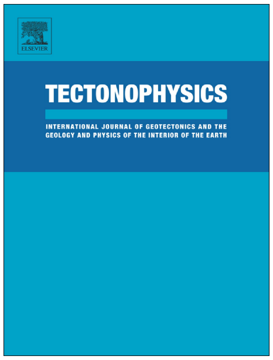

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A middle miocene (13.5 -12 ma) deformational event constrained by volcanism along the puna-eastern cordillera border, NW Argentina

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Abstract

The features of Middle Miocene deposits in the Puna-Eastern Cordillera transition (Valles Calchaquíes) indicate that Cenozoic deformation, sedimentation and volcanism follow a complex spatiotemporal relationship. The intense volcanic activity recorded in the eastern Puna border between 14 and 11.5 Ma coincides with the occurrence of one of the most important deformation events of the Neogene tectonic evolution in the region.

Studies performed across the Puna-Eastern Cordillera transition show different relationships between volcanic deposits of ca. 13.5-12.1 Ma and the Oligocene-Miocene Angastaco Formation. In this paper we describe the ash-flow tuff deposits which are the first of this type found concordant in the sedimentary fill of Valles Calchaquíes. Several analyses performed on these pyroclastic deposits allow a correlation to be made with the Alto de Las Lagunas Ignimbrite (ca. 13.5 Ma) of the Pucarilla-Cerro Tipillas Volcanic Complex located in the Puna. Outcrops of the ca. 13.5 Ma pyroclastic deposits are recognised within the Puna and the Valle Calchaquí. However, in the southern prolongation of the Valle de Hualfín (Tiopampa-Pucarilla depression) that separates the Puna from the Valle Calchaquí at these latitudes, these deposits are partially eroded and buried, and thus their occurrence is recorded only by abundant volcanic clasts included in conglomerates of the Angastaco Formation. The sedimentation of the Angastaco Formation was aborted at ca. 12 Ma in the Tiopampa-Pucarilla depression by the Pucarilla Ignimbrite, which unconformably covers the synorogenic units. On the contrary, in the Valle Calchaquí the sedimentation of the Angastaco Formation continued until the Late Miocene.

The different relationships between the Miocene Angastaco Formation and the ignimbrites with ages of ca. 13.5 and ca. 12 Ma reveal that in this short period (~1.5 m.y.) a significant deformation event took place and resulted in marked palaeogeographic changes, as evidenced by stratigraphic-sedimentological and chronological records in the Angastaco Formation.

Keywords: Angastaco Formation, Miocene deformation, Alto de Las Lagunas Ignimbrite, Luingo caldera, Foreland

1. Introduction

The Altiplano–Puna of the Central Andes is the second largest and highest plateau on the Earth after the Tibet and is the prominent feature that characterises the Andean mountain range along the western border of South America (Isacks, 1988). The origin, evolution and timing of uplift of the plateau are still under debate.

The southern portion of the plateau, the Puna, is understood as the result of crustal thickening and uplift related to crustal shortening (e.g., Isacks, 1988; Allmendinger et al., 1997) aided by basin isolation (e.g., Sobel and Strecker, 2003; Riller and Oncken, 2003) that induced local climate change and hence the impossibility of sediment removal (Strecker et al., 2009; Pingel et al., 2016). An other condition that may have favoured uplift is lithospheric delamination, that could have, in turn, triggered volcanism, deformation and isostatic rebound (Kay and Coira, 2009; Bianchi et al., 2013; Guzmán et al., 2014; Zhou and Schoenbohm, 2015). To a lesser extent, crustal magmatic addition may have also played a role (e.g., Allmendinger et al., 1997).

Previous studies indicated that the origin and growth of the Puna occurred during the Miocene (e.g., Jordan and Alonso, 1987; Allmendinger et al., 1997), but new evidence accounts for Paleaogene deformation across the Puna and its transition with the Eastern Cordillera (Valles Calchaquíes[*]) (Kraemer et al., 1999; Coutand et al., 2001; Carrapa et al., 2005; Hongn et al., 2007; Payrola Bosio et al., 2009; del Papa et al., 2013a).

There is still no consensus about a spatiotemporal correlation between deformation and magmatism peaks, as some authors suggest they evolve independently (e.g., Trumbull et al., 2006), whereas others indicate the opposite (e.g., Isacks, 1988; Lamb et al., 1997; Victor et al., 2004).

Volcanism in the Altiplano-Puna began to be increase at about 25 Ma (e.g., Trumbull et al., 2006; Fig. 1). During the Middle Miocene, both volcanism and deformation showed a significant broadening (migration and propagation) within the southern Puna (25-28°S) (Allmendinger et al., 1997; Oncken et al., 2006; Trumbull et al., 2006; Guzmán et al., 2014) that characterises one of the most important periods of plateau construction. During the 14.5-11.5

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[*] *We use "Valle Calchaquí" to refer to the main valley through which the Calchaquí River runs and "Valles Calchaquíes" to refer to a set of principal and secondary valleys: Calchaquí, Santa María, Amblayo, Tonco, Luracatao, Colomé, Hualfín and Pucará that extend 24°-27° S and 65°30'-66°30'W.*

Ma interval, volcanism was restricted to the Luingo caldera (Guzmán and Petrinovic, 2010) and to the Vicuña Pampa Volcanic Complex in the southeastern Puna border, while effusive volcanism was active in the main volcanic arc (Guzmán et al., 2014).

In this paper we present detailed studies of the Miocene Angastaco Formation at the Valle Calchaquí (San Lucas and Las Viñas areas) and the southern prolongation of the Valle de Hualfín (which we call "Tiopampa-Pucarilla depression" see Fig. 1). We recognise the first Middle Miocene ash-flow tuff interbedded in the sedimentary strata of the foreland in the Calchaquí Valley. This discovery allows us to determine the age and identify the source of these pyroclastic deposits by correlating absolute age determination, whole-rock geochemistry, petrographic characterisation and mineral chemistry.

2. Geological setting

The study area is located in a segment of the Valles Calchaquíes (25º45'- 26º00'S and 66º25'- 66º 00' W), within the Eastern Cordillera (see Fig. 2) (Turner and Mon, 1979). It is next to the eastern margin of the Puna and includes the main Valle Calchaquí and smaller valleys such as Colomé, Hualfín and Pucará (see Fig. 2). These valleys are N-S elongated depressions separated by basement-cored ranges bordered by reverse faults with dominant westward vergence (Mon and Salfity, 1995; Carrera and Muñoz, 2008).

The stratigraphy of the area (Fig. 3) consists of Neoproterozoic-Lower Palaeozoic basement that includes very low to high-grade metamorphic rocks of the Puncoviscana and La Paya formations (Hongn and Seggiaro, 2001) and plutonic rocks of the Oire Eruptive Complex (Blasco et al., 1996), in some cases milonitised and metamorphised.

The Salta Group (Cretaceous-Middle Eocene) covers the basement rocks and its formation is related to the development of an intracontinental rift. Deposits reach a thickness of more than 5,000 m and are formed from base to top by the Pirgua (synrift stage: Reyes and Salfity, 1973), Balbuena and Santa Bárbara Subgroups (postrift stage: e.g., Moreno, 1970; Salfity and Marquillas, 1994; Marquillas et al., 2005).

The Pirgua Subgroup crops out in the Valles de Hualfín and Pucará (Villanueva García, 1992; Sabino, 2002), while the postrift succession is only represented by the Santa Bárbara Subgroup within the San Lucas-Las Viñas area (Vergani and Stark, 1989; Aramayo, 2015). In the San Lucas area the complete succession of this subgroup is exposed and consists of Mealla, Maíz Gordo and Lumbrera formations, while in the Las Viñas area only the Lumbrera Formation is recognised (Fig. 2).

The Andean foreland basin fill in this region is mainly represented by the continental succession of the Payogastilla Group (Fig. 3; Díaz and Malizzia, 1983; Díaz et al., 1987). From base to top it is formed by the Quebrada de los Colorados (Middle Eocene-Late Oligocene), Angastaco (Late Oligocene-Late Miocene), Palo Pintado (Late Miocene-Early Pliocene) and San Felipe (Late Pliocene-Early Pleistocene) formations. The Payogastilla Group consists of a more than 6,000 m-thick succession, made up of pelites, sandstones and conglomerates with interlayered volcaniclastic levels; the succession displays a general upwards coarsening and thickening (Díaz and Malizzia, 1983). At the westernmost parts of the study area (Valles de Hualfín and Pucará) the Payogastilla Group is only represented by the Quebrada de los Colorados and Angastaco formations, while in the easternmost parts, the complete Payogastilla Group crops out (Angastaco, Las Viñas and San Lucas areas) (Fig. 3).

In the eastern margin of the Puna there are voluminous outcrops of the Pucarilla-Cerro Tipillas Volcanic Complex (PCTVC; Fig. 2; González et al., 1999) that overlie basement rocks and the Payogastilla Group. Volcanic rocks from the PCTVC include pyroclastic deposits and effusive rocks (Guzmán and Petrinovic, 2010; Guzmán et al., 2011). The Luingo caldera is the eruptive centre associated with most of the volcanic deposits found in this area. Two major events of ignimbrites formation were recognised in the PCTVC: the first one formed the Alto de Las Lagunas Ignimbrite at ca. 13.5 Ma, and the second one produced the Pucarilla Ignimbrite and its intracaldera equivalents associated with the collapse event that formed the Luingo caldera at ca. 12 Ma (Guzmán and Petrinovic, 2010). Pucarilla and Alto de Las Lagunas are medium to high-grade dacitic ignimbrites, with moderate to intense welding, and mostly devitrified (Guzmán and Petrinovic, 2010).

3. Methods

In order to study the relationship between magmatism and deformation in this sector of the Puna and Valles Calchaquíes of NW Argentina, we carried out stratigraphic, structural, geochemical and geochronological studies. The stratigraphic sections were logged in key places (Las Viñas and San Lucas areas) whereas the structural (i.e., strike and dip of planes and lineations) and palaeocurrent data were measured in all areas. Palaeocurrent directions were derived from clast imbrications as well as from planar and trough cross-stratification following DeCelles et al. (1983) methodology.

Field work included a cartographic survey aided by satellite images (Landsat 7 ETM), aerial photographs and earlier maps of the area (Marrett et al., 1994; Hongn and Seggiaro, 2001; Carrapa et al., 2011; Carrera and Muñoz, 2008; Guzmán and Petrinovic, 2010); the final maps were done with Arc-GIS (IBIGEO license). ^{40}Ar/^{39}Ar dating was performed in mineral separates (biotite) of one pumice sample at the Geochronology Laboratory of the Universität Potsdam (Germany) (see Supplementary Material for details).

Volcanic materials were correlated based on field descriptions, petrographic studies (11 thin sections, including modal estimation of mineral phases), microprobe analysis and two whole-rock geochemical analyses. Thin sections were done at the Laboratorio de Petrotomía of the Universidad Nacional de Salta (Argentina), geochemical analyses at the ACME Laboratories (Canada) by X-Ray Fluorescence for major elements and ICP-MS for minor elements, including rare earth elements. Lost on ignition (LOI) was determined by weight difference after heating at 1000 °C. Microprobe analyses were carried out at the LAMARX (Universidad Nacional de Córdoba, Argentina). Details on laboratory determinations are given in the Supplementary Material.

The Appendix contains further details on the correlation between the interlayered pyroclastic deposits in the Angastaco Formation of Las Viñas and San Lucas areas and the ignimbrite clasts included in the Angastaco Formation in the Tiopampa-Pucarilla depression. Moreover, the results obtained from our research were correlated with pyroclastic deposits described in the literature, including contributions reported in scientific journals, congressional proceedings, workshops, geologic maps of the local geological survey agencies (SEGEMAR, Argentina and

SERNAGEOMIN, Chile), PhD theses (Stein, 2000; Arnosio, 2002; Soler, 2005; Guzmán, 2009), and unpublished reports.

4. Geology of Las Viñas and San Lucas areas (Valle Calchaquí)

Las Viñas and San Lucas areas are located at the southwestern border of the Valle Calchaquí (Fig. 4A). In both locations the sedimentary succession is formed by the Santa Bárbara Subgroup and the Payogastilla Group. The Payogastilla Group begins with the Quebrada de los Colorados Formation, which is ca. 240 m thick in Las Viñas and ca. 190 m thick in San Lucas. It shows a fining and thinning upward pattern and is formed in the lower section by fine-grained conglomerates and coarse-grained sandstones that alternate with siltstone levels. Towards the upper section it grades to fine-grained sandstones and siltstones. The palaeoenvironment of these deposits was interpreted as related to wide and shallow braided rivers with mixed-load (Aramayo, 2015). The Quebrada de los Colorados Formation is covered by the Angastaco Formation which comprises a lower member, named Tin Tin Member, and an upper one, named Las Flechas Member (Díaz and Malizia, 1983; del Papa et al., 2013b). The Tin Tin Member is characterised by grey to white siltstones and fine to medium-grained sandstones with trough cross-stratification at megascale, rounded grains and good sorting. The characteristics of these deposits suggest a palaeoenvironment of aeolian dune complexes. In both profiles (Las Viñas and San Lucas areas) the Tin Tin Member is ca. 60 m thick (Fig. 5).

In the Las Viñas and San Lucas areas the contact between the Tin Tin Member and the sandy-conglomeratic facies of the Las Flechas Member is sharp and concordant, and thus differs from other profiles of the Valles Calchaquíes (e.g., Angastaco and Tin Tin areas) where their contact relationship is transitional (del Papa et al., 2013b). In Las Viñas we studied the first 820 m of the Las Flechas Member. It begins with clast-supported, cobbly conglomerates with imbricated-clast fabrics that alternate with conglomeratic sandstones and scarce pelitic beds developed towards the top, indicating deep channels filled with gravelly longitudinal and transverse-bars in the first 300 metres of the Las Flechas Member (Fig. 5A). The facies association of the remaining section is interpreted as a shallow braided river of sandy bedload with overbank development (Fig. 5A).

In the San Lucas area we studied the first 690 m of the stratigraphic succession of the Las Flechas Member, which shows a decrease in grainsize upsection. The first 400 m consists of massive, light-brown deposits of medium to fine-grained conglomerates interbedded with massive sandstones and laminated, silty-clayey beds. The upper section consists of light-brown, medium to fine-grained sandstones with parallel lamination and dark-brown, massive, occasionally thin-laminated, silty-clayey beds; the latter being more frequent towards the top, reaching thicknesses of up to 2 m. We interpret the Angastaco Formation in this area as the result of a shallow, sandy, braided river that grades upwards to a braided, mix-load channel deposit (Fig. 5B).

The Las Viñas and San Lucas areas host anticlines with gentle west vergence, with western limbs displaced by faults; the cores are formed by the Neoproterozoic-Lower Palaeozoic Puncoviscana Formation (Vergani and Starck, 1989; Carrera and Muñoz, 2008). The eastern limbs of both folds are composed of the Santa Bárbara Subgroup and the Payogastilla Group, while in the western limbs only the Payogastilla Group is preserved (Fig. 4A).

The trend of Las Viñas anticline changes from N-S to NE-SW with a NE-plunging hinge zone (Fig. 4A). The western limb of Las Viñas anticline is cut by two, steep, parallel, NE-to SW-striking reverse faults that dip towards the SE. The Las Viñas Fault is the main one and thrusts basement over the Quebrada de los Colorados Formation, resulting in a locally overturned drag fold. The secondary fault is a splay of the Las Viñas Fault and displaces the Quebrada de los Colorados Formation and the lower levels of the Angastaco Formation on the upper conglomeratic deposits of the Angastaco Formation (Fig. 4A). The displacement of both faults decreases towards the NE, transferring part of the shortening to the Las Viñas anticline. At the anticline’s closure, the Quebrada de los Colorados Formation progressively overlaps the Lumbrera Formation (Balbuena Subgroup) until lying directly on the basement rocks close to the fold hinge (Fig. 4A). This relationship is probably a result of syntectonic sedimentation for this unit. The Quebrada de los Colorados Formation, resting on the basement, is also observed along the southern segment of the eastern limb of the anticline. The lack of faults along the eastern limb of the Las Viñas anticline results in a continuous exposure of the sedimentary succession (Fig. 4A); here the Angastaco Formation preserves a well-defined, intraformational unconformity surface related to syntectonic sedimentation during the Middle Miocene.

This internal unconformity is much better constrained in the San Lucas anticline hinge (Carrera and Muñoz, 2008), where it separates N-S-trending beds which dip towards the east below the unconformity surface, from E-W- trending beds that dip northwards disposed above it (Fig. 4A). The San Lucas anticline is curved (NE-SW to N-S trend) and shows a pronounced plunge towards the north (Fig. 4A). This anticline is faulted in its western limb by the San Lucas Fault, which is a high-angle reverse fault with west vergence that in its northern segment thrusts the basement over the Angastaco Formation.

A reverse fault affecting the western limb of the Las Viñas anticline (Fig. 4A) puts the Quebrada de los Colorados Formation and the basal levels of the Angastaco Formation over the upper sections of the Angastaco Formation, also affecting the pyroclastic succession, which is partially preserved. On the other hand, the eastern limb of the anticline remains unaffected, thus preserving the entire ca. 8.5-m-thick volcanic succession. These pyroclastic beds lie at approximately 500 m from the base of the Angastaco Formation. In the San Lucas area the pyroclastic deposit was recognised only in the eastern limb of the anticline, approximately 470 m from the base of the Angastaco Formation, with a thickness of up to 7 m (Fig. 4A). The pyroclastic levels interbedded in the Angastaco Formation are below the unconformity surface (Fig. 4A and 4B).

5. Geology of the Tiopampa-Pucarilla depression

The Tiopampa-Pucarilla depression extends from north to south, from the Pucarilla hamlet to the Arremo River (see Figs. 2 and 4B). The eastern border of this depression is marked by the Vallecito range, formed by basement rocks and sediments of the Quebrada de Los Colorados Formation, while the western border corresponds to a range of plutonic basement (Oire Eruptive Complex). The Vallecito and Jasimaná faults are Cretaceous normal faults with tectonic inversion during the Cenozoic Andean shortening (Hongn and Seggiaro, 2001; Sabino, 2002; Carrera and Muñoz, 2008, 2013). These faults uplifted the ranges defining the eastern borders of the Valle de Hualfín (north) and Tiopampa-Pucarilla depression (south) (Fig. 4B).

In the western border of the Tiopampa-Pucarilla depression, the fine-grained conglomerates and sandstones of the Quebrada de los Colorados Formation unconformably overlie the basement (Fig. 4B). The Angastaco Formation overlies the Quebrada de Los Colorados Formation, both units being folded and unconformably covered by the ca. 12 Ma Pucarilla Ignimbrite (Marrett et al., 1994) and by Quaternary deposits (Fig. 4B). Outcrops of the Angastaco Formation are sparse and discontinuous as a result of the younger cover in this depression where the aeolian levels (Tin Tin Member) are not exposed. Instead, the Las Flechas Member consists of conglomerates interpreted as proximal alluvial fan facies. Laterally, in different and unconnected outcrops, these conglomerates show notable changes in clast composition. The basal levels are formed by coarse-grained conglomerates composed primarily of clasts of granites (Oire Eruptive Complex) and Palaeozoic volcanic rocks (both up to 70 cm across). In the upward succession, the most notorious change is evidenced by the presence of levels rich in light grey ignimbrite boulders (up to 60 cm across). Between this point and the next well-preserved outcrops eastwards and westwards, several hundred meters of the stratigraphic succession (Quebrada de los Colorados and Angastaco formations) are covered by younger units (see Fig. 4B).

The sedimentary fill of the Tiopampa-Pucarilla depression describes a series of NW-SE-trending folds that are also observed within the Valle de Hualfín. The section of the Carrizal River shows a main syncline with a series of second-order folds in the hinge zone (Fig. 4B, cross-section). At the eastern limb of the main syncline (Fig. 4B), Carrera and Muñoz (2008) describe a progressive unconformity covered by ignimbrites interbedded in the Angastaco Formation that they assign to the ca. 12 Ma Pucarilla Ignimbrite (see Carrera and Muñoz, 2008; Fig. 8).

Conglomeratic levels containing ignimbrite boulders are the westernmost outcrops of the Angastaco Formation, where they are part of a small syncline exposed in the Carrizal River section (see box in Fig. 4B). The contact between the facies containing ignimbritic boulders and the facies rich in Lower Palaeozoic granitic and volcanic rocks has not been identified in the Tiopampa-Pucarilla depression, probably due to its overburden given the intense folding observed in this area.

In the Valle de Hualfín, the profile of the Angastaco Formation displays several key features that indicate the existence of an unconformity surface similar to that recognised by Carrera and Muñoz (2008) on the eastern border of the Tiopampa area (Fig. 4B). The key features are: a) abrupt changes in palaeocurrent directions (longitudinal and transversal drainage at the lower and upper parts, respectively), b) changes in the maximum clasts sizes (up to 9 cm at the lower part and up to 30 cm at the upper part) and c) dip variations in the bedding of the succession (up to 15°). These changes are observed at 480 m from the base of the unit.

6. Pyroclastic deposits in Las Viñas and San Lucas areas

6.1- General features of the pyroclastic deposits

The pyroclastic beds interbedded in the Angastaco Formation are massive to stratified lapilli-tuffs which are well-preserved. The primary deposits are recognised only in San Lucas and Las Viñas areas while in the Tiopampa-Pucarilla depression a reworked pyroclastic deposit has been identified. A set of lithofacies were distinguished as follows:

Stratified lapilli-tuff (xlT)

This facies is characterised by moderately-sorted medium ash to fine lapilli. The beds do not exceed 15 cm in thickness. They are crystal-rich, and show parallel stratification (Fig 6 A), as well as both low-angle (Fig 6 B) and high-angle cross stratification (Fig 6 C). This facies is recognised in San Lucas and Las Viñas and is frequently interbedded with decimetre-sized clayey beds (*cF*; Fig. 6A). It is covered by massive to diffusely stratified crystal-rich lapilli-tuff facies (see below).

Massive to diffusely stratified crystal-rich lapilli-tuff (*mdxcrlT*)

This is the thickest pyroclastic facies, reaching up to 6 m, indurated but not welded. It is mainly massive, grading to diffusely stratified. The diffusely stratified character is given frequently by a pumice concentration, but it is also seen at the base of some deposits where it may occur as diffuse low-angle cross-stratification (Fig 6 D). In these cases the basal contact is erosive and undulated. It is light grey to green, crystal-rich (ca. 50 vol.%) with plagioclase, amphibole, biotite, alkaline feldspar and titanite. It is formed by pumices (20 to 40 vol.%), crystal fragments and scarce lithic fragments; the matrix varies from fine ash to fine lapilli and is moderately to poorly-sorted. Juvenile fragments consist of white and subrounded pumices and scarce pink fiamme. Pumices are usually of fine lapilli, but some layers are rich in coarse lapilli pumices (up to 2.5 cm). Lithic fragments are rare (< 1 vol.%) and subangular of granite and ignimbrite composition, with a maximum size of 7.4 cm.

Massive very fine-tuff (mT)

This facies is dark grey, 20 cm thick and formed by very fine ash with very good sorting. It was recognised only in the San Lucas profile where it shows a transitional contact (Fig 6 E) over the massive to diffusely stratified crystal-rich lapilli-tuff facies.

Massive fine lapilli-tuff (mlT)

It is dark grey and reaches up to 2 m in thickness. It is massive, with a matrix of very fine ash and about 10 to 15 vol.% white pumices (Fig 6 F); the only type of lithic fragment is accidental pelites, which are rare. Pumices are white and subrounded with maximum sizes of 5 cm; the smaller fragments (usually 2 mm diametre) are slightly flattened. The deposit is indurated but not welded.

The pyroclastic facies described above belong to primary pyroclastic deposits formed by pyroclastic flows. These facies were reworked upwards and laterally in the succession in several places by fluvial processes.

6.2- Age of pyroclastic deposits

We dated one sample of the pyroclastic deposits using ^{40}Ar/^{39}Ar geochronology on biotite separates. Additional details of sample analysis and summary tables are in the Supplementary Material (Supplementary Material, Table B-1).

The sample was collected from the middle section of the Las Flechas Member at 440 m from the base of the Las Viñas profile (Fig. 5A). Absolute age determinations were repeated three times and a confident result was obtained in the sample C14036 that provided a plateau age of 13.40 ±

0.1 Ma (Fig. 7; 7 contiguous steps, 85.1% of total ^{39}Ar released). The isochrone age of 13.26 ± 0.16 Ma (Supplementary Material, Table B-1) is in agreement with the plateau age within uncertainty.

6.3- Correlation of the pyroclastic deposits

One important point to elucidate is the source of the primary pyroclastic deposits interbedded in the Angastaco Formation in Las Viñas and San Lucas profiles and also the possible source of the lithic fragments included in the Angastaco Formation in the Tiopampa-Pucarilla depression.

Several correlation approaches were used to identify the source of the newly discovered volcanic deposits, including age, distance from the inferred volcanic centre, mineral association, relative crystals percentages, mineral composition, whole-rock geochemistry and types and abundance of lithic fragments (see Supplementary Material). Our data allows us to confidently correlate the newly identified pyroclastic deposits in Las Viñas and San Lucas areas and the lithic clasts included into the Angastaco Formation in the Tiopampa-Pucarilla depression with the Alto de Las Lagunas Ignimbrite, a unit erupted from the PCTVC located approximately at 65 km SW of San Lucas and Las Viñas (Fig. 8).

7. Discussion

The lapilli-tuff of the Valle Calchaquí is the first of this type found interbedded and preserved within sedimentary units that fill the foreland basin in the Valles Calchaquíes, where, until now, only fall-out deposits were known (e.g., Coira et al., 2014). Our new data reveals that the pyroclastic deposit of ca. 13.5 Ma of the PCTVC is interbedded in the sedimentary units of Angastaco Formation in Las Viñas and San Lucas areas (Fig. 9 B); there is, however, a 50 km gap (mainly in the Tiopampa-Pucarilla depression) where no ca. 13.5 Ma ignimbrites are observed. The absence of outcrops of these primary pyroclastic deposits within the Tiopampa-Pucarilla depression points to their partial erosion and burying (Fig. 9 C). This interpretation is reinforced by the presence of ignimbrite boulders (sourced by the PCTVC) included in conglomerates of stratigraphically younger levels of Angastaco Formation within the Tiopampa-Pucarilla depression.

The ca. 13.5 Ma ignimbrites are therefore marker layers of the Angastaco Formation and thus make it possible to deepen the knowledge of sedimentation and deformation evolution in this area. Within the Valle Calchaquí (east), in Las Viñas and San Lucas areas, immediately above the ca. 13.5 Ma pyroclastic deposits there is a marked intraformational unconformity in the Angastaco Formation (Carrera and Muñoz, 2008; Aramayo, 2015), which was also recognised near the Angastaco village by Carrapa et al. (2011). However, the partial erosion and burying of the pyroclastic deposits in the Tiopampa-Pucarilla depression make it impossible to identify this intraformational angular unconformity. In this regard, we interpret that the ignimbrite boulders sourced by the PCTVC were incorporated in the Angastaco Formation just after 13.5 Ma and that this is related to the tectonic event that led to the local surface uplift and exhumation of the ignimbrite (Fig. 9C). Therefore, there should be an angular unconformity below these ignimbrite-rich conglomerates, likely correlatable with the unconformity preserved in the eastern region (San Lucas, Las Viñas and Angastaco areas).

Thus, a shortening increment period after the ca. 13.5 Ma ignimbrite deposition provoked relief rejuvenation generating source areas, mainly located near the Luingo caldera (PCTVC) in the eastern border of the Puna, and, to a lesser extent, in the Tiopampa-Pucarilla depression, which supplied ignimbrite clasts to the Angastaco Formation. Ongoing folding of the previous deposits resulted in the unconformity, whose better expressions are preserved in the San Lucas and Las Viñas areas but not in the Tiopampa-Pucarilla depression, where the ignimbrite-rich conglomerates represent the uppermost levels above the unconformity (Fig.9D).

The failure to recognise this stratigraphic discontinuity in the Tiopampa-Pucarilla depression may be related to several causes that are discussed below.

Folding of the Angastaco Formation in the Carrizal River (Tiopampa-Pucarilla depression, see Fig. 4B) is interpreted mainly as the result of a deformation event that started just before the initial activity of the PCTVC (ca. 13.5 Ma) and ended just before the final activity of the Luingo caldera (ca. 12 Ma) represented by the Pucarilla Ignimbrite. The internal angular unconformity in the Angastaco Formation is the result of a period of increased shortening.

The Pucarilla Ignimbrite marks the interruption of the sedimentation in the Tiopampa-Pucarilla depression (Guzmán, 2009; Aramayo, 2015), which is supported by the absence of Angastaco

Formation above it. Furthermore, this indicates the attenuation of the deformation since this ignimbrite defines a subhorizontal bed that lies in angular unconformity above the Quebrada de los Colorados and Angastaco formations. The map of figure 4B clearly shows that the Pucarilla Ignimbrite is subhorizontal, covering the basal units of the Payogastilla Group. Therefore, it is possible to infer that the ignimbrites described by Carrera and Muñoz (2008) interbedded in the Angastaco Formation belong to the ca. 13.5 Ma and not to the ca. 12 Ma volcanic event. Our interpretation is additionally supported by the fact that ash-flow tuffs deposition is an almost instantaneous process and thus very short compared with the time required to generate a progressive unconformity. Hence, we interpret that the progressive unconformity described by Carrera and Muñoz (2008) is placed below the ignimbrites we assign to the ca. 13.5 Ma eruption and that it is related to the beginning of the Middle Miocene deformation (Fig. 9 A and B).

Although there is no exposition of the unconformity in the Tiopampa-Pucarilla depression, some characteristics of the Angastaco Formation including changes in grain-size of the clasts, in palaeocurrent directions and in strata attitude in the Pucarilla area (Valle de Hualfín), are interpreted as part of the same deformation period registered by Carrera and Muñoz (2008) on the eastern border of the Tiopampa-Pucarilla depression. Hence, our interpretation is that possibly in the Carrizal River (Tiopampa-Pucarilla depression) the intraformational unconformity is located at the segment where the sedimentary succession of the Angastaco Formation is covered by the Pucarilla Ignimbrite. Afterwards, deformation continued, generating new folds which affected the intra Angastaco Formation unconformity (Fig. 9 D).

Moreover, it is important to note that the ca. 13.5 Ma pyroclastic deposits in the Tiopampa-Pucarilla depression may have been thinner than at more distal locations (e.g., Valle Calchaquí). This is supported by the features of archetypal pyroclastic flow deposits, which do not drape the landscape but thicken into, or are confined to valleys (e.g., Wilson and Houghton, 2000). The continuation of deformation that occurred around 13.5 Ma took place before this time and increased the uplift rate. It is therefore possible that the Tiopampa-Pucarilla depression at 13.5 Ma was at a “filled” stage (Catuneanu, 2004), with little available accommodation space. In those conditions, the deposition of a thick pile of the ca. 13.5 Ma pyroclastic deposits may have been hindered, depositing thinner piles at proximal positions (Tiopampa-Pucarilla depression) than at distal positions (Valle Calchaquí).

In addition, with high uplift rates the growth of a structure (e.g., fold) is associated with high erosion rates and/or sedimentation, hence during the initial stages of folding the recently formed strata constitute the crest of the fold, thus remaining exposed to erosion (Burbank et al., 1996). Therefore, a growing structure (e.g., unconformity) may be hidden, being recognised only by dip changes and by variations of the facies types involved in the growing structure, as is seen at the outcrops of Tiopampa-Pucarilla depression.

Given the observations described above, we suggest that between ca. 13.5 and ca. 12 Ma (~1.5 m.y.) a deformation increment took place at the margin between the eastern Puna border and the Valles Calchaquíes. The intense tectonic activity may have promoted new inversion stages of the Jasimaná Fault as well as the activity of east vergent faults that affected the plutonic rocks of the Oire Eruptive Complex. In addition, the ca. 13.5 Ma pyroclastic flow deposits found at Las Viñas and San Lucas allow us to temporally constrain the Middle Miocene deformation events for the Valle Calchaquí according to the identified growing geometries preserved in the stratigraphic profiles (Carrera and Muñoz, 2008; Carrapa et al., 2011; Aramayo, 2015).

This Middle Miocene deformation was also documented in other locations of the Puna and Eastern Cordillera and seems to be in line with a number of multidisciplinary studies. The Apatite Fission Track ages document the exhumation of the eastern border of the Puna (Deeken et al., 2006; Coutand et al., 2006; Pearson et al., 2012). Geochronologic data (DeCelles et al., 2011) combined with stratigraphic, structural and provenance studies constrain the signs of active deformation in some areas of the Eastern Cordillera (Marrett and Strecker, 2000; Vezzoli et al., 2012). Palaeoclimatic studies, including palaeoaltitude estimations, confirm the orogenic growth (Vandervoort et al., 1995; Hartley, 2003; Carrapa et al., 2014; Quade et al., 2015; Pingel et al., 2016). Finally, tectonic control through reverse faults shows evidence of emplacement and fast exhumation of plutonic bodies of Middle Miocene age (Insel et al., 2012), particularly the Acay monzodiorite emplaced and exhumed in a short period close to 14 Ma (Haschke et al., 2005).

In summary, all data suggests the existence of a 250-300-km belt of active deformation during the Middle Miocene, which includes the eastern border of the Puna and a significant part of the Valles Calchaquíes that was already established, possibly since the Palaeogene, with a well-defined period of deformation increment between ca. 13.5 and 12 Ma.

8. Conclusions

We identified the first Middle Miocene ash-flow tuff deposits interbedded in sedimentary sequences in the central portion of the Valles Calchaquíes. These pyroclastic deposits belong to the PCTVC (eastern Puna border) and show W-E changes in their stratigraphic relationship. In the eastern Puna border they cover basement rocks. In the Tiopampa-Pucarilla depression they are reworked and included as ignimbrite boulders in the Angastaco Formation, while within the Valle Calchaquí they are preserved and interbedded in the Angastaco Formation. Based on the absence of exposed primary pyroclastic deposits in the Tiopampa-Pucarilla depression, we propose that an increment of deformation took place between ca. 13.5 and ca. 12 Ma in the segment of Puna-Eastern Cordillera (Valles Calchaquíes) transition, generating a pronounced topographic relief above the local base level, in agreement with an uplift rate higher than the aggradation rate. This led to folding, erosion and reworking of the original ca. 13.5 Ma pyroclastic flow deposit and then produced an intraformational unconformity surface in the Angastaco Formation. This surface is eroded or buried in the Tiopampa-Pucarilla depression and well-preserved in the eastward areas that contain more continuous and complete successions (San Lucas, Las Viñas, Angastaco areas). The pyroclastic flow deposits found in the Valles Calchaquíes suggest that if there was an isolation between Puna and Eastern Cordillera, it was after 13.5 Ma and before 12 Ma, given that the ca. 12 Ma Pucarilla Ignimbrite did not overpass the proto-Vallecito range adjoining the eastern border of the Tiopampa-Pucarilla depression. However, it is more plausible that, notwithstanding the high uplift rate of the surrounding ranges, the sedimentary supply was not interrupted from western positions towards the Valle Calchaquí.

Our proposal of a well-constrained deformation event at the eastern Puna border and Eastern Cordillera (Valles Calchaquíes) during the Middle Miocene (between ca. 13.5 and 12 Ma) reveals the relationship in space and time between uplift, exhumation, and basin evolution. The suggested deformation event is consistent with results from Apatite Fission Track (AFT) ages (Deeken et al., 2006; Coutand et al., 2006; Pearson et al., 2012), geochronologic data (plutonic bodies) (Haschke et al., 2005; Insel et al., 2012), and structural, sedimentologic and palaeoclimatic studies (Vandervoort et al., 1995; Hartley, 2003; Carrera and Muñoz, 2008; Carrapa et al., 2011; DeCelles et al., 2011; del Papa et al., 2013a; Carrapa et al., 2014; Quade et al., 2015; Aramayo, 2015; Pingel et al., 2016; among others) along the Puna-Valles Calchaquíes (Valles Calchaquíes) transition between 24° and 27° S.

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Appendix A. Correlation of the pyroclastic deposits

Below we describe a set of approaches (geochronology, petrography, whole-rock geochemistry and mineral chemistry) in order to establish a correlation between the interlayered pyroclastic deposits in the Angastaco Formation of Las Viñas and San Lucas areas and the ignimbrite clasts included in the Angastaco Formation in the Tiopampa-Pucarilla depression.

A-1. Bulk correlation

Guzmán et al. (2014) showed that between 14.5 and 11.5 Ma explosive Cenozoic volcanism of the southern Puna migrated suddenly eastwards from 67ºW to the eastern Puna border and is represented by the PCTVC and by small pyroclastic deposits of the Vicuña Pampa Volcanic Complex (see Fig. 1 for location; Guzmán et al., 2014).

Most of the volcanic deposits of this time interval (14.5-11.5 Ma) are located in the southern Puna between 67 and 66º 15’W. Some exceptions are the ignimbrites at the Pedernal area

(Richards et al., 2013), the Agua Escondida Ignimbrite (Coira and Pezzutti, 1976), the pyroclastic deposits located north of Cerro Galán both in Bequeville range (Marrett et al., 1994) and Diablillos area (Stein, 2001) and other deposits within the transition of northern and southern Puna, such as those from El Morro, Organullo and Rupasca domes and the Vizcachayoc Ignimbrite (Petrinovic et al., 1999; see Fig. 1 for location).

We identify potential sources based on two main criteria. First, its age, of ca. 13.4 Ma, and second, its maximum expected distance from the source, which should not exceed 200 km, taking the examples in the literature into account (Self, 2006).

We first researched volcanic centres of similar age, and in particular we focused our attention on the volcanic structures that may produce the most explosive eruptions, i.e., collapse calderas. A compilation of this type of volcanoes in a 200 km radius from the position of the newly identified ash-flow tuff deposit is presented in Figure 8. The deposits that have a similar age to the ones studied here are displayed in green, and their general features are presented in Table B-2 in the Supplementary Material.

The first attempts of correlation indicate that Diablillos, Agua Escondida, Alto de Las Lagunas and Vizcachayoc Ignimbrites overlap in age (including 2σ values) with pyroclastic deposits of Las Viñas and San Lucas areas (Fig. 8 A). Moreover, the only unit that is farther than 200 km is the Agua Escondida Ignimbrite (Fig. 8 B) and the ones that are spatially closer are the lithic fragments included in the Angastaco Formation in the Carrizal River, the Alto de Las Lagunas Ignimbrite and the Diablillos Ignimbrites.

The mineral composition of the pyroclastic deposit at Las Viñas area matches completely with that of the Alto de Las Lagunas Ignimbrite (Fig. 8 C), while the lithic fragments in the Carrizal River (Tiopampa-Pucarilla depression) share the same mineralogy except for the absence of titanite. Likewise, Agua Escondida Ignimbrite contains similar minerals, but it lacks alkaline feldspar. Between the Alto de las Lagunas Ignimbrite and the ash-flow tuff at the Valle Calchaquí there is also partial correlation in relative crystal contents (see below), lithic fragments and pumice fragments, as well as in the geochemical characteristics of the samples. The sum of all these features indicates that these rocks may be correlated and belong to the same volcanic unit.

Therefore, based on the mineralogy, ages and distance from the source we find that possible sources are the Alto de Las Lagunas Ignimbrite and, to a lesser extent, the Diablillos Ignimbrite. However, we think the products of the Agua Escondida caldera should be included in an exhaustive comparative study because this caldera was recently interpreted (Coira et al., 2014) as the source of the fall-out deposits interlayered in the Angastaco Formation.

A-2. Field and petrographic correlation

From the above-mentioned pyroclastic units and/or volcanic centres, we further provide detailed petrographic and field observations for the Alto de las Lagunas Ignimbrite, which is welded and contains up to ca. 40 vol. % of crystals and ca. 10 vol. % of crystals within pumices. Its fiamme contain plagioclase, alkaline feldspar, amphibole, biotite, quartz as well as scarce clinopyroxene and accessory phases of titanite, apatite, zircon and Fe-Mg oxides; plagioclases show zoning and sieve textures.

The massive pyroclastic deposits found in Las Viñas and San Lucas have a variable crystal content reaching approximately 80 vol.%; however, its pumice fragments are crystal-poor (5 vol.%). This is a fines depleted ignimbrite, so its matrix is very crystal-rich, with scarce glass shards. Pumices are formed by phenocrysts and microphenocrysts of plagioclase, biotite, amphibole, titanite, opaques, quartz and alkaline feldspars; it also contains negligible amounts of clinopyroxene and zircon. Plagioclases are zoned and twined, some of them showing sieve textures.

The lithic fragments in the Tiopampa depression contain about 35 vol.% of crystals formed by plagioclase, biotite, amphibole (pseudomorphs), quartz and alkaline feldspars. Much of the plagioclase phenocrysts show sieve textures, with biotite and opaques inclusions. The sample is altered to calcite and kaolinite.

A-3 Geochemical correlation

For the geochemical correlation we analysed one sample from the massive pyroclastic unit at Las Viñas and compared it with published data of the Alto de Las Lagunas Ignimbrite (Guzmán et al., 2011). Both ignimbrites were analysed in whole-rock samples by XRF (major elements) and ICP-MS (minor and trace elements) at ACME labs. In our geochemical comparison we also included samples from Diablillos (Stein, 2001) and Agua Escondida ignimbrites (Coira and Pezzutti, 1976), and the fall-out deposits from the Angastaco Formation (Coira et al., 2014) (See Table B-3 in the Supplementary Material).

The Alto de Las Lagunas Ignimbrite and the massive pyroclastic deposits in Las Viñas and San Lucas are classified as dacites on a volatile-free basis, while Diablillos and Agua Escondida ignimbrites classify as andesites (see Fig. S1-A in the Supplementary Material). Multielement diagrams (see Fig. S1-B in the Supplementary Material) show very similar patterns between Las Viñas-San Lucas pyroclastic deposits and Alto de Las Lagunas Ignimbrite, with small differences in Th and in some mobile elements such as K, Rb and Sr. Furthermore, the differences with the Agua Escondida Ignimbrite are somewhat greater, especially in the case of Ti, Sr, Rb, Th and Nb, Ta. Other diagrams are less efficient for discriminating the differences of the pyroclastic units selected for comparison: rare earth elements diagrams show similar patterns between the pyroclastic deposits of Las Viñas with those of Alto de Las Lagunas and Agua Escondida ignimbrites (see Fig. S1 in the Supplementary Material).

Bivariate diagrams (Fig. S1 in the Supplementary Material) also show good correlation between samples from Alto de Las Lagunas Ignimbrite and Las Viñas pyroclastic deposits.

A-4. Mineral chemistry correlation:

To strengthen the results of correlation we performed chemical analyses on plagioclases, alkaline feldspars, biotites and amphiboles on thin sections of the pyroclastic deposits in Las Viñas and San Lucas areas and repeated some analysis of the Alto de Las Lagunas Ignimbrite in order to avoid possible differences in data acquired with different microprobes. Table B-4 in the Supplementary Material shows representative analyses.

Feldspars:

The composition of plagioclases is andesine and labradorite for Alto de Las Lagunas Ignimbrite ($An_{35\text{-}52}$) and andesine for the pyroclastic sequences at the Las Viñas area ($An_{39\text{-}48}$). Alkaline feldspars are sanidines in both cases: Alto de Las Lagunas Ignimbrite ($Or_{75\text{-}82}$) and samples at Las Viñas area ($Or_{77\text{-}78}$). Figures S2-A and S2-B in the in the Supplementary Material indicate overlapping compositions for both pyroclastic units.

Micas:

Micas are classified as Mg-biotites in all cases using the diagrams (not shown) by Yavutz et al. (2001), with mgli>2, Mgli<4, feal<4 and feal>0. TiO_2 values are >4 in all cases. Biotite is titanium rich (TiO_2%: 4-5) as are most biotites of the Puna ignimbrites (e.g., Vilama: Soler, 2005; Atana: Lindsay et al., 2001). The MgO vs TiO_2 plot shows a good correlation in the composition of the biotites (See Fig. S2 in the Supplementary Material).

Amphiboles:

Phenocrysts from both pyroclastic units are calcic amphiboles. The diagram of molar Si vs. Mg/(Mg+Fe_2) shows good correlation (See Fig. S2 in the Supplementary Material).

A-5. Discussion about correlation:

The similarities between pyroclastic deposits interbedded in the Angastaco Formation in Las Viñas and San Lucas areas, the lithic fragments included in the Angastaco Formation in the Tiopampa-Pucarilla depression and the Alto de las Lagunas Ignimbrite correspond to a set of pyroclastic rocks erupted from the PCTVC at ca. 13.5 Ma which travelled farther than earlier believed, i.e., from ca. 5 km to ca. 65 km from the source (Fig. 8). One possibility is that the pyroclastic density currents that produced the ca. 13.5 Ma ignimbrites had different rheological properties from those of the 12 Ma Pucarilla Ignimbrite, which was blocked by the Vallecito range (Guzmán and Petrinovic, 2010), and hence travelled only 40 km from the source. Therefore, it is possible that the 13.5 Ma pyroclastic flows had the capability of surpassing topographic highs while those of 12 Ma did not.

It is not clear yet whether or not the Alto de las Lagunas Ignimbrite (the first pyroclastic product of the PCTVC) resulted from a collapse event (Guzman and Petrinovic, 2010). However, if these deposits were generated from a volcano-tectonic collapse caldera (see Aguirre-Díaz, 2008), the successions recognised in San Lucas and Las Viñas may be easily explained. These types of calderas are characterised by the extrusion of high volumes of pyroclastic material and their sequences usually contain stratified-lapilli tuffs at their basal levels (Aguirre-Díaz, 2008). So, the stratified pyroclastic facies may be related to these first products. The observation that some of these distal deposits are interlayered with thin clayey beds may be explained by the occurrence of ephemeral flood events or sporadic storms that led to the reworking of pyroclasts by rainfall runoff during eruption, as was interpreted for pyroclastic deposits interlayered in Permian deposits in the Pyrenees (Martí, 1996). In fact, the deposits found interlayered at Angastaco Formation resemble those of the Pyrenees (Martí, 1996), where a high concentration of crystals in the matrix is also observed. The different pyroclastic facies recognised in this contribution may be explained by the transition from concentrated to diluted pyroclastic flows that travelled long distances and lost most of their fines by elutriation and hence were enriched in crystal fragments (Walker, 1972). Associated with these elutriation processes, the massive very fine-tuff facies may be interpreted as deposited from the co-ignimbrite ash cloud. Reworking and redeposition of some of these pyroclastic deposits by fluvial processes further enhanced crystal concentration.

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Figure captions

Fig. 1: Hillshade map generated from SRTM data of the 24°–27°S segment of the Central Volcanic Zone of the Central Andes showing the distribution of the calderas and cenozoic

ignimbrites. The red and black stars indicate the position of the pyroclastic deposits recognised and described in this contribution. Modified from Petrinovic et al. (2010).

References: LP, Valle de La Poma; LU, Valle de Luracatao; CH, Valle Calchaquí; T, Valle del Tonco; A, Valle de Amblayo; H, Valle de Hualfín; P, Valle de Pucará; SM, Valle de Santa María; TPD, Tiopampa-Pucarilla depression. Ages from (1) Guzmán and Petrinovic (2010), (2) Richards et al. (2013), (3) Coira and Pezzutti (1976), (4) Stein (2001), (5) Marrett et al. (1994), (6) Petrinovic et al. (1999).

Fig. 2: Geological map of the study area, showing the middle portion of the Valles Calchaquíes, the position of the Luingo caldera within the Puna and the distribution of volcanic rocks from the PCTVC. Modified from Guzmán and Petrinovic (2010) and Aramayo (2015).

Fig. 3: Stratigraphic chart of the PCTVC in the eastern border of the Puna and western border of the Valles Calchaquíes (including the valles de Hualfín, Pucará and Calchaquí), indicating the lateral variation in the occurrence of the units.

Fig. 4: A) Detailed map and schematic cross-sections of the Las Viñas and San Lucas areas, showing the main sedimentary sequences, the structures and the outcrops of the pyroclastic deposits (see location in Fig. 2). B) Detailed map and schematic cross-sections of the Tiopampa-Pucarilla depression. 1) The box indicates the position of the conglomerate outcrops of the Angastaco Formation with clasts of ignimbrites; 2) The box indicates the possible unconformity inside the Angastaco Formation in the Valle de Hualfín.

The undifferentiated ignimbrite (black fill and white circle in the map) was defined by Carrera and Muñoz (2008) as equivalent to the Pucarilla Ignimbrite of ca. 12 Ma. Conversely, we assign this deposit to the volcanic event occurred at ca. 13.5 Ma.

Fig. 5: Detailed sedimentological logs of the Angastaco Formation, showing the main lithologies and sedimentary environments. A) Las Viñas area, B) San Lucas area.

Fig. 6: Profile and pictures showing, in detail, the features of the different facies that form the ash-flow tuff deposits. A,B,C) Stratified lapilli-tuff level, D) Massive to diffusely stratified crystal-rich lapilli-tuff level, E) Massive very fine- tuff level, F) Stratified lapilli-tuff level.

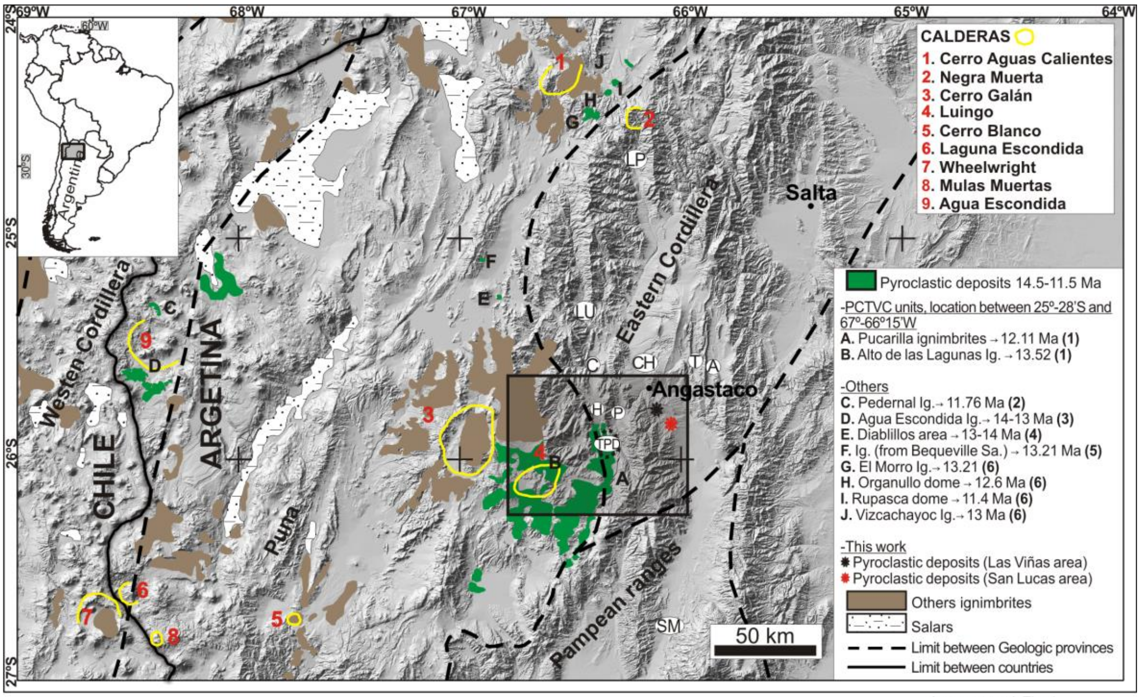
Fig. 7: ^{40}Ar–^{39}Ar age spectra carried out for this study. See Table B-1 in the Supplementary Material for a summary of ^{40}Ar–^{39}Ar data.

Fig. 8: A) Comparative diagram of ignimbrites' absolute ages between 14 and 11.5 Ma in a radius of 200 km from Las Viñas and San Lucas areas, B) Diagram showing the distance of the ash-flow tuffs of Las Viñas and San Lucas in relation to ignimbrites of similar ages, C) Comparative table that shows the minerals found in each pyroclastic deposit and possible matches between them.

Fig. 9: Schematic evolution sections between the eastern border of the Puna and the Eastern Cordillera (middle segment of the Valles Calchaquíes), showing possible stratigraphic relationships of the ignimbrites erupted at ca. 13.5 Ma from the PCTVC at different places and times. See text for detail.

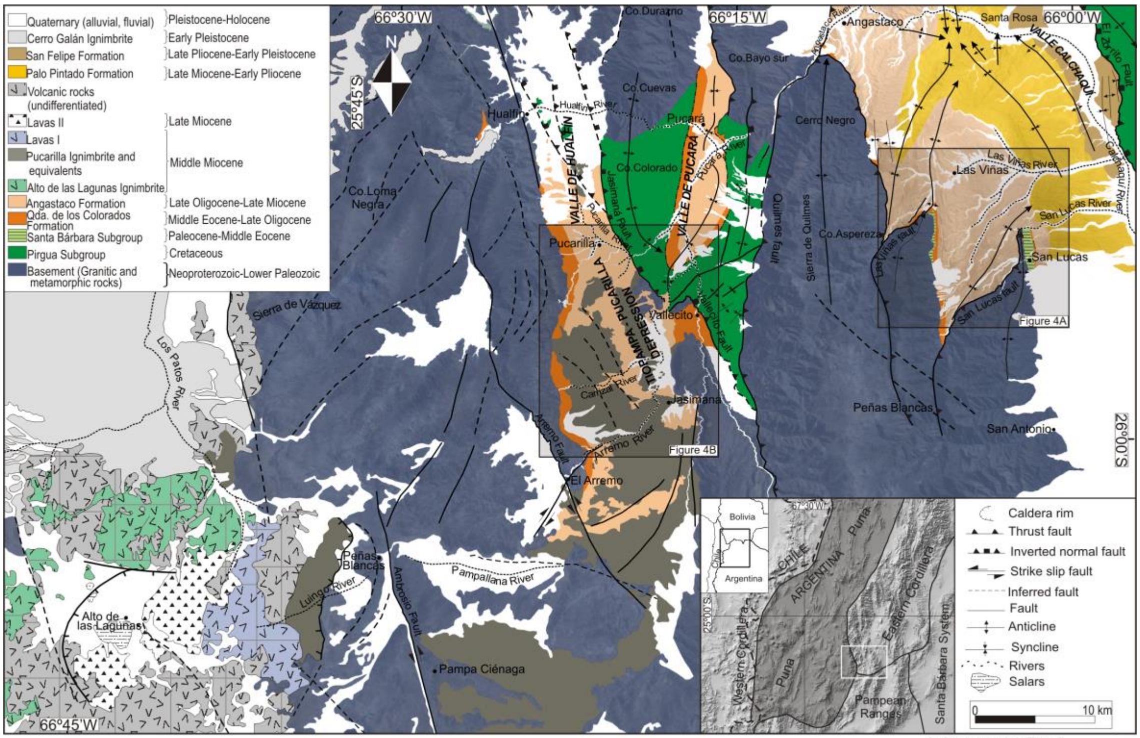
Note that this is a general scheme without a straight direction. In particular we include the Valle de Hualfín (H: located in the same longitudinal position as the TPD, but further north) and the Valle de Pucará (P) (located to the north of Vallecito range) because they are important for identifying the sedimentary and structural evolution of the area. However, we must note that the pyroclastic flows did not cross the Valles de Hualfín and Pucará.

Intra Angastaco Formation unconformity: 1) Tiopampa-Pucarilla depression (this work), 2) Valle de Pucará, unconformity was not identified. We interpret it was formed (stage C) and subsequently eroded, 3) Angastaco village (Carrapa et al., 2011), 4) Las Viñas area (Aramayo, 2015), 5) San Lucas area (Carrera and Muñoz, 2008).



Aramayo et al. Fig. 1

Fig. 1



Aramayo et al. Fig. 2

Fig. 2

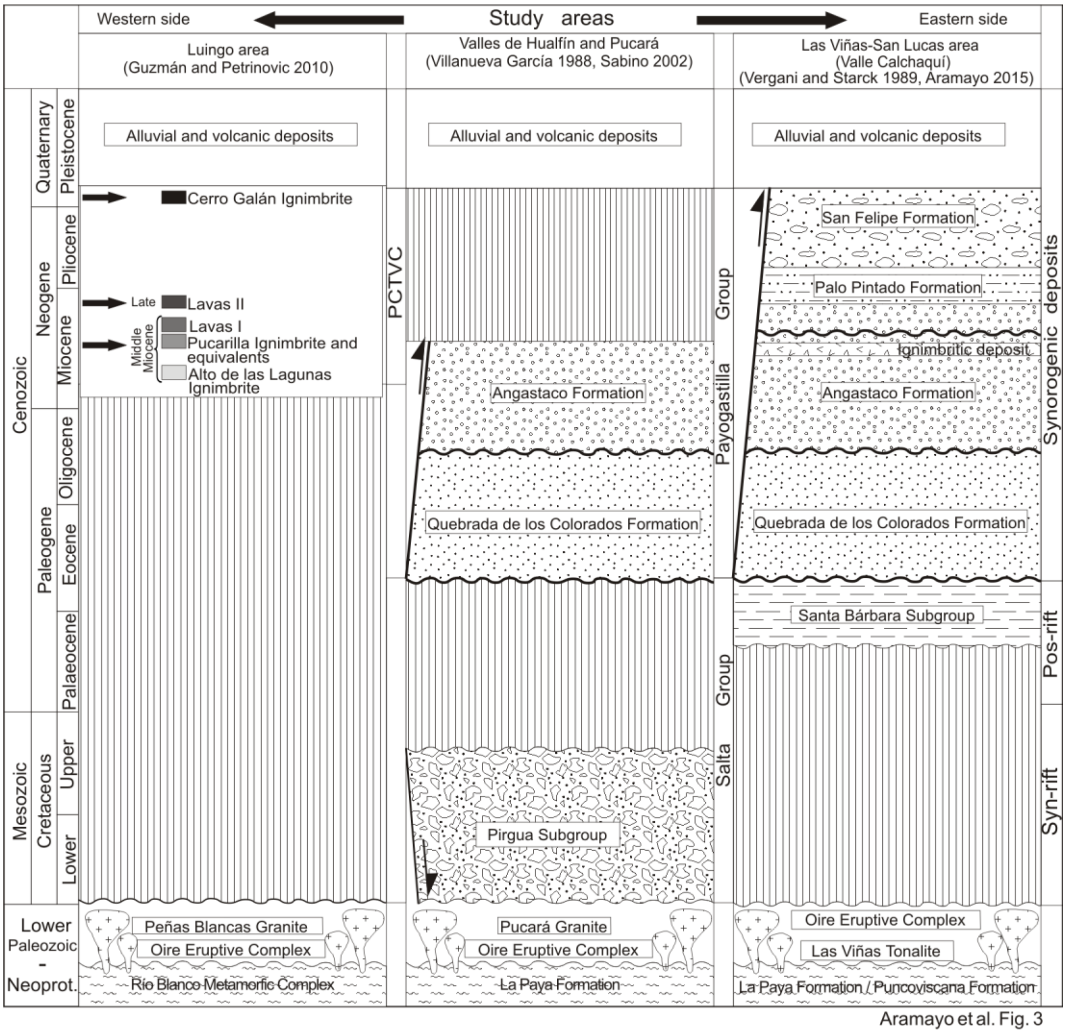
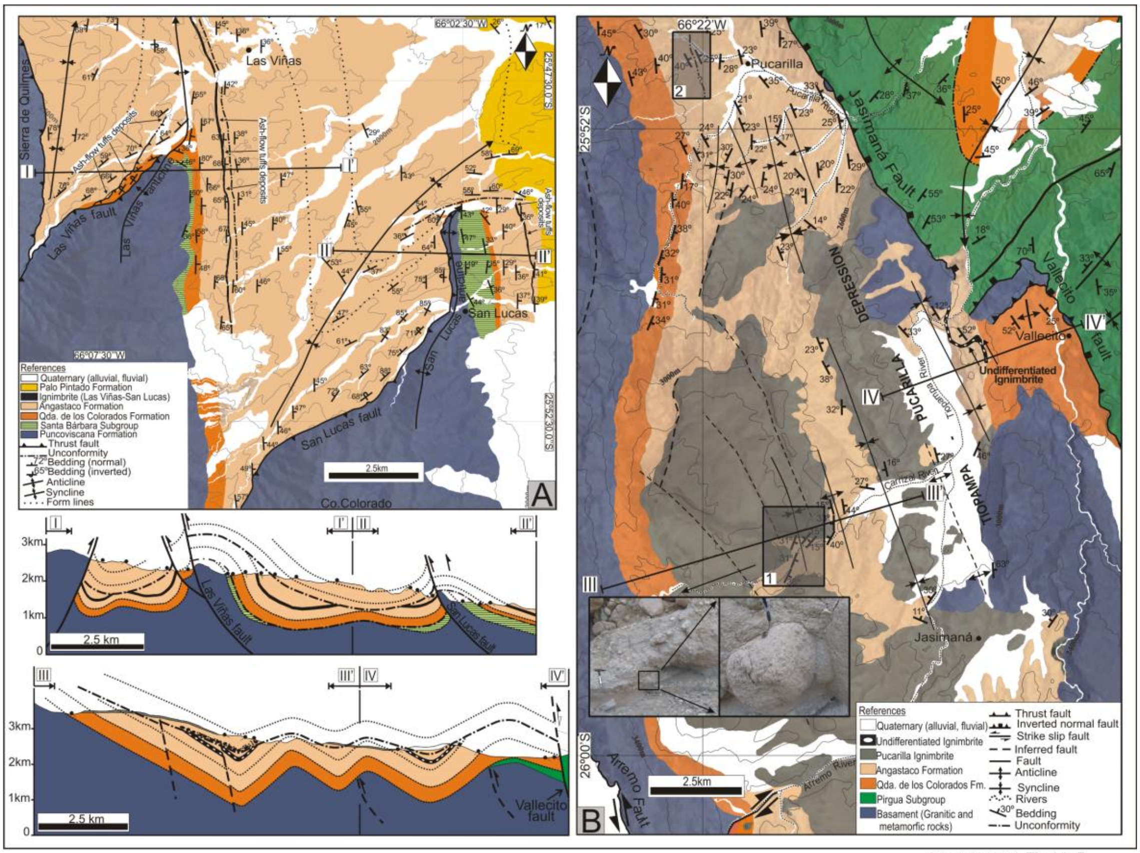

Western side
Study areas
Eastern side
Luingo area
(Guzmán and Petrinovic 2010)
Valles de Hualfín and Pucará
(Villanueva García 1988, Sabino 2002)
Las Viñas-San Lucas area
(Valle Calchaquí)
(Vergani and Starck 1989, Aramayo 2015)
Cenozoic
Quaternary
Pleistocene
Neogene
Pliocene
Miocene
Paleogene
Oligocene
Eocene
Palaeocene
Mesozoic
Cretaceous
Upper
Lower
Lower Paleozoic - Neoprot.
Alluvial and volcanic deposits
Alluvial and volcanic deposits
Alluvial and volcanic deposits
Cerro Galán Ignimbrite
Late
Lavas II
Middle Miocene
Lavas I
Pucarilla Ignimbrite and equivalents
Alto de las Lagunas Ignimbrite
PCTVC
Angastaco Formation
Quebrada de los Colorados Formation
Pirgua Subgroup
Payogastilla Group
Salta Group
San Felipe Formation
Palo Pintado Formation
Ignimbritic deposit
Angastaco Formation
Quebrada de los Colorados Formation
Santa Bárbara Subgroup
Synorogenic deposits
Pos-rift
Syn-rift
Peñas Blancas Granite
Oire Eruptive Complex
Río Blanco Metamorfic Complex
Pucará Granite
Oire Eruptive Complex
La Paya Formation
Oire Eruptive Complex
Las Viñas Tonalite
La Paya Formation / Puncoviscana Formation
Aramayo et al. Fig. 3

Fig. 3



Aramayo et al. Fig 4 A, B

Fig. 4

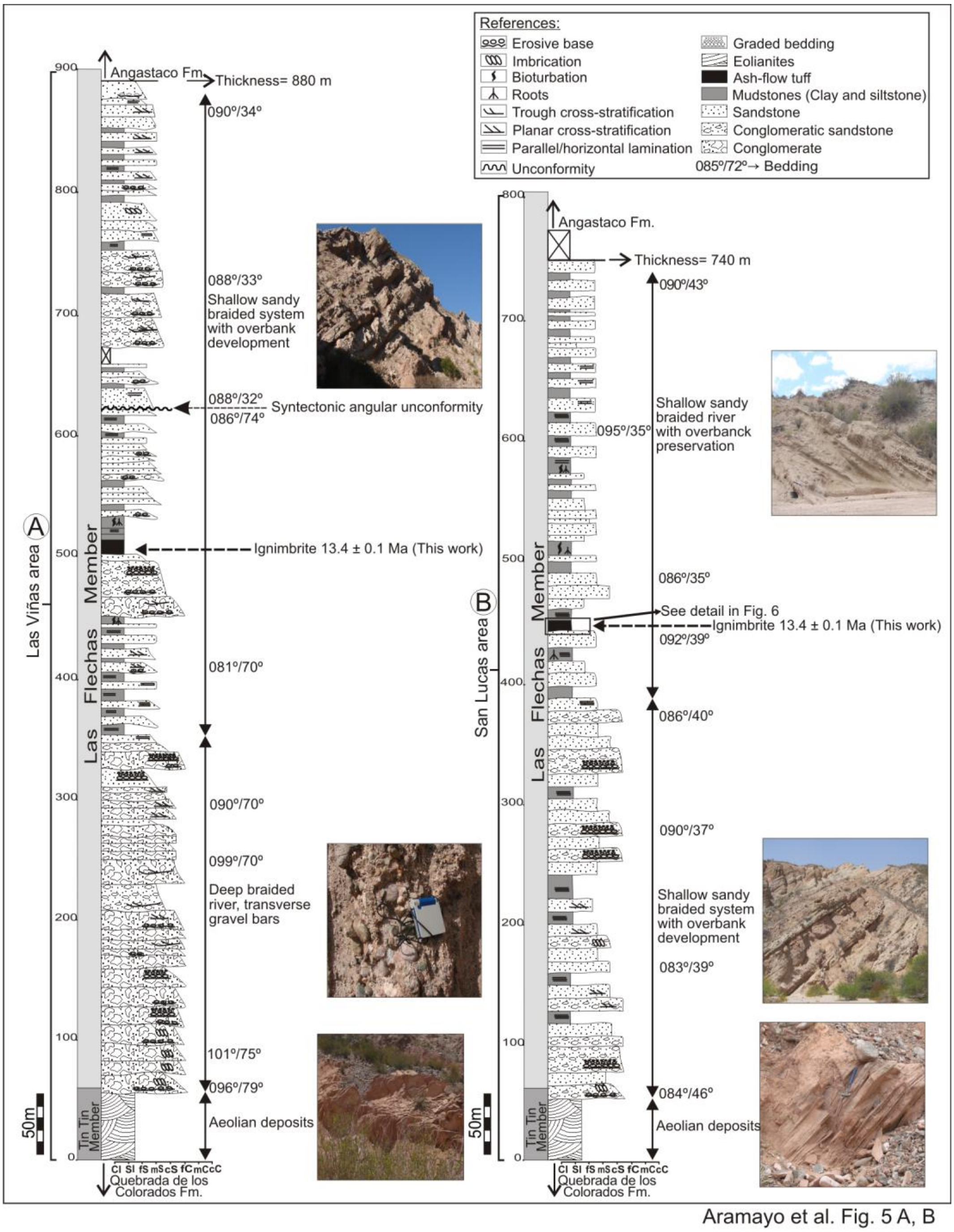
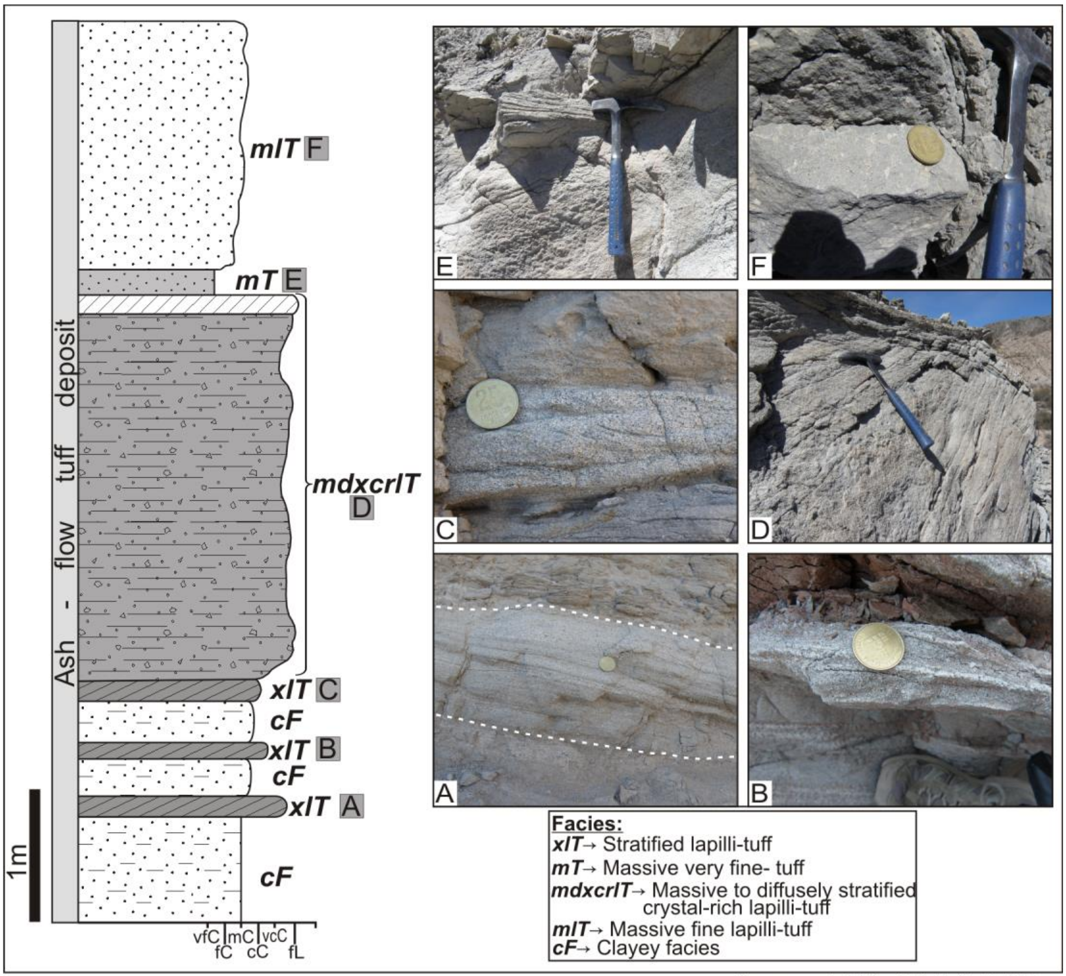
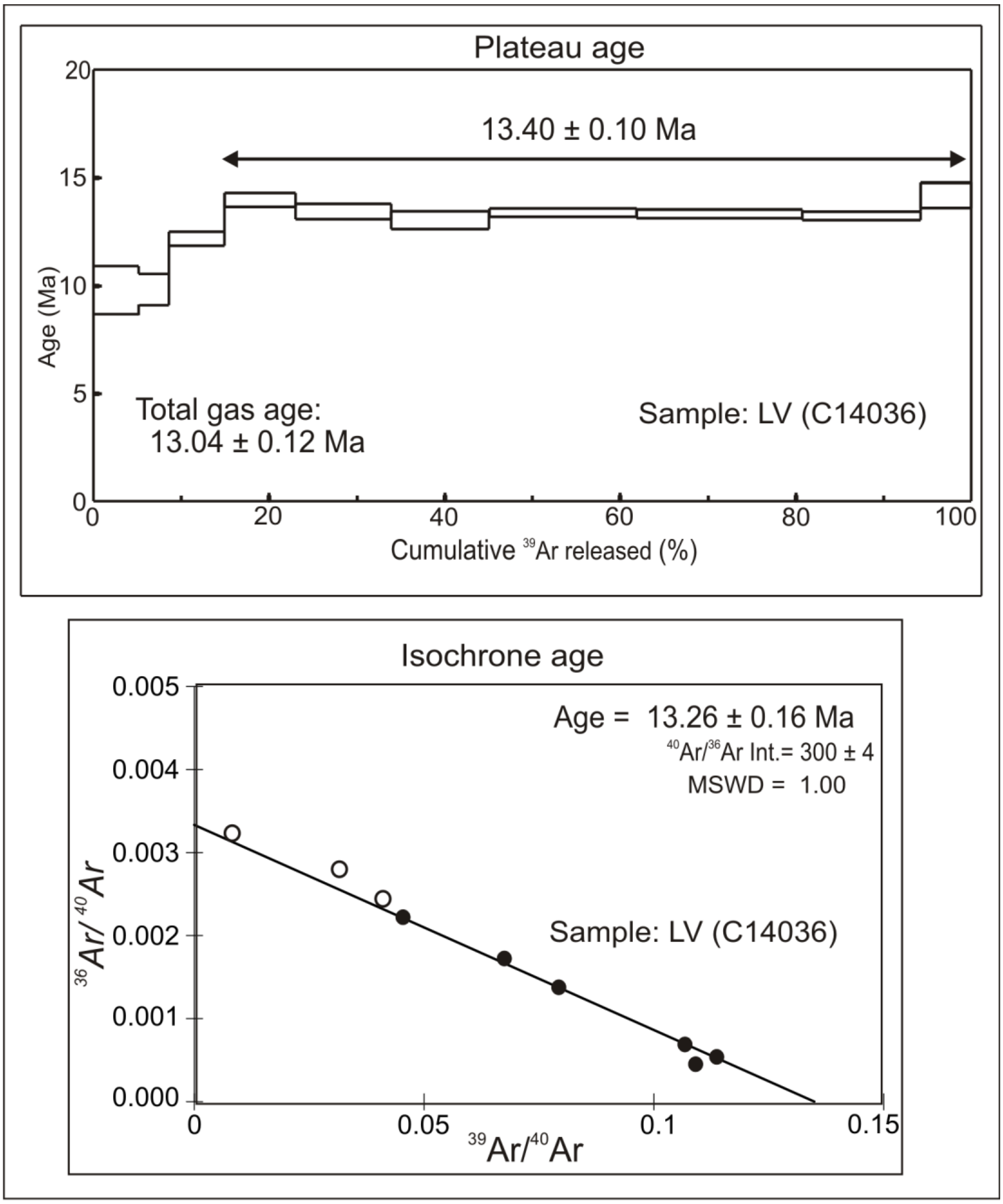

References:
Erosive base
Imbrication
Bioturbation
Roots
Trough cross-stratification
Planar cross-stratification
Parallel/horizontal lamination
Unconformity
Graded bedding
Eolianites
Ash-flow tuff
Mudstones (Clay and siltstone)
Sandstone
Conglomeratic sandstone
Conglomerate
085º/72º→ Bedding
A
Las Viñas area
Las Flechas Member
Tin Tin Member
Angastaco Fm.
Thickness= 880 m
090º/34º
088º/33º
Shallow sandy braided system with overbank development
088º/32º
Syntectonic angular unconformity
086º/74º
Ignimbrite 13.4 ± 0.1 Ma (This work)
081º/70º
090º/70º
099º/70º
Deep braided river, transverse gravel bars
101º/75º
096º/79º
Aeolian deposits
Quebrada de los Colorados Fm.
Cl Sl fS mS cS fC mC cC
50m
0
100
200
300
400
500
600
700
800
900
B
San Lucas area
Las Flechas Member
Tin Tin Member
Angastaco Fm.
Thickness= 740 m
090º/43º
Shallow sandy braided river with overbanck preservation
095º/35º
086º/35º
See detail in Fig. 6
Ignimbrite 13.4 ± 0.1 Ma (This work)
092º/39º
086º/40º
090º/37º
Shallow sandy braided system with overbank development
083º/39º
084º/46º
Aeolian deposits
Quebrada de los Colorados Fm.
Cl Sl fS mS cS fC mC cC
50m
0
100
200
300
400
500
600
700
800
Aramayo et al. Fig. 5 A, B

Fig. 5



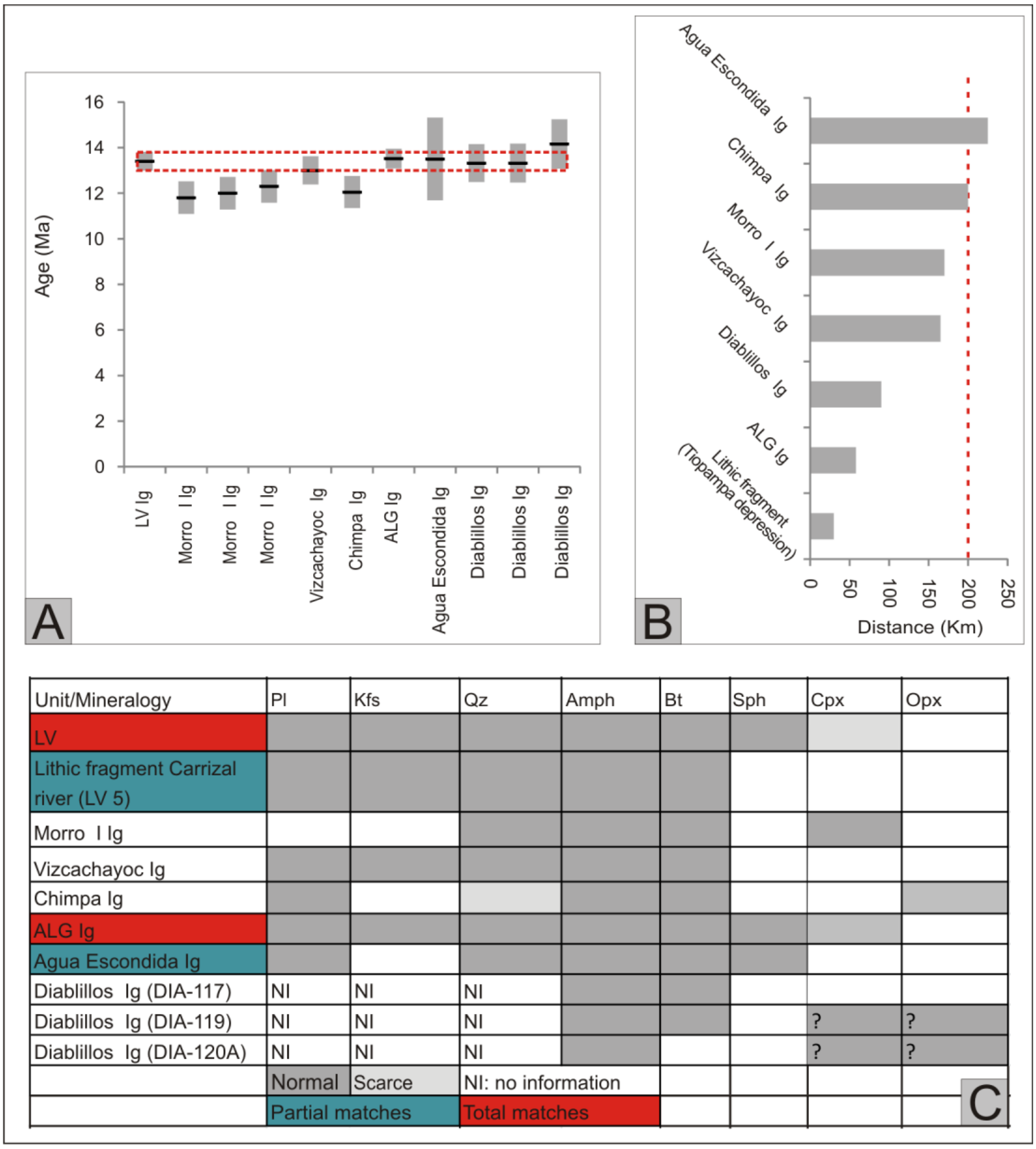
Aramayo et al. Fig. 6 A, B, C, D, E, F,

Fig. 6



Aramayo et al. Fig. 7

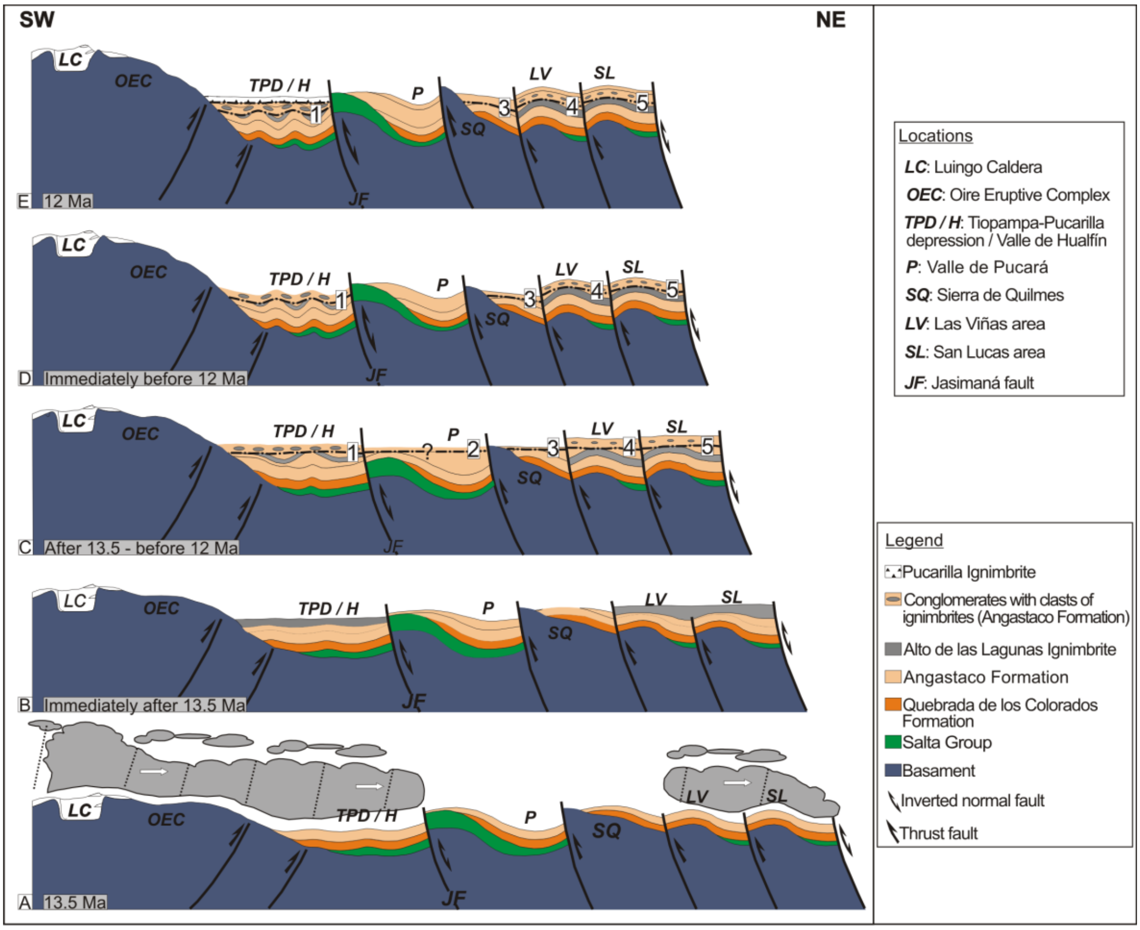
Fig. 7



Unit/Mineralogy	Pl	Kfs	Qz	Amph	Bt	Sph	Cpx	Opx
🟥 LV	▓	▓	▓	▓	▓	▓	░	
🟦 Lithic fragment Carrizal river (LV 5)	▓	▓	▓	▓	▓			
Morro I Ig			▓	▓	▓		▓	
Vizcachayoc Ig	▓	▓	▓	▓	▓			
Chimpa Ig	▓		░	▓	▓			▒
🟥 ALG Ig	▓	▓	▓	▓	▓	▓	▒	
🟦 Agua Escondida Ig	▓		▓	▓	▓	▓		
Diablillos Ig (DIA-117)	NI	NI	NI	▓	▓			
Diablillos Ig (DIA-119)	NI	NI	NI	▓	▓		▓ ?	▓ ?
Diablillos Ig (DIA-120A)	NI	NI	NI	▓			▓ ?	▓ ?
	▓ Normal	░ Scarce	NI: no information					
	🟦 Partial matches		🟥 Total matches					

Aramayo et al. Fig. 8A, B, C

Fig. 8



Aramayo et al. Fig. 9. A, B, C, D, E

Fig. 9

Highlights

- Spatiotemporal relationship between volcanism, uplift, exhumation and basin evolution
- Recognition of Middle Miocene primary pyroclastic deposits in the Valles Calchaquíes
- Variable stratigraphic relationships of 13.5-12 Ma ignimbrites with sedimentary units
- 13.5 and 12 Ma: deformation event at the eastern Puna border and Valles Calchaquíes