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Local high relief at the southern margin of the Andean plateau by 9 Ma: evidence from ignimbritic valley fills and river incision

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ABSTRACT

A valley-filling ignimbrite re-exposed through subsequent river incision at the southern margin of the Andean (Puna) plateau preserves pristine geological evidence of pre-

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late Miocene paleotopography in the northwestern Argentine Andes. Our new ^{40}Ar/^{39}Ar dating of the Las Papas ignimbrites yields a plateau age of 9.24 ± 0.03 Ma, indicating valley-relief and orographic-barrier conditions comparable to the present-day. A later infill of Plio-Pleistocene coarse conglomerates has been linked to wetter conditions, but resulted in no additional net incision of the Las Papas valley, considering that the base of the ignimbrite remains unexposed in the valley bottom. Our observations indicate that at least 550 m of local plateau margin relief (and likely >2 km) existed by 9 Ma at the southern Puna margin, which likely increased the efficiency of the orographic barrier to rainfall along the eastern and southeastern flanks of the Puna and caused aridity in the plateau interior.

Keywords: Puna, valley-filling ignimbrite, paleotopography, orogenic plateau, ^{40}Ar/^{39}Ar geochronology, late Miocene

Introduction

Unraveling the spatiotemporal patterns in the topographic development of mountain belts is key to understanding how tectonic forcing can influence climate and surface processes, particularly when assessing the role of deep-seated, mantle-driven uplift mechanisms (Allmendinger *et al.*, 1997; Garzione *et al.*, 2006). The implications of such studies are even broader when orographic-barrier evolution is viewed in light of its influence on rainfall and erosion gradients (Bookhagen and Strecker, 2012), speciation patterns (Semaw e*t al.*, 2005), or the emplacement of supergene mineral deposits (Hartley and Rice, 2005). The development of steep, deeply dissected flanks of Cenozoic orogenic plateaus and their impacts on climate make plateau margins ideal sites to investigate how surface and deep-seated processes interact in creating and shaping these environments.

Studies attempting to elucidate the surface-uplift history of the Andean (Altiplano-Puna) plateau have employed stable isotopes in pedogenic carbonates and hydrated volcanic glass (e.g., Garzione *et al.*, 2006; Pingel *et al.*, 2014; Saylor and Horton, 2014), leaf morphology (e.g., Gregory-Wodzicki *et al.*, 1998), and geomorphic/geologic evidence of relief development (e.g., Gubbels *et al.*, 1993; Barke and Lamb, 2006; Hoke *et al.*, 2007; Schildgen *et al.*, 2007; Thouret *et al.*, 2007; Guzmán and Petrinovic, 2010; Jordan *et al.*, 2010). Most of the investigated areas lie along the flanks of the northern Andean plateau (Altiplano), and studies suggest surface uplift of ca. 1 to 3.4 km since the late Miocene (e.g. Gregory-Wodzicki, 2000). Ambiguities remain owing to a lack of well-constrained chronologies and because of the potential for topographically induced changes in climate to influence the stable isotopic (e.g., Ehlers and Poulsen, 2009) or incision (e.g., Lease and Ehlers, 2013) proxy data. Limited information on topographic development exists for the eastern sectors of the plateau, and virtually nothing is known about the elevation history of its southern margin.

Shortening and surface uplift of individual ranges in the present-day Puna plateau and adjacent regions had already occurred by the middle Eocene-Oligocene (e.g., Kraemer *et al.*, 1999; Coutand *et al.*, 2001; Hongn *et al.*, 2007; Nóbile and Dávila, 2011). These uplifted ranges constituted orographic barriers to northeast and east-southeast moisture-laden winds, helping to sustain semiarid to arid conditions in the plateau interior region since that time (e.g., Strecker *et al.*, 2007). Internal drainage conditions could have initiated by 15 Ma (Alonso *et al.*, 1991; Vandervoort *et al.*, 1995). Despite this geologic evidence for early topographic and relief development of the Puna plateau, a recent study suggests that relief within canyon systems did not develop along the eastern margin of the Altiplano plateau in Bolivia until the onset of wetter conditions during the Pliocene (Lease and Ehlers, 2013), implying potentially long delays between surface uplift and river incision.

In this study, we contribute to efforts to determine the timing of plateau uplift and relief development by constraining the incision and filling history of a deeply incised canyon that drains across the southern margin of the Puna plateau in northwest Argentina (Fig. 1). We present $^{40}Ar/^{39}Ar$ ages from two samples of an ignimbrite in the Las Papas valley, which once covered an erosional paleotopography and is now being re-incised. These new dates allow us to place a minimum age on the high relief along the southern margin of the Puna plateau. Also, even though global cooling and possible changes in surface processes were initiated during the Pliocene, we demonstrate that no additional net incision occurred in the Las Papas valley associated with these changes.

Geological framework

The Andean (Altiplano-Puna) plateau is located between 15º and 27º S latitude (Fig. 1), with a mean elevation of 3.7 km and an areal extent of ca. 500,000 km^2. The Puna (Turner, 1972) constitutes the southern plateau, which is characterized by internally drained Cenozoic sedimentary basins, widespread Cenozoic volcanism, and N-S-oriented basement-cored ranges with peaks >6000 m a.s.l. The Las Papas valley is one of several deeply incised valleys along the southern flanks of the Puna plateau, and drains the E-W-oriented Cordillera de San Buenaventura (Fig. 1). The Las Papas valley has its headwaters atop the Puna at elevations around 4300 m, where it traverses Proterozoic to early Paleozoic basement rocks and late Miocene-Pliocene volcanic rocks (Montero *et al.*, 2010a). Toward the south, the valley exposes the Neogene Las Papas Ignimbrites (Montero, 2009) and Quaternary ignimbrites (Cerro Blanco Volcanic Complex, Seggiaro *et al.*, 2006; Montero *et al.*, 2010b). Locally, the basement rocks and the Neogene ignimbrites are covered by the Plio-Pleistocene Punaschotter conglomerates (Penck, 1920). This diachronous unit comprises disorganized, poorly sorted boulder conglomerates, which filled valleys and basins throughout the Puna margin (Penck, 1920; Turner, 1973; Bossi *et al.*, 2001; Strecker *et al.*, 2009). U-Pb ages of volcanic ashes intercalated within the Punaschotter of the Fiambalá Basin to the south (Fig. 1) are between 3.05 ± 0.44 Ma and <3.77 ± 0.10 Ma (Carrapa *et al.*, 2008), while ages range from ca. 1.2 to 2.9 Ma in other basins (Bossi *et al.*, 2001; Strecker *et al.*, 2009). These strata are in turn unconformably overlain by coarse river-terrace conglomerates. Terraces were sculpted into the underlying bedrock and sedimentary strata, and in places are 1 km higher than the Las Papas valley floor (Schoenbohm and Strecker, 2009).

A series of nearly N-S striking, west-dipping reverse faults associated with open folds has been related to the growth of the ranges comprising the southern Puna margin (Rubiolo et al., 2001), carrying basement rocks over the Las Papas ignimbrites and the Punaschotter conglomerates (Schoenbohm and Strecker, 2009; Montero *et al.*, 2010a). Locally, these units are tilted approximately 15º SW in the region of the Las Papas valley.

The Las Papas river drains into the Fiambalá Basin, which is bounded by reverse-faulted ranges (Fig. 1). Deformation and uplift of the Fiambalá Basin's northern ranges, through which the Las Papas valley has incised, is inferred to have started no later than the late Miocene, based on AFT exhumation ages of ca. 6 Ma (Carrapa *et al.*, 2006).

Las Papas ignimbrites and their topographic relationships

Along the Las Papas valley, several pyroclastic units with similar characteristics make for a complex volcanic stratigraphy. In the section studied here, there are at least two different ignimbrites that we refer to as the Las Papas ignimbrites (Montero, 2009). The ignimbrites are exposed only along the central and southern sectors of the valley (Figs. 2 and 3), up to 2810 m a.s.l. in the central section of the valley and as low as 2260 m a.s.l. in the southern section, implying at least 550 m of topographic relief at the Puna margin at the time of ignimbrite deposition based on the outcrop pattern (Fig. 3b). To the north of the Las Papas valley, the ignimbrites are not exposed, while to the east of the valley, younger ignimbrites are dated at 7.17 Ma ($^{40}Ar/^{39}Ar$ in biotite, Montero *et al.*, 2010b).

Despite the incision of the Las Papas river, the base of the lowest ignimbrite is not exposed anywhere along the valley bottom. In the middle part of the river-long profile, the Las Papas ignimbrites are exposed between elevations of 2300-2350 m at the valley bottom and up to 2700 m on interfluves to the east, indicating a minimum thickness of 240 m after correcting for the post-depositional SW tilting (Figs. 2b and 3). Based on the overall outcrop pattern (Fig. 2a), we conclude that this region records the existence of a southward-directed fluvial system that drained the Puna region, and thus significant plateau margin (> 550 m) and river valley (>240 m) relief at the time of ignimbrite emplacement.

Geochronology

The Las Papas ignimbrites comprise pink-white to pale-purple colored, indurated and welded pyroclastic deposits with eutaxitic texture and columnar jointing (Fig. 4) and a mineral association of quartz, plagioclase, K-feldspar, biotite, and zircon. To constrain the age of paleotopography and relief development within the Las Papas valley, we dated two samples of the Las Papas ignimbrites using $^{40}Ar/^{39}Ar$ geochronology on biotite separates from pumice by stepwise heating of multi-grain aliquots (6-14 mg of biotite separate). The results show good plateau and inverse isochron ages, with $^{40}Ar/^{36}Ar$ values close to the ^{40}Ar atmospheric value, implying no contamination and reinforcing the robustness of our biotite ages. Additional details of sample analysis and summary tables are in the Supplementary Material.

The sample collected from the lower section of the ignimbrite profile exposed at the valley bottom (LP-07, 2334 m a.s.l.) provided a plateau age of 9.24 ± 0.03 Ma (Fig. 5a, 6 contiguous steps, 83.7% of total ^{39}Ar released). The normal and inverse isochron ages of 9.33 ± 0.09 Ma (Supplementary material Table 1) from the plateau steps agree with the plateau age within uncertainty. The second sample (Pa-08, 2436 m a.s.l.) was taken several meters up-section and yielded a plateau age of 8.47 ± 0.04 Ma (Fig. 5b). Although the plateau age adopted here comprises only two contiguous steps (10 and 11) and covers 43.6% of total ^{39}Ar released, it is consistent with the total gas age (8.47 ± 0.02 Ma) and also with normal and inverse isochron ages from the plateau steps (8.47 ± 0.09 Ma and 8.46 ± 0.09 Ma) (Fig. 5b and Supplementary material Table 2). Therefore, we conclude that the plateau age is geologically meaningful.

Discussion and conclusions

When volcanism was active in the southern Puna, pyroclastic flows followed the course of the Las Papas paleo-valley, and in some cases overtopped the interfluves. Subsequently, this paleo-landscape was re-incised, and rivers draining the Puna margin adjusted to the regional base level in the Fiambalá Basin to the south. Based on the ages of the ignimbrites and field observations of their valley-filling morphology, we first deduce that the southern rim of the Puna constituted a topographic high with at least 550 m of relief and an established river network draining the present-day plateau margin before 9.24 ± 0.03 Ma. Second, incision of the Las Papas river through the ignimbrites is at least 240 m and continues to the present-day without having exposed their base, implying that cross-valley relief has not increased since ignimbrite deposition. Finally, because differential uplift of the plateau margin relative to the Fiambalá Basin would have resulted in incision of the Las Papas valley, the lack of exposure of the base of the ignimbrite also argues against significant post-9 Ma differential uplift. Hence, the total local plateau-margin relief of ca. 2 km (Fig. 3b) has likely changed little since 9 Ma.

This process of filling and renewed incision was repeated again during the deposition of the Plio-Quaternary Punaschotter conglomerates, which covered the erosional paleo-topography that had developed within the late Miocene ignimbrites and basement rocks. Although diachronous, these coarse deposits have the unifying characteristic of having partly re-incised or filled paleo-topography along the southern and eastern Puna margin (Strecker *et* *al.*, 2009; Pingel *et al.*, 2013), implying that a high-elevation, high-relief plateau rim incised by river valleys already existed during the late Miocene. Because incision failed to expose the base of the Las Papas ignimbrites, we infer that the most important phase of downcutting and relief development of the Las Papas valley reflects pre-late Miocene differential uplift of the Puna margin relative to the Fiambalá Basin, rather than Pliocene climate-driven processes that may have changed the precipitation and runoff regimes, a scenario that has been proposed by Lease and Ehlers (2013) for the more humid Bolivian Andes, but has recently been challenged (Gasparini and Whipple, 2014).

Overall, our observations and data from the Las Papas valley indicate that topographic relief structure similar to that of today existed by late Miocene time along the southern Puna margin. This constraint on past relief is in agreement with the ages for paleotopographic construction reported farther east and northeast (i.e., ca. 12 Ma, Vicuña Pampa Volcanic Complex, Guzmán *et al.*, 2014; 12.1 Ma, Luingo caldera, Guzmán and Petrinovic, 2010) along the southeastern Puna margin (Fig. 1), and thus represents a phenomenon of regional importance. Moreover, the restriction of the 7 Ma ignimbrites to the north of 27º S latitude implies that a topographic barrier prevented their distribution farther south into the Fiambalá Basin (Montero *et al.*, 2010b).

An elevated region coinciding with the present-day margin of the plateau would have constituted an efficient orographic barrier to east-southeasterly derived moisture. Indeed, sedimentary characteristics (Starck and Anzótegui, 2001; Coutand *et al.*, 2006) and stable isotope data (Kleinert and Strecker, 2001) record a change from arid to more humid conditions at ca. 9 Ma in the adjacent Angastaco and Santa María basins to the north, while deposits from the plateau interior reflect protracted aridity (Alonso *et al.*, 1991). Taken together, our new observations add to a growing body of evidence that the southeastern Puna margin constituted a high orographic barrier to moisture during the late Miocene.

The infilling nature of the Las Papas ignimbrites and the lack of exposure of their base in the modern Las Papas valley imply no additional net incision of the valley since deposition of the ignimbrites, despite subsequent changes in climate and precipitation along the eastern and southern flanks of the Andes (e.g., Vera *et al.* 2006; Strecker *et al.*, 2007), and also no significant differential uplift of the plateau margin relative to the Fiambalá Basin. Hence, we propose that the plateau margin and valley relief of the southern Puna margin at ca. 9 Ma must have been comparable to that of today in the vicinity of the Las Papas valley, and likely also in other parts of the southeastern Puna margin, based on integration of our data with regional paleoclimatic and sedimentologic observations.

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Figure captions

Figure 1: Digital Elevation Model (DEM) of northwest Argentina showing the location of the Puna plateau. White box shows location of study area. CSB: Cordillera de San Buenaventura; FB: Fiambalá Basin; BP: Bolsón de Pipanaco; VP: Vicuña Pampa; LC: Luingo Caldera.

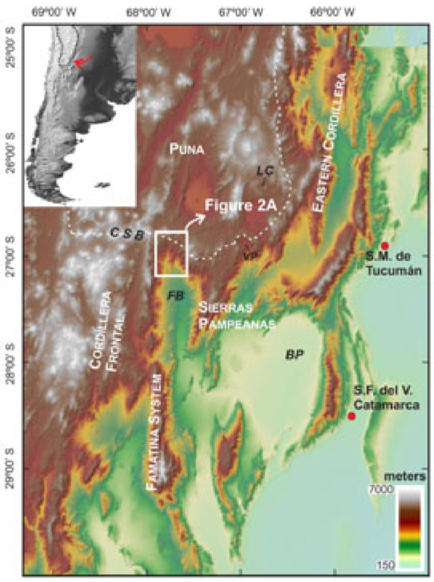
Figure 2: A- Geological map of the middle and southern part of the Las Papas valley showing the distribution of the Las Papas ignimbrites and Punaschotter conglomerates, and sample locations. B- AA′ cross profile illustrates the relationship between the Las Papas ignimbrites and paleotopography. See the bar tilted 15° to the SW, indicating the (minimum) measured thickness of the Las Papas ignimbrites.

Figure 3: A- 3D perspective view of the outcrop pattern of the late Miocene ignimbrites that filled local paleotopography across the southern Puna plateau margin. B- Long river profile of the Las Papas River with the sample locations and the units exposed along the valley.

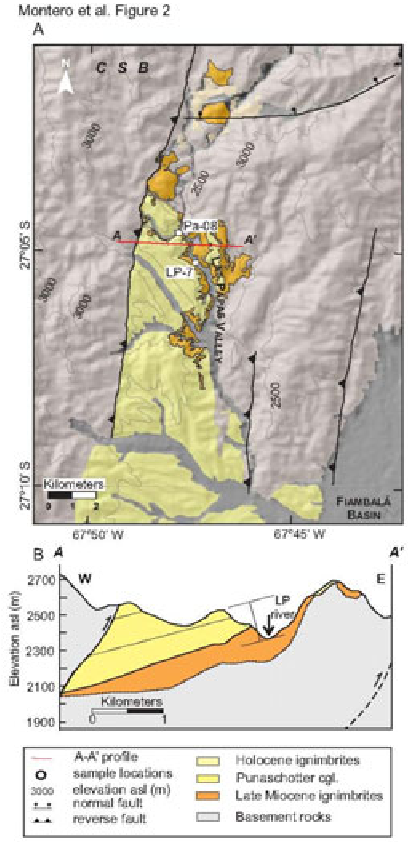
Figure 4: View of the Las Papas ignimbrites from the Las Papas River (approximately at the location of the AA´ profile of Figure 2B).

Figure 5: $^{40}Ar/^{39}Ar$ step-heating experiment results and plateau ages of Las Papas ignimbrites. A- Sample LP-7 (27º04′52.4″S, 67º47′21.4″W); B- Sample Pa-08 (27º04′11.6″S, 67º47′48.8″W).

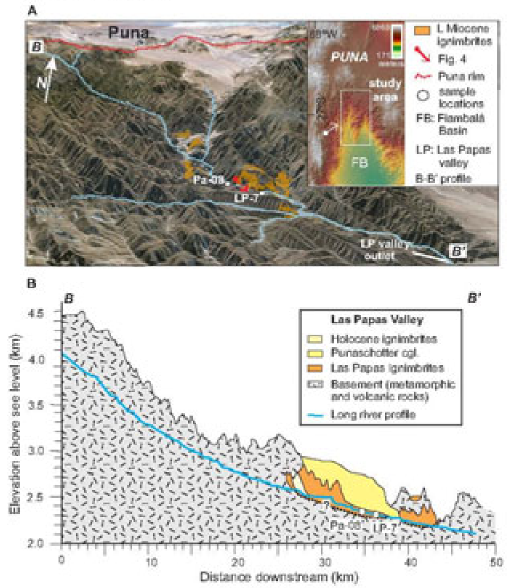
Montero et al. Figure 1



Montero et al. Figure 2



Montero et al. Figure 3



Montero et al. Figure 4

Montero et al. Figure 5