Melting under the Colorado Plateau, USA

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ABSTRACT

Mafic volcanism gradually encroaching on the tectonically stable Colorado Plateau in the southwestern United States appears to originate from within Paleoproterozoic lithosphere. New Hf and Nd isotope data strengthen evidence for magma source heterogeneity; other geochemical signatures show these sources to consist dominantly of peridotite. Tomographic and receiver function analyses reveal that young volcanism occurs above or outboard of a pronounced shallowing in the lithosphere-asthenosphere boundary. Melt extraction extends to the base of lithosphere thinned to <75 km, with more shallowly derived melts characterized by higher degrees of partial melting. Accordingly, decompression melting of a reactivated chemical boundary layer ± asthenosphere, rather than in situ lithospheric melting or melting of lithospheric mantle drips/delaminations, appears to be responsible for recent Colorado Plateau magma generation.

INTRODUCTION

Some of the youngest volcanism in the southwestern United States is associated with the Colorado Plateau (CP), an elevated region of nominally thick Paleoproterozoic continental lithosphere (120–150 km; West et al., 2004). Melt barometry (Lee et al., 2009) (Fig. 1), isotopic signatures distinct from those of mantle asthenosphere (Carlson and Nowell, 2001, and references therein), and geochemical evidence for melting above the garnet-spinel transition zone (Asmerom, 1999, and references therein) suggest melt generation in CP lithosphere. Thermal relaxation of lithosphere adjacent to warmer asthenosphere could promote in situ melting (e.g., Roy et al., 2009; van Wijk et al., 2010), especially if the lithosphere was metasomatized during Laramide-age (80–40 Ma) shallow subduction of the Farallon plate, and/or if more fusible components such as sediments and metabasalts were introduced at its base. Melts could alternatively be generated by compression of downwelling refertilized and hydrated lithosphere (Elkins-Tanton, 2007) and/or by the accompanying return flow of asthenospheric mantle such as indicated by recent models for CP dynamics (van Wijk et al., 2010; Levander et al., 2011). Here we use new geophysical and geochemical observations to more rigorously examine the conditions of CP melt generation and show that melting does not occur statically within the thermal boundary layer or by lithospheric downwelling, but rather by high-temperature decompression melting of mantle peridotite at or below the seismological proxy for the lithosphere-asthenosphere boundary (LAB).

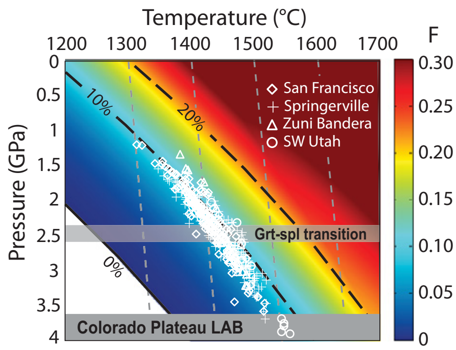

Figure 1. Comparison of melt equilibration conditions to melt fractions (F) for melting near Colorado Plateau margins. Pressure-temperature estimates are from Si- and Mg-thermobarometry (Lee et al., 2009) using NAVDAT (the North American Volcanic and Intrusive Rock Database) and other data for lavas with MgO ≥8 wt% (Item DR3 in the GSA Data Repository [see footnote 1]), and assuming Fo_{90} source and melts with Fe^{3+}:Fe = 0.1 and 0.5 wt% H_2O. Melt fractions derived from model of Katz et al. (2003) for source with 0.05 wt% H_2O (cf. Li et al., 2008). Melt fraction contours shown by long-dashed lines; mantle adiabats shown by near-vertical, short-dashed lines. The Putirka (2008b) formulation of the same barometer gives lower values with increasing *P*, with differences being >13% at *P* > 3 GPa. Depth for Colorado Plateau lithosphere-asthenosphere boundary (LAB) from West et al. (2004).

SEISMIC STRUCTURE OF CP MANTLE ASSOCIATED WITH MELTING

The southern CP is bounded by the Basin and Range province to the west and south, and the Rio Grande Rift to the east (Fig. 2). Widespread mid-Tertiary ignimbrite volcanism and orogenic collapse characterized the Basin and Range province in the wake of removal of the shallowly subducting Farallon slab (Humphreys et al., 2003) but does not appear to have significantly affected the CP. P-wave tomographic images show that the southwestern CP is underlain by relatively low-velocity upper mantle (Schmandt and Humphreys, 2010) that could have infiltrated the channel formerly occupied by the Farallon slab (West et al., 2004).

A map computed from P_S and S_P receiver functions using USArray data (Fig. 2A) shows that the LAB attains a depth of >110 km under much of the northern half of the Colorado Plateau, consistent with a shear wave model for the northwest-southeast Colorado Plateau/Rio Grande Rift Seismic Transect Experiment (LA RISTRA) transect through the center of the CP (West et al., 2004). In contrast, the LAB shoals dramatically under the southern CP where it transitions to the Basin and Range and Rio Grande Rift provinces. The LAB is at a depth of ~90 km beneath the 4–6 Ma Hopi Buttes volcanic field and much of the Oligocene–Miocene Navajo volcanic field. Younger (<1 Ma) volcanic fields to the south and west lie outboard of a step-like change in lithospheric thickness from relatively thicker (>90 km) to thin (<70 km) lithosphere that occurs over distances of <30 km. When cross sections through the crust and mantle beneath three of these volcanic fields are considered—as imaged in P_S common conversion point stacks and by V_S (Figs. 2B–2D, and Fig. DR1 in the GSA Data Repository[1], respectively)—as well as the seismic profiles of Levander et al. (2011), it can be seen that they lie above or somewhat outboard of the stepwise changes in depths to the Moho and LAB. Several of these fields are also at the margins of a proposed lithospheric delamination (Schmandt

[1]GSA Data Repository item 2012120, Item DR1 (supplementary seismological figures); Item DR2 (Hf and Nd isotope data for CP lavas); Item DR3 (compositional data sources summary); and Item DR4 (Lu/Hf and Sm/Nd fractionation modeling), is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

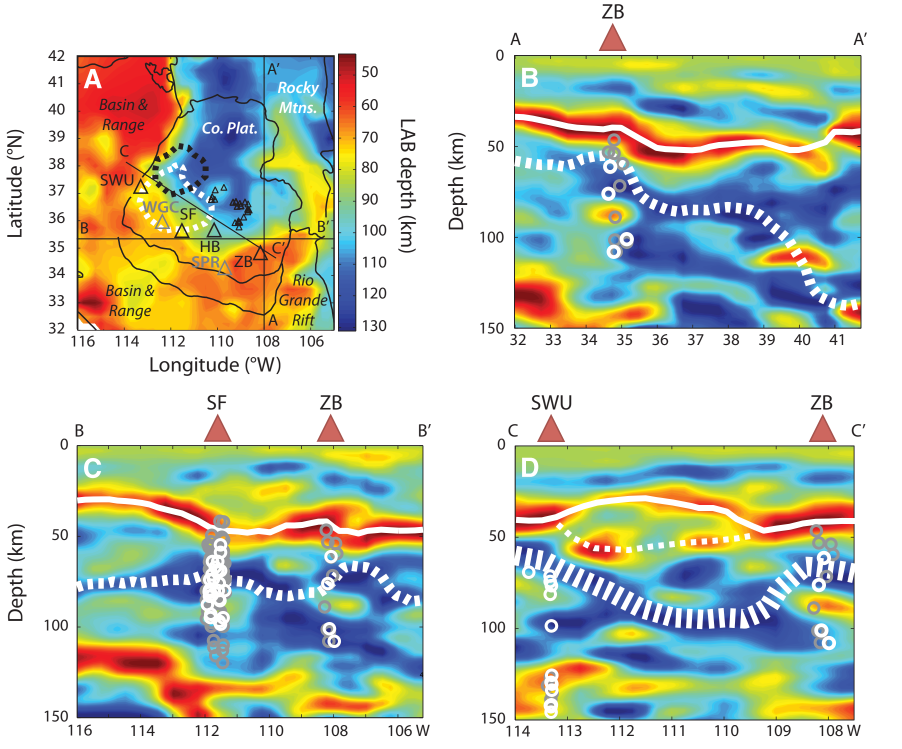

Figure 2. Relationship of Colorado Plateau (CP) volcanic fields to upper mantle structure obtained using seismic data. A: Average lithosphere-asthenosphere boundary (LAB) depth determined from USArray Ps and Sp receiver functions and Rayleigh wave tomography (modified after Levander et al., 2011). Regions of lower crustal delamination and crustal thinning (white dashed line) and mantle downwelling at 200 km depth (black dashed line) are those identified by Levander et al. (2011). Black triangles show locations of volcanic fields for which new Hf isotope data are presented here: SWU—southwest Utah; SF—San Francisco volcanic field; HB—Hopi Buttes; ZB—Zuni Bandera; unlabeled small triangles—Navajo. Gray triangles indicate other young volcanic field locations: WGC—western Grand Canyon; SPR—Springerville. B–D: P_S common conversion point stacking of cross sections through the CP at locations shown in A. Color scale represents P to S converted signals (positive values are red). Solid and thick dashed white lines represent surfaces picked for the Moho and LAB, respectively. Thin dashed line in D shows location of a possible crustal delamination (Levander et al., 2011). Circles are melt equilibration pressures as in Figure 1, except that gray circles represent lower-confidence results (Sc contents are ≤25 ppm, or data are lacking).

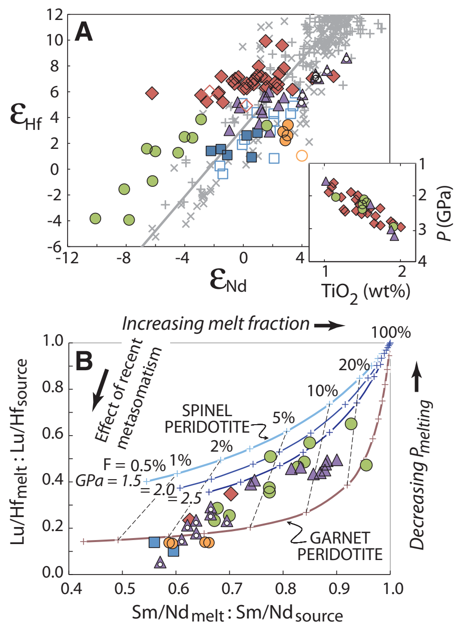

Figure 3. Selected isotopic and chemical characteristics of Colorado Plateau (CP) lavas. Symbols as in Figure 1, with the addition of the following: orange circles—Hopi Buttes (versus green for southwest Utah); squares—Navajo; open symbols—previously published CP data (Item DR2 in the GSA Data Repository [see footnote 1]). Alkaline Zuni Bandera samples distinguished by small circles within triangles. A: ε_{Hf} versus ε_{Nd}. Crosses—mid-oceanic-ridge basalt; x—ocean island basalts; line—oceanic mantle array (Vervoort et al., 1999). Inset shows pronounced decrease in primary TiO_2 contents of mafic CP melts with decreasing pressure. B: Fractionation of pairs of elements (Lu/Hf and Sm/Nd) between melt (measured) and source (estimated). Ratios for source depend on time-integrated age of source (taken to be 1.7 Ga), initial isotopic ratios (taken to be $\varepsilon_{Hf}(0)$ = +8 and $\varepsilon_{Nd}(0)$ = +4.5), and measured isotopic ratios. Source ages ≤1.4 Ga produce some unacceptably large Sm/Nd fractionation factors (>1). Reference curves show fractionation anticipated for melting in the spinel (1.5–2.5 GPa; blue curves) and garnet (brown curve) peridotite stability fields; tick marks show melt fractions. General effects of recent metasomatic processes shown. See Item DR4 for additional details.

and Humphreys, 2010; Levander et al., 2011) (Figs. 2A and 2D).

Within ~100–200 km of the Basin and Range province, the CP is encircled by a nearly continuous band of seismically slow mantle at 100 km depth. At 80 km (Levander et al., 2011), the overall low-velocity zone and low-velocity minima within it broaden; by 50 km depth (Fig. DR2), the seismic anomaly is considerably diminished. This could be evidence of asthenospheric upwelling associated with edge-driven convection or cascading delamination events (van Wijk et al., 2010; Levander et al., 2011). All of the volcanic centers are somewhat to distinctly interior to the margins of the CP, and at the edge or interior to the low-velocity ring at 100 km depth. Low-velocity S-wave anomalies in the mantle are absent under the mid-Tertiary Navajo volcanic field. Parts of the encircling low-velocity anomaly have high V_P/V_S, characteristic of low-volume partial melts (Schmandt and Humphreys, 2010).

MANTLE HETEROGENEITY AND ITS IMPLICATIONS FOR COLORADO PLATEAU MELT GENESIS

Seventy-nine new Hf and 42 new or replicate Nd isotope analyses considerably expand the known isotopic range for CP-related volcanism (Carlson and Nowell, 2001, and references therein) (Table DR1). The volcanic areas that are the foci of these new data span the entire compositional, temporal, and much of the geographical range of mafic lavas associated with the CP (Fig. 2; Item DR3 in the Data Repository). Those proximal to the margins of the CP are mostly weakly alkaline to subalkaline in composition with rare basanites, except for Hopi Buttes lavas, which are dominantly basanites and nephelinites. Mafic rocks from the Navajo volcanic field at the CP center are moderately to strongly silica-undersaturated.

Isotopic characteristics for CP mantle straddle the oceanic mantle array or, at lower ε_{Nd}, lie above it (deviations from the mantle array in ε_{Hf} range from −6 to +11). Each volcanic field defines a discrete range of isotopic characteristics (Fig. 3A). Notably, Hf isotope signatures for the San Francisco field vary only slightly over a comparatively wide range of >7 ε_{Nd} units. Data for alkaline lavas from the Zuni Bandera field are displaced from but otherwise parallel the mantle array, whereas data for tholeiitic lavas trend across it. Results for southwestern Utah lie uniformly above the mantle array. Collectively, Hf isotope data support evidence from Nd isotopes that melts are isotopically enriched relative to most oceanic basalts and sourced in heterogeneously depleted to enriched mantle.

Isotopic compositions of CP lavas that lie close to the mantle array could reflect derivation from sources depleted by melt extraction and subsequently sequestered from the convecting mantle as Paleoproterozoic-aged lithosphere. For the other lavas, enrichment processes in the mantle are required (it is shown elsewhere that crustal contamination cannot account for most of the heterogeneity observed; e.g., Carlson and Nowell, 2001, and references therein). Besides lherzolites and harzburgites, xenoliths of mantle origin include olivine-poor lithologies such as pyroxenites, eclogites, and garnetites (e.g., Porreca et al., 2006, and references therein). Near-horizontal arrays for the San Francisco field and, to a more subdued degree, the Zuni Bandera field are evocative of mantle enrichment by mixing with pelagic ± terrigenous sediments (e.g., Vervoort et al., 1999). Sediments could hypothetically have accumulated along with other slab-related lithologies (e.g., eclogite) at or near the base of the continental lithosphere during shallow Farallon plate subduction (e.g., Usui et al., 2006). The range in coupled Hf-Nd isotope characteristics of CP lavas could alternatively reflect aging of melt-metasomatized mantle since the Proterozoic.

Ratios between Zn and Fe provide a promising means of identifying whether olivine-poor lithologies, including sediments, are responsible for mantle melts (Le Roux et al., 2010). Zn/Fe ratios of 13–22 × 10^4 for the Hopi Buttes and Navajo volcanic fields are permissive of significant contributions from olivine-poor sources, including sediments (Zn/Fe often >20 × 10^4; Plank and Langmuir, 1998). Mantle array–like Hf-Nd isotope characteristics of these lavas are, however, probably better explained by melting pyroxenites and/or eclogites with high modal abundances of garnet and clinopyroxene (see also Alibert et al., 1986; Carlson and Nowell, 2001). Magnesian lavas (>8 wt% MgO) from the other three volcanic fields are characterized by a restricted range in Zn/Fe (average 10.9–11.3 × 10^4; $1\sigma < 1 \times 10^4$ in all cases) that is consistent with melting of homogeneous mantle composed dominantly of peridotite (LeRoux et al., 2010). Hafnium and Nd isotope heterogeneity of these lavas may, therefore, reflect sources characterized by cryptic metasomatism rather than larger-scale lithological heterogeneity. In further support of this premise, $^{206}Pb/^{204}Pb$ values <18.5 and as low as 17 characterize samples with Hf isotope signatures that are putatively sediment-influenced (data of Alibert et al., 1986; Reid and Ramos, 1996), whereas values >18.5 would be expected if Cordilleran and other sediments had been incorporated into their sources (Plank and Langmuir, 1998; Usui et al., 2006). We conclude that sediments subducted into the mantle during the Laramide either foundered along with the rest of the Farallon plate or do not contribute significantly to CP lavas.

Genesis of at least three of the CP volcanic fields by melting of peridotite allows use of Si- and Mg-thermobarometry to obtain melting pressure-temperature (*P-T*) conditions, if oxygen fugacity and water contents in the source can be delimited. We infer Fe^{3+}:Fe_{tot} for CP lavas similar to that for mid-oceanic-ridge basalt (MORB) sources (i.e., ~0.1) based on V/Sc ratios that cluster around 7 and 8 in relatively unfractionated San Francisco and Zuni Bandera lavas (Sc contents >25 ppm; Lee et al., 2005). Magmatic water contents are taken to be 0.5 wt% based on evidence that water contents in CP mantle olivine overlap the range estimated for olivine in MORB sources (Li et al., 2008). Using these constraints, pressure estimates (Lee et al., 2009) obtained from the chemical compositions of primary mafic lavas show that CP-related melts may have last equilibrated near to well below the seismologically defined LAB (Figs. 2B–2D). Estimated average mantle potential temperatures of >1465 °C for the more deeply derived basalts could be in excess of ambient upper-mantle potential temperature (e.g., Putirka, 2008a), unless water contents are an order of magnitude greater than our estimate, in which case most *T* and *P* would be ~50–60 °C and <0.15 GPa lower, respectively.

Absolute incompatible element abundances covary with melt equilibration pressure, as illustrated by a greater-than-twofold decrease in TiO_2 contents with decreasing pressure (Fig. 3A), and this could reflect dilution of these elements at shallower depths by greater degrees of melting. Melt fractions estimated from *P-T* conditions using the model of Katz et al. (2003) could also imply increasingly larger melt fractions at shallower depths (Fig. 1). If, as expected, melt H_2O follows a trend similar to that of TiO_2, even greater differences in melt fraction over the depth interval of melt extraction would be involved (and lesser difference is implied if the geobarometer formulation of Putirka, 2008b, applies).

To further investigate melting conditions, variations in magmatic ratios of Lu/Hf and Sm/Nd against time-integrated ratios for the sources as defined by the Hf and Nd isotope characteristics of the lavas were modeled. Melt-source fractionations of these ratios are sensitive to the presence or absence of residual garnet as well as to variations in the degree of partial melting. Lu/Hf and Sm/Nd fractionation factors for some lavas (e.g., Navajo and alkaline Zuni Bandera lavas) lie on or close to garnetiferous melting curves (Fig. 3B) and, therefore, can be explained by melting of such sources. Fractionation factors for the other volcanic fields extend to values above the garnet peridotite melting curve and thus require contributions from melting of peridotite at depths shallower than the garnet-spinel transition (~75 km), as expected from melt barometry. Changes in the relative magnitudes of fractionation factors also provide evidence that more shallowly derived melts are characterized by larger melt fractions. Recent metasomatic contributions from depleted mantle melts and their minerals would tend to dampen the range in apparent depths of melt extraction (Fig. 3B) but might not constitute more than 15% of melt sources (Fig. DR3).

MELT GENESIS ASSOCIATED WITH THE COLORADO PLATEAU

For the strongly alkaline Hopi Buttes and Navajo lavas, new constraints from Zn/Fe and coupled Lu/Hf and Sm/Nd fractionation, as well as V/Sc ratios of 11–18, support models for their generation as small-degree melts of metasomatized garnet-bearing mantle under reducing conditions. Considered together with LAB depths (Fig. 2), melt extraction probably occurred at ≥90 km, potentially by localized thinning and/or reheating of the lithosphere in response to removal of the Farallon slab and/or lithospheric delamination (Fig. 4). For the remaining volcanic fields, chemical and temperature signatures imply that mantle domains are undergoing decompression melting and are hybrids of Proterozoic-aged mantle and more deeply derived components. The volcanic fields are proximal to zones where hotter Basin and Range asthenosphere is juxtaposed against cooler CP lithosphere in a step-like fashion. Transition zone lithosphere hence may be locally remobilized by conductive warming, lateral melt invasion of the CP lithosphere, edge-driven convection, and/or delamination (Fig. 4) (Roy et al., 2009; van Wijk et al., 2010;

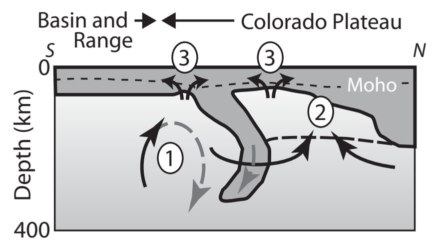

Figure 4. Composite cartoon of possible mantle dynamics associated with the Colorado Plateau. Upwelling zones indicated by black lines; downwelling zones indicated by gray dashed lines. Numbers signify potential zones of mantle upwelling associated with (1) small-scale convection and resulting lithospheric drip (van Wijk et al., 2010), (2) mantle downwelling/delamination and replacement of lithosphere by sublithospheric mantle (simplified after Levander et al., 2011), and (3) localized zones of lithospheric thinning resulting from extension associated with drips/delamination (after Gogus and Pysklywec, 2008; J. Van Wijk, 2011, personal commun.).

Levander et al., 2011). Downwelling drips or delaminations, if highly metasomatized, could undergo compression melting (Elkins-Tanton, 2007), in which case melt fractions should increase with increasing pressure. This is not what is observed. Decompression melting could occur in mantle upwelling in tandem with drips or delaminated lithosphere (Fig. 4), but sourcing of melts mainly in chemically depleted asthenosphere is also not observed. Rather, the thermally reactivated Proterozoic chemical boundary layer melts as it becomes entrained in upwelling asthenosphere, and/or melting occurs where localized lithospheric thinning and extension (Gogus and Pysklywec, 2008) accompany foundering of the lithosphere. Accurate knowledge of melt water contents should better illuminate the relationship between these scenarios and apparently high magma temperatures.

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