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Late Eocene–Pliocene basin evolution in the Eastern Cordillera of northwestern Argentina (25°–26°S): regional implications for Andean orogenic wedge development

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ABSTRACT

Important aspects of the Andean foreland basin in Argentina remain poorly constrained, such as the effect of deformation on deposition, in which foreland basin depozones Cenozoic sedimentary units were deposited, how sediment sources and drainages evolved in response to tectonics, and the thickness of sediment accumulation. Zircon U-Pb geochronological data from Eocene–Pliocene sedimentary strata in the Eastern Cordillera of northwestern Argentina (Pucará–Angastaco and La Viña areas) provide an Eocene (*ca.* 38 Ma) maximum depositional age for the Quebrada de los Colorados Formation. Sedimentological and provenance data reveal a basin history that is best explained within the context of an evolving foreland basin system affected by inherited palaeotopography. The Quebrada de los Colorados Formation represents deposition in the distal to proximal foredeep depozone. Development of an angular unconformity at *ca.* 14 Ma and the coarse-grained, proximal character of the overlying Angastaco Formation (lower to upper Miocene) suggest deposition in a wedge-top depozone. Axial drainage during deposition of the Palo Pintado Formation (upper Miocene) suggests a fluvial-lacustrine intramontane setting. By *ca.* 4 Ma, during deposition of the San Felipe Formation, the Angastaco area had become structurally isolated by the uplift of the Sierra de los Colorados Range to the east. Overall, the Eastern Cordillera sedimentary record is consistent with a continuous foreland basin system that migrated through the region from late Eocene through middle Miocene time. By middle Miocene time, the region lay within the topographically complex wedge-top depozone, influenced by thick-skinned deformation and re-activation of Cretaceous rift structures. The association of the Eocene Quebrada del los Colorados Formation with a foredeep depozone implies that more distal foreland deposits should be represented by pre-Eocene strata (Santa Barbara Subgroup) within the region.

INTRODUCTION

Tectonic and erosional processes related to Cenozoic shortening within the central Andes (Puna Plateau and Eastern Cordillera) of northwestern Argentina were responsible for deposition of widespread, thick accumulations of fluvial, alluvial and lacustrine sediments that were incorporated into the Andean thrust belt as the deformation front migrated eastwards into the frontal Santa Barbara ranges (Fig. 1; Jordan & Alonso, 1987). Along the eastern and southeastern margins of the Puna Plateau of NW Argentina, thick sequences of late Cenozoic synorogenic deposits are preserved within and along the deformed margins of modern topographic basins (Fig. 1); previous authors have interpreted these deposits as parts of a formerly regionally integrated foreland basin that was disrupted by local uplift during the late Miocene (Jordan & Alonso, 1987; Starck & Vergani, 1996). The Angastaco area contains one of the best-exposed remnants of these middle to upper Cenozoic strata. More than six km of Cenozoic Payogastilla Group strata (Figs 1 and 2) related to Eastern Cordillera mountain building (e.g. Díaz & Malizzia, 1983; Starck & Vergani, 1996) are preserved in spectacular outcrops surrounding the village of Angastaco. Upper Eocene through Pliocene strata in the area were deposited in association with deformation in the Eastern Cordillera, and were subsequently deformed as the orogenic front migrated eastwards through the region (Carrera & Muñoz, 2008; Carrapa *et al.*, 2011). Despite the excellent

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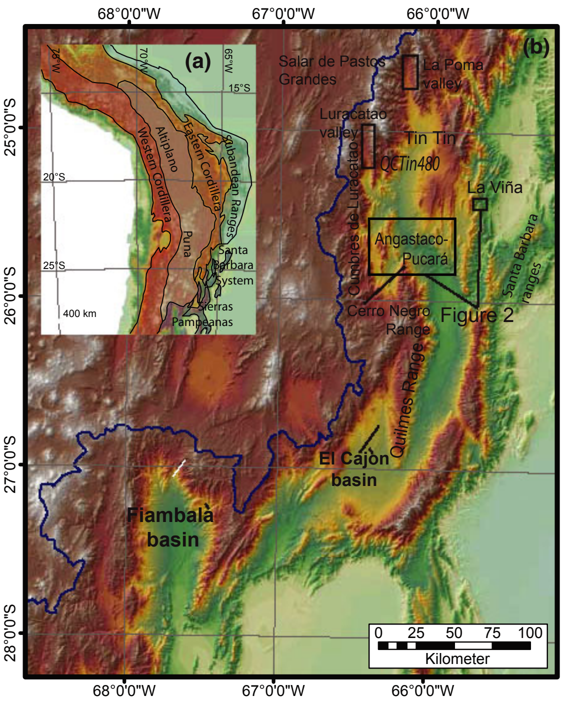

(c)

Angastaco Basin		Age* (Ma)	La Viña Basin	
Payogastilla Group	San Felipe Fm.	~5-2	Orán Group	Piquete Fm.
	Palo Pintado Fm.	~9-5		Guanaco Fm.
	Angastaco Fm.	~21-9		Jesus Maria Fm. Anta Fm. Rio Seco Fm.
	Quebrada de los Colorados Fm.	38?-21		
Lumbrera Fm. (Santa Barbara Subgroup)		Salta Group		

Fig. 1. (a) Simplied tectonic map of the Central Andes; inset square represents (b). (b) Digital elevation model of the study area. (c) Schematic stratigraphy of the Eastern Cordillera of NW Argentina; *approximate stratigraphic ages from this study, Bywater-Reyes *et al.* (2010) and Carrapa *et al.* (2011).

exposures, these rocks remain poorly dated, and important details regarding their palaeogeography and relationships with other Cenozoic strata and coevally active structures farther west (e.g. Puna Plateau) and east (frontal Andes) remain unclear. Discrepancies in the interpretation of Eocene–Oligocene strata preclude a coherent basin reconstruction. Jordan & Alonso (1987) proposed that a single sedimentary basin covered the Puna–Altiplano during the Eocene?–Oligocene. Similarly, Carrapa & DeCelles (2008) suggested that the upper Eocene Geste Formation within the Puna Plateau represents wedge-top deposition related to a larger foreland basin system propagating through the region at *ca*. 38 Ma. This scenario implies the existence of a foredeep to the east of the eastern Puna margin during the late Eocene, consistent with observations by Starck & Vergani (1996), Bosio *et al.* (2009), and Carrera & Muñoz (2008) suggesting that the upper Eocene to Oligocene Quebrada de los Colorados Formation in the Eastern Cordillera was deposited in a distal to proximal foredeep setting. Conversely, Hongn *et al.* (2007) suggested that *ca*. 38 Ma strata preserved in the Eastern Cordillera represent wedge-top deposits. The Angastaco area is ideally situated to address these seemingly conflicting interpretations because it contains a long-term stratigraphic record (Eocene–Pliocene) that was deposited in the transition zone between the Eastern Cordillera and the frontal Santa Barbara ranges. We present sedimentological, petrographic, and U-Pb geochronological data from the Pucará, Angastaco, Tin Tin and La Viña areas to determine their regional stratigraphic context and tectonic implications. The new data from this study form the basis for regional correlations with other Cenozoic deposits throughout the NW Argentina Andes and allow for an integrated interpretation of the entire Eocene–Pliocene succession in its evolving tectonic context (Jordan & Alonso, 1987; Hongn *et al.*, 2007; Carrapa & DeCelles, 2008; Bosio *et al.*, 2009).

GEOLOGICAL SETTING

The Andes Mountains of South America are the type example of a Cordilleran-type orogeny, with a north–south length of *ca*. 7000 km (Isacks, 1988; Montgomery *et al.*, 2001). Shortening and crustal thickening in the central Andes are the result of subduction of the Nazca plate beneath the South American plate (Isacks, 1988; Allmendinger *et al.*, 1997; Ramos, 2009). The orogen reaches its maximum width of *ca*. 800 km and highest average elevation of >3.5 km in the Central Andes (Isacks, 1988). This area of extensive high elevation, low internal relief and aridity is defined as the Central Andean Plateau (also the Puna–Altiplano Plateau, Fig. 1; e.g. Isacks, 1988; Allmendinger *et al.*, 1997). A retroarc foreland basin formed in response to crustal thickening and loading, which started during the Late Cretaceous–early Cenozoic to the west of the study area in Chile and the Argentine Puna (e.g. Jordan & Alonso, 1987; DeCelles & Horton, 2003; Arriagada *et al.*, 2006; Carrera & Muñoz, 2008; Carrapa *et al.*, 2009). These foreland basin deposits were deformed and uplifted as the Andes grew, and are now preserved within the Central Andean Plateau and in the Eastern Cordillera. Evidence of shortening and eastward migration of a regional foreland basin system from Paleocene through Pliocene time is available at 19°–22°S latitude in the Eastern Cordillera and Subandes of Bolivia (DeCelles & Horton, 2003; Uba *et al.*, 2006). However, farther south, in the Eastern Cordillera of NW Argentina, a lack of data hinders comparison with the Bolivian system. It thus remains unclear whether the NW Argentine Cenozoic strata accumulated in a regionally integrated foreland basin system (*sensu* DeCelles & Giles, 1996), or in more local depocenters that formed within the evolving Andean orogenic wedge. In turn, the depositional setting of the Cenozoic strata has major implications for the kinematic history of this part of the Andes.

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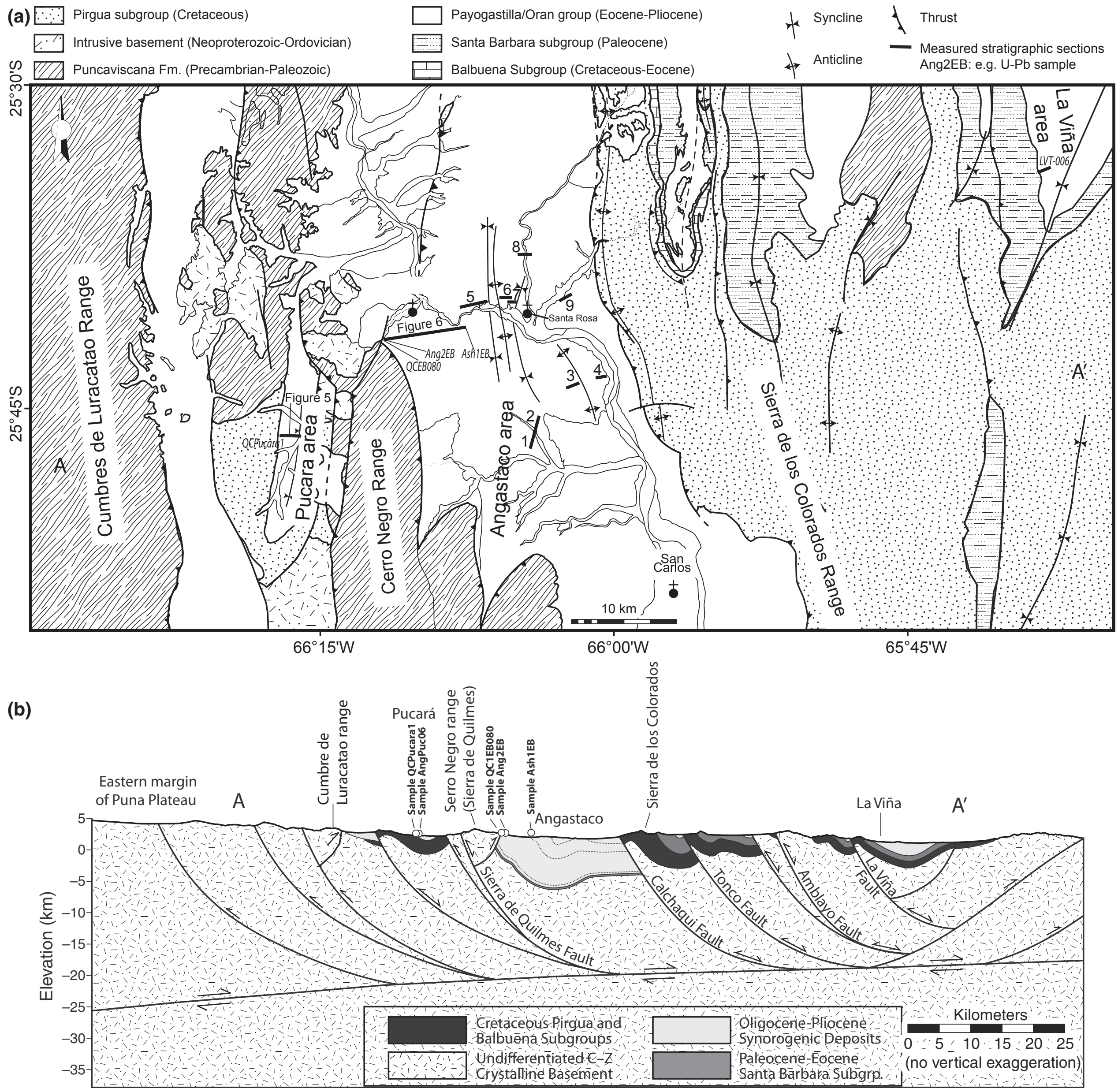

Fig. 2. (a) Simplified geological map of the Angastaco area modified after Coutand *et al.* (2006) with location of the measured stratigraphic sections in Fig. S1. (b) Simplified cross-section across the Pucará–Angastaco and La Viña areas (modified after Coutand *et al.*, 2006 and Carrapa *et al.*, 2011).

Sparse early Cenozoic synorogenic sedimentary rocks have been documented in the present-day Puna interior and along its margins (Jordan & Alonso, 1987; Starck & Vergani, 1996; Carrapa & DeCelles, 2008; Carrapa *et al.*, 2011; Fig. 1). Sedimentological and thermochronolgical data from the Salar de Pastos Grandes and Salar de Antofalla areas document the existence of Eocene–Oligocene alluvial fan deposits and rapid source terrane exhumation during the Eocene (*ca*. 39–34 Ma; DeCelles *et al.*, 2007; Carrapa & DeCelles, 2008; Carrapa *et al.*, 2011).

The study area lies at the transition zone between the Eastern Cordillera and the Sierras Pampeanas tectonomorphic domains and includes the Pucará, Angastaco–La Viña and south Tin Tin areas (Figs 1 and 2). The Angastaco and Pucará areas are bounded by high-angle reverse faults related to reactivated (inverted), eastward-dipping normal faults that formed in the Cretaceous Salta rift system (Sobel & Strecker, 2003; Mortimer *et al.*, 2007; Carrera *et al.*, 2006; Carrera & Muñoz, 2008). Faults generally dip towards the east due to inherited geometry; however, this does not seem to affect the regional eastward migration of deformation (Carrapa *et al.*, 2011), which is most likely controlled by a regional westward dipping mid-crustal detachment (Fig. 2b).

The Angastaco area was once part of the regional Andean foreland basin system that extended from west to east from the Puna Plateau interior to the Eastern Cordil-

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lera of northwestern Argentina and along strike from *ca*. 26°S to at least 20°S. Provenance, structural and low-temperature thermochronological data indicate that disruption of this regional foreland started in the study area at *ca*. 14 Ma with the uplift of the Cerro Negro Range to the west separating the Angastaco from the Pucará sub-basins (Coutand *et al.*, 2006; Carrera & Muñoz, 2008; Carrapa *et al.*, 2011). Deformation propagated eastwards from *ca*. 14 Ma to *ca*. 3 Ma progressively incorporating Angastaco foreland basin strata within the orogenic wedge (Carrapa *et al.*, 2011). The Cerro Negro Range is composed of Precambrian–Early Cambrian metasedimentary rocks of the Puncoviscana Formation (Turner & Mon, 1979), intruded by Cambrian and Ordovician granites (Carrera *et al.*, 2006), as well as red breccias, conglomerates, sandstones and shales of the Cretaceous Pirgua Subgroup of the Salta Group (e.g. Salfity & Marquillas, 1994). Today, the Cerro Negro is in thrust contact with the Cenozoic section to the east (Fig. 3). The Angastaco and La Viña areas are structurally separated by a west-verging reverse fault of the Sierra de los Colorados Range (e.g. Coutand *et al.*, 2006; Carrera & Muñoz, 2008). These areas are also thought to have been connected prior to uplift of the Sierra de los Colorados Range (e.g. Jordan & Alonso, 1987), as supported by recent apatite U/(Th-He) ages (Carrapa *et al.*, 2011). The Sierra de los Colorados Range is composed of the Cambrian–Precambrian Puncoviscana Formation, the Cretaceous Pirgua Subgroup, and Maastrichtian-lower Eocene Balbuena and Santa Bárbara Subgroups of the Salta Group (Marquillas *et al.*, 2005; Bosio *et al.*, 2009). The Balbuena Subgroup is composed of distinctive limestone and green shale (Marquillas *et al.*, 2005). The Salta Group is overlain by the Payogastilla Group, which consists of the Quebrada de los Colorados, Angastaco, Palo Pintado and San Felipe Formations (Figs 1b and 2) (Díaz & Malizzia, 1983). In the La Viña area to the east, the Payogastilla Group correlates with the Orán Group (Figs 1b and 2; e.g. Díaz & Malizzia, 1983; Starck & Vergani, 1996).

The 'Quebrada de los Colorados Formation' is well exposed in the Pucará area and in the Tin Tin area (Figs 1 and 4). The maximum depositional age of the Quebrada de los Colorados Formation is 37.6 ± 1.2 Ma in the Pucará area based on $^{206}Pb/^{238}U$ ages of detrital zircons (this study). The Quebrada de los Colorados Formation consists of red sandstones, siltstones and palaeosols interpreted to represent alluvial plain deposits (Fig. 5). The tectonic and stratigraphic relationships between the Quebrada de los Colorados Formation and the Angastaco Formation have not previously been described. In the Pucará area, the Quebrada de los Colorados Formation overlies Cretaceous Pirgua Subgroup in angular unconformity (Fig. 4). The Quebrada de los Colorados Formation in this region is tilted moderately towards the east and has a total thickness of *ca*. 400 m; it is overlain by the lower Angastaco Formation, which consists of aeolian and fluvial facies (Starck & Anzotegui, 2001). Farther north along strike from the Angastaco area (in the southern Tin Tin area; Fig. 1a), the Quebrada de los Colorados Formation crops out along the Rio Puerta Chica, northeast of the town of Seclantas (Fig. 1). Here, the Quebrada de los Colorados Formation is more than 500 m thick (see below), but its lower and upper contacts are not exposed. In the Angastaco area, a sliver of Quebrada de los Colorados Formation in the proximal footwall of the western basin-bounding fault is stratigraphically overlain by the aeolian facies of the lower Angastaco Formation. The latter is also strongly folded and faulted in proximity to the high-angle reverse fault that juxtaposes the Puncoviscana Formation against the Quebrada de los Colorados Formation (Fig. 3).

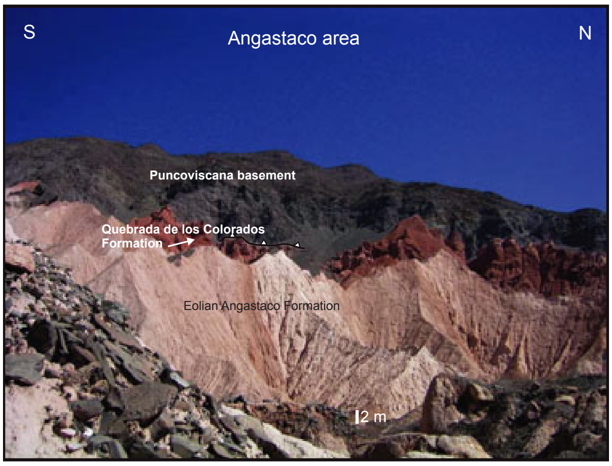

Fig. 3. Photograph of the thrust contact between the Puncoviscana basement rocks on the Quebrada de los Colorados Formation in the Angastaco area.

Fig. 4. Photograph of the unconformity between the Cretaceous Pirgua Subgroup and the Quebrada de los Colorados Formation in the Pucará area (e.g. 110/60° indicates dip direction and dip angle of strata). Sample QC Pucará 1 was collected at the base of the Quebrada de los Colorados Formation at this location for U-Pb geochronology.

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Fig. 5. Photographs of most common lithofacies within the Quebrada de los Colorados (a), Angastaco (b–d), Palo Pintado (e) and San Felipe (f) Formations.

The 'Angastaco Formation' (*ca*. 21 to *ca*. 9 Ma) overlies the Quebrada de los Colorados Formation in the study area and consists of *ca*. 3300 m of sandstone and conglomerate (Figs 5 and 6). This formation contains *ca*. 300 m of aeolian sandstone in its lower part (Starck & Vergani, 1996) followed by fluvial and alluvial conglomerate and sandstone (Fig. 7) (e.g. Díaz & Malizzia, 1983). The youngest U-Pb detrital zircon ages establish a maximum depositional age of this basal unit at 21.4 ± 0.7 Ma (this study). A biotite $^{40}Ar/^{39}Ar$ age of 13.4 ± 0.4 Ma was obtained by Grier & Dallmeyer (1990) from an ash within the lower fluvial deposits. An intraformational unconformity exists between the 21.4 ± 0.7 and 13.4 ± 0.4 Ma strata, suggesting local deformation during deposition of these units (Carrapa *et al.*, 2011). This Angastaco Formation is correlated with the Jesús María, Rio Seco and Anta Formations in the La Viña area (Fig. 2b). An ash within what has been interpreted to be the Anta Formation in the La Viña area has been dated at 14.5 ± 1.4 Ma by zircon fission-track (Reynolds *et al.*, 2000) and is supported by new zircon U-Pb ages from this study.

The 'Palo Pintado Formation' (*ca*. 9 to *ca*. 5 Ma) is gradational with the Angastaco Formation (Figs 5 and 6) and consists of *ca*. 2300 m of green mudrocks and tan sandstones previously interpreted as meandering stream and associated wetland deposits (Díaz & Malizzia, 1983; Díaz & Miserendino Fuentes, 1988). Palaeontological evidence suggests an age of 9 ± 1 Ma for the base of the formation (Marshall *et al.*, 1983). U-Pb ages of zircons from an ash within the upper Palo Pintado Formation average 5.27 ± 0.28 Ma (Coutand *et al.*, 2006). Based on fossil assemblages (Starck & Anzotegui, 2001) and stable isotope values of pedogenic carbonate nodules and rodent incisor enamel, this formation is interpreted to have been deposited under relatively more humid conditions with respect to the overlying San Felipe Formation, but still in a semi-arid climate (Bywater-Reyes *et al.*, 2010). This formation is correlated and was once contiguous with the Guanaco Formation in the La Viña area before the two

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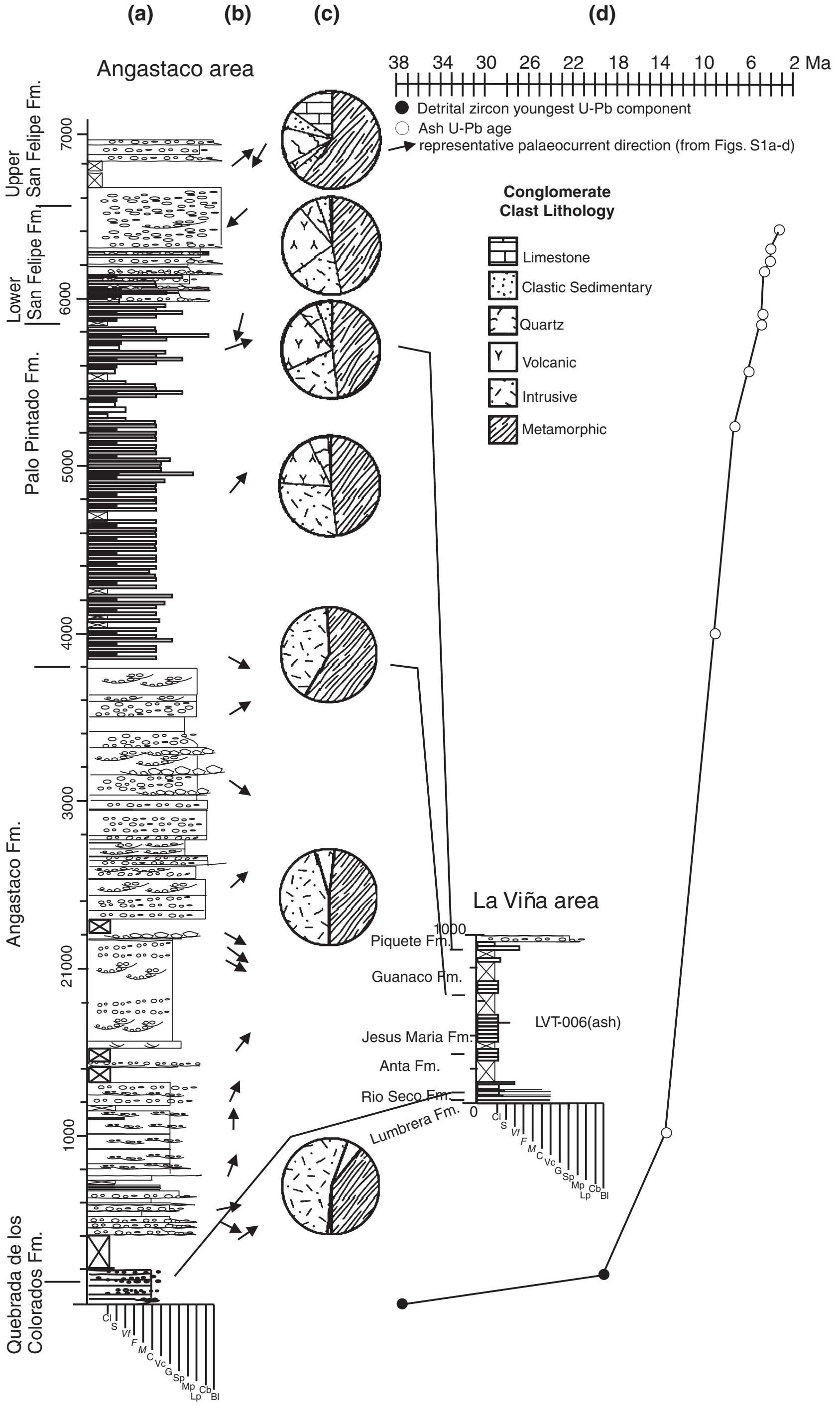

Fig. 6. Compiled stratigraphy for the Angastaco–Pucará–La Viña areas with average palaeocurrent directions, average conglomerate compositions (compiled from this study and Coutand *et al.* (2006)) and stratigraphic ages (compiled from this study, Bywater-Reyes *et al.* (2010), Grier & Dallmeyer (1990), and Marshall *et al.* (1983)). For more details on measured sections, refer to Fig. S1. For location, refer to Fig. 2a.

areas were separated by uplift of the Sierra de los Colorados at *ca.* 4 Ma (Bywater-Reyes *et al.*, 2010; Carrapa *et al.*, 2011); the Guanaco Formation has been dated at 8.73 ± 0.25 Ma by K/Ar on biotite from an ash (Del Papa *et al.*, 1993). An ash in the same formation to the northeast of La Viña area, near Coronel Moldes, was dated by zircon U-Pb geochronology at 9.31 ± 0.31 Ma (Hain *et al.*, 2011).

The 'San Felipe Formation' (*ca.* 5 to *ca.* 2 Ma) is gradational with the Palo Pintado Formation (Figs 5 and 6) and consists of *ca.* 800 m of cobble conglomerate and fining-upward sandstone units previously interpreted to be braided stream and distal alluvial fan deposits (Díaz & Malizzia, 1983; Díaz & Miserendino Fuentes, 1988). The upper part of the formation yields compositional evidence for unroofing of the eastern basin-bounding range (Starck & Vergani, 1996; Starck & Anzotegui, 2001; Coutand *et al.*, 2006; Bywater-Reyes *et al.*, 2010). This unroofing, from which uplift of the Sierra de los Colorados is inferred, has been dated at *ca.* 4 Ma based on palaeodrainage and provenance reorganization (Bywater-Reyes *et al.*, 2010) and is consistent with (U-Th)/He data and evidence of growth structures in the San Felipe Formation (Carrera & Muñoz, 2008; Carrapa *et al.*, 2011). The San

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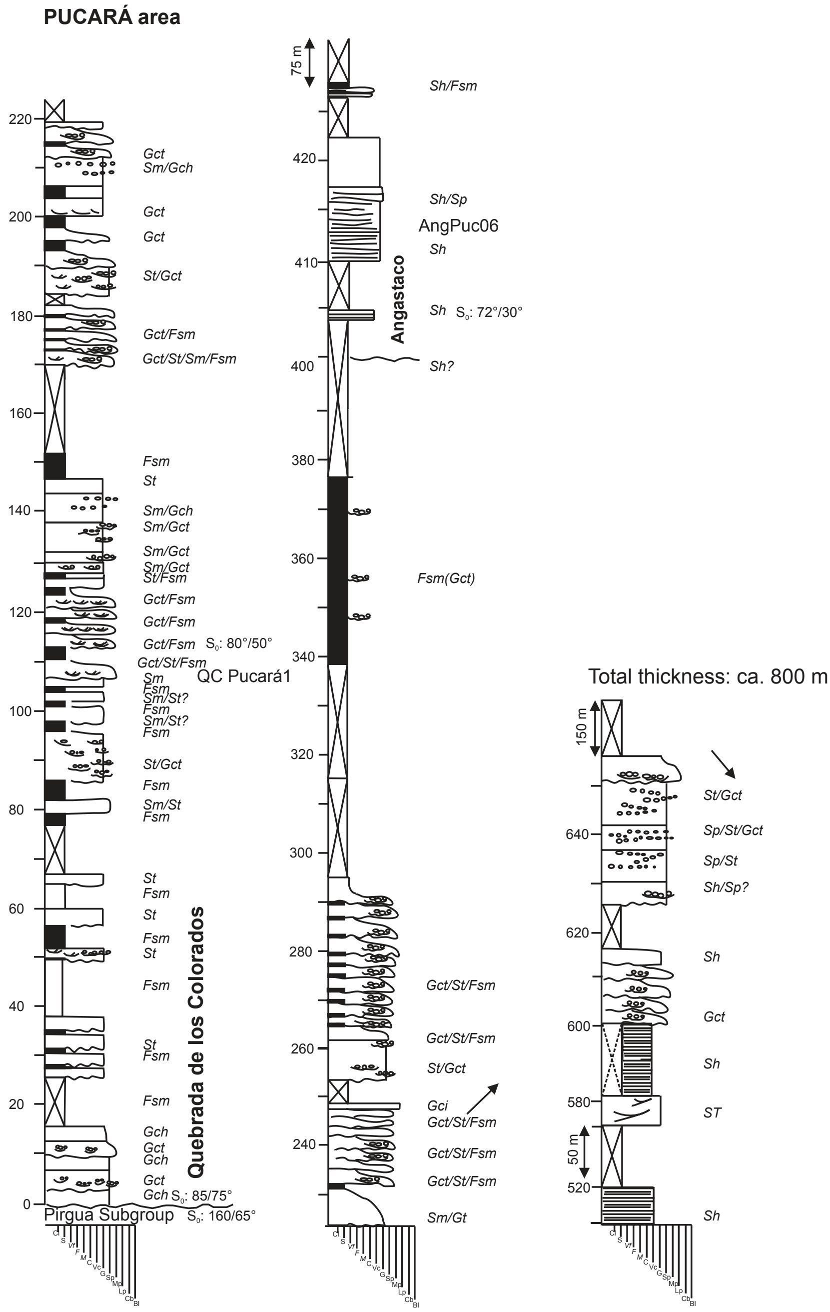

Fig. 7. Measured straigraphic sections within the Quebrada de los Colorados and Angastaco Formations in the Pucará area. For location, see Fig. 2a.

Felipe Formation is correlated with the Piquete Formation in the La Viña area, which has been dated at *ca.* 5 to *ca.* 2 Ma by magnetostratigraphy (Reynolds *et al.*, 2000).

SEDIMENTOLOGY AND PROVENANCE

Lithofacies descriptions and sedimentological interpretations are based on detailed centimetre to metre scale bed-by-bed measurements. Conglomerate provenance data were collected in the Quebrada de los Colorados, Palo Pintado and San Felipe Formations by counting 100 clasts at each location in the field using a regular grid spacing according to clast size. Previously published petrographic data from the Angastaco Formation (Coutand *et al.*, 2006) are used for comparison. Palaeocurrent directions were obtained by measuring imbrications (at least 10 per location) in conglomerates and limbs of trough cross-strata following method I of DeCelles *et al.* (1983). Interpretation of depositional environments is based on the newly acquired sedimentological data. Facies codes modified from Miall (1996) are adopted in the following for descriptive purposes (Table 1).

Pucará area

In the Pucará area, the Quebrada de los Colorados Formation rests in angular unconformity on top of a thick clastic succession of the Cretaceous Pirgua Subgroup (Fig. 4). Directly below the unconformity, the Pirgua consists of

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Table 1. Facies code explanation and interpretation used in this study based on Miall (1996)

Facies codes	Lithofacies	Sedimentary structures	Interpretation
Gmm	Conglomerate, matrix-supported	Structureless, disorganized	High-strength (cohesive) debris flow
Gcm	Conglomerate, clast-supported	Structureless to crude horizontal stratification, imbrication	Clast-rich (noncohesive) debris flow and sheetflood deposits
Gch	Conglomerate, Clast-supported	Horizontal stratification, local imbrication	Longitudinal gravel bars, lag deposits
Gct	Conglomerate, clast-supported	Trough and planar cross-beds	Minor channel fills, 3D gravelly bedforms
Gci	Conglomerate, clast-supported	Imbricated clasts	Channel fills and longitudinal bar deposits
Sm	Sandstone, fine- to coarse-grained	Massive or faint lamination	Hyperconcentrated flows, slurry flows
St	Sandstone, fine- to very coarse-grained, locally pebbly	Trough cross-beds	Subaqueous 3D dunes, sustained unidirectional currents
Sh	Sandstone, fine- to very coarse-grained, locally pebbly	Horizontal laminations/low-angle (<15°) cross-beds	Shallow supercritical flows
Fsm	Fine-grained sandstone, siltstone, mudstone	Massive, desiccation cracks	Overbank deposits, abandoned channel fills and drape deposits

ca. 15 m of parallel laminated, green, fine-grained sandstone that grades up-section into rippled red and white sandstone beds capped by siltstone units. In this area, the lower *ca*. 300 m of the Quebrada de los Colorado Formation is characterized by red, clast-supported, trough cross-stratified conglomerate (Gct), red trough cross-stratified sandstone (St), and massive, red sandy siltstone (Fsm) (Fig. 7). The coarser grained units have erosional basal surfaces and exhibit broadly lenticular geometry. The silty lithofacies commonly contain evidence for pedogenesis (peds, rootlets, mottling, absence of stratification). These facies are interpreted as fluvial channel and overbank deposits. The up-section increase of cross-stratified and imbricated conglomerate and trough cross-stratified sandstone suggests an increasingly channelized depositional system. From the *ca*. 290 to 400 m levels of the section, red mudstone is the dominant lithology. These rocks are poorly exposed, but where outcrops are present, the lithofacies include Fsm and local accumulations of pebbly conglomerate suggesting overbank deposits and minor channels.

The fluvial deposits of the Quebrada de los Colorado Formation are overlain by *ca*. 220 m of white sandstone (Fig. 7) containing abundant frosted grains. This unit is dominated by fine- to medium-grained sandstone containing rhythmic, laterally continuous, centimetre-scale parallel lamination (Sh). Up-section, medium- to coarse-grained, large-scale (*ca*. 5 m thick) planar cross-stratified (Sp) white sandstone beds follow. We interpret the rhythmically laminated sandstones as the deposits of climbing aeolian ripples; surfaces separating laminations are probably climbing translatent surfaces produced by the migration of aeolian ripples at a low angle of climb (Hunter, 1977; Rubin & Hunter, 1982). The large-scale planar cross-stratified sandstone units are interpreted as aeolian dune deposits (Kocurek, 1981). Following Starck & Vergani (1996), we consider this distinctive unit to be the lower part of the Angastaco Formation.

The aeolian facies of the Angastaco Formation is overlain by *ca*. 350 m of massive (Sm), horizontally laminated (Sh), planar cross-stratified (Sp) and trough cross-stratified (St) coarse-grained to pebbly, grey, pink and white sandstone. Up-section, these sandy facies become coarser grained and eventually are replaced by grey, clast-supported, horizontally stratified and trough cross-stratified (Gct) conglomerates and sandstones (St, Sh), which show slightly lenticular bedding. Finer grained material is generally absent. We interpret these facies as the deposits of laterally unstable shallow gravelly channels, perhaps in a braided fluvial system (e.g. Miall, 1996).

Angastaco area

In the Angastaco area, the section starts with *ca*. 150 m of Quebrada de los Colorado Formation in thrust contact with the structurally overlying metamorphic basement rocks (Fig. 3); *ca*. 50 m of rhythmic facies of the lower Angastaco Formation follow. We did not measure a detailed section in the first *ca*. 200 m of the succession near this contact because the rocks are highly deformed with mesoscale structures related to the main fault. However, we describe the facies below. Detailed measurements were conducted in the less deformed part of the overlying Angastaco Formation (Figs 8 and S1).

The Quebrada de los Colorados Formation at this location is characterized by alternating red siltstone and massive sandstone (Sm) for the first *ca*. 50 m, transitioning upwards into trough cross-stratified and horizontally laminated sandstone intercalated with siltstone (Fig. 8). The base of the Angastaco Formation is identified by a change to thick varicoloured sandstone beds that grade into white-grey conglomerate and coarse-grained sandstone (Fig. 5). The first few tens of metres (below the base of the measured section in Fig. 8) of this facies is made of well-sorted and well-rounded, fine- to coarse-grained white and red sandstone with abundant frosted grains, locally intercalated with siltstone (Fig. 5). The dominant

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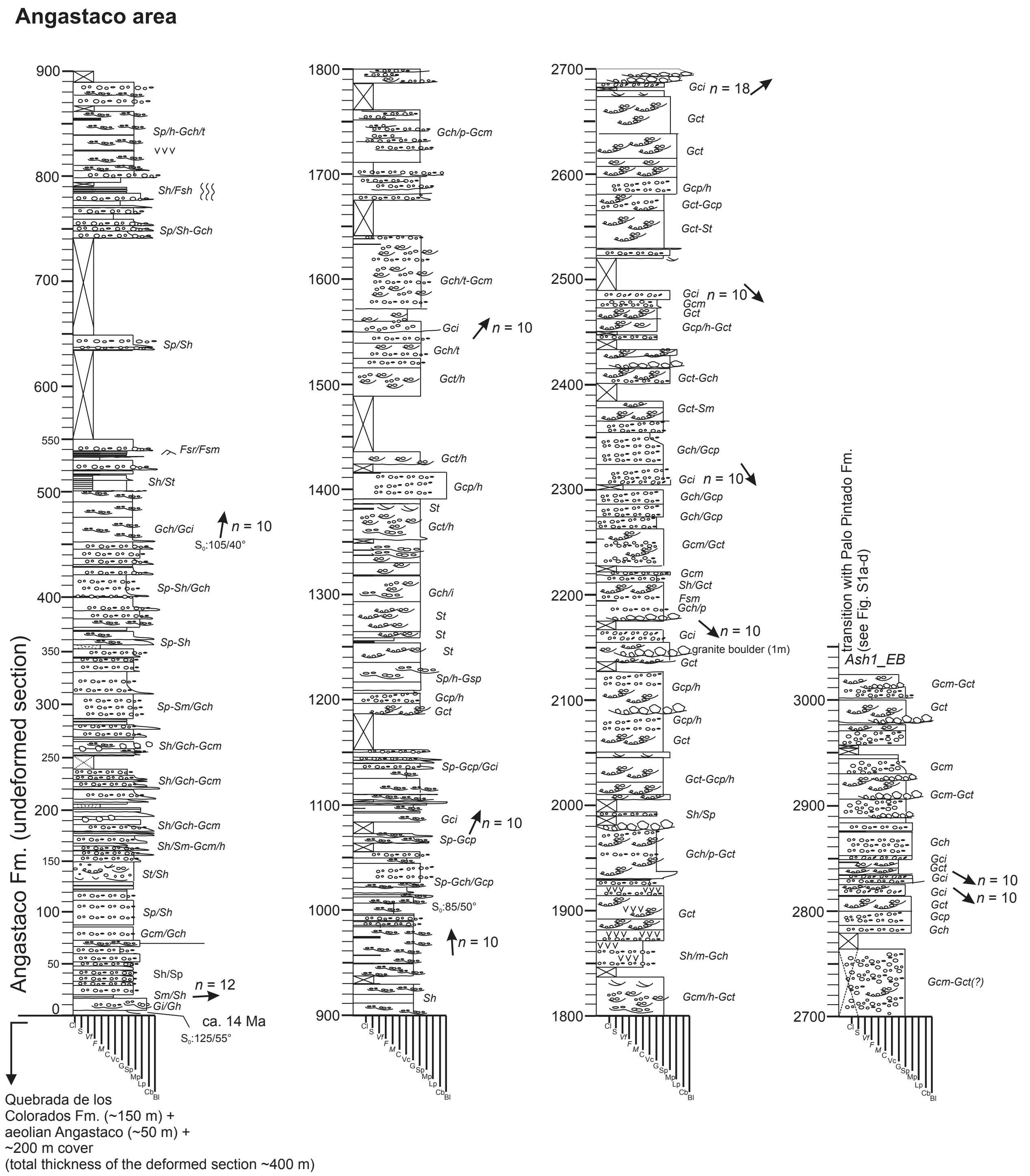

Fig. 8. Measured stratigraphic section of the undeformed Angastaco Formation in the Angastaco area.

sedimentary structure in this facies is rhythmically laminated sandstone (Sh), similar to the lower Angastaco Formation in the Pucará area on the western side of Cerro Negro Range (Fig. 2). As in the Pucará area, we interpret the lower part of the Angastaco Formation in the Angastaco area as aeolian deposits (e.g. Kocurek, 1981).

This deformed part of the section (*ca.* 200 m) is separated by *ca.* 200 m of covered interval from the homoclinally eastward-dipping bulk of the Angastaco Formation. From this point upwards, the Angastaco Formation exhibits a general coarsening and thickening trend (Figs 6 and S1). Beds of horizontally (Sh) and planar cross-stratified sandstone (Sp), imbricated and horizontally stratified conglomerate (Gci, Gch), and intercalated thin siltstone and very fine-grained sandstone give way up-section to mainly horizontally stratified (Gch) (Fig. 5c) and massive (Gcm), poorly organized conglomerate beds. Individual sandstone and conglomerate bodies have planar to broadly irregular

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erosional lower surfaces, and locally fine crudely upwards. In addition to these coarse-grained lithofacies, the lower 1000 m of the Angastaco section contains intercalated beds of well-sorted and well-rounded, light-coloured sandstone with abundant frosted grains similar to the aeolian lithofacies described above. Upwards from about the 1400 m level of the measured section (Fig. 8), the Angastaco Formation is dominated by coarse- to very coarse-grained sandstone and thickly bedded conglomerate (Fig. 5d). Common lithofacies include clast-supported massive (Gcm), cross-stratified (Gcp, Gct) and horizontally stratified (Gch) conglomerate; and massive and horizontally stratified sandstone (Sm, Sh). Conglomerates are composed of pebble- to cobble-sized clasts, with local lenticular accumulations of coarser conglomerate (10–20 cm cobbles). Boulder beds, with clasts >1 m in long dimension, become increasingly abundant up-section above the 1950 m level (Fig. 8). Many beds have erosional basal surfaces, and grade crudely upwards to massive, silty sandstone caps (Sm). Bedding in the upper part of the formation is up to 7 m thick, but many units are amalgamated into multistory intervals with no clear textural breaks.

The assemblage of lithofacies in the Angastaco Formation (Gcm, Gct, Gct, St, Sp, Sh, Sm) is typical of coarse-grained, proximal fluvial systems. The general absence of matrix-supported disorganized conglomerate, coupled with the imbricated conglomerate fabrics and abundance of broadly lenticular bedding and erosional basal surfaces, suggests deposition in shallow, laterally unstable braided channels (Hein & Walker, 1977; Cant & Walker, 1978; Nemec and Postma, 1993; Miall, 1996). The crude upward fining textural trends in many beds may have resulted from filling and abandonment of braided anabranch channels (Miall, 1996). Imbricated, horizontally stratified conglomerates are typical of longitudinal mid-channel bar deposits (Miall, 1996). Local finer grained accumulations represent waning-stage sediment fallout. The trough cross-stratified conglomerates and sandstones were deposited by large subaqueous dunes (or large 3D ripples) in fast-flowing confined channels. These braided stream deposits could have accumulated in braidplain or stream-dominated alluvial fan environments (Ori, 1982; Ridgway & DeCelles, 1993).

Overlying the Angastaco Formation in gradational contact, the first *ca*. 200 m of the Palo Pintado Formation consists of tan-coloured medium-grained sandstone beds with trough cross-stratification fining upwards to fine-grained sandstone with asymmetrical ripples (Figs 5 and S1a-d). These sandstone bodies usually have a lenticular geometry. Subrounded pebble-sized lag deposits are present, but less abundant. Above the *ca*. 620 m level, finer grained deposits increase and sandstones become more amalgamated. Above the *ca*. 900 m level, sandstone beds are isolated and laminated mudrocks comprise *ca*. 1/3 of the succession (Fig. 5e). The next *ca*. 1400 m of the formation is predominantly fine-grained with dispersed trough cross-stratified and rippled sandstone beds. Mudrocks are mainly green or red with parallel or ripple lamination.

The first *ca*. 200 m of the Palo Pintado Formation is best explained by the point-bar meandering stream model of Allen (1963) (Figs 6 and S1a–d). The scoured bases of the coarser grained sandstone units, followed upwards by trough cross-stratified, rippled, and horizontally laminated sandstone and siltstone represent classic upward fining point-bar deposits in laterally migrating meandering rivers. The finer grained, tabular sandstone beds associated with these lenticular channel deposits may have accumulated in small crevasse-splay deltas (Allen, 1970; Tye & Coleman, 1989).

Above the *ca*. 620 m level (Fig. S1a), the amalgamated sandstone beds are interpreted to represent stacked point-bar deposits with larger amounts of floodplain, crevasse-splay, and lacustrine deposits similar to those described by Miall (1996). Above *ca*. 900 m (Fig. S1c), finer grained siliciclastic mudrocks become even more abundant and after *ca*. 1400 m, they dominate the strata. These finer grained strata consist of horizontally laminated and rippled green and grey siltstone. Rippled, very fine-grained sandstone to siltstone units are interbedded within this overall mudrock-dominated section. The laminated mudrocks are interpreted as shallow lacustrine deposits, which accumulated in proximity to marginal lacustrine deltas (Starck & Vergani, 1996; Bywater-Reyes *et al.*, 2010). Russo (1948) reported mammal (*Pleurolestodon avitus*) and bivalve (*Diplodon* and *Corbicula*) fossils in the Palo Pintado Formation and Bywater-Reyes *et al.* (2010) found fossil rodent incisors. Overall, we interpret the lithofacies of the lower portion (first *ca*. 900 m) of the Palo Pintado Formation to represent a meandering stream system that eventually was inundated by lacustrine waters during deposition of the upper portion of the formation (above *ca*. 900 m).

The Pliocene San Felipe Formation (Figs 6 and S1d) rests gradationally on top of the Palo Pintado Formation. The San Felipe Formation consists of crudely imbricated, horizontally stratified, sub-rounded, clast-supported, pebble- and cobble conglomerates (Fig. 5f). Locally, medium-grained trough cross-stratified sandstone and green laminated siltstone beds are interbedded with the coarser grained lithofacies. In the upper part of the section, it is not uncommon for conglomerate units to be >10 m thick, composed of several amalgamated beds. Maximum clast size is 10–12 cm. The uppermost portion of the San Felipe Formation (Fig. S1) contains beds of finer grained, matrix- and clast-supported, pebble conglomerate that is locally stained red. This lithofacies is interbedded with the typical coarser grained, horizontally stratified, imbricated conglomerate of the remaining San Felipe Formation. The predominance of crudely horizontally bedded coarse-grained sandstones and imbricated conglomerates (Fig. 5f) is best explained as the deposits of a gravelly braided fluvial system (Stanistreet & McCarthy, 1993; Miall, 1996).

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Tin Tin area

Along the southeastern flank of the Tin Tin anticline (southern Tin Tin area; Figs 1 and 9), we measured a 650-m-thick section, which contains a partial exposure of the Quebrada de los Colorados Formation. The Quebrada de los Colorados Formation in this area is mainly characterized by red to pale pink, trough cross-stratified pebbly conglomerate (Gcp, Gct) with occasional massive (Gcm), horizontally stratified (Gch) and low-angle stratified conglomerates. The conglomerate beds often have erosional bases. Beds of medium- to fine-grained trough and planar cross-stratified sandstone (St, Sp) and massive to laminated siltstone layers (Fsm), commonly containing floating pebbles, are intercalated within the conglomerate beds.

The conglomeratic portion of the Quebrada de los Colorados Formation in the Tin Tin area is similar to, but thicker than, the Quebrada de los Colorados Formation in the Angastaco and Pucará areas. Accordingly, we interpret it as the deposits of gravelly braided streams.

La Viña area

Along the road between Salta and Cafayate, we measured a *ca*. 1000 m section of the Oran Group and Metán

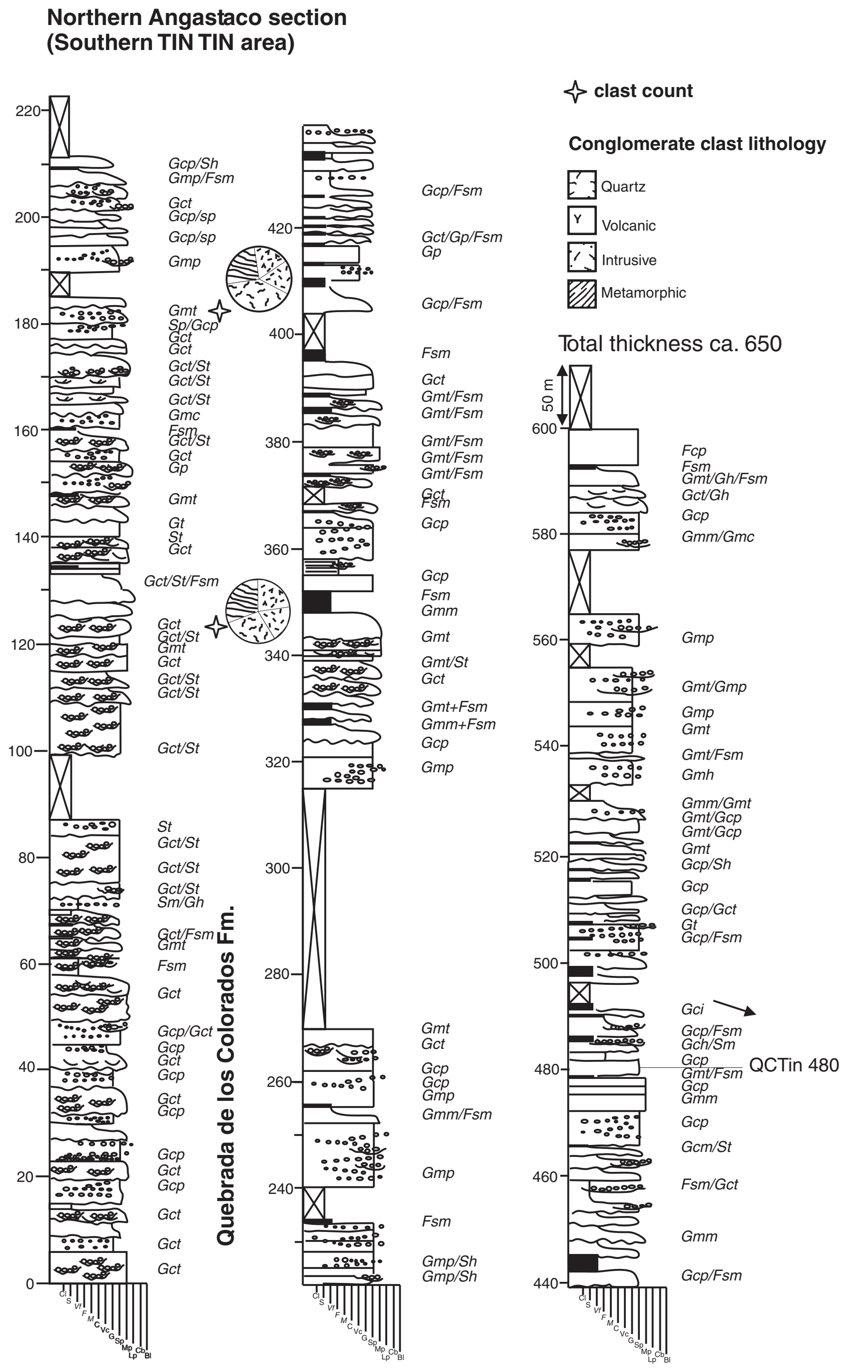

Fig. 9. Measured stratigraphic section of part of the Quebrada de los Colorados Formation in the Angastaco–Pucará area, in the southern Tin Tin area (east of the town of Seclantas). For location, refer to Fig. 1.

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Subgroup (Fig. 6). The section starts north of Alemanía (Table S4), just above the contact between the Lumbrera Formation and the overlying Rio Seco Formation (Fig. 1c). The Rio Seco Formation is *ca*. 50 m thick and is composed of well-sorted quartzose white to purple sandstone interbedded with fine- to medium- grained, horizontally laminated to trough cross-stratified sandstone. A 5-m-thick bed of well-rounded, well-sorted coarse-grained sandstone within the middle of this formation is interpreted to represent aeolian deposits. A 5-m thick interval of grey carbonaceous siltstone marks what we think is the contact between the Rio Seco and Anta Formations.

The Anta Formation transitions into what we interpret to represent the Jesús María Formation based on characteristic lithofacies. This formation is composed of *ca*. 250 m of laminated and rippled brick-red mudstone. Ash LVT-006 was collected within the green mudstone (Fig. 6). These units are interpreted to represent lacustrine deposition. The upper 100 m of the Jesús María Formation is covered. Above the covered section, *ca*. 280 m of red, tan, and brown silty mudstone and well-sorted, angular, quartzose, trough cross-stratified sandstone beds follow. These units are interpreted to represent the Guanaco Formation. The Guanaco Formation is overlain by tan siltstone, sandstone and cobble conglomerates of the Piquete Formation, which only partially crops out in the study area. Overall, these deposits are interpreted to represent fluvio-lacustrine deposition and the distal, condensed, equivalent of the Angastaco and Palo Pintado Formations.

SEDIMENT PROVENANCE

Sandstone point-count data

Medium-grained sandstones were collected along the measured stratigraphic sections for standard modal petrographic point-counting (Fig. 10). Thin sections were stained for K-feldspars and calcium plagioclase using standard methods. Point-count modal analyses were conducted following the Gazzi–Dickinson method by counting at least 300 framework grains per thin section and *ca*. 100 lithic grains when possible (Gazzi, 1966; Dickinson, 1970; Ingersoll *et al.*, 1984; Table S1). Nine sandstone samples from the Palo Pintado Formation, six from the lower San Felipe Formation, five from the upper San Felipe Formation, two from the Rio Seco Formation, one from the Anta Formation, two from the Guanaco Formation and one from the Piquete Formation were analysed for a total of 26 samples. Our results and those from Coutand *et al.* (2006) from Angastaco Formation

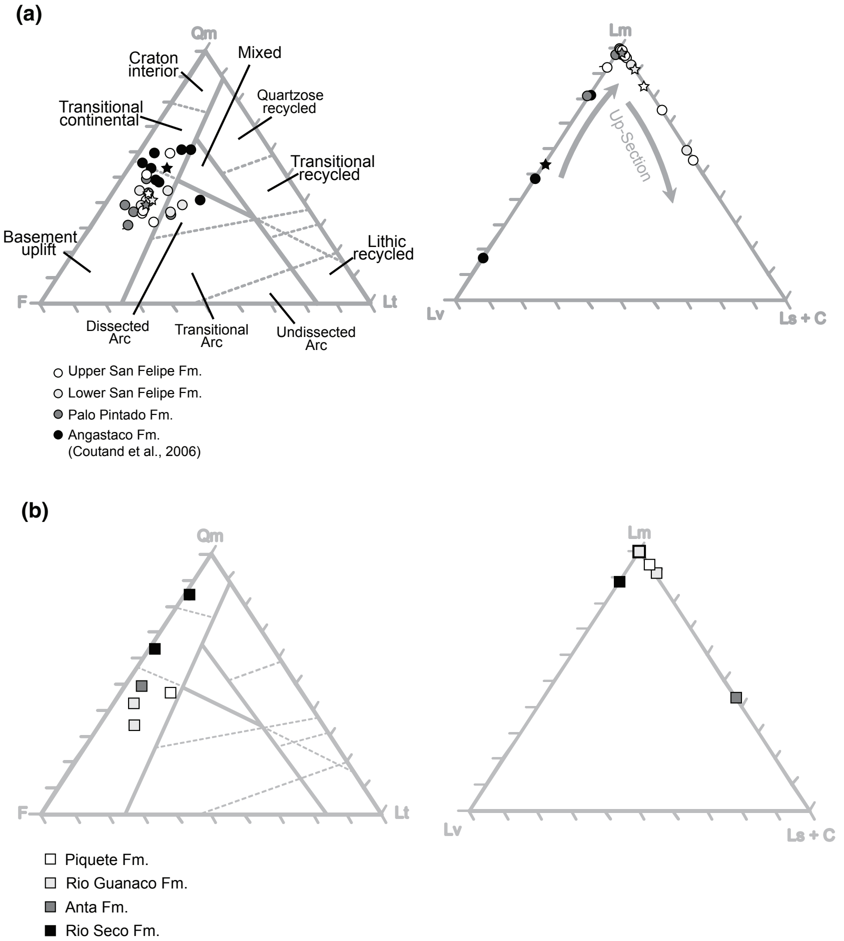

Fig. 10. (a) Sandstone petrographic data from the Angastaco, Palo Pintado and San Felipe Formations in the Angastaco area. (b) Sandstone petrographic data from the Anta, Jesús María and Piquete Formations in the La Viña area. See text for details. Fields after Dickinson *et al.* (1983).

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samples are plotted on standard ternary diagrams in Fig. 10.

Angastaco area

The average QmFLt modes of the Palo Pintado and San Felipe Formations are not significantly different (Fig. 10a). However, Palo Pintado Formation sandstones plot in the basement-uplift provenance field, whereas the San Felipe Formation sandstones have a wider range, with samples plotting in the unroofed arc (AT3-7; AT3-8; lower San Felipe Formation) and recycled orogen (AT6-8; upper San Felipe Formation) fields in addition to the basement-uplift field (Fig. 10a). The LmLv(Ls + C) ternary diagram (Fig. 10b) documents a decrease in Lv and increase in Lm in the Palo Pintado Formation and a decrease in Lm and increase in Ls + C in the San Felipe Formation. Note that the first appearance of limestone grains (derived from eastward sources) occurs in the upper San Felipe Formation (Bywater-Reyes *et al.*, 2010).

Interpretation

Sandstone samples from both the Palo Pintado and San Felipe Formations plot in the basement-uplift provenance field, consistent with derivation from thick-skinned basement uplifts of the Eastern Cordillera involving metasedimentary and igneous rocks. When these data are compared with data from the Angastaco Formation (Coutand *et al.*, 2006), it is clear that, on average, the Angastaco Formation is more quartz-rich (Fig. 10a). The compositional difference between the Angastaco Formation and the younger formations is interpreted as being the result of exhumation of the Cerro Negro Range, which is composed predominantly of fine-grained, low-grade metasedimentary rocks of the Puncoviscana Formation, during Angastaco Formation deposition (Coutand *et al.*, 2006). This range now separates the Angastaco area from the Pucará area to west, the latter of which has been uplifted and eroded since *ca*. 14 Ma (Coutand *et al.*, 2006; Carrapa *et al.*, 2011). Rocks that were originally deposited in the Pucará area, as well as strata that might have once covered the Cerro Negro Range and the basement rocks of the range (Puncoviscana Formation and associated Ordovician intrusive rocks), are possible sources for the Angastaco Formation sandstones. The increase in feldspar content in the Palo Pintado Formation as compared with the Angastaco Formation may reflect first-cycle sources in Orodvician granitic rocks of the Cerro Negro Range and/or recycling from feldspathic sandstones in the Pirgua Subgroup.

The LmLv(Ls + C) trends (Fig. 10a) are consistent with data presented by Coutand *et al.* (2006) showing a decreasing proportion of Lv and increasing Lm from the Angastaco Formation to Palo Pintado Formation. The increasing proportion of (Ls + C) for the upper part of the San Felipe Formation is consistent with conglomerate clast-count data and palaeocurrent data (next section) and with the interpretation that a new eastern source was present at *ca*. 4 Ma (Bywater-Reyes *et al.*, 2010; Carrapa *et al.*, 2011).

La Viña area

The lowest sandstone sample, LT1-1 of the Rio Seco Formation plots in the transitional continental field on the QmFLt ternary diagram (Fig. 10b). Sample LT1-2, collected from an aeolian sandstone, plots within the craton interior field. All other samples, collected from the Anta, Guanaco and Piquete Formations plot within the basement-uplift provenance field. The lithic populations of Rio Seco Formation sandstones are dominated by Lm, with subordinate Lv (Fig. 10b). The single sandstone from the Anta Formation contains subequal amounts of Lm and (Ls + C), whereas samples from the Guanaco and Piquete Formations are dominated by Lm fragments.

Interpretation

The QmFLt compositions of Miocene strata in the La Viña and Angastaco areas are remarkably similar, supporting the interpretation of Starck & Vergani (1996) that the these strata were contiguous between these two areas during deposition, with deposits in the La Viña area representing the distal counterparts of Angastaco area deposits. On the other hand, different modal compositions of the Piquete Formation (La Viña area) and the upper San Felipe Formation (Angastaco area) support conglomerate compositional data and the interpretation that the Sierra de los Colorados had begun to develop as a significant topographic high by *ca*. 4 Ma (see also Bywater-Reyes *et al.*, 2010). The lithic fractions also exhibit similar trends up-section, with Lm and Lv grains abundant in lower Miocene rocks (Rio Seco and Angastaco Formations), and Lm and (Ls + C) increasing in the upper Miocene–Pliocene. Normalized LmLv(Ls + C) data from the Angastaco and La Viña areas overlap almost completely, with the exception of a single sample of the Anta Formation, which contains much more (Ls + C) than the correlative Palo Pintado Formation.

Conglomerate clast-count data

The lithologies in potential source areas are well documented for the study region. Southwestern and western sources consist mainly of Neoproterozoic and lower Palaeozoic phyllites and quartzites intruded by Cambrian and Ordovician granites, whereas limestones are only found in eastern sources. The Puna interior is characterized by abundant Neogene volcanic rocks.

The Quebrada de los Colorados Formation contains abundant quartzite and volcanic clasts, which are typical lithologies of Ordovician sedimentary and igneous rocks in the Puna (Fig. 9; Carrapa & DeCelles, 2008), suggesting a drainage extending from the Angastaco region into

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the Puna interior. The presence of granitic clasts in the Quebrada de los Colorados Formation conglomerates, together with the relatively coarse grain size (average pebble size), is also consistent with nearby sources in plutonic rocks in the Cumbres de Luracatao Range to the west, which was possibly an area of significant remnant palaeotopography along the western margin of the Salta rift. Therefore, we interpret the overall composition of the Quebrada de los Colorados Formation conglomerates in the Tin Tin area as the result of erosion of rocks typical of both Puna and Eastern Cordillera areas.

Conglomerate clast compositions for three localities in the Palo Pintado Formation, 14 in the lower San Felipe Formation, and 10 in the upper San Felipe Formation, were also determined (section 9 in Fig. 1a and S1a–d). Overall, low-grade metamorphic and siliciclastic clast types increase up-section, and limestone clasts, which must have been derived from an easterly source, first appear in the upper San Felipe Formation (Figs S1a–d).

PALAEOCURRENT DATA

Palaeoflow directions were determined by measuring the orientations of ripples, imbricated conglomerate clasts and limbs of trough cross-stratification (e.g. DeCelles *et al.*, 1983) at 11 locations in the Angastaco Formation, 10 localities within the Palo Pintado Formation, 10 within the lower San Felipe Formation, and 13 within the upper San Felipe Formation (Figs 6 and S1). Overall, palaeoflow indicators show directions mainly towards the north and east–southeast for the Angastaco Formation (Fig. 6), north-northeast for the Palo Pintado Formation, east–northeast for the lower San Felipe Formation and towards west–southwest for the upper San Felipe Formation.

These data document a change in palaeodrainage organization through time, consistent with the results of the provenance analysis. During deposition of the Angastaco, Palo Pintado and lower San Felipe Formations, drainage was mainly transversal to axial, flowing generally towards the east and northeast. During deposition of the upper San Felipe Formation, the drainage pattern changed to predominantly westward flow (Fig. 6). This is consistent with the interpretation that the eastern basin-bounding range, the Sierra de los Colorados, became a sediment source for the basin at *ca.* 4 Ma (Bywater-Reyes *et al.*, 2010), reversing the regional drainage pattern and isolating the Angastaco and La Viña areas from each other. The axial nature of the drainage during deposition of the Palo Pintado Formation suggests concentrated subsidence parallel to the western basement ranges (Eastern Cordilleran ranges). This is also consistent with the Angastaco and Palo Pintado Formations representing deposition within a wedge-top basin. By the time of deposition of the upper San Felipe Formation (*ca.* 4 Ma), the Angastaco area was structurally isolated from the regional foreland basin by the Sierra de los Colorados to the east.

U-PB DETRITAL GEOCHRONOLOGY

Zircon U-Pb geochronology applied to detrital sedimentary rocks can provide information on provenance and maximum stratigraphic age of the zircon-hosting strata (e.g. DeCelles *et al.*, 2007; Gehrels *et al.*, 2009; Dickinson & Gehrels, 2009). U-Pb geochronological analyses were conducted by laser ablation-multicollector-inductively coupled plasma mass spectrometry (LA-MC-ICPMS) at the University of Arizona LaserChron Center. Details of analytical procedures, standards and data analysis are provided by Gehrels *et al.* (2006, 2008). As we were particularly interested in obtaining ages from the youngest detrital zircons (which provide a maximum depositional age) in these samples, the first 25–30 analyses are targeted specifically towards morphologically young-looking grains (fresh, euhedral crystals). The subsequent 75–100 analyses are from randomly chosen grains. Three samples from the Quebrada de los Colorados Formation and three samples from the Angastaco Formation (Fig. 11) were analysed to determine sample provenance and maximum depositional ages of the samples. A total of 588 U-Pb ages are reported in Table S2.

Quebrada de los Colorados Formation

Sample QC Pucará1 was collected from the Quebrada de los Colorados Formation *ca.* 110 m above its basal contact with the underlying Pirgua Subgroup in the Pucará area (Figs 2b and 7; Table S2). This sample produced detrital ages mainly in the 500–650, 1000–1200 and 1600–2400 Ma ranges. The dominant cluster of ages is in the 500–650 Ma range. No Mesozoic–Cenozoic grains were found (Fig. 11).

Sample QCEB080 (Fig. 2b, Table S2) was collected at the fault contact between the basement and the Quebrada de los Colorados Formation in the Angastaco area, *ca.* 150 m below the base of the Angastaco Formation. This sample contains a cluster of young ages at *ca.* 37.6 ± 2 Ma, which provides a maximum depositional age for the formation at this location. A similar age was obtained for the Geste Formation in the Puna Plateau (DeCelles *et al.*, 2007). Other ages are consistent with sample QC Pucará 1 (Fig. 9) and typical of Ordovician bedrock sources (DeCelles *et al.*, 2007).

A sample of the Quebrada de los Colorados Formation was collected and analysed at the 480-m level (QCTin480) in the southern Tin Tin area (Fig. 2b, Table S2). This sample produced ages mainly around 475–628 Ma and small numbers of younger (*ca.* 290 Ma) and older ages (*ca.* 1000, 1400, 2900 Ma). No Cenozoic ages were recorded in this sample. Overall, samples from the Quebrada de los Colorados Formation exhibit U-Pb ages that are typical of Ordovician igneous (granitoid) and sedimentary source terranes, including major components of Cambrian–early Ordovician grains, late Neoproterozoic grains and Grenville–Sunsas age grains (Fig. 11).

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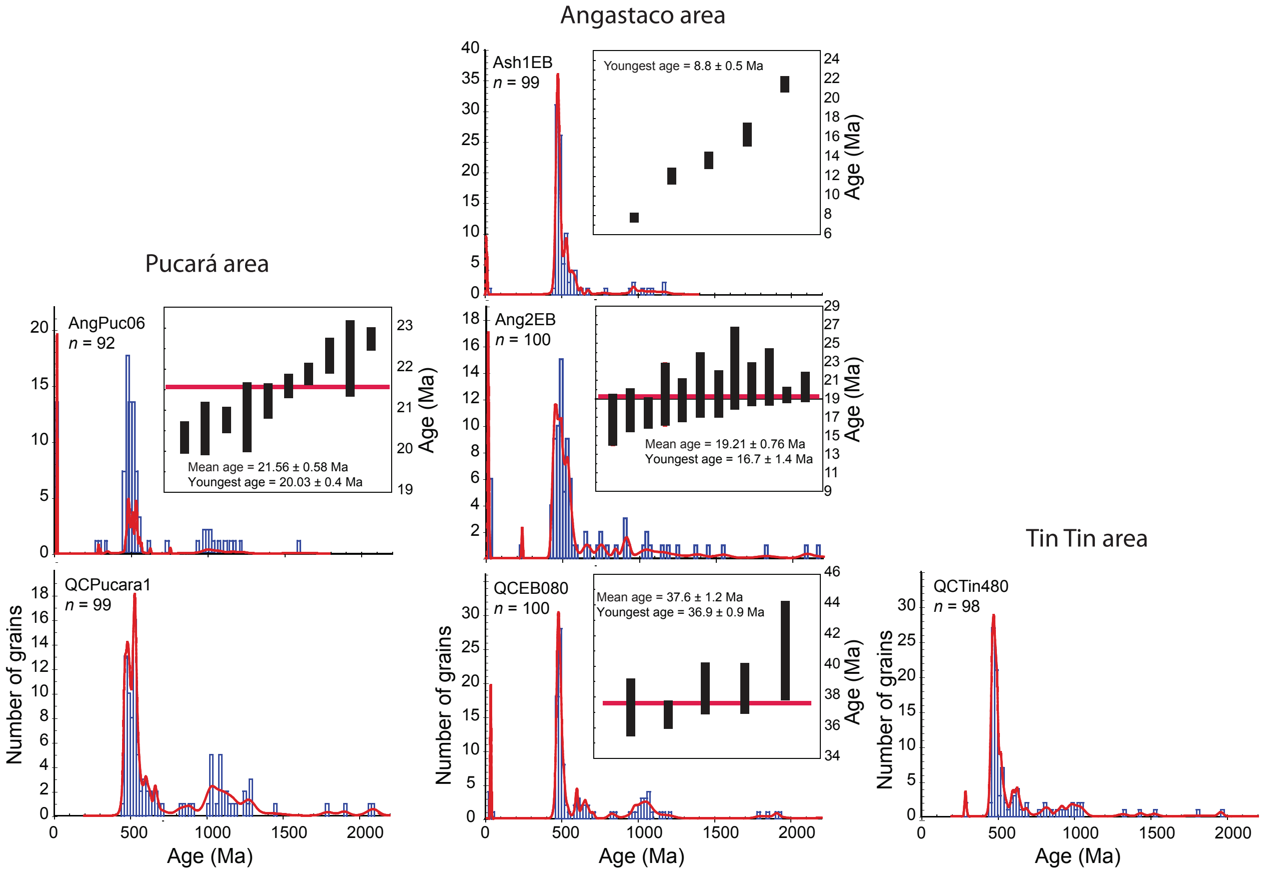

Fig. 11. Detrital zircon U-Pb ages of the Quebrada de los Colorados and Angastaco Formation samples; for location, refer to Figs 1, 2 and Table S4.

Angastaco Formation

The Angastaco Formation has been previously loosely dated by mammal fossils and geo-thermochronology (e.g. Coutand *et al.*, 2006 and references therein). However, the age of the lowest part of the section (the aeolian facies) in both the Angastaco and Pucará areas has never been determined.

We collected two samples from the Angastaco area and one from the Pucará area for detrital zircon U-Pb geochronology (Table S2). The sample from the Pucará area is from the aeolian facies (AngPuc06), at *ca*. 415 m (Figs 2b and 7); and samples from the Angastaco area are from the base of the deformed section (Ang2EB; Fig. 2b) and near the top, at the transition into the Palo Pintado Formation (Ash1EB) (Figs 2b and 8).

Sample AngPuc06 is a sandstone that yielded a cluster of young ages (eight grains) with a weighted mean of 21.4 ± 0.7 Ma (Fig. 11). Older detrital zircon ages are clustered around 400–500, 1000–1200 and 1200–1700 Ma. Sample Ang2EB is a sandstone that yielded a cluster of young ages (12 grains) with a weighted mean of 19.2 ± 0.76 Ma. Older detrital zircon ages from this sample are mainly Cambrian–Ordovician, with a few scattered ages in the 600–2600 Ma range. Sample Ash1EB from an impure (reworked) ash was collected from the fluvial facies of the Angastaco Formation at the transition with the Palo Pintado Formation; this sample yielded a cluster of young ages with a mean of 13.2 ± 6.8 and a youngest age of 8.8 ± 0.5 Ma. Although we do not ascribe statistical significance to this single age determination, it is consistent with the age of the transition from the Angastaco Formation to the Palo Pintado Formation as determined by $^{40}Ar/^{39}Ar$ on tuffs by Grier & Dallmeyer (1990).

U-PB GEOCHRONOLOGY OF VOLCANIC ASHES

An ash was collected for U-Pb geochronological analysis from 500 m above the Eocene Lumbrera Fm in the La Viña area, in lacustrine facies (Figs 1c and 6) interpreted to represent the Jesús María Formation. Epoxy grain mounts of hand-selected zircons were ground and polished to expose grain interiors. After ultrasonic cleaning with soapy water, diluted HCl and distilled water, the Au-coated mounts were transferred into a high vacuum chamber (>10^{-8} Torr) and kept overnight. $^{206}Pb/^{238}U$ zircon analysis was performed using the UCLA Cameca ims 1270 ion microprobe with a mass-filtered, *ca*. 15-nÅ $^{16}O^{-}$ beam focused to a 25–30 μm diameter spot. The sample chamber was flooded with O_2 at a pressure of

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ca. 4×10^{-3} Pa to enhance Pb^+ yields by roughly a factor of 1.5. Secondary ions were extracted at 10 kV with an energy band pass of 50 eV. Following a 4-min presputter period during which secondary beam alignment, mass centring and charge compensation routines are automatically applied, intensities for $^{94}Zr_2O^+$, $^{204}Pb^+$, $^{206}Pb^+$, $^{207}Pb^+$, $^{208}Pb^+$, $^{238}U^+$, $^{232}Th^{16}O^+$ and $^{238}U^{16}O^+$ were sequentially measured in 10 cycles at a mass resolution of *ca*. 4800, which is sufficient to resolve most molecular interferences.

The relative sensitivities for Pb and U were determined on reference zircon AS-3 (Paces & Miller, 1993) using a calibration technique similar to Compston *et al.* (1984). U and Th contents were calculated from $^{238}U^{16}O^+/^{94}Zr^2O^+$ and Th^+/U^+ calibrated on reference zircon 91500 (Wiedenbeck *et al.*, 2004). Unknown $^{206}Pb/^{238}U$ ages were calculated from common-Pb and disequilibrium corrected U/Pb isotopic ratios. Corrections for common-Pb are based on anthropogenic compositions (Sañudo-Wilhelmy & Flegal, 1994) and initial disequilibrium ^{230}Th was calculated from measured Th/U_{zircon} and a model Th/U_{melt}, using the average Th/U value for Southern Central Andes ignimbrites (Siebel *et al.*, 2001).

Fifteen grains were analysed; see Table S3 for results. A mean age of 14.4 ± 0.6 Ma was obtained. This age corresponds to deposition of the Angastaco Formation and is consistent with a zircon fission-track age reported by Reynolds *et al.* (2000). These results suggest that the ash analysed in this study is equivalent to the one analysed by Reynolds *et al.* (2000). Whereas Reynolds *et al.* (2000) interpreted this ash to represent the base of the Anta Formation, on the basis of reported thickness for this formation and our facies analysis, we propose that this ash is within the overlying Jesus María Formation.

DISCUSSION AND CONCLUSIONS

Sedimentological and provenance data presented here help resolve the palaeogeography, depositional environments, and changing regional tectonic context of the Cenozoic foreland basin in the central Andes (Fig. 12). The Eocene–Pliocene succession in the Angastaco region can be interpreted in terms of foreland basin depozones. Our data indicate that the Quebrada de los Colorados Formation was deposited in the distal to proximal foredeep (Fig. 12a), in agreement with Starck & Vergani (1996). Lithofacies data indicate that the Quebrada de los Colorados Formation was deposited in a low-sinuosity, mixed sandy-gravelly fluvial system, whereas the Angastaco Formation was mainly deposited by coarse-grained, stream-dominated alluvial fans derived from source terranes located to the west–southwest. Alonso (1992) and Carrapa & DeCelles (2008) documented lithofacies that are similar to but coarser grained than those in the Quebrada de los Colorados Formation in the coeval upper Eocene (*ca*. 39–34 Ma) Geste Formation in the Puna Plateau, *ca*. 130 km to the northwest of the Angastaco–Pucará region. Eocene deposits within the Puna Plateau and along its eastern margin (La Poma and Luracatao areas; Fig. 1) contain features typical of syndepositional deformation (Hongn *et al.*, 2007; Carrapa & DeCelles, 2008; Bosio *et al.*, 2009). On the basis of this evidence, we interpret the Geste Formation and other upper Eocene deposits at the Puna margin to represent the lateral, wedge-top equivalents of the Quebrada de los Colorados Formation. Alternatively, these deposits could represent deposition in isolated intramontane sedimentary basins. The presence of structural growth during the Eocene, as suggested by Hongn *et al.* (2007) and Bosio *et al.* (2009) in the La Poma and Luracatao valleys, 50 km north and west, respectively, of our Tin Tin area section suggests that the along-strike palaeogeographical front of deformation might have been complex, with large eastward salients and reentrants. The lack of structural growth in the equivalent Quebrada de los Colorados Formation in the Angastaco–Pucará area instead suggests that these deposits represent distal to proximal foredeep facies.

The presence of aeolian lithofacies in the lower Angastaco Formation indicates that by 21.6 Ma (the youngest detrital zircon U-Pb age component of the aeolian Angastaco Formation; Fig. 11), the depositional environment was characterized by arid, or at least episodically dry, climatic conditions. The intraformational angular unconformity within the Angastaco Formation between *ca*. 14 and *ca*. 21 Ma (Carrapa *et al.*, 2011) suggests that the Angastaco Formation was deposited in close proximity to a tectonically active source terrane (Fig. 12b) as supported by source exhumation ages (Deeken *et al.*, 2006). Thus, the orogenic front had reached the Angastaco region no later than *ca*. 14 Ma (the age of the Angastaco Formation above the unconformity). At that point in time, the Angastaco area was within a wedge-top position (Fig. 12c) and characterized by coarse-grained, stream-dominated alluvial fans derived from source terranes located to the west–southwest. The formerly continuous foreland basin was disrupted by uplift of the thick-skinned Cerro Negro Range, resulting in the separation of the Angastaco area from the Pucará area to the west (Coutand *et al.*, 2006; Carrapa *et al.*, 2011; Fig. 12c).

Between *ca*. 9 and *ca*. 5 Ma, deposition of the Palo Pintado Formation took place in meandering stream and ephemeral lacustrine environments. The axial geometry of the drainage during deposition of the Palo Pintado Formation, paralleling the Cerro Negro Range, is consistent with a wedge-top setting (Fig. 12d). Deposition during the Pliocene is represented by braided stream and alluvial deposits of the San Felipe Formation (Fig. 12e), which accumulated in an isolated intramontane basin by *ca*. 2.5 Ma (Fig. 12f).

Although other workers have also reported abundant evidence for structural disruption of the Eastern Cordillera during middle to late Miocene time (e.g. Carrera & Muñoz, 2008; Mazzuoli *et al.*, 2008; Hain *et al.*, 2011), it has not been clear how this deformation and the proximal synorogenic sediments associated with it are related to the

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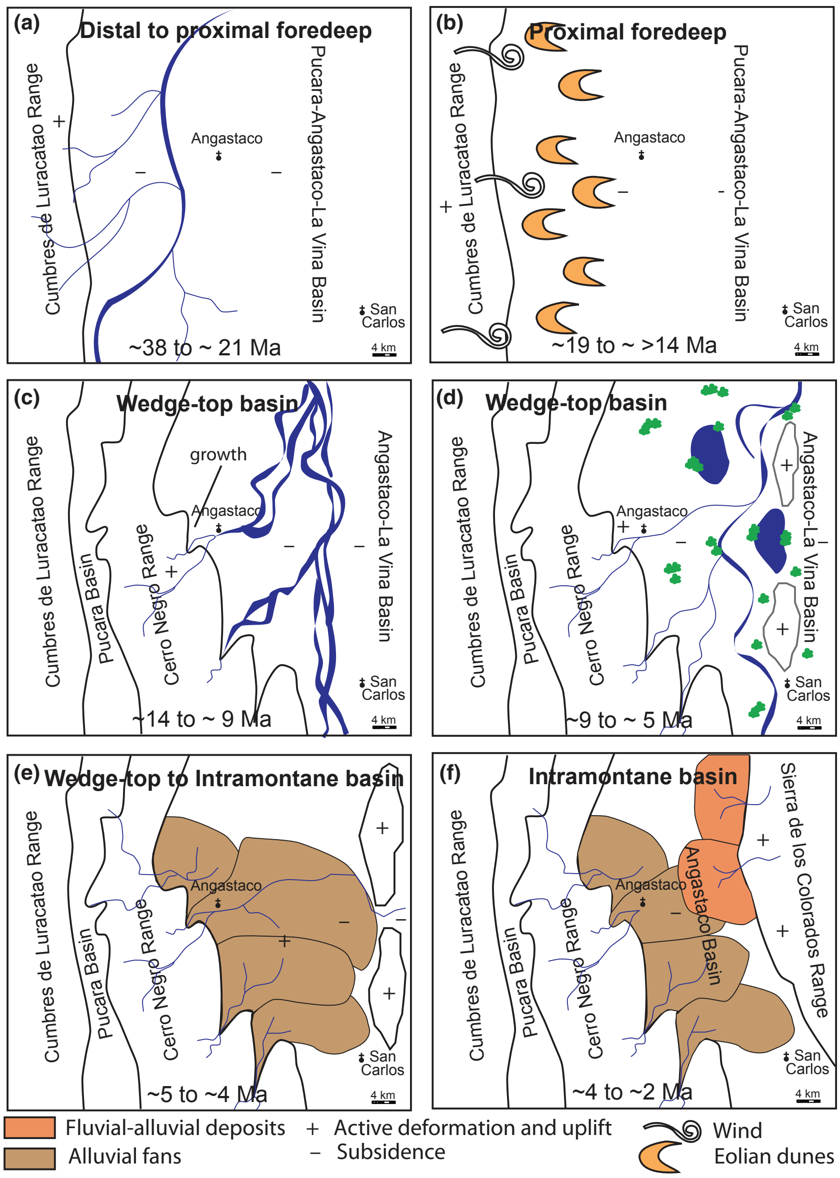

Fig. 12. Schematic diagram showing the palaeogeographical evolution of the study area from Eocene (a) to Pliocene (f) time.

long-term evolution of the central Andean foreland basin system. We view this late-stage disruption of the palaeogeography (Fig. 12c–f) as a predictable outcome of the eastward expansion of the Andean orogenic belt into regions that were formerly occupied by the foredeep depozone. The stratigraphic result of the eastward migration of the coupled thrust belt and foreland basin system is the vertical stacking of foredeep followed by wedge-top depozones (DeCelles and Giles, 1996).

Provenance and palaeocurrent data document the unroofing of source terranes to the west–southwest during deposition of the Angastaco, Palo Pintado and lower San Felipe Formations, and the onset of local intraforeland deformation during deposition of the San Felipe Formation at *ca.* 4 Ma (Bywater-Reyes *et al.*, 2010). Exhumation and uplift of the eastern basin-bounding Sierra de los Colorados Range can be inferred based on the first occurrence of coarse-grained sediment derived from this range at *ca.* 4 Ma (Bywater-Reyes *et al.*, 2010). However, (U-Th)/He cooling ages indicate that initial exhumation of the Sierra de los Colorados may have started as early as *ca.* 9 Ma (Carrapa *et al.*, 2011). The thermochronological data can be explained by removal of finer grained distal foreland basin deposits from the top of the Sierra de los Colorados range. The relatively fine grain-size of these hypothetically eroded sediments would preclude detection in conglomerate and sandstone compositional and palaeocurrent records, helping to explain why westward palaeocurrents are not recorded before *ca.* 4 Ma (Bywater-Reyes *et al.*, 2010). This implies that uplift and formation of enough relief to create a topographic high (owing to gradually increasing exposure of more resistant rocks) and production of the San Felipe and Piquete conglomerates occurred between *ca.* 9 and 4 Ma (Fig. 12). Overall, this study documents a continuous foreland basin system between *ca.* 38 and 14 Ma, which was subsequently disrupted by intra-basin deformation and uplift. Local sediment sources and palaeohighs, possibly inher-

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ited from a complex Salta Rift palaeogeography, may have strongly influenced basin geometry, local provenance and palaeodrainage during the Palaeogene. The dataset presented in this study also implies that the sedimentary record of more distal foreland basin depozones (distal foredeep, forebulge and backbulge deposits) is older than late Eocene in the Eastern Cordillera, and should correspond to the Paleocene–Eocene Santa Barbara Subgroup.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Figure S1. Detailed measured stratigraphic sections of the Palo Pintado and San Felipe Formations; (a) sections 1 and 2; (b) sections 3 and 4; (c) sections 5, 6 and 7; (d) sections 8 and 9. For section locations, refer to Fig. 2.

Table S1. Recalculated modal sandstone petrographic data.

Table S2. U-Pb geochronological data from detrital samples using the MC-LA-ICPMS at the University of Arizona.

Table S3. U-Pb geochronological data for ash LT1-6 in the La Viña area, analysed using the UCLA Cameca ims 1270 ion microprobe.

Table S4. Latitude and longitude coordinates of samples and measured stratigraphic sections.

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