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Lindsay M. Schoenbohm and Barbara Carrapa

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Lindsay M. Schoenbohm*
Department of Chemical and Physical Sciences, University of Toronto Mississauga, Mississauga, ON L5L 1C6, Canada

Barbara Carrapa
Department of Geosciences, University of Arizona, Tucson, Arizona 85721, USA

ABSTRACT

Lithospheric foundering may be a fundamental phenomenon in diverse tectonic settings and has been shown to affect surface deformation, subsidence, and uplift. In the central Andes, lithospheric removal has been proposed to have acted at the scale of the whole orogenic system, at a smaller scale, and cyclically. Although geophysical and geochemical data have led workers to infer lithospheric foundering beneath the central Andes, there is no consensus on the timing, magnitude, and location of such foundering events. New field mapping, sedimentology, and 40Ar/39Ar and U-Pb geochronology from the Puna Plateau in NW Argentina document the timing and spatial distribution of basaltic magmatism, contraction, and basin formation, and subsequent extension, all of which are predicted results of small-scale lithospheric drips. Our data are consistent with the formation of at least two small-scale (50–100 km) foundering events, alternating between the northern and southern Puna Plateau. Such “driplets” could be common in cordilleran systems and other plateaus and can contribute to significant recycling of lithosphere without causing extensive exhumation and surface uplift.

INTRODUCTION

There is growing recognition of the importance of lithospheric foundering, given that orogenic regions commonly host thinner mantle lithosphere than expected according to shortening estimates, and that orogenic continental crust is dominantly intermediate in composition, requiring recycling of dense, mafic residues into the mantle (Ducea, 2011). Although debated, lithospheric removal as drip-like Rayleigh-Taylor instabilities has been proposed for several orogens around the world, including the Puna Plateau (Bianchi et al., 2013; Ducea et al., 2013; Kay and Kay, 1993; Kay et al., 2010, 2011) and the Altiplano Plateau (Garzione et al., 2008; Molnar and Garzione, 2007) of the central Andes, the Sierra Nevada (Ducea and Saleeby, 1998), Tibet (Turner et al., 1996), the Tien Shan (Molnar and Houseman, 2004), the Great Basin in the western United States (West...
et al., 2009), and the Colorado Plateau (Levander et al., 2011). In some cases, Rayleigh-Taylor instabilities have been imaged geophysically (e.g., Bianchi et al., 2013; Gilbert et al., 2007; Hales et al., 2005; Schurr et al., 2006; West et al., 2009) as dense features below or adjacent to regions of thin crust and lithosphere. Although immensely valuable in identifying recent foundering events, geophysical data are inherently limited in their ability to recognize older drips, which have descended deeply into the mantle. Geochemical data have also been used to identify Rayleigh-Taylor instabilities (e.g., DeCelles et al., 2009; Ducea et al., 2013; Kay and Kay, 1993; Manley et al., 2000) and can resolve older foundering events, but the magmatic response to foundering is highly variable, depending on the size and composition of foundering material (Elkins-Tanton, 2007), and surface erosion can remove evidence of the small-volume mafic volcanism often associated with lithospheric foundering. A possible recorder of the location and timing of past Rayleigh-Taylor instabilities, therefore, is surficial deformation. Although the pattern of deformation may vary depending on composition, size, and type of removal (e.g., single or double removal; Molnar and Houseman, 2004), analogue models have shown that in the case of a single drip, contraction and subsidence are predicted during drip formation, and uplift and extension should follow drip detachment (e.g., Göğüş and Pysklywec, 2008; Neil and Houseman, 1999; Pysklywec and Cruden, 2004). For example, surface subsidence and subsequent uplift have been successfully used to infer detachment of a dense plutonic root beneath the Wallowa Mountains in northeast Oregon in the mid-Miocene (Hales et al., 2005), which has since been confirmed by geophysical data (e.g., Darold and Humphreys, 2013).

In the Puna Plateau of northwest Argentina (Fig. 1), geochemical and geophysical data have been used to argue for removal of lithosphere through the formation and detachment of Rayleigh-Taylor instabilities (e.g., Kay and Kay, 1993; Kay et al., 1994; Schurr et al., 2006). Recent studies have further argued for small-scale (diameter of 50–100 km), repeated foundering events in the Puna Plateau (Bianchi et al., 2013; Calixto et al., 2013; Ducea et al., 2013; Kay et al., 2010, 2011). However, the precise timing and location of past drips are unknown, with inconsistencies between geophysical and magmatic indicators. We adopt a holistic approach, combining new structural, sedimentological, and geo-chronological data with existing geophysical, magmatic geochemical, and paleoelevation data to understand the history of the region.

We present new data from two key regions, Pasto Ventura in the southern Puna Plateau and the Arizaro region in the northwestern Puna Plateau (Fig. 1), which record evidence of shortening, followed by extension several million years after passage of the orogenic front through the region. This sequence of events is similar to model predictions and may be the result of past lithospheric foundering. These observations are corroborated by new 40Ar/39Ar geochronology of small-volume, mafic volcanism. Although other factors, such as wedge dynamics, gravitational spreading, and orogen-parallel extension, may play a role in surficial deformation in the Puna Plateau, when combined with existing geophysical and geochemical data, we will show that this history is best explained by the formation of multiple small drips, with the two most recent forming beneath the Arizaro region at 17–16 Ma and the southern Puna at 8–7 Ma. This interpretation contrasts with lithospheric foundering proposed for the Altiplano Plateau to the north, in which wholesale foundering and significant surface uplift are argued to have occurred at 10–7 Ma (Molnar and Garzione, 2007).

**GEOLOGIC SETTING**

Convergence between the Nazca and South American plates in the central Andes has resulted in formation of the broad, high-elevation (~3500 m) central Andean Plateau consisting of the internally drained Altiplano Plateau in Bolivia and the Puna Plateau in NW Argentina (Allmendinger et al., 1997). The Puna Plateau is distinguished from the Altiplano by higher elevations and relatively rugged topography with structurally bounded ranges and intervening basins (Fig. 1).

The mantle lithosphere is less than 10 km beneath most of the Altiplano and Puna Plateaus (Tassara and Echaurren, 2012). Moho depth is highly variable, ranging from 55 to 80 km, constrained by forward modeling of the Bouguer gravity anomaly (Tassara et al., 2006; Tassara and Echaurren, 2012), P-to-S teleseismic wave conversion (Yuan et al., 2000, 2002), and receiver-function analysis (Bianchi et al., 2013). However, the crust is thinned to <60 km in a quasi-circular region (Bianchi et al., 2013; Tassara et al., 2006; Tassara and Echaurren, 2012), with a diameter of 150–200 km, centered at 24°45’S, 67°45’W (Fig. 1B). High v_p/v_s ratios and low P-wave attenuation values have been used to argue for the presence of hot, asthenospheric mantle at shallow levels below the Puna Plateau and to infer the presence of sinking, detached lithosphere resting on the downgoing Nazca slab between 23°S and 24°S (Fig. 1B; Schurr et al., 2006). This feature is irregularly shaped, but it has a diameter of ~100 km in its longest dimension. In the southern Puna region, teleseismic tomography and Rayleigh-wave phase velocities indicate a region of dense material with a diameter of ~50 km resting on the subducting slab at a depth of 140–190 km (Fig. 1B; Bianchi et al., 2013; Calixto et al., 2013). In map view, this anomaly is located between 25°S and 26°S, just north of the Cerro Galan eruptive center (Fig. 1B), and it is also argued to be a detached lithospheric block (Bianchi et al., 2013; Calixto et al., 2013). Trench-parallel asthenospheric flow, based on shear-wave velocity anomalies, suggests that the anomalies may have migrated northward from their point of origin (Calixto et al., 2013).

Aspects of the magmatic history of the plateau are also consistent with lithospheric foundering. Small-volume, mafic, back-arc volcanism has developed in the southern Puna Plateau since ca. 7.3 Ma (Fig. 1B; Kay et al., 1994; Risse et al., 2008). Zn/Fe ratios of the most primitive of these flows indicate they are derived from melting of a peridotite source within 5–10 km below the base of the Moho (Ducea et al., 2013). These observations are consistent with modeling results (Elkins-Tanton, 2007), which suggest that magma is generated by heating and melting...
of small-volume (<50 km) lithospheric drips. Small drips are also indicated by the remnants of stable mantle lithosphere beneath the Puna Plateau in some locations since the Ordovician (Drew et al., 2009), precluding wholesale lithospheric removal, as suggested for the Altiplano (Molnar and Garzione, 2007). Ignimbrites within the Puna Plateau have also been linked to repeated lithospheric foundering events (Kay et al., 2010, 2011) and could result from asthenospheric upwelling and melting (thermal conversion) of the mantle lithosphere after drip detachment.

Shortening began in the Chilean Cordillera in the early Cenozoic (Arriagada et al., 2006; Mpodozis et al., 2005), was within the Puna Plateau and its eastern margin at 38 Ma (Carrapa and DeCelles, 2008; Coutand et al., 2001), was within the Eastern Cordillera from ca. 21 Ma to ca. 4 Ma (Carrapa et al., 2011a, 2011b; Deeken et al., 2006), and migrated into the Santa Bárbara Subandes after ca. 4 Ma (Echavarria et al., 2003; Reynolds et al., 2000) (Fig. 2). Thus, although structural complexities exist, an in-sequence progression of the onset of deformation associated

Figure 1. (A) Regional map on GTOPO30 DEM base (digital elevation model with horizontal grid spacing of 30 arc seconds), showing major tectonic units within the central Andes. (B) Shuttle Radar Topography Mission (SRTM) DEM showing age distribution of mafic volcanism (Risse et al., 2008; Zhou et al., 2011, personal commun.; this study), distribution of normal faulting (Schoenbohm and Strecker, 2009), contours of the Moho (Tassara and Echaurren, 2012, using a natural neighbor surface interpolation), the location of major ignimbrites (Ignm.; Kay et al., 2011), and the location of foundered lithospheric blocks inferred from vp/vs ratios, Op values, teleseismic tomography, and Rayleigh-wave phase velocities (Bianchi et al., 2013; Calixto et al., 2013; Schurr et al., 2006). Proposed Rayleigh-Taylor instabilities are numbered sequentially.
Figure 3. (A) Geologic map of the western margin of the Arizaro Basin on air photo base. Locations of samples dated in this study are indicated. (B) Cross section from southern part of western Arizaro Basin. (C) Cross section from northern part of western Arizaro Basin.
with west-to-east propagation of an orogenic wedge is present in the northern and central Puna Plateau (Carrapa et al., 2011a). In the Puna Plateau, widespread, low-magnitude extension has occurred since the late Miocene (Fig. 1B; Allmendinger, 1986; Montero Lopez et al., 2010; Risse et al., 2008; Schoenbohm and Strecker, 2009; Zhou et al., 2013). This extension likely reflects a combination of lithospheric foundering, gravitational spreading, and orogen-parallel extension (Riller et al., 2012; Schoenbohm and Strecker, 2009).

Deuterium ratios in volcanic glass suggest that elevations in the western Puna Plateau have been within 1 km of present values since at least 36 Ma (Canavan, 2012), suggesting uplift coincident with shortening and exhumation in the plateau (Arriagada et al., 2006; Carrapa and DeCelles, 2008; Coutand et al., 2001; Mpodozis et al., 2005). This is consistent with the gradual removal of excess lithospheric material through the detachment of small Rayleigh-Taylor instabilities, which would have a less significant impact on surface elevation that wholesale removal (Beiki-Ardakani et al., 2010). In contrast, paleoamplitude proxies from the Altiplano suggest a rapid increase in surface elevation (~3 km) between 10 and 7 Ma, which has been used to argue for wholesale plateau delamination there (Garzione et al., 2008; Molnar and Garzione, 2007).

METHODS

We document the structural and sedimentological history of two key regions: Pasto Ventura along the southern margin of the plateau, where normal faulting and basaltic volcanism are abundant, and the Salar de Arizaro in the northwestern plateau, for which geophysical data suggest thin lithosphere (Fig. 1B). We completed geological maps at a scale of 1:50,000 on an air photo base (Instituto Geografico Militar, Argentina) in a well-exposed section along the western margin of the Salar de Arizaro (Fig. 3) and within the northern Pasto Ventura basin (Fig. 4). We also measured a sedimentary section in the Pasto Ventura area (Fig. 4).

U-Pb zircon analyses on six intercalated ashes from both the Arirazo and Pasto Venturo regions were performed using the Cameca IMS 1270 ion microprobe at the University of California–Los Angeles (UCLA) National Ion Microprobe Facility (for pure ash layers in the Pasto Ventura section) and the inductively coupled plasma–mass spectrometer (ICP-MS) at the LaserChron Laboratory at the University of Arizona (for ignimbrite and impure ash layers in the Salar de Arizaro). Results are shown in Table 1, and additional details are available in Figures DR1 and Tables DR1 and DR2 of the GSA Data Repository. Two ignimbrites in the Arizaro region have ages of 18.4 ± 0.7 Ma and 17.7 ± 0.5 Ma; an ash intercalated with Quaternary strata farther north is 0.6 ± 0.2 Ma. Ages in the Pasto Ventura sedimentary section range from 7.77 to 10.5 Ma. Additional methodological details are available in the GSA Data Repository (see footnote 1).

We complement our mapping data with 40Ar/39Ar dating of nine previously undated basaltic lava flows from the Arirazo, Calalaste, and Hombre Muerto regions (Fig. 1). These were dated at the U.S. Geological Survey (USGS) facility in Denver, Colorado, following standard methods. As summarized in Table 1 and Figures DR2–DR10 (see footnote 1), these range in age from ~0.02 ± 0.03 Ma (A09B-2) to the oldest of the small-volume, mafic eruptions yet dated in the Puna Plateau at 8.7 ± 0.04 Ma (A10B-5). Additional methodological details are available in the GSA Data Repository (see footnote 1).

RESULTS

Arizaro Region

The Salar de Arizaro is a modern evaporite basin. It lies to the west of the Miocene Arizaro Basin, which contains ~3 km of eolian, alluvial, fluvial, and lacustrine sediment (Donato, 1987). We focused our mapping on the western margin of the modern salar. The major structure in this region is a NNE-striking, moderately WNW-dipping reverse fault (Fig. 3A). Its hanging wall consists of Ordovician Chuculaqui granodiorite and the volcaniclastic Lower Oligocene to Upper Miocene Quebrada de Agua complex (Zappetini et al., 2003). These units are carried over the upper Quebrada de Agua Formation in the south and Quaternary alluvial pebble-to-cobble conglomerate in the north (Fig. 3). In the southern footwall, volcaniclastic strata form a prominent asymmetric syncline, with an overturned western limb adjacent to the thrust fault and a shallowly dipping (20°–30°) eastern limb (Figs. 3A and 3C). Dips within the syncline progressively shallow up section, suggesting the presence of growth strata (Fig. 5), and therefore syndepositional deformation. In the northern footwall, Quaternary strata dip shallowly, mostly toward the northwest, toward the thrust fault (Figs. 3A and 3B).

The region is also cut by normal faults. The southern part of the major thrust is reactivated in a normal sense, as evidenced by a prominent bench where it crosses ridgelines, a result of extension along the fault. However, the major thrust is sealed in the north by basalt A09B-1, indicating no normal or thrust sense motion, at least along the northern portion of this fault, since this flow occurred (Fig. 3A). A normal fault in the interior of the range (Fig. 3A) offsets the Chuculaqui (Zappetini et al., 2003) basalt flow by ~120 m, with the hanging wall down to the west. Several small, monogenetic cinder cones and lava flows have erupted along the western margin of the Salar de Arizaro. These basalts are aligned along NNE trends, one along the edge of the modern salar, and one ~10 km to the west, close to the trace of the reverse fault, suggesting possible fault control.

Apatite fission-track (AFT) ages from the region are Oligocene and older (Carrapa and DeCelles, this volume). An age of 37.3 ± 4.8 Ma (A09FT-2; Fig. 3A) from the hanging-wall...
Figure 4. (A) Geologic map of the Pasto Ventura region on air photo base. (B) Legend for map. (C) Sedimentary log of units N1 and N2 in Pasto Ventura region. Ages shown on right are U-Pb dates on intercalated air-fall tuffs. Location of log is indicated on map. (D) Cross section with no vertical exaggeration.
granodiorite indicates limited exhumation (<6 km) of the basin margin in the Cenozoic. Inverse thermal modeling of a cobble from the footwall volcanics (A09-FT1) supports cooling and exhumation in the Cretaceous and between ca. 30 Ma and 25 Ma, followed by heating between ca. 20 Ma and 18 Ma, most likely associated with sediment burial. Ignimbrites within the growing syncline are dated to 18.4 ± 0.7 Ma (A10I-1) and 17.7 ± 0.5 Ma (A10I-2) (Fig. 3A; Table 1; Fig. DR1; Table DR1 [see footnote 1]), supporting this interpretation. Relations among this syntectonic deformation, movement along the adjacent thrust fault, and cooling of sample A09-FT1 suggest active sedimentation and contraction across the western margin of the Salar de Arizaro at ca. 20–18 Ma.

No additional deformation was recorded until the late Quaternary. Conglomerate in the northern part of the study area contains a 0.6 ± 0.2 Ma (Ash10-1) intercalated air-fall tuff (Figs. 3A and 3C; Table 1; Fig. DR1; Table DR1). Because these rocks were overthrust, compressional deformation must have occurred as recently as 0.6 Ma. Normal faulting in the area is at least younger than 2.52 ± 0.05 Ma (A10B-2), the 40Ar/39Ar age of the volcanic flow in the interior of the range offset by 120 m along a normal fault (Fig. 3A; Table 1; Fig. DR7 [see footnote 1]). The basalt flows along the NNE trend are considerably younger at, from north to south, 0.20 ± 0.02 Ma (P09B-14), 0.22 ± 0.07 Ma (P09B-13), 0.08 ± 0.06 Ma (A09B-1; Fig. 3A), and 0.13 ± 0.01 Ma (A09B-16; Fig. 3A; Table 1; Figs. DR2–DR5 [see footnote 1]). A flow to the southeast of the mapped area yields an even younger age: –0.02 ± 0.03 Ma (A09B-2) (Table 1; Fig. DR6 [see footnote 1]). If the onset of basaltic volcanism here reflects the onset of extension, as it does elsewhere in the Puna Plateau (Marrett and Emerman, 1992; Risse et al., 2008), then extension only began in the last ~200 k.y. in the study area.

**Pasto Ventura Region**

The Pasto Ventura region in the southern Puna Plateau lies in the zone of relatively thick crust and mantle lithosphere, with extensive normal faulting and volcanism (Fig. 1). Similar to the Arizaro region, a NE-striking, moderately NW-dipping thrust fault, later reactivated in a normal sense, dominates the structure of the Pasto Ventura study region (Fig. 4A). This fault carries the Early Cambrian (Escayola et al., 2011) Puncoviscana Formation in the hanging wall over deformed Cenozoic strata. To the west, undated Cenozoic strata in the hanging wall lie in depositional contact with Puncoviscana basement. Cenozoic strata in the footwall consist of ~200 m of lacustrine-fluvial deposits, which transition up section into eolian deposits (Fig. 4C). Paleo–wind directions in the eolian strata indicate a southward transport direction. An asymmetric syncline lies in the footwall of the thrust, with an overturned western limb and a more gently dipping 40°–50° eastern limb (Figs. 4A and 4F). Small folds and internal unconformities are present in the east limb of the syncline (Fig. 6), indicating
syndepositional deformation. A second, subparallel thrust fault cuts the strata east of the major syncline. To the east of this fault, strata dip uniformly 30°–35° to the east. Several basalt flows and cinder cones erupted along the trace of the major thrust. Reactivation of the major thrust in an oblique right-lateral/normal sense is evidenced by offset Quaternary features in the south and cinder cones in the north (Fig. 4A).

Intercalated ashes are 10.5 ± 0.1 Ma in the lower fluvial-lacustrine unit and 7.88 ± 0.58 Ma and 7.77 ± 0.21 Ma in the upper, eolian unit (Fig. 4C; Table 1; Table DR2 [see footnote 1]). The internal unconformities (Fig. 6) are located at a stratigraphic location equivalent to the 10.5 Ma ash, indicating ongoing deformation at this time. Deformation must have continued until after ca. 7.8 Ma, the age of the youngest dated...
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tilted strata. Since ca. 7.8 Ma, the Pasto Ventura region has undergone a shift to extensional deformation, indicated by the reactivation of the major reverse fault as an oblique normal fault. Zhou et al. (2013) dated the basalt flow along the northern part of the fault (Fig. 4A) to 0.76 ± 0.16 Ma and mapped 16.1 m of normal sense and 34 m of right-lateral displacement. A 0.47 Ma flow is offset as well (Zhou et al., 2013). Therefore, the shift from shortening to extension occurred between ca. 7.8 and 0.47 Ma. Other faults that offset basalt flows or Quaternary surfaces are present across the region as well, indicating NE-SW to NNE-SSW extension at a slow, time-integrated rate of 0.02–0.08 mm/yr since 0.8-0.5 Ma. Other data have been used to argue for extension as early as 7.3 Ma north of the Pasto Ventura area based on the presence of basaltic volcanism (Risse et al., 2008). Our dating indicates an even earlier onset of extension and volcanism, from an 8.7 ± 0.4 Ma ash collected in the Calalaste Range to the northwest (Table 1; Fig. DR8 [see footnote 1]).

Figure 6. Syndepositional deformation in the Pasto Ventura region. (A) View to the N of T1 strata. The white lines highlight bedding contacts, while the heavy lines indicate minor thrust faults. (B) Sketch of the main features from the photo in A. (C) Strata retrodeformed such that the youngest strata in the photo are flat-lying. Two internal unconformities are present in this section, indicating syndepositional deformation. These strata contain ashes that are 9.9 ± 0.17 Ma and 10.5 ± 0.1 Ma (Table 1) in age, indicating contractional deformation at ca. 10 Ma.
Mafic Magmatism

A few hundred small-volume, monogenetic cinder cone eruptions are concentrated around the Calalaste Range, Salar de Antofogasta, and Salar de Antofalla, at ~26°S, 67°45′W, just west of the Cerro Galan ignimbrite complex (Drew et al., 2009; Ducea et al., 2013; Murray et al., this volume; Risse et al., 2008, 2013). Flows are found as far as 150 km to the NNW in the Arizaro region and 125 km to the SSE in the Pasto Ventura region. Age data are now available for 39 of these flows (Risse et al., 2008, and references therein; Zhou et al., 2013, personal commun; this study). The frequency of dated lava flows increases toward the present (Fig. 7), with no dated flows older than 8.7 Ma (this study). These data show an interesting spatial pattern as well (Fig. 1B). The oldest flows are located in the center of the eruptive region; over time, the eruptive region expanded, eventually reaching Arizaro and Pasto Ventura in the last million years. The pattern of increasing frequency with time could reflect an increase in eruptive activity toward the present or decreasing preservation and exposure with age. Alternatively, the eruption of mafic lavas at the surface could reflect the state of stress of the upper crust. Mafic magmas are dense enough that they may not erupt at the surface until the region undergoes extension (Marrett and Emerman, 1992). Significant residence time in the crust, as indicated by the geochemistry of these lava flows, is consistent with this latter scenario (Ducea et al., 2013; Murray et al., this volume; Risse et al., 2013).

DISCUSSION AND CONCLUSIONS

Even though the idea of lithospheric foundering in the Puna Plateau has been around for two decades (e.g., Kay and Kay, 1993) and has gained considerable traction, particularly based on recent geophysical (Bianchi et al., 2013; Calixto et al., 2013; Tassara and Echaurren, 2012) and geochemical (Ducea et al., 2013; Murray et al., this volume) data, our structural data could reflect other processes, and they are limited to observations in only two locations. Our data are sparse on the Puna Plateau, given the poor exposure (slopes are mantled with debris) and the necessity of on-the-ground studies because of reactivation of older, shortening-related structures in recent extensional deformation (Schoenbohm and Strecker, 2009). There are, in fact, few other places in the southern Puna region in which such mapping is possible. We, thus, proceed with caution in interpreting our data in the larger geodynamic context.

Out-of-sequence deformation, such as we observe in the Arizaro and Pasto Ventura regions, could reflect normal wedge dynamics, in which the orogenic system is in subcritical state and deforming internally in order to build taper (e.g., Davis et al., 1983). Removal of material from the orogenic system, by erosion for example, is predicted to reduce taper and to drive the wedge into a subcritical state (e.g., DeCelles et al., 2009). Although out-of-sequence shortening within the plateau could be explained by wedge dynamics, the localized nature of deformation and the pattern of shortening followed by extension and associated mafic magmatism do not satisfy a wedge-dynamics explanation. Extension, alternatively, could be explained by gravitational spreading (e.g., Schoenbohm and Strecker, 2009), although this would not explain the shortening phase of deformation, which immediately preceded extension, and is, therefore, an incomplete explanation for our observations. Similarly, orogen-parallel extension (e.g., Riller et al., 2012), while allowing for simultaneous shortening and extension on the plateau, does not allow reactivation of structures of the same orientation over time, such as in Arizaro and Pasto Ventura.

Our favored mechanism to explain the observed geology, including out-of-sequence contraction followed by extension and mafic volcanism, is lithospheric foundering. Only a few modeling studies make specific predictions about the response of the surface to Rayleigh-Taylor instabilities, whether above marginal (Molnar and Houseman, 2004) or central (Göğüş and Pysklywec, 2008; Neil and Houseman, 1999) “drips.” According to these models, during growth of a single Rayleigh-Taylor instability, material draws toward the locus of the drip, causing out-of-sequence shortening and thickening of overlying crust (Göğüş and Pysklywec, 2008; Neil and Houseman, 1999) in a spoke-like, radial pattern if the drip is cylindrical (Pysklywec and Cruden, 2004). The mantle lithosphere above the Rayleigh-Taylor instability may be substantially thinned if the event is large, lateral flow is insufficient to feed the drip, or the drip exhibits a nonlinear, temperature-independent rheology. Alternatively, thinning might occur more broadly with only a small local deflection in the lithosphere-asthenosphere boundary if the drip is small, the lithospheric viscosity is low enough to permit rapid lateral flow, or the drip rheology is temperature-dependent, allowing only the lower part of the lithosphere to be involved in dripping.

Figure 7. Frequency with time of dated small-volume mafic cinder cones and lava flows. Note increase in frequency with time, which could reflect a true increase or a poor preservation of earlier eruptions.
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(Conrad and Molnar, 1999; Elkins-Tanton, 2007; Göğüş and Pysklywec, 2008). In its initial stages, the negative buoyancy of the Rayleigh-Taylor instability overcomes the buoyant effect of crustal thickening, leading to subsidence. However, as the drip necks and detaches, the viscous traction of the drip decreases, and dense mantle lithosphere is simultaneously replaced by more buoyant asthenosphere, resulting in uplift (estimated from a few meters [Elkins-Tanton, 2007] to several kilometers [Molnar and Garzione, 2007]), and consequent extension over the locus of the drip (Elkins-Tanton, 2007; Göğüş and Pysklywec, 2008; Neil and Houseman, 1999). With smaller, multiple Rayleigh-Taylor instabilities (“driplets”) at the scale of single basins (<100 km), surface subsidence, uplift, shortening, and extension are muted (Beiki-Ardakani et al., 2010). The effect of Rayleigh-Taylor instabilities on lithospheric topography may be short-lived as a result of lateral flow and conductive cooling, leading to a flat lithosphere-asthenosphere boundary a few million years after the event (Elkins-Tanton, 2007), particularly if the drip is small. Decompression melting of upwelling asthenosphere and dewatering of the sinking mantle lithosphere produce small-volume, high-potassium, mafic volcanism throughout the foundering event (Elkins-Tanton, 2005; Kay and Kay, 1993; Schott and Schmeling, 1998), but such dense magmas may not erupt at the surface until extension begins after drip detachment (Marrett and Emerman, 1992). Ignimbrite eruptions have been associated with Rayleigh-Taylor instabilities as well (Kay et al., 2010). In the case of small-scale lithospheric “driplets,” low volumes of mafic magmatism are expected (Drew et al., 2009), with source material for melts dominated by pyroxenites derived from melting of downgoing lithosphere rather than by peridotites from an asthenospheric source (Ducea et al., 2013).

Based on these modeling predictions, we see evidence for two Rayleigh-Taylor instabilities in the Puna Plateau, which refine the location and timing of previously inferred foundering events (Fig. 8). We suggest that the first Rayleigh-Taylor instability reflected in our data began to form underneath the Arizaro sedimentary basin around 20 Ma. Subsidence in this basin is recorded by thick sediment accumulation between ca. 20 and ca. 11 Ma with rapid accumulation between ca. 19.5 and ca. 16 Ma (Boyd, 2010; DeCelles et al., this volume). The pattern of subsidence recorded by these strata led DeCelles et al. (this volume) to attribute basin formation to lithospheric foundering. To the west of the Arizaro Basin, along the western margin of the modern salar, we observe contraction simultaneous with sediment accumulation, recorded by syndepositional deformation of the ca. 18 Ma volcaniclastic rocks in the footwall of a major thrust fault (Fig. 3). Active deformation at this time is also indicated by folded strata of the middle Vizcachera Formation (ca. 19 to ca. 16 Ma), within the Arizaro Basin, in the footwall of a west-dipping reverse fault, placing the Macon Range crystalline basement rock on top of Miocene strata (Boyd, 2010). Detachment of the drip after 17–16 Ma is suggested by eruption of nearby ignimbrites of the Aguas Calientes caldera between 17.2 Ma and 10.5 Ma (Kay et al., 2010). However, there is no evidence for mafic volcanism or normal faulting following Rayleigh-Taylor instability detachment. This may reflect the ephemeral nature of such evidence; normal faulting would be overprinted by subsequent shortening associated with a second drip (see following), and mafic volcanism was minor, and therefore subject to removal by erosion. Ages of dated mafic magmas decrease with time, supporting such a scenario (Fig. 7). Alternatively, the lack of mafic magmatism could reflect the size of the foundering material, with a large foundered block heating more slowly. Such a scenario would favor asthenospheric upwelling and eruption of large-volume ignimbrites (Kay et al., 2010, 2011). A relatively large foundered block is also favored by geophysical data, showing significant thinning of the crust and mantle lithosphere beneath the Arizaro region (Bianchi et al., 2013; Tassara et al., 2006; Tassara and Echaurren, 2012) and a relatively large anomaly (>100 km) located to the NE of the Arizaro region interpreted as foundered lithospheric material (Schurr et al., 2006). Shear-wave velocity anomalies suggest northward trench-parallel asthenospheric flow (Calixto et al., 2013), which could explain NE displacement of the imaged, foundered block from the region we propose for drip formation.

We also find evidence to support formation of a second Rayleigh-Taylor instability in the southern Puna Plateau, again refining the location and timing of a foundering event inferred
from geochemical and geophysical data (Fig. 8; e.g., Kay and Kay, 1993; Bianchi et al., 2013). The record of formation of this drip includes subsidence of the Pasto Ventura basin and syn-sedimentary contractional deformation from at least 10.5 Ma to 7.8 Ma. However, although deformation may have been more widespread (it is difficult to constrain in this poorly exposed region, which is dominated by reactivation of structures during multiple generations of deformation), it appears as though subsidence and deposition were less widespread than for the drip recorded in the Arizaro Basin. There is abundant support for the detachment of a Rayleigh-Taylor instability. Mafic volcanism began around 8.7 Ma in the Calalaste Range and migrated outward with time, reaching the Pasto Ventura and Arizaro regions in the last million years (Fig. 1B). This may indicate growth over time of the region affected by mafic magmatism, or it may reflect the growth of the region of horizontal extension in the crust, allowing an extant magma source to finally reach the surface. We favor the former interpretation, as there is evidence that extension reached the margins of the plateau as early as 6 Ma (Schoenbohm and Strecker, 2009). Shortening was followed by extension in both our study regions, with an earlier occurrence in Pasto Ventura (ca. 7–4 Ma) and a later occurrence in the Arizaro region (<0.6 Ma). The pattern of shortening followed by extension, although based on only two data points, thus also appears to migrate outward from the Calalaste region with time. Detachment of a Rayleigh-Taylor instability after 8 Ma is further suggested by eruption of the Cerro Galan ignimbrites between 6.6 Ma and 2.06 Ma (Kay et al., 2011). In the southern Puna Plateau, there is no evidence for extensive crustal thinning as there is in the northern Puna beneath the Arizaro region (Bianchi et al., 2013; Tassara et al., 2006; Tassara and Echaurren, 2012), suggesting that the foundered block may have been smaller, leaving less of a mark on crustal and mantle-lithospheric thickness (Elkins-Tanton, 2007). Indeed, a mantle anomaly interpreted as a foundered block slightly northeast of Cerro Galan has a diameter of ~50 km, about half that of the imaged anomaly north-east of Arizaro. Foundering of a smaller block could explain the lower degree of subsidence and the higher incidence of mafic magmatism in the Pasto Ventura region.

In summary, our study, combined with a growing body of additional evidence, supports partial, small-scale lithospheric removal in the Puna region, rather than wholesale plateau delamination as has been proposed for lithospheric removal in the Altiplano (e.g., Garzione et al., 2008; Molnar and Garzione, 2007). Evidence includes: (1) the irregular thinning of the lithospheric mantle and crust with a diameter of <100 km (Bianchi et al., 2013; Tassara et al., 2006; Tassara and Echaurren, 2012; Yuan et al., 2000, 2002); (2) the small volume and geochemical complexity of mafic magmatism, which suggest that drips could be <50 km in diameter (Ducea et al., 2013; Murray et al., this volume); (3) eruption of the Aguas Calientes and Cerro Galan ignimbrites (Kay et al., 2010, 2011); (4) low total horizontal extension (Schoenbohm and Strecker, 2009) at a low rate (Zhou et al., 2013); (5) geophysically imaged foundered lithosphere with a diameter of ~50 km northeast of Cerro Galan (Bianchi et al., 2013; Calixto et al., 2013) and >100 km northeast of Arizaro (Schurr et al., 2006); and (6) the spatial and temporal pattern of out-of-sequence contraction and subsidence followed by extension, mafic volcanism, and basin incision that we document in this study. In addition, deuterium ratios in volcanic glass from the Puna Plateau suggest that the elevation has been within 1 km of modern values since at least ca. 36 Ma (Canavan, 2012): If lithospheric foundering is characterized by multiple, repeating, small-scale Rayleigh-Taylor instabilities, then the change in surface elevation as a result of each event is expected to be relatively small (<500 m; Beiki-Ardakani et al., 2010). We argue that a relatively large (~100 km) Rayleigh-Taylor instability formed and detached beneath the Arizaro Basin at ca. 17–16 Ma, and a second, smaller (~50 km) Rayleigh-Taylor instability detached beneath the southern Puna region at 8–7 Ma. It is likely that earlier driplets formed beneath the Puna Plateau, but their presence is not preserved in the geologic record due to overprinting by subsequent events.

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