The tectonic significance of high-K_2O volcanism in the Sierra Nevada, California

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ABSTRACT

K_2O contents have long been recognized as a potential indicator of tectonic processes, and in the Sierra Nevada, California, high-K_2O volcanism has been attributed to lithosphere root delamination. However, new data from the central Sierra suggest a very different control: K_2O concentrations can be explained by variations in the degree of partial melting in the mantle, where high-K_2O volcanics are derived from low-degree partial melts of mantle lithosphere. Field evidence in the central Sierra further suggests that the pulse of high-K_2O volcanism there was synchronous with the development of a pull-apart structure along a series of right-stepping dextral transtensional faults at the onset of Walker Lane transtensional faulting. In our alternative interpretation, high-K, low-degree partial melts were tapped by the inception of transtensional stresses, recording the birth of a plate boundary. We speculate that high-K_2O lavas in the southern Sierra are similarly related to the onset of transtensional stresses, not delamination. A regional southward increase in incompatible element contents and decrease in erupted volumes are also consistent with a model for crustal thickness controls on magmatism. Depth-integrated density models show that dry mafic magmas beneath thick crust have insufficient buoyancy to erupt, but low-degree partial melts carry sufficient volatiles to allow eruption; as with K_2O, degree of partial melting, not source-region heterogeneity, controls water contents and buoyancy.

Keywords: Sierra Nevada, volcanism, Basin and Range, transtension, delamination, lithosphere.

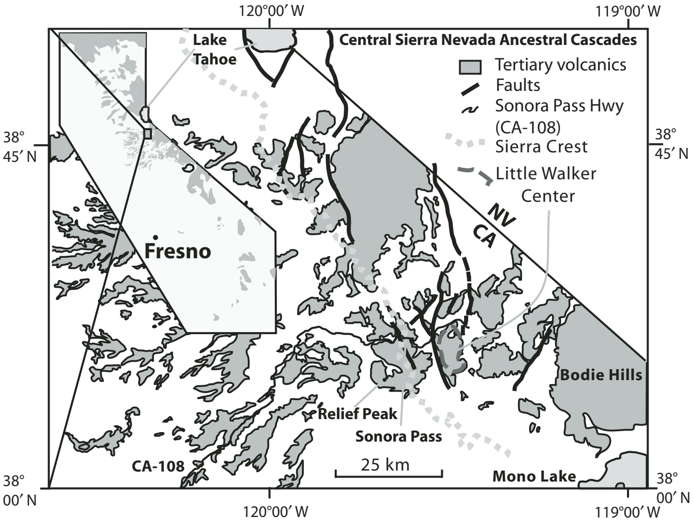

Figure 1. Tertiary volcanic and intrusive rocks and frontal fault system of central Sierra Nevada. These faults form part of dextral transtensional Walker Lane belt at western edge of Basin and Range extensional province. Sierran range-front faults generally step left along range front, but we recognize a local right (releasing) step-over that was active during 10–9 Ma high-K_2O magmatism at Little Walker Center. Inset shows southward decrease in Tertiary magmatic rocks within Sierra Nevada.

INTRODUCTION

The Sierra Nevada has recently become the archetype of lithosphere delamination (e.g., Ducea and Saleeby, 1996; Zandt et al., 2004). Building upon models developed for the Andes (Kay and Kay, 1993) and Tibet (Turner et al., 1996), it has been proposed that Pliocene high-K magmas in the southern Sierra signal the initiation of lithosphere delamination (Feldstein and Lange, 1999; Farmer et al., 2002). In this model, delamination presumably exposed a K_2O-enriched lower-crust or upper-mantle source that was subsequently partially melted (Feldstein and Lange, 1999; Farmer et al., 2002). Our new data from the central Sierra Nevada (Fig. 1) cast doubt on the K_2O-delamination link. We show that high-K_2O volcanism is better explained by variations in the degree of partial melting (F) in the mantle source region, and that thick crust impedes the eruption of all but low-F magmas under conditions of high tensile stress; in the Sierra Nevada, tensile stresses were controlled by the onset of Walker Lane transtension at the eastern edge of the Basin and Range Province.

There are several reasons for doubting that high-K Pliocene magmas indicate the initiation of lithosphere removal. Ducea and Saleeby's (1996) delamination model involves the removal of >100 km of lithosphere. This should have increased melt production, leading to greater melt volumes with *lower* incompatible element contents. But in the southern Sierra, Pliocene "postdelamination" melt volumes are not greater than Miocene "predelamination" volumes (Moore and Dodge, 1980; Farmer et al., 2002), and Pliocene lavas have elevated incompatible element concentrations. Furthermore, La/Nb ratios (DePaolo and Daley, 2000) demonstrate greater lithosphere involvement for Pliocene compared to Miocene magmas (Fig. 2), which is opposite of that predicted by delamination. A Pliocene delamination initiation event also does not explain a ca. 10 Ma magmatic flare-up in the Sierra, following a >50 m.y. magmatic hiatus. The physical model also seems implausible, i.e., that the base of the lithosphere is removed across a discrete surface to expose a previously untapped, enriched source. Lithosphere removal is likely governed by Rayleigh-Taylor instabilities (Platt and England, 1994) and should remove enriched lithosphere, not expose it; the term "delamination" may be a misnomer.

TECTONIC AND GEOLOGIC BACKGROUND

Rocks of the Sonora Pass region in the central Sierra Nevada, California (Fig. 1), provide a test of the high-K–delamination link. These rocks include the type example of "latite" (Ransome, 1898), and they were likely erupted in a subduction setting (Atwater, 1989). Our new data indicate that Ancestral Cascades arc volcanism began in the central Sierra at 15 Ma due to trenchward migration of the arc from Nevada into California (Busby et al., 2007a, 2007b). Arc volcanism was shut off by 6 Ma in the central Sierra due to passage of the Mendocino triple junction (Busby et al., 2007a, 2007b). In the Sonora Pass region (Fig. 1), this ca. 15–6 Ma andesite arc activity was interrupted by a ca. 10–9 Ma episode of voluminous high-K_2O volcanism, which is referred to as the Stanislaus Group (Busby et al., 2007a, 2007b).

Central Sierran arc volcanic rocks are divided on the basis of $^{40}Ar/^{39}Ar$ age dates and mapping of volcanic-volcaniclastic lithofacies and intrusions and faults (Busby et al., 2007a, 2007b). Samples were analyzed for major oxides by X-ray fluorescence at the California State University,

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Fresno. Trace elements were obtained by inductively coupled plasma–mass spectrometry (ICP-MS) at the Universidad Nacional Autónoma de México (see Busby et al., 2007b). Whole-rock compositions range from basalt to rhyolite; most rocks are "trachytic," with medium- to high-K contents (Busby et al., 2007b). Major element data are in Busby et al. (2007b); trace element data are available in the GSA Data Repository.[1]

Field and age data show that the high-K_2O Little Walker Center, the proposed source of the Stanislaus Group (Noble et al., 1974; Priest, 1979), is the largest Miocene volcanic center in the Sierra Nevada. We propose that it formed at a releasing step-over on dextral transtensional faults along the western edge of the Walker Lane belt at its inception, at 10 Ma—coincident with the high-K_2O eruptions (Fig. 1). The Sonora Pass region also marks a distinct geologic transition. To the south, there is the "high" Sierra, where peaks exceed 3500 m and Mesozoic tonalite and granodiorite are the dominant rock type (Bateman, 1992) and rocks have initial $^{87}Sr/^{86}Sr > 0.706$ (Kistler and Peterman, 1973). To the north, elevations decrease, initial $^{87}Sr/^{86}Sr$ is < 0.706 for granitic basement, and Tertiary volcanic and intrusive rocks dominate the landscape (Fig. 1). As we show, this corresponds to a southward increase in granitic crustal thickness (Mavko and Thompson, 1983), which prevents dry, high-*F* mantle melts from reaching the surface.

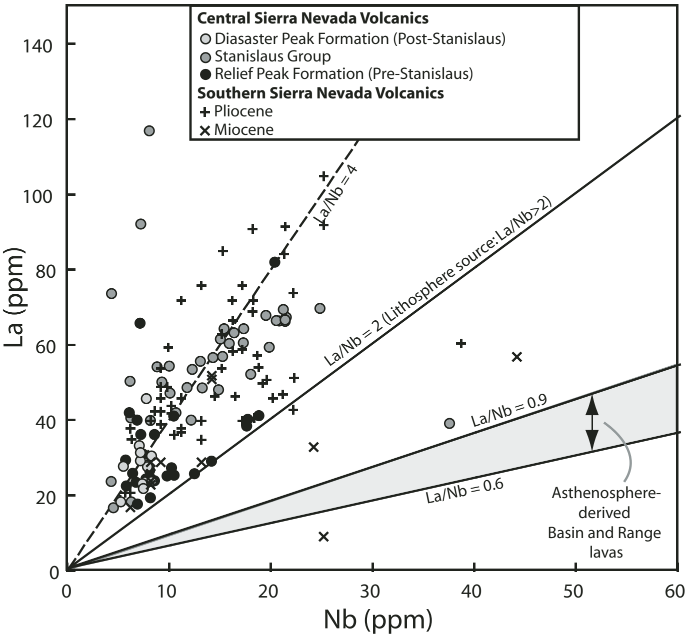

Figure 2. La versus Nb for volcanic rocks from central and southern Sierra Nevada (Feldstein and Lange, 1999; Farmer et al., 2002), with boundaries for asthenosphere-derived Basin and Range lavas in gray (DePaolo and Daley, 2000). Sierra Nevada lavas have high La/Nb, indicating a mantle lithosphere source. Pliocene lavas from southern Sierra have higher La/Nb (range = 1.5–6.5; avg. = 3.9) compared to their Miocene counterparts (La/Nb < 4; avg. = 2.5), indicating an increasing lithosphere component with time, which is counter to a lithosphere delamination model.

GEOCHEMICAL RESULTS AND DISCUSSION

The latites of Sonora Pass represent a pulse of high-K_2O volcanism at ca. 10 Ma. Like the southern Sierra, central Sierra lavas have high Ba/Nb and La/Nb ratios that indicate a mantle lithosphere source (Kempton et al., 1991; DePaolo and Daley, 2000). There is also an interesting spatial pattern in the Sierra: maximum K_2O contents (at a given MgO or SiO_2 content) increase from north (Lassen) to south. These variations can be explained by a combination of varying *F* in the source region, followed by fractional crystallization—with no need for K-metasomatism or other source enrichments that are unique to one part of the Cordillera. Mafic Stanislaus Group lavas, for example, require primitive melts that have 1% more K_2O than earlier and later volcanics (Fig. 3). Using average K_2O contents for Sierran peridotite xenoliths (Beard and Glazner, 1995), such K_2O contents can be generated when *F* is 4%–5% (Fig. 2). Medium-K_2O pre- and post-Stanislaus magmas require $6\% < F < 10\%$, and ultrapotassic southern Sierra lavas are explained by $F = 0.5\%–1.0\%$; the lowest SiO_2 contents in the southern Sierra are best explained by a garnet- rather than a spinel-peridotite residue. In contrast, mafic lavas at Lassen require *F* as high as 10% (Clynne and Borg, 1997). This is not to say that the mantle is not enriched; subduction-related modification of the mantle throughout the Cordillera has been documented (Kempton et al., 1991; Ormerod et al., 1991; Clynne and Borg, 1997; Lee, 2005). But the factors that govern inter- and intrasuite K_2O variations require no special forms of mantle enrichment.

If K_2O contents are controlled by *F*, then so must be the concentrations of other highly incompatible elements, and indeed, K_2O contents are highly correlated with Rb (R = 0.88), Ba (R = 0.83), La (R = 0.73), Pb (R = 0.83), Th, (R = 0.82), and U (R = 0.85). Like K_2O, trace-element abundances increase from north to south and can be explained by similar variations in *F* (Fig. 4). This does not mean that the source regions of these volcanics are identical. Stanislaus Group latites have high Th and U, and southern Sierra Pliocene lavas have high Sr (Fig. 4); heterogeneity is assured. However, the broader variations in highly incompatible elements do not require wholesale changes in the mantle source.

Notably, a phlogopite-bearing source has been postulated for high-K_2O lavas (Van Kooten, 1980; Feldstein and Lange, 1999), but such a source is not required to generate high-K_2O magmas in the Sierra (Fig. 4), and as presented in Ormerod et al. (1991), a phlogopite-bearing residue is

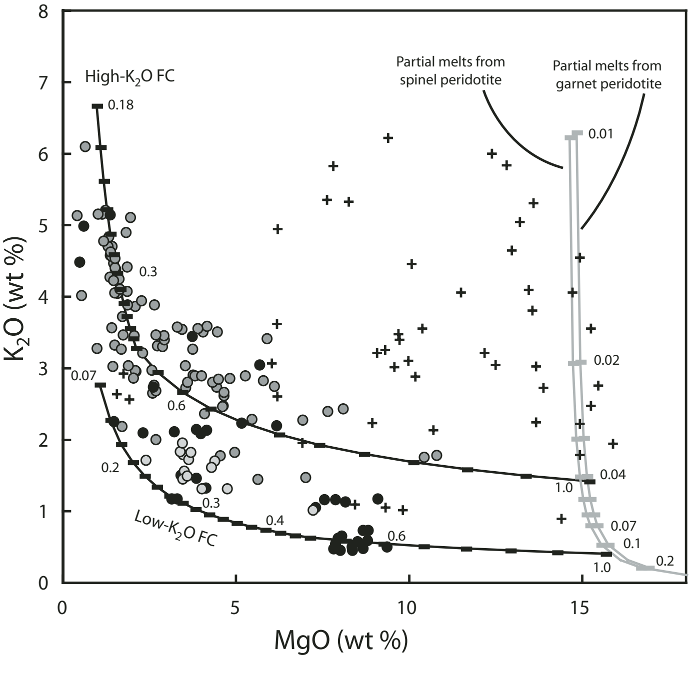

Figure 3. K_2O versus MgO. Near vertical gray lines show partial melts of a peridotite using average xenolith compositions (Beard and Glazner, 1995); partitioning is based on mineral/liquid compositions from Walter (1998); hachure marks indicate partial-melt fraction (*F*). Dark solid lines are fractional crystallization (FC) trends (olivine + plagioclase + clinopyroxene, followed by olivine + plagioclase + clinopyroxene + hornblende ± apatite). All K_2O variations can be explained by variations in degrees of partial melting, followed by fractional crystallization—there is no need for special enrichment or depletion processes in mantle source.

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[1] GSA Data Repository item 2007228, trace element contents for Sonora Pass volcanic rocks, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

inconsistent with Rb-Ba-K systematics in the central and southern Sierra. High-K_2O magmas might still reach phlogopite saturation as they evolve, but not all minerals present upon eruption need be present as residua in the mantle source.

SUMMARY AND CONCLUSIONS

We conclude that *F* (degree of partial melting) is the primary control on intersuite variations in K_2O and other highly incompatible elements, and that high-K volcanics are related to delamination only by coincidence and require no special source enrichments. Instead, field data in the central Sierra suggest that the transport and eruption of high-K, low-*F* magmas were triggered by the onset of Walker Lane transtensional stresses, which are expected to increase magma driving pressure (Rubin, 1990) and facilitate the eruption of deep, low-*F* magmas (Takada, 1994).

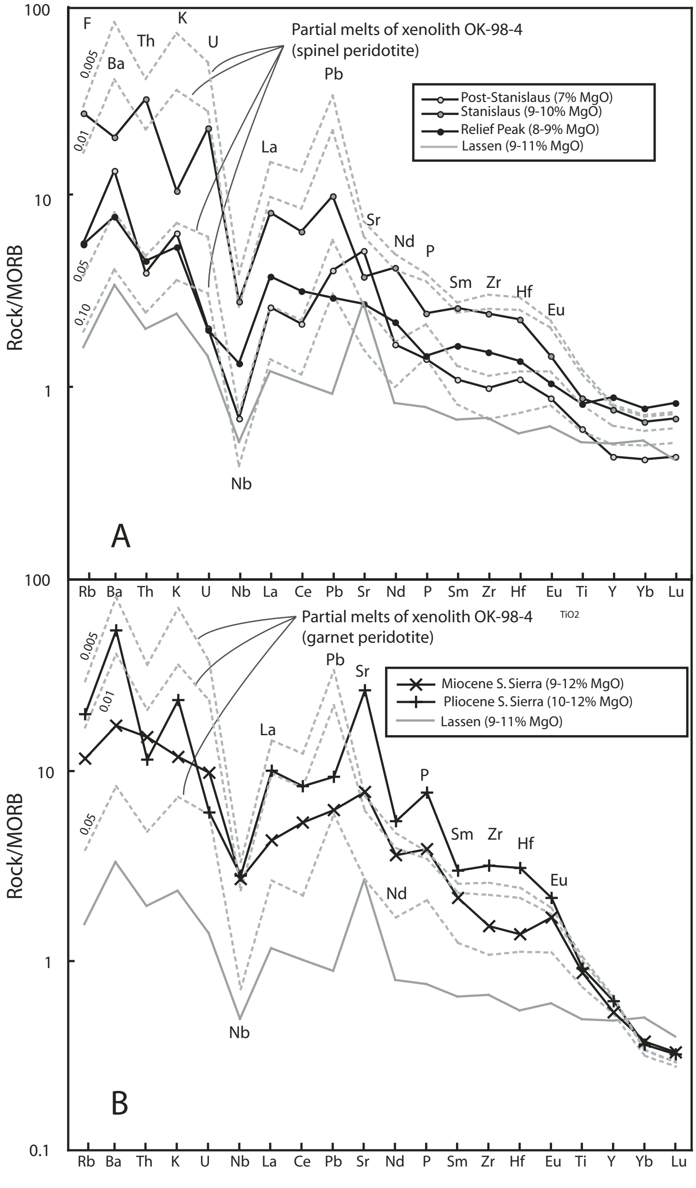

Figure 4. Mid-ocean-ridge basalt (MORB)–normalized trace-element contents for mafic rocks from the central (A) and southern (B) Sierra Nevada, compared to mafic Lassen volcanics (Bullen and Clynne, 1990), and calculated partial melts from a peridotite source. As with K_2O, incompatible elements increase from Lassen to southern Sierra and can be explained by variations in partial-melt fraction (*F*). Partial melting curves use peridotite xenolith OK-98–4 (Lee, 2005), with a spinel-peridotite mineralogy for central Sierra, and a garnet-peridotite mineralogy for southern Sierra. Calculated positive Pb anomalies derive from very low D_{Pb} (= 0.004) and Pb enrichment in xenoliths (Lee, 2005). D_i values are for basalts and alkali basalts from the Geochemical Reference Earth Model (GERM; http://earthref.org/index.html).

In addition, a trend of decreasing *F* from north to south follows a north-to-south increase in summit elevations and thickness of low-density crust (Mavko and Thompson, 1983; Fliedner and Ruppert, 1996). We propose an eruption-control mechanism linking *F* to water contents and crust thickness. Feldstein and Lange (1999) proposed that southern Sierra magmas required volatile enrichments to erupt, but they only considered buoyancy at the base of the crust. In the absence of excess driving pressure in the source region, depth-integrated magma densities must have been less than depth-integrated densities of overlying crust to allow eruption. Dry magmas at Lassen can erupt due to density-driven buoyancy forces alone (Fig. 5), but they would not reach the surface in the central and southern Sierra; H_2O contents of 0.4%–0.7% are required to yield sufficient buoyancy for eruption (Fig. 5). As with K_2O, however, the southern Sierra source need not be H_2O enriched. Magmas generated at low *F* would be sufficiently wet and buoyant, even assuming a "normal Cordilleran" mantle (Fig. 5). A crustal thickness control also explains the northward increase in volcanic rock volumes. At Sonora Pass (~lat 38°N), granitic basement (with initial $^{87}Sr/^{86}Sr$ >0.706) gives way to volcanic cover (and basement granitoids with initial $^{87}Sr/^{86}Sr$ <0.706; Kistler and Peterman, 1973), and the small volcanic centers at Sonora Pass (Busby et al., 2007b) are replaced by large volcanic centers at Lassen (Clynne, 1990). Undoubtedly, low-density granitic materials impede throughput of mantle-derived magmas.

However, is there any connection between volcanism and uplift? Preliminary seismic data (Gilbert et al., 2006) suggest that the lithosphere beneath Sonora Pass has been removed. Our age dates, and those of Farmer et al. (2002), further suggest a Sierra-wide Miocene magmatic "flare up" beginning at ca. 10–15 Ma, which approximates an inflection in Sierra-wide uplift rates (Cecil et al., 2006). Lithosphere thinning or

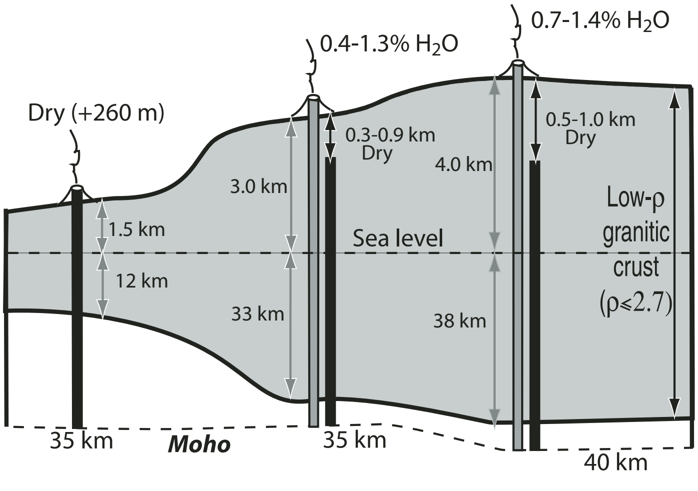

Figure 5. Integrated density contrasts between crust and magma. Crustal densities and thicknesses are from Mavko and Thompson (1983), Fliedner and Ruppert (1996), and Gilbert et al. (2006); magma densities were calculated from Lange and Carmichael (1990) and Ochs and Lange (1999). We assumed no addition of low-density crust since Cretaceous, and that rocks with $\rho \leq 2.7$ g/cm^3 were not subducted or delaminated. Dry mafic magmas at Lassen can rise 260 m above surface due to density contrasts alone, but in southern Sierra, they fall 1.0 km short of surface; minimum H_2O contents of 0.4%–0.7% are required for eruption. However, water contents need not vary between source regions: if D_{H_2O} = 0.01, the mantle has 0.05% H_2O, and *F* is as in Figure 4, then low-*F* magmas are sufficiently water-enriched to reach the surface: S. Sierra, 3.6%; Sonora Pass, 2.1%; Lassen, 0.48% H_2O.

removal may well have been the cause for partial melting in the southern Sierra. However, we surmise that: (1) where thick crust is present, the eruption of all but buoyant, low-*F* magmas was inhibited, and even then, high tensile stresses may have been needed to facilitate eruption; (2) high-K magmas record the onset of Walker-lane style transtensional stresses, which occurred as early as 10 Ma in both the central and southern Sierra, and again at 4–3 Ma in the southern Sierra, and perhaps Sierra-wide; (3) high-K lavas were derived from "normal, Cordilleran-enriched" mantle lithosphere; and (4) Miocene and Pliocene volcanic pulses may represent a Sierra-wide, two-step encroachment of Walker Lane deformation and Sierran uplift, as has been suggested for the Sierra near Reno, Nevada (Henry and Perkins, 2005).

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