Mantle lithosphere as a source of postsubduction magmatism, northern Sierra Nevada, California

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ABSTRACT

Age, chemical, and isotopic data from late Cenozoic volcanic rocks in the northern Sierra Nevada, California (USA), from Lake Tahoe north to the southern end of the modern Cascades volcanic arc, were obtained to investigate the evolution of the upper mantle beneath this continental margin during the transition from active subduction to the opening of a slabless window, and to test the possibility that the foundering of mantle lithosphere proposed for the southern Sierra Nevada extended to the northern reaches of the mountain range. Our data are consistent with previous work in the region and illustrate that volcanism shifted from widespread intermediate composition magma production of immediately postsubduction mantle lithosphere. However, the younger volcanic rocks have higher high field strength element (HFSE) and higher phosphorus abundances, and higher (La/Yb)N, than their older counterparts, suggesting that they are not simply the products of smaller degrees of partial melting of the same mantle lithosphere involved in the older magmatism. The high HFSE and P contents were more likely controlled by metasomatic accessory carrier phases such as rutile and apatite, the stabilities of which control the abundance of these elements in melts produced from the lithospheric mantle after 3 Ma. One possibility is that the accessory phases were introduced to lithosphere during melting or assimilation of the remaining lithospheric mantle triggered by postsubduction heating or melting of the slab-below mantle. Our data are consistent with lithospheric mantle serving as a melt reactor during the earlier subduction-related magmatism that was baked out during later conductive heating, a process that may be relevant to the production of immediately postsubduction magmatism along other continental margins.

INTRODUCTION

The response of slab-metasomatized mantle and any overlying lithospheric mantle to the opening of a slabless window beneath a continental margin is not well understood. The orphaned mantle wedge remain in place or is it displaced downward into the mantle during upwelling of asthenosphere, possibly in conjunction with foundering of overlying remnants of continental mantle lithosphere (Elkins-Tanton, 2007)? Do any of these processes result in the production of postsubduction mantle melting, or is postsubduction magmatism simply a matter of extracting small-volume melts that were generated from the upper mantle during active subduction (Negrete-Aranda and Cañon-Tapia, 2008; Till et al., 2009; Valentine and Perry, 2007)? These issues are relevant to understanding the tectonic evolution of continental margins and to determining the conditions under which slab-metasomatized mantle can be preserved beneath continents (Farmer, 2003).

One region in which the fate of continental-margin mantle above a subduction zone can be addressed is in the Lake Tahoe region of California (USA), where late Cenozoic volcanic rocks were erupted during a transition from continental subduction to postsubduction magmatism, synchronous with the opening of a slabless window associated with formation of the San Andreas transform fault system (Atwater and Menard, 1970; Cousins et al., 2008, 2011). Exactly what melted to produce the late Cenozoic magmatism in this region and the processes involved in inducing that melting remain unclear. In this study we concentrate on these issues through additional age determinations, chemical analyses, and Sr, Nd, and Pb isotopic data from late Cenozoic volcanic rocks principally in and north of the Lake Tahoe region.

GEOLOGIC SETTING

The Sierra Nevada mountain range in eastern California (Fig. 1) has been the subject of intense investigation into the processes involved
Mantle lithosphere as a source of postsubduction magmatism

in batholith formation along continental convergent margins and those leading to high-elevation mountain belts. The Sierra Nevada is composed predominantly of Mesozoic granitic rocks produced during long-lived subduction of oceanic lithosphere beneath the western margin of North America (Bateman, 1992; Hamilton, 1969). The southern half of the batholith was apparently built within preexisting Precambrian continental lithosphere and overlying miogeoclinal sedimentary rocks (DePaolo, 1981), but north of ~38°N the batholith is embedded in allochthonous to parautochthonous early Paleozoic eugeoclinal sedimentary rocks and overlying Paleozoic to early Mesozoic arc volcanic rocks (Kistler, 1990; Schreiber, 1981; Snow and Scherer, 2006; Van Buer and Miller, 2010). Magmatic activity that produced the batholith occurred episodically from the Triassic until ca. 80 Ma, at which point arc magmatism ceased in the Sierra Nevada region, apparently in response to an episode of low-angle subduction. Cretaceous magmatism was followed by at least 50 m.y. of magmatic quiescence in the region (Chen and Moore, 1982; Coney and Reynolds, 1977; Dumitriu et al., 1991; Saleeby et al., 1990).

A resurgence of igneous activity in the Sierra Nevada was manifested by sporadic mafic to silicic volcanic activity throughout the range. Late Cenozoic volcanism in the southern Sierra Nevada (herein defined as region south of Yosemite Valley at lat ~37.7°N) has been extensively studied and consists of small-volume trachybasalts to rhyolites that erupted in three discrete pulses in the Miocene, Pliocene, and Quaternary (Dodge and Moore, 1981; Farmer et al., 2002; Van Kooten, 1981). In contrast, volcanic rocks in the northern Sierra Nevada are more voluminous and widespread (Fig. 1). Oligocene volcanic rocks in this region consist largely of distal pyroclastic flow deposits that originated in caldera-forming eruptions to the east in central Nevada, and are now preserved as basal deposits in paleocanyons that drained this area (Hagan et al., 2009; Henry, 2008). Locally erupted volcanic rocks appeared in the Miocene when intermediate to silicic composition volcanism developed discontinuously from northeasternmost California south to Sonora Pass (Fig. 1) (Busby et al., 2008; Henry, 2008; Koerner et al., 2009). These rocks are compositionally similar to continental margin arc magmatism and have been interpreted as a southern extension of the ancestral Cascades (Colgan et al., 2011; Cousens et al., 2008). This intermediate-composition volcanism ceased after ca. 3 Ma in the northern Sierra Nevada and was supplanted by smaller volume, and more geographically restricted, basaltic andesites to trachyandesites. Known Plinian and younger volcanic rocks are concentrated in the western and northern Lake Tahoe region (Cousens et al., 2011), although there is a locality to the south in the Sonora Pass region (Columns of the Giants) (Huber, 1983) (Fig. 1).

The transition from voluminous, older than 3 Ma, calc-alkaline volcanism to smaller...
volume, younger than 3 Ma, basaltic andesites and andesites in the northern Sierra Nevada correlates roughly with the timing of passage of the subducted Mendocino Fracture Zone beneath this region and the opening of a slabless window (Fig. 1; Atwater and Stock, 1998; Cousens et al., 2008). Understanding the origin of the compositional distinction between younger than 3 Ma and older than 3 Ma volcanic rocks (referred to as the younger and older volcanic suites in the following) is the main goal of this paper.

SAMPLES

Volcanic rock samples analyzed for this study were obtained primarily from northern Lake Tahoe and vicinity and from the Quincy-Beckwourth area ~100 km farther north (Fig. 1).

Lake Tahoe–Truckee region

Volcanism in the north Lake Tahoe–Truckee region has been extensively studied and includes widespread examples of both the older and younger volcanic suites (Cousens et al., 2008, 2011; Kortemeier and Schweickert, 2007; Latham, 1985; Saucedo, 2005). Older volcanism contributed ~200–300 km³ of intermediate lava flows and volcaniclastic rocks, most of which erupted episodically from 16 to 3 Ma onto a low-relief land surface (Cousens et al., 2008; Schweickert, 2009). Average eruptive rates based on the volumes of preserved volcanic rocks were ~0.02 km³/k.y., about an order of magnitude less than Quaternary eruptive rates for Mount Shasta and Lassen Peak in the southernmost Cascade Range (Hildreth, 2007). In contrast, younger volcanism is restricted largely to small-volume centers (<1 km³; Cousens et al., 2011) in a narrow corridor from Truckee to the northwestern shore of Lake Tahoe (Fig. 1). These rocks are largely composed of trachybasalt and trachybasaltic andesite, although recent work has revealed that the youngest volcanic rocks are trachyandesites (Kortemeier, 2012). Overall, this younger volcanism was coincident with westward encroachment of late Cenozoic extensional faulting into the Sierran block and development of the Lake Tahoe graben (Cousens et al., 2008; Schweickert, 2009).

Samples for this study were obtained from west of Truckee in the vicinity of Donner Pass, in the corridor between Truckee and the north end of Lake Tahoe, and from the Crystal Basin Recreation Area west of Lake Tahoe (Fig. 1). The Donner Pass samples are basaltic andesites and andesites and crop out along the interstate (I-80) corridor (Hudson, 1951) (Table 1). Only one sample from the Donner Pass area was dated (TR09–2). From the Truckee region, six samples of 1.2–3 Ma olivine-phyric basaltic trachyandesites were obtained, many from same flows studied by Cousens et al. (2011) (Fig. 1; Table 1). Detailed petrography for these flows is available in Cousens et al. (2011). Several late Cenozoic basaltic rocks were samples from the Crystal Basin Recreation Area. None of these rocks have been previously dated or subjected to detailed geochemical studies, although previously it was assumed that they were erupted in Middle to Late Miocene time (Armstrong et al., 1983). Sampled rocks include two olivine-phyric trachybasalts, both of which contain matrix olivine and plagioclase, one from a flow remnant near Forni Lake and one from a possible volcanic plug at Brown Mountain near Loom Lake. A third sample from Four Corner Peak is from a basalt flow remnant consisting of partially iddingsitized olivine and fresh augite phenocrysts set in a matrix of plagioclase microlites. Two of the Crystal Basin samples were selected for Ar-Ar age determinations (Table 1).

Columns of the Giants (Central Sierra Nevada)

The Quaternary Columns of the Giants lava flow was sampled for this study (Table 1). This trachybasalt is found in the central Sierra Nevada west of Sonora Pass (Fig. 1) (Huber, 1983), and has a whole-rock K-Ar age of ca. 150 ka (Dalyrmple, 1964). This rock was selected for chemical, isotopic, and ⁴⁰Ar/³⁹Ar age determinations.

Northern Sierra Nevada: Quincy-Beckwourth Region

We obtained 13 samples of Miocene volcanic rocks from the Quincy-Beckwourth region (Table 1). Few age or chemical data were previously available for these rocks, which are largely intermediate lava flows, pyroclastic rocks, and debris flows (Durell, 1987). Phenocryst assemblages are generally plagioclase + olivine ± augite in the more mafic rocks, plagioclase + augite ± hornblende in basaltic andesites, and plagioclase + hornblende in andesites. Eight of these samples were selected for ⁴⁰Ar/³⁹Ar age determinations (Table 1).

METHODS

Major and trace element analyses were obtained commercially by inductively coupled plasma–mass spectrometry (Tables 1 and 2). Radiogenic isotope data were obtained at the University of Colorado (Boulder), the analytical details for which are given in Table 3. All Sr, Nd, and Pb isotopic data are reported as initial values.

The ⁴⁰Ar/³⁹Ar determinations were performed at either the New Mexico Geochronology Research Laboratory or at the U.S. Geological Survey (USGS) in Denver (Colorado). For the USGS analyses, high-purity mineral separates and standards were irradiated in the central thimble position of the USGS TRIGA reactor in 3 separate irradiations of 10 min, 10 h, and 20 h. The irradiations were done at 1 MW power using cadmium lining to prevent nucleogenic production of ⁴⁰Ar. The neutron flux was monitored using Fish Canyon Tuff sanidine, with an age of 28.201 ± 0.08 Ma (Kuiper et al., 2008) and isotopic production ratios were determined from irradiated CaF₂ and KCl salts. For these irradiations, the following production values were measured: 20 h irradiation: (⁴⁰Ar/³⁹Ar)Ca = (2.764 ± 0.028) × 10⁴; (⁴⁰Ar/³⁹Ar)K = (6.971 ± 0.044) × 10⁴; (⁴⁰Ar/³⁹Ar)KCl = (0.196 ± 0.008) × 10⁴; 10 h irradiation: (⁴⁰Ar/³⁹Ar)Ca = (2.769 ± 0.023) × 10⁴; (⁴⁰Ar/³⁹Ar)K = (6.889 ± 0.039) × 10⁴; (⁴⁰Ar/³⁹Ar)KCl = (0.196 ± 0.008) × 10⁴; 1 h irradiation: (⁴⁰Ar/³⁹Ar)Cs = (2.44 ± 0.05) × 10⁴; (⁴⁰Ar/³⁹Ar)K = (6.587 ± 0.103) × 10⁴; (⁴⁰Ar/³⁹Ar)KCl = (0.196 ± 0.008) × 10⁴. The irradiated samples and standards were loaded into 3 mm wells within a stainless steel planchette attached to a fully automated ultrahigh vacuum extraction line also constructed of stainless steel. Samples were incrementally heated until fusion using a 20W CO₂ laser equipped with a beam homogenizing lens. The gas was expanded and purified by exposure to a cold finger maintained at −135 °C and two hot SAES GP50 getters. Following purification, the gas was expanded into a Mass Analyzer Products 215–50 mass spectrometer and argon isotopes were measured by peak jumping using an electron multiplier operated in analog mode. Data were acquired during 10 cycles and time zero intercepts were determined by best-fit regressions to the data. Ages were calculated from data that were corrected for mass discrimination, blanks, radioactive decay subsequent to irradiation, and interfering nucleogenic reactions.

RESULTS

⁴⁰Ar/³⁹Ar Age Determinations

The ⁴⁰Ar/³⁹Ar age determinations are reported in Table 1; raw data are given in the Supplemental Table¹. The majority of the analyses yielded

¹Supplemental Table. Results of Ar-Ar step furnace heating determinations, Crystal Basin volcanic rocks, at New Mexico Geochronology Research Laboratory. If you are viewing the pdf of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00885.S1 or the full-text article on www.gsapubs.org to view the Supplemental Table.
TABLE 1. Ar-Ar AGE DETERMINATIONS AND MAJOR ELEMENT COMPOSITIONS OF MIOCENE AND YOUNGER VOLCANIC ROCKS, NORTHERN LAKE TAHOE AREA

<table>
<thead>
<tr>
<th>Sample Location or flow</th>
<th>Latitude (DD)†</th>
<th>Longitude (DD)</th>
<th>Rock type§</th>
<th>Age††</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃(T)</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>P₂O₅</th>
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<td>0.177*</td>
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<td>7.64</td>
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<td>51.0</td>
<td>17.3</td>
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Note: Ar-Ar ages in bold are generally whole-rock plateau ages by stepped laser heating at U.S. Geological Survey, Lakewood, Colorado. Exceptions are FR09-26, which is a plateau age from an amphibole separate, and FR09-19, which is total gas age. Plain text ages are literature K-Ar ages from Doell et al. (1966) (07CA SNF-2) and Dalrymple (1964) (07CA SNF3,4,6,7) as recalculated by Saucedo (2005), and Ar-Ar age from Henry and Perkins (2001) (07CA SNF-5).

*Bold face values are inductively coupled plasma mass spectrometry analyses through Activation Laboratories (Ancaster, Ontario, Canada). All oxide percentages are renormalized to 100% (anhydrous). Others are X-ray fluorescence analyses performed at the University of North Carolina, Chapel Hill. Actual analysis totals reported in final column. Total iron reported as Fe₂O₃.

†Sample locations given in decimal degrees.

§Rock types from total alkali vs. silica chemical classification. BTA is basaltic trachyandesite, TB is trachybasalt, B is basalt, BA is basaltic andesite, A is andesite.

††Ages are in Ma. Ar-Ar plateau ages in italics stepped furnace heating of groundmass, New Mexico Geochronology Research Laboratory, Socorro.
Farmer et al.

Note:

Concentrations (ppm) by inductively coupled plasma-mass spectrometry at Activation Laboratories (Ancaster, Ontario, Canada).

Estimates of reproducibility are percent of mean standard concentrations measured during study period.

The Columns of the Giants flow yielded a \(^{40}\)Ar/\(^{39}\)Ar plateau age of 177 ± 7 ka, which is ~25 k.y. older, but within error, of the K-Ar age previously obtained for this flow (151 ± 30 Ma, recalculated from Dalrymple, 1964, using International Union of Geological Sciences decay constants of Steiger and Jager, 1977).

Quincy-Beckwourth area rocks yield a spectrum of ages from 11.4 to 3.95 Ma. Of 10 samples, 9 yielded \(^{40}\)Ar/\(^{39}\)Ar plateau ages, and for those the plateau and total gas ages agreed within 0.06 m.y., except for one sample where they agreed within 0.34 m.y. The ages cluster between 9 and 3.95 Ma. Two are from Smith Peak, one from the capping basalt and one from a hornblende-rich andesite plug exposed on the side of the peak. The andesite unit was the only hornblende separate analyzed. The third 11 Ma sample is from a noncapping unit in the Portola region.

Chemical and Isotopic Compositions

Our data reinforce the clear compositional distinction between the older and younger volcanic suites identified by Cousens et al. (2011) (Tables 1–3). The older suite in the Quincy-Beckwourth area rocks yield a spectrum of ages, but within error, of the K-Ar age previously obtained for this flow (151 ± 30 Ma, recalculated from Dalrymple, 1964, using International Union of Geological Sciences decay constants of Steiger and Jager, 1977).

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TABLE 3. Nd, Sr, and Pb isotopic data from Miocene and younger volcanic rocks, Northern Lake Tahoe area.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Column of Giants</th>
<th>Northern Lake Tahoe and Truckee River</th>
<th>Crystal Basin Recreation Area</th>
<th>Quincy-Beckwourth Area</th>
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*Isotope dilution concentration determinations accurate to ~1% for Rb and Sr, and 0.5% for Sm and Nd. Total procedural blanks averaged ~1 ng for Sr and Pb, and 100 pg for Nd, during study period. The μ and κ values were determined using inductively coupled plasma-mass spectrometry concentrations given in Table 2.

†87Sr/86Sr ratios were analyzed using four-collector static mode measurements; 55 measurements of SRM-987 during study period yielded mean 87Sr/86Sr = 0.710292 ± 0.001 (2σ of mean). Errors are 2σ of mean and refer to last two digits of the 87Sr/86Sr ratio.

§Measured 143Nd/144Nd normalized to 146Nd/144Nd = 0.7219. Analyses were dynamic mode, three-collector measurements; 32 measurements of the La Jolla Nd standard during the study period yielded a mean 143Nd/144Nd = 0.511840 ± 0.002 (2σ of mean).

**εNd values calculated using a present-day 143Nd/144Nd (CHUR, chondritic uniform reservoir) = 0.512638.
The Sr, Nd, and Pb isotopic compositions of young volcanic rocks from the Truckee area and Crystal Basin span a restricted range of bulk compositions from trachybasalts to basaltic andesite. The younger rocks all have higher weight percent Na2O (~3.0 wt% to ~4.0 wt%), K2O (~1.5 wt% to ~3.0 wt%) and TiO2 (~1.4 wt% to ~1.7 wt%), and lower weight percent CaO than the older volcanic suite over an equivalent range of weight percent MgO (Fig. 3). The younger rocks have heavy (H)REE abundances similar to those of their older counterparts, but have significantly higher LREE element abundances (Fig. 4). The younger suite rocks also have high absolute LILE, Pb, and HFSE abundances relative to the older rocks (Figs. 3 and 5). The highest weight percent MgO samples (~6 wt%) have high Ni (~100 ppm) and high Cr (>200 ppm) contents similar to those of the older volcanic suite rocks.

The Columns of Giants flow in the central Sierra is also shoshonitic, and has major element and trace element compositions similar to those of the younger volcanic suite in the Lake Tahoe area, albeit with lower HFSE abundances and higher (Sr/Pb)N (Figs. 3–6).

Younger volcanic rocks from the Truckee area and Crystal Basin span a restricted range of bulk compositions from trachybasalts to basaltic trachyandesites. These rocks generally belong to the shoshonitic magma series (Morrison, 1980) and show steep increases in weight percent K2O with decreasing weight percent MgO (Fig. 3). Many have K2O/Na2O (weight percent basis) >0.6 at 50% SiO2 and are typically hypersthene-olivine normative. The younger rocks all have higher weight percent Na2O (~3.0 wt% to ~4.0 wt%), K2O (~1.5 wt% to ~3.0 wt%) and TiO2 (~1.4 wt% to ~1.7 wt%), and lower weight percent CaO than the older volcanic suite over an equivalent range of weight percent MgO (Fig. 3). The younger rocks have heavy (H)REE abundances similar to those of their older counterparts, but have significantly higher LREE element abundances (Fig. 4). The younger suite rocks also have high absolute LILE, Pb, and HFSE abundances relative to the older rocks (Figs. 3 and 5). The highest weight percent MgO samples (~6 wt%) have high Ni (~100 ppm) and high Cr (>200 ppm) contents similar to those of the older volcanic suite rocks.

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The Sr, Nd, and Pb isotopic compositions of young volcanic rocks overlap those of the older suite. The Truckee area volcanic rocks, for example, have εNd between 0 and ~–3.0, overlapping the range of isotopic compositions determined for these rocks by Cousens et al. (2011) and those determined for the older volcanic suite (Fig. 6). The εNd values for both groups range from ~–3 to ~+2 and are independent of bulk composition (Fig. 8). However, any interaction between high
Mantle lithosphere as a source of postsubduction magmatism

$\varepsilon_{Nd}$, low $^{87}$Sr/$^{86}$Sr mantle-derived magmas (such as the high alumina olivine tholeiites parent magmas; Hart, 1985), and average lower $\varepsilon_{Nd}$ higher $^{87}$Sr/$^{86}$Sr northern Sierra granitic rocks should generate a spectrum of magma compositions where $\varepsilon_{Nd}$ values generally decrease with decreasing weight percent MgO (Fig. 8) or decreasing $P_{O_2}/K_{O}$ (not shown), but such patterns are not seen. These observations strongly suggest that the chemical and isotopic compositions of both the older and younger suites are not the result of crustal assimilation.

Isotopic variability in these rocks is more likely inherited from the mantle source regions of the mafic magmas from which both volcanic suites were derived. The high MgO (>~8 wt%) and high Ni contents (>150 ppm) of the most mafic volcanic rocks in both suites are consistent with melting of ultramafic source rocks, even if none are primary melts (O’Hara and Herzberg, 2002), although there is the possibility that high-pressure melting (<~2 GPa) of olivine-poor mafic rocks such as clinopyroxenites in the upper mantle played a role in the production of at least the younger rocks (see following).

Given the observed spectrum of Nd, Sr and Pb isotopic compositions, multiple isotopically distinct mantle sources were likely involved in magma production. The range of isotopic compositions observed, however, can be accounted

Figure 3. Selected major element oxide and trace element abundances for studied volcanic rocks. Symbols as in Figure 2.
for by as few as two mantle sources. One source is the high \( \varepsilon_{\text{Nd}} \), low \( ^{187}\text{Sr}/^{186}\text{Sr} \), and low \( ^{206}\text{Pb}/^{204}\text{Pb} \), \( ^{207}\text{Pb}/^{204}\text{Pb} \), and \( ^{208}\text{Pb}/^{204}\text{Pb} \) mantle involved in production of older volcanic rocks with high \( \text{Sr}/\text{Pb} \) ratios (Fig. 6). Basalts in the modern southern Cascades with high \( \text{Sr}/\text{Pb} \) and high \( \varepsilon_{\text{Nd}} \) are interpreted to be the products of flux melting of high \( \varepsilon_{\text{Nd}} \) peridotite as a consequence of an influx of fluids rich in Sr and Pb into the mantle wedge above actively subducting oceanic lithosphere (Borg et al., 1997). A similar origin for the older high \( \text{Sr}/\text{Pb} \) basaltic rocks in the northern Sierra Nevada is consistent not only with the isotopic characteristics of these rocks, but also with the observation that high \( \text{Sr}/\text{Pb} \) basaltic rocks are absent from the younger suite, which formed after the slably subducted region (Fig. 1).

The second mantle source is responsible for the low \( \varepsilon_{\text{Nd}} \), high \( ^{187}\text{Sr}/^{186}\text{Sr} \), and relatively radiogenic initial Pb isotopic compositions of low \( \text{Sr}/\text{Pb} \) volcanic rocks in both the older and younger suites. This mantle is unlikely to be Miocene or younger mantle wedge polluted by low \( \varepsilon_{\text{Nd}} \) subducted sedimentary material or by crust eroded from the forearc. Although there is little geochemical information available for the subducted sediments that may have been involved in northern Sierra arc magmatism, many have used modern Pacific plate sediments to estimate the isotopic characteristics of subducted material involved in modern southern Cascades volcanism (Leeman et al., 2004). These sedimentary materials generally have \( \varepsilon_{\text{Nd}} > +2 \), in which case it is unlikely that sediments subducted beneath the northern Sierra Nevada in the Miocene could have been responsible for the lowest \( \varepsilon_{\text{Nd}} \) values observed in either the older or younger volcanic suites studied here. Similarly, the continental margin of North America in northern California during Miocene subduction was composed of Paleozoic accreted terranes dominated by high \( \varepsilon_{\text{Nd}} (>+5) \) volcanic rocks (Brouxel and Lapierre, 1988; Brouxel et al., 1988), and so any crustal material added to the subduction channel from subduction erosion of overlying continental crust in the Miocene is unlikely to have added sufficiently low \( \varepsilon_{\text{Nd}} \) components. We recognize that these arguments do not preclude the possibility of low \( \varepsilon_{\text{Nd}} \) having been delivered to the active Miocene mantle wedge. However, even in the southern Sierra Nevada, where deep portions of the Mesozoic arc are exposed and where the Mesozoic arc was built on or adjacent to, low \( \varepsilon_{\text{Nd}} \) Precambrian basement and overlying siliciclastic sedimentary rocks, the Nd delivered to the base of the Mesozoic arc by subducting components was characterized by positive \( \varepsilon_{\text{Nd}} \) values (Lackey et al., 2005).

We conclude instead that the low \( \varepsilon_{\text{Nd}} \) mantle was most likely sub–Sierra Nevada lithospheric mantle, as also concluded previously (Cousens et al., 2008, 2011). By lithospheric mantle, we are referring to the uppermost, presumably thermally conducting, portion of the mantle, which has distinctly different isotopic characteristics, such as lower \( \varepsilon_{\text{Nd}} \) from the underlying sublithospheric mantle. The presence of low \( \varepsilon_{\text{Nd}} \) basaltic rocks in both the older and younger groups indicates that low \( \varepsilon_{\text{Nd}} \) lithospheric mantle was present throughout the late Cenozoic and was involved in magma production regardless of whether oceanic lithosphere was actively being subducted beneath the region (Borg et al., 2002; Cousens et al., 2008, 2011).

**Northern Sierra Nevada**

**Lithospheric Mantle**

Although the existence of low \( \varepsilon_{\text{Nd}} \) lithospheric mantle beneath the northern Sierra Nevada is likely, based on the volcanic rock isotopic compositions, no direct samples of the upper mantle have yet to be identified in this region that can be used to confirm such or to directly determine the lithologies that might compose it. In the southern Sierra Nevada, in contrast, upper mantle xenoliths are found in several Neogene lava flows and can be used to reconstruct the lithologic and compositional characteristics of the continental lithosphere beneath this area through time (Chin et al., 2012; Dodge et al., 1986; Ducea and Saleeby, 1998a; Lee et al., 2006; Mukhopadhyay and Manton, 1994). Xenoliths entrained in Miocene lavas in the central Sierra Nevada in the San Joaquin volcanic field (Fig. 1) reveal that a deep lithospheric keel (termed arclogite by Anderson, 2005) existed beneath the region at the onset of Neogene
The most straightforward explanation for the compositional distinction between the older and younger volcanic suites found in this region.

**Origin of Older and Younger Volcanic Suite Compositional Differences**

A remaining question is why consistent differences exist in the chemical compositions of lithosphere-derived low $\epsilon_{Nd}$ volcanic rocks in the older and younger suites. One possibility is that the two suites were derived from sources with distinctly different mineral modes and/or bulk compositions, due to differences in the degree of mantle metasomatism by aqueous fluids and/or silicate melts or due to differences in the depth of melting and whether melting occurred in the spinel or garnet stability field (Grove et al., 2002; Kelemen et al., 1998, 1999; Pilet et al., 2011; Salters and Hart, 1989; Weaver et al., 2011). Other potential explanations include differences in the extent to which mafic lithologies were involved in magma generation through time (Pertermann, 2003; Sobolev et al., 2007), differences in the degree that magmas underwent fractional crystallization at mantle depths (Alonso-Perez et al., 2009), and differences in the extent of partial mantle melting (Kushiro, 1996).

The most straightforward explanation for the compositional distinction between the older and younger volcanic suites found in this region.

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**Figure 5. N-MORB normalized trace element abundances from this study.**

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younger rocks requires a decrease in the extent of lithospheric mantle melting through time (Cousens et al., 2011). We address this possibility using trace and minor element compositions of older and younger suite volcanic rocks in the Crystal Basin region. These rocks are among the most mafic in this study, have similar Sr, Nd, and Pb isotopic compositions and similarly low (Sr/P)N that we interpret as evidence that these were derived dominantly from the lithospheric mantle, but have significantly different trace element abundances characteristic of the older and younger volcanic suites throughout the northern Sierra Nevada. If these rocks all represent the products of batch melting of compositionally and mineralogically equivalent sources (whether mafic or ultramafic in composition), then the ratio between minor and trace elements in the younger (Cliq, i, < 3 Ma) and older (Cliq, i, > 3 Ma) at Crystal Basin will be influenced principally by the extent of source melting, F, in Equation 1:

\[
\frac{C_{\text{liq}, i, < 3 \text{ Ma}}}{C_{\text{liq}, i, > 3 \text{ Ma}}} = \frac{C_{0, i, < 3 \text{ Ma}}}{C_{0, i, > 3 \text{ Ma}}} \left[ \frac{F_{< 3 \text{ Ma}} + D_{< 3 \text{ Ma}} \left( 1 - F_{< 3 \text{ Ma}} \right)}{F_{< 3 \text{ Ma}} + D_{< 3 \text{ Ma}} \left( 1 - F_{< 3 \text{ Ma}} \right)} \right],
\]

where \( C_{0, i} \) are the initial concentrations of element \( i \) in the mantle source, and \( D_i \) are pertinent bulk partition coefficients (Gast, 1968; Shaw, 1970). For the case of chemically equivalent sources, equivalent residual mineralogies, and equivalent bulk partition coefficients during melting (e.g., \( C_{0, i, < 3 \text{ Ma}} = C_{0, i, > 3 \text{ Ma}} \) and \( D_{< 3 \text{ Ma}} = D_{> 3 \text{ Ma}} = \) constant during melting), the ratio of liquid concentrations between the older and younger volcanic rocks is only a function of \( F \) and \( D_i \), regardless of the extent of partial melting or the original solid chemical compositions.

This simple end-member case provides a convenient reference for addressing the range of concentration ratios expected for low degrees of partial mantle melting for the production of alkalic basaltic liquids (\( F < 0.05 \)) (Kushiro, 1996). For incompatible elements, the concentration ratio as defined in Equation 1 is always >1 if \( F_{< 3 \text{ Ma}} < F_{> 3 \text{ Ma}} \) increases rapidly as \( D_i \) decreases for moderately incompatible elements (0.001–1), and reaches a plateau value for highly incompatible elements (\( D_i < 0.001 \)) that increases little with decreasing \( D_i \) (Fig. 9). In the latter case, the plateau concentration ratio increases as the difference in \( F \) values between the younger and older cases increases (Fig. 9). In contrast, the concentration ratio for compatible element (\( D_i > 1 \)) is only slightly <1, regardless of the difference in the degree of mantle melting represented by younger and older rocks (Fig. 9).

Figure 6. 87Sr/86Sr, \( \epsilon_{\text{Nd}} \), and 206Pb/204Pb versus (Sr/P)N for studied volcanic rocks. Primitive mantle normalization concentrations for Sr and P are from Sun and McDonough (1989).
Figure 7. Initial $^{208}\text{Pb} / ^{204}\text{Pb}$ and $^{207}\text{Pb} / ^{204}\text{Pb}$ (bottom) versus $^{206}\text{Pb} / ^{204}\text{Pb}$ for studied volcanic rocks. Ranges of isotopic compositions for younger than 10 Ma basaltic rocks in southern Nevada, the late Cenozoic Cima volcanic field (southeast California), younger than 20 Ma volcanic rocks in the Cascade arc, and for Miocene and Pliocene volcanic rocks in the southern Sierra Nevada are from multiple original sources extracted from the online North American Intrusive and Volcanic Rocks Database. NHRL—Northern Hemisphere Reference Line (Hart, 1984); V.F.—volcanic field.

Within this framework, those elements most likely to have behaved as compatible elements include the HREE, Y, Ni, Co, Cr, and Sc (Fig. 10). The HREE and Y abundances can be attributed to the presence of residual pyropic garnet during partial melting in both the younger and older suites (Hauri et al., 1994), while the compatibility of Ni, Co, and Cr likely results from residual olivine ± orthopyroxene ± clinopyroxene (De Hoog et al., 2010; Le Roux et al., 2011). Residual clinopyroxene could also account for the apparent compatibility of scandium (Hill et al., 2011). The lack of a prominent Na enrichment in these rocks suggests that melting occurred at sufficiently high pressures (>2 GPa) that there was a significant jadeitic component in the residual clinopyroxene (Blundy et al., 1995).

Incompatible elements during partial melting include the LREE, LILE, Pb, HFSE, and the minor elements Ti, Na, and P. However, highly incompatible elements such as Rb, Th, U, and Ba show a range of concentration ratios from 1.5 to 4, despite the expectation that these very low D elements would reach the same plateau ratio (Fig. 10). Furthermore, elements that are moderately incompatible with respect to either peridotite or eclogite and/or clinopyroxene mineral assemblages, such as Sr, Ce, and P, have concentration ratios similar to those of the highly incompatible elements, and, in the case of the Nb and Ta, have ratios up to 10 times higher (Fig. 10). We conclude that the fact that incompatible element concentrations of the younger suite are uniformly higher than those of the older suite is consistent with the younger rocks representing the smaller degrees of mantle melting, but the range of incompatible element enrichments observed in the younger suite reveals that additional factors must also have influenced their incompatible elements abundances.

A likely possibility is that at least some of the incompatible element concentrations in the younger suite were controlled by the behavior of accessory, rather than major, mineral phases during mantle melting. In particular, the high Nb and Ta concentrations in the younger rocks are best explained if their abundances were controlled by the demise of an accessory phase during partial melting (O’Hara et al., 2001a, 2001b). A likely carrier phase for these elements in the lithospheric mantle, along with Hf and Zr, is rutile. Rutile is a common accessory phase in metasomatized lithospheric mantle, as sampled by some mantle xenoliths and alpine peridotites (Aulbach et al., 2011; Grégoire et al., 2002; Gysi et al., 2011), and in both mafic and metasomatized ultramafic lithologies, >90% of Nb and Ta can be hosted in rutile (Foley et al., 2000; Kalfoun et al., 2002). In peridotite, rutile is a near-solidus phase and is rapidly consumed during partial melting due to the high solubility of titanium in mafic melts (Green and Pearson, 1986; Ryerson and Watson, 1987). As a result, the concentrations of rutile-compatible elements will rapidly increase during batch melting of a rutile-bearing mantle source, reaching a maximum when rutile is completely consumed, and decreasing thereafter due to dilution (O’Hara et al., 2001a). The high Nb and Ta abundances in the younger volcanic rocks throughout the northern Sierra Nevada suggest that melting of rutile-bearing metasomatized mantle occurred and that it is probable that little or no rutile remained in the mantle source after melt extraction.

The abundances of P and the LREE in the younger volcanic suite may also reflect the stability of an accessory phase, in this case apatite, which is a carrier phase for P. Apatite is commonly found in hydrous metasomatized mantle (Frost, 2006; O’Reilly and Griffin, 2000; Watson, 1980) and, as with rutile in peridotite, is a near-solidus phase that is highly soluble in mafic melts (Konzett and Frost, 2009; Watson, 1980). As a result, apatite is a likely source of LREE and P in partial melts of metasomatized mantle. The fact that the younger volcanic rocks are enriched in LREE and P, as well as Sr, U, and Th, is consistent with the possibility that these rocks represent the product of partial melting.
of apatite-bearing mantle. Apatite is not stable even at subsolidus temperatures in the asthenosphere (Konzett and Frost, 2009), so the presence of apatite in the source of the younger volcanic suite is consistent with the Nd isotopic compositions in requiring a cooler lithospheric mantle source.

The abundances of other incompatible elements in the younger volcanic rocks are not as clearly attributable to the melting behavior of metasomatically introduced accessory minerals, although the possibility remains. Phlogopite, for example, can serve as the dominant host for K, Rb, and Ba in metasomatized peridotite (Luth, 1997; Schmidt et al., 1999). Phlogopite is not stable at relatively high temperature in the convecting mantle, and is generally considered to be restricted to cooler lithospheric mantle (Frost, 2006; Furman, 1995). Unlike apatite and rutile, phlogopite is not a near-solidus phase in peridotites (Conceição and Green, 2004) and rather than congruent dissolution undergoes incongruent melting to garnet, olivine, and liquid (Fumagalli et al., 2009; Modreski and Boettcher, 1973; Tronnes, 2002). In the younger volcanic suite, K, Ba, and Rb are all higher in concentration than their older counterparts, which is at least consistent with contributions to the melt from dehydration melting of phlogopite. However, K contents in the younger rocks throughout the northern Sierra Nevada are not correlated with any index of partial melting (e.g., La contents), implying that phlogopite could not have been an important residual phase in the source region of their parental magmas (Maria and Luhr, 2008).

Similarly, there is no evidence that amphibole was a residual phase in the source of Crystal Basin volcanic rocks, or in any of the northern Sierra Nevada 2–3 Ma basaltic trachyandesites. Amphibole has an affinity for the middle (M) REEs that should result in a low MREE/HREE [e.g., (Dy/Yb)N] ratio in melts derived from rocks in which amphibole remains as a residual mineral (Davidson et al., 2007). This is not the case for the majority of the younger volcanic rocks (Fig. 11) and so either melting occurred at depths greater than the stability limit of amphibole (Frost, 2006) or no amphibole remained in the source rocks after melting. The sole exceptions are the 1 Ma trachyandesites from the Tahoe City region. These are the youngest and most Si rich of the younger volcanic rocks, and have low (Dy/Yb)N (Fig. 11) that can be interpreted as the product of residual amphibole or fractional crystallization of amphibole (Korte meier, 2012).

In summary, these observations suggest that those volcanic rocks in both the younger and older volcanic suites interpreted to be derived from continental mantle lithosphere were...
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Figure 11. (A) Zn/Fe ·10000 versus weight percent MgO for studied volcanic rocks. (B) (Dy/Yb)_N versus weight percent MgO. Symbols as in Figure 2.

Timing of Mantle Metasomatism

The preceding considerations do not distinguish between whether the metasomatic components were part of the post-Cretaceous, sub-basaltic mantle when it was frozen into the lithosphere in the Paleogene, or whether these components were added after the lithosphere stabilized; both options are possible. For example, apatite and rutile are common accessory phases in garnet pyroxenite xenoliths found in the Miocene lavas from the southern Sierra Nevada (Ducea and Saleeby, 1996, 1998a, 1998c). If analogous arclogite lithologies existed beneath the northern Sierra Nevada during the Cenozoic, then the accessory phases required to account for the trace element abundances in the younger volcanic suite could have been present in the lithospheric mantle prior to the onset of late Cenozoic magmatism. In this case, the distinction between the older and younger volcanic suites can be attributed solely to variations in the degrees of partial melting of this heterogeneous mantle source through time.

However, because both apatite and rutile are near-solidus phases during partial melting and are not stable at asthenospheric mantle temperatures (Ionov et al., 1999; Konzett and Frost, 2009), the metasomatized lithospheric mantle must have remained at subsolidus temperatures from the time these phases were introduced until partial melting occurred in the Pliocene. From this perspective, it is not obvious that the younger volcanic suite could simply represent smaller degrees of partial melting of the same metasomatized mantle involved in the older magmatism. If the base of the mantle
Figure 12. Stability fields of selected minerals and melting relations. (A) Metasomatized peridotite. Hydrous and anhydrous solidi for ultramafic mantle compositions and amphibole-out curve are after Green et al. (2010). Spinel-garnet transition in peridotite is from Walter et al. (2002). Phlogopite-out curve for H2O undersaturated, metasomatized peridotite is from Conceição and Green (2004). Ridge adiabat is after Herzberg et al. (2007) and references therein. The ap/rut out curve is approximate and is simply meant to depict the fact that both apatite and rutile are likely near-solidus phases during melting of metasomatized mantle. Model geotherms shown in both A and B represent transient temperature conditions in lithospheric mantle at increasing time intervals (1–5 m.y.) after an instantaneous heating event (t = 0) caused by emplacement of asthenospheric mantle at the base of the lithosphere (see text). (B) Mafic lithologies. Hydrous solidus for basalt anatexis is from Green (1982). Rutile-out shaded area delineates the low-pressure and high-temperature limits of where rutile persists as a residual phase during partial melting of alkalic, low-Ti metabasalt with water contents ranging from anhydrous to 5 wt% H2O (Xiong et al., 2005). Apatite-out shaded area is estimated from experimental results of Konzett and Frost (2009). Amphibole-out and garnet-in curves are for the alkali-rich basalt studied by Rapp and Watson (1995). Water-saturated solidus is from Lambert and Wyllie (1972). Solidus and liquidus curves for K-rich eclogite are from Spandler et al. (2007).
drive their chemical differentiation. Once subduction ceased, these same components were remobilized and incorporated into the younger magmas. At this point the lithospheric mantle was a source, and no longer a sink, for magmatism. This hypothesis is obviously speculative and its testing will require a better understanding of how arc-related melts interact with lithospheric mantle during ascent. For example, it is not clear that the older, low-Ti magmas percolating through the continental mantle lithosphere will necessarily be saturated with respect to rutile, although the possibility exists given the apparent reduction in the solubility of rutile in basaltic melts with decreasing temperature at uppermost mantle pressures (Gaetani et al., 2008; Green and Pearson, 1986; Xiong et al., 2009). Other HFSE-bearing accessory phases, such as ilmenite, should also be considered as a source of the HFSE in the younger magmatism (Pilet et al., 2010). Similarly, the fact that apatite solubility increases with decreasing Si contents in silicate melts (Green and Watson, 1982) argues against the possibility that parent magmas of the older volcanic suite could have been in equilibrium with apatite, even given their low P₂O₅ (~0.2 wt%). However, apatite solubility in mafic to intermediate-composition melts decreases markedly to <1% P₂O₅ with increasing pressure and decreasing temperature (Green and Watson, 1982). Recent experimental data demonstrate that apatite can precipitate from even anhydrous mafic melts differentiating at high temperature ( > 1000 °C) and pressure (1.5 GPa) (Pilet et al., 2010). These observations do not require that the parent magmas of the older volcanic suite precipitated apatite in the lithospheric mantle, but do leave open the possibility.

**Triggering of Lithospheric Mantle Melting**

Whether the continental lithospheric mantle beneath the northern Sierra Nevada was refertilized by Miocene arc magmatism, there remains the issue of how this mantle was induced to melt after the cessation of subduction magmatism and the opening of a slabs window beneath the region. Numerous mechanisms for continental mantle lithosphere melting have been invoked for Cenozoic magmatism in the Sierra Nevada, including lithosphere decomposition during extension (Cousens et al., 2011), melting in convectively removed material or in the remaining intact continental mantle lithosphere (Elkins-Tanton, 2003; Farmer et al., 2002; Manley et al., 2000), or lateral conductive heating of intact continental mantle lithosphere during its postsubduction disaggregation (Putirka et al., 2012).

In the southern half of the Sierra Nevada, the case for an association between lithospheric downwelling and volcanism was built on the ages and the chemical and isotopic compositions of late Cenozoic volcanic rocks that erupted at different times from similar geographic positions in the San Joaquin volcanic field (Fig. 1). Miocene (12–8.6 Ma) volcanism in the southern Sierra Nevada as a whole, including the San Joaquin volcanic field, postdates the opening of a slabs window in this region and can be interpreted as being the product of decompression melting of upwelling asthenosphere followed by extensive crustal assimilation (Farmer et al., 2002). Pliocene volcanism in the San Joaquin volcanic field occurred over a short (~1 m.y.) time interval ca. 3.5 Ma, after an ~5 m.y. hiatus in volcanic activity. In contrast to their Miocene counterparts, the Pliocene volcanic rocks are ultrapotassic (weight percent K₂O/weight percent Na₂O > 1) and have discreetly lower εNd values ranging to as low as ~9 (Fig. 14). The low εNd values point to a lithospheric source for these volcanic rocks, but the only known lithology in the Miocene lithosphere mantle column with sufficiently low εNd was the remnant shallow spinel peridotite of Precambrian mantle.

The need to expose this shallow, colder lithospheric mantle to supersolidus conditions in the Pliocene suggests that the mantle that sourced the 3.5 Ma volcanic rocks was either entrained in downwelling lithosphere or embedded in upwelling asthenosphere during lithospheric removal between 8 and 3.5 Ma (Elkins-Tanton, 2003; Farmer et al., 2002).

In the northern Sierra Nevada, an equivalent shift to low εNd ultrapotassic, volcanic rock compositions does not occur, either because a low εNd mantle does not exist in this region, or because mantle lithosphere removal has not taken place, at least not directly beneath those areas that underwent late Cenozoic volcanism. Recent numerical modeling of the timing and trigger mechanism for lithospheric removal in the southern Sierra Nevada suggests that instantaneous heating of the base of the arclogite lithosphere, due to the opening of a slabs window at 20 Ma, ultimately led to removal of the lithosphere by a combination of Rayleigh-Taylor instabilities and lithospheric delamination (Le Pourhiet et al., 2006; Saleeby et al., 2012). Saleeby et al. (2012) proposed that melting of the shallow arclogite lithosphere was a natural consequence of its delamination and exposure to upwelling asthenosphere, albeit ~16 m.y. after the slabs window first developed. Although we recognize that the initial thermal conditions, composition, and thickness of arclogite in the northern Sierra Nevada need not match those used in the Saleeby et al. (2012) numerical models, the fact remains that only a few million years have elapsed since the opening of a slabs window beneath the Lake
While no low $\varepsilon_{Nd}$ ultrapotassic volcanic event analogous to the 3.5 Ma volcanicism in the southern half of the mountain range took place in the northern Sierra Nevada, it is also true that southern Sierra Nevada lacks high LREE abundance, high Nb/Y volcanism similar to that of the immediately postsubduction volcanism in the northern Sierra Nevada (Fig. 14). Because the northern Sierra Nevada lithosphere, but not the regions beneath the San Joaquin volcanic field to the south, underwent Neogene subduction-related magmatism, it is possible that the unique compositions of the younger volcanic suite are related to this earlier episode of subduction-related magmatism. The simplest interpretation of the younger volcanic suite in the Lake Tahoe region is that it was derived from mantle lithosphere that was metasomatized by subduction-related melts in the Miocene but remained in place during the transition from active subduction and cooling of the continental mantle lithosphere to the formation of a slabless window and the transition toward a steady-state geotherm beneath the northern Sierra Nevada (Cousens et al., 2011). The process envisioned is akin to the refrigeration of the accretionary prism and continental margin during active subduction, followed by heating, metamorphism, crustal anatexis, and mantle-derived melt infiltration of the forearc during subsequent opening of a slabless window (Madsen et al., 2006). Pliocene–Pleistocene magmatism that occurred ~200 km west of the Lake Tahoe region in the Coast Ranges, including the Clear Lake volcanic field (Fig. 1), may correspond to postsubduction forearc magmatism. Volcanism in this region has been attributed to injection of asthenosphere-derived basaltic magma into the lower crust during opening of the same slabless window likely responsible for postsubduction magmatism in the northern Sierra Nevada (Hammersley and DePaolo, 2006; Sweetkind et al., 2011). Post–3 Ma magmatism in the northern Sierra Nevada may represent an inboard manifestation of the same general process (Miller et al., 2010), in a location with a significantly thicker mantle lithosphere. Our suggestion is that during the Miocene, the continental mantle lithosphere must have been remained sufficiently cool that percolation of mantle wedge–derived melts that reacted with the continental mantle lithosphere stabilized near-solidus accessory phases (Fig. 15). This requirement implies that continental mantle lithosphere was maintained in the northern Sierra Nevada over at least 13 m.y. of active subduction-related magmatism, albeit of relatively small volume relative to modern Cascade Range volcanoes, and that advection of heat to the continental mantle lithosphere by infiltrating melts was insufficient to offset conductive cooling imposed on the continental mantle lithosphere via refrigeration of the forearc mantle by the subducting oceanic lithosphere (Abers et al., 2006; Wada et al., 2011). Refrigeration would also offset the reduction in viscosity, and strength, in the mantle imposed by hydrous metasomatism (Li et al., 2008), and so helped to keep the mantle lithosphere in place. Cessation of active subduction exposed the metasomatized base of the continental mantle lithosphere to the higher temperatures associated with upwelling asthenosphere, resulting in the conductive heating and then melting of the continental mantle lithosphere (Fig. 15).

To assess the plausibility of the latter process, consider a continental lithosphere thickness of 100 km, the base of which is sufficiently deep and cool ($\leq$1000 °C) to allow stabilization of clinopyroxene, garnet, and rutile, but not amphibole, from infiltrating melts and surrounding wall rocks (Alonso-Perez et al., 2009) during Miocene magmatism. Instantaneous emplacement of 1290 °C potential temperature mantle against the base of the continental mantle lithosphere, whether by simple passive upwelling of asthenosphere after slab removal or by secondary convection induced along the edge of the opening slabless window (Thorkelson and

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**Figure 14. Northern and southern Sierra Nevada volcanic rocks.** (A) Volcanic rock age versus weight percent K$_2$O/weight percent Na$_2$O. (B) Volcanic rock age versus $\varepsilon_{Nd}$. (C) Volcanic rock age versus Nb/Y. Southern Sierra Nevada data are from Farmer et al. (2002). Symbols as in Figure 2; color fields as in Figure 6.
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Breitsprecher, 2005), is adequate to induce partial melting at the base of the hydrous, metasomatized continental mantle lithosphere, leaving behind garnet and clinopyroxene in the melt residue and consuming all rutile and apatite (Fig. 12). After only 1 m.y., temperatures increase sufficiently in the shallower amphibole stability field in either amphibole-bearing mafic or ultramafic rocks (Fig. 12) that temperatures sufficient for dehydration melting of these rocks are reached, which could account for the transition through time in the younger volcanic rocks in the northern Lake Tahoe region from trachybasaltic andesites, with evidence of residual garnet and clinopyroxene, to younger trachyandesites that show evidence of residual amphibole (Kortemeier, 2012).

This model is simplistic, and we can arbitrarily adjust lithosphere thickness, degree of mantle hydration, and mantle composition to produce a variety of outcomes in terms of volcanic rock compositions. Our intent is only to demonstrate that postsubduction conductive heating of thick, metasomatized continental mantle lithosphere in the northern Sierra Nevada is all that is required to produce the younger volcanism observed in this region. We cannot rule out physical removal of the mantle lithosphere in the late Cenozoic, as proposed for southern portions of the Sierra Nevada, but our data can be explained simply if the mantle lithosphere beneath at least the western Lake Tahoe region has remained principally intact over the past 20 m.y.

Seismological Evidence for Preserved Continental Mantle Lithosphere Beneath Northern Sierra Nevada?

Seismological evidence bearing on the possible preservation of mantle lithosphere in the Lake Tahoe region is ambiguous. Farther south in the Sierra Nevada, the combination of a sharp, high-amplitude P-to-S conversion of teleseismic P waves at the Moho above 40 km depth and low upper mantle wave speeds argues not only for the late Cenozoic removal of the mantle lithosphere and the arclogite related to batholith formation (Anderson, 2005), but also for the upwelling and attendant decompression melting of asthenosphere to depths at least as shallow as 50 km (Frassetto et al., 2011). At the latitude of Lake Tahoe, however, a transition occurs from this sharp Moho to the south in the eastern Sierra to a slightly more subdued Moho to the north. This observation, combined with the fact the Lake Tahoe region is at northern end of the deep Moho inferred under the western foothills of the Sierra, led Frassetto et al. (2011) to suggest that the Tahoe area Moho has a different origin than in areas to the south. In contrast, the P-wave tomography (Reeg, 2008) indicates that Lake Tahoe east of the Sierran crest overlies a swath of low-wave-speed material near the Moho extending along the Sierran crest from the Cascades to near the southern end of the Sierra, suggesting a greater continuity with structures to the south.

Just west of Lake Tahoe and closer to the source vents of the lavas studied here, low-wave-speed material near the Moho and the sharp Moho defined by the P-to-S receiver functions are replaced by a weaker and more ambiguous Moho conversion and neutral to slightly higher wave-speed material (Fig. 16). No substantial Cenozoic thinning or delamination is evident in this area; Frassetto et al. (2011) interpreted receiver functions in this region as the product of a tectonic doubling of the crust from Mesozoic tectonic activity. Somewhat elevated (~+1%) mantle P wave speeds extend to depths of ~130 km and could reflect surviving pre-Neogene mantle lithosphere. If limited to a narrower depth range, this anomaly would have proportionally higher amplitude. This material appears to be a somewhat lower amplitude extension of the foothills high-wave-speed anomaly found farther south. The top of the body

Figure 15. Illustration of modification of continental lithosphere mantle (CLM). (A) During infiltration by Miocene arc-related fluids (older than 3 Ma) (cpx—clinopyroxene). (B) During subsequent heating after opening of slabless window.
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Figure 16. East-west cross section of P-wave speed perturbations at latitude of northern Lake Tahoe derived from teleseismic tomography started from the crustal and uppermost mantle shear wave model of Moschetti et al. (2010). The Moho determined by Frassetto et al. (2011) is superimposed for reference (it is not included in the tomographic inversion, so areas with a deeper Moho would be expected to have lower wave speeds near Moho depths in the tomography than shown).

is less defined, owing to trade-offs with crustal wave-speed perturbations. This contrasts sharply with very low wave speeds under the Clear Lake volcanic system farther west (Fig. 16; Schmandt and Humphreys, 2010) that appear to reflect very high temperatures and the probable presence of melt (Levandowski et al., 2012). The presence of melt in the shallow mantle beneath the northern Coast Ranges is likely the result of upwelling and decompression melting of asthenosphere in the Clear Lake region (Schmandt and Humphreys, 2010), probably from the creation of a slab window as the Mendocino triple junction has moved northward (Dickinson, 1997). This conclusion is consistent with the high $\epsilon_{Nd}$ (+6) of late Cenozoic basalts at this volcanic center (Hammersley and DePaolo, 2006).

Overall, the seismological evidence suggests that upwelling asthenosphere is present near Clear Lake but no shallower than ~120–150 km under the Sierra west of Lake Tahoe. The prominent low-wave speeds seen in and east of the Tahoe area near the Moho likely reflect elevated temperatures and plausibly melt, but the origin of any such melts is unclear from seismic evidence alone. Seismic anomalies more in accord with upwelling asthenosphere nearing the crust are found farther east (~119°W) or north, in the Cascade backarc (Reeg, 2008).

Comparison to Cenozoic Volcanism in Baja California

If lithospheric mantle played a lead role in the production of postsubduction magmatism in the northern Sierra Nevada, it is possible that this may be a normal response to the opening of a slabless window along a continental margin. For example, Cenozoic magmatism that followed the development of a slabless window in Baja California has long been attributed to partial melting of mantle previously metasomatized by slab components (Pullares et al., 2008; Saunders et al., 1987). Although the suite of postsubduction volcanic rocks in Baja California includes Nb-enriched basalts that have not yet been recognized in the northern Sierra Nevada (Calmus et al., 2010; Castillo, 2008), there are some similarities in other volcanic rock types found in both regions. For example, high-Mg andesites (bajaites) in Baja California and the northern Sierra Nevada trachybasaltic andesites of the younger volcanic suite are similar compositionally and have overlapping major and trace element compositions, although the bajaites tend to have higher LILE contents and lower HFSE abundances (Pullares et al., 2008). The bajaites could represent the products of conductive heating and melting, in the presence of residual garnet, of mantle wedge metasomatized during the earlier subduction episode, a conclusion consistent with the relatively high $\epsilon_{Nd}$ values >+3 determined for these rocks (Benoit et al., 2002). We have also interpreted the northern Sierra Nevada trachybasaltic andesites as the products of partial melting of slab-metasomatized mantle, but the low $\epsilon_{Nd}$ values of these rocks rule out their derivation by melting of a convecting mantle wedge in the late Cenozoic. If instead continental mantle lithosphere was involved in production of the northern Sierran basaltic trachyandesites, it is possible that this...
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Mantle lithosphere may apply to Baja California as well. The higher $f_{\text{eq}}$ values of the Baja California volcanic rocks may simply reflect high $f_{\text{eq}}$ of the mantle lithosphere in this region, a possibility given that at least the western portion of peninsular California is composed of a juvenile accreted Mesozoic island-arc complex (Johnson et al., 1999).

**CONCLUSIONS AND BROADER IMPLICATIONS**

The results of our study suggest that in the northern Sierra Nevada continental mantle lithosphere played a major role in the production of late Cenozoic magmatism in this region. During the Miocene the continental mantle lithosphere was infiltrated by subduction-related fluids produced in the underlying mantle wedge, and essentially served as a lithospheric mantle melt reactor. Rock-melt reactions altered both the compositions of the infiltrating melts and the continental mantle lithosphere. After the cessation of subduction, the continental mantle lithosphere was heated by upwelling asthenosphere, which resulted in a bake-out of the lithospheric melt reactor, the products of which are manifested in the younger volcanism. The role of the continental mantle lithosphere in the northern Sierra Nevada may be clearly recognizable because thick mantle lithosphere was present prior to the onset of arc magmatism, whereas arc magmatism was relatively small in volume, short lived (~25 m.y.), and followed by the opening of a slabless window. It may be profitable to address the possibility that continental mantle lithosphere plays a similar role in other continental arcs and to attempt to define how the continental mantle lithosphere responds to longer lived arc magmatism, where arc magmatism was relatively small in volume, short lived (~25 m.y.), and followed by the opening of a slabless window. It may be profitable to address the possibility that continental mantle lithosphere plays a similar role in other continental arcs and to attempt to define how the continental mantle lithosphere responds to longer lived arc magmatism, where arc magmatism was relatively small in volume, short lived (~25 m.y.), and followed by the opening of a slabless window.

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