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Geochemical evidence for an orogenic plateau in the southern U.S. and northern Mexican Cordillera during the Laramide orogeny

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ABSTRACT

Previous studies of the central United States Cordillera have indicated that a high-elevation orogenic plateau, the Nevadaplano, was present in Late Cretaceous to early Paleogene time. The southern United States Cordillera and northern Mexican Cordillera share a similar geologic history and many of the same tectonic features (e.g., metamorphic core complexes) as the central United States Cordillera, raising the possibility that a similar plateau may have been present at lower latitudes. To test the hypothesis of an elevated plateau, we examined Laramide-age continental-arc geochemistry and employed an empirical relation between whole-rock La/Yb and Moho depth as a proxy for crustal thickness. Calculations of crustal thickness from individual data points range between 45 and 72 km, with an average of 57 ± 12 km (2σ) for the entire data set, which corresponds to 3 ± 1.8 km paleoelevation assuming simple Airy isostasy. These crustal thickness and paleoaltimetry estimates are similar to previous estimates for the Nevadaplano and are interpreted to suggest that an analogous high-elevation plateau may have been present in the southern United States Cordillera. This result raises questions about the mechanisms that thickened the crust, because shortening in the Sevier thrust belt is generally not thought to have extended into the southern United States Cordillera, south of ~35°N latitude.

INTRODUCTION

High-elevation orogenic plateaus like the modern Tibetan, Anatolian, and Altiplano-Puna plateaus commonly develop in the interior, or hinterland, of convergent orogenic systems. Construction of such plateaus is arguably among the most significant tectonic phenomena of Cenozoic time. The plateaus influence Earth systems in a wide variety of ways, including disrupting atmospheric circulation patterns (Molnar et al., 1993), driving past climate change (Raymo and Ruddiman, 1992; Strecker et al., 2007), concentrating metallic and other natural resources (Hou and Cook, 2009), and altering plate motions (Patriat and Achache, 1984; Iaffaldano et al., 2006).

A similar plateau—the Nevadaplano, analogous to the Altiplano in the central Andes—was present in the Great Basin region of the central United States Cordillera (~35°N–45°N latitude; Fig. 1) during Late Cretaceous to early Paleogene time (DeCelles, 2004; Best et al., 2009; Snell et al., 2014). The Nevadaplano was isostatically supported by thickened continental crust formed by retroarc shortening in the Sevier thrust belt and in precursor thrust belts such as the Luning-Fencemaker (Jones et al., 1998; DeCelles, 2004). Previous estimates for crustal thickness in the Nevadaplano using igneous geochemical proxies, similar to the technique employed in this study, range from 55 to 65 km (Chapman et al., 2015). Structural restoration of late Paleogene to Holocene extension, including zones of high-magnitude extension associated with the Cordilleran metamorphic core complexes (Fig. 1), also suggests that the Nevadaplano was supported by thick (40–65 km) crust (Coney and Harms, 1984).

Some researchers have suggested that the Nevadaplano may have extended farther southeast (Whitney et al., 2004; Copeland et al., 2017). This idea is contentious, however, because the Sevier thrust belt does not extend into the southern United States Cordillera and northern Mexican Cordillera (Fig. 1; Yonkee and Weil, 2015; Fitz-Díaz et al., 2018). Instead, Late Cretaceous to Paleogene contractional strain in these areas is generally characterized by basement-involved uplifts accompanying high-angle reverse faulting, formed during the Laramide orogeny (Krantz et al., 1989; Clinkscales and Lawton, 2017; Fitz-Díaz et al., 2018). Horizontal shortening recorded by these high-angle reverse faults is insufficient to have significantly thickened the crust (Davis, 1979). Thus, if the Laramide orogeny in southern Arizona and northern Sonora resulted in thickened crust, mechanisms in addition to tectonic shortening are required.

To evaluate the possibility of thick crust supporting an orogenic plateau in the southern United States and northern Mexican Cordillera, we used whole-rock La/Yb ratios in Laramide-age, intermediate-composition continental-arc rocks as a proxy for crustal thickness (Fig. 2), following the method of Profeta et al. (2015). As crustal thickness increases, whole-rock heavy rare earth element (HREE) concentrations decrease and light rare earth element (LREE) concentrations increase, due to the high-pressure stabilization of HREE-enriched phases such as amphibole and garnet at the expense of LREE-enriched phases such as plagioclase (Hu et al., 2017; Müntener and Ulmer, 2018). Despite the low concentration of LREE in plagioclase, the mineral is important because of its abundance in continental-arc rocks and because it is unstable at higher pressure, in contrast to other LREE-bearing accessory phases such as monazite.

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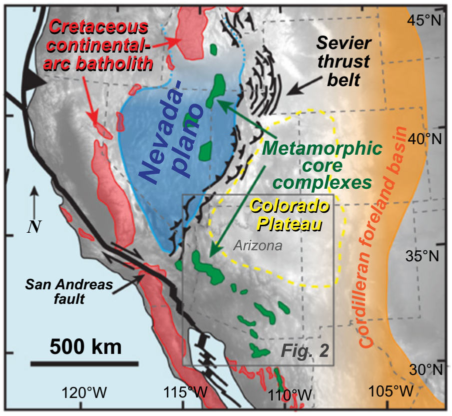

Figure 1. Overview map of present-day configuration of central United States Cordillera, southern United States Cordillera, and northern Mexico Cordilleran orogen.

GEOLOGIC BACKGROUND

Some early studies of the southern United States Cordillera suggested that the Sevier thrust belt was continuous from southern Nevada to northern Chihuahua (Drewes, 1978). However, subsequent research has demonstrated that many of the thrust faults used to support a thrust belt interpretation are low-angle normal faults or other types of geologic contacts such as unconformities (Dickinson, 1984; Krantz et al., 1989; Clinkscales and Lawton, 2017). As a result, most researchers now believe that the Sevier thrust belt terminates in the Mojave region of southern California (DeCelles, 2004; Yonkee and Weil, 2015) and that shortening in southern Arizona and northern Sonora was temporally restricted to the Laramide orogeny and predominantly occurred along high-angle reverse faults, in part reactivating Late Jurassic to Early Cretaceous rift-related structures (Davis, 1979; Krantz et al., 1989; Lawton, 2000; Favorito and Seedorff, 2018; Fitz-Díaz et al., 2018).

Continental-arc magmatism migrated eastward through the study area (Fig. 2) during the Laramide orogeny as the subduction angle of the Farallon slab shallowed (Coney and Reynolds, 1977). Laramide igneous rocks in southern Arizona and northern Sonora are mainly intermediate, metaluminous, and calc-alkaline rocks that have radiogenic isotopic compositions inherited from the lithospheric province into which they were emplaced (Lang and Titley, 1998; González-León et al., 2011; Chapman et al., 2018). During mid-Eocene time, toward the end of the Laramide orogeny and after arc magmatism had migrated through the region, silicic (SiO_2 >70 wt%), peraluminous granitoids were emplaced as sills, dikes, and plutons interpreted as products of crustal melting (Miller and Bradfish, 1980; Haxel et al., 1984; Miller and Barton, 1990; Fornash et al., 2013).

METHODS AND RESULTS

To estimate crustal thickness, we utilized an empirical relation between igneous whole-rock La/Yb and Moho depth for modern continental arcs (Profeta et al., 2015). The method was limited here to intermediate-composition rocks in order to avoid generally more mafic rocks that originated directly from the mantle and generally more felsic rocks that originated by partial melting of middle to upper crust or from highly fractionated melts. We used data only from rocks within the compositional ranges of SiO_2 = 55–70 wt%, MgO = 1–4 wt%, and Rb/Sr = 0.05–0.25 (Chapman et al., 2015; Profeta et al., 2015). These ranges exclude all analyses of Eocene peraluminous rocks. The filtered data set consisted of 105 whole-rock geochemical analyses, 16 new and 89 compiled from literature sources. Only minimally altered and unmineralized samples were included. Sample information, geochemical data for new and compiled analyses, and analytical methods are presented in the GSA Data Repository[1].

Samples analyzed in this study came from locations between 108.5°W and 114°W longitude and 30°N and 35°N latitude (Fig. 2). Crystallization ages of samples that passed through geochemical filters ranged from 81 to 50 Ma (see the Data Repository). All available data were used in the calculation of crustal thickness except for analyses from intrusive rocks associated with the Ray copper porphyry deposit in central Arizona (Fig. 2; Lang and Titley, 1998). These were excluded because they exhibit anomalous REE trends compared to the rest of southern Arizona and northern Sonora (Fig. 3). The unusual REE patterns at the Ray deposit may be related to derivation from or assimilation of the 1.4 Ga Ruin Granite, a HREE-enriched A-type granite that is the predominant component of the upper crust around Ray (Banks et al., 1972).

Estimates of crustal thickness from individual rock analyses range from 45 to 72 km, with an average uncertainty (1σ) of 10 km (Fig. 2; Table DR2 in the Data Repository). Average crustal thickness estimates and average crystallization ages for areas with ≥ 5 samples are labeled in Figure 2 to provide a representation of data variability. Crustal thickness estimates for specific areas range from 48 to 62 km (Fig. 3), with uncertainty ranging from 10 to 12 km (2σ). No clear correlation of age, location, and calculated crustal thickness was distinguishable in the data set, although the resolution of the data does not preclude possible correlations (Fig. DR1). As a result, we suggest that the best estimate of crustal thickness during the Laramide orogeny is obtained by considering the data collectively. Figure 4 presents all of our crustal thickness estimate results from the entire data set as a histogram and a kernel density estimate (KDE), which uses an adaptive bandwidth. The KDE is characterized by a large population of thicknesses (~40% of data) centered on 61 km and a broad distribution of thickness values between 47 and 57 km. Average crustal thickness for

[1]GSA Data Repository item 2020047, new and compiled geochemical data, data references, analytical methods, and supplementary figures; and new and compiled data in an Excel file, is available online at http://www.geosociety.org/datarepository/2020/, or on request from editing@geosociety.org.

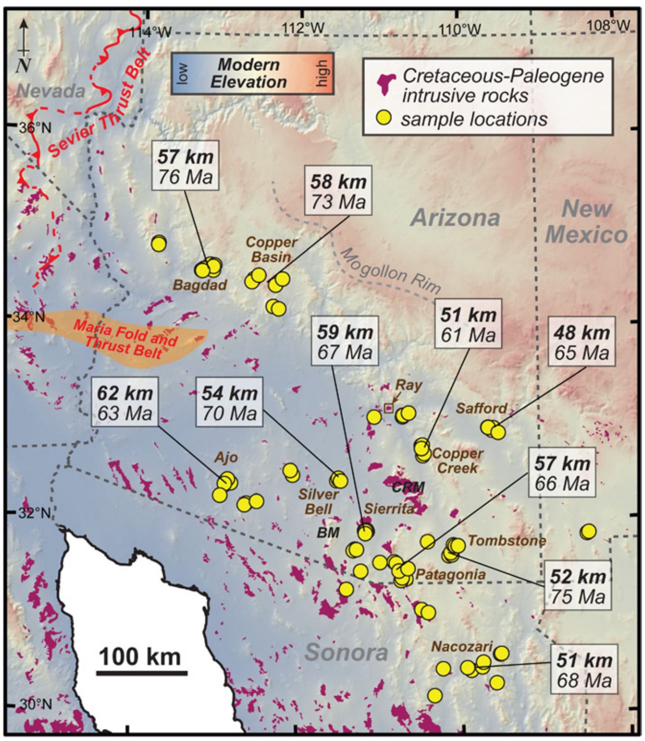

Figure 2. Map showing locations of samples analyzed to estimate crustal thickness during the Laramide orogeny. Text in white boxes is the average crustal thickness and average age for locations (labeled in brown) with ≥ 5 samples. Crustal thickness uncertainty (2σ) for individual locations is 10–12 km, and age uncertainty (2σ) is ≤ 10%. Red line delineating the easternmost location of the Sevier thrust belt is modified from Wells and Hoisch (2008). The Maria fold-and-thrust belt location is from Spencer and Reynolds (1990). CRM—Catalina-Rincon Mountains, BM—Baboquivari Mountains.

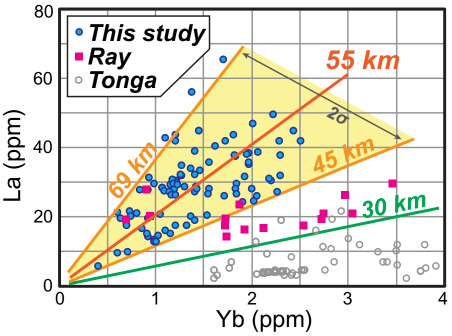

Figure 3. Intermediate (see text for discussion of geochemical filters) whole-rock La and Yb data used in this study (blue filled circles), data from the Ray Cu-porphyry system (Arizona, USA) (pink squares), and data from the Quaternary Tonga arc (gray open circles; compiled from the GEOROC database, http://georoc.mpch-mainz.gwdg.de). Solid lines are crustal thickness calculated from La/Yb using the empirical relation of Profeta et al. (2015). The modern Tonga arc has a geophysically determined crustal thickness of ~20 km (Contreras-Reyes et al., 2011) and is only shown for comparison.

the entire data set is 57 ± 12 km (2σ), where the reported uncertainty is the average single measurement uncertainty and standard deviation added in quadrature. Application of the empirical relation between whole-rock Sr/Y and crustal thickness as presented in Chapman et al. (2015) to the filtered data set indicates a median crustal thickness and median absolute deviation of 58 ± 16 km (1σ). We focused on the evaluation based on La/Yb primarily because of the lower uncertainty.

DISCUSSION AND CONCLUSIONS

Our estimate, 57 ± 12 km, for the average crustal thickness in the southern United States Cordillera and northern Mexican Cordillera during the Laramide orogeny is consistent with the concept of a high-elevation orogenic plateau. This crustal thickness estimate is similar to previous estimates (55–65 km) for the Nevadaplano during the same time span, ca. 90–45 Ma (Chapman et al., 2015). The crustal thickness reported in this study is slightly higher than crustal thickness estimates (40–55 km) based on structural restoration of Cenozoic extension in southern Arizona (Coney and Harms, 1984). For comparison, the average crustal thickness beneath the highest elevations in the Altiplano in the Central Andes is 60–70 km (Ryan et al., 2016). An outstanding question is whether the southern United States and northern Mexican Cordillera was a true plateau—a low topographic relief surface—during the Laramide orogeny. Evidence for crustal anatexis during Late Cretaceous to Eocene time (Miller and Bradfish, 1980; Haxel et al., 1984) suggests hot and low-viscosity middle to lower crust, which would have favored development of a low-relief orogenic plateau (Bird, 1991).

Using average values for continental crust density (2800 kg/m^3), upper mantle density (3300 kg/m^3), and continental crust thickness (37 km; Rudnick and Gao, 2003) and assuming Airy isostatic compensation, 57-km-thick crust corresponds to a paleoelevation of ~3 km during or immediately following the Laramide orogeny. This paleoelevation falls within the range of estimates (1.5–4.5 km) based on carbonate $\delta^{18}O$ for the Eocene American Southwest (Licht et al., 2017). Sedimentary provenance and paleocurrent data from gravels along the Mogollon Rim of central Arizona ("rim gravels"; Fig. 2) also indicate an uplifted sediment source region south of the Colorado Plateau during the Laramide orogeny (Elston and Young, 1991). Paleoaltimetric studies for the Nevadaplano suggest minimum elevations of 2.2–3.1 km during Late Cretaceous time based on carbonate clumped-isotope thermometry (Snell et al., 2014) and as much as 3.5 km elevation during Oligocene time based on δD values of ancient meteoric water preserved in ignimbrite glasses (Cassel et al., 2014).

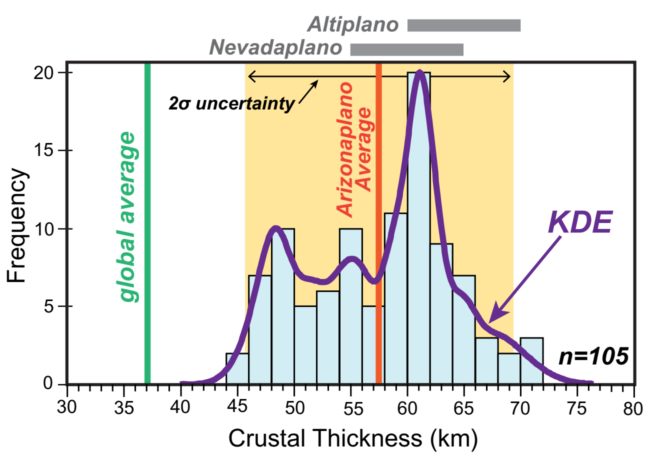

Figure 4. Histogram and kernel density estimate (KDE) showing the distribution of calculated crustal thicknesses for all data analyzed in this study. Average crustal thickness estimate for the postulated Arizonaplano (United States Cordillera) is 57 ± 12 km (2σ), which is significantly higher than the global average of continental crust thickness (Rudnick and Gao, 2003). Gray bars show the range of crustal thicknesses estimated for the Late Cretaceous Nevadaplano (United States Cordillera) from Chapman et al. (2015) and for the modern Altiplano (central Andes) (Ryan et al., 2016).

The major implication of this study is that some mechanism is required to have thickened the crust in the southern United States and northern Mexican Cordillera during the Laramide orogeny. Unlike the central United States Cordillera (the location of the Nevadaplano), the southern United States Cordillera was marked by extension associated with the Bisbee-McCoy-Sabinas rift system during Late Jurassic to Early Cretaceous time (Dickinson and Lawton, 2001). Aptian–Albian marine limestone in southern Arizona suggests that the region was at or below sea level during mid-Cretaceous time (Dickinson and Lawton, 2001) and only transitioned to a contractional regime at the start of the Laramide orogeny (Chapman et al., 2018). Structural studies in the area indicate that deformation primarily occurred by folding or slip associated with high-angle reverse faults, which only accumulated a few to several tens of kilometers of horizontal shortening (Davis, 1979; Krantz et al., 1989; Clinkscales and Lawton, 2017; Favorito and Seedorff, 2018). Conversely, parts of the thin-skinned Sevier thrust belt in the central United States Cordillera accommodated ≥ 300 km of horizontal shortening (DeCelles and Coogan, 2006). To significantly thicken the crust in southern Arizona and northern Sonora, either (1) low-angle thrust faults are more prevalent than currently recognized, or (2) processes other than crustal shortening may have prevailed.

Late Cretaceous, north-south–directed shortening in the Maria fold-and-thrust belt (Spencer and Reynolds, 1990; Tosdal, 1990; Fig. 2) may have locally thickened the crust in west-central Arizona, but cannot explain elevated thicknesses elsewhere in the region. Despite the view that Laramide shortening in southern Arizona and northern Sonora primarily occurred by high-angle reverse faulting, low-angle thrust faults have been locally documented, including in the Catalina-Rincon Mountains (e.g., Gehrels and Smith, 1991; Arca et al., 2010; Spencer et al., 2011) and in and around the Baboquivari Mountains (Haxel et al., 1984; Goodwin and Haxel, 1990; Fig. 2). More work is needed to document shortening magnitudes in these areas and test whether they are representative of a larger structural province or only local complexities. Erdman et al. (2016) suggested that magmatic additions in central Arizona during the Laramide orogeny may have thickened the crust and formed a Nevadaplano-like feature. Other mechanisms to form orogenic plateaus include underthrusting/underplating (Zhou and Murphy, 2005), crustal inflation by lateral channel flow (Bird, 1991; Husson and Sempere, 2003), and intracontinental subduction (Tapponnier et al., 2001). None of these processes has been explicitly evaluated in the southern United States and northern Mexican Cordillera, which highlights how the postulated plateau challenges existing paradigms of the tectonic and geodynamic history of the region and raises questions as to whether this plateau is the southern extension of the Nevadaplano or a separate, distinct feature—the Arizonaplano.

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