between the enclaves and host granite to produce the felsic halos and complimentary mafic rims in the enclaves, but it is difficult to discern if diffusion of sodium is responsible for the current composition of the enclaves. The observed Na-enrichment is similar to that seen in some continental-arc volcanoes, and therefore may represent the original composition of the enclave magma. However, it is also possible that the current compositions of the enclaves results from later chemical exchange with their granitic host the El Capitan Granite after mingling.

The large plagioclase crystals of the mafic enclaves are considered here to be phenocrysts of the enclaves themselves. Core compositions exhibit different ranges than plagioclase crystals of both the El Capitan Granite and the DOTR, and minerals absent in the El Capitan Granite are present as inclusions within the enclave plagioclase phenocrysts. The large plagioclase crystals also exhibit strong compositional and textural similarities to the groundmass plagioclase; further indicating that they have not been transported from a different magma source. The albitic nature of the plagioclase crystals could therefore be due to 1) their crystallization from an abnormally Na-rich original magma, or 2) the result of Ca-Na exchange after mingling as they approach phase-equilibria with their new host. Further investigation of the compositions of plagioclase
feldspars as a function of distance from the enclave/granite boundary as well as the compositions of the enclaves as a function of their distance from the DOTR would be useful in determining if elemental diffusion is significantly altering the final composition of these enclaves.
REFERENCES


Ratajeski K (1999) Field, geochemical, and experimental study of mafic to felsic plutonic rocks associated with the intrusive suite of Yosemite Valley, California. Dissertation, University of North Carolina at Chapel Hill


Shaw HR (1963) Obsidian-H$_2$O viscosities at 1000 and 2000 bars in the temperature range 700 to 900°C. Journal of Geophysical Research 68:6337-6344
Sisson TW, Grove TL (1993) Experimental investigations of the role of H$_2$O in calc-alkaline differentiation and subduction zone magmatism. Contributions to Mineralogy and Petrology 113: 143-166

Slaby E, Götze J (2004) Feldspar crystallization under magma-mixing conditions shown by cathodoluminescence and geochemical modeling – a case study from the Karkonosze pluton (SW Poland). Mineralogical Magazine 68:561-577


Wager LR, Bailey EB (1953) Basic magma chilled against acid magma. Nature 172:6-72


Watson EB (1982) Basalt contamination by continental crust: some experiments and models. Contributions to Mineralogy and Petrology 80:73-87


Wenner JM (2001) Testing the viability and significance of magma mixing in continental arcs using the Sierra Nevada batholith, California, as an example. Dissertation, Boston University


