GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G52455.1

Manuscript received 7 June 2024
Revised manuscript received 9 September 2024
Manuscript accepted 3 October 2024



Published online 18 October 2024

# Crustal bobbing in response to lithospheric foundering recorded by detrital proxy records from the central Andean Plateau

B. Carrapa[1,*], G. Jepson[2], P.G. DeCelles[1], S.W.M. George[2], M. Ducea[1,3], C. Campbell[1], and R.R. Dawson (née Canavan)[4]
[1]Department of Geosciences, University of Arizona, 1040 E. 4th Street, Tucson, Arizona 85721, USA
[2]School of Geosciences, University of Oklahoma, 100 E. Boyd Street, Norman, Oklahoma 73019, USA
[3]University of Bucharest, Faculty of Geology and Geophysics, Bucharest, Romania, 010040
[4]Department of Earth, Geographic, and Climate Sciences, University of Massachusetts–Amherst, 627 N. Pleasant Street, Amherst, Massachusetts 01003, USA

## ABSTRACT

**Lithospheric foundering is an important mechanism of crustal deformation and recycling, basin subsidence, and surface uplift in orogenic systems. The Arizaro Basin, in the Puna region of NW Argentina, is a place where foundering was proposed to have taken place during the late Miocene. The Arizaro Basin has been described as a "bobber" basin produced by Miocene lithospheric foundering. The geometry, sedimentology, deformation, and paleoelevation history of the Arizaro Basin and surrounding arc suggest dynamic processes associated with lithospheric removal. Although analogue and numerical models support this hypothesis, the history of crustal thickness in response to lithospheric removal remains unconstrained. Here, we used a novel approach exploiting the geochemistry of detrital zircons from volcanic ashes intercalated within the Arizaro Basin stratigraphy to reconstruct the paleocrustal thickness of the neighboring magmatic sources throughout the Cenozoic. Our data indicate that the sources of volcanism for the Arizaro Basin were characterized by relatively thick crust (~53 km) since ca. 36 Ma. Thickening between ca. 20 and 13 Ma and thinning after ca. 13 Ma are consistent with formation and subsequent removal of a crustal root under the nearby arc and Aguas Calientes caldera.**

## INTRODUCTION

Gravitational removal of overthickened lithosphere/crust has long been recognized as an important mechanism under orogenic belts and plateaus (e.g., Bird, 1979; Houseman and McKenzie, 1981); however, the details and timing of lithospheric removal, the surface response (deformation, subsidence, uplift), and the degree of crustal involvement in the process remain poorly quantified. In the central Andean Plateau, geological, geophysical, and geodynamic modeling studies have pointed to foundering and removal of the mantle lithosphere and lower crust as an important mechanism for plateau development during the Cenozoic (e.g., Beck et al., 2015; Garzione et al., 2017; Wang et al., 2021). The Puna region, within the central Andean Plateau, has a thinner lithosphere and crust compared to the Altiplano (Fig. 1), suggesting lithospheric removal (e.g., Wang et al., 2021; McMillan and Schoenbohm, 2022), which in turn produced localized magmatism (e.g., Kay et al., 1994; Ducea et al., 2013), deformation, dynamic subsidence and uplift, and "bobber"-type basins (DeCelles et al., 2015). In the Altiplano region, various degrees of diachronous lithospheric removal, including wholesale delamination, have been invoked as the primary mechanism of >2 km of surface uplift since ca. 10 Ma (e.g., Garzione et al., 2017, and references therein). In the Puna region, a wealth of data show that high elevations similar to modern were reached by ca. 36 Ma in response to shortening and crustal thickening, whereas smaller-scale lithospheric removals (piecemeal style) are consistent with limited elevation changes (≤1 km) since ca. 20–10 Ma (Canavan et al., 2014; Quade et al., 2015; Wang et al., 2021).

The Arizaro Basin, located south of the southern Altiplano-Puna volcanic complex (APVC) and within the Central volcanic zone (CVZ) and active arc (Fig. 1), has a modern average elevation of ~3.5 km and preserves a record of dynamic processes associated with lithospheric foundering (Schoenbohm and Carrapa, 2015; DeCelles et al., 2015; McMillan and Schoenbohm, 2022). The crust beneath the Arizaro Basin today is between ~55 km and ~43 km thick (Bianchi et al., 2013; Beck et al., 2015), which is significantly thinner than the surrounding regions (Fig. 1B). Numerical and analogue models suggest that as a lithospheric root forms, the surface above and near the root may be deflected downward by viscous stresses associated with lateral entrainment of lower crust/lithospheric mantle toward the growing root; local shortening occurs in the upper crust due to distributed contractional stresses. As the root begins to drop off, the crust thins and extends, and the surface rebounds isostatically (Wang et al., 2021; Andersen et al., 2022). Mafic or bimodal magmatism occurs synchronously with lithospheric removal and is volumetrically proportional to the size of the drip (Ducea et al., 2013; McMillan and Schoenbohm, 2022).

The Arizaro Basin fill is composed of ~3 km of eolian, lacustrine, and fluvial strata deposited between ca. 21 and 9 Ma. The basin center experienced symmetrical shortening as it subsided and then subsequent exhumation. The quasi-circular shape of the basin (Fig. 1D), nature of sedimentation, and history of subsidence coupled with the basin's deformation and uplift history indicate that it may have formed by dynamic processes during and following lithospheric foundering (DeCelles et al., 2015; Wang et al., 2021; Andersen et al., 2022). Numerical models show a coupling between the surface and lithospheric removal (McMillan and Schoenbohm, 2022). Corner flow in the mantle may have entrained foundering lithosphere, expanding lithospheric removal from areas to the east of the basin, where the crustal root may have formed (e.g., Aguas Calientes caldera), into the arc region west of the

B. Carrapa https://orcid.org/0000-0003-2508-6421
*bcarrapa@arizona.edu

CITATION: Carrapa, B., et al., 2025, Crustal bobbing in response to lithospheric foundering recorded by detrital proxy records from the central Andean Plateau: Geology, v. 53, p. 29–33, https://doi.org/10.1130/G52455.1

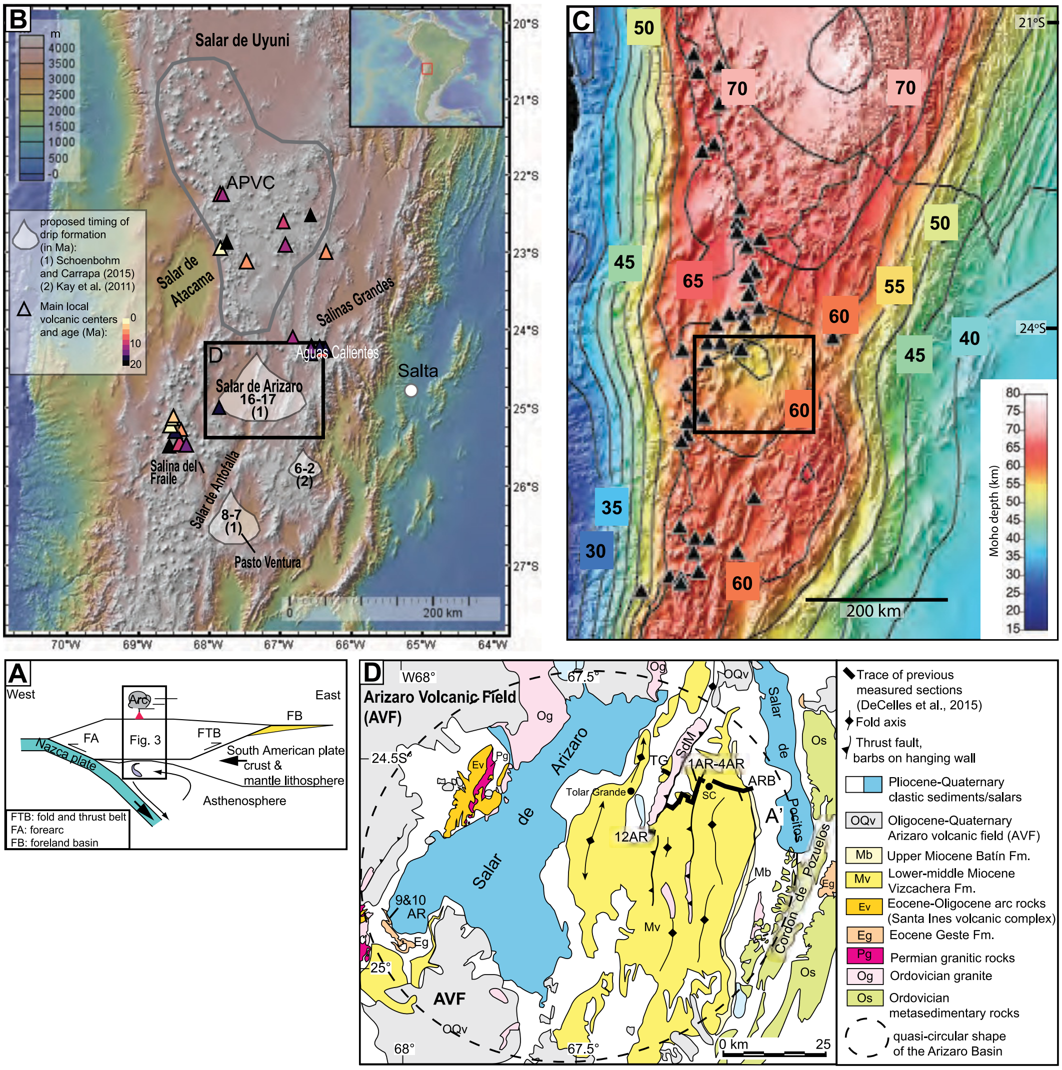


**Figure 1. (A) Schematic cross section across Central Andes with locations of main features discussed in text; rectangle corresponds to cartoon in Figure 3. (B) Digital elevation model of NW Argentina with location of Altiplano-Puna volcanic complex (APVC) and main sedimentary basins and volcanic centers (with time of drip activity in Ma) discussed in main text after Kay et al. (2010, 2011), Petrinovic et al. (1999), Richards et al. (2013), and Simón et al. (2021). (C) Map of Puna region showing depth to Moho (contours in km), modified after Beck et al. (2015). (D) Geologic map of Arizaro Basin with locations of measured stratigraphic sections where samples were collected (modified after DeCelles et al., 2015). For sample locations, refer to Table S4 (see text footnote 1).**

Arizaro Basin (Wang et al., 2021). Eocene and Miocene–Pliocene volcanism in the region was characterized by large ignimbrites, which are generally associated with lithospheric removal (e.g., Kay et al., 2010). Overall, volcanism of the CVZ and APVC (~21°S–24°S) starting ca. 11 Ma produced mostly calc-alkaline, high-K dacites with minor rhyolites, which have been interpreted to represent crustal melts resulting from crustal thickening (Kay et al., 2010). Eocene–Quaternary arc rocks to the SW (Arizaro volcanic field [AVF] and Santa Ines volcanic complex) and large ignimbrites (typical of lithospheric removal) of the Aguas Caliente caldera (ca. 17 and ca. 10 Ma; Petrinovic et al., 1999) directly to the NE are likely proximal volcanogenic sources of the Arizaro Basin as supported by the timing and nature of magmatism (Petrinovic et al., 2010). Other active Neogene sources are located to the SW of the Arizaro Basin (Figs. 1B and 1D). Hence, ashes within the Arizaro Basin provide a unique opportunity to reconstruct paleocrustal thicknesses within the coupled arc-basin region. Here, we present isotopic and trace-element data from comagmatic zircons sampled from volcanic ashes and a detrital sample preserved in the Arizaro Basin (Fig. 1) with the goal of reconstructing the history of crustal thickness of the region during the formation and subsequent gravitational removal of a lithospheric root.

## METHODS AND RESULTS

### Zircon U-Pb Geochronology, Hf Analyses, and Trace Elements

Zircon U-Pb and trace-element data were collected by high-resolution single-collector laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS), and Lu/Hf isotopes were collected by multicollector (MC) LA-ICP-MS at the Arizona LaserChron Center (Linde et al., 2016; Balica et al., 2020) (Tables S1 and S2 in the Supplemental Material[1]). The Lu/Hf isotopes were analyzed to characterize the magmatic source of zircons based on their values compared to intermediate εHf values (near chondrite uniform reservoir [CHUR]) (Table S3).

Whole-rock and zircon chemistry can be used to estimate paleocrustal thickness using mohometry (Chiaradia, 2015; Profeta et al., 2015; Farner and Lee, 2017; Balica et al., 2020; Luffi and Ducea, 2022). We analyzed zircon U-Pb and selected trace-element concentrations from 10 ashes and one detrital sample from the Miocene Vizcachera and Batín formations in the Arizaro Basin (Table S4). Zircons were analyzed simultaneously for U-Th-Pb ages and trace and rare earth element (TREE) geochemistry following the method described by Balica et al. (2020) (Table S2). We filtered samples for zircons that were geochemically consistent with derivation from intermediate igneous rocks (55%–70%) following the protocol outlined by Belasouva et al. (2002), Sundell et al. (2022), and Balica et al. (2020). We also removed zircons with anomalously high phosphorus (>1000 ppm) from our analysis because of possible derivation from S-type granites (Zhu et al., 2020). Zircon trace-element concentrations were then converted into whole-rock geochemical estimates

[1]Supplemental Material. Description of analytical methods. Please visit https://doi.org/10.1130/GEOL.S.27173115 to access the supplemental material; contact editing@geosociety.org with any questions.

using partition coefficients from Chapman et al. (2016). Here, we used the La/Yb ratios derived from whole-rock geochemical estimates to produce paleocrustal thickness after Profeta et al. (2015) and Balica et al. (2020) (Fig. 2A; Fig. S1). We present all data with error bars in Figure S1. We also calculated paleocrustal thickness directly from zircon Eu anomalies (Tang et al., 2021) for comparison (Fig. S2).

### Magma Source and Crustal Thickness Estimates

We analyzed 10 ash samples ranging in age between ca. 36 and 11 Ma (Fig. 2A; Table S4) and one detrital sample (AR6) that contained a component of early Miocene detrital zircons (ca. 20 Ma) (Table S4). Most ash samples contained some detrital zircons (Table S1). We produced a time-resolved paleocrustal thickness record for the Arizaro Basin using Eocene to late Miocene zircon U-Pb single-grain ages (Fig. 2A). Zircon geochemical precision is far greater (∼10%) than what is considered reasonable for paleocrustal thickness estimates (∼25%; Sundell et al., 2022); thus, when converted to whole-rock and then to crustal thickness estimates, zircon geochemistry results in unreasonably precise single-grain crustal thicknesses. To account for this, we combined a general uncertainty of ±10.8 km proposed by Sundell et al. (2022) with ∼3% uncertainty on La and Yb concentrations from zircon (Fig. S1; Table S2). Crustal thickness estimates were then subjected to a bootstrap analysis to create median values with a 2 m.y. rolling window following methods outlined in Triantafyllou et al. (2023).

The bootstrap analysis of Eocene to late Miocene zircons showed paleocrustal thicknesses between ∼60 and 50 km (Fig. 2A). Crustal thickness of ∼53 km at ca. 36 Ma (Fig. 2A) may reflect a source from the arc to the W and NW (Fig. 1), consistent with paleowind directions from eolian facies at the base of the Vizcachera Formation showing eastward winds (DeCelles et al., 2015). Not enough data were available to interpret a trend between ca. 35 and ca. 20 Ma. Our analysis shows that the source of the ca. 20–10 Ma age zircons from ashes in the Arizaro Basin was characterized by different crustal thicknesses through time. An apparent increase in crustal thickness between ca. 20 and 13 Ma and a decrease after ca. 13 Ma are consistent with the history of uplift and subsidence (Fig. 2B) and with thickening during drip formation and thinning during drip removal (Fig. 3). Eu-based crustal thicknesses, albeit generally higher, show similar crustal variability and a thinning trend (Fig. S2). The Hf isotopic data from a subset of the analyzed samples show variable εHf values, suggesting contributions from both crustal and mantle sources (Fig. S3; Table S3).

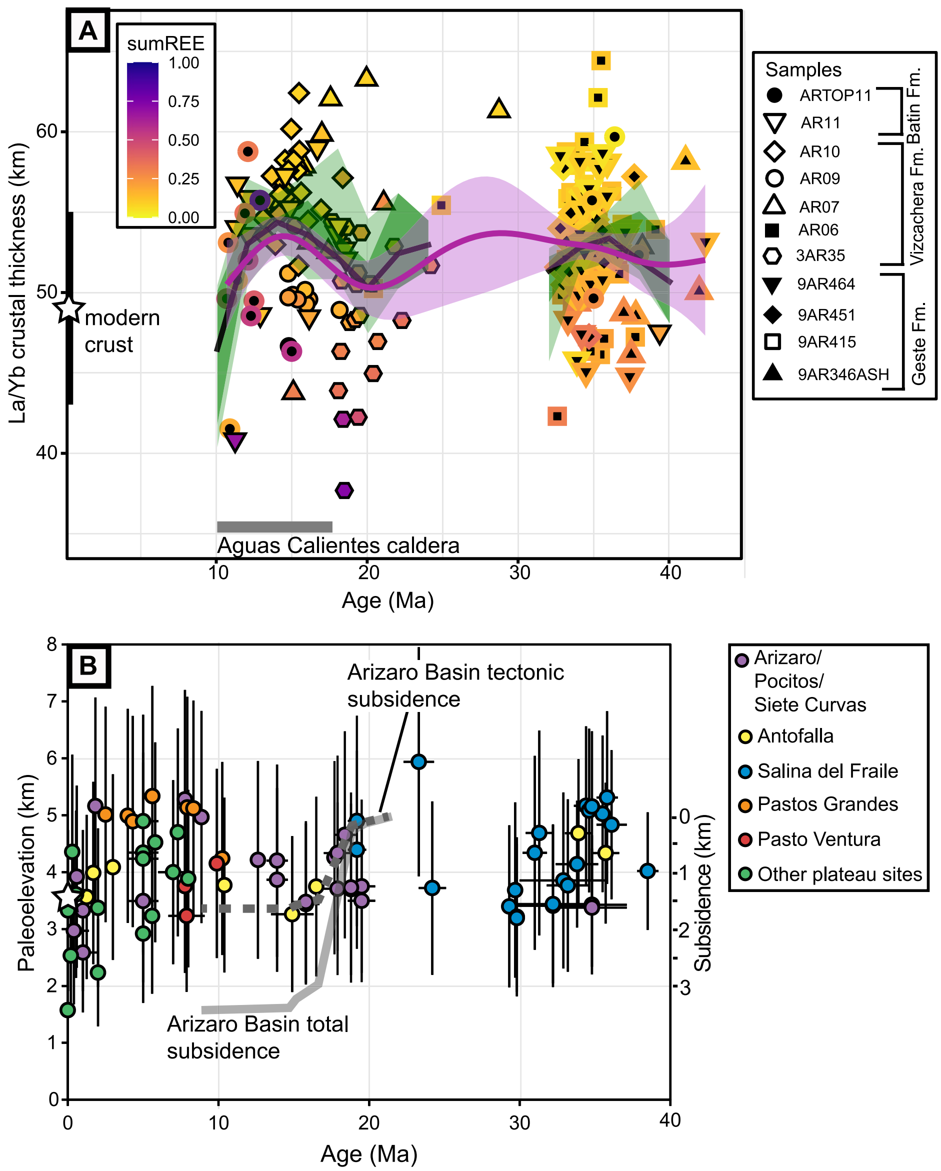


**Figure 2. (A) Eocene–Miocene single-grain zircon U-Pb ages from ashes and one detrital sample from Arizaro Basin plotted against single-grain zircon to whole-rock La/Yb crustal thickness values (Table S2 [see text footnote 1]). Time series was produced using maximum likelihood of median values of paleocrustal thickness distribution from bootstrap iteration analysis applied on 2 m.y. rolling window at 2 m.y. steps (Triantafyllou et al., 2023). Green envelopes (dark green—1σ uncertainty; light green—3σ uncertainty) were derived from bootstrap analysis that excluded zircon grains with phosphorous >1000 ppm. Pink line and associated light-pink envelope represent generalized additive model fitted to data trend. (B) Paleoelevation estimates based on volcanic ashes from Puna region from this and previous studies (Canavan et al., 2014; Quade et al., 2015; Carrapa et al., 2024; Pingel et al., 2023, and references therein). Paleoelevations were estimated using atmospheric thermodynamic model from Rowley (2007), which is based on isotopic lapse rate of precipitation. Sampled $\delta D_{glass}$ values were used in calculating isotopic value of high-altitude precipitation and low-altitude values were derived from literature. See Supplemental Material text for details (text footnote 1). Error bars are 2σ. Subsidence curves are modified after DeCelles et al. (2015).**

Overall, our results are consistent with the geochemical variability of ca. 14–6 Ma ignimbrites from the central Puna region, which have been interpreted to reflect melting in the deep crust and differences in crustal melt fractionations of small and large ignimbrites during the generation of hybrid magmas and contributions from both mantle and crustal sources (Kay et al., 2010; Ducea et al., 2013). Alternatively, these data represent different sources characterized by different crustal thicknesses.

## DISCUSSION AND CONCLUSIONS

Our data show that the source of the Arizaro Basin ashes was characterized by a relatively thick crust (∼53 km) at ca. 36 Ma, consistent with high elevations (Canavan et al., 2014; Quade et al., 2015; Carrapa et al., 2024) and

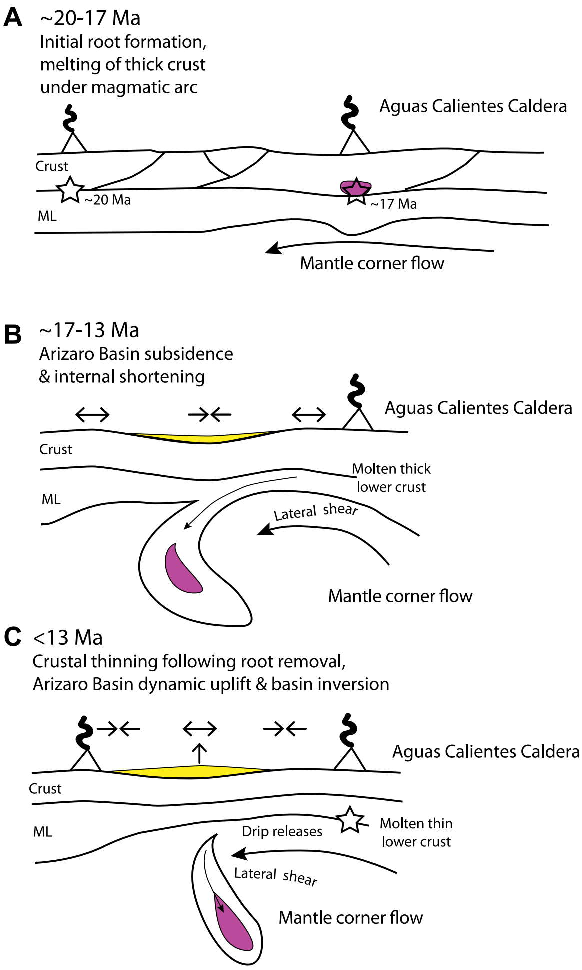


**Figure 3. Cartoon showing possible source of zircons (star) and crustal evolution of Arizaro Basin and surrounding regions, including arc, modified after McMillan and Schoenbohm (2022) and Wang et al. (2021). (A) Circa 20–17 Ma: Possible source of thick crust under arc to west (ca. 20 Ma) and Aguas Calientes caldera (ca. 17 Ma) to east. (B) Circa 17–13 Ma: Melting of thickened lower crust under Aguas Calientes caldera, and westward displacement of lower-crustal root driving Arizaro Basin subsidence and internal basin deformation (shortening). (C) Since 13 Ma: Melting of thinned lower crust following lithospheric removal; dynamic uplift and basin inversion and exhumation. ML—mantle lithosphere.**

with the bulk of shortening occurring in the Puna region before ca. 20 Ma (Henriquez et al., 2023). Neogene paleocrustal thickness estimates support thickening associated with drip formation associated with a weak crust, under the magmatic arc, where a dense root created a lateral pressure gradient, driving crustal flow in the weak layer and crustal thickening (Wang and Currie, 2017), and then thinning following drip removal (McMillan and Schoenbohm, 2022; Göğüş et al., 2022).

Our data can be explained by ash sources in the arc to the W at ca. 20 Ma and in the Aguas Calientes caldera to the NE at ca. 17 Ma; in this scenario, foundering of a lithospheric drip from the Aguas Calientes caldera was later entrained and displaced westward by mantle flow, which caused dynamic subsidence in the Arizaro Basin (Fig. 3A; Wang et al., 2021). This is also the time when we observe a possible decrease in surface elevation (Fig. 2B). Crustal thinning after ca. 13 Ma is interpreted to represent the removal of the crustal root during foundering and displacement of the dense root to the W due to corner flow (Fig. 3B; Wang et al., 2021). The magnitude of Miocene thinning recorded by our data is consistent with model predictions showing that 5–10 km of crustal thinning (starting with a 60-km-thick crust) over ~10 m.y. produces ~1.2 km of tectonic subsidence followed by uplift (Wang et al., 2021). This history of crustal removal is consistent with the observed subsidence history (DeCelles et al., 2015), can reconcile variabilities observed in paleoaltimetry data, and can help to resolve controversies about the uplift history of the region (Fig. 1B; Pingel et al., 2023). Other geodynamic models support crustal thinning associated with detachment of the lower crust (e.g., Göğüş et al., 2022). Alternatively, the thickening and thinning trends may reflect local variations in crustal thicknesses in the Puna region as a result of localized drip removal involving a mix of strong and weak crust, resulting in different modes of removal (McMillan and Schoenbohm, 2022), local variations in magma composition, different magmatic sources, and/or magmatic differentiation during crustal thickening (Farner and Lee, 2017). These data underscore the complexity of the lithospheric structure and history of lithospheric removal under the central Andean Plateau.

## ACKNOWLEDGMENTS

We thank George Gehrels for analytical support and National Science Foundation grant EAR-FRES 2020935 for funding this research. MND acknowledge funding by the program (PNRR-III-C9-2023–I8) of Romanian MCID (64/30.07.2023). We also thank the editor, three anonymous reviewers, and Matthew Malkowski for constructive criticism.

## REFERENCES CITED

Andersen, J., Göğüş, O.H., Pysklywec, R.N., Santimano, T., and Uluocak, E.Ş., 2022, Symptomatic lithospheric drips triggering fast topographic rise and crustal deformation in the Central Andes: Nature–Communications Earth & Environment, v. 3, 150, https://doi.org/10.1038/s43247-022-00470-1.

Balica, C., Ducea, M.N., Gehrels, G.E., Kirk, J., Roban, R.D., Luffi, P., Chapman, J.B., Triantafyllou, A., Guo, J., Stoica, A.M., Ruiz, J., Balintonia, I., Profeta, L., Hoffman, D., and Petrescu, L., 2020, A zircon petrochronologic view on granitoids and continental evolution: Earth and Planetary Science Letters, v. 531, https://doi.org/10.1016/j.epsl.2019.116005.

Beck, S.L., Zandt, G., Ward, K.M., and Scire, A., 2015, Multiple styles and scales of lithospheric foundering beneath the Puna plateau, Central Andes, *in* DeCelles, P.G., et al., eds., Geodynamics of a Cordilleran Orogenic System: The Central Andes of Argentina and Northern Chile: Geological Society of America Memoir 212, p. 43–60, https://doi.org/10.1130/2015.1212(03).

Belousova, E.A., Griffin, W.L., O'Reilly, S.Y., and Fisher, N.J., 2002, Igneous zircon: Trace element composition as an indicator of source rock type: Contributions to Mineralogy and Petrology, v. 143, p. 602–622, https://doi.org/10.1007/s00410-002-0364-7.

Bianchi, M., Heit, B., Jakovlev, A., Yuan, X., Kay, S.M., Sandvol, E., Alonso, R.N., Coira, B., Brown, L., Kind, R., and Comte, D., 2013, Teleseismic tomography of the southern Puna plateau in Argentina and adjacent regions: Tectonophysics, v. 586, p. 65–83, https://doi.org/10.1016/j.tecto.2012.11.016.

Bird, P., 1979, Continental delamination and the Colorado Plateau: Journal of Geophysical Research, v. 84, p. 7561–7571, https://doi.org/10.1029/JB084iB13p07561.

Canavan, R., Carrapa, B., Clementz, M., Quade, J., DeCelles, P.G., and Schoenbohm, L., 2014, Early Cenozoic uplift of the Puna plateau, Central Andes, based on stable isotope paleoaltimetry of hydrated volcanic glass: Geology, v. 42, p. 447–450, https://doi.org/10.1130/G35239.1.

Carrapa, B., DeCelles, P.G., Dawson (née Canavan), R.D., Quade, J., Clementz, M.T., and Schoenbohm, L., 2024, Uplift of the Puna plateau was not limited to Miocene and younger time: Proceedings of the National Academy of Sciences of the United States of America, v. 121, https://doi.org/10.1073/pnas.2406528121.

Chapman, J.B., Gehrels, G.E., Ducea, M.N., Giesler, N., and Pullen, A., 2016, A new method for estimating parent rock trace element concentrations from zircon: Chemical Geology, v. 439, p. 59–70, https://doi.org/10.1016/j.chemgeo.2016.06.014.

Chiaradia, M., 2015, Crustal thickness control on Sr/Y signatures of recent arc magmas: An Earth scale perspective: Scientific Reports, v. 5, https://doi.org/10.1038/srep08115.

DeCelles, P.G., Carrapa, B., Horton, B.K., McNabb, J., Gehrels, G., and Boyd, J., 2015, The Miocene Arizaro Basin, central Andean hinterland: Response to partial lithosphere removal?, *in* DeCelles, P.G., et al., eds., Geodynamics of a Cordilleran Orogenic System: The Central Andes of Argentina and Northern Chile: Geological Society of America Memoir 212, p. 359–386, https://doi.org/10.1130/2015.1212(18).

Ducea, M.N., Seclaman, A.C., Murray, K.E., Jianu, D., and Schoenbohm, L.M., 2013, Mantle-drip magmatism beneath the Altiplano-Puna plateau, Central Andes: Geology, v. 41, p. 915–918, https://doi.org/10.1130/G34509.1.

Farner, M.J., and Lee, C.-T.A., 2017, Effects of crustal thickness on magmatic differentiation in subduction zone volcanism: A global study: Earth and Planetary Science Letters, v. 470, p. 96–107, https://doi.org/10.1016/j.epsl.2017.04.025.

Garzione, C.N., McQuarrie, N., Perez, N.D., Ehlers, T.A., Beck, S.L., Kar, N., Eichelberger, N., Chapman, A.D., Ward, K.D., Ducea, M.D., Lease, R.O., Poulsen, C.J., Ehlers, T., Insel, N., Wagner, L., Saylor, J.E., Zandt, G., and Horton, B.K., 2017, The tectonic evolution of the central Andean Plateau and geodynamic implications for the growth of plateaus: Annual Review of Earth and Planetary Sciences, v. 45, p. 529–559, https://doi.org/10.1146/annurev-earth-063016-020612.

Göğüş, O.H., Sundell, K., Uluocak, E.S., Saylor, J., and Çetiner, U., 2022, Rapid surface uplift and crustal flow in the Central Andes (southern Peru) controlled by lithospheric drip dynamics: Scientific Reports, v. 12, 5500, https://doi.org/10.1038/s41598-022-08629-8.

Henriquez, S., DeCelles, P.G., Carrapa, B., and Hughes, A.N., 2023, Kinematic evolution of the central Andean retroarc thrust belt in northwestern Argentina and implications for coupling between shortening and crustal thickening: Geological Society of America Bulletin, v. 135, p. 81–103, https://doi.org/10.1130/B36231.1.

Houseman, G.A., and McKenzie, D.P., 1981, Convective instability of a thickened boundary layer and its relevance for the thermal evolution of continental convergent belts: Journal of Geophysical Research, v. 86, p. 6115–6132, https://doi.org/10.1029/JB086iB07p06115.

Kay, S.M., Coira, B., and Viramonte, J., 1994, Young mafic back arc volcanic rocks as indicators of continental lithospheric delamination beneath the Argentine Puna Plateau, Central Andes: Journal of Geophysical Research, v. 99, p. 24,323–24,339, https://doi.org/10.1029/94JB00896.

Kay, S.M., Coira, B.L., Caffe, P.J., and Chen, C.-H., 2010, Regional chemical diversity, crustal and mantle sources and evolution of central Andean Puna plateau ignimbrites: Journal of Volcanology and Geothermal Research, v. 198, p. 81–111, https://doi.org/10.1016/j.jvolgeores.2010.08.013.

Kay, S.M., Coira, B., Wörner, G., Kay, R.W., and Singer, B.S., 2011, Geochemical, isotopic and single crystal $^{40}Ar/^{39}Ar$ age constraints on the evolution of the Cerro Galán ignimbrites: Bulletin of Volcanology, v. 73, p. 1487–1511, https://doi.org/10.1007/s00445-010-0410-7.

Linde, G.M., Trexler, J.H., Jr., Cashman, P.H., Gehrels, G., and Dickinson, W.R., 2016, Detrital zircon U-Pb geochronology and Hf isotope geochemistry of Paleozoic and Triassic passive margin strata of western North America: Geosphere, v. 12, p. 1016–1031, https://doi.org/10.1130/GES01252.1.

Luffi, P., and Ducea, M.N., 2022, Chemical mohometry: Assessing crustal thickness of ancient orogens using geochemical and isotopic data: Reviews of Geophysics, v. 60, https://doi.org/10.1029/2021RG000753.

McMillan, M., and Schoenbohm, L.M., 2022, Diverse styles of lithospheric dripping: Synthesizing gravitational instability models, continental tectonics, and geologic observations: Geochemistry, Geophysics, Geosystems, v. 24, https://doi.org/10.1029/2022GC010488.

Petrinovic, I.A., Mitjavila, J., Viramonte, J.G., Marti, J., Becchio, R., Arnosio, M., and Colombo, F., 1999, Geoquímica y Geocronología de secuencias volcánicas Neógenas de trasarco, en el extremo oriental de la Cadena Volcánica Transversal del COT, noroeste de Argentina, *in* Colombo, F., et al., eds., Geología de los Andes Centrales Meridionales: El Noroeste Argentino: Acta Geológica Hispánica, v. 34, p. 255–273.

Petrinovic, I.A., Martí, J., Aguirre-Díaz, G.J., Guzmán, S., Geyer, A., and Salado Paz, N., 2010, The Cerro Aguas Calientes caldera, NW Argentina: An example of a tectonically controlled, polygenetic collapse caldera, and its regional significance: Journal of Volcanology and Geothermal Research, v. 194, p. 15–26, https://doi.org/10.1016/j.jvolgeores.2010.04.012.

Pingel, H., Alonso, R.N., Bookhagen, B., Cottle, J.M., Mulch, A., Rohrmann, A., and Strecker, M.R., 2023, Miocene surface uplift and orogenic evolution of the southern Andean Plateau (central Puna), northwestern Argentina: Proceedings of the National Academy of Sciences of the United States of America, v. 120, https://doi.org/10.1073/pnas.2303964120.

Profeta, L., Ducea, M.N., Chapman, J.B., Paterson, S.R., Gonzales, S.M.H., Kirsch, M., Petrescu, L., and DeCelles, P.G., 2015, Quantifying crustal thickness over time in magmatic arcs: Scientific Reports, v. 5, https://doi.org/10.1038/srep17786.

Quade, J., Dettinger, M.P., Carrapa, B., DeCelles, P., Murray, K.E., Huntington, K.W., Cartwright, A., Canavan, R.R., Gehrels, G., and Clementz, M., 2015, The growth of the Central Andes, 22°S–26°S, *in* DeCelles, P.G., et al., eds., Geodynamics of a Cordilleran Orogenic System: The Central Andes of Argentina and Northern Chile: Geological Society of America Memoir 212, p. 277–308, https://doi.org/10.1130/2015.1212(15).

Richards, J.P., Jourdan, F., Creaser, R.A., Maldonado, G., and DuFrane, S.A., 2013, Geology, geochemistry, geochronology, and economic potential of Neogene volcanic rocks in the Laguna Pedernal and Salar de Aguas Calientes segments of the Archibarca lineament, northwest Argentina: Journal of Volcanology and Geothermal Research, v. 258, p. 47–73, https://doi.org/10.1016/j.jvolgeores.2013.04.004.

Rowley, D.B., 2007, Stable isotope–based paleoaltimetery: Theory and validation, *in* Kohn, M.J., ed., Paleoaltimetry: Geochemical and Thermodynamic Approaches: Mineralogical Society of America Reviews in Mineralogy and Geochemistry 66, p. 23–52, https://doi.org/10.1515/9781501508608-004.

Schoenbohm, L., and Carrapa, B., 2015, Miocene–Pliocene shortening, extension, and mafic magmatism support small-scale lithospheric foundering in the Central Andes, NW Argentina, *in* DeCelles, P.G., et al., eds., Geodynamics of a Cordilleran Orogenic System: The Central Andes of Argentina and Northern Chile: Geological Society of America Memoir 212, p. 167–180, https://doi.org/10.1130/2015.1212(09).

Simón, V., Arnosio, M., Trumbull, R.B., Caffe, P., Rocholl, A., Sudo, M., Lucassen, F., and Huidobro, F., 2021, Geology, geochemistry and geochronology of Lindero porphyry gold deposit in the southern Puna plateau, Argentina: Journal of South American Earth Sciences, v. 105, https://doi.org/10.1016/j.jsames.2020.103047.

Sundell, K.E., George, S.W.M., Carrapa, B., Gehrels, G.E., Ducea, M.N., Saylor, J.E., and Pepper, M., 2022, Crustal thickening of the northern central Andean Plateau inferred from trace elements in zircon: Geophysical Research Letters, v. 49, https://doi.org/10.1029/2021GL096443.

Tang, M., Ji, W.-Q., Chu, X., Wu, A., and Chen, C., 2021, Reconstructing crustal thickness evolution from europium anomalies in detrital zircons: Geology, v. 49, p. 76–80, https://doi.org/10.1130/G47745.1.

Triantafyllou, A., Ducea, M.N., Jepson, G., Hernández-Montenegro, J.D., Bisch, A., and Ganne, J., 2023, Europium anomalies in detrital zircons record major transitions in Earth geodynamics at 2.5 Ga and 0.9 Ga: Geology, v. 51, p. 141–145, https://doi.org/10.1130/G50720.1.

Wang H., and Currie, C., 2017, Crustal deformation induced by mantle dynamics: Insights from models of gravitational lithosphere removal: Geophysical Journal International, v. 210, p. 1070–1091, https://doi.org/10.1093/gji/ggx209.

Wang, H., Currie, C.A., and DeCelles, P.G., 2021, Coupling between lithosphere removal and mantle flow in the Central Andes: Geophysical Research Letters, v. 48, https://doi.org/10.1029/2021GL095075.

Zhu, Z., Campbell, I.H., Allen, C.M., and Burnham, A., 2020, S-type granites: Their origin and distribution through time as determined from detrital zircons: Earth and Planetary Science Letters, v. 536, https://doi.org/10.1016/j.epsl.2020.116140.

Printed in the USA