

Geology, geochronology, and geochemistry of the Miocene–Pliocene Ancestral Cascades arc, northern Sierra Nevada, California and Nevada: The roles of the upper mantle, subducting slab, and the Sierra Nevada lithosphere

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ABSTRACT

The assemblage of ca. 28–3 Ma volcanic rocks exposed in the Lake Tahoe–Reno region of the northern Sierra Nevada, United States, is interpreted to be part of the Ancestral Cascades volcanic arc. The volcanic rocks are commonly highly porphyritic, including abundant plagioclase with clinopyroxene, amphibole, and rare biotite, and range from basaltic andesite to dacite in composition. Less common are poorly phyric, olivine- and clinopyroxene-bearing basalts and basaltic andesites. Porphyritic lavas dominate composite volcanic centers, whereas the poorly phyric lavas form isolated cinder cone and lava flow complexes. Tahoe–Reno arc lavas are calc-alkaline, enriched in the large ion lithophile elements but depleted in Nb and Ta relative to the light rare earth elements, and have highly variable radiogenic isotopic compositions. Compared to the modern south Cascade arc, Tahoe–Reno region basalts are enriched in the light rare earth and large ion lithophile elements and have higher $^{87}\text{Sr}/^{86}\text{Sr}$ and lower $^{143}\text{Nd}/^{144}\text{Nd}$ that are consistent with an old, subduction-modified lithospheric mantle source, such as that proposed for lavas of the Western Great Basin. Melting of the lithospheric mantle may be enhanced by

fluid flux from the subducting slab if the Juan de Fuca slab dip is shallow. Andesites and dacites evolved from basaltic magmas by a combination of fractional crystallization and assimilation of lower crustal melts. Available geochronological data indicate that the westward sweep of Cenozoic volcanism through Nevada was associated with steepening of the slab dip, but the dip angle was lower during Miocene–Pliocene arc volcanism than it is today beneath the modern south Cascades.

INTRODUCTION

Late Tertiary volcanoclastic and volcanic rocks blanket a large area of the Sierra Nevada of northeastern California and adjacent western Nevada (Lindgren, 1897; Hudson, 1951; Thompson and White, 1964; Saucedo and Wagner, 1992; Dickinson, 1997; Wagner et al., 2000; Busby et al., 2008a, 2008b). Despite excellent exposure and the occurrence of large epithermal gold-silver deposits (e.g., Comstock, Bodie, Tonopah, and Aurora districts; John, 2001) within late Tertiary volcanic rocks of the area, very little is known of the volcanology, geochronology, and geochemistry of this magmatic suite. This region therefore constitutes a large gap in our understanding of the volcanic history and tectonic evolution of the western United

States when compared to surrounding volcanic provinces such as the modern Cascade arc (e.g., Borg et al., 2002; Strong and Wolff, 2003; Lee-man et al., 2004; Green and Sinha, 2005), Yellowstone and the Snake River Plain (e.g., Camp, 1995; Christiansen et al., 2002b; Jordan et al., 2004), the Western Great Basin (e.g., Fitton et al., 1988; Ormerod et al., 1988; Rogers et al., 1995; Cousens, 1996), the Mojave Desert and Basin and Range (e.g., Glazner et al., 1991; Perry et al., 1993; Farmer et al., 1995; Yogodzinski et al., 1996), and the San Andreas fault and offshore California (e.g., Cole and Basu, 1995; Davis et al., 1995; Dickinson, 1997).

The Miocene–Pliocene geological history of volcanism in the northern Sierra Nevada is complicated by potentially overlapping volcanotectonic settings, including arc volcanism resulting from subduction of the Farallon (Juan de Fuca) plate (e.g., Lipman, 1992; Dickinson, 1997), the incursion of Basin and Range extension westward into the Sierra Nevada (Guffanti et al., 1990; Henry and Perkins, 2001), and the potential influence of hotspot magmatism related to the Columbia River flood basalts (Wagner et al., 2000; Garrison, 2004; Coe et al., 2005).

Although the extent of the Ancestral Cascade arc that was roughly coincident with the modern Cascade arc is well established (i.e., the Eocene–Miocene Western Cascades; Priest,

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1990; Du Bray et al., 2006), the character and even the existence of a Miocene–Pliocene Ancestral Cascade arc in the Sierra Nevada south of the modern Cascades has been controversial. Christiansen and Yeats (1992), Lipman (1992), John (2001), and Dickinson (1997; 2002, 2004) showed an arc along and east of the northern Sierra Nevada during much of the middle and late Cenozoic. In contrast, Glazner et al. (2005) and Glazner and Farmer (2008) argued that the ancestral Cascades existed only in the area of the modern Cascades, i.e., equivalent to the Western Cascades, and was absent south of Mount Shasta, based on their analysis of magmatic space-time patterns from the North American Volcanic and Intrusive Rock database (NAVDAT).

Basin and Range extension and thinning of the lithosphere along the eastern margin of the southern and central Sierra Nevada are proposed to cause melting of the lithospheric mantle, producing the alkalic basaltic to bimodal volcanism of the Western Great Basin (Fitton et al., 1988; Ormerod et al., 1991; Asmerom et al., 1994; Yogodzinski et al., 1996). In addition, late Cenozoic uplift of the southern Sierra Nevada is linked to the completion of delamination of the underlying lithospheric mantle, based on geophysical (Wernicke et al., 1996; Boyd et al., 2004; Zandt et al., 2004) and geological and petrological (Ducea and Saleeby, 1996, 1998; Manley et al., 2000; Ducea, 2001; Lee et al., 2001) arguments. Delamination may also coincide with Pliocene potassic volcanism in the southern and central Sierra Nevada (van Kooten, 1980; Dodge et al., 1986; Feldstein and Lange, 1999; Farmer et al., 2002; Elkins-Tanton and Grove, 2003). Although some geophysical surveys support a similar delamination model for uplift of the northern Sierra Nevada as well (Jones et al., 2004), to date no potassic volcanism has been identified north of Sonora Pass in the central Sierra (Roelofs et al., 2004; Busby et al., 2008b) and no petrological data (e.g., from mantle xenoliths) exist to support delamination beneath the northern Sierra.

This study focuses on the geochemistry of Miocene–Pliocene lavas and volcanoclastic rocks in a broad area around Lake Tahoe and Reno, and includes rocks east of Reno that have been considered as a type locality for mafic to intermediate composition volcanism throughout the region (Birkeland, 1963; Thompson and White, 1964; Schwartz and Faulds, 2001). The goals of this study are to (1) characterize the chronology, petrography, and geochemistry of Miocene–Pliocene volcanic rocks in the Tahoe-Reno region; (2) evaluate what petrologic and tectonic processes influence magma evolution at deep and shallow levels; (3) assess mantle source compositions, compare these sources with those

proposed for other volcanic suites around the Sierra Nevada, and propose a tectonomagmatic setting for these volcanic rocks; and (4) present a model for the temporal migration of magmatism in Nevada and eastern California.

GEOLOGIC SETTING

Miocene–Pliocene volcanic rocks extend south of the modern Lassen volcanic field (the termination of the modern Cascades volcanic arc) along the east side of the Sierra Nevada batholith into western and southern Nevada and adjacent eastern California (Fig. 1) (Christiansen and Yeats, 1992; Saucedo and Wagner, 1992; Wagner et al., 2000). Volcanic edifices are composed of lava flows, dome collapse breccias, and debris flows (Figs. 2A, 2B), erupted upon granitoids and metamorphic rocks of the Mesozoic Sierra Nevada batholith. Miocene–Pliocene volcanic centers in the Lake Tahoe area are extensively glaciated, and only remnants of volcanic centers remain (Fig. 2A). Volcanoclastic rocks shed from these edifices flowed westward across the Sierra Nevada and into the eastern Sacramento Valley, and are called the Mehrten Formation (Wagner and Saucedo, 1990; Wagner et al., 2000). Eroded remnants of lava flows commonly overlie Mehrten volcanoclastic rocks west of the high Sierra crest (Lindgren, 1897; Saucedo and Wagner, 1992). Volcanic necks, such as Squaw Peak, form the high points on the north and northwestern sides of the Lake Tahoe area (Harwood, 1981; Saucedo and Wagner, 1992).

Although Tertiary volcanism in the Sierra Nevada is dominated by volcanoclastic breccias and reworked volcanic rocks (Hudson, 1951; Saucedo and Wagner, 1992; Wagner et al., 2000; Busby et al., 2008a), lava flow–dominated volcanic complexes are common in the Lake Tahoe and Reno region. Lavas are primarily highly porphyritic andesites, dominated by plagioclase phenocrysts accompanied by either pyroxene or hornblende with rare biotite (Fig. 2C). Less phyric, olivine-clinopyroxene basalts and basaltic andesites are volumetrically less abundant, occurring in the Verdi Range northeast of Lake Tahoe (Ladybug Peak, Fig. 2D), north of Boca Reservoir (Fig. 1), the Carson Range immediately east of Lake Tahoe, along Interstate 80 west of Reno, in the Virginia Range east of Reno, and as isolated flows within several andesitic volcanic complexes (Saucedo and Wagner, 1992; Henry and Perkins, 2001; Prytulak et al., 2002). Collectively, the porphyritic volcanic rocks are commonly termed the Kate Peak Formation (Daley, 1949; Thompson and White, 1964), whereas the less-phyric, olivine-clinopyroxene units are commonly termed the Lousetown Formation (Birkeland, 1963), despite the large age

range and geographic breadth in each formation. In this paper these two contrasting rock types are referred to as the porphyritic and nonporphyritic suites, respectively.

TIMING AND DISTRIBUTION OF MAGMATISM NEAR LAKE TAHOE

Volcanism near Lake Tahoe occurred from 28 Ma to 1 Ma, with major pulses at 16 Ma, 12 Ma, 10 Ma, 8–6 Ma, 5–3 Ma, and 2.6–1 Ma (Table 1; Morton et al., 1977; Saucedo and Wagner, 1992; Henry and Sloan, 2003). The oldest Cenozoic igneous rocks near Lake Tahoe, and the oldest rocks examined in this study, are minor pyroxene andesite lavas erupted in the Carson Range at 28 Ma (Fig. 3; Table 1). Pyroxene-hornblende andesite reportedly from the Mount Lincoln area gave a plagioclase K-Ar date of 26.4 ± 0.8 Ma (Morton et al., 1977; Saucedo and Wagner, 1992). However, the sample location and even what rock was dated are poorly documented. Based on the small outcrop in the Carson Range and, at most, small outcrop near Mount Lincoln, very small volumes of magma erupted at this time in the Tahoe area.

The next documented volcanic episode near Lake Tahoe was ca. 16 Ma, when basaltic lava was emplaced west of Babbitt Peak (BP, Fig. 1) and voluminous andesites erupted around and east of Babbitt Peak. Although volcanic activity between 28 and 16 Ma has not been found near Lake Tahoe, activity was extensive farther east during that interval (Fig. 3). For example, particularly voluminous andesites that host the rich Comstock Ag-Au veins erupted in three episodes between 18 and 14 Ma near Virginia City (Castor et al., 2005).

An episode ca. 12 Ma was particularly voluminous and extensive. A major andesitic stratovolcano developed around the north end of the Carson Range (Henry and Perkins, 2001), and additional andesites erupted to the west and northwest (Fig. 3). This episode was coeval with a major episode of extension recognized along much of the eastern margin of the Sierra Nevada (Stewart, 1992; Stockli et al., 2000; Henry and Perkins, 2001).

Numerous basaltic andesite lavas erupted shortly before 10 Ma along the Interstate 80 corridor and in the Verdi Range (Table 1; Henry and Perkins, 2001; Prytulak et al., 2002). These rocks are collectively termed the I-80 suite. One of these vent and flow complexes, Ladybug Peak, is dated as 10.1 Ma and is not Quaternary in age, as previously inferred (Latham, 1985).

Volcanism between 8 and 6 Ma includes possibly two distinct andesite stratovolcanoes, one centered around Martis Peak and the other near Mount Lincoln (Fig. 3). Two andesites at

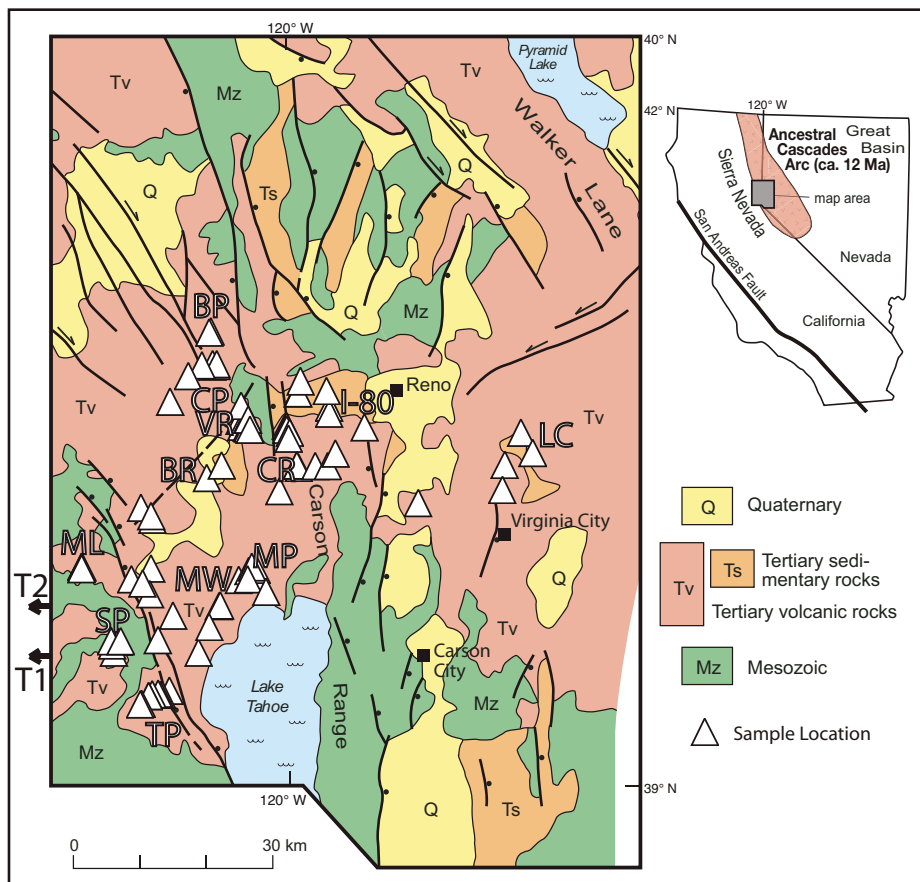


Figure 1. Simplified geology of the study area in the northern Sierra Nevada and western Nevada (modified from Henry and Perkins, 2001). Inset map shows extent of Ancestral Cascade arc from John (2001). Triangles indicate sample locations. Black lines are faults. Localities: TP—Twin Peaks; SP—Squaw Peak; ML—Mount Lincoln; MW—Mount Watson; MP—Mount Pluto; BR—Boca Reservoir; VR—Verdi Range; CR—north Carson Range; CP—Crystal Peak; BP—Babbitt Peak; I-80—I-80 suite area; LC—Lousetown—Clark Mountain.

active Cascade arc (Hildreth, 2007) and significantly larger than 15–6 Ma volcanic and volcanoclastic rocks near Carson Pass south of Lake Tahoe (Busby et al., 2008a).

The broad 5–3 Ma burst of activity around Lake Tahoe was followed by a more volumetrically and geographically restricted, east-west array of younger than 2.6 Ma mafic (rarely dacitic to rhyolitic) volcanic events extending from the north shore of Lake Tahoe east to the Carson Sink in Nevada (B. Cousins and C. Henry, 2006, personal observ.); Dalrymple, 1964; Saucedo and Wagner, 1992) and possibly west to Sutter Buttes in central California (Hausback et al., 1990; Swisher et al., 2000). These rocks are petrographically and chemically distinct from the Miocene–Pliocene volcanic rocks described in this paper and are not considered to be part of the Miocene–Pliocene suite (Cousens et al., 2000, 2003; Gupta et al., 2007). Volcanic rocks younger than 4 Ma in age are absent between Lake Tahoe and the Lassen volcanic region.

LOCAL GEOLOGY AND SAMPLING LOCALITIES

Highly eroded volcanic complexes, including volcanoclastic rocks, lava flows, dikes, and volcanic necks, cap high Sierra Nevada granitoids from the west side of Lake Tahoe north to Donner Pass. Examples include Twin Peaks, Stanford Peak, Squaw Peak, and Mount Lincoln (Harwood, 1981; Saucedo and Wagner, 1992). The original size of volcanic edifices is difficult to ascertain, due to erosion and to the fact that a large proportion of the rocks are volcanoclastic and some have been reworked and deposited in paleovalleys (e.g., Fosdick et al., 2004). The most abundant rock type is bedded volcanic breccia that forms distinctive debris aprons over granitoid rocks (Figs. 2A, 2B). Volcanic fragments are subrounded to rounded and range from millimeters to 30 cm in diameter. At Squaw Peak and Mount Lincoln, prominent flow units include volcanic fragments that are angular to subrounded and are petrographically indistinguishable from the volcanic matrix, and thus are block-and-ash flow deposits resulting from a lava dome collapse (Freundt et al., 2000). Subordinate lava flows are commonly >10 m thick, massive, and highly plagioclase porphyritic. Olivine-clinopyroxene basalt and basaltic andesite lava flows are volumetrically minor. Where cut by dikes, the surrounding volcanoclastic rocks and the dike are commonly hydrothermally altered.

North of Lake Tahoe, most volcanic rocks at intermediate elevation are of Miocene–Pliocene age, including Mount Pluto, Mount Watson, Martis Peak, Sardine Peak, and Babbitt Peak (Saucedo and Wagner, 1992). Almost 1000 m

Martis Peak have hornblende ⁴⁰Ar/³⁹Ar dates of ca. 6.4 Ma (W. Wise, 2003, personal commun.). Hornblende andesite east of Mount Lincoln has an indistinguishable ⁴⁰Ar/³⁹Ar age of 6.37 ± 0.25 Ma (Table 1), which is probably indicative of the age of the andesitic activity in that area. Slightly older basaltic lavas and dikes were emplaced ca. 8–7 Ma (Table 1) (Dalrymple, 1964).

A major burst of volcanic activity in the Lake Tahoe area occurred between 5 and 3 Ma. A particularly voluminous center was in the Twin Peaks and Squaw Peak area (Fig. 3), where whole-rock K-Ar ages on 15 samples of andesite to basalt lavas and dikes range from 5.4 to 3.0 Ma (D.S. Harwood, in Saucedo and Wagner, 1992). A basalt lava from west of this center has a matrix ⁴⁰Ar/³⁹Ar age of 3.83 ± 0.14 Ma (Table 1), and biotite and plagioclase ⁴⁰Ar/³⁹Ar ages from a biotite-hornblende andesite at Mount Watson in the eastern part of this center are

ca. 3.5 Ma (W. Wise, 2003, personal commun.). The basaltic Boca Hill vent and lava flows to the north give ⁴⁰Ar/³⁹Ar ages of 4.41 ± 0.03 Ma, 4.12 ± 0.40 Ma, and 3.98 ± 0.30 Ma (Table 1).

Incomplete mapping, disruption by extensive normal faulting, and variable glaciation allow only semiquantitative estimates of magma volumes. In general, all except the oldest (28 Ma) pulse produced major volumes of dominantly intermediate rocks. Based on the distribution of andesites over 300–500 km², the two largest pulses, at 12 and 5–3 Ma, each erupted at least 100 km³ of magma. Pulses at 16, 8, and 6 Ma erupted at least several tens of cubic kilometers. The smallest episode, the 10 Ma basaltic andesite group, is spread thinly over a large area; the total volume is probably <10 km³. Both the absolute volumes and the relative proportions of intermediate to relatively mafic rocks are similar to those in the Lassen area of the southernmost

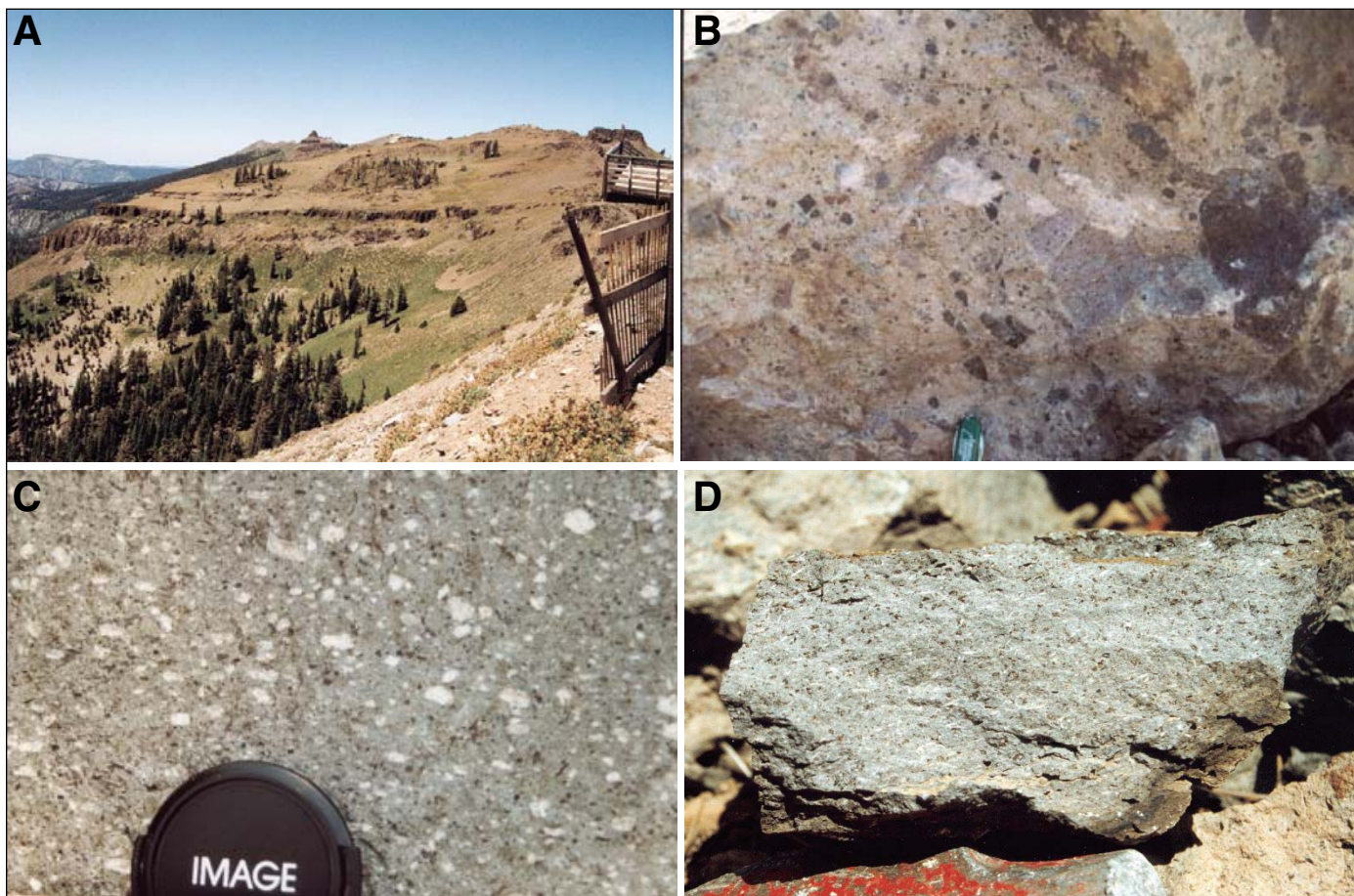


Figure 2. (A) View looking north from Squaw Peak at block and ash flows overlying Sierran granitoids. Small peak in middle ground is a volcanic neck. Fence is 1.5 m high. (B) Volcaniclastic breccias at Mount Lincoln, typical of Miocene–Pliocene rocks in the central and northern Sierra (Wagner et al., 2000; Busby et al., 2008a). Portion of knife in field of view is 4 cm long. (C) Biotite–amphibole–plagioclase andesite from Mount Watson, typical of the porphyritic lava suite. Lens cap is 5 cm in diameter. (D) Clinopyroxene–olivine basalt from Ladybug Peak, typical of the nonporphyritic suite. Red hammer head is 12 cm long.

of stratigraphy are exposed at Mount Pluto and Martis Peak. Although exposure is fair to poor, lava flows are very common within these edifices compared to those at higher elevation. The lavas are primarily highly plagioclase porphyritic, with either pyroxene and/or hornblende (Figs. 2C and 4A), although rare nonporphyritic basaltic flows are exposed.

North and east of Lake Tahoe, the Verdi and Carson Ranges represent a faulted block of the Sierra Nevada. Both ranges consist of Mesozoic Sierra Nevada granitoids blanketed by porphyritic Miocene–Pliocene andesites and dacites and capped by small-volume, nonporphyritic lava flows (Birkeland, 1963; Thompson and White, 1964; Latham, 1985).

Along the Interstate 80 corridor between the Verdi Range and Reno are several isolated exposures of nonporphyritic basalt flows that are dismembered by Basin and Range faults (Henry and Perkins, 2001). All of the lavas dated by

the $^{40}\text{Ar}/^{39}\text{Ar}$ technique are ca. 10 Ma in age, the same as the Ladybug Peak complex and a nonporphyritic, olivine-bearing lava flow capping a highly altered, porphyritic andesite ~5 km northwest of Stampede Reservoir (Saucedo and Wagner, 1992). Based on their similar ages and petrographic character, these rocks are considered as a group that we term the I-80 suite.

In the Virginia Range east of Reno, most of the surface exposures are porphyritic volcanic rocks of the Kate Peak Formation, similar in age and petrography to Miocene–Pliocene rocks in the Sierra Nevada (Morton et al., 1977; Stewart, 1999; Schwartz and Faulds, 2001). Also in this area is the type locality for the Lousetown Formation, consisting of a maximum 150-m-thick sequence of thin basaltic lava flows that are dated by $^{40}\text{Ar}/^{39}\text{Ar}$ as 7.5 Ma (Schwartz and Faulds, 2001). Another mafic lava complex of Miocene–Pliocene age in the area, north of the Lousetown exposures, is

Clark Mountain, dated by $^{40}\text{Ar}/^{39}\text{Ar}$ as 9.6 Ma (LC in Figs. 1 and 3).

ANALYTICAL TECHNIQUES

Samples of Miocene–Pliocene lavas and volcaniclastic rocks were collected in 1995, 1997, and 2001, primarily along highway and railway cuts, Forest Service roads, and hiking trails, and all were precisely located using a handheld global positioning system (GPS) unit. Sample locations are shown in Figure 1, and GPS coordinates are listed in Supplemental Table 1¹.

Electron microprobe analyses of phenocrysts, groundmass minerals, and matrix glasses were

¹If you are viewing the PDF of this paper or reading it offline, please visit <http://dx.doi.org/10.1130/GES00166.S1> (Supplemental Table 1) or the full-text article on www.gsjournals.org to view Supplemental Table 1.

performed using the Camebax MBX at Carleton University. A beam current of 20 nA and an accelerating potential of 15 kV were used for silicates and oxides. Peak counting times for each element were 15–40 s, and backgrounds were collected on both sides of the peak. Raw X-ray data were converted to element weight percent by the Cameca PAP matrix correction software.

Rock samples were slabbed, crushed in a Bico Chipmunk jaw crusher, and ground to a fine powder in an agate ring mill. Whole-rock major and trace element contents were determined by fused-disc X-ray fluorescence spectrometry (University of Ottawa) and solution-mode inductively coupled plasma–mass spectrometry (Ontario Geological Survey). The precisions of the data, based on replicate analyses of samples and blind standards, are listed in Supplemental Table 1 (see footnote 1). Samples were analyzed for Pb, Sr, and Nd isotopic ratios at Carleton University (techniques of Cousens, 1996). All Pb mass spectrometer runs are corrected for fractionation using NIST SRM981. The average ratios measured for SRM981 are $^{206}\text{Pb}/^{204}\text{Pb} = 16.890 \pm 0.012$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.429 \pm 0.014$, and $^{208}\text{Pb}/^{204}\text{Pb} = 36.502 \pm 0.048$. The Pb fractionation correction is $+0.13\%$ /amu (based on the values of Todt et al., 1984). Sr isotope ratios are normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.11940$. Two Sr standards are run at Carleton, NIST SRM987 ($^{87}\text{Sr}/^{86}\text{Sr} = 0.710251 \pm 18$) and the Eimer and Amend (E&A) SrCO_3 ($^{87}\text{Sr}/^{86}\text{Sr} = 0.708037 \pm 30$). Nd isotope ratios are normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.72190$. Analyses of the U.S. Geological Survey standard BCR-1 yield $^{143}\text{Nd}/^{144}\text{Nd} = 0.512668 \pm 20$ ($n = 4$), and 54 runs of the La Jolla standard average $^{143}\text{Nd}/^{144}\text{Nd} = 0.511877 \pm 18$. All quoted uncertainties are 2σ standard deviations of the mean. Chemical analyses of a representative set of lavas are presented in Table 2, and all geochemical analyses are listed in Supplemental Table 1 (see footnote 1).

PETROGRAPHY AND MINERAL CHEMISTRY

As discussed earlier, the Miocene–Pliocene lavas are divided into two distinct suites, a dominant porphyritic suite and a less abundant nonporphyritic, olivine-clinopyroxene-bearing suite. Porphyritic suite lavas and volcanoclastic rocks dominate the large volcanic complexes. The porphyritic suite is characterized by abundant, highly zoned, blocky plagioclase megacrysts as large as 1 cm, composing from 10% to 50% of the rock (Fig. 4A). These megacrysts commonly exhibit reverse or oscillatory zoning, and also commonly have sieve texture (Fig. 4B). Within individual samples, plagioclase megacryst cores can range in An content by as much

as 35 An units (e.g., An_{80-45}), while rims can range by 30 An units (e.g., An_{60-30}). Groundmass plagioclase microlites exhibit a smaller within-sample range, up to 20 An units, and are similar to the rims of coexisting megacrysts. Euhedral to subhedral pyroxene to 1 mm in size, making up 5%–15% of the rock, is the next most abundant phenocryst phase. Clinopyroxene (augite) and less commonly orthopyroxene (En_{64-70}) are present as phenocrysts and as groundmass phases. Amphibole-bearing porphyritic lavas, commonly also including pyroxene, are found in all Miocene–Pliocene volcanic complexes. Amphibole crystals are 1–5 mm in size and constitute 1%–10% of the rock. Compositionally, the amphiboles are calcic edenite or pargasite (Alcazar, 2004). With rare exceptions, the amphibole crystals have opaque reaction rims that may extend to the core of the grain, where the hornblende has broken down to an anhydrous assemblage of plagioclase, pyroxene, and magnetite (Fig. 4C). Biotite is present in most of the porphyritic lavas and is particularly abundant in lavas from Mount Watson (Lindgren, 1897). Biotites occur as subhedral phenocrysts (0.1–0.3 cm) and have K_2O contents between 8.5 and 9.3 wt%. Biotite grains can be deep red in thin section due to oxidation of iron oxide inclusions. Plagioclase dominates the fine-grained groundmass of the lavas, accompanied by Fe-Ti oxides, rare apatite, and high- SiO_2 glass (Alcazar, 2004).

Nonporphyritic lava flows rarely occur within the large volcanic complexes, such as at Mount Lincoln, Squaw Peak, and near Babbitt Peak, but they dominate isolated cinder cone and/or flow complexes such as Ladybug Peak. Many of the lavas have a pronounced trachytic texture formed by flow orientation of plagioclase laths in the matrix. In general, nonporphyritic lavas include as much as 15% euhedral to subhedral olivine phenocrysts <1 mm in size that range from Fo_{88} to Fo_{51} in composition (Fig. 4D). Olivines can vary by as much as 15 Fo units within an individual flow (Brownrigg, 2004). Clinopyroxene is the next most abundant phenocryst phase (5%–15%) and is augite in composition, clustering about an average composition of $\text{En}_{45}\text{Fs}_{12}\text{Wo}_{43}$. Orthopyroxene (En_{82-65}) is rarely found rimming clinopyroxene phenocrysts, but has not been identified as a phenocryst phase. Plagioclase is a rare phenocryst phase but is a major constituent of the groundmass, and ranges from An_{87} to An_{31} . Feldspar An contents can vary by as much as 30 An units within a single sample, and phenocryst and groundmass feldspars are commonly out of equilibrium (Brownrigg, 2004).

Several nonporphyritic suite lavas include a glass phase in the matrix that is interstitial to plagioclase microlites. The glasses are very SiO_2 , TiO_2 , and alkali rich compared to the

TABLE 1. $^{40}\text{Ar}/^{39}\text{Ar}$ AGES OF ANCESTRAL CASCADE VOLCANIC ROCKS, LAKE TAHOE AREA, CALIFORNIA AND NEVADA

Sample*	Rock type	Location	Latitude (°N)	Longitude (°W)	Material	Plateau age (Ma) [§]	^{39}Ar (%) [‡]	Steps	Isochron ages (Ma) [§]	$^{40}\text{Ar}/^{39}\text{Ar}$ ±2σ	MSWD	Total gas
01-LT-48	Basaltic andesite lava	Carson Range	39.4280	119.9610	matrix	3.17	0.02	73.5	2/9	0.01	288	2.98
Towle1	Basalt lava	Sawtooth Ridge	39.2000	120.6670	matrix	3.83	0.14	72.2	5/9	0.08	289	3.59
H00-161	Basaltic andesite lava	north of Boca Reservoir	39.4287	120.0855	matrix	4.41	0.03	44.3	6/11	0.09	288	3.2
H99-34	Basaltic andesite lava	Boca Hill	39.4100	120.1160	matrix	4.61	0.07	54.3	5/11	0.30	306.1	4.42
H99-20	Basaltic andesite vent	Boca Hill	39.3819	120.1206	matrix	NM		49.4		0.40	295	6.39
H00-113	Hornblende andesite plug	north of Donner Lake	39.3400	120.3048	hornblende	6.37	0.25	85.8	4/10	NC		6.00
H00-63	Basaltic dike	east of Donner Pass	39.3232	120.3127	matrix	8.5	0.4	65.5	5/9	6.8	302.6	6.39
07-LT-41	Basaltic andesite lava	Verdi basin, west of Reno	39.5214	119.9595	matrix	10.17	0.10	51.5	3/12	0.38	311	9.7
662	Basaltic andesite lava	Verdi basin, west of Reno	39.5367	119.9506	matrix	NM				0.12	309	11.33
07-LT-45	Basaltic andesite lava	Verdi basin, west of Reno	39.5266	119.9107	matrix	NM				0.14	323.5	11.40
H00-117	Basaltic andesite lava	central Carson Range	39.2373	119.8830	matrix	NM				0.87	293	14.41
H00-150	Pyroxene andesite lava	base of section, Babbitt Peak	39.5570	120.0862	plagioclase	15.86	0.11	51.4	5/11	0.40	325	14.25
Towle2	Basalt lava	Lowell Hill Ridge	39.2500	120.7917	matrix	NM				0.06	293.1	16.3
H00-154	Pyroxene andesite lava	central Carson Range	39.2087	119.8603	plagioclase	27.98	0.20	88.6	8/10	0.41	307	16.34
											7.1	28.46

Note: MSWD—mean square of weighted deviates.

*Samples in regular type were analyzed at the New Mexico Geochronological Research Laboratory (methodology in McIntosh et al., 2003); samples in italics were analyzed at the Nevada Isotope Geochronology Laboratory (Justet and Spell, 2001). Neutron flux monitor Fish Canyon Tuff sanidine (FC-1). Assigned age = 28.02 Ma (Renne et al., 1998).

[‡] ^{39}Ar = percentage of ^{39}Ar used to define plateau age.

[§]Ages in bold are best estimates of emplacement age. Sample H00-63 gave a disturbed spectrum for which either plateau or isochron ages are possible.

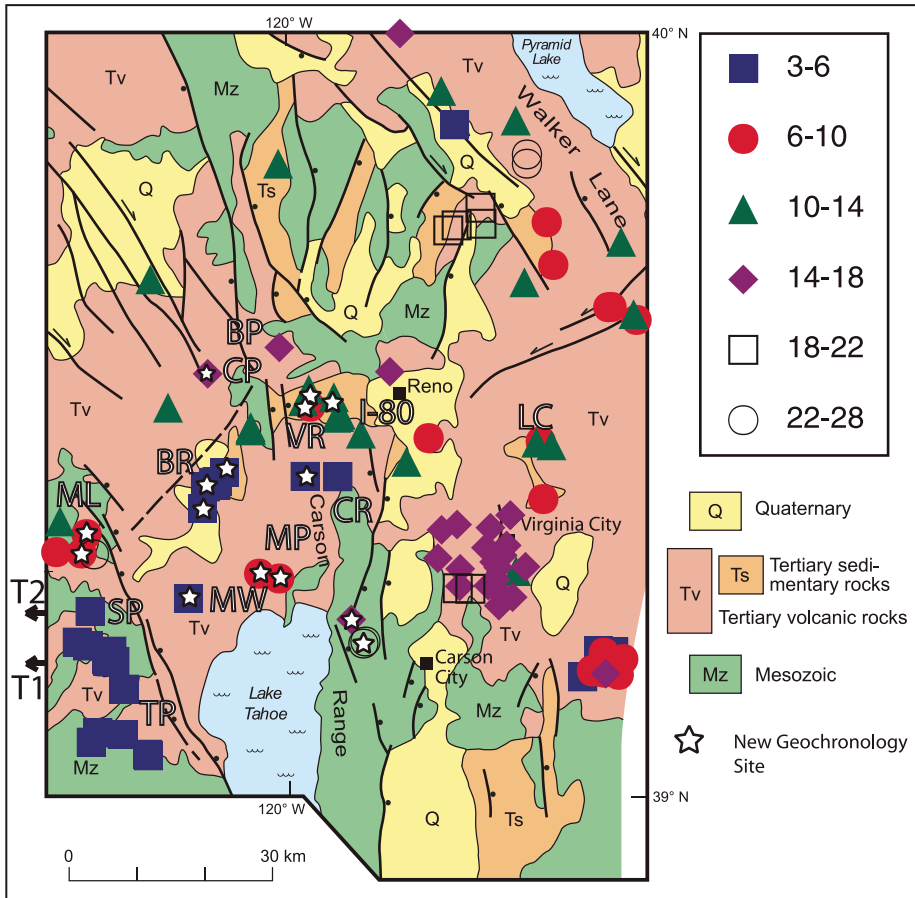


Figure 3. Compilation of K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ ages (in Ma) from volcanic rocks of the Tahoe-Reno region (Henry and Sloan, 2003; Sloan et al., 2003). New $^{40}\text{Ar}/^{39}\text{Ar}$ dating sites are indicated by stars (Table 1; W. Wise, 2003, personal commun.). Towle1 and Towle2 samples are located west of the map area. Localities are from Figure 1.

whole-rock compositions, ranging from dacite to high-silica rhyolite in composition. The glass pools appear to represent quenched interstitial liquid that records the final stage of solidification of flows at the surface. The glass pools commonly include a “bright” phase in backscattered images, which we have identified as apatite based on electron microprobe and scanning electron microscope analysis (Prytulak et al., 2001, 2002; Brownrigg, 2004).

Although the relative abundances and sizes of phenocryst phases differ between the porphyritic and nonporphyritic suites, the ranges of plagioclase and pyroxene compositions in the two suites overlap completely. Groundmass glass is common in the nonporphyritic lavas, but is only rarely found in porphyritic volcanic rocks.

GEOCHEMISTRY

For graphical purposes, the Tahoe-Reno region lavas have been grouped geographically into four porphyritic groups and five nonporphyritic groups, although each group likely includes lavas of slightly different age and, potentially, different petrogenesis. The distribution of these groups is listed in Table 3 and shown in Figure 1.

With only two exceptions, the lavas are subalkaline, and range in composition from basalt to dacite (Fig. 5A) (Le Bas et al., 1986). Porphyritic and nonporphyritic suite lavas are similar in composition to lavas from the modern south Cascade Range, although both suites are shifted to slightly more alkaline compositions relative to the modern Cascades. There is also some overlap between the nonporphyritic suite and the least alkaline lavas of the Western Great Basin. Lavas from individual large volcano complexes (e.g., Twin Peaks, Squaw Peak, Martis Peak) commonly span most of the compositional range (Fig. 5B). Although we do not have detailed stratigraphic coverage, there is no obvious tendency toward more evolved compositions with time (e.g., uppermost block-and-ash flow exposed at Mount Lincoln is less SiO_2 rich than underlying debris

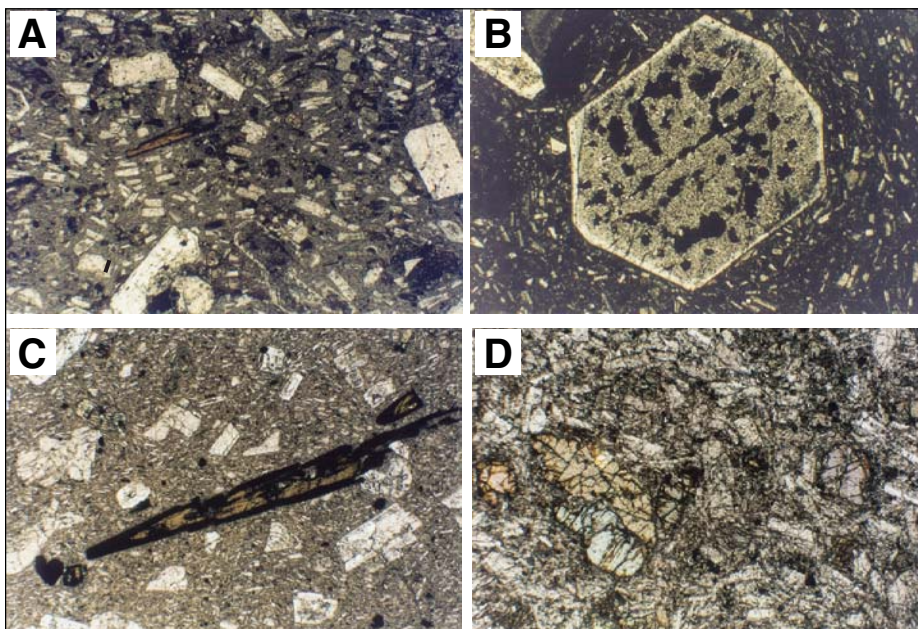


Figure 4. (A) Photomicrograph of hornblende-plagioclase andesite 01-LT-08 from Martis Peak. Note amphibole reaction rims and sieve texture in plagioclase megacrysts. (B) Sieve texture in plagioclase, sample 01-LT-34 from Crystal Peak area. (C) Reaction rim on amphibole crystal, sample 01-LT-37 from Mount Lincoln. (D) Holocrystalline basalt with olivine and pyroxene phenocrysts, sample 01-LT-31 from Crystal Peak area. Field of view is 5 mm across for all.

TABLE 2. REPRESENTATIVE MAJOR, TRACE ELEMENT, AND ISOTOPIC COMPOSITIONS

Sample Complex	01-LT-33 Babbitt Peak	01-LT-39 Mount Lincoln	01-LT-58 Lousetown	97-LT-82 Ladybug Peak	01-LT-04 Martis Peak	97-LT-53 Carnelian Bay	97-LT-87 Verdi Peak	01-LT-50 Carson Range	97-LT-47 Brockway
Type	b	b	b	b	ha	pa	bha	b	ha
SiO ₂	49.82	50.25	51.32	54.18	56.46	57.58	58.66	59.52	60.91
TiO ₂	0.73	0.74	0.81	0.93	0.71	0.82	0.67	0.94	0.69
Al ₂ O ₃	16.82	13.84	17.99	18.06	18.24	17.57	17.29	16.50	17.34
Fe ₂ O _{3t}	8.85	8.87	8.62	8.11	7.23	6.96	6.78	5.26	5.40
MnO	0.15	0.17	0.14	0.14	0.12	0.12	0.11	0.09	0.10
MgO	7.76	8.60	5.15	4.86	3.74	3.86	3.32	3.20	2.04
CaO	11.06	10.55	9.75	7.51	6.92	6.78	6.47	5.02	5.08
Na ₂ O	2.56	2.20	3.07	3.66	3.79	3.43	3.21	3.85	3.73
K ₂ O	0.94	1.28	1.00	1.39	1.39	2.03	2.28	2.80	2.91
P ₂ O ₅	0.20	0.23	0.18	0.32	0.23	0.27	0.19	0.40	0.27
LOI	0.60	2.40	1.20	0.70	0.90	0.50	0.90	1.10	1.00
V	249	228	242	190	172	177	171	103	123
Cr	253	397	101	102	26	28	54	72	21
Ni	80	47	26	44	20	12	17	51	10
Rb	9.3	17.2	7	22	28	49	61	64	81
Sr	710.8	965.8	721	913	712	746	611	748	655
Y	15	17.5	17	20	18	20	21	22	24
Zr	64	96.6	67	125	105	159	148	264	216
Ba	442	738	496	1355	788	1089	948	1669	1549
La	16.01	25.73	14.49	25.14	11.63	26.94	20.78	41.67	40.15
Nd	17.49	27.41	16.51	25.50	12.57	26.48	20.75	36.05	32.84
Yb	1.52	1.58	1.59	1.76	1.21	1.65	1.84	1.58	1.87
Nb	2.87	3.74	2.72	4.72	4.66	6.97	5.55	19.05	9.49
Cs	0.68	0.60	0.23	0.88	1.13	1.86	1.92	1.41	2.34
Hf	1.81	2.70	1.90	3.22	2.82	4.10	4.16	6.08	5.69
Th	4.68	5.26	3.39	5.25	2.58	6.06	7.43	6.19	10.51
Pb	8.93	7.25	7.37	9.54	7.20			12.18	
⁸⁷ Sr/ ⁸⁶ Sr	0.704288	0.703670	0.704134	0.704638	0.705388	0.705531	0.704860	0.705382	0.705505
¹⁴³ Nd/ ¹⁴⁴ Nd	0.512806	0.512805	0.512791	0.512760	0.512615	0.512553	0.512655	0.512619	0.512575
²⁰⁶ Pb/ ²⁰⁴ Pb	18.896	18.917	18.914	18.932	19.027	19.026	19.028	19.058	19.029
δ ¹⁸ O	+6.32			+7.08		+7.21		+8.01	+7.56

Note: Major elements by fused-disk X-ray fluorescence (XRF), in weight percent oxides. V through Ba by fused disk XRF (in weight parts per million). La through Th by solution-mode inductively coupled plasma-mass spectrometry (ICP-MS) (in weight parts per million). Pb by isotope dilution mass spectrometry, in weight parts per million. B—basalt; ha—hornblende andesite; pa—pyroxene andesite; bha—biotite hornblende andesite. See text for analytical details.

flow fragments). Note that lavas in the porphyritic and nonporphyritic suites overlap in this plot, although the nonporphyritic suite as a group plots closer to the subalkaline-alkaline boundary. In particular, lavas from the Carson Range plot close to this boundary, consistent with their young, Pliocene–Pleistocene ages (see Post-Arc field, Fig. 5A). In a plot of K₂O versus SiO₂, the Miocene–Pliocene lavas are all medium- to high-K calc-alkaline

in composition (not shown). All lavas follow a calc-alkaline fractionation trend in an AFM (alkalis-FeO-MgO) diagram, and again the porphyritic and nonporphyritic suites overlap in composition. Miocene volcanic rocks in the central Sierra Nevada also have these major element geochemical characteristics (Busby et al., 2008a).

Major element oxide abundances vary regularly with increasing SiO₂ (Fig. 6). TiO₂ con-

tents are rarely >1%, increasing slightly from 48% to 55% SiO₂ then decreasing monotonically with increasing SiO₂. Similarly, MgO, FeO^t, and CaO form tight, negatively correlated arrays with SiO₂, whereas K₂O and to a lesser extent Na₂O are positively correlated with SiO₂. CaO and FeO^t abundances in nonporphyritic suites are slightly lower, and TiO₂ and K₂O contents are slightly higher, than in porphyritic suite rocks. Al₂O₃ appears to behave

TABLE 3. GEOGRAPHIC LOCALITIES IN PETROGRAPHIC GROUPS

Group	Age range (Ma)	Porphyritic	Nonporphyritic
North Tahoe	ca. 3.5–6	Northwest shore Lake Tahoe; along Hwy. 89; Martis Peak; Mount Watson; Alder Hill; Tahoe City	
Carson, Verdi	< 2–12	Carson Range; Verdi Range	Boca and Stampede Reservoir; Carson Range
Squaw, Twin, Lincoln	3.5–16	Twin Peaks; Stanford Peak; Squaw Peak; Mount Lincoln	Squaw Peak; Mount Lincoln; Lowell Ridge; Sawtooth Ridge
Crystal Peak, Babbitt	> 10	Jones Peak, Crystal Peak; Babbitt Peak; Sardine Peak	Babbitt Peak
I-80 Suite	ca. 10		Ladybug Peak; Stampede Reservoir; isolated outcrops between Verdi and Reno
Lousetown	6.5–9.5		Lousetown flows; Clark Mountain

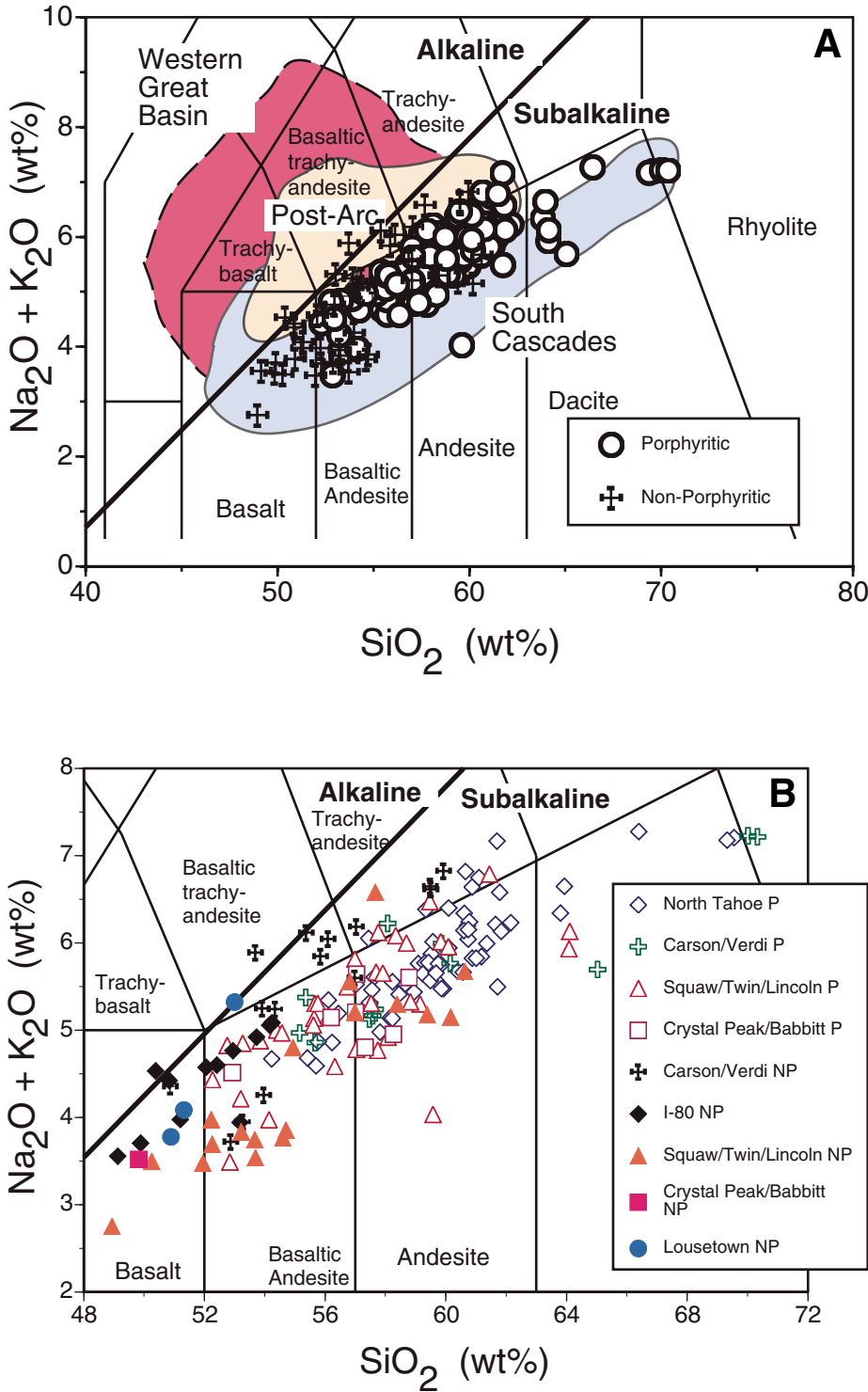


Figure 5. (A). Alkalies-silica diagram (Le Bas et al., 1986) comparing Western Great Basin (red field), modern south Cascade arc (blue field), post-3 Ma (post-Arc, orange field; B. Cousens, 2007, personal observ.) lavas from the Lake Tahoe region, and Miocene–Pliocene lavas from the Tahoe-Reno region split into porphyritic and nonporphyritic groups. Data for Western Great Basin and modern south Cascade arc are from the GEOROC (2007) database. (B) Tahoe-Reno region lavas only, split by region (see Table 3). Open symbols are porphyritic suite (P), filled symbols are nonporphyritic suite (NP).

differently in volcanic rocks with $<55\%$ SiO_2 or $>55\%$ SiO_2 , being positively and negatively correlated, respectively. Al_2O_3 is especially low in the Lousetown flows. P_2O_5 is highly enriched in Carson Range lavas and in some hornblende-bearing porphyritic andesites compared to other nonporphyritic and porphyritic suite lavas. With the exception of basalts with $<15\%$ Al_2O_3 , $\text{CaO}/\text{Al}_2\text{O}_3$ ratios decrease in an almost linear fashion with increasing SiO_2 , a trend that is mimicked by $\text{P}_2\text{O}_5/\text{K}_2\text{O}$. The variation of major element oxides in the study area is similar to that of the modern south Cascade Range, with the exception that modern Cascade lavas are commonly richer in TiO_2 and poorer in K_2O .

Compatible trace elements such as V, Ni, Cr, and Sc (not shown) all decrease with increasing SiO_2 (Fig. 7), consistent with their incorporation into Fe-Ti oxides, olivine, chrome spinel, and clinopyroxene, respectively. None of the lavas has Ni > 400 ppm, a lower limit for melts in equilibrium with mantle lherzolite. In general, less evolved lavas of the nonporphyritic suite overlap the porphyritic suite rocks, although more evolved nonporphyritic lavas of the Carson Range are slightly richer in Ni and Cr than porphyritic suite lavas.

Incompatible element abundances vary by as much as a factor of 10 in the Miocene–Pliocene lavas (Fig. 7). Some elements, such as Sr, show no correlation with SiO_2 . The light rare earth elements (REE) (e.g., La) and Th show good correlations with SiO_2 in some groups (e.g., Carson Range nonporphyritic rocks), but significant scatter in others; La concentrations vary by a factor of three at any SiO_2 content. Ba, Zr, and Pb are positively correlated with SiO_2 , although nonporphyritic Carson Range lavas have slightly higher abundances of most incompatible elements compared to porphyritic rocks with comparable SiO_2 contents (a characteristic of post-arc volcanism; Cousens et al., 2000). Compared to the modern south Cascades, Sr and Zr contents are commonly higher in the Miocene–Pliocene lavas, and La in modern Cascade rocks exhibits the same factor of three (or greater) variability at any given SiO_2 content.

The apparent scatter in incompatible element abundances versus SiO_2 is reduced considerably if plotted versus Zr concentration (Fig. 8). Both compatible and incompatible (except Sr) elements vary as a function of Zr content in both porphyritic and nonporphyritic lavas. Lavas from the modern south Cascade arc are highly depleted in the large ion lithophile elements (LILE) (e.g., Ba), slightly depleted in the light (L) REE (e.g., La), and commonly slightly enriched in Nb when plotted versus Zr content, compared to the Miocene–Pliocene rocks of this study.

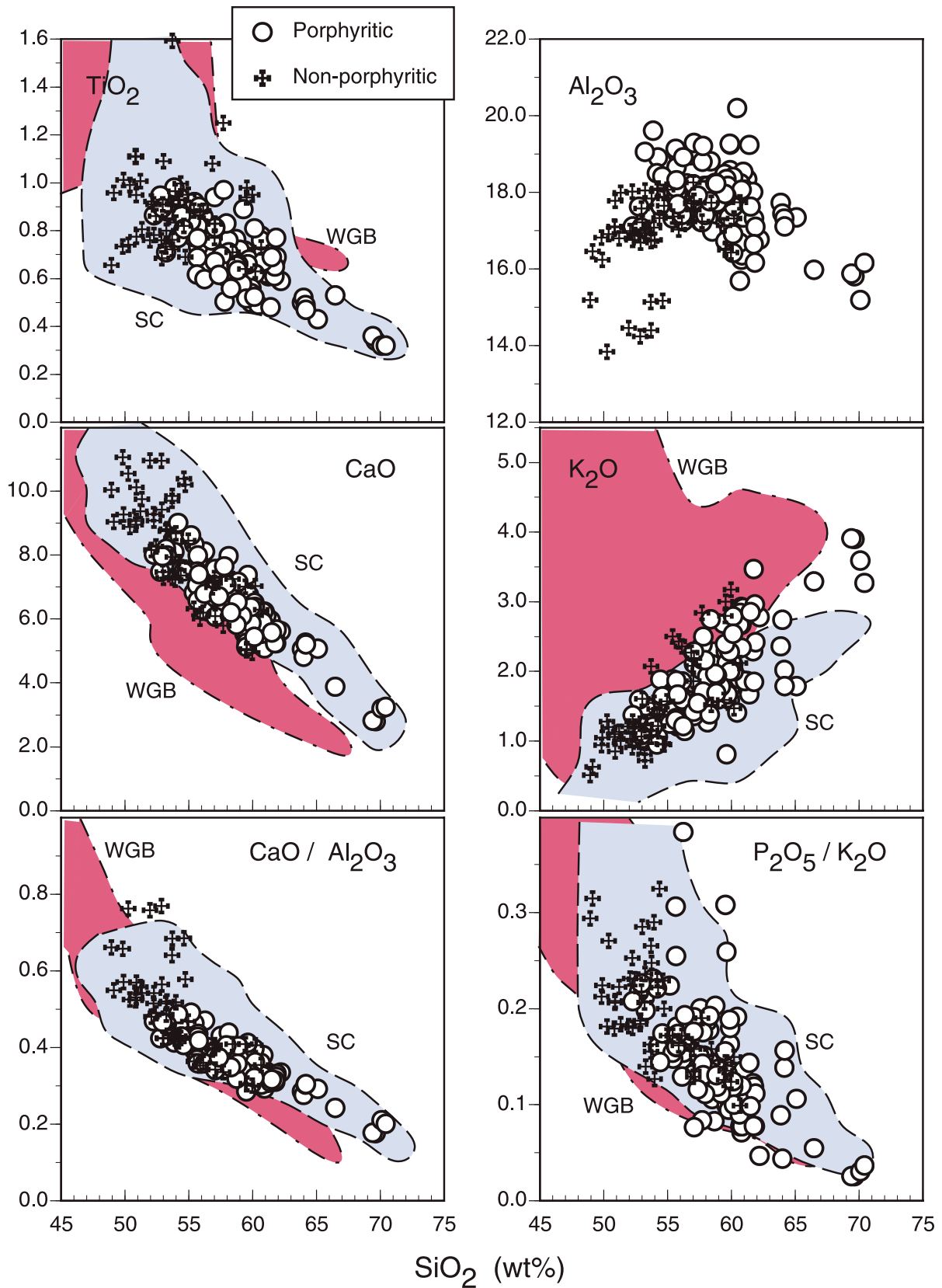


Figure 6. Major element Harker plots for Ancestral Cascade arc lavas, split into porphyritic (P) and nonporphyritic (NP) groups. Blue field encloses modern south Cascades (SC), red field encloses Western Great Basin (WGB) (data from GEOROC, 2007).

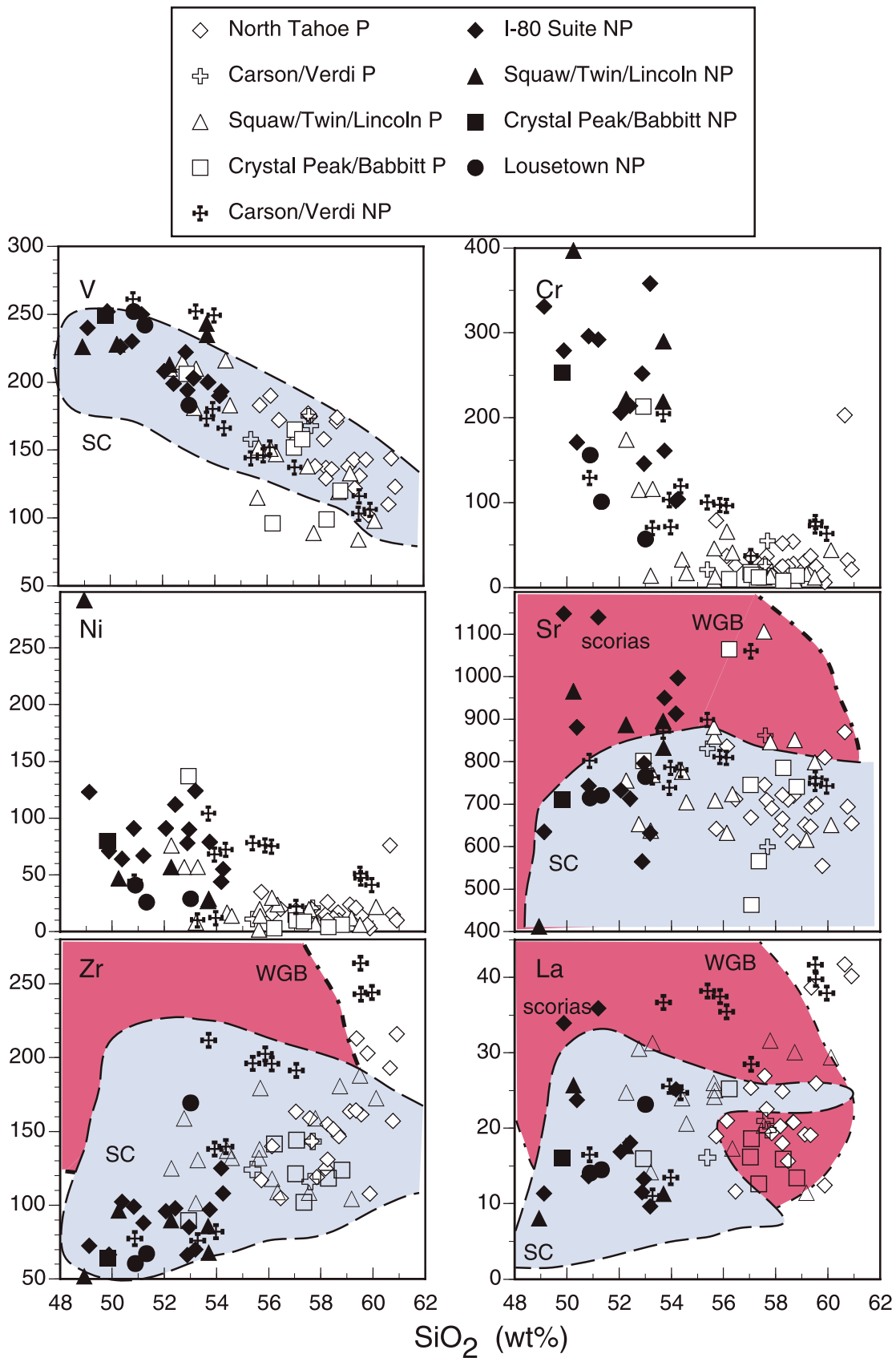


Figure 7. Harker plots for trace elements in Tahoe-Reno region lavas, split by region and into porphyritic (P) and nonporphyritic (NP) groups. Blue field encloses modern south Cascades (SC), red field encloses Western Great Basin (WGB) (data from GEOROC, 2007). Note that WGB lavas extend off scale to very high Sr, Zr, and La at low SiO₂, whereas SC lavas extend below scale to Sr concentrations <400 ppm.

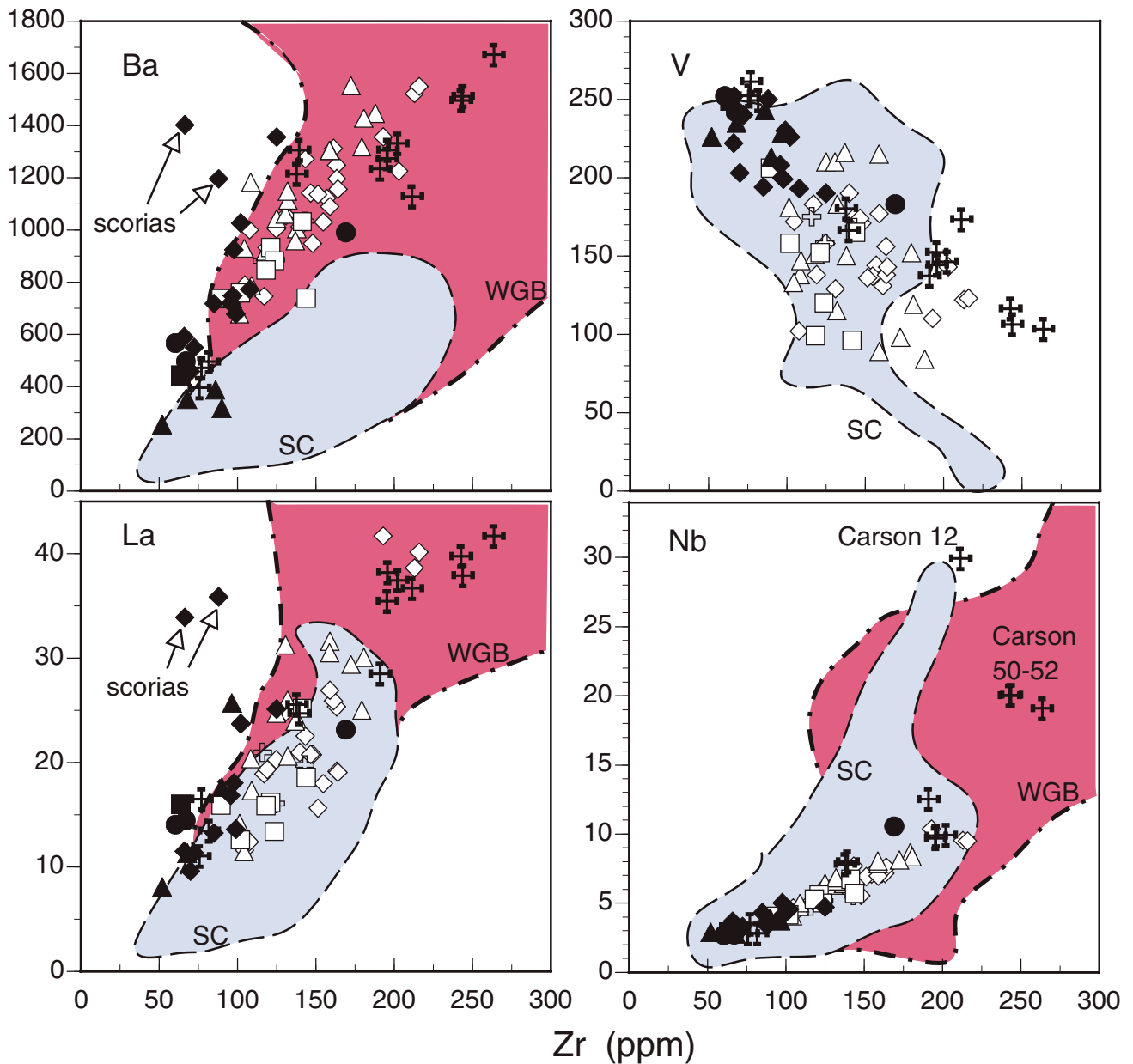


Figure 8. Variation in incompatible element concentrations with Zr concentration. Tahoe-Reno region lavas are split by region and into porphyritic and nonporphyritic groups (symbols as in Fig. 7). Blue field encloses modern south Cascades (SC), red field encloses Western Great Basin (WGB) (GEOROC, 2007). Note that three Carson Range lavas have anomalously high Nb contents that are more typical of post-arc lavas of the region. Scoria blobs from the Ladybug Peak phreatic cone are indicated by arrows.

An unusual feature of Ladybug Peak samples is that in terms of incompatible element abundances, fresh scoria fragments (scorias, Figs. 7 and 8) from the phreatic cone are different from the lavas that flowed downslope from the cone.

Primitive mantle normalized (Sun and McDonough, 1989) incompatible element patterns for a selection of basalts, basaltic andesites, and andesites are shown in Figure 9. All of

the volcanic rocks are LREE enriched and are characterized by positive spikes in Ba, Pb, and Sr, whereas Nb and Ta are deficient compared to Th and La. A notable feature of the patterns is the clear positive Zr and Hf spike in andesitic porphyritic and nonporphyritic lavas that is not observed in basaltic lavas and only rarely seen in basaltic andesites. La/Sm_{pmn} (primitive mantle normalized) values are 2–3 in basalts, 2–4 in basaltic andesites, and 3–6 in andesites, show-

ing that the lavas become more LREE enriched with increasing magma evolution. However, Sm/Yb_{pmn} are constant, ranging between 2 and 4, over the entire SiO_2 spectrum.

Sr and Nd isotope ratios are highly variable in the Miocene–Pliocene lavas (Fig. 10A): $^{87}Sr/^{86}Sr$ ranges from 0.7037 to 0.7062, whereas $^{143}Nd/^{144}Nd$ varies from 0.5128 to 0.5124. There is overlap between porphyritic and nonporphyritic lavas, although the high $^{87}Sr/^{86}Sr$ lavas are

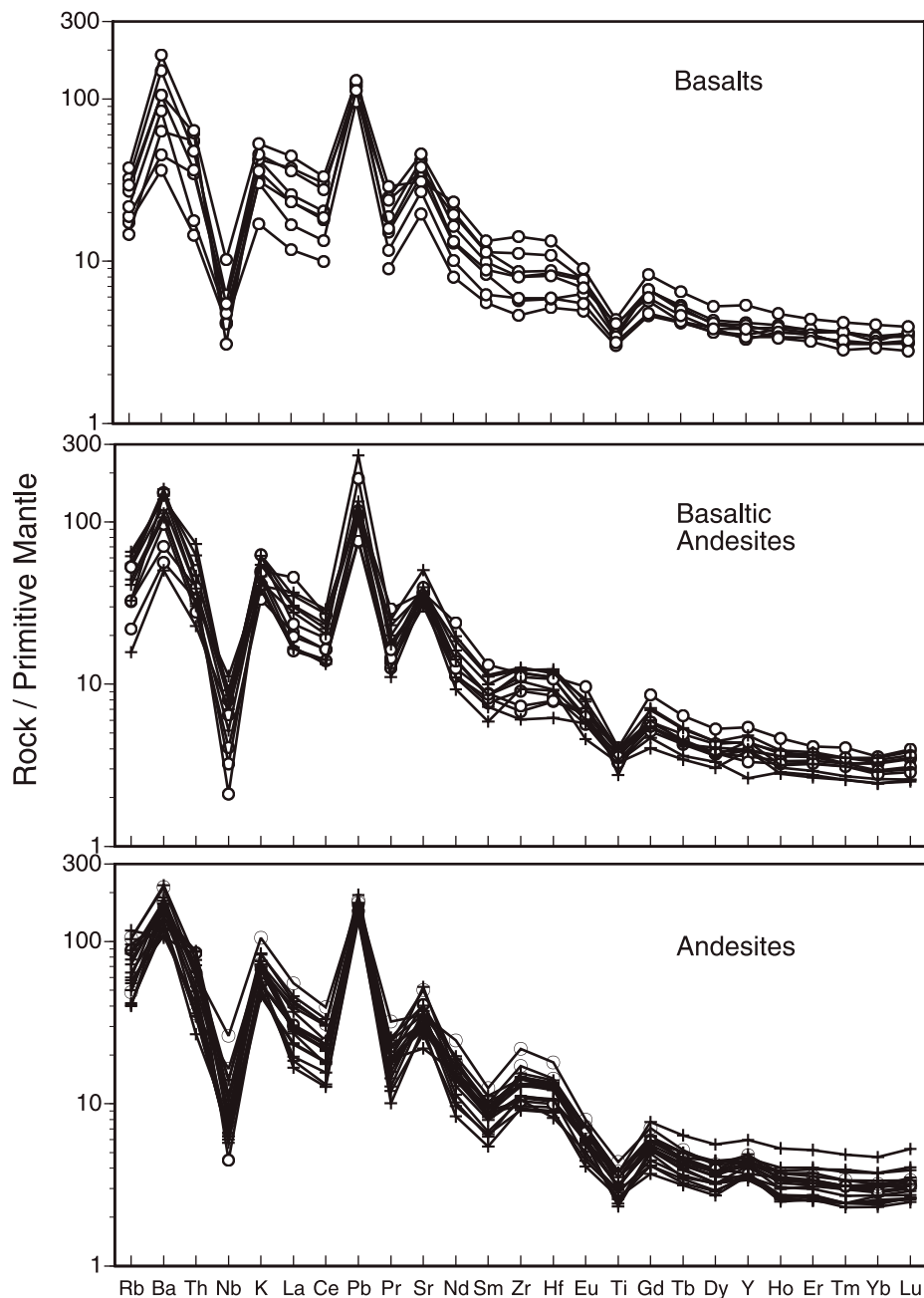


Figure 9. Primitive mantle normalized (Sun and McDonough, 1989) incompatible element patterns for Tahoe-Reno region basalts, basaltic andesites, and andesites.

primarily porphyritic. Porphyritic and nonporphyritic lavas from single edifices, such as Squaw Peak or Mount Lincoln, cover much of the range of isotopic compositions (e.g., Mount Lincoln $^{87}\text{Sr}/^{86}\text{Sr} = 0.70367\text{--}0.70534$). Two analyses of a nonporphyritic basalt unit from Squaw Peak have somewhat low $^{143}\text{Nd}/^{144}\text{Nd}$ given their $^{87}\text{Sr}/^{86}\text{Sr}$ of ~ 0.7039 . The 16.3 Ma nonporphyritic lava from Lowell Ridge (sample Towle2) also plots to the left of the array formed by the majority of the Miocene–Pliocene

lavas. Otherwise, the relationship between the two isotopes is roughly linear. Similarly, Pb isotope ratios correlate linearly (Figs. 10B, 10C): $^{206}\text{Pb}/^{204}\text{Pb}$ varies from 18.85 to 19.12, $^{207}\text{Pb}/^{204}\text{Pb}$ from 15.58 to 15.74, and $^{208}\text{Pb}/^{204}\text{Pb}$ from 38.32 to 39.02. As is the case with Sr and Nd isotopes, the lavas form a linear array and porphyritic and nonporphyritic lavas overlap almost completely.

In five Miocene–Pliocene samples analyzed for whole-rock $\delta^{18}\text{O}$, values range from +6.32

to +8.01. Sample 01-LT-33, a basalt from the Babbitt Peak area, has the lowest $\delta^{18}\text{O}$ of +6.32, a value only slightly above the average mantle value of +5.7 (Eiler, 2001). The $\delta^{18}\text{O}$ correlates positively with SiO_2 and $^{87}\text{Sr}/^{86}\text{Sr}$ (Fig. 11). Although $\delta^{18}\text{O}$ increases in residual liquids as a result of fractional crystallization, the size of the increase from basalt to andesite and the correlation with $^{87}\text{Sr}/^{86}\text{Sr}$ suggests that processes other than simple fractional crystallization are responsible for the variation in $\delta^{18}\text{O}$.

DISCUSSION

Porphyritic versus Nonporphyritic Lavas and Magma Evolution

In the field, the contrast in mineralogy and texture between porphyritic and nonporphyritic lavas is an outstanding characteristic of Miocene–Pliocene volcanism in the northern Sierra Nevada. Whereas porphyritic volcanic rocks dominate the large volcanic complexes, nonporphyritic rocks are rarely found within the large volcano complexes, but are the sole lava type at isolated pyroclastic cone and/or lava vents. Unfortunately, the extent of glacial erosion of the large volcano complexes has obscured the geographic relationship between the interstratified nonporphyritic and porphyritic lavas. Were the nonporphyritic lavas erupted from satellite vents or from summit vents? This distinction has implications for the magmatic plumbing system beneath the large volcanic edifices that we cannot address with this data set.

Compositionally, there are few distinctions between porphyritic and nonporphyritic lava groups. The nonporphyritic lavas tend to be less evolved in composition, but the Carson Range lavas in particular show that nonporphyritic lavas can range up to andesite in composition. The apparent crystallization histories from Figures 5 and 6 indicate only subtle differences between the two groups. Normalized incompatible element patterns are indistinguishable in shape, and variations in trace element contents follow the same trends in both groups (Figs. 7 and 8). The porphyritic and nonporphyritic groups overlap isotopically, especially in Pb isotopic composition (Fig. 10). We conclude that the two groups were derived from generally similar parental magmas, thus inheriting overlapping trace element and isotopic characteristics.

We propose that the mineralogical and textural differences between the porphyritic and nonporphyritic lavas are due almost entirely to differences in upper crustal residence history. Porphyritic lavas are dominated by large crystals of plagioclase, amphibole, and clinopyroxene, set in a fine-grained groundmass.

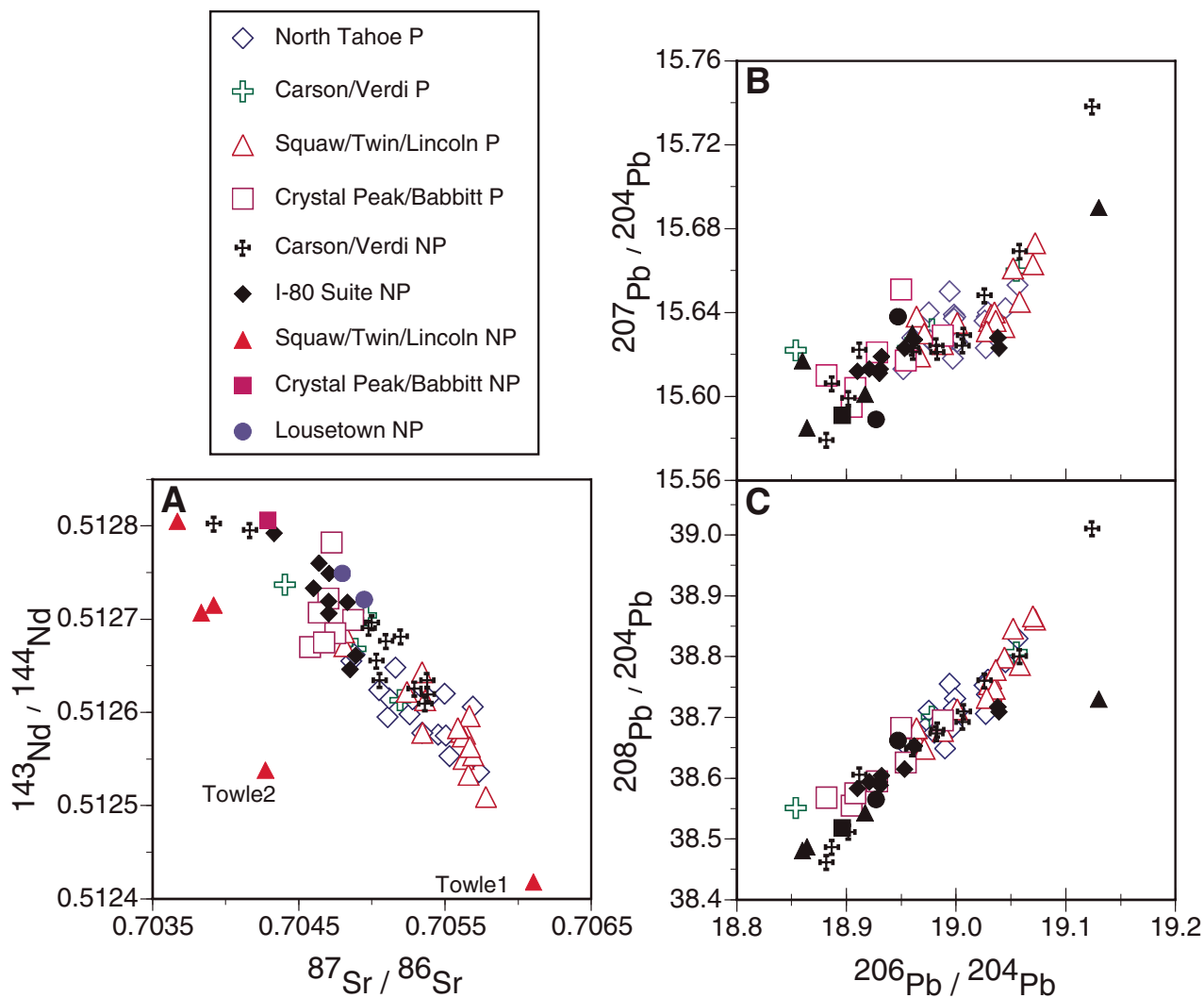


Figure 10. Sr, Nd, and Pb isotope ratios in Tahoe-Reno region lavas, split by geographic region and into porphyritic (P) and nonporphyritic (NP) groups.

Amphibole crystals show clear evidence of disequilibrium that results either from preeruption volatile loss in a shallow magma reservoir beneath a volcano (e.g., Rutherford et al., 1998; McCanta and Rutherford, 1999) or slow ascent through the crust and across the amphibole stability field. Plagioclase crystals are commonly sieve textured and/or reversely zoned, indicating that they spent some period of time within a magma reservoir that was periodically recharged from below. Their complex history indicates that they should not be considered to be true phenocrysts, and their contribution to the whole-rock chemistry of the lavas needs to be evaluated further. Initial plagioclase crystallization and the destabilization of amphibole may both have been triggered by degassing of the magma reservoir at shallow depth that may also have added clinopyroxene to the list of crystallizing phases. The fine-grained ground-

mass, rarely including a glass phase, shows that the flows cooled rapidly after extrusion on the surface.

In contrast, nonporphyritic lavas include primarily olivine and clinopyroxene phenocrysts, with plagioclase usually relegated to the groundmass. This mineral assemblage is more consistent with partial crystallization at depth, perhaps within the lower crust, where olivine and clinopyroxene are liquidus phases but plagioclase is not (e.g., Bender et al., 1978). The presence of H_2O also suppresses plagioclase crystallization (Michael and Chase, 1987). The nonporphyritic magmas must have risen relatively quickly through the lithosphere to the surface, bypassing shallow magma reservoirs beneath composite volcanoes, and erupted somewhat explosively at the surface to produce pyroclastic and phreatic cones followed by extrusion of lava flows.

An important characteristic of the Miocene–Pliocene volcanic rocks is the positive correlation of many incompatible trace element and isotopic ratios with increasing SiO_2 . These include La/Sm, Ba/La, Zr/Sm, total alkali contents, $\text{CaO}/\text{Al}_2\text{O}_3$, $\text{K}_2\text{O}/\text{Na}_2\text{O}$, and to a lesser extent $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$. In addition, incompatible element abundances increase dramatically with increasing SiO_2 , including Ba, Nb, Zr, La, and Pb. Although major element differences between Miocene–Pliocene basalts and andesites can be modeled by fractional crystallization of amphibole, pyroxene, and plagioclase, the observed increases in incompatible elements, their ratios, and isotopic compositions are generally indicative of increasing crustal contamination as magmas evolve from basalt to dacite in composition. Even stronger is the correlation between all of the geochemical indices listed above with Zr concentration or Zr/Sm,

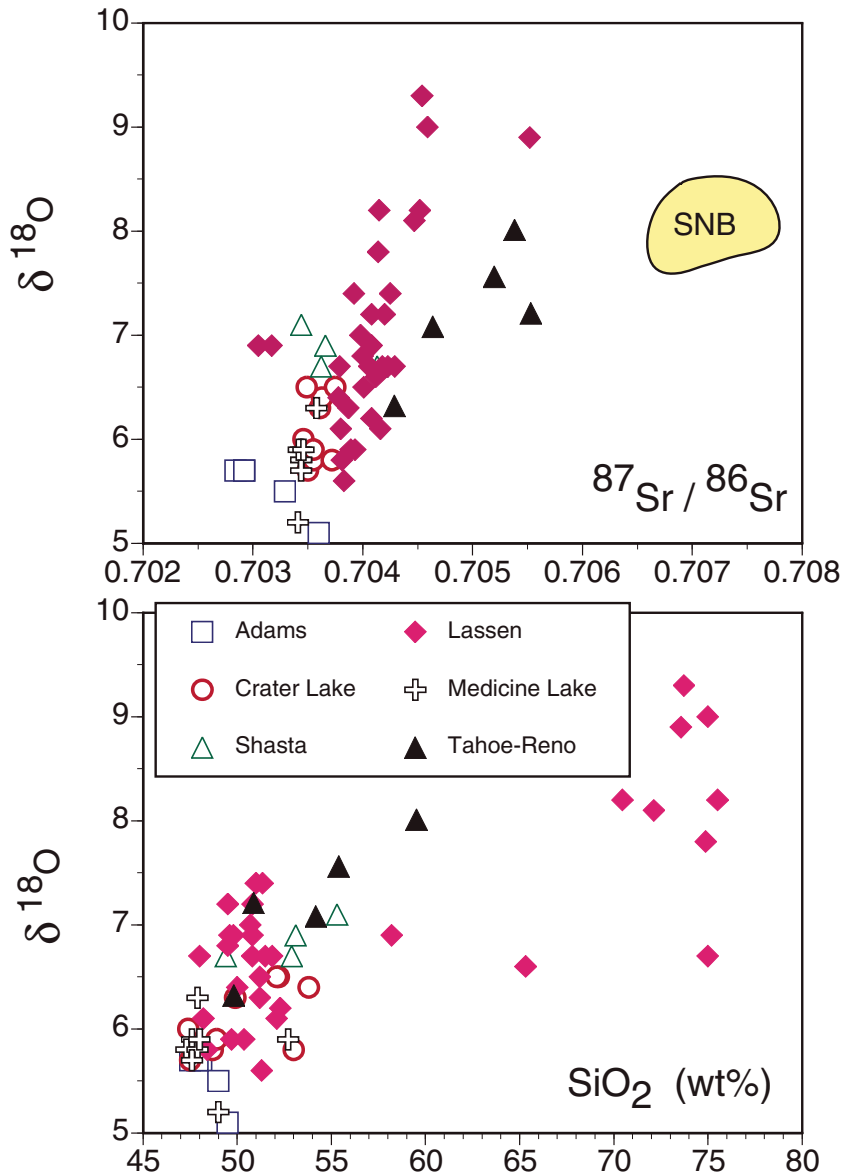


Figure 11. $\delta^{18}\text{O}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ and SiO_2 content for Tahoe-Reno region lavas, modern south Cascade volcanoes (Bacon et al., 1997; Borg et al., 1997; Borg and Clynne, 1998), and Tuolumne Intrusive Suite granitoids (SNB field; Kistler et al., 1986).

which appears as a positive Zr (and Hf) anomaly in primitive mantle normalized incompatible element patterns (Figs. 8 and 9).

The creation of a positive Zr anomaly as a result of assimilation of Sierra Nevada granitoids is possible, given that our analyses of local Sierran granitoids show that they are slightly enriched in Zr relative to Sm in primitive mantle normalized plots. However, Zr is usually sequestered in zircon that is a residual phase during melting, and thus assimilation by partial melting of granitoid should not necessarily produce a significant positive Zr anomaly. An alternative

possibility is that heating of a more mafic component of the middle to lower crust will generate a low-degree felsic melt of adakitic composition (e.g., Rapp et al., 1999; Petford and Gallagher, 2001). Experimental work has shown that these melts can be enriched in Zr relative to Sm, in addition to the well-documented enrichment of Sr over Y (Rapp et al., 1999). Addition of these felsic melts to an evolving mafic magma will produce enrichment in the LREEs, Ba, and Zr relative to Sm (Fig. 12). A mixture of 30% basalt with 70% adakitic melt will yield the major element characteristics of an evolved

andesite, although concurrent fractional crystallization is required (and expected) in order to boost incompatible element abundances to the levels seen in the Miocene–Pliocene andesites. Mixing of basalt with dacitic liquid of adakite-like composition to produce andesite has been demonstrated at Mount Shasta (Streck et al., 2007), showing that the above-described mixing origin for modern south Cascade andesites is also important in the Miocene–Pliocene volcanic rocks of this study.

Comparison with Modern South Cascade Arc Volcanism

Reconstruction of the position of the Mendocino triple junction and southern edge of the Juan de Fuca slab through time (Atwater and Stock, 1998) indicates that a continental volcanic arc should have been present along the northern Sierra Nevada in the Miocene and Pliocene. This volcanic activity was part of what Dickinson (1997, 2006) referred to as the Ancestral Cascades arc that extended from British Columbia south to the California–Nevada–Arizona state boundary intersection at 15 Ma. Modeling of the movement of the trailing edge of the Juan de Fuca plate relative to North America shows that it has moved progressively northward over the past 20 m.y., leaving a slab window in its wake (Atwater and Stock, 1998). The south edge of the subducting Juan de Fuca slab reached the latitude of Lake Tahoe ca. 6 Ma and is now stalled just north of the lake at $\sim\text{lat } 39.5^\circ\text{N}$ (Benz et al., 1992; Atwater and Stock, 1998; Biasi, 2006). The slab edge is well south of the Lassen volcanic field, the generally accepted southern end of the active Cascades arc (Clynne, 1990), perhaps as a result of the highly fragmented Gorda plate being dragged southward into the slab window (Benz et al., 1992). As we show in the following sections, Miocene–Pliocene volcanism in the Tahoe-Reno region closely resembles modern south Cascade volcanism in terms of geology and petrology, and we conclude that Tertiary magmatism in the northern Sierra Nevada is indeed part of the Ancestral Cascades arc.

Due to the northward migration of the Juan de Fuca plate edge, Miocene–Pliocene subduction-related volcanism should have ceased progressively northward in eastern California and western Nevada if the dominant process responsible for volcanic activity is the loss of fluids from the subducted slab. However, compilations of volcanic rock ages in the region of the proposed Ancestral Cascades arc south of Lassen Peak show a complex scatter of activity that provides little or no evidence for such a pattern (Henry and Sloan, 2003; Glazner et al., 2005). The

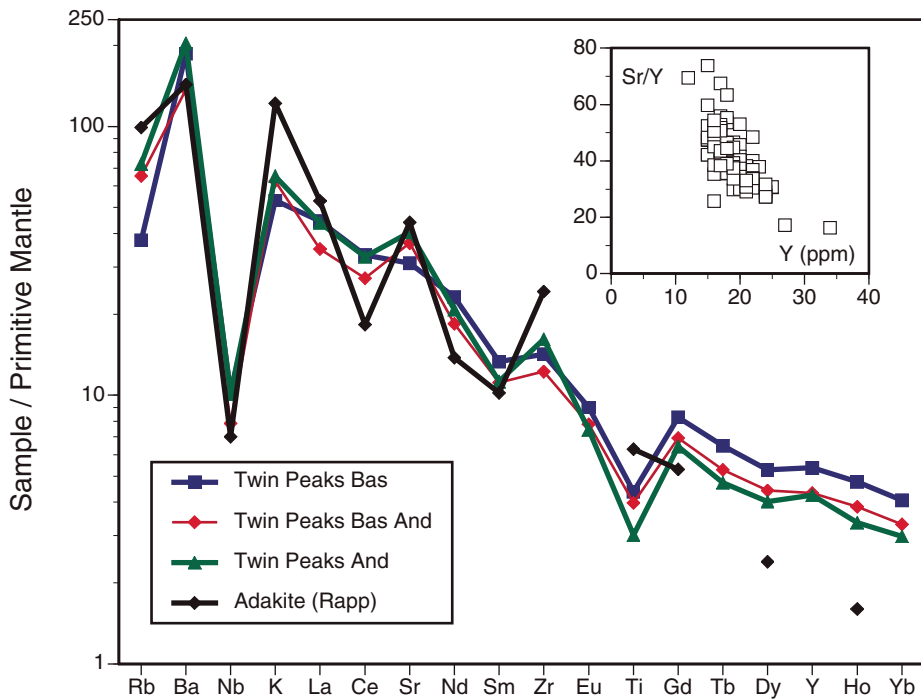


Figure 12. Normalized incompatible element plot showing evolution from basalt (Bas), basaltic andesite (Bas And) to andesite (And) at Twin Peaks. Note decrease in heavy rare earth elements (REE) and Y and increase in light REE and Sr that are consistent with addition of adakite-like felsic melt (solid diamonds) (Rapp and Watson, 1995) into basalt to produce andesite. Inset: Sr/Y versus Y concentration in Tahoe-Reno region lavas. Note dramatic increase in Sr/Y with decreasing Y content, an adakite signature (e.g., Petford and Gallagher, 2001).

High-Alumina Olivine Tholeiites

There are significant geochemical differences between Miocene–Pliocene Tahoe-Reno region lavas and volcanic rocks of the modern south Cascades. First, high-alumina olivine tholeiite (HAOT) or low-K tholeiite (LKT) are common mafic rocks in the modern Cascades, and the western United States in general, that are thought to represent near-primary melts of a relatively dry subarc to backarc mantle or unmetasomatized lithospheric mantle (Guffanti et al., 1990; Hughes, 1990; Baker et al., 1994; Bacon et al., 1997; Conrey et al., 1997; Hart et al., 1997; Lee-man et al., 2005). These lavas are characterized by high Al₂O₃, MgO, Ni, and Cr contents, near-flat REE patterns, and slight LILE element enrichment (Fig. 13). No HAOTs or LKTs have been found in any volcanic sequences in the Tahoe-Reno region. Calc-alkaline basaltic rocks from south Cascade volcanoes have normalized REE patterns similar to those of Tahoe-Reno region basalts, but in general south Cascade basalts have lower LREE and LILE abundances (Fig. 13).

At least three possibilities exist to explain the lack of HAOT in the Tahoe-Reno part of the Ancestral Cascades arc. First, primitive Miocene–Pliocene magmas did not have HAOT compositions. If so, melting of relatively dry mantle peridotite appears to have been an exceedingly rare occurrence beneath the Sierra Nevada during the Miocene–Pliocene, and the source of basalts in the mantle always had H₂O contents >3% (based on modeling of Baker et al., 1994). Second, no primary Miocene–Pliocene magmas of HAOT composition made it to the surface without undergoing significant modification by interaction with the continental lithosphere. An evaluation of the geochemistry of HAOT across the northwestern Great Basin, from the Medicine Lake Highlands east of Mount Shasta to the Snake River Plain, shows that small degrees of interaction between asthenospheric melts and the lithospheric mantle strongly influences radiogenic isotopic compositions, although its influence on incompatible element abundances and δ¹⁸O is more subtle (Hart, 1985; Hart et al., 1997). No HAOTs in the western USA show the LREE enrichment and curvature of REE patterns exhibited by Tahoe-Reno region basalts. Third, HAOT was a primary magma type but was never erupted. This possibility is supported by the model of Putirka and Busby (2007), who proposed that dry magmas, including HAOT, cannot be erupted through thick Sierra Nevada crust (relative to the Lassen area) due to a lack of sufficient magma buoyancy. They suggested that magmas require a minimum of 0.4%–1.3% H₂O in order to be buoyant enough to reach the surface of the northern and central Sierra.

lack of a clear pattern of northward arc shut-down probably reflects at least four factors: (1) lack of detailed study of much of the region; (2) the complex reestablishment of Tertiary magmatism that migrated westward from the Great Basin, resulting from delamination of the shallow Laramide slab; (3) overlap of arc volcanism with Walker Lane and/or Basin and Range deformation; and (4) potential derivation of magmas from non-subduction processes. Subduction-related volcanism in the Tahoe-Reno area overlapped with crustal deformation in the Walker Lane along the east side of the Sierra Nevada (e.g., Henry and Perkins, 2001; John, 2001; Faulds and Henry, 2002, 2005; Faulds et al., 2005; Henry and Faulds, 2006; Busby et al., 2008b). In this case, lithospheric-scale faults of the Walker Lane and Basin and Range probably provided conduits for mantle-derived magmas to ascend to the surface after subduction had ceased. In addition, a major pulse of non-subduction magmatism that occurred in the southern Sierra Nevada between 3 and 4 Ma is probably related to delamination of a dense eclogitic root to the batholith (Manley

et al., 2000). A major magmatic pulse related to initiation of the Yellowstone hotspot began ca. 16 Ma in northwestern Nevada (Pierce and Morgan, 1992), east of the ancestral arc belt.

Field and Petrographic Characteristics

There are both similarities and differences between volcanoes of the modern south Cascades (Lassen, Shasta) and the Ancestral Cascade lavas of the Tahoe-Reno region. In the field, both the modern south Cascades and the Tahoe-Reno region include volcanic complexes composed of both volcanoclastic rocks (and debris flow and/or lahar deposits) and lava flows, as well as satellite mafic cones that are commonly basalt to basaltic andesite in composition (Christiansen, 1982; Christiansen et al., 2002a; Strong and Wolff, 2003). South Cascade andesites are commonly plagioclase-clinopyroxene-hornblende porphyritic, much like lavas of the Tahoe-Reno region. However, Tahoe-Reno volcanoes lack felsic pyroclastic or rhyolitic flows that are common, although volumetrically minor, in the Lassen region (Borg and Clynne, 1998).

Trace Element and Isotopic Contrasts

Modern south Cascade basalts and Tahoe-Reno region mafic lavas show large differences in incompatible element characteristics and radiogenic isotope ratios (Figs. 13 and 14). Although some overlap exists and patterns are similar in shape, many modern Cascade basalts have lower abundances of the more incompatible elements but similar abundances of the heavy REEs. The higher incompatible element abundances in Tahoe-Reno region lavas is also consistent with the model of Putirka and Busby (2007), who showed that Miocene–Pliocene Sierran lavas are derived by lower degrees of partial melting than are Lassen area lavas. In particular, Tahoe-Reno lavas are enriched in Ba, Th, Pb, and Sr relative to modern Cascade lavas.

Figure 14 demonstrates the variation in Sr relative to P at a given $^{87}\text{Sr}/^{86}\text{Sr}$ in Tahoe-Reno region basalts compared to other basaltic rocks of the western United States. At Lassen Peak, $\text{Sr}/\text{P}_{\text{pmm}}$ is interpreted to reflect variable slab-derived fluid addition to the mantle wedge: lavas with low $\text{Sr}/\text{P}_{\text{pmm}}$ were interpreted as melts of unmodified mantle wedge peridotite, whereas lavas with high $\text{Sr}/\text{P}_{\text{pmm}}$ imply melting of hydrous, Sr-enriched, metasomatized mantle peridotite (Borg et al., 1997). $\text{Sr}/\text{P}_{\text{pmm}}$ also correlates with trace element ratios, such as Ba/Nb, that are also sensitive to fluid addition from the subducting slab. At Lassen, lavas with low $^{87}\text{Sr}/^{86}\text{Sr}$ have high $\text{Sr}/\text{P}_{\text{pmm}}$, suggesting that slab-derived fluids have mid-ocean ridge basalt (MORB)-like Sr isotope ratios, whereas lavas with high $^{87}\text{Sr}/^{86}\text{Sr}$ have low $\text{Sr}/\text{P}_{\text{pmm}}$, consistent with melts from an enriched, oceanic island basalt (OIB)-like mantle source (Borg et al., 1997). Recent Hf isotopic results on low $\text{Sr}/\text{P}_{\text{pmm}}$ lavas from the Lassen area, however, are more consistent with an old (Mesozoic?) metasomatized mantle source (lithospheric mantle?) for the low $\text{Sr}/\text{P}_{\text{pmm}}$ chemical signature (Borg et al., 2002). In the Tahoe-Reno region, basalts cover the same range of $\text{Sr}/\text{P}_{\text{pmm}}$ as in the south Cascades, but at much higher $^{87}\text{Sr}/^{86}\text{Sr}$. None of the lavas has MORB-like Sr isotopic compositions, although they trend toward the same low $^{87}\text{Sr}/^{86}\text{Sr}$ (~0.7030) at the high $\text{Sr}/\text{P}_{\text{pmm}}$ end of the south Cascade field. However, the conclusions reached by Borg et al. (2002) for the Lassen area also apply to the Tahoe-Reno lavas: the high $^{87}\text{Sr}/^{86}\text{Sr}$, low $\text{Sr}/\text{P}_{\text{pmm}}$ component is not a fluid component, and must either be an enriched component in the mantle wedge or a lithospheric mantle component. Cascadia sediments and lavas of the Western Great Basin also have high $^{87}\text{Sr}/^{86}\text{Sr}$ at low $\text{Sr}/\text{P}_{\text{pmm}}$, but OIB-like mantle (Mojave) does not extend to such high $^{87}\text{Sr}/^{86}\text{Sr}$.

Figure 15A compares the Sr and Nd isotopic compositions of Tahoe-Reno region Miocene–

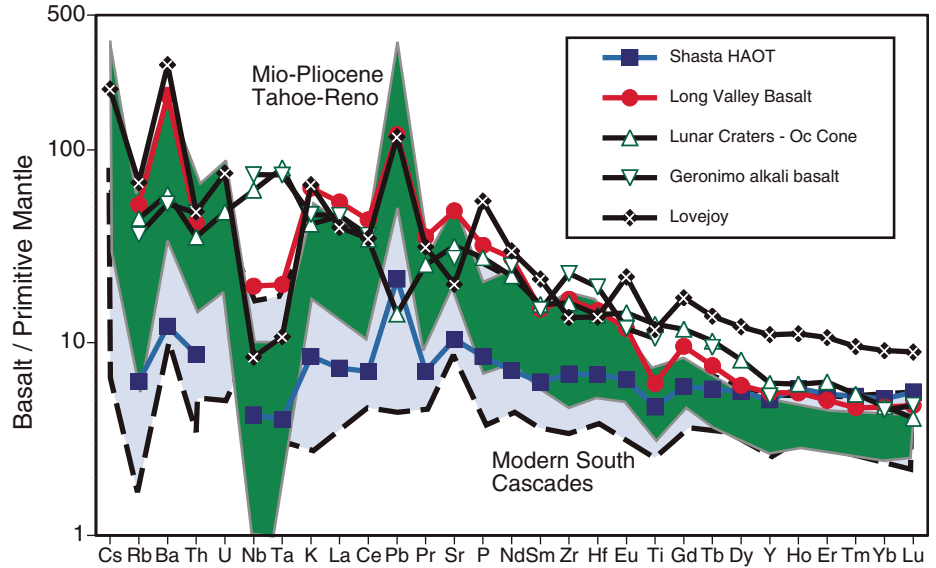


Figure 13. Comparative normalized incompatible element plot for modern south Cascade basalts (blue field) (GEOROC, 2007) and Tahoe-Reno region basalts (green field), a high-alumina olivine tholeiite (HAOT) from Mount Shasta (B. Cousens, 1999, personal observ.), a Long Valley caldera basalt (Cousens, 1996), Basin and Range lavas from the Lunar Craters (Nevada) (Dickson, 1997) and Geronimo (Arizona) (Kempton et al., 1987) volcanic fields, and the Lovejoy basalt (this study).

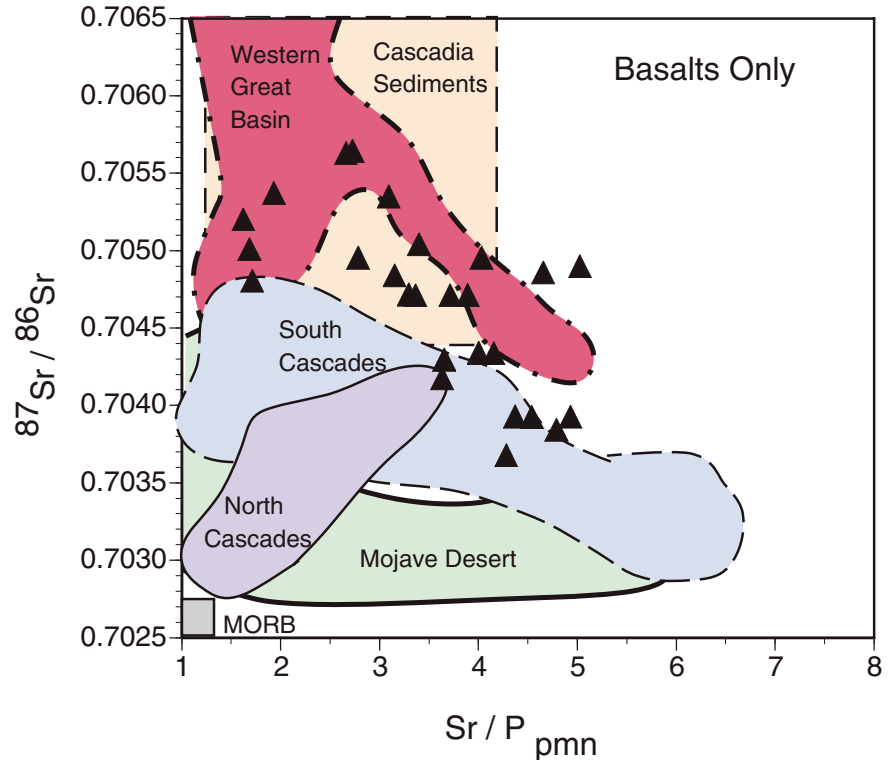


Figure 14. $^{87}\text{Sr}/^{86}\text{Sr}$ versus $\text{Sr}/\text{P}_{\text{pmm}}$ (primitive mantle normalized) for north Cascade, south Cascade, Mojave Desert, Western Great Basin (GEOROC, 2007), and Tahoe-Reno region (triangles) basaltic lavas. MORB—Gorda Ridge mid-ocean ridge basalts (Davis and Clague, 1987). Cascadia sediments (dashed box) have $^{87}\text{Sr}/^{86}\text{Sr} > 0.7045$ and $\text{Sr}/\text{P}_{\text{pmm}}$ from 1.2 to 4.1 (Davis et al., 1998; Prytulak et al., 2006).

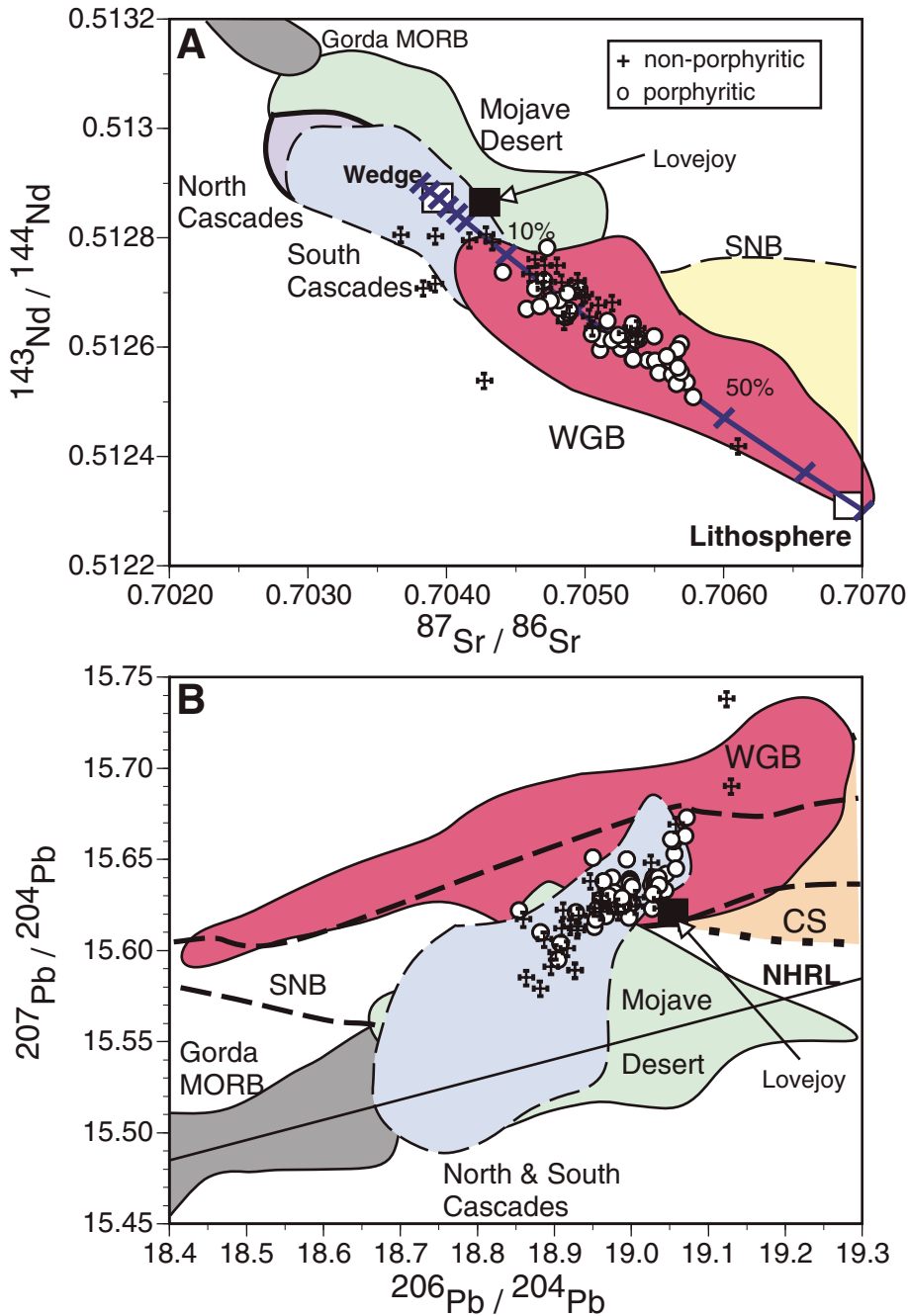


Figure 15. (A) Sr versus Nd isotope plot comparing Tahoe-Reno region lavas, split into porphyritic and nonporphyritic groups, to fields for Gorda Ridge mid-ocean ridge basalt (MORB) (gray), north Cascade (blue), south Cascade (light blue), Mojave Desert (green), Western Great Basin (red), and Sierran granitoids (SNB, yellow) (data from GEOROC, 2007). Black box indicates composition of two Lovejoy basalt flows (B. Cousens, 2007, personal observ.). Mixing curve is for melts of lithosphere ($\text{Sr} = 1200$ ppm, $\text{Nd} = 38$ ppm, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7070$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.5123$) and melts of mantle wedge ($\text{Sr} = 550$ ppm, $\text{Nd} = 15$ ppm, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7038$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.5129$) with tick marks showing percentage of lithospheric melt in the mix (modified from Yogodzinski et al., 1996). (B) Pb-Pb plot with fields as above, but including Cascadia sediments (CS, orange) field (Davis et al., 1998; Prytulak et al., 2006). Heavy dashed lines enclose Sierra Nevada granitoids (SNB). NHRL—Northern Hemisphere Reference Line for MORB and oceanic island basalt (Hart, 1984).

Pliocene basalts with other basaltic rocks from the western United States. Compared to modern Cascade basalts, Tahoe-Reno lavas extend to much higher $^{87}\text{Sr}/^{86}\text{Sr}$ and lower $^{143}\text{Nd}/^{144}\text{Nd}$ with only minor overlap between the two groups. In contrast, Pb isotope ratios in modern south Cascade and Tahoe-Reno basalts overlap completely at the more radiogenic end of the modern south Cascade field (Fig. 15B).

Mantle Sources of Basaltic Rocks

Basalts from the Ancestral Cascades arc in the Tahoe-Reno region should approximately retain the characteristics of their mantle sources, even though some may undergo contamination by crustal rocks during passage to the surface. Given the association of the Ancestral Cascades arc with subduction of the southern Juan de Fuca plate beneath the continental margin during the Miocene–Pliocene, in a setting virtually identical to that of the modern south Cascades, a Lassen-like origin for mafic arc magmas would be expected. However, the relative enrichment in incompatible elements (Ba, Th, Sr, Pb) and the distinctive Sr and Nd isotopic compositions compared to modern south Cascade arc lavas indicate that this is not entirely the case. Some other component is required to explain these geochemical differences. The proximity of Western Great Basin volcanic fields south of the study area with a distinctive lithospheric mantle source, combined with the exposure of the Lovejoy flood basalt with Columbia River basalt-like composition just north of the study area, allow that Tahoe-Reno region arc lavas include mantle (and/or crustal) components that are not (as) evident in modern arc rocks of the Cascade Range. Table 4 lists some geochemical contrasts between Tahoe-Reno region arc basalts, modern Cascade basaltic rocks, and other potential components discussed in the following.

Other distinct mantle sources that have been proposed for Cenozoic volcanic rocks in the western United States include: (1) ancient enriched domains in the subcontinental lithospheric mantle beneath the Western Great Basin of the eastern Sierra Nevada (Fitton et al., 1988; Ormerod et al., 1988, 1991; Kempton et al., 1991; Rogers et al., 1995; Cousens, 1996; Beard and Glazner, 1998; Feldstein and Lange, 1999; DePaolo and Daley, 2000) and east of the modern Cascade arc (Oregon Plateau and Columbia River basalts; Carlson, 1984; Carlson and Hart, 1987; Hooper and Hawkesworth, 1993); (2) enriched OIB-like mantle sources, commonly interpreted to be small- to medium-degree melts of enriched components (blobs, veins) in the asthenospheric upper mantle or

TABLE 4. PRIMITIVE MAGMA CHARACTERISTICS OF MODERN CASCADE AND ANCESTRAL CASCADE LAVAS, AND POTENTIAL CONTAMINANTS

	South Cascade HAOT	South Cascade basaltic andesite	Ancestral Cascade basalt	Cascadia sediments	Sierra Nevada granitoids	Simcoe enriched basalts
SiO ₂ (%)	~ 48	~ 52	~ 49	55–73	57–69	47–50
TiO ₂ (%)	~ 1	0.6–1	~ 0.7	0.45–0.95	0.4–1.0	2.2–3.6
K ₂ O (%)	< 0.1	0.6–1.0	0.5–1	2.2–3.5	1.7–6.0	0.7–2.2
Ba (ppm)	< 150	100–400	200–1400	460–1200	500–3200	180–670
Sr (ppm)	150–250	200–700	400–1200	160–450	280–570	500–1000
Nb (ppm)	1–3	1–7	2–4	11–26	3–13	20–60
Pb (ppm)	0.5–2	1–5	3–8	10–19		2–8
Ce (ppm)	4–18	10–50	20–55	45–95	25–145	35–85
Ba/La	10–20	15–35	30–55	12–41	7–40 (rare 90)	11–16
Ba/Nb	10	50–75	20–200 (scoria 400)	24–64	44–120 (rare 800)	9–12
Th/Yb	< 1	1–2.5	0.5–3 (scoria 9)	3.2–5.1	1–11 (rare 30)	0.8–2.0
La/Sm _{pmm}	0.6–1.2	1.5–2.8	2–3	3.2–4.7	2–14	1.8–3.1
Sr/P _{pmm}	2.1–2.9	1.3–6.5	3.1–5.0	1.2–4.1	2.1–4.2	1.1–1.4
⁸⁷ Sr/ ⁸⁶ Sr	< 0.7038	< 0.7038	> 0.7036	0.704–0.711	0.705–0.712	< 0.7031

Note: HAOT—high-alumina olivine tholeiites. Data Sources: Bacon et al. (1997); Barbarin et al. (1989); Borg et al. (1997); Davis et al. (1994); Leeman et al. (1990); Prytulak et al. (2006).

lowermost lithospheric mantle; for example, in the Mojave Desert and central Basin and Range (Kempton et al., 1987; Leat et al., 1988; Glazner et al., 1991; Farmer et al., 1995; Leventhal et al., 1995; Yogodzinski et al., 1996), western California and offshore California (Cole and Basu, 1995; Dickinson, 1997; Davis et al., 2002), and in the arc and backarc of the modern Cascades (Strong and Wolff, 2003; Leeman et al., 2005); and (3) a mantle plume, the Columbia River–Yellowstone hotspot (Westaway, 1989; Parsons et al., 1994; Murphy et al., 1998).

Hotspot Component?

The ca. 15 Ma Lovejoy basalt, proposed to be a flood basalt unit originating in eastern California associated with the Miocene Columbia River basalts of Washington and Oregon (Wagner et al., 2000; Garrison, 2004; Coe et al., 2005), provides evidence that hotspot-related mantle may potentially flow beneath the lithosphere far from the locus of hotspot activity. If true, then hotspot-related mantle could have been a component in the source of Ancestral Cascade arc magmas. Lovejoy basalts are characterized by much higher heavy REE abundances compared to all Tahoe-Reno region and modern Cascade calc-alkaline basalts (Fig. 13). Because no Tahoe-Reno region basalts approach the heavy REE abundances of the Lovejoy, we see no evidence for a Columbia River basalts-like component in any basaltic rocks from this segment of the Ancestral Cascades. The low Sr and high Nd isotope ratios in the Lovejoy flows (Fig. 15A) also show that this plume component is not the isotopically enriched component in Miocene–Pliocene basalts from the Tahoe-Reno region.

There is also no evidence for an enriched (OIB like) component in the upper mantle being an important contributor to primary magmas in the Tahoe-Reno area during the Miocene–Pliocene. Enriched mantle appears to be a minor mantle source in the south Cascades (Strong and Wolff, 2003) as well as to the east of the Mount St. Helens–Mount Adams area in the north Cascade Range (Leeman et al., 1990), but this component does not have high enough ⁸⁷Sr/⁸⁶Sr to be the isotopically enriched component in the Tahoe-Reno region of the Ancestral Cascades arc (Table 4).

Sediments in the Mantle Wedge

In many respects, the high ⁸⁷Sr/⁸⁶Sr component in the Tahoe-Reno region basalts appears sedimentary in composition. The high-⁸⁷Sr/⁸⁶Sr lavas have low Ce/Pb, low Sr/P_{pmm} (Fig. 14), and high La/Sm_{pmm}, all of which are characteristic of sediments from the continental margin of California and Oregon (Davis et al., 1994; Prytulak et al., 2006). However, Tahoe-Reno region basalts have Ba/Zr and Ba/La that are much higher than Cascadia sediments. In addition, the small (if any) Pb isotopic distinctions between modern south Cascade and Tahoe-Reno region basalts (Fig. 15B) cannot be explained by an extra sediment component in the Miocene–Pliocene mantle source because both the Tahoe-Reno region and modern Cascade basalts form an array that extends to ²⁰⁷Pb/²⁰⁴Pb higher than Cascadia sediments.

Lithospheric Component

High ⁸⁷Sr/⁸⁶Sr, low ¹⁴³Nd/¹⁴⁴Nd, and high ²⁰⁷Pb/²⁰⁴Pb compared to most modern Cascade arc lavas are consistent with an enhanced ancient lithospheric component in Tahoe-Reno

region arc sources. If so, how is this lithospheric influence imparted to the Tahoe-Reno region arc magmas?

Assimilation of upper crustal granitoids of the Sierra Nevada Batholith is a possible cause of the distinctions between modern south Cascade and Tahoe-Reno region basalts. Isotopically, most Sierran granitoids have the high ⁸⁷Sr/⁸⁶Sr, low ¹⁴³Nd/¹⁴⁴Nd, and high ²⁰⁷Pb/²⁰⁴Pb required to be the enriched component in Tahoe-Reno region basalts (Fig. 15). However, Ba/La and Sr/P_{pmm} are lower in Sierran granitoids than in Tahoe-Reno region basalts. Figure 16 shows that Rb/Sr increases slightly in both south Cascade and Tahoe-Reno region basalts as magmas become more evolved, but ⁸⁷Sr/⁸⁶Sr ratios do not increase dramatically with increasing Rb/Sr. Mixing between modern south Cascade basalt and Sierran granite would produce a roughly linear mixing relationship in Figure 16 that would pass through the Ancestral Cascade array. This is not evident; all of the granitoids have Rb/Sr greater than a viable high ⁸⁷Sr/⁸⁶Sr mixing end member. Partial melting, rather than bulk assimilation, of Sierran granitoids would produce liquids with even higher Rb/Sr and ⁸⁷Sr/⁸⁶Sr than the bulk granitoid, since one of the first phases to melt is high Rb/Sr biotite (Kaczor et al., 1988; Knesel and Davidson, 1996). Thus we conclude that the lithospheric component does not have an upper crustal granitoid source.

Alternatively, Tahoe-Reno region parental magmas were derived partially or primarily from the lithospheric mantle above the mantle wedge. In general, modern Cascade arc magmas are thought to include only a small slab-derived fluid component due to the young age of the subducting plate (Green and Sinha, 2005). Fluid

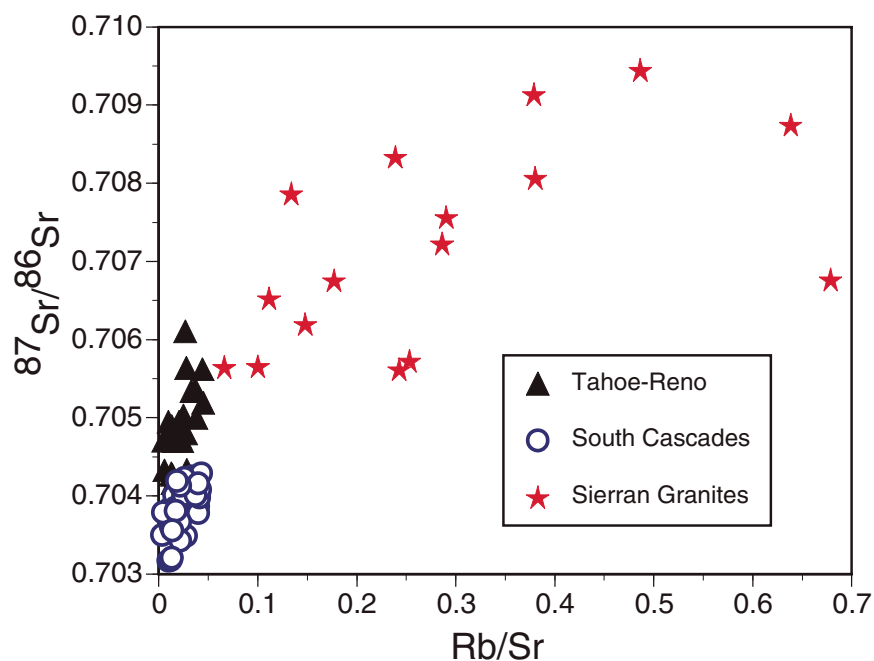


Figure 16. $^{87}\text{Sr}/^{86}\text{Sr}$ versus Rb/Sr for Sierra Nevada granitoids (this study; Kistler and Peterman, 1973; Barbarin et al., 1989), modern south Cascade basalts (GEOROC, 2007) and Tahoe-Reno region basalts. Note that Tahoe-Reno region basalts do not plot on a mixing line between modern south Cascade basalts and Sierran granitoids.

loss from the subducting slab occurs primarily in the forearc rather than beneath the arc, and the subduction signature in arc magmas is proposed to come from the lithospheric mantle (Leeman et al., 1990, 2005; Borg et al., 1997). This may also be the case for the Ancestral Cascades in the Tahoe-Reno region, because the subducting plate was also relatively young and hot during the Miocene (Dickinson, 1997). The importance of a lithospheric mantle source is supported by the observation that Tahoe-Reno region mafic lavas commonly resemble alkaline to potassic, Miocene–Pliocene lavas from the Western Great Basin in terms of trace element (Fig. 13; Long Valley basalt) and radiogenic isotope ratios (Fig. 15A) (e.g., Fitton et al., 1988; Beard and Glazner, 1995; Manley et al., 2000). Western Great Basin magmas are proposed to be partial melts of the Sierra Nevada subcontinental lithospheric mantle, which was metasomatized by earlier subduction episodes beneath the western margin of the southwestern U.S. (e.g., Ormerod et al., 1991). Thus magmas derived from this source have incompatible element patterns that mimic modern subduction-related magmas but have much higher $^{87}\text{Sr}/^{86}\text{Sr}$ and lower $^{143}\text{Nd}/^{144}\text{Nd}$ that reflect the antiquity of the lithosphere. However, the subalkaline composition of Tahoe-Reno region arc lavas, the abundance of highly porphyritic lavas typical of continental arcs, and the evidence for larger volcanic edi-

ces with dome collapse and debris flow deposits indicate to us that Miocene–Pliocene rocks of the Tahoe-Reno region should not be included in the magmatic province defined as the Western Great Basin (Menzies et al., 1983; Ormerod et al., 1988; Fitton et al., 1991).

If lavas from both the Ancestral Cascades of the Sierra Nevada and the Western Great Basin include a lithospheric component, then the subalkaline nature and greater eruptive volume of the Ancestral Cascades compared to the generally alkaline composition of Western Great Basin cinder cones and lavas suggest a higher degree of melting of the lithosphere, perhaps combined with melting of hydrated mantle wedge material. The more subalkaline nature of Ancestral Cascades arc magmas could be due to lower pressures of mantle melting compared to Western Great Basin magmas. Mavko and Thompson (1983) proposed that lithospheric thickness, and hence inferred pressure of melting, is actually greater (~100 km) in the Lassen and Lake Tahoe regions compared to ~50 km at Mono Lake in the northern Western Great Basin. However, recent geophysical evidence leans toward a thinner lithosphere beneath the Sierra (to the southeast, at least) than the Basin and Range (e.g., Wernicke et al., 1996; Jones et al., 2004). Putirka and Busby (2007, their Fig. 3) showed that Ancestral Cascades arc rocks from the central Sierra Nevada are 6%–10% melts of

Sierran lithospheric mantle, utilizing an average of mantle xenoliths as a source composition (Beard and Glazner, 1995), whereas south Sierran (Western Great Basin) lavas are explained by <6% melting of a chemically similar, but possibly garnet-bearing, mantle source. Tahoe-Reno region mafic lavas also fall within the 6%–10% partial melting range in the Putirka and Busby (2007) model. One way to raise the degree of melting in the lithospheric mantle is to introduce hydrous fluids from the subducting Juan de Fuca slab directly into the base of the lithospheric mantle, particularly if the slab dip was low and the mantle wedge was very thin. In addition, any mantle wedge–derived magmas could cause partial melting or melt–rock reaction with lithospheric mantle peridotite along conduit walls, and subsequently mixing of the two magma types may occur prior to eruption (e.g., Yogodzinski et al., 1996).

All late Cenozoic volcanic rocks emplaced in the Sierra Nevada appear to be dominated by a lithospheric mantle component that is evident in normalized incompatible element patterns and in Sr and Nd isotopic compositions (this work; Menzies et al., 1983; Kempton et al., 1991; Feldstein and Lange, 1999; DePaolo and Daley, 2000; Manley et al., 2000; Elkins-Tanton and Grove, 2003; Putirka and Busby, 2007). No other suite of late Cenozoic volcanic rocks in California or Nevada outside of the Sierra Nevada includes this trace element and isotopic signature (Figs. 15A and 17). We propose that the term “Sierran Province” originally applied only to volcanic rocks of the Western Great Basin (e.g., Menzies et al., 1983), should be expanded to include all Miocene and younger volcanic rocks of the Sierra Nevada regardless of their tectonic setting. This includes Miocene–Pliocene arc rocks of the Tahoe-Reno region, post-arc (Pliocene–Pleistocene) lavas from the Lake Tahoe area, the cinder cone and/or lava fields of the Western Great Basin (Big Pine, Long Valley, Coso), and ultrapotassic (commonly latite) rocks of the southern and central Sierra Nevada (red box, Fig. 17). Note that lithospheric mantle–derived volcanic rocks from the southern and eastern margins of the Basin and Range Province (Lake Mead, Death Valley, Colorado River extensional areas) have lower $^{143}\text{Nd}/^{144}\text{Nd}$ than lavas from the western margin (eastern Sierra extensional area; DePaolo and Daley, 2000), supporting the highly regional character of the lithospheric mantle source beneath the Sierran Province. Trace element signatures in mantle xenoliths also support chemically distinct lithospheric mantles beneath the Sierra Nevada and the Colorado Plateau (Lee, 2005).

Proposed driving forces for Western Great Basin and ultrapotassic magmatic events in the

central and southern Sierra include lithospheric thinning and lithospheric mantle delamination (Feldstein and Lange, 1999; Farmer et al., 2002). The dominance of a similar lithospheric component in arc-related magmatism of the northern Sierra, prior to incipient Basin and Range extension or proposed delamination events in the Sierra, shows that other mechanisms aside from lithospheric extension or delamination may initiate melting in the lithospheric mantle.

Development of the Ancestral Cascades Arc in the Lake Tahoe Region

In the Lake Tahoe–Reno region of the Ancestral Cascades arc, the apparent involvement of old lithospheric mantle with a higher Rb/Sr and lower Sm/Nd compared to the asthenosphere and the idea that a shallow slab dip and thin lithospheric wedge would potentially aid its involvement are particularly interesting, and we

propose that they fit the space-time patterns of magmatism in the southwestern United States.

The character of the Miocene–Pliocene Ancestral Cascade arc in the Sierra Nevada has been controversial. Lipman (1992), and Dickinson (2002, 2004, 2006) indicated an arc along the length of the northern and central Sierra Nevada during much of the middle and late Cenozoic. However, Glazner et al. (2005) suggested “subduction-type volcanism is poorly linked to the subduction system” (p. 98). This debate may arise from the complex patterns of post-Cretaceous, subduction-related and other magmatism during which the Ancestral Cascade arc in the Sierra Nevada was reestablished as volcanism migrated westward from the Great Basin.

Late Cretaceous subduction-related magmatism ended near Lake Tahoe ca. 90 Ma as activity of the Sierra Nevada batholith migrated eastward, presumably as a result of shallowing of the Farallon slab (Dickinson and Snyder, 1978;

Lipman, 1992). Magmatism migrated back to Nevada ca. 40–45 Ma via a southward sweep from Washington, Idaho, and Oregon (Christiansen and Yeats, 1992; Humphreys, 1995). Intermediate, arc-like andesite and dacite were the major components of this activity in northeastern Nevada (Brooks et al., 1995; Henry and Ressel, 2000; Ressel and Henry, 2006). Although migration north of Nevada was generally southward, migration changed to a distinctly southwestward direction once in Nevada. By 34 Ma, a northwest-trending belt of rhyolitic ash-flow calderas began to develop through central Nevada, the well-known ignimbrite flare-up (Best et al., 1989). Intermediate magmatism accompanied the rhyolitic activity but also reached as far west as westernmost Nevada, just east of the present Sierra Nevada (Fig. 18). The oldest activity near Lake Tahoe, at 28 Ma, was too small in volume and too discontinuous to be considered a continental volcanic arc, at least in the Sierra Nevada. However, between 28 and ca. 18 Ma, the westward edge of magmatism migrated southwestward into what is now the eastern Sierra Nevada, increased in volume, and started to form major volcanic centers, including stratovolcanoes. An unequivocally Ancestral Cascade arc in western Nevada and eastern California was well developed by ca. 15 Ma, although its axis was ~75 km east of its location ca. 5 Ma (Fig. 18). Busby et al. (2008b) concluded that ancestral arc magmatism also began ca. 15 Ma near Sonora Pass. Arc magmatism ceased ca. 3 Ma near Lake Tahoe as the Mendocino triple junction migrated to the north of the region (Atwater and Stock, 1998), and the southern end of the active Cascade arc is now generally considered to be at Lassen Peak, ~150 km to the north. The trend of the active arc is west of the trend of the 5 Ma arc, suggesting further westward migration of the arc.

Two overlapping interpretations have been offered for the south and southwestward migration of magmatism from the northwestern U.S. into Nevada. Dickinson (2002) suggested that the shallow Farallon slab resteepped by generally westward-directed rollback or foundering from beneath the overlying continental lithosphere. Arc or possibly backarc magmatism followed the edge of the foundering slab. Humphreys (1995) proposed that simple westward foundering of the Farallon slab explains neither the Eocene–Miocene southward sweep of magmatic activity in the northern Great Basin nor the coincident northwestward magmatic sweep through the southern Great Basin. Humphreys (1995) proposed that the shallow-dipping slab detached from the overlying lithosphere along east-west trends near the U.S.–Canada and U.S.–Mexico borders and along a north-south trend

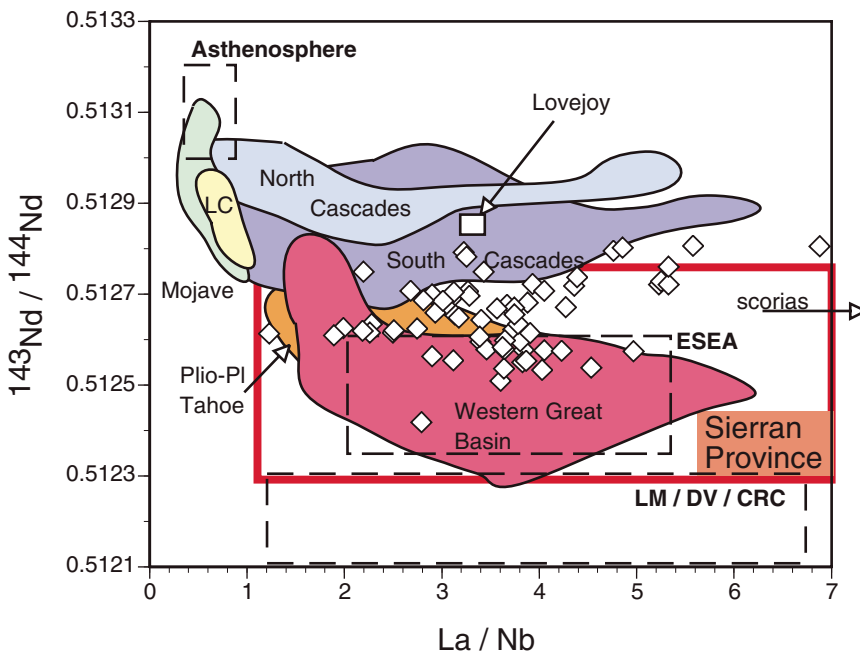


Figure 17. $^{143}\text{Nd}/^{144}\text{Nd}$ versus La/Nb diagram to distinguish asthenospheric from lithospheric sources for lavas from the southwestern U.S. (DePaolo and Daley, 2000). Lavas from the Tahoe-Reno region (open diamonds) range in $^{143}\text{Nd}/^{144}\text{Nd}$ between modern south Cascade lavas and lavas from the Western Great Basin. Ladybug scorias plot off the diagram at higher La/Nb . Lovejoy basalts are indicated as a white square. The asthenosphere, ESEA (Eastern Sierra extensional area), and LM/DV/CRC (Lake Mead, Death Valley, Colorado River extensional areas) dashed box fields are from DePaolo and Daley (2000). The large red box encloses rocks that we include within the Sierran Province. Data sources: Mojave Desert (green field, Glazner et al., 1991; Farmer et al., 1995), Lunar Craters volcanic field of central Nevada (LC; Dickson, 1997), north Cascades (Leeman et al., 1990; Green and Sinha, 2005), south Cascades (Bacon et al., 1997; Borg et al., 1997), Western Great Basin (Ormerod, 1988; Ormerod et al., 1991; Cousens, 1996), and Pliocene–Pleistocene lavas from the Lake Tahoe area (Plio-Pl Tahoe; B. Cousens, 2000, personal observ.).

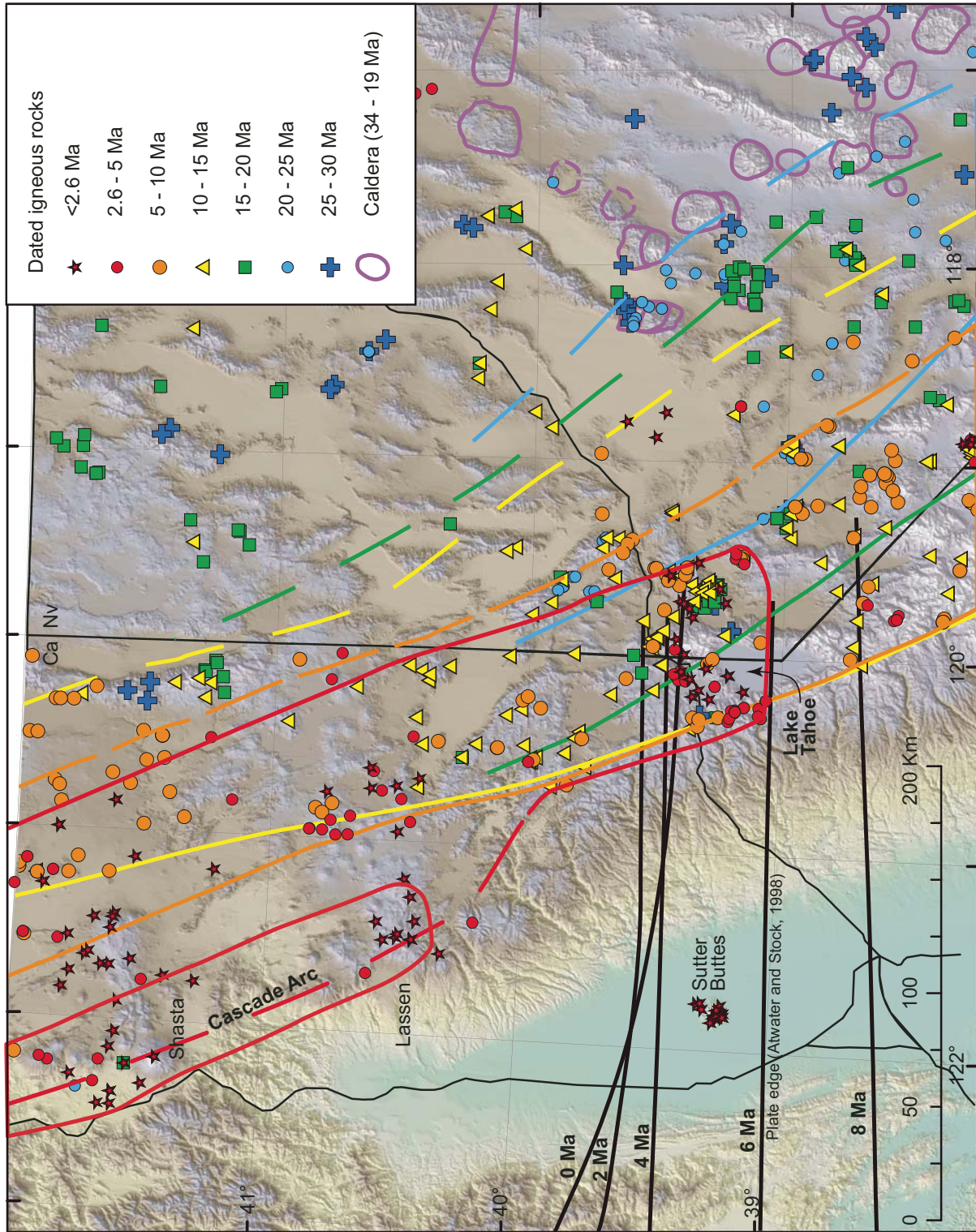


Figure 18. Distribution of dated igneous rocks (Henry and Sloan, 2003; Sloan et al., 2003), excluding distal ash-flow tuffs, divided into 5 m.y. groups between 30 and 0 Ma, and the inferred location of the Ancestral Cascades arc through time. Solid and dashed lines depict the western and eastern limits, respectively, of arc volcanism for each time group. Magmatism migrated generally west-southwestward in broadly linear belts, and an ancestral arc was well established along the Sierra Nevada by at least 15 Ma. The last arc-related magmatism in the Lake Tahoe area occurred ca. 3 Ma, and the south end of the arc is now at the Lassen volcanic field, although the south edge of the subducting slab remains just north of Lake Tahoe. A prominent west-east band of post-arc (younger than 2.6 Ma) magmatism trends from Sutter Buttes (Hausback et al., 1990) through the north end of Lake Tahoe to the Carson Sink. See text for further discussion.

near the trench. The detached slab then foundered along an east-west-trending axis through what is now the central Great Basin, giving it a U-shaped, folded cross section, pulling the north edge of the slab southward and the south edge of the slab northward. Pressure-release melting of upwelling asthenosphere around the edges of the slab induced magmatism in the wake of the foundering slab. This model serves to explain the migration of volcanism in the Great Basin, but does not explain the late reestablishment of the Ancestral Cascades arc south of the Oregon-California border compared to the arc north of the border.

We suggest that the shallow slab detached from the overlying continental lithosphere along a roughly north-south trend in Washington and Oregon, where Ancestral Cascades magmatism (there termed the Western Cascades) resumed by ca. 40 Ma (Christiansen and Yeats, 1992), but remained attached near the trench through California, where magmatism did not resume until much later. Some form of tear probably separated steep- and shallow-dipping slabs near the California-Oregon border. The foundering slab beneath California pulled both southward and southwestward, with a significant component toward the trench, in an apparent attempt to reestablish steep subduction. The last westward step ca. 3 Ma from the Tahoe area to Lassen Peak probably reflects the latest foundering and/or steepening of the slab.

CONCLUSIONS

Volcanic rocks of the Ancestral Cascades arc in the Tahoe-Reno area are calc-alkaline basalts through dacites that range in age from ca. 28 Ma to ca. 3 Ma. Large volcanic edifices consist of debris flows, dome collapse deposits, and lava flows that are dominantly plagioclase-pyroxene-amphibole phyrlic. Nonporphyritic mafic lavas are rare, but can be found as isolated volcanic vents and lava complexes. Porphyritic and nonporphyritic lava types generally overlap in chemical composition. The more evolved andesites and dacites also show strong evidence for interaction with lower crustal rocks of the underlying Sierra Nevada batholith, such that major element characteristics, incompatible element ratios, and isotope ratios (Sr, O) all covary with increasing SiO₂. Nonporphyritic lavas appear to have risen rapidly from their source regions without undergoing much crustal-level modification.

Compared to lavas from the modern south Cascade arc, Ancestral Cascade lavas in the Tahoe-Reno region are LREE and LILE enriched and have isotopic compositions that require addition of an enriched source component, such as that found in basalts of the Western Great Basin of

the eastern Sierra Nevada. This source may be lithospheric mantle peridotite that melts due to addition of fluids from the subducting slab, or melts from the lithospheric mantle may be mixed with primary melts from the subduction-modified mantle wedge. We propose that all late Cenozoic lavas erupted through the Sierra Nevada, not just the Western Great Basin, constitute a "Sierran Province," because they all include a dominant lithospheric mantle component that is not evident in surrounding volcanic suites. However, several mechanisms may cause melting of this lithospheric mantle component.

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