Distinct mantle sources for Pliocene–Quaternary volcanism beneath the modern Sierra Nevada and adjacent Great Basin, northern California and western Nevada, USA

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ABSTRACT

Latest Pliocene to Quaternary, mildly alkaline, mafic to intermediate volcanic activity extends in a swath from the Lake Tahoe region in the eastern Sierra Nevada across the western Great Basin to the Battle Mountain area, Nevada. From west to east, the volcanic centers exhibit a dramatic gradient in chemical and isotopic composition. Centers situated in or adjacent to the Sierra Nevada have incompatible element and isotopic compositions consistent with an old, subduction-modified lithospheric mantle source ($^{87}$Sr/$^{86}$Sr > 0.7045; $^{143}$Nd/$^{144}$Nd < 0.5127; $\delta^{18}$O > +6.5‰). Mafic volcanic centers east of the Sierra Nevada, in the Carson Sink and in the Buffalo Valley region, have an intraplate incompatible element and isotopic signature ($^{87}$Sr/$^{86}$Sr < 0.7045; $^{143}$Nd/$^{144}$Nd > 0.5127; $\delta^{18}$O < +6.5‰) consistent with an asthenospheric mantle source. Earlier 20–3 Ma arc volcanism in the Sierra Nevada also tapped the old lithospheric mantle source along with the mantle wedge, indicating that the lithospheric mantle source existed well prior to the onset of Tertiary arc volcanism and probably prior to Mesozoic igneous activity of the Sierra Nevada. Thus, the lithospheric mantle beneath the Sierra Nevada has remained a geochemically consistent, fertile, fusible source for at least the past 20 m.y. Old lithospheric mantle likely still exists east of the Sierra Nevada, but lithospheric thinning and/or exhaustion of fusible components inhibit its melting, such that during the Quaternary, melting could only occur in the asthenosphere.

INTRODUCTION

The Great Basin of the southwestern United States is well known for its abundance of Tertiary mafic to felsic igneous rocks that are associated with rollback of the shallow-subducting Laramide slab (e.g., Colgan et al., 2008; Dickinson, 2006; Du Bray et al., 2009; Farmer and DePaolo, 1983; Farmer et al., 1989; Feuerbach et al., 1993; Henry et al., 1998; Humphreys et al., 2003; Humphreys, 1995; Perry et al., 1993; Ryskamp et al., 2008; Valentine et al., 2006; Wooden et al., 1998). Most of the youngest volcanic activity is concentrated at the margins of the Great Basin (DePaolo and Daley, 2000), specifically along the western margin of the Colorado Plateau (Conway et al., 1997; Johnsen et al., 2010; Lee, 2005; Smith et al., 1999; Tanaka et al., 1986), in southern Nevada (Feuerbach et al., 1993; Valentine et al., 2006), and along the eastern margin of the Sierra Nevada (Ormerod et al., 1988; Rogers et al., 1995). Only rarely does Late Tertiary to Quaternary volcanism occur away from the margins of the Great Basin (Cousens and Henry, 2008; Dickson, 1997; McKee, 1970; Smith et al., 2002; Stickney, 2004; Valentine et al., 2006; Yodoginski et al., 1996).

Between 20 and 3 Ma, Tertiary volcanism along the western margin of the Great Basin occurred primarily within the Sierra Nevada of northern California and adjacent western Nevada due to rollback of the former Laramide slab (now the Juan de Fuca plate) and a return to a steep subduction angle. This event produced a swath of volcanic rocks extending from the southern end of the modern Cascade Range (Lassen volcanic region) south at least as far as Bodie, California, that has been termed the southern Ancestral Cascades arc (Dickinson, 1997; Du Bray et al., 2009). Radiogenic isotopic and incompatible trace-element data point to an important role for an old, subduction-modified lithospheric mantle source for southern Ancestral Cascades arc volcanic rocks (Cousens et al., 2008), whereas modern Cascade volcanoes originate primarily from the mantle wedge and include only a minor lithospheric mantle component (e.g., Borge et al., 1997, 2002). A recent study of Ancestral Cascades arc volcanism from Lake Tahoe north to the Lassen volcanic region showed that the contribution of the ancient lithospheric mantle source diminishes northward, as the northern edge of the Sierra Nevada Batholith is approached (Stoffers, 2010).

Although arc volcanic activity died out as the southern edge of the Juan de Fuca plate moved northward during the Tertiary, mildly alkaline, predominantly mafic postarc volcanism (<3 Ma) is found along the eastern margin of the Sierra Nevada (western Great Basin) and in the Lake Tahoe region (Tahoe-Truckee volcanic field; Beard and Glazner, 1995; Blondes et al., 2008; Cousins, 1996; Cousins et al., 2011; Ormerod et al., 1988). As with the older Tertiary volcanic rocks, radiogenic isotopes and trace elements indicate that postarc lavas have a source in ancient, subduction-modified lithospheric mantle. Based on available data, it appears that all Cenozoic volcanic rocks that erupted through or directly adjacent to the Sierra Nevada Mountains have a distinct, sub-Sierran lithospheric mantle source. In contrast, geochemical studies show that the Pliocene–Pleistocene Reveille Range–Lunar Craters and Buffalo Valley volcanic fields in the central Great Basin originated from “intraplate” mantle, with no subduction trace-element signature, and radiogenic isotope ratios that trend toward a more depleted mantle
source (Cousens and Henry, 2008; Dickson, 1997; Stickney, 2004; Yogodzinski et al., 1996). Where does the influence of the sub-Sierran lithospheric mantle source end, and what transition exists between it and the central Great Basin intraplate source?

To evaluate the transition from Sierra to Great Basin mantle sources, we investigated several small-volume, latest Pliocene to Holocene, mafic volcanic centers located in a swath through western and north-central Nevada. Quaternary volcanic activity began in the Lake Tahoe–Truckee area, California, extending through the Carson City–Reno area east to Fallon, Nevada, and ending near Battle Mountain, Nevada (Fig. 1). The volcanic centers lie on the Humboldt Lineament, an east-northeast– to northeast-striking zone of faults, with relatively high seismicity, high heat flow, and geothermal activity that includes two producing geothermal plants (Faulds et al., 2005; Fultz et al., 1984; Rowan and Wetlaufer, 1981). The Humboldt Lineament appears to be a region of thin lithosphere (Louie et al., 2004) beneath which mantle-derived melts are able to make it to the surface.

REGIONAL GEOLOGY

This study focuses on late Pliocene to Quaternary volcanic rocks mapped within the Reno 1° by 2° quadrangle, covering an area from the Sierra Nevada in California into the Great Basin (Fig. 1). Basement rocks include igneous, metamorphic, and sedimentary rocks ranging in age from Paleozoic through Holocene, although in the Great Basin, they are dominantly mid- to Late Tertiary in age. Mid-Tertiary volcanism was primarily rhyolitic in composition, resulting from the "ignimbrite flare-up" in the central Great Basin. Late Tertiary volcanism, including abundant volcaniclastic rocks (landslide, debris flow, dome collapse), was dominantly porphyritic andesite in the western Great Basin and Sierra Nevada (Cousens et al., 2008; Du Bray et al., 2009; John, 2001; Varve et al., 2011).

Subsequent to the termination of Late Tertiary arc activity in the Sierra Nevada, a post–3 Ma suite of mafic to intermediate flow complexes was emplaced on the northwest side of Lake Tahoe, California, and along the course of the Truckee River between Lake Tahoe and the northern Carson Range in western Nevada (Birkeland, 1963; Latham, 1985; Lindgren, 1897; Saucedo, 2005; Sylvester et al., 2007; Thompson and White, 1964). We refer to this suite as the Tahoe-Truckee volcanic field (Cousens et al., 2011). Unlike the older arc volcanic rocks, the post–3 Ma suite includes only small-volume volcanic centers that lack the...

Figure 1. Physiographic map of the Sierra Nevada and Great Basin in the Lake Tahoe to Carson Sink region. Locations of lavas sampled from the western Nevada volcanic field are shown as red circles. The distribution of flows of the Tahoe-Truckee volcanic field (TTVF) is enclosed by the blue field. Inset: Map of northern Nevada showing location of Tahoe-Truckee volcanic field and western Nevada volcanic field (large red box) and Fish Creek Mountains-Buffalo Valley (FCMBV, small red box). Gray line labeled "HL" is Humboldt Lineament.
highly plagioclase-porphyritic rocks and common volcaniclastic deposits that dominate the arc volcanic centers (Cousens et al., 2008).

Latest Pliocene to Quaternary volcanic centers in western Nevada extend east from the Tahoe-Truckee volcanic field, and, like it, they lack the highly plagioclase-porphyritic lavas that are common during Late Tertiary arc volcanism. However, the eruptive volume of volcanic centers in western Nevada is significantly less than that of the Tahoe-Truckee volcanic field, even though the western Nevada centers are located in highly extended and faulted terrains.

LOCAL GEOLOGY

Latest Pliocene to Holocene volcanic fields in western Nevada include the northern Carson Range; the Steamboat Hills (Springs) basaltic andesite and rhyolite; the McClellan Peak alkalic basalt flows around Carson City, Virginia City, and the Chalk Hills; and the Buffalo Valley volcanic field south of Battle Mountain. For the purposes of this paper, we collectively refer to this area as the western Nevada volcanic field. All are included on the Reno 1° by 2° quadrangle geological map (Greene et al., 1991), with the exception of the Buffalo Valley (Fish Creek Mountains) volcanic field of north-central Nevada (Fig. 1, inset) (Cousens and Henry, 2008; Stewart and Carlson, 1976). Lavas from the Carson Range are described in Cousens et al. (2011).

Steamboat Hills (Springs)

The Steamboat Hills volcanic center occurs along the Sierra Nevada frontal fault zone between Reno and Carson City, Nevada (Thompson and White, 1964). The concentration of geothermal activity in this region is likely a combination of fault control and Quaternary mafic to felsic volcanism that crosses the Steamboat Hills (Arehart et al., 2003; Fultz et al., 1984). K-Ar ages for the Steamboat Hills basaltic andesite flow range from 2.0 to 2.6 Ma (Fultz et al., 1984), but we have recently dated the basaltic andesite by 40Ar/39Ar at 2.14 Ma (Table 1). K-Ar analyses from local pumiceous rhyolite domes range from 1.1 to 3.0 Ma, but our 40Ar/39Ar ages are more consistent at 1.19 ± 0.013 Ma, 1.210 ± 0.021 Ma (Table 1).

One sample was collected from the Steamboat Hills basaltic andesite (01-LT-54; Fig. 2A), and additional trace-element data are reported in Fultz et al. (1984).

McClennan Peak Alkaline Basalt

A group of ca. 1.2–1.4 Ma basalt to basaltic andesite lavas and two cinder cones in the Virginia Range are collectively known as the McClennan Peak Basalt (Bingler, 1977; Hudson et al., 2009; Schwartz and Faulds, 2001; Thompson and White, 1964). McClennan Peak Basalt occurs in two geographic groups in the southern and northern parts of the range. Basalt is present in both areas, whereas basaltic andesite is only present in the south. For geochemical comparisons, these rocks are divided into the New Empire basaltic andesite rocks and the McClennan Peak basalt.

A cinder cone near McClennan Peak in the northwest corner of the New Empire 7.5′ quadrangle north of Carson City (Fig. 2B) is the source of at least two basaltic andesite lavas that flowed southward to what is now U.S. Highway 50 (Fig. 2B) (Bingler, 1977). Of the two flow units identified, QTb1 is contemporaneous with the cinder cone, and a slightly younger QTb2 unit is dated by K-Ar at 1.36 ± 0.29 Ma (Bingler, 1977). The QTb1 flow (sample 04-LT-77 and 04-LT-78) is an aphyric, gray basaltic andesite that includes flow breccia and an upper surface with prominent ridges, both of which likely reflect a high viscosity.

Other rocks of the McClennan Peak Basalt are true basalt. One basalt lava sequence (04-LT-74 and 04-LT-75) lies east of McClennan Peak in the Virginia City quadrangle (Fig. 2C) and may have erupted from an eroded plug on the peak’s east flank (Hudson et al., 2009). A conventional K-Ar date for this locality is 1.17 ± 0.04 Ma (Doell et al., 1966). Another lava (01-LT-56) flowed from a cinder cone in the northern Carson Range down the valley to the modern Truckee River and is dated by 40Ar/39Ar at 1.44 ± 0.01 Ma (Chalk Hills; Schwartz and Faulds, 2001). Lava flows from both localities are dark gray and vesicular, with 10%–15% large phenocrysts of olivine, lesser clinopyroxene, and plagioclase in a finely crystalline matrix that includes some glass (Fig. 2D). Euhedral to subhedral olivine crystals can reach a few millimeters in size and commonly occur in clots. Olivine- and clinopyroxene-rich xenoliths are common in the Virginia City quadrangle exposures, along with rare granite xenoliths.

### Table 1. 40Ar/39Ar Ages of Pliocene–Quaternary Volcanic Rocks, Reno, Nevada

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<th>Sample Number</th>
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<th>Longitude</th>
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<td>Rhyolite lava dome</td>
<td>39.37831</td>
<td>119.75170</td>
<td>2.142</td>
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</tbody>
</table>

Note: All samples were analyzed at the New Mexico Geochronological Research Laboratory (methodology in McIntosh et al., 2003). Neutron flux monitor: Fish Canyon Tuff sanidine (FC-1). Assigned age = 28.02 Ma (Renne et al., 1998). Sanidine was separated from crushed, sieved samples by standard magnetic and density techniques, leached with dilute HF to remove matrix, and handpicked. Weighted mean 40Ar/39Ar ages of sanidine were calculated by the method of Samson and Alexander (1987). Decay constants and isotopic abundances are after Steiger and Jäger (1977); λb = 4.963 × 10–10 yr–1; λe+e′ = 0.581 × 10–10 yr–1; 40K/K = 1.167 × 10–4.

**MSWD**—mean square of weighted deviates.

*Ages in bold are best estimates of emplacement age. Both plateau and isochron ages are valid for 01-LT-54A.

%39Ar—percentage of 39Ar used to define plateau age.

Sample number is used in age calculation. Number of grains analyzed.

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Rattlesnake Hill

Rattlesnake Hill in Fallon is one of three Quaternary volcanic centers in the Carson Desert near Fallon, Nevada. The hill is an eroded cone, ~1.2 km in diameter and 70 m high (Fig. 2E). K-Ar ages range from 1.03 to 1.20 Ma, and a recent 40Ar/39Ar date of 0.91 ± 0.04 Ma has been obtained from sample GD-03–05 (G. Arehart and M. Coolbaugh, 2006, personal commun.). Two basaltic trachyandesites from Rattlesnake Hill were collected from a massive flow beneath the microwave tower. The rock is olivine-, pyroxene-, and plagioclase-phyric, with fine-grain opaque minerals, set in a holocrystalline matrix.

Soda Lakes

West of Fallon, the Soda Lake complex consists of a pyroclastic cone hosting two water-filled craters, Soda and Little Soda Lakes (Fig. 2F). These maar volcanoes are composed of basaltic lapilli and bombs, tufa, lacustrine sediments, and pebbly sands (Fultz et al., 1984). Attempts
to date Soda Lake basalt have been unsuccessful, most recently as a result of a complete lack of radiogenic argon (G. Arehart and M. Coolbaugh, 2006, personal commun.). Based on the relationship with Lake Lahontan sediments and the absence of tufa, the uppermost deposits are estimated to be younger than 6 k.y. in age.

Two volcanic bombs from the surface of the Soda Lake cone were selected for analysis (04-LT-14, 04-LT-15). The bombs are olivine- and plagioclase-phyric, with very dense glassy matrices. Rare large plagioclase crystals with sieve-texture cores are visible in hand specimen matrices. Most of the eruptive centers of the Buffalo Valley volcanic field are cinder cones distributed commonly in a glassy matrix.

Upsal Hogback

Upsal Hogback is a group of low-lying maars, tuff rings, and surge deposits adjacent to U.S. Highway 95 north of Fallon. The tuff rings are composed primarily of brown, indurated basaltic cinder tuff that includes large basaltic bombs. In the central part of the complex, the tuff rings overlie relatively flat-lying layers of less-altered basaltic lapilli and a thick layer of white-gray ash with abundant rounded and plagioclase-phyric, with very dense glassy matrices. Rare large plagioclase crystals with sieve-texture cores are visible in hand specimen matrices. Rare large plagioclase crystals with sieve-texture cores are visible in hand specimen matrices.

Five samples of basalt from Upsal Hogback were collected: 06-LT-01 and 06-LT-02 are basaltic bombs embedded in the brown cinder ash from the central ring, 06-LT-01 from the base of the hogback and 06-LT-02 from the top (Fig. 2G); 06-LT-03 is from the flat-lying, basaltic lapilli horizon beneath the hogback of the central ring (Fig. 2H); and 06-LT-04 is a basaltic bomb from the north ring, as is GD-03–04. Olivine crystals are euhedral to subhedral and commonly skeletal, and they can be as large as 7 mm in size.

Buffalo Valley Volcanic Field

Most of the eruptive centers of the Buffalo Valley volcanic field are cinder cones distributed along the northwestern margin of the Fish Creek Mountains, a mid-Tertiary caldera complex located ~250 km northeast of Fallon (Cousens and Henry, 2008; McKee, 1970). Previous K-Ar and 40Ar/39Ar dating indicates that the cones are between 1.4 and 0.95 Ma in age (Arehart and Coolbaugh, 2006, personal commun.). Two nearby late Pliocene–Quaternary volcanic centers are mapped, one northeast of the Fish Creek Mountains with a K-Ar date of 3.3 Ma and a second within the center of the Fish Creek caldera complex. The lavas and scoria fragments range from alkali basalt to trachybasalt in composition.

Lavas from the Buffalo Valley cones have vesicular flow tops and massive interiors. They are all similar petrographically, including 1%–2% olivine phenocrysts and megacrysts up to 1 cm in size, and characteristic large plagioclase megacrysts that are rarely up to 4 cm long, commonly in a glassy matrix.

ANALYTICAL TECHNIQUES

Four samples from the study area were dated by 40Ar/39Ar. Sample locations, analytical details, plateau and isochron ages, and uncertainties are reported in Table 1. New age data from the Buffalo Valley region are presented in Varve et al. (2011).

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, Sudbury). The precision values for the data, based on replicate analyses of samples and blind standards, along with analyses of the lavas, are listed in Table 2. A subset of samples was selected for Pb, Sr, and Nd isotopic analysis utilizing a Thermo Finnigan Triton T1 thermal ionization mass spectrometer at Carleton University (techniques of Cousens, 1996). All Pb mass spectrometer runs were corrected for fractionation using NIST SRM981. The average ratios measured for SRM981 are 206Pb/204Pb = 16.890 ± 0.012, 207Pb/204Pb = 15.429 ± 0.014, and 208Pb/204Pb = 36.502 ± 0.028, based on 15 runs between September 2006 and May 2009. The fractionation correction is +0.13%/amu (based on the values of Trott et al., 1984). Sr isotope ratios are normalized to 87Sr/86Sr = 0.71000. Two Sr standards were run at Carleton University, NIST SRM987 (87Sr/86Sr = 0.710251 ± 16, n = 20, September 2006–May 2009) and the Eimer and Amend (E&A) SrCO3 (87Sr/86Sr = 0.708017 ± 20, n = 5, September 2006–May 2009). Nd isotope ratios are normalized to 143Nd/144Nd = 0.72190. Twenty runs of the La Jolla standard averaged 143Nd/144Nd = 0.511849 ± 8 (September 2006–May 2009). All quoted uncertainties are 2σ standard deviations of the mean. Isotopic data are listed in Table 3.

GEOCHEMISTRY

Lavas from the Carson Range, at the eastern edge of the Tahoe-Truckee volcanic field, range from basaltic trachyandesite to trachyandesite in composition (Fig. 3). The Steamboat Hills mafic flow is a basaltic trachyandesite, as are the New Empire flows and the Rattlesnake Hill lavas. The McClellan Peak, Upsal Hogback, and Soda Lake volcanic rocks are alkaline basalt. Lavas from the Buffalo Valley field range from alkaline basalt to trachybasalt. All of the western Nevada rocks are alkaline in composition, like most lavas of the Tahoe-Truckee volcanic field but unlike Tertiary lavas of the Ancestral Cascades arc.

The differences between volcanic fields are best demonstrated using primitive mantle–normalized incompatible element plots (Fig. 4). Lavas from the Carson Range, which straddle the transition between the Tertiary arc and Placocene–Pleistocene Tahoe-Truckee volcanic field in the Lake Tahoe region, have patterns that fall between arc and Tahoe-Truckee volcanic field lavas (Fig. 4A). The patterns have large positive spikes in Ba, Pb, and Sr, and a negative spike at Nb-Ta. Slightly to the east, volcanic rocks from McClellan Peak, New Empire, and Steamboat Hills flows resemble Tahoe-Truckee volcanic field lavas, but with less depletion in Nb-Ta and variably lower enrichments in Ba, Pb, and Sr (Fig. 4b). Note the differences in incompatible element patterns between McClellan Peak basaltic lavas from the Chalk Hills (basaltic andesite) and Virginia City (basalt) areas, including differing heavy (H) rare earth element (REE), Ti, and Nb-Ta characteristics. Further to the east, Rattlesnake Hill and Soda Lake lavas are significantly different from Tahoe-Truckee volcanic
field rocks, with only minor positive spikes at Ba and Pb, no Sr spike, almost no depletion in Nb and Ta relative to K and La, and higher HREE abundances (Fig. 4C). The five samples from Upsal Hogback, north of Fallon, have slightly variable but parallel patterns, all with neither Nb-Ta depletion nor Sr-Pb enrichment relative to La. For these samples, light (L) REE abundances are lower than Tahoe-Truckee volcanic field lavas, while HREE abundances are higher (Fig. 4D). A pattern for a ca. 3 Ma Buffalo Valley lava, 250 km northeast of Fallon, is shown in Figure 4D, and it is very similar to that of the Upsal Hogback lavas. The Buffalo Valley alkalic basalt lacks a negative Nb and Ta anomaly and is more similar to many intraplate alkaline volcanic rocks (e.g., Farmer et al., 1995; Sun and McDonough, 1989). Overall, from west to east, there is a shift from incompatible element patterns with subduction-zone characteristics to patterns with intraplate characteristics.

Sr and Nd isotopic ratios in the western centers, the Carson Range, New Empire, and Steamboat Hills, all fall within the range of Tahoe-Truckee volcanic field mafic lavas, with \( \varepsilon_{\text{Nd}} > +1 \); values than Tahoe-Truckee volcanic field lavas, as do the Buffalo Valley alkaline basalts. Pb isotope ratios in western Nevada volcanic rocks completely overlap the range measured in the Tahoe-Truckee volcanic field and Tertiary arc lavas (Fig. 5, inset), and they plot in an array at an angle to the Northern Hemisphere reference line (NHRL; Hart, 1984).

Oxygen isotope ratios vary between +8.2 and +6.0‰ within the western Nevada volcanic field. Carson Range lavas have the highest \( \delta^{18}O \) values, between +8.2‰ and +7.6‰. The New Empire and Steamboat Hills basaltic andesites range from +7.5‰ to +7.2‰, and McClellan Peak alkalic basalts range from +7.0‰ to +6.6‰. A Rattlesnake Hill lava has a \( \delta^{18}O \) value of +6.5‰, a Soda Lake bomb has a value of +6.1‰, and

TABLE 2. MAJOR- AND TRACE-ELEMENT COMPOSITIONS

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<tr>
<td>Total</td>
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<td>97.96</td>
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<td>98.88</td>
<td>98.53</td>
<td>98.66</td>
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</table>

(continued)
two Upsal Hogback samples range from +6.2‰ to +6.0‰. Three Buffalo Valley lava samples range from +6.4‰ to +5.6‰. In comparison, δ18O values in Tahoe-Truckee volcanic field mafic lavas range from +8.2‰ to +7.6‰, and mafic rocks of the Ancestral Cascades arc in the Lake Tahoe region have δ18O values between +8.1‰ and +6.3‰ (Cousens et al., 2008, 2011).

**DISCUSSION**

**Mantle Source versus Crustal Contamination Effects on Geochemistry**

Lavas from the western Nevada volcanic field range from basalt to trachyandesite in major-element composition. Whereas the basalts are likely to retain the characteristics of their mantle source, modified by some degree of crystallization, the more evolved rocks from the New Empire and Carson Range fields have undergone differentiation and possible crustal contamination.

The basement rocks for these fields are largely Sierra Nevada granitoids. These intrusive rocks have distinctively low P2O5/K2O, high present-day 87Sr/86Sr, and high Rb/Sr compared to basalts of the Ancestral Cascades arc or the Tahoe-Truckee volcanic field (Fig. 6). When compared with basaltic rocks of the Ancestral Cascades and Tahoe-Truckee volcanic field that record mantle source characteristics, P2O5/K2O in the New Empire flows and the least SiO2-rich (<55 wt%) Carson Range flows overlap with ratios in the Ancestral Cascade and Tahoe-Truckee volcanic field mafic lavas that are a good indicator of mantle source compositions. However, Carson Range flows with >55 wt% SiO2 clearly trend toward Sierra Nevada granitoids. Similarly, Rb/Sr values in New Empire and Carson Range low-SiO2 flows overlap with basalts of the Tahoe-Truckee volcanic field and Ancestral Cascades arc, whereas high-SiO2 lavas from the Carson Range also trend toward high Rb/Sr and 87Sr/86Sr of Sierran granitoids. We conclude that crustal contamination has strongly affected only the high-SiO2 lavas of the Carson Range, and has had only a weak or negligible effect on New Empire and low-SiO2 Carson Range lavas. Since we are primarily interested in source characteristics,
the following discussion will include the New Empire and low-SiO₂ Carson flows but will exclude the high-SiO₂ Carson Range lavas.

**Geochemical Trends with Geography**

Trace-element and isotopic compositions show a strong gradient east from the Tahoe-Truckee volcanic field across western Nevada toward the Fallon area. Tahoe-Truckee volcanic field lavas are characterized by enrichments in the large ion lithophile elements (LILEs) and deficiencies in the high field strength elements (HFSEs) relative to the REEs, commonly interpreted as a subduction-zone geochemical signature. However, Tahoe-Truckee volcanic field lavas also have high Sr and low Nd isotopic ratios, leading Cousins et al. (2011) to propose that Tahoe-Truckee volcanic field primary magmas are melts of ancient, subduction-modified lithospheric mantle beneath the Sierra Nevada (see also Cousins et al., 2008). Compared to the Tahoe-Truckee volcanic field, western Nevada volcanic field lavas do not have the same degree of enrichment in LILEs or depletion in HFSEs, differ in the slope of REE patterns, and have isotopic compositions that require mantle sources with lower ⁸⁷Sr/⁸⁶Sr and higher ¹⁴³Nd/¹⁴⁴Nd.

The longitudinal variation in key trace-element ratios and Sr isotope ratios is shown in Figure 7. In addition to Tertiary arc and younger postarc analyses, we include data from Tertiary mafic rocks of the Great Basin within the study area (small crosses: Stillwater Range, Bell Mountains, Hotspur Mountains, Truckee and Virginia Ranges, Fish Creek Mountains; A. Timmermans, 2004, personal commun.). The TiO₂ and Ba/La values, the size of the negative Nb anomaly (defined as Nb pmn /([Th + La] pmn /2), where pmn is primitive mantle–normalized), and Sr isotope ratios, all elements and ratios that help to discriminate subduction from intraplate signatures, exhibit shifts in value from the Tahoe-Truckee volcanic field, at 120°W to 120.5°W, east to the Buffalo Valley field. TiO₂ increases, while Ba/La, the size of the negative Nb anomaly, and the ⁸⁷Sr/⁸⁶Sr ratio all decrease from west to east. To the west, arc and postarc volcanic rocks have a chemical signature related to melting of old lithospheric mantle enriched by subduction-related fluids, including lavas in the Carson
Range, the New Empire flows, and the McClellan basalt from the Virginia City area. With the exception of Great Basin Tertiary mafic rocks, between 120°W and 119.5°W, there is a poorly defined shift to a mixed subduction-zone–intraplate signature, where lavas have smaller negative Nb anomalies and lower Ba/La values. East of 119°W, an intraplate signature dominates in the Pliocene–Quaternary volcanic rocks, with virtually no negative Nb anomaly and lower 87Sr/86Sr ratios in the lavas. At the east end of the sampled volcanic centers, the Buffalo Valley Quaternary lavas appear to define an intraplate end member, both chemically and geographically. Note the large difference in chemistry between Tertiary and Quaternary basalts in the Buffalo Valley area (117°W to 117.5°W; Fig. 7).

The strong correlation between the Nb anomaly and isotopic characteristics in younger than 3 Ma volcanic rocks of the Tahoe-Truckee volcanic field and western Nevada volcanic field is shown in Figure 8. As the Sr isotope ratio and δ¹⁸O values in Tahoe-Truckee volcanic field and western Nevada volcanic rocks decrease, so too does the size of the negative Nb anomaly. In Figure 8A, the mafic Carson Range lavas fall in the center of the Ancestral Cascades field but on the edge of the Tahoe-Truckee volcanic field, reflecting that the Carson Range eruptions occurred at the transition between arc and postarc activity and thus have characteristics in common with both settings (Cousens et al., 2011). Steamboat Hills, New Empire, and the McClellan Peak flow from Virginia City (the western part of the western Nevada volcanic field centers) all plot in or very close to the Tahoe-Truckee volcanic field. The Rattlesnake Hill, Soda Lakes, and Upsal Hogback lavas (eastern part of the western Nevada volcanic field centers) plot closer to the Buffalo Valley lavas with a strong intraplate signature. Like the Nb anomaly, other chemical indicators of a subduction-zone signature, such as Ba/La or Sr/Nd, also correlate strongly with 87Sr/86Sr. The δ¹⁸O values correlate well with Nb*, and also with Sr and Nd isotopic ratios, ranging from values >+7‰ in the Tahoe-Truckee volcanic field and

<table>
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<th>Complex:</th>
<th>Upsal Hogback</th>
<th>Upsal Hogback</th>
<th>Upsal Hogback</th>
<th>Upsal Hogback</th>
<th>Buffalo Valley</th>
<th>Precision</th>
<th>Average %</th>
<th>deviation of duplicates</th>
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<tr>
<td>Age (Ma):</td>
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Note: Major-element oxides (wt%) and trace elements V through Ba (ppm) were analyzed by X-ray fluorescence; La through Pb (ppm) were analyzed by acid-dissolution–inductively coupled plasma–mass spectrometry. Fe₂O₃t—total iron expressed as Fe₂O₃; bdl—below detection limit; LOI—loss on ignition; CH—Chalk Hills; VC—Virginia City. Precisions are based on repeat analyses of duplicate rocks over 5 yr time period.

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Pliocene–Quaternary volcanism beneath the modern Sierra Nevada and adjacent Great Basin

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western section of the western Nevada volcanic field lavas to +6‰ or lower in the eastern section of the western Nevada volcanic field and Buffalo Valley lavas. The latter volcanic centers have δ18O that are typical of magmas from an asthenospheric source (Eiler, 2001).

Of local geological significance, the McClellan Peak Basalt group includes the New Empire basaltic trachyandesites and the Virginia City quadrangle and Chalk Hills quadrangle alkalic basalt exposures (Thompson, 1956; Thompson and White, 1964). Although lumped into a single map unit, it is unlikely that these three lavas are related to one another. All three localities have distinct isotopic compositions, Nb anomalies, and TiO2 contents (Figs. 5 and 7). We conclude that these three units represent three different eruptive events that are close in age but different in terms of mantle source and petrologic history.

Mantle Sources beneath the Sierra Nevada of Northeastern California: Miocene to Quaternary

Tertiary through Quaternary volcanism in the northern Sierra Nevada and adjacent western Nevada has tapped several different mantle sources through time. During the Miocene and Pliocene, volcanism in the northern and central Sierra Nevada was the result of subduction of the Farallon plate as it rolled back from its Late Cretaceous–early Cenozoic shallow dip beneath North America (e.g., Busby et al., 2008; Couzens et al., 2008; Dickinson, 1997, 2004; Humphreys et al., 2003; Putirka and Busby, 2007). Although lumped into a single map unit, it is unlikely that these three lavas are related to one another. All three localities have distinct isotopic compositions, Nb anomalies, and TiO2 contents (Figs. 5 and 7). We conclude that these three units represent three different eruptive events that are close in age but different in terms of mantle source and petrologic history.

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Figure 4. Primitive mantle–normalized (Sun and McDonough, 1989) incompatible element abundances in lavas from the western Nevada volcanic field. Dashed green field encloses mafic lavas of the Ancestral Cascades arc, and red lines enclose lavas of the Tahoe-Truckee volcanic field. Data sources are as in Figure 3.
whereas magmatism north of the Sierra Nevada has the lower Sr isotope ratio signature. This led Cousens et al. (2008) to propose that the location of the older, more-enriched mantle source for the Ancestral Cascades was subduction-modified lithospheric mantle beneath the Sierra Nevada. Arc volcanism during the Tertiary can be modeled as a mixture of contributions from this old lithospheric mantle source and the Miocene mantle wedge (Cousens et al., 2008).

The lavas of the Tahoe-Truckee volcanic field postdate the passage of the south edge of the subducting Juan de Fuca plate and represent post-arc volcanism associated with a slab window beneath the northern Sierra Nevada. Compared to the older arc volcanic rocks, Tahoe-Truckee volcanic field lavas are small in volume, nonporphyritic, and mildly alkalic. Tahoe-Truckee volcanic field lavas have a subduction signature in primitive mantle-normalized plots but, compared to the older arc rocks, are enriched in the LREEs, Nb, and Ta, and depleted in the LILEs. Isotopically, Tahoe-Truckee volcanic field rocks overlap with Ancestral Cascade arc lavas, although most Tahoe-Truckee volcanic field rocks fall at the high $\delta^{18}$O end of the range of Ancestral Cascade compositions. Postarc lavas also have high $\delta^{18}$O values that fall at the isotopically heavy end of the Ancestral Cascade arc range (+8.1‰ to +7.3‰). Postarc lavas primarily tapped a lithospheric mantle source (high $\delta^{18}$O, $\delta^{13}$C), triggered by hot asthenospheric mantle upwelling around the south edge of the Juan de Fuca slab and impinging on the base of the lithosphere (Cousens et al., 2011). Tahoe-Truckee volcanic field lavas include a much lower proportion of melts from the (now, ex-) mantle wedge, since slab fluids were no longer supplied to the mantle beneath this region. The lithospheric mantle source for the Tahoe-Truckee volcanic field is similar chemically and mineralogically to that of the Big Pine volcanic field and Long Valley caldera in the western Great Basin (Cousens et al., 2011). Thus, Tahoe-Truckee volcanic field and western Great Basin lavas share the same subduction-modified, sub-Sierran lithospheric mantle source (Cousens et al., 2011).

Mantle Sources beneath Western Nevada: Miocene to Quaternary

Few published geochemical data exist for Miocene to Pliocene volcanic rocks in western Nevada. Geochemical data from mafic volcanic rocks from the west (Hotsprings Mountains, Virginia and Truckee Ranges) and east (Stillwater Range, Bell Mountains) sides of the Carson mountain show that most lavas have low TiO$_2$, high Ba/La, large negative Nb anomalies (Nb$_* \approx$ 0.1–0.6), and high $^{87}$Sr/$^{86}$Sr > 0.7040 (Fig. 7; Cousens et al., 2009). In the Buffalo Valley area, Tertiary basalts (thin cross symbols in Fig. 7) have Nb$_* \sim$ 0.3 and $^{87}$Sr/$^{86}$Sr as high as 0.70706 (Cousens and Henry, 2008). We propose that Tertiary volcanism in the entire study region includes an ancient subduction geochemical signature derived from melting of the lithospheric mantle during rollback of the Farallon slab (Gupta et al., 2007). Efforts to characterize the geochemistry of Tertiary volcanism in the north-central to western Great Basin are ongoing (e.g., Varve et al., 2011).

Mafic lavas of the western Nevada volcanic field demonstrate a good correlation between $^{87}$Sr/$^{86}$Sr and $^{143}$Nd/$^{144}$Nd that can be modeled as mixing between melts derived from the lithospheric mantle (LM, Sierran source) and a typical Buffalo Valley magma (BV, Great Basin intraplate source) (Fig. 9). The lithospheric mantle composition was chosen based on analyses of basalts from the Tahoe-Truckee volcanic field and the Big Pine volcanic field (Ormeord et al., 1991). Carson Range (low-SiO$_2$ only), New Empire, Steamboat Hills, and McClellan Peak basalts include 25%–50% melt derived from the lithospheric mantle, whereas Rattlesnake Hill, Soda Lakes, and Upsal Hoback lavas include only 10%–20%. However, as noted by Gupta et al. (2007), the western group of volcanic centers (Carson Range, Steamboat, New Empire, and McClellan Peak basalts) forms an array with a much steeper trajectory than the mixing curve, whereas most of the eastern centers (Soda Lakes, Upsal Hoback, Rattlesnake Hill) plot below the curve. Thus, this two-component mixing model appears to be overly simple. In Figure 8, the relationship between Nb$_*$ and $^{87}$Sr/$^{86}$Sr (as well as $^{87}$Sr/$^{86}$Sr) appears to be roughly linear from the Carson Range to Buffalo Valley. As in Figure 9, this trend may represent mixing of melts derived from a “Sierran” lithospheric mantle source (LM in Fig. 8) and a “Great Basin”
asthenospheric mantle source (AS in Fig. 8) (Gupta et al., 2007). However, the large Sr/Nb ratio in Sierra Nevada postarc rocks compared to Buffalo Valley lavas means that mixing curves will be markedly curved, not linear. The upper mixing curve in Figure 8 assumes a lithospheric mantle source with the highest measured Sr isotope ratio in Tahoe-Truckee volcanic field lavas, and this curve does not reproduce the western Nevada volcanic field—Buffalo Valley data array. Assuming a McClellan Peak basalt mixing end member produces a curved mixing trend (lower curve, Fig. 8) that more closely approximates the western Nevada volcanic field—Buffalo Valley trend.

### Controls on Depth and Degree of Melting

The depth of melting and the mineralogy of the mantle source for Great Basin basaltic rocks have been estimated using partial melting models focusing on the rare earth elements. Cousens et al. (2011) modeled lavas from the Ancestral Cascades arc and Tahoe-Truckee volcanic field as partial melts of metasomatized spinel peridotite, inferring that depths of melting in the mantle were <70 km. In contrast, Bradshaw et al. (1993) and Smith et al. (1999) considered that basalts from the Colorado River Trough (southern Great Basin) and Colorado Plateau transition zone (eastern Great Basin) melted in the garnet stability field with garnet left behind in the residue. A comparison of trace-element and isotopic characteristics between western Nevada volcanic field lavas and young volcanic rocks of the southern and eastern Great Basin...
shows remarkable similarity, and thus we feel that the melting model of Bradshaw et al. (1993) is an excellent starting point.

Figure 10 shows the variation of Ce/Yb_{pnn} (pnn = primitive mantle–normalized) with Yb_{pnn} in mafic lavas from the Ancestral Cascades arc, the Tahoe- Truckee volcanic field, and the western Nevada volcanic field, with partial melting curves (black curves) for garnet peridotite with varying garnet content and for a garnet-free peridotite with the same bulk composition. Melting curves assume the same composition and batch melting equation as Bradshaw et al. (1993). Also shown are two melting curves for an enriched (ESP, blue curve) and a depleted (DSP, orange curve) spinel peridotite from the Big Pine volcanic field (Cousens et al., 2011). Ancestral Cascades arc lavas can be modeled as 10%–15% partial melts of a source that includes 5%–3% garnet. Tahoe-Truckee volcanic field lavas are lower-degree melts of a source similar to that of the Ancestral Cascades arc lavas, and the McClellan Peak alkalic basalts overlap with the Tahoe-Truckee volcanic field. The Rattlesnake Hill and Soda Lakes volcanic centers are spread along the 2% garnet-bearing source, ranging from 3% to 10% melting. Upsal Hogback basalts plot between the 2% and 1% garnet-bearing peridotite melting curves, at degrees of melting between ~4% and 10%. Less garnet in the source is consistent with the overall flattening of middle-to-heavy REE patterns in the eastern section of the western Nevada volcanic field compared to the western section, and crossing REE patterns are typical of lavas with variable proportions of garnet in the source (e.g., Garcia et al., 2010) (Fig. 4).

One implication of the differing garnet contents in sources for the western versus the eastern western Nevada volcanic field lavas is that melting in the western localities occurs at a depth greater than that of the eastern localities. Another possibility is that the bulk composition of the mantle sources beneath the Fallon area is different from that of the near-Sierra volcanic centers, perhaps shifted to lower Ce/Yb and higher Yb content than the model garnet lherzolite used here.

**Lithospheric versus Asthenospheric Mantle Sources and Volcanism in the Great Basin**

The geochemical characteristics of Tertiary to Quaternary volcanism in the Sierra Nevada of northeastern California and western Nevada are consistent with at least three mantle source types in the region between Lake Tahoe and Fallon. Tertiary lavas are derived by mixing of components from two sources, one being the lithospheric mantle with high 87Sr/86Sr and δ18O, low 143Nd/144Nd, and normalized incompatible element patterns with strong subduction-related signatures, the second being the underlying mantle wedge with a composition roughly similar to that beneath the modern South Cascades (Cousens et al., 2008). The lithospheric mantle beneath the Sierra Nevada (and elsewhere surrounding the Great Basin) was variably enriched during both ancient and Mesozoic to Early Tertiary subduction events (e.g., Bradshaw et al., 1993; DePaolo and Daley, 2000; Ormerod et al., 1991). Pliocene
and younger lavas that erupted along the eastern margin of the Sierra Nevada, such as the Big Pine volcanic field and the Tahoe-Truckee volcanic field, have the same geochemical characteristics as the high-$\delta^{18}$O Tertiary arc lavas and thus share the same sub-Sierra lithospheric mantle source. East of the eastern edge of the Sierra Nevada, Quaternary western Nevada volcanic field centers have more of an intraplate geochemistry, and the lavas lack the strong subduction signature that characterizes the nearby Tertiary lavas erupted in the same region.

Other studies of volcanic fields in the Great Basin have described many of the same geochemical characteristics with time as is seen in the western Nevada volcanic field, including the Cima volcanic field in the Mojave Desert, the Hurricane volcanic field in Utah, and the Colorado River Trough. Miocene volcanism in the Mojave Desert tapped variable but ancient mantle sources, both with $^{208}$Pb/$^{206}$Pb well above the NHRL (MT east and west, Fig. 11) (Miller et al., 2000; Mukasa and Wilshire, 1997). Younger Cima basalts are mostly purely intraplate-type lavas with low $^{87}$Sr/$^{86}$Sr ($<0.7030$), $\delta^{18}$O ($+5.8\%$ to $+6.4\%$), and Pb isotope ratios close to the NHRL (Cima, Fig. 11) (Farmer et al., 1995). The Quaternary Hurricane field includes alkali basalts that are Nb-depleted and Sr-enriched relative to the REEs, and have generally high $^{87}$Sr/$^{86}$Sr ($<0.7050$) ratios, and basanites that have smooth intraplate-type trace-element patterns with high Nb contents, lower $^{87}$Sr/$^{86}$Sr ratios ($<0.7040$), and Pb isotopic ratios just above the NHRL (Hurricane, Fig. 11) (Smith et al., 1999). The Colorado River Trough in the southern Great Basin is a zone of Miocene extension with associated mildly alkaline basaltic volcanism (Bradshaw et al., 1993). Most of the basaltic rocks have an ancient lithospheric mantle geochemical signature (Bradshaw et al., 1993; Daley and DePaolo, 1992), but a few low-volume, post-extensional volcanic centers were sampled with intraplate-type incompatible element patterns, lower $^{87}$Sr/$^{86}$Sr ($<0.7050$), and Pb isotope ratios closer to the NHRL (CRT, Fig. 11). In all three of the examples, the association of younger lavas with intraplate-type sources is a common characteristic of Great Basin volcanism.

Smith et al. (1999), Farmer et al. (1995), and Bradshaw et al. (1993) disagree, however, on the location of the intraplate-type mantle source. Smith et al. argued that melting of a heterogeneous lithospheric mantle has produced all of the magmas erupted in the Hurricane volcanic field, based on the uniformly low $^{4}$He/$^{He}$ and Th-isotopic characteristics of lavas from the eastern margin of the Great Basin (Reid and Graham, 1996; Reid and Ramos, 1996). Pb isotope ratios in all Hurricane volcanic rocks also plot above the NHRL (Hart, 1984). Bradshaw et al. linked the Nb-depleted, high-$^{87}$Sr/$^{86}$Sr to a ca. 1.6 Ga lithospheric source, and thus argued that any intraplate-like source must be in the asthenosphere. The intraplate-type basalts of the Colorado River Trough also plot closer to the NHRL than do Nb-depleted volcanic rocks. In agreement with Bradshaw et al., Farmer et al. placed the source of Cima intraplate-type lavas in the asthenosphere, based on radiogenic isotopic ratios and oxygen isotope ratios that overlap with mid-ocean-ridge basalts (MORB). Cima lavas have $^{4}$He/$^{He}$ (R/R$_\infty$ = 7.7–7.9), just slightly below that of MORB (Reid and Graham, 1996). A Pleistocene Lunar Craters basalt from central Nevada has $^{4}$He/$^{He}$ within the MORB range (Dodson et al., 1998), consistent with a source in the asthenosphere.

In the case of the western Nevada volcanic field, oxygen isotope ratios in the basaltic western lavas, close to the Sierra Nevada, are higher than oxygen isotope ratios in the basaltic eastern lavas and Buffalo Valley alkalic basalts, consistent with an asthenospheric upper-mantle source for the eastern volcanic centers. What other evidence can be used to infer a lithospheric or asthenospheric source? Lavas of the western Nevada volcanic field have Pb isotope ratios that overlap with Tertiary arc lavas of the Sierra Nevada as well as those of the Tahoe-Truckee volcanic field (bright-yellow field, Fig. 11). There is only a subtle shift toward more asthenospheric compositions in the Fallon area volcanic centers. The sole Pb isotopic analysis of Buffalo Valley alkalic basalt does plot closer to the NHRL, as do the youngest Pliocene lavas (episode 2) from Reveille Range in central Nevada (Yogodzinski et al., 1996), consistent with an asthenospheric source for young basaltic centers in central Nevada. Since Pb isotopes are generally more sensitive to ancient crustal or mantle inputs than Sr or Nd isotopes, we tentatively propose that eastern sections of western Nevada volcanic field lavas include a small Pb component originating from the lithosphere, but they are primarily melts of the asthenosphere. Upsal Hogback lavas have particularly high Mg

Figure 9. Best-fit mixing curve for melts of lithospheric mantle (LM) and Buffalo Valley (BV) magmas. Only mafic rocks from the Ancestral Cascades arc (ACA) and Tahoe-Truckee volcanic field (TTVF) are plotted. Tick marks show the percentage of LM melt in the mix.
numbers and are least likely to be contaminated by upper-crustal rocks, and they plot closest to, but still above, the NHRL.

The western Nevada volcanic field to Buffalo Valley corridor is a region of high geothermal gradient and lies within the Humboldt Lineament, a zone of thinned lithosphere (Louie et al., 2004). Lithospheric thinning might serve to remove deeper parts of the lithospheric mantle that has incurred more ancient metasomatism, and thus leave only the upper, less metasomatized, less fusible lithospheric mantle in the Humboldt Lineament. Lithospheric thinning also allows asthenosphere to rise to shallower depth, potentially resulting in partial melting. Thus, mantle melting beneath the Humboldt Lineament should occur primarily in the asthenosphere, as is evidenced by the composition of Quaternary volcanic rocks erupted in the Fallon and Buffalo Valley areas.

CONCLUSIONS

Small-volume, latest Pliocene to Holocene, volcanic rocks are exposed in western Nevada, herein collectively referred to as the western Nevada volcanic field. Lavas from the western part of the western Nevada volcanic field, including the Carson Range, Steamboat Hills, the New Empire, and McClellan Peak basalt localities, are very similar chemically to lavas of the Pliocene–Quaternary Tahoe-Truckee volcanic field in the Lake Tahoe region to the west. Considering only basaltic lavas (McClellan Peak) and some more evolved lavas that show minimal interaction with continental crust (New Empire, some Carson Range lavas), radiogenic and oxygen isotope ratios are consistent with a metasomatized lithospheric mantle source like that of Tahoe-Truckee volcanic field lavas. However, lavas from the eastern part of the western Nevada volcanic field, including Rattlesnake Peak, Soda Lakes, and Upsal Hogback in the Carson Sink, have incompatible element patterns and radiogenic isotope ratios that are more similar to postextension, intraplate lavas in central Nevada, such as Buffalo Valley and Lunar Crater alkaline basalts. There is a dramatic geographic gradient in chemical and isotopic composition across the western Nevada volcanic field from the eastern edge of the Sierra Nevada to the Carson Sink. The intraplate mantle source lacks any subduction signature and is geochemically consistent with an asthenospheric source. Partial melting models indicate that garnet may be present in the intraplate source.

Compared to the eastern part of the western Nevada volcanic field, latest Pliocene to Quaternary volcanism in the Sierra Nevada distin-

![Figure 10](image1.png)

**Figure 10.** Melting model for garnet peridotite from Bradshaw et al. (1993). Black curves are melting curves for 5%, 4%, 3%, 2%, 1%, and 0% (gar-free) garnet in peridotite. Tick marks indicate percent melting of each model composition. Parent garnet lherzolite is from the Big Pine volcanic field (Beard and Glazner, 1995). ESP (blue curve) and DSP (orange curve) are enriched and depleted spinel peridotite melting curves from Cousens et al. (2011), also based on peridotite xenoliths from Big Pine, with tick marks showing percent melting. Blue field—Ancestral Cascades arc (ACA) mafic rocks. Yellow field—Tahoe-Truckee volcanic field (TTVF) mafic lavas. Sources are as in Figure 6, plus data from Lunar Craters (Dickson, 1997; Stickney, 2004).

![Figure 11](image2.png)

**Figure 11.** Pb isotope plot for lavas of the Great Basin and Mojave Desert. Eastern part of the western Nevada volcanic field lavas plot closer to the Northern Hemisphere reference line (NHRL; Hart, 1984) than western section of western Nevada volcanic field lavas, consistent with a larger asthenospheric mantle source component in the former. Data sources are as in Figure 6, plus Bradshaw et al. (1993); Farmer et al. (1995); Miller et al. (2000); Mukasa and Wilshire (1997); Smith et al. (1999); and Yogodzinski et al. (1996).
guished itself by retaining a mantle source that dominantly resides in the lithospheric mantle (Cousens et al., 2011). This lithospheric mantle source appears to have existed prior to the voluminous phase of Mesozoic arc activity that created the Sierra Nevada Batholith, since most Sierra Nevada plutonic rocks also have high initial \(^{187}\text{Os}/^{187}\text{Os}\) and low \(^{143}\text{Nd}/^{144}\text{Nd}\) ratios, which are consistent with melts of an old mantle component mixing with crustal rocks (Barbarin et al., 1989; Kistler et al., 1986; Kistler, 1990; Sisson et al., 1996). Tertiary volcanic rocks of the Ancstral Cascades are in the Sierra Nevada also have this lithospheric mantle signature (Cousens et al., 2008), as do extension-related volcanic rocks of the western Great Basin along the eastern margin of the Sierra Nevada (e.g., Beard and Glazner, 1995; Blonesd et al., 2008). Although poorly studied, Eocene through Miocene igneous rocks in the Great Basin appear to have a Sierra-like, metasomatized mantle source (Fig.7). However, Pliocene and younger volcanic rocks erupted in the central Great Basin lack this older lithospheric mantle signature and are largely derived from the asthenosphere (this study; Cousens and Henry, 2008; Yogodzinski et al., 1996). We suggest that Tertiary extension and igneous activity in the Great Basin has thinned the lithospheric mantle and/or depleted it in fusible components, such that subsequent volcanism away from the margins of the extensional zone can only have an asthenospheric source (if conditions for melting permit). Thus, the sub-Sierra Nevada lithospheric mantle, formed prior to the Mesozoic, remains an island of fusible, old, subduction-modified mantle material in the southwestern United States.

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