Shrinking of the Colorado Plateau via lithospheric mantle erosion: Evidence from Nd and Sr isotopes and geochronology of Neogene basalts

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ABSTRACT

Geochronologic data from the southern margins of the Colorado Plateau (western United States) show an inboard radial migration of Neogene basaltic magmatism. Nd and Sr isotopic data show that as basaltic volcanism migrates inboard it also becomes increasingly more asthenospheric. Strongly asthenospheric alkali basalt ($\varepsilon_{Nd} > 4$) appeared on the western plateau margin ca. 5 Ma, on the southeastern margin at 7 Ma, and is lacking from the plateau's other margins. Tomographic data suggest that low-velocity mantle underlies almost all recent (younger than 1 Ma) basaltic volcanism in a ring around much of the Colorado Plateau at a depth of 80 km. The combined isotopic and tomographic data indicate that the low-velocity mantle is asthenosphere along the western and southeastern margins of the plateau, but modified lithosphere around the remaining margins. Temporal and spatial patterns suggest a process by which upwelling asthenosphere is progressively infiltrating and replacing lithospheric mantle, especially where Proterozoic boundaries exist. This model explains (1) the dramatic velocity contrast seen well inboard of the physiographic edge of the plateau, (2) the inboard sweep of Neogene magmatism, and (3) isotopic evidence that much (but not all) of the low-velocity mantle is asthenospheric. These data support models that ongoing uplift of the edges of the Colorado Plateau is driven by mantle processes.

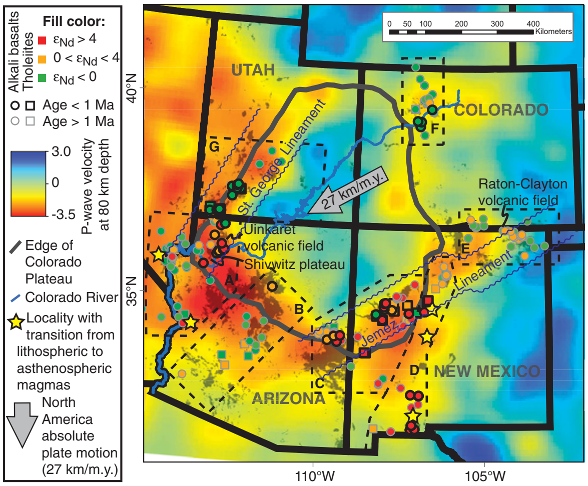

Figure 1. Relative P wave velocity at 80 km depth for southwestern United States. Dark gray areas show locations of late Tertiary basalts. Asthenospheric Nd isotopic compositions are red, lithospheric are green, and mixed are orange. Dashed lines are subregions shown in Figure 3. See Table DR2 for references (see footnote 1).

INTRODUCTION

Recent models have hypothesized that Neogene and ongoing upper mantle convection is modulating surface uplift of the Colorado Plateau region of the western United States (Karlstrom et al., 2008; Moucha et al., 2008, 2009; van Wijk et al., 2010). This study focuses on testing those models by examining the geochemistry of young basalts as a record of lithosphere-asthenosphere interactions.

Like the long-recognized Arizona transition zone (Peirce, 1984), the western and southeastern edges of the Colorado Plateau also mark transitions between areas of different lithospheric thickness and between zones with markedly different extensional and magmatic histories. In some parts of the plateau margin (e.g., the western Grand Canyon), extension and magmatism migrated toward the plateau's center through the Neogene (Wenrich et al., 1995). Causal links between mantle processes and the spatial and temporal migration of volcanism and faulting have long been suggested in this area (Best and Brimhall, 1974). Natural source seismic tomography confirms a profound mantle velocity gradient (5%–8% Vp) inboard of the plateau's edge (Fig. 1; Sine et al., 2008). Magnetotelluric data show a strong crustal conductor in the Basin and Range and plateau margin that rapidly transitions to higher resistivity at deeper levels in the plateau's center (Wannamaker et al., 2008). These findings indicate the presence of a deep keel of high-velocity, nonconductive, and probably cooler mantle under the central Colorado Plateau relative to its margins, to depths of ~125 km.

Although geophysical studies can be used to investigate variations in mantle velocity and conductivity, other methods are needed to interpret the significance of these variations in terms of compositional and/or temperature differences in the mantle. Basaltic lavas are important probes because (1) they erupt from different depth regions in the mantle (typically alkali basalts originate at deeper levels than their tholeiitic counterparts; 50–90 km for alkali basalts, 25–50 km for tholeiites; Takahashi and Kushiro, 1983; Lee et al., 2009); (2) their $^{143}Nd/^{144}Nd$ ratios can distinguish lithospheric from asthenospheric mantle source region components (due to the relative compatibility of Sm compared to Nd); and (3) they can be dated directly using $^{40}Ar/^{39}Ar$ dating to constrain mantle evolution through time. This study focuses on combining geochemical data from basalts and geophysical images of the mantle (Schmandt and Humphreys, 2010) to resolve whether low-velocity mantle regions are depleted mantle asthenosphere or partially melted enriched lithosphere and to track the lithosphere-asthenosphere boundary through time.

Previous studies have interpreted temporal changes in Nd isotopes from a single volcanic field to indicate lithospheric thinning (see stars in Fig. 1) (Daley and DePaolo, 1992; Heatherington and Bowring, 1991; Livaccari and Perry, 1993; McMillan et al., 2000; Perry et al., 1987, 1988). This study focuses on temporal trends throughout the southwestern United States by presenting new geochemical data from 5 Ma to 1 ka basalt flows from the western Grand Canyon in the context of a regional compilation of Nd and Sr isotopic data with reliable age constraints.

RESULTS

Uinkaret Samples

We analyzed 11 new samples from the western Grand Canyon for Nd and Sr isotopes (see the GSA Data Repository[1] for an explanation of

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[1]GSA Data Repository item 2011027, expanded methods section, discussion of crustal contamination, Table DR1 (analytical results), Table DR2 (compilation of Nd and Sr analyses), Figure DR1 ($^{87}Sr/^{86}Sr$ vs. age), and Figure DR2 (Nb/La vs. age), is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Geology, January 2011; v. 39; no. 1; p. 27–30; doi: 10.1130/G31611.1; 5 figures; Data Repository item 2011027.

methods used); 10 samples were from the Uinkaret volcanic field and 1 was from Grassy Mountain on the Shivwitz Plateau (Fig. 1). The Uinkaret volcanic field samples range from 600 to 1 ka (dated using ^{40}Ar/^{39}Ar and ^{3}He cosmogenic dating techniques; Fenton et al., 2001; Karlstrom et al., 2007); the Shivwitz volcanic field sample is 5.4 Ma (see Table DR1 in the Data Repository).

Uinkaret volcanic field samples have ε_{Nd} values of +7.71 to −1.46 and ^{87}Sr/^{86}Sr values of 0.702890–0.706378 (Table DR1), and plot along the Nd-Sr mantle array, indicating derivation from mixed mantle reservoirs (Fig. 2). Uinkaret volcanic field basalts with similar major element chemistry do not show marked change in ε_{Nd} and ^{87}Sr/^{86}Sr values over the past 600 k.y. (Fig. 2A). It is important that the 1 ka basanitic Little Springs flow has the highest ε_{Nd} of any basalt in the region (+7.7) and is indistinguishable from mid-oceanic ridge basalt (MORB). In addition, it has $^{230\text{Th}}$/^{238}U enrichment, with (^{230}Th/^{238}U) = 1.134 and (^{230}Th/^{232}Th) = 1.256, indicative of a mantle source in the garnet stability field (i.e., deeper than 70–80 km; Asmerom et al., 2000). The combined data for this sample show that the modern-day low-velocity mantle at ~80 km beneath the western Colorado Plateau is predominantly MORB composition asthenosphere, not conductively heated lithosphere (cf. Roy et al., 2009).

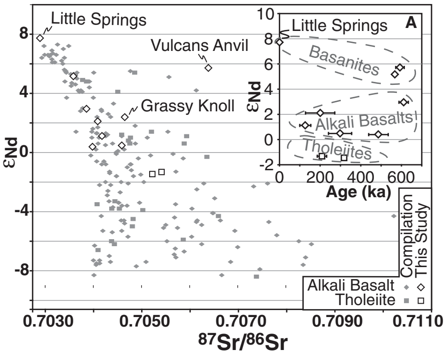

Figure 2. εNd versus ^{87}Sr/^{86}Sr for basalts from Uinkaret volcanic field (open symbols) compared to those from throughout southwestern United States. Inset graph shows that geochemically distinct basalt groups have maintained similar isotopic compositions over past 600 k.y. in Uinkaret volcanic field.

Regional Temporal and Spatial Trends in Basaltic Volcanism

A compilation of published Nd isotopic data from reliably dated Neogene basalts of the Colorado Plateau region yielded analyses on 363 samples from 39 studies (references in Table DR2 in the Data Repository). Most data come from the margins of the Colorado Plateau where the majority of late Tertiary basaltic volcanism has occurred (Fig. 1). The data were subdivided into seven subregions: A, The western Grand Canyon; B, central Arizona; C, the southern Jemez lineament; D, the Rio Grande rift; E, the Raton-Clayton volcanic field; F, northwestern Colorado; and G, southern Utah (Fig. 1). These subdivisions allow us to explore any influences of older northeast-trending Proterozoic compositional domains on late Tertiary basaltic volcanism (Magnani et al., 2005).

In all seven subregions, ε_{Nd} values of basaltic magmas increase with decreasing age (Fig. 3). ε_{Nd} values increased at an average rate of 0.33 ε units/m.y. along the margins of the Colorado Plateau, with an increased rate of 0.5–3 ε units/m.y. along the southern margins of the plateau (Fig. 3). In the western Grand Canyon, southern Jemez lineament, and Rio Grande rift, basalts with strongly asthenospheric signatures (i.e., ε_{Nd} > 4) started erupting at 4.6 Ma, 7.2 Ma, and 9.8 Ma, respectively. Only in the western Grand Canyon and the Rio Grande rift have basalts with Nd isotopic values indistinguishable from MORB (i.e., ε_{Nd} >7) erupted. This temporal trend toward more asthenospheric basalts is linked to a spatial trend, as magmatism has swept inboard toward the Colorado Plateau center at a rate of 1–8 km/m.y. (Roy et al., 2009). Figure 4 shows the average rate of encroachment for each subregion measured perpendicular to the modern Colorado Plateau margin (shown by the thick gray line). The trend toward increasingly asthenospheric basalts through time is further

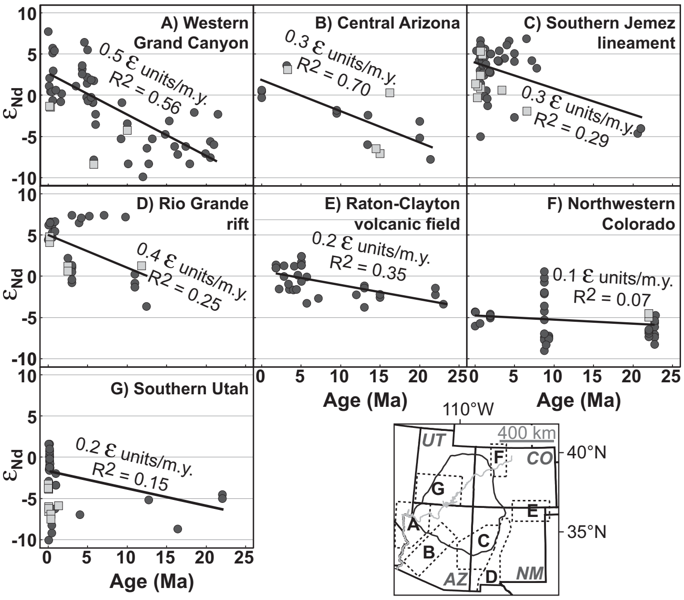

Figure 3. ε_{Nd} versus eruption age for Neogene basalts from southwestern United States, showing increase in ε_{Nd} with decreasing age. Rates are given by linear regression through points, excluding tholeiites (squares), which come from shallower depth. This relationship is strongest around southern plateau margin (zones A–E). Circles represent alkali basalts.

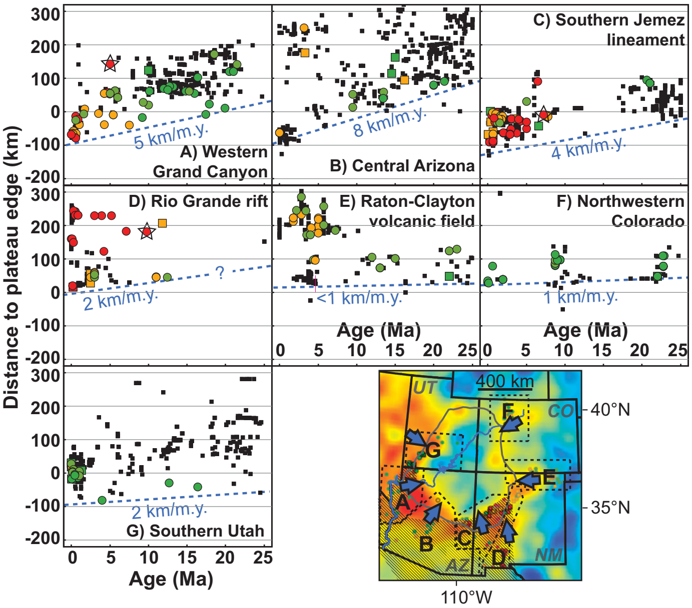

Figure 4. Distance inboard (–) or outboard (+) from modern plateau edge (0) versus eruption age for basalts from southwestern United States. Velocity at which basaltic volcanism has migrated toward plateau's center is shown by fitting a line through locus of leading volcanism (dashed blue line; after Roy et al., 2009). Squares—tholeiites; circles—alkali basalts; fill colors keyed to ε_{Nd} values as in Figure 1. Black squares from Western North American Volcanic and Intrusive Rock Database (http://www.navdat.org) show location and age of Neogene volcanism in expanded subregions. Stars mark first basaltic eruption with strongly asthenospheric signature in each subregion. Inset map shows direction of volcanic migration for each subregion. Diagonal fill pattern shows zone from which asthenospheric basalts were derived (Livaccari and Perry, 1993).

supported by a decrease in $^{87}Sr/^{86}Sr$ ratios with decreasing age (at 0.0001–0.0002/m.y.; Fig. DR1) and by an increase in Nb/La ratios at a rate of 0.04/m.y. (Fig. DR2).

Although ε_{Nd} has increased with decreasing eruption age in the central Arizona, Raton-Clayton volcanic field, northwestern Colorado, and southern Utah subregions, strongly asthenospheric basalts ($\varepsilon_{Nd} > 4$) have yet to erupt there. Mixing trends suggest that the same process of replacement of lithosphere by asthenosphere is taking place, but the process has progressed farther along the south and west sides of the Colorado Plateau relative to the north and east sides.

Tomography

The absence of thick lithosphere beneath the western margin of the Colorado Plateau is supported by new teleseismic body-wave tomography, which uses relative traveltime residuals from the USArray (http://www.usarray.org/) and more than 1700 additional stations to invert for three-dimensional P and S velocity variations (Schmandt and Humphreys, 2010). The central plateau is underlain by laterally continuous high-velocity mantle down to ~125 km depth, but the western, and to a lesser extent the southeastern, margin of the plateau is underlain by low-velocity mantle (Fig. 1). Almost all of the younger-than-1-Ma basalts were derived from the low-velocity ring around the plateau or in the Rio Grande rift (Fig. 1). The westward transition from the plateau to the eastern Basin and Range defines one of the strongest lateral velocity gradients in the western United States upper mantle. We interpret this to represent asthenosphere juxtaposed against a step-like transition to cool, thick lithosphere beneath the central plateau (Sine et al., 2008).

DISCUSSION

Mantle Structure and Evolution

The U, Th, Sr, and Nd isotopic data from the Colorado Plateau and elsewhere in the western United States show that there is demarcation between the isotopic value of asthenospheric mantle–derived magmas and their lithospheric mantle–derived counterparts (e.g., Asmerom, 1999; Asmerom et al., 2000). Nd isotopic data from basalts around the Colorado Plateau show remarkably consistent temporal and spatial trends that can not be explained by crustal contamination (for a discussion, see the Data Repository). On both sides of the Colorado Plateau, younger mafic lavas generally erupt closer to the Colorado Plateau center and have isotopic and geochemical signatures that are increasingly more asthenospheric. Basalts of a similar age in a given subregion can show a range of ε_{Nd} values (Fig. 3), as is expected when basalts are extracted from varying depths. For example, younger than 600 ka tholeiites, alkali basalts, and basanites from the Uinkaret volcanic field give ε_{Nd} values that range from −1.5 to −1.3 for tholeiites, 0.4 to 3 for alkali basalts, and 5.2 to 7.7 for basanites, due to the increasing depth from which these basalt types were extracted (Lee et al., 2009; Takahashi and Kushiro, 1983). Although conductive heating of the lithosphere alone might be able to explain the temporal migration of volcanism toward the plateau's center (Roy et al., 2009), it does not explain the increase in the ε_{Nd} values and decrease in $^{87}Sr/^{86}Sr$ ratios with decreasing age. The increasing asthenospheric signature in the basalt source region requires a convectively upwelling depleted mantle source.

Complex replacement of lithosphere by asthenosphere, as manifested by the basalt geochemical data, is likely due to a combination of processes including (1) deep mantle convection associated with the foundering Farallon slab and/or the East Pacific Rise (Moucha et al., 2008, 2009), (2) drip-like lithospheric instabilities and resulting return flow (e.g., Li et al., 2008; Elkins-Tanton, 2007), (3) progressive infiltration of asthenospheric melts into the base of the lithosphere, and/or (4) step-induced upper mantle convection (Fig. 5; van Wijk et al., 2010). Observed spatial and temporal patterns seem best explained by small-scale upper mantle convection due to lateral variations in temperature structure between the Colorado Plateau and surrounding extended provinces (van Wijk et al., 2010). In this model, lithospheric thinning in the Rio Grande rift and Basin and Range would create a step-like transition to the deeply keeled Colorado Plateau that would focus upper mantle convection, leading to migrating lithospheric thinning and magma infiltration. The relative dearth of asthenospheric melts in subregions E and F and the lack of strong spatial trends there can be explained by the lack of lithospheric thinning and extension in those areas or their greater distance from the hypothesized locations of large-scale convection cells associated with the East Pacific Rise and the foundering Farallon slab (Moucha et al., 2008, 2009).

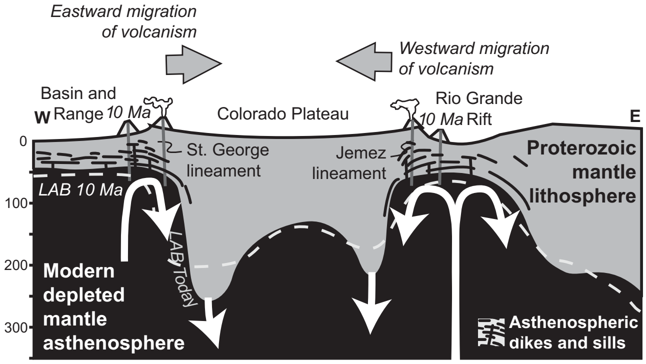

Figure 5. Stages and interacting processes for lithospheric thinning and modification of Colorado Plateau. Asthenospheric upwelling is shown to contribute asthenospheric material to lithosphere via magma infiltration and produce lithospheric thinning. Modern lithosphere-asthenosphere boundary (LAB) is shown, as well as hypothesized location of LAB at 10 Ma. Basalts migrate toward Colorado Plateau center and have increasing ε_{Nd} values due to both lithospheric removal and infiltration of depleted mantle into lithosphere.

Strongly asthenospheric basalts in the western Grand Canyon and the southern Jemez lineament suggest that lithospheric thinning is most effective in the area of Proterozoic compositional boundaries, like the Jemez and St. George lineaments (Magnani et al., 2005), which may represent preexisting lithospheric weaknesses. These zones would thus facilitate the preferential transfer of magma to the surface and be more susceptible to lithospheric replacement. In zones far from these weaknesses, like central Arizona, modest amounts of lithospheric thinning are inferred from the temporal trends and the lack of strongly asthenospheric basalts. In those areas, the low-velocity mantle imaged geophysically is likely lithospheric mantle modified by infiltration of asthenospheric melts but not yet entrained in asthenospheric flow.

CONCLUSIONS

Neogene convective replacement of lithospheric by asthenospheric mantle around the Colorado Plateau is supported by combined geochemical data and tomographic data. The youngest (younger than 1 Ma) basalts erupted above pronounced S and P wave anomalies at depths of 80 km. Isotopic and elemental tracers indicate that Colorado Plateau basalts become increasingly asthenospheric with time and erupt closer to the center of the plateau. Basalts with strongly asthenospheric signatures occurred in the western Grand Canyon and the southern Jemez lineament starting ca. 5–7 Ma. Boundaries between Proterozoic compositional domains in those areas likely impart weaknesses to the lithosphere that facilitate thinning and passage of asthenospheric melts to the surface. In these same zones, the migration of asthenospheric melts toward the plateau center has been occurring at a rate of ~4–5 km/m.y. Although southern Utah and central Arizona show negative S and P wave anomalies at the depth from which alkali basalts are derived, these areas lack basalts with strong asthenospheric signatures. This suggests that modification of lithosphere by upwelling depleted asthenosphere is starting to create mixed source regions, but has not yet replaced the lithosphere in the basalt source region.

The lack of asthenospheric basalts on the northeastern margins of the Colorado Plateau is best explained by the lack of large-scale late Cenozoic extension and lithospheric thinning, which promotes upper mantle convection (van Wijk et al., 2010), or their greater distance from the hypothesized large-scale convection cells of Moucha et al. (2008, 2009).

Areas of young asthenosphere-derived basalts are also areas of high surface elevation and coincide with geoid anomalies (Karlstrom et al., 2008). This and numerical modeling (Moucha et al., 2008, 2009; van Wijk et al., 2010) suggest that upper mantle flow can produce 600–700 m of epeirogenic uplift of the Colorado Plateau edge. This magnitude of uplift was originally proposed by geological studies of differential uplift between the western Grand Canyon (50–70 m/m.y.) and eastern Grand Canyon (150–170 m/m.y.) (Karlstrom et al., 2007) over the past 6 m.y. (Karlstrom et al., 2008). The differential incision data suggest that this mantle-driven differential uplift is expressed at multiple scales both as epeirogenic block movement and simultaneous ~100 m/m.y. fault slip on Colorado Plateau–bounding normal faults. The proposed ~600-m-scale Neogene uplift is a significant fraction of the 2 km of uplift that has occurred since the Late Cretaceous, but necessitates earlier Laramide and mid-Tertiary uplift events (Flowers et al., 2008; Liu and Gurnis, 2010).

The combined spatial and temporal trends in age and geochemistry of basalts, elevation patterns, mantle velocity structure, and numerical modeling are best explained by upper mantle convection of asthenosphere, which is progressively infiltrating and replacing the lithosphere. Neogene and ongoing dynamic surface uplift of the Colorado Plateau driven by mantle convection represents an important geodynamic process in the overall Colorado Plateau uplift history.

ACKNOWLEDGMENTS

Support for this research was provided by National Science Foundation grants EAR-0711546 (to Karlstrom) and ISE-0610393 (to Karlstrom and Crossey). We thank Grand Canyon National Park officials for a research agreement that allowed access to the river corridor for sampling. Field and laboratory assistance from Washington State University's GeoAnalytical Lab, Laura Crossey, and Kimberly Samuels is gratefully acknowledged. Reviews from Jolante van Wijk and an anonymous reviewer improved the paper.

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Manuscript received 23 July 2010
Manuscript accepted 2 August 2010

Printed in USA