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Role of arc magmatism and lower crustal foundering in controlling elevation history of the Nevadaplano and Colorado Plateau: A case study of pyroxenitic lower crust from central Arizona, USA

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ABSTRACT

Garnet–pyroxenite xenoliths from a 25 Ma volcano on the southern edge of the Colorado Plateau in central Arizona (USA) are shown here to have crystallized as deep-seated cumulates from hydrous arc magmas, requiring the generation of a large complement of felsic magmas. U–Pb dating of primary titanite grains indicates that crystallization probably occurred around 60 Ma. These observations suggest that voluminous arc magmatism reached as far inland as the edge of the Colorado Plateau during the Laramide orogeny. Here, we employ a combination of petrology, petrophysics, and seismic imaging to show that the formation and subsequent removal of a thick, dense, cumulate root beneath the ancient North American Nevadaplano modified the buoyancy of the orogenic plateau, possibly resulting in two uplift events. A late Cretaceous–early Tertiary uplift event should have occurred in conjunction with thickening of the crust by felsic magmatism. Additional uplift is predicted if the pyroxenite root later foundered, but such uplift must have occurred after ∼25 Ma, the age of the xenolith host. We show that seismic velocity anomalies and seismic structures in the central part of the Colorado Plateau could represent pyroxenitic layers that still reside there. However, under the southern and western margins of the Colorado Plateau, the seismic signatures of a pyroxenite root are missing, despite xenolith records and geochemical evidence for their existence prior to 25 Ma. We suggest that these particular regions have undergone recent removal of the pyroxenite root, leading to late uplift of the plateau. In summary, our observations suggest that the Nevadaplano, west of the Colorado Plateau and now represented by the Basin and Range province, was underlain by high elevations in the late Cretaceous through early Tertiary due to magmatic thickening. This may have facilitated an east-directed drainage pattern at this time. Subsequent collapse of the Nevadaplano, culminating in Basin and Range extension and coupled with delamination-induced uplift of the margins of the Colorado Plateau in the late Cenozoic, may have reversed this drainage pattern, allowing rivers to flow west, as they do today.

1. Introduction

A combination of processes, including voluminous magmatism and tectonic thickening, leads to thickened crust in continental arc settings (Ducea et al., 2009; Lee et al., 2015). Such processes can lead to the development of large-scale, high-standing, low-relief plateaus. Ultimately, orogenic plateaus undergo extensional collapse due to their thickened crust, and the complex internal topographies that result from gravitational collapse provide insight into how continents are destroyed.

The ancient, exhumed North American Cordillera provides an excellent natural laboratory to study the construction and subsequent destruction of orogenic plateaus. Recent studies show that crustal thickening accompanied peak magmatism during the Late Cretaceous, contributing to an ancient high-elevation plateau, or Nevadaplano, in the hinterland of the Sevier orogenic belt (Cassel et al., 2014; Chapman et al., 2015; DeCelles, 2004; Henry et al., 2012; Paterson and Ducea, 2015). Magmatism ceased along the western margin of the continent and swept inland throughout the southwestern US during the Laramide orogeny, reaching as far inland as central Arizona, as indicated by the presence of Late Cretaceous–early Tertiary granites (Fig. 1B). In the magmatic lull that followed, crustal thinning and orogenic collapse began by Miocene time (Cassel et al., 2014; Chapman et al., 2015; Henry et al., 2012; Horton and Chamberlain, 2006). The resulting complex

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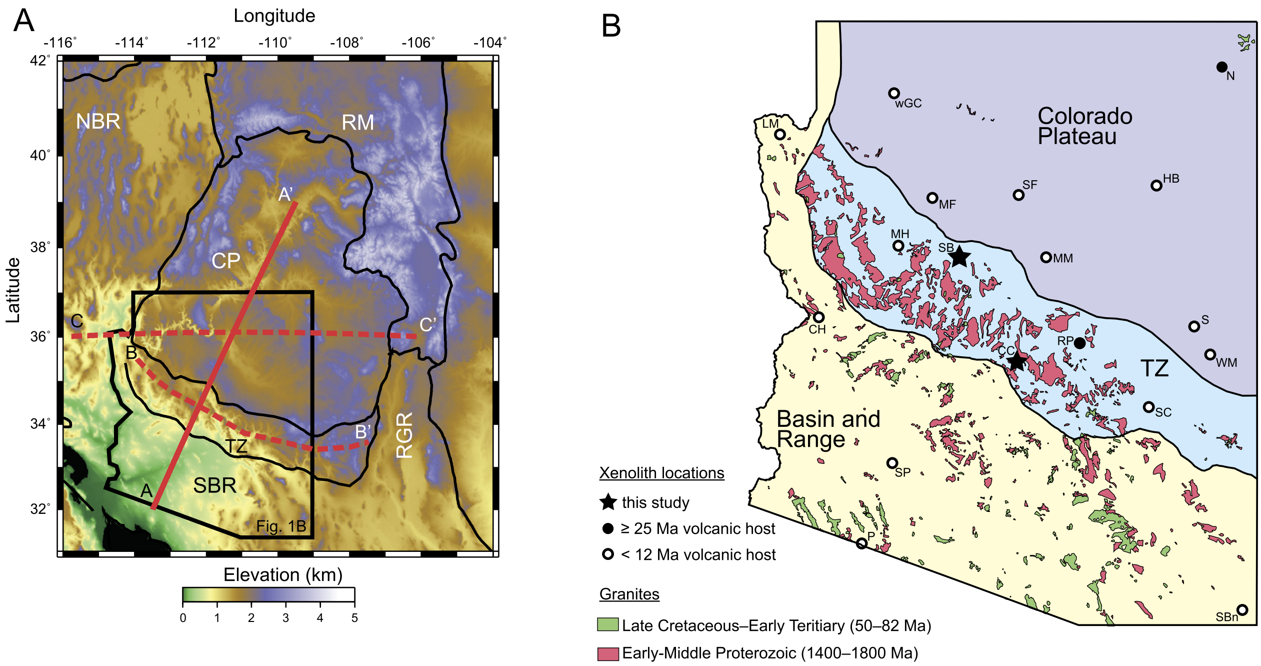

Fig. 1. Topography and simplified geologic map of the study region. (A) Topography of the Colorado Plateau and surrounding physiographic provinces (thin black lines). CP, Colorado Plateau; NBR, northern Basin and Range; SBR, southern Basin and Range; RGR, Rio Grande rift; RM, Rocky Mountains; TZ, Basin and Range–Colorado Plateau (BR-CP) Transition Zone. Profile AA' is the location of the seismic cross-sections in Fig. 4. Profiles BB' and CC' are shown in Supplementary Figs. 3–4. The thick black line outlines the map location in (B). (B) Simplified geologic map of Arizonan granite outcrops and sample locations (stars), modified from the Geologic Map of Arizona (Richard et al., 2002). Pastel colors shade the Colorado Plateau (purple), Basin and Range (yellow), and the BR-CP Transition Zone (blue) physiographic provinces. Other xenolith locations are marked by a circle, where closed circles mark volcanic hosts 25 Ma or older and open circles denote younger volcanic hosts. Garnet–pyroxenite xenoliths are conspicuously missing in young volcanic fields, which are dominated by mantle lithologies, such as spinel peridotite. Xenolith field locations are as follows: CC, Camp Creek; CH, Castaneda Hills; HB, Hopi Buttes; LM, Lake Mead; MF, Mount Floyd; MH, Mount Hope; MM, Mormon Mountain; N, Navajo; P, Pinacate; RP, Reno Pass; S, Springerville; SB, Sullivan Buttes; SBn, San Bernardino; SC, San Carlos; SF, San Francisco; SP, Sentinel Plains; wGC, western Grand Canyon; WM, White Mountains. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

topography of the North American Cordillera is exemplified by the relatively undeformed, low-relief Colorado Plateau within an otherwise highly deformed orogenic belt (Dickinson, 1989) (Fig. 1A). Marine sedimentary deposits atop the plateau suggest it was at or below sea level in the Late Cretaceous, but today rests 2 km above the surrounding regions. Free-air gravity indicates isostatic compensation across the Basin and Range and Colorado Plateau regions, yet the plateau's current crustal thickness of 40–50 km, especially along its edges, alone cannot support its elevation, requiring a sub-Moho component of buoyancy (Levander et al., 2011; Thompson and Zoback, 1979). Crustal thickness estimates vary considerably, approaching 55 km in some models, and suggest there is some complexity to the structure of the Colorado Plateau (e.g. Zandt et al., 1995).

Buoyancy gives rise to the Colorado Plateau's high elevations, yet how the buoyancy and elevation of the plateau evolved through time is unclear. Hypothesized explanations for epeirogenic uplift of the Colorado Plateau are varied and include: delamination of the Farallon plate following flat slab subduction (Bird, 1979; Humphreys, 1995), dynamic topography (Moucha et al., 2008), thermal expansion of the cold lithosphere after Farallon slab removal (Roy et al., 2009), mid-crustal flow from thickened crust (McQuarrie and Chase, 2000), and lithospheric foundering (Levander et al., 2011). Exactly when the plateau uplifted is also debated. Apatite U–Th/He thermochronometry studies from the Grand Canyon of northern Arizona yield conflicting results (Flowers, 2010), suggesting uplift occurred in the late Cretaceous (Flowers and Farley, 2012) or late Cenozoic (Karlstrom et al., 2014).

One way to assess paleo-elevations of a region is to examine the effect on nearby drainage systems. A recent thermochronometry study of surficial deposits on the southwestern Colorado Plateau presents evidence for two-stage incision of the Grand Canyon, and suggests the canyon was dominantly carved by an east-flowing river by 70 Ma followed by reversal of the river to flow westward in the Tertiary to excavate the final few hundred meters of the Grand Canyon (Flowers and Farley, 2012). Such dramatic hydrologic changes must have occurred in response to changes in topography, requiring high elevations in the west during the Cretaceous and collapse of the western highlands by Tertiary time.

Drivers of uplift are most likely sourced in the buoyancy of the crust, lithospheric mantle or asthenosphere. To gain insight into these deep sources of uplift, we integrate here new geochemical data and petrophysical calculations of lower crustal xenoliths with published seismic studies of the deep crust and upper mantle of the southwestern USA. Lower crustal xenoliths erupted within the 25 Ma Sullivan Buttes (Krieger et al., 1971) and similar-aged Camp Creek latites from the Basin and Range–Colorado Plateau Transition Zone (BR-CP TZ) in central Arizona provide a rare glimpse of the deep architecture of the plateau. The BR-CP TZ represents the transition between the thick crust of the stable, undeformed Colorado Plateau and the thin crust of the actively extending Basin and Range Province. The Arizonan lower crustal xenoliths are dominated by garnet–pyroxenite with minor amphibolite (Esperança et al., 1988). This mineralogy is compositionally denser than asthenospheric mantle (Lee, 2014; Lee et al., 2006), thus, their formation and removal could influence elevation. Pyroxenites also indicate a complementary volume of felsic magmas were emplaced into the crust. The low density of felsic magmas would contribute positive buoyancy to the continent. Here we show that magmatism influences elevation, via magmatic inflation of the crust and lower crustal foundering.