Development of an incipient Paleogene topography between the present-day Eastern Andean Plateau (Puna) and the Eastern Cordillera, southern Central Andes, NW Argentina

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Abstract
The structural and topographic evolution of orogenic plateaus is an important research topic because of its impact on atmospheric circulation patterns, the amount and distribution of rainfall, and resulting changes in surface processes. The Puna region in the north-western Argentina (between 13°S and 27°S) is part of the Andean Plateau, which is the world’s second largest orogenic plateau. In order to investigate the deformational events responsible for the initial growth of this part of the Andean plateau, we carried out structural and stratigraphic investigations within the present-day transition zone between the northern Puna and the adjacent Eastern Cordillera to the east. This transition zone is characterized by ubiquitous exposures of continental middle Eocene redbeds of the Casa Grande Formation. Our structural mapping, together with a sedimentological analysis of these units and their relationships with the adjacent mountain ranges, has revealed growth structures and unconformities that are indicative of syntectonic deposition. These findings support the notion that tectonic shortening in this part of the Central Andes was already active during the middle Paleogene, and that early Cenozoic deformation in the region that now constitutes the Puna occurred in a spatially irregular manner. The patterns of Paleogene deformation and uplift along the eastern margin of the present-day plateau correspond to an approximately north-south oriented swath of reactivated basement heterogeneities (i.e. zones of mechanical weakness) stemming from regional Paleozoic mountain building that may have led to local concentration of deformation belts.

Key words
Andean Plateau, Eastern Cordillera, Eocene deformation, growth structures, northern Puna, northwestern Argentina, southern Central Andes
INTRODUCTION

The southern Central Andes in north-western Argentina and southern Bolivia are an integral part of the largest Cenozoic non-collisional mountain belt on Earth. Its structural and topographic evolution has been the subject of controversial discussion over the last 25 years, resulting in a number of different models for the uplift of the Andean Plateau and adjacent morphotectonic provinces (Allmendinger, Jordan, Kay, & Isacks, 1997; Garzione et al., 2017; Jordan et al., 1983; Oncken, Hindle, Kley, Victor, & Schemman, 2006). In this study, we address some of the issues concerning the spatiotemporal evolution of deformation in north-western Argentina and focus on tectono-sedimentary patterns exposed within the transition zone between the present-day Andean Plateau and the Eastern Cordillera, in order to assess two possible scenarios, one (a) involving systematic eastward-directed plateau growth, and the second (b) involving more diachronous and spatially irregular patterns of uplift and sedimentation for the mountain ranges and basins that compass the present-day plateau region.

The Andean Plateau (between latitudes 13°S and 27°S; Isacks, 1988) is a largely internally drained region in the interior of the Andean orogen (Figure 1a), with an average elevation between 3.5–4 km asl, which is bordered by the Eastern and Western cordilleras (Figure 1a). The Argentine sector of the plateau in particular (Figure 1b), i.e. the Puna (Turner, 1972), is characterized by numerous basins, some of which are isolated, with intervening reverse-fault-bounded mountain ranges and volcanic edifices that reach elevations of 5–7 km asl (Allmendinger et al., 1997; Isacks, 1988; Turner, 1972). A set of related research questions currently under discussion is whether the present-day elevation of this sector of the Andes was achieved during the Paleogene (e.g. Canavan et al., 2014; Quade et al., 2015), as a result of large-scale surface uplift much later during the Neogene (e.g. Garzione et al., 2008; Ghosh, Garzione, & Eiler, 2006), or a result of episodic growth (e.g. Pingel et al., 2020; Reiners et al., 2015). Other discussions have focused on whether early Cenozoic mountain building was characterized by an eastward-directed younging of deformation (Carrapa & DeCelles, 2015; DeCelles, Carrapa, Horton, & Gehrels, 2011; Reiners et al., 2015), or whether deformation and uplift were spatially distributed across the entire region that now constitutes the Andean Plateau and Eastern Cordillera during the Paleogene (e.g. Aramayo, Hongn, & del Papa, 2017; Hongn et al., 2007; del Papa et al., 2013).

Previous investigations have demonstrated the existence of two Eocene-Oligocene deformation belts coinciding with the present-day Western and Eastern cordilleras that border the proto-Altiplano in Bolivia, and that deformation propagated from these belts towards the interior of the Altiplano (Ege, Sobel, Scheuber, & Jacobshagen, 2007; Elger, Oncken, & Glodny, 2005; Lamb & Hoke, 1997; Oncken et al., 2006). For our investigations we focused on the region of the southern continuation of the eastern Bolivian deformation belt into north-western Argentina. Compared to the well-documented Paleogene deformation in the Altiplano, the isolated outcrops of syntectonic sedimentation along the western and eastern borders of the Puna have yielded relatively little information about the early history along its margins (Hongn et al., 2007; Mpodozis et al., 2005; del Papa et al., 2013), and within the interior of the Puna (Carrapa et al., 2005; Carrapa & DeCelles, 2008; Jordan & Mpodozis, 2006; Kraemer et al., 1999). Despite the limited data available, a number of hypotheses have been proposed for the structural and topographic evolution of the area during the Paleogene. Canavan et al. (2014) and Quade et al. (2015), for example, suggested on the basis of stable isotope palaeoaltimetry that a plateau of about 4 km asl elevation already existed during the late Eocene. Other authors have, in contrast, suggested the existence of a broad, low-elevation plain in the region of the present-day Puna during the Paleogene that was interrupted by uplifts of isolated mountain ranges with generally subdued topography (e.g. Adelmann, 2001; Carrapa et al., 2005; DeCelles, Carrapa, & Gehrels, 2007; Pingel, Alonso, Altenberger, Cottle, & Strecker, 2019; Pingel et al., 2020).

Some of the best evidence for the first manifestations of crustal shortening during Eocene-Oligocene times has been preserved in the transition zone between the Puna and the Eastern Cordillera, south of 24.5°S (e.g. Hongn et al., 2007; Payrola Bosio, Powell, del Papa, & Hongn, 2009). This evidence comprises syntectonic sedimentation features such as growth strata, progressive unconformities, and intraformational unconformities, located along structures that delimit irregularly distributed basins with internal drainage (e.g. del Papa et al., 2013). There is, however, a gap in the records of Paleogene deformation and associated sedimentation in the
transition zone between the Puna and the Eastern Cordillera, between 22°S and 24.5°S (Figure 1b,c), with most of the evidence of Eocene-Oligocene tectonism coming from areas within the Puna (Montero-López, del Papa, Hongn, Strecker, & Aramayo, 2018 and references therein).

In this study, we highlight the importance of the southern continuation into the Eastern Cordillera in north western Argentina of the Paleozoic eastern Bolivian deformation belt in controlling regional Cenozoic deformation in the transition zone between the Puna and the Eastern Cordillera. This region of transition zone corresponds to the Sierra Alta mountain range (between approximately 23°S and 24°S), which marks the present-day morphological border between the Puna and the Eastern Cordillera (Figure 1b,c). Inherited Paleozoic structures and Cretaceous normal faults in the Sierra Alta (Monaldi, Salfity, & Kley, 2008; Rodríguez-Fernández, Heredia, Seggiaro, & González, 1998) were reactivated during the Cenozoic Andean orogeny (e.g. Barrabino, Seggiaro, & Gallardo, 2017; Kley, Rosello, Monaldi, & Habighorst, 2005), as can also be commonly observed at many other locations in north-western Argentina.

In addition to the Sierra Alta, other topographic highs constituting the present-day eastern margin of the Puna would also have been affected by these reactivations during Cenozoic Andean shortening (e.g. Grier, Salfity, & Allmendinger, 1991; Oncken et al., 2006; Pearson et al., 2013). The formation of new thrusts and the inversion/reactivation of inherited heterogeneities during Andean shortening have been investigated in detail by Hongn, Mon, Petrinovic, del Papa, and Powell (2010), who demonstrated the influence of the lithological contacts between the different units that constitute the pervasively deformed Paleozoic basement (e.g. Hongn & Riller, 2007) along the eastern Puna margin. These crustal heterogeneities are likely to have acted as stress guides and facilitated Cenozoic reactivation of pre-existing structures (Hongn et al., 2010).

In order to unravel the initial phase and characteristics of the Cenozoic Andean orogeny along the present-day eastern
margin of the Puna, we carried out a detailed structural and sedimentological investigation of Paleogene-Neogene deposits in the Tucsa-Laguna Colorada area (23.7°S, Figure 1c). North-trending mountain ranges in this area delimit intermontane basins filled with thick successions of continental sediments, whose provenance and depositional characteristics are crucial to understanding the early Andean shortening and uplift events (e.g. Carrapa et al., 2005; Kraemer et al., 1999; Montero-López et al., 2018). Whereas previous investigations within the study area have focused mainly on large-scale pre-Andean structures and the Paleozoic stratigraphy (e.g. Astini, Waisfeld, Toro, & Benedetto, 2004; Barrabino et al., 2017; Mon, Mena, & Amenguall, 1996; Monaldi et al., 2008; Moya & Monteros, 1999), we have focused instead on the tectono-sedimentary characteristics of the Paleogene-Neogene deposits along the eastern margin of the Puna (for which we present new data herein) and then evaluated their significance in the context of the incipient stages of topographic build-up.

As part of our tectono-sedimentary analysis of the early Cenozoic foreland strata we also present new data on Paleogene units that outcrop to the east in the adjacent present-day intermontane Humahuaca Basin (~23.8°S, Figure 1), including the Quebrada Colorada (QC), Purmamarca (Pu) and Tumbaya Grande (TG) areas (see the locations in Figures 1 and 3). By comparing our results with published data from the present-day Calchaquí intermontane basin to the south which lies in the southern part of the Eastern Cordillera and border the southern Puna between about 24.5°S and 26°S (Figure 1), we have been able to reconstruct the Paleogene geological framework for the eastern border of the Puna plateau.

2 | REGIONAL AND GEOLOGICAL SETTING

The transition zone between the northern Puna and the Eastern Cordillera (~23.7°S), is characterized by reverse-fault-bounded, high-elevation mountain ranges that separate the basins of the Puna to the west from the Eastern Cordillera to the east, both structurally and hydrologically. While the Puna plateau (mean elevation of 4 km asl) has an internally drained, low-relief landscape with thick and areally extensive sedimentary basin fills, the Eastern Cordillera is characterized by basement-cored mountain ranges and intervening, narrow intermontane basins, which are externally drained and often bordered by divergent thrust and reverse fault systems (e.g. Mon et al., 1996). The Calchaquí and Humahuaca basins belong to these fault-bounded intermontane basins that straddle the transition between the eastern flank of the Puna and the Eastern Cordillera (Figure 1).

The basement rocks of the northern Puna (Figure 2) mainly comprise marine, Neoproterozoic to Paleozoic metamorphic rocks including metamorphosed slates, phyllites and turbiditic sandstones of the Puncoviscana Formation, Cambrian quartzites and marine sandstones of the Mesón Group, Ordovician marine shales and sandstones of the Santa Victoria Group and very low metamorphic related units (e.g. Seggianaro, Becchio, Bercheñi, & Ramallo, 2015; Turner, 1960), migmatic rocks of the Ordovician Puna Eruptive Belt (Coira, Davidson, Mpodozis, & Ramos, 1982; Méndez, Navarini, Plaza, & Viera, 1973), and diancites of the Ordovician Zapla Formation (Schlagintweit, 1943). There are isolated outcrops of Silurian-Devonian sandstones and ferriferous layers comprising the Lipeón and Arroyo Colorado formations (Astini et al., 2004; Moya & Monteros, 1999). Rift-related mudstones, sandstones and carbonates of the Cretaceous-Paleogene Salta Group (Moreno, 1970) were then deposited on top of a mostly erosional and locally angular unconformity. Here, the Salta Group comprises the synrift Pirhua Subgroup, together with postrift deposits of the Balbuena (mainly represented by the distinctly yellow-coloured shallow marine to lacustrine carbonates of the Yacoraite Formation) and Santa Bárbara subgroups (Mealla, Maiz Gordo, and Lumbra formations). These units are overlain by Eocene continental deposits of the Casa Grande Formation (Fernández, Bondesio, & Pascual, 1973; Mon et al., 1996) that are in turn unconformably overlain by Neogene and Quaternary sediments (Figure 2).

The Neoproterozoic–Paleozoic and Cretaceous rocks exposed in the Eastern Cordillera are generally similar to equivalent units in the northern Puna but without any Silurian-Devonian sequences (Figure 2). In the Eastern Cordillera, Paleogene sequences (Casa Grande Formation and equivalent units including the Quebrada de Los Colorados Formation in the Calchaquí Valley and the Gest Formation in the southern Puna) are only exposed along the reverse-fault-bounded margins of intermontane basins and are often overlain by continental Neogene sediments. The Neogene sediments are grouped together in the Orán Group (Turner, 1960; Figure 2), but are named after the localities in which they are exposed. In the Humahuaca Basin (~23.5°S), these Neogene deposits comprise the Maimará and Tílcar formations (Píngel, Strecke, Alonso, & Schmitt, 2013; Salfity, Gorustovich, Moya, & Amenguall, 1984), while in the Cianzo area they are represented by the Río Grande Formation (Pascual, Vucetich, & Fernández, 1978; Siks & Horton, 2011). Further south in the Calchaquí area (~25.5°S), Neogene deposits are represented by the Upper Payogastilla Group (Díaz & Malizzia, 1983; del Papa et al., 2013). Finally, many intermontane basins of the Eastern Cordillera record a unique and complex Quaternary basin evolution that has resulted in generally thick, but strongly incised, fluvial conglomerates (reviewed in Píngel et al., 2020; Strecke et al., 2007; Streit et al., 2015).

Our main study area comprises the Puna-Eastern Cordillera transition zone between 23.6°S and 23.8°S,
in the Tucsa-Laguna Colorada area (Box a in Figure 3). Structurally, this area is characterized by the Tucsa syncline (López Steinmetz & Galli, 2015; Monaldi et al., 2014), which affects Cretaceous to Cenozoic units. Two major reverse-fault-bounded mountain ranges (Figures 1c and 3) flank the syncline: (a) the Cerro Morado range in the west has been uplifted along the west-dipping Cerro Morado Fault (CMF), juxtaposing Paleozoic basement rocks with deposits of the Casa Grande Formation, and (b) the Sierra Alta to the east, part of which has been uplifted along the east-dipping Lipán Fault (LF, Figures 3 and 6). Previous investigations in this region have interpreted the northern part of the Tucsa syncline to be bounded by east-dipping Cretaceous normal faults (Los Colorados and Lipán faults, LCF and LF in Figure 3), which were reactivated and inverted during Cenozoic Andean shortening (Barrabino et al., 2017; Monaldi et al., 2014).

The Paleogene-Neogene sedimentary deposits exposed within the study area along the eastern Puna margin, comprise the Casa Grande Formation (Fernández et al., 1973) and the Río Grande Formation (Pascual et al., 1978). These units, which were defined in the Aguilars Mine-Casa Grande area (Figure 1), are transitional (Boll & Hernández, 1986; Montero-López et al., 2018) and comprise red to reddish-brown siltstones, sandstones and conglomeratic sandstones. From their fossil record (CG site in Figure 1c) they have been assigned an age range that extends from the middle Eocene to the Miocene (Bond & López, 1995; Herrera, Powell, & del Papa, 2012). In the Cianzo Basin (23°14’S, 65°11’W) of the Eastern Cordillera (Figure 1), a number of tuff layers interbedded within the middle to upper sections of the Río Grande Formation have yielded 40Ar/39Ar ages between 16.3 and 9.7 Ma (Siks & Horton, 2011). Unfortunately, there are no tuff beds exposed in either of these two formations within our study area, which makes it difficult to establish any unambiguous correlation between the Cianzo and Tucsa-Laguna Colorada areas. Moreover, there is at present no detailed stratigraphic column available for the Río Grande Formation in the Puna-Eastern Cordillera transition zone.

**FIGURE 2** Stratigraphic overview of (a) the northern Puna plateau, (b) the northern Eastern Cordillera (Humahuaca Basin), and (c) the southern Eastern Cordillera (Calchaquí Valley). G: Group; SG: Subgroup.
3 | METHODS

We carried out detailed field mapping of the geological units and progressive unconformities exposed within the study area. Stratigraphic and structural analyses were carried out in the vicinity of Cenozoic structures to evaluate whether or not Paleogene sedimentary rocks record syn-sedimentary deformation. Our fieldwork focused on lithological contacts, unconformities and pinch-outs, structures and sediment provenance. To support our mapping effort in sectors of particular interest we generated a high-resolution Digital Elevation Model (DEM) with data from a multi-rotor UAV (unmanned aerial vehicle, Phantom 4 Pro). The UAV was equipped with a 1-inch CMOS sensor stabilized by a 3-axis electromechanical gimbal system and acquired photos with a resolution of 20 megapixels.

We measured five stratigraphic sections within the Casa Grande Formation (Figure 4) using a Jacob staff, two in the eastern limb of the Tucsa syncline (sections A and B in Figure 4) and three in the western limb (sections C, D and E in Figure 4). Our field observations also included 28 clast-counting stations in the conglomeratic beds; we counted at least 100 clasts at each of these stations, using a 20 × 20 cm grid. The counted clasts were grouped into six major lithotypes: undifferentiated quartz (L1), purple and pink quartzite (L2), grey and green mudstone (L3), calcareous mudstone and sandstone (L4), volcanics (L5) and granitoids (L6). Table 1 summarizes the nomenclature used for facies interpretation following the classification scheme of Miall (1996). Structural data on planar surfaces (beds, faults, unconformities, etc.) were collected using a stratum compass (dip direction/dip format).

U-Pb analyses on detrital zircon collected from a medium-grained quartz sandstone at the base of the Casa Grande Formation (Figure 4, Section D) were used to determine possible sources for the sediments. Zircons were separated at the
laboratory of the National University of Salta (Argentina) using standard crushing and hand panning methods. Zircon grains were mounted in epoxy, polished and imaged under CL using a Quanta FEI400f Field Emission Scanning Electron Microscope; they were then analyzed for U, Th and Pb isotopes using a Laser Ablation Multi-Collector (LA-MC-ICPMS) system housed at the University of California, Santa Barbara, USA (see Appendix A). The zircon ages obtained were then plotted and analyzed using DensityPlotter software (Vermeesch, 2012). All analytical results are documented in the supplementary material, together with additional methodological information.

4 RESULTS

4.1 Stratigraphy

In the Tucsa-Laguna Colorado area, we mapped fine to coarse sedimentary layers, which, in order to simplify the
stratigraphy and for the purposes of this study, we assigned to the Eocene Casa Grande Formation.

The Casa Grande Formation is mainly composed of red to reddish brown siltstones, and sandstones, together with pale brown conglomeratic sandstones and fine conglomerates. These sediments are subdivided into a lower Casa Grande 1 member (CG1) and an upper Casa Grande 2 member (CG2, Montero-López et al., 2018). The contact between these two sequences is marked by an intraformational unconformity (Montero-López et al., 2018) in the Casa Grande Basin (Figure 1c), where there are excellent outcrops of both members. Moreover, mammal fossils obtained from CG1 member, immediately south of the Casa Grande settlement (CG in Figure 1c) mean that this unit can be reliably assigned to the middle Eocene (Bond & López, 1995; Herrera et al., 2012). The upper age limit of these sediments, however, is only poorly constrained; it can be approximated by generalized correlation with the middle Miocene Rio Grande Formation in the Cianzo Basin (Ci in Figure 1c).

The most complete stratigraphic section in the Tucsa-Laguna Colorada area is found along the northern part of the eastern limb of the Tucsa syncline, with a thickness of >800 m (Figure 4, Section A). The basal CG1 member is up to 55 m thick of this eastern limb (Figure 4, sections A and B) compared to thicknesses of 5–17 m or less on the western limb (Figure 4, sections C and D). The basal section of CG1 member includes white, fine-grained quartzitic sandstones and two grey layers of accretionary bodies (i.e. pisolite) (Sm to Sh facies in sections A, B, C and D), which we used as marker horizons to define the contact with the underlying Salta Group. The middle to upper sections of the CG1 member comprise dark-red siltstones and sandy siltstones with gypsum nodules and veins (Fl facies), and bioturbated siltstone toward the top (Fr facies). These facies indicate overbank or waning flood deposits alternating with plane-bed flow deposits (Miall, 1996) that may have been associated with shallow-lake deltas (Montero-López et al., 2018).

In our detailed mapping we established the change from CG1 to CG2 by changes in colour and lithofacies, with the appearance of the first fluvial channel indicating the beginning of the CG2 sequence. The overlying CG2 member has a thickness that ranges between 110 m in the western limb of the Tucsa syncline (Figure 4, Section C) to 770 m on the eastern limb (Figure 4, Section A). It comprises pale orange to brown, fine to medium-grained sandstones, intercalated with pebble horizons in lenticular beds with plane-parallel lamination and burrow traces (Sh facies). Pale brown, coarse-grained sandstones to fine conglomerates become increasingly common up-sequence (Sm, Gcm, Gp and Gcfa facies) forming thick tabular beds (0.8–2.5 m thick) with calcareous cement and trough-cross lamination (Sp and Gp facies; Figure 4, sections A, B, C, D and E). Towards the top of the sequence, massive conglomeratic sandstones (Sm) alternate with pale brown, massive gravel conglomerates (Gcm facies), both showing reverse grading (Figure 4, Section D). Massive siltstone beds (Fm facies) intercalate with the sandstones in some locations.

The depositional environments of the CG2 sequence are mainly subaerial (aeolian, fluvial and alluvial). We used the most complete section (Figure 4, Section A) as a reference. Towards the base of this section, dark red, well-rounded and medium-grained sandstones are interbedded with siltstones. These strata have thin horizontal laminations and cross-stratification that may indicative of aeolian deposits (Sh facies; Miall, 1996).

Continuing up sequence, the portion of the CG2 profile between 80 and 210 m above the base of Section A (Figure 4),

| Facies codes | Lithofacies | Sedimentary structures | Interpretation |
|--------------|-------------|------------------------|----------------|
| Gmm          | Fine grained conglomerate | Structureless, disorganized | Plastic debris flow |
| Gcm          | Coarse grained conglomerate | Structureless to crude horizontal laminations | Pseudoplastic debris flow |
| Gci          | Coarse grained conglomerate | Imbricated clasts | Channel fills and longitudinal bar deposits |
| Gp           | Coarse grained conglomerate | Planar-cross beds | Transverse bedforms, deltaic growths from older bar remnants |
| Sp           | Coarse grained sandstone | Trough-cross laminations | Transverse and linguoid bedforms (2-D dunes) |
| Sh           | Fine-to coarse-grained sandstone | Horizontal and low angle laminations | Plane-bed flow (critical flow) |
| Sm           | Fine-to coarse-grained sandstone | Massive or faint lamination | Sediment-gravity flow deposits |
| Fl           | Siltstone and sandy siltstone | Nodular structure | Overbank, abandoned channel, or ripples waning flood deposits |
| Fm           | Siltstone | Massive structure | Overbank, abandoned channel, or drape deposits |
| Fr           | Siltstone | Bioturbation | Root bed, incipient soil |
is characterized by fluvial channels with multi-episodic filling and gravel-bed loading (Sm, Gp facies), suggesting a low-energy environment. In the middle to upper sections of the profile (between 210 and 420 m) there are imbricated conglomerates with erosive bases indicating an environment of increasing energy, possibly varying from deep river channels to shallower channels with transverse gravel bars (Gcm facies), or migrating straight-rage megaripples (Sh and Sm facies; Miall, 1996). The upper section of the CG2 profile, corresponding to the last 400 m, is characterized by detrital cohesive-flow deposits (Gmm facies) alternating with gravity-flow deposits (Sm facies) inferred to have been deposited in braided river environments with a mixed-charge load (Miall, 1996) and an incipient development of silty flood-plains or secondary channels, interpreted as crevasse and crevasse-splay deposits.

4.2 | Clast compositions

We performed clast counts at 28 stations within the conglomerate beds in the middle to upper part of the Casa Grande Formation where the clasts first appear (Figure 4). Our results indicate that the middle part of this unit (in all sections investigated) is characterized by calcareous mudstone and sandstone clasts (L4: 85%–92%), with minor occurrences of purple and pink quartzite (L2 < 15%), and of grey and green mudstones (L3 < 8%). Except in Section A, the up-sequence proportion of calcareous mudstone and sandstone clasts (L4) reduces down to 44% while the proportions of purple and pink quartzite (L2: 44%) and grey and green mudstone (L3: 12%) clasts increase. Towards the top of the formation (Figure 4, sections B, C, D and E) the grey and green mudstone clasts (L3) become dominant (41%) and there are only rare occurrences of calcareous mudstone and sandstone clasts (L4), together with sporadic volcanic (L5) and plutonic (L6) clasts.

4.3 | U-Pb detrital zircon dating

We analysed a total of 124 zircon grains from a basal sample of the CG1 member (2017-02-02 sample; 23.7114°S-65.7043°W - see location on Section D in Figure 4). The U-Pb detrital zircon age spectrum obtained (Table S1) reveals three main populations (Figure 5), which is in agreement with the clast compositions across the measured sections of the Casa Grande Formation.

The main population (~71%) had an average age of 484 ± 1 Ma, which could correspond to: (a) the regionally exposed Ordovician units (e.g. Moya, Diez Gómez, & Eveling, 2017), as represented by the L3 lithotype or, (b) the locally exposed Cretaceous-Paleogene Salta Group (as represented by the L1, L2 and L4 lithotypes), which in other locations (i.e. Tres Cruces and Cianzo basins) contains recycled Ordovician zircons (DeCelles et al., 2011; Siks & Horton, 2011). U-Pb zircon data from Ordovician units cropping out to the west of the study area have yielded ages of 483 ± 3 Ma from volcanoc-sedimentary successions (Hauser, Matteini, Omarini, & Pimentel, 2011) and 490–460 Ma from the Eastern Puna Eruptive Belt (Bahlburg & Berndt, 2016), and these could therefore represent a third possible source. However, we only observed igneous clasts (L5 and L6 lithotypes) towards the top of the measured sections whereas our detrital zircon sample was collected from the base of the sequence.

The second population (~19%) yielded a mean U-Pb age of 530 ± 1 Ma, which correlates with radiometric ages obtained from the Puncoviscana Formation (e.g. Adams, Miller, Aceñolaza, Toselli, & Griffin, 2011; Aparicio González, Pimentel, Hauser, & Moya, 2014; Hauser et al., 2011; Pearson et al., 2012). This age population is correlated with the L3 lithotype. The third population of U-Pb ages (~6%) has late Mesoproterozoic to early Neoproterozoic ages of between 1 and 1.1 Ga. This age population is well-documented and most likely represents recycled zircons from the Puncoviscana Formation, which would have received sediments from the late Paleoproterozoic Sunsás Orogen (DeCelles et al., 2011; Siks & Horton, 2011).

The first and the second obtained age clusters are thus related to the unroofing of rocks that were associated with Paleozoic tectono-thermal events. The age clusters spanning 530–570 Ma reflect the Pampean event (Aceñolaza & Toselli, 1973) and the ages between 500 and 435 Ma represent the Famatinian event (Aceñolaza & Toselli, 1973); both of these age clusters are present in the Cianzo (Siks & Horton, 2011) and Casa Grande samples. There is, however, a notable difference since the age peak at Cianzo is Pampean in age, whereas Famatinian ages are dominant in our sample. This difference reinforces the hypothesis of derivation from Ordovician units in the west, but the evidence is
not sufficient for the recycling hypothesis to be completely discarded. Further research will be required to resolve this issue.

5 | STRUCTURAL CHARACTERISTICS

5.1 | Tucsa Syncline

The southward-plunging, asymmetric Tucsa syncline is the main contractional structure in our area involving both the Salta Group and the Casa Grande Formation (Barrabino et al., 2017; López Steinmetz & Galli, 2015; Monaldi et al., 2014; Montero-López, Hongn, & López Steinmetz, 2017). We mapped the differences in bed thickness of the units involved in both fold limbs which revealed that the beds are thicker in the eastern fold limb, where the complete sequence of the Salta Group is exposed (Figure 6).

The contact relationships in the eastern limb of the Tucsa fold are structurally complex. In the northern part of this limb, the Balbuena Subgroup (Yacoraite Formation) overthrusts the Santa Bárbara Subgroup (Mealla and Maíz Gordo formations) and this succession has in turn been locally thrust westward over the Casa Grande Formation (Figures 6 and 7a). To the south, the limb exposes a continuous Cretaceous-Paleogene sequence, with minor faulting; the outcrops reveal a gradual southward thinning of the Santa Bárbara Subgroup until it eventually pinches out. This then brings the Balbuena Subgroup (Yacoraite Formation) into contact with the CG1 sequence (Figures 6 and 7b). Bedding-parallel internal faults within the Yacoraite Formation, probably related to flexural-slip, have generated complex disharmonic structures and resulted in thickening of the unit.

The main reverse fault bordering the western limb of the Tucsa syncline (the CMF-Cerro Morado Fault in Figures 3 and 6) has progressively thrust Ordovician basement rocks from north to south over the Pirgua, Balbuena, and Santa Bárbara subgroups and over the fine-grained sediments of the CG1 member. In the southern part of the western fold limb the CMF only cuts through the Ordovician basement (Figure 6). In the central part (i.e. several kilometers southwest of the Tucsa settlement), the fault plane dips 59°W.

**FIGURE 6** (a) Detailed geological map of the Tucsa-Laguna Colorada area (Box a in Figure 3). The red box indicates the area covered by the high-resolution UAV image shown in Figure 8. (b) Geological cross sections showing the main structures along the Tucsa syncline.
FIGURE 7  (a) Fault contact (red line) between the Salta Group (Santa Bárbara Subgroup) and the Casa Grande Formation in the northern part of the eastern limb of the Tucsa syncline. (b) Unconformity (black dashed line) between the Yacoraite Formation and the Casa Grande Formation in the southern part of the eastern limb of the Tucsa syncline. (c) Outcrop photograph and (d) interpretation showing the contact (thick black line) between the Yacoraite Formation (in green) and the Casa Grande 1 member (in orange), in the southern part of the western limb of the Tucsa syncline. The contact between the Yacoraite Formation and the Casa Grande 1 member is erosive, resulting in an angular unconformity, as shown in (e) and (f). Bedding dips and dip directions. Photos showing the erosional unconformity between the Casa Grande Formation and different units of the Salta Group (Yacoraite and Mealla formations): (g) in the Quebrada Colorada area, and (h) in the Tumbaya Grande area. Note that in (g) the up-section thickness of the Mealla Formation (white line) above the stromatolite bed decreases northwards at Quebrada Colorada.
5.2 | Erosion surfaces and angular unconformities

We identified a major erosional surface between the Yacoraite Formation and the Casa Grande Formation (CG1 member), very well-exposed in the southern part of the western Tucsa fold limb. This erosion surface cuts through different stratigraphic levels of the Yacoraite Formation, which dips 65° SE (see Figure 7c,d,e,f); the CG1, dipping between 45° and 50° SE, overlies the erosion surface. This setting is the most distinct angular unconformity reported to date between the Salta Group and the Andean synorogenic deposits in this sector of the transition zone between the northern Puna and the Eastern Cordillera.

We also mapped a similar erosion surface in the Quebrada Colorada (QC in Figures 3 and 8a), which is further east, in the Humahuaca Basin, where sediments of the Casa Grande Formation cover different strata of the Mealla Formation in the Santa Bárbara Subgroup (Figure 7g). This erosion surface coincides locally with an isolated stromatolite bed within the uppermost Mealla Formation, which pinches out towards the north. The erosion surface and the associated gently inclined angular unconformity were also observed in the Tumbaya Grande area (TG in Figures 3 and 8c), within the southern continuation of the Humahuaca Basin (Figure 7h). We have recorded variations in the thickness of the Salta Group between these localities, documenting about 146 m at the QC, 26–57 m at Purmamarca (Pu in Figures 3 and 8b), and up to 170 m in the TG area.

5.3 | Folded angular and progressive unconformities

There is unambiguous evidence for ongoing tectonism during the deposition of the Casa Grande Formation in the northern part of the western limb of the Tucsa syncline (Figure 9a). For example, the CG1 strata exhibit strike and dip variations associated with angular intraformational unconformities that have in turn been folded (Figure 9b,c). The stereoplot in Figure 9 shows clearly the variations in the attitude between beds located below the internal unconformity surface, marked as white planes and those above it, marked as yellow planes (Figure 9c); the strikes and dips in the lower beds differ from those in the upper beds.

Moreover, on both limbs of the syncline there are well-exposed outcrops showing fan-shaped geometries in the medium to coarse grained sandstone strata of the CG2 member (Figure 10a). For example, on the western limb of the syncline the strata define a fan-shaped geometry with the dip changing up-section from about 55° ESE in the lower sections to 40° SE above, and with a northward stratigraphic thickening from 70 m in the southern profile to 235 m in the northern profile (Figure 10b), forming an onlap-shaped growth wedge.

On the eastern fold limb, the middle section of the CG2 member reveals progressively shallower dips towards the top of the sequence, with a variation of 28° over a stratigraphic interval of about 100 m (Figure 10c). This could indicate offlap stratal terminations associated with accelerated uplift (e.g. Riba, 1976).

**FIGURE 8** Detailed geological map of the Humahuaca areas (Box b in Figure 3). (a) Quebrada Colorada (QC); (b) Purmamarca (Pu), and (c) Tumbaya Grande (TG) (after Díaz, 2015; Jiménez et al., 2002)
During the middle Eocene to late Oligocene/early Miocene (?), fluvial and alluvial sediments of the Casa Grande Formation filled the Tucsa-Laguna Colorada depocenter and covered the palaeo-topography, previously sculpted into the Cretaceous-Paleogene rift deposits of the Salta Group. The irregular erosion surface cutting across the Balbuena and Santa Bárbara subgroups and the angular unconformity with the overlying Casa Grande sediments clearly reflect the effect of pre-middle Eocene tectonism and erosion in this region. This is indicated, for example, by the predominance of calcareous mudstone and sandstone (L4) clasts in the basal section of the CG2 member, which were clearly a result of the unroofing of the Salta Group. This unroofing of the Balbuena and Santa Bárbara subgroups identified by our sedimentological analyses refutes the hypothesis that changes in thickness in the postrift successions of the Salta Group within the area of investigation are related to depositional pinch-out against basement highs (e.g. Hernández, Gómez Omil, & Boll, 2008).

Minor quantities of undifferentiated quartz and quartzite lithotypes among the conglomerate clasts (L1 and L2), together with our U-Pb detrital zircon ages, suggest either (a) additional sources in exposed Paleozoic basement lithologies (Figure 2), or (b) the presence of recycled Paleozoic zircons from the Pirgua or Santa Bárbara subgroups (Siks & Horton, 2011). We interpret the up-section increase in clasts of these two lithotypes (L1 and L2, see sections C and D in Figure 4) to reflect enhanced sediment supply from local sources in Paleozoic basement rocks associated with the uplift and exhumation of the Cerro Morado range to the west, which consists primarily of Cambrian and Ordovician units. Alternatively, it could reflect the exposure of the Salta Group affected by the CMF in the northern part of the Tucsa syncline (Figure 3), which could also have provided the recycled Ordovician zircons. Both of these interpretations are compatible with the pre-middle Eocene deformational and erosional events documented within the study area. However, the existence of syntectonic features mapped in the basal CG1

FIGURE 9  (a) UAV-derived aerial photograph showing in detail the western limb of the Tucsa syncline, where Ordovician basement has been thrust eastward over Paleogene redbeds of the Casa Grande Formation. White lines show discontinuous bedding along-strike from the CG1 member, which reveals intraformational unconformities that have been subsequently folded. The stereographic plot is of the beds defining the intraformational unconformity, with beds below the unconformity shown as white lines and those above as yellow lines. (b) Enlarged colour enhanced subset of Figure 9a, showing details of folded intraformational unconformities and structural data. (c) Outcrop of a folded angular unconformity (view towards northeast). See Figure 9a for location

6 | DISCUSSION

6.1 | Eocene to Miocene tectono-sedimentary evolution of the Puna to Eastern Cordillera transition zone between 23.5ºS and 24ºS

During the middle Eocene to late Oligocene/early Miocene (?), fluvial and alluvial sediments of the Casa Grande Formation filled the Tucsa-Laguna Colorada depocenter and covered the palaeo-topography, previously sculpted into the Cretaceous-Paleogene rift deposits of the Salta Group. The irregular erosion surface cutting across the Balbuena and Santa Bárbara subgroups and the angular unconformity with the overlying Casa Grande sediments clearly reflect the effect of pre-middle Eocene tectonism and erosion in this region. This is indicated, for example, by the predominance of calcareous mudstone and sandstone (L4) clasts in the basal section of the CG2 member, which were clearly a result of the unroofing of the Salta Group. This unroofing of the Balbuena and Santa Bárbara subgroups identified by our sedimentological analyses refutes the hypothesis that changes in thickness in the postrift successions of the Salta Group within the area of investigation are related to depositional pinch-out against basement highs (e.g. Hernández, Gómez Omil, & Boll, 2008).

Minor quantities of undifferentiated quartz and quartzite lithotypes among the conglomerate clasts (L1 and L2), together with our U-Pb detrital zircon ages, suggest either (a) additional sources in exposed Paleozoic basement lithologies (Figure 2), or (b) the presence of recycled Paleozoic zircons from the Pirgua or Santa Bárbara subgroups (Siks & Horton, 2011). We interpret the up-section increase in clasts of these two lithotypes (L1 and L2, see sections C and D in Figure 4) to reflect enhanced sediment supply from local sources in Paleozoic basement rocks associated with the uplift and exhumation of the Cerro Morado range to the west, which consists primarily of Cambrian and Ordovician units. Alternatively, it could reflect the exposure of the Salta Group affected by the CMF in the northern part of the Tucsa syncline (Figure 3), which could also have provided the recycled Ordovician zircons. Both of these interpretations are compatible with the pre-middle Eocene deformational and erosional events documented within the study area. However, the existence of syntectonic features mapped in the basal CG1
member strengthens our interpretation of early Paleogene activity along the Cerro Morado Fault (CMF in Figures 3 and 6), which juxtaposes Ordovician basement with both the Salta Group and the CG1 member.

Although the chronological order of events remains somewhat uncertain, our interpretation is based on the presence of syntectonic features in older strata of the Casa Grande Formation (i.e. the basal beds of the CG1 sequence) in the western limb of the syncline rather than the eastern limb (present in the middle levels of the CG2 sequence). We suggest that following the initial shortening in the west, the inversion of the Lipán normal fault (Barrabino et al., 2017) along the Sierra Alta (LF in Figures 3 and 6) on the eastern limb of the syncline was responsible for the initial westward-directed thrusting of Cambrian-Ordovician basement over Cretaceous and Paleogene deposits during deposition of the CG2 strata.

Progressive unconformities in the middle and upper sections of the Casa Grande Formation can be seen on the eastern limb of the Tucsa syncline, revealing an early stage of Paleogene inversion of the Cretaceous rift-related normal faults. Moreover, López Steinmetz and Galli (2015) reported paleoflow directions from the ENE directions for the middle to upper part of the Casa Grande Formation stratal within the study area, suggesting the existence of higher palaeo-topography to the east. The upward-coarsening trend of the Casa Grande Formation suggests a transition from low-energy to high-energy depositional environments. For example, the accumulation of such coarse deposits in a modern plateau environment would typically occur in upward-coarsening depositional systems associated with increasing slopes steepness due to the effect of tectonic uplift of the bounding ranges. From a larger perspective, prograding (or upward coarsening) depositional systems are formed, under suitable climatic condition during changes to the relative base level (i.e. an increase and/or decrease as a result of aggradation, flexure, isostatic compensation, etc.), and changes to headwaters as a result of tectonic movements and exhumation (e.g. Weissman et al., 2015).

Within our study area the transition from low-energy to high-energy depositional environments, as reflected by strata in the Casa Grande Formation, is consistent with the interpretation of an early-stage Andean mountain-building in which the slope steepness increased due to tectonic control and consequent associated with changes to the relative positions of depositional basin floors and headwater areas.

Although we have not observed any syntectonic depositional features in the greater Humahuaca Basin (QC, Pu, and TG in Figures 3 and 8), we were able to document an erosional unconformity intersecting the middle and upper part of the Salta Group (Figure 7g,h). In the Tumbaya Grande locality (Figure 8c), for example, the Casa Grande Formation covers both the Balbuena and the Santa Bárbara subgroups. The sediment thickness of the Salta Group is also highly variable, ranging from about 146 m at the Quebrada Colorada (QC) locality in the north to between 36 m and 57 m at Purmamarca (Pu); the thickness then increases again to about 170 m farther south at Tumbaya Grande (TG).
findings of an erosional unconformity and the marked thickness variations over short distances (10 km) indicate intense erosion of the Salta Group prior to deposition of the Casa Grande Formation rather than a depositional pinch-out of the Salta Group post-rift units.

6.2 Paleogene topography of the Puna-Eastern Cordillera transition zone as a regional feature

The new sedimentological and structural data that we present herein, particularly the syntectonic features that characterize the Casa Grande Formation (but also the thickness variations due to erosion of the Salta Group), extend our knowledge of Paleogene deformation and exhumation along the present-day northern part of the transition between the Puna and the Eastern Cordillera; the resulting interpretations are independently supported by regional thermochronological data (e.g. Deeken, Sobel, Haschke, & Riller, 2005; Insel et al., 2012). Our data thus fill an important gap and, together with information from other areas to the north and south of the study area, show that Paleogene deformation occurred along the entire eastern border of the present-day Puna plateau (Figure 11). It is important to note that this deformation and the concomitant erosion and deposition took place prior to the formation of the plateau. Paleogene exhumation ages have, for example, been reported from the Puna farther west (i.e. in the Aguilar Range, Insel et al., 2012) and from the Eastern Cordillera (i.e. in the Sierra de Santa Rosa de Tastil, Cachi Range, Cerro Durazno, Sierra de Chango Real, and Filos del Pelado; Andriessen & Reutter, 1994; Coutand et al., 2006; Deeken et al., 2006; Payrola et al., 2020; Pearson et al., 2013; Villagrán, 2020) – see Figure 11. Similar exhumation ages have been reported from the Eastern Cordillera of Bolivia (e.g. Anderson et al., 2018; Ege et al., 2007; Tawackoli, Jacobshagen, Wemmer, & Andriessen, 1996). Taken together, this early phase of exhumation could reflect the impact of initial horizontal crustal shortening that affected...
different localities within the present-day Puna and Eastern Cordillera (e.g. Coutand et al., 2001; Hongn et al., 2007).

On the basis of currently available sedimentological, structural, subsurface and thermochronological data (e.g. Coutand et al., 2001; Haschke et al., 2005; Hongn et al., 2007), we suggest the existence of moderately elevated mountain ranges within the Puna-Eastern Cordillera transition zone since the middle Eocene. López Steinmetz, Ávila, and Dávila (2020) have also recently proposed relief formation along the margin of the present-day Salinas Grandes basin in the Puna (Figure 1b), which is immediately to the west of the study area, as early as the late Eocene. In this context, an important observation is that in the Tica-Laguna Colorada area, clasts from the Yacoraite Formation occur in the basal section of the CG2 sequence whereas farther north in the Aguilar Mine area, clasts from this unit do not appear until the upper CG2 sequence. This may reflect a non-systematic pattern of deformation, range uplift and exhumation in the headwater areas, or alternatively, it could imply that the sedimentation of the CG2 member was diachronous, and hence older in the Tica-Laguna Colorada area than in the Mina Aguilar area.

The formation of the proto-Sierra Alta within the study area started with the uplift of isolated ranges during the Paleogene (Figure 11). Growth structures and the presence of basement clasts in the Eocene strata of the Calchaqui Valley indicate that a similar isolated proto-mountain range also existed at that time further to the south (Figure 11; Aramayo et al., 2017; Hongn et al., 2007; del Papa et al., 2013), characterized by rocks of the Ordovician Puna Eruptive Belt. Erosion products from the exhumation of this proto-range were transported towards depocenters in the west (Geste Formation; DeCelles et al., 2007), as well as to the east (Quebrada de Los Colorados Formation; Aramayo et al., 2017; del Papa et al., 2013; Payrola Bosio et al., 2009). Farther to the north, Lamb and Hoke (1997) and Oncken et al. (2006) proposed a very similar Paleogene topographic development for the margins of the Bolivian Altiplano.

As in the Bolivian Eastern Cordillera, Cretaceous normal faults mapped within our study area have undergone subsequent contractional inversion during the Cenozoic (Barrabino et al., 2017; Monaldi et al., 2008). However, there are also other zones of crustal weakness that have influenced shortening in the southern Central Andes during the Cenozoic including a regional north-south-trending belt of inherited heterogeneities within the Paleozoic basement (Figure 11; Hongn et al., 2010). These are heterogeneities in the orientation of the metamorphic fabrics of early Paleozoic rocks that are mainly associated with north-striking, reactivated shear zones of the Ordovician Eastern Puna Eruptive Belt (Bahlburg, 1990; Bahlburg & Hervé, 1997; Hongn, 1994; Hongn & Riller, 2007) and have been subsequently exploited by Cenozoic reverse faults (Hongn, Mon, Acuña, Kirschbaum, & Menegatti, 2006; Hongn et al., 2010). The study area coincides spatially with the transition zone between basement units with internal pervasive early Paleozoic deformation (which are widely distributed within the Puna) and exposures of the Santa Victoria and Mesón groups within the Eastern Cordillera, which record little or no early Paleozoic deformation (Mon & Hongn, 1987). This implies a strong change in the mechanical properties and different behaviours during the Cenozoic shortening. Accordingly, the Puna has a thicker, more rigid igneous-metamorphic basement consisting of both Neoproterozoic-Lower Cambrian and Cambrian-Ordovician complexes, while the Mesón and Santa Victoria groups of the Eastern Cordillera deformed as typical sedimentary rocks. This marked difference in mechanical properties between the two areas constitutes a major regional heterogeneity that resulted in different degrees of reactivation of pre-existing zones of weakness during the Cenozoic shortening (Hongn et al., 2006, 2010). In the Tica-Laguna Colorada area, Paleozoic deformation appears to have been weak, but the complex basement architecture resulting from the above-mentioned crustal heterogeneities (Figure 11) may nevertheless have affected the structural development during the Andean Cenozoic orogeny, at various scales.

Data from this study, together with information gleaned from other investigations in north-western Argentina and southern Bolivia (e.g. Lamb & Hoke, 1997; Adelman, 2001; Coutand et al., 2001; Carrapa et al., 2005; Elger et al., 2005; Ege et al., 2007; Hongn et al., 2007; del Papa et al., 2013; Aramayo et al., 2017; Anderson et al., 2018; Montero-López et al., 2018; López Steinmetz et al., 2020; Payrola et al., 2020), consistently supports the existence of rather isolated but widespread elevated Paleogene topography in the area of the present-day Puna-Eastern Cordillera transition zone, as well as in the present-day Puna (Figure 11). However, little is known about exactly when this region first became a highland area with the plateau characteristics that define todays.

In this regard, some authors have suggested the existence of a plateau with an elevation of about 4 km asl since the Paleogene on the basis of stable isotope data (Canavan et al., 2014; Quade et al., 2015). Others have suggested that these palaeoaltimetric assessments are based on simplistic models and that the influence of complex factors such as deep convective rainfall (Pingel et al., 2016; Rohrmann et al., 2014) and palaeoclimatic (Ehlers & Poulsen, 2009), also need to be taken into consideration. Furthermore, a recent reinterpretation of the stable isotope data from Canavan et al. (2014), involving comparisons with regional datasets of hydrogen stable isotope in volcanic glass from low to high elevation sites across the eastern Andean margin, has interpreted early to middle Miocene palaeoelevations of about 2.5 km and an inferred elevation of about 2 km for the Puna plateau during the late Paleogene (Pingel et al., 2020). In this context, Pingel et al. (2019) have suggested that the middle Miocene Los
Patos Conglomerate (14.5 Ma, del Papa & Petrinovic, 2017) from the eastern margin of the Puna (at 24.2°S) formed as a result of topographic growth of the Eastern Cordillera, as this unit was deposited over a pronounced angular unconformity in deformed Paleogene units.

It also needs to be borne in mind that previous studies have convincingly demonstrated more recent topographic uplift of the western flank of the Andean plateau in Chile, of about 1 km during the Miocene (Jordan et al., 2010) and a maximum palaeoelevation of 2 km asl in the Altiplano of Bolivia during the early Miocene (e.g. Garzione et al., 2017 and references therein).

In order to obtain a satisfactory estimate of Paleogene palaeo-elevation, a number of additional proxies, such as marine facies, flora and mammal fossils, climate indicators, and together with data on upper crustal shortening, also need to be taken into account. Unfortunately, this type of information is still rather scarce (e.g. Gregory-Wodzicki, 2000), but recent advances in tectonic, palaeoenvironmental, palaeoecological, and paleontological assessments have shed new light on these issue (e.g. Anderson et al., 2018; Cadena, Anaya, & Croft, 2015; Catena, Hembree, Saylor, Anaya, & Croft, 2017; Croft et al., 2016; Ortiz Jaureguizar, 2003).

Firstly, the presence of marine units within the Salta Group (Marquillas, del Papa, & Sabino, 2005; Sempere et al., 1997) indicates that the present-day Andean Plateau and Eastern Cordillera region was at sea level during the Cretaceous-Paleocene transition. These marine units were subsequently replaced by continental sedimentary facies, indicating emergence of the region above sea level by the middle Eocene (ca. 45–40 Ma). Other palaeoenvironmental evidence also supports these interpretations. For example, during the early Eocene the region would have had a humid temperate climate (Quattrociocchio & Volkheimer, 2000), which is consistent with the sedimentary facies and fossil mammal record from the Casa Grande and Quebrada de Los Colorados formations (Bond & López, 1995; Herrera et al., 2012).

Secondly, skeletal fragments of the Crocodilia order (Sebecidae Fam.) in the Eocene Geste Formation of the southern Puna associated with deeply weathered, iron-oxide-rich paleosols indicate lowland plains with a warm, humid climate (Alonso & Fielding, 1986; García-López & Babot, 2014; Gasparini, De la Fuente, & Donadio, 1986; López, 1997). Moreover, fragments from the Geste Formation assigned to Boinae or Madtsoinae (Serpentes suborder, López, 1997) suggest an environment characterized by warm temperatures and a base level of less than 1 km for this time.

Thirdly, approximately 200 km north of the study area, within the Eastern Cordillera of southern Bolivia, tortoise and freshwater chelid turtle remains from the fossil-rich Quebrada Honda site (approximately 21.9°S, 65.1°W) suggest palaeo-elevations of less than 1 km for the Middle Miocene (Cadena et al., 2015). Mammalian fossil evidence and paleosol characteristics at this location indicate a semi-humid to humid wooded environment, with more than double the precipitation of the currently semiarid highlands (e.g. Catena et al., 2017; Croft et al., 2016). This assessment is also supported by discoveries of fossils of herbivorous and frugivorous marsupials (Abderitidae) that were adapted to warm, humid woodlands (Ortiz Jaureguizar, 2003; Pascual & Ortiz Jaureguizar, 1990). Mammal fossils (Xenarthra) and phytoliths from the late to middle Miocene Tafna Formation in the Casira and Calahoyo areas (~22°S, 65.8°W) further support this notion (Quítones et al., 2019; Zurita et al., 2017). In summary therefore, these various observations combine to cast doubt on an early plateau-uplift scenario for the southern Altiplano and the northern Puna.

With regard to the crustal shortening required to form the Andean plateau, a number of authors have calculated a value of 30% for the shortening accumulated during the Neogene, which is insufficient to account for the total crustal thickness of the Andean plateau (Hongn et al., 2007; Kley & Monaldi, 1998). Balanced cross-sections from the Eastern Cordillera of Argentina have indicated between 27% and 47% shortening for the Neogene (Jiménez, Peñaloza, Mon, Gambarruta, & Eremchuk, 2002; Mon et al., 1996; Montero López, 2006; Pearson et al., 2013). There have to date been no estimates reported of Paleogene shortening. However, structural and thermochronological studies have indicated about 60% pre-Neogene shortening in the Bolivian Eastern Cordillera and the inter-Andean zone (McQuarrie, Barnes, & Ehlers, 2008). Pearson et al. (2013) surveyed a regional transect at 24.75°S, from the Puna to the Santa Bárbara System in the Andean foreland and proposed that a significant proportion of the shortening deficiency could be accounted for by Paleogene shortening within the region of the present-day Puna plateau and that this deformation event was controlled by Cretaceous rift architecture. Paleogene shortening documented along the present-day Puna-Eastern Cordillera transition zone (Aramayo et al., 2017; Coutand et al., 2001; Hongn et al., 2007; Montero-López et al., 2018; del Papa et al., 2013; Payrola Bosio et al., 2009; amongst others) has yet to be calculated, but is likely to account for at least some of the shortening deficiency.

We propose that the first regional shortening in the Andean backarc of north-western Argentina during the Paleogene (mainly during the middle Eocene) resulted in localized up-lift of individual ranges within an extensive, low-elevation region (Figure 11); this region may have been analogous to the Neogene-to-recent broken foreland of the Santa Bárbara System (Mon & Salfity, 1995; del Papa et al., 2013). A remarkable feature of the study area is the moderate palaeo-re lief of the proto-Sierra Alta, which must nevertheless have been extensive enough to at least partially interrupt fluvial connectivity between the depocenters to the east and west, as in other parts of the Puna-Eastern Cordillera transition
zone (e.g., del Papa et al., 2013). Numerical landscape evolution models that reproduce available thermochronological datasets for this regions, have shown that some portions of the Puna-Eastern Cordillera transition zone, particularly along the Aguilar Range, could have attained altitudes of between 1 and 2 km asl during the Eocene (López Steinmetz et al., 2020). According to this scenario, a watershed would have been established during the Eocene in an area that coincides with the present-day transition zone between the Puna and the Eastern Cordillera. This interpretation agrees with our findings that suggest a disruption of the formerly continuous sedimentary basin into separate depozones to the west and east of the Sierra Alta mountain range at that time. Furthermore, our data reveal that this proto-high acted as a boundary for Eocene shortening, which started with greater intensity in the western part of the proto-Sierra Alta, i.e., within the present-day Puna plateau.

Although our new structural and sedimentological data are limited in areal extent, when combined with the previously published structural, sedimentological, thermochronological and palaeoenvironmental findings discussed above provide an important link between the early Cenozoic deformation history of the northern Puna, the southern Altiplano and the Eastern Cordillera of the southern Central Andes. During the Paleogene this region evolved as a broken foreland, with spatially isolated range uplifts and the formation of intervening sedimentary basins (e.g., Carrapa et al., 2005; Deeken et al., 2006; Elger et al., 2005; Horton, 2005; Kraemer et al., 1999). During this stage in the evolution of what was later to become a plateau region, and well into Miocene time, this part of the southern Central Andes had similar structural and sedimentological characteristics to the Neogene-to-present broken foreland of the Santa Bárbara morphotectonic province farther east (Carrapa et al., 2005; Montero-López et al., 2018; del Papa et al., 2013; Strecker et al., 2007). Climatic and topographic conditions allowed for the existence of a subtropical, humid environment (Catena et al., 2017; Ortiz Jaureguizar, 2003; Pascual & Ortiz Jaureguizar, 1990) and an orographic barrier that would account for the present-day arid conditions of the orogen’s interior; the wet eastern flanks of the eastern Andes did not yet exist (Ehlers & Poulsen, 2009; Mulch, Uba, Strecker, Schoenberg, & Chamberlain, 2010; Pingel et al., 2020; Rohrmann et al., 2016; Strecker et al., 2007). The Paleogene steps in the evolution of the region that was to become the Andean Plateau in northern Argentina and southern Bolivia thus generated a pre-strained broken-foreland that subsequently experienced rapid, wholesale uplift accompanied by fundamental topographic and environmental changes in South America (Anderson et al., 2018; Garzione et al., 2008; Strecker et al., 2007).

In their detailed review of plateau-uplift mechanisms, Garzione et al. (2017) suggests a mantle-lithosphere delamination mechanism (Kay, Coira, & Viramonte, 1994; Sobolev & Babeyko, 2005) and orogen-normal shortening that drove rapid regional surface uplift of the Andean Plateau and the formation of an efficient eastern orographic barrier during the Neogene. This was coupled with major changes in exhumation, precipitation, and sedimentation patterns (Bookhagen & Strecker, 2008; Leier, DeCelles, & Pelletier, 2005; Mulch et al., 2010), together with aridification of the Andean Plateau (Strecker et al., 2007) and rapid vertical and lateral growth of the adjacent sub-Andean orogenic wedge (Anderson et al., 2018; McQuarrie et al., 2008; Uba, Strecker, & Schmitt, 2007).

7 CONCLUSIONS

The investigations outlined above have resulted in three main conclusions:

1. In the Tucsa-Laguna Colorada in the Puna and the Humahuaca areas of the Eastern Cordillera the middle Eocene Casa Grande Formation overlies a variety of different formations of the Cretaceous to Paleogene Salta Group with angular unconformity, implying regional pre-middle Eocene deformation in this part of the southern Central Andes. We have also identified intraformational unconformities and tectonically determined growth strata within the stratigraphic sequence of the Casa Grande Formation, which supports the concept of sustained deformation throughout the Paleogene.

2. Combining our new structural, stratigraphic, and provenance data with previously published structural and thermochronological data has allowed us to infer an incipient palaeo-high in the region of the present-day eastern Puna border, which aligns with the continuation of the Paleozoic deformation belt of eastern Bolivian. Previous investigations in this part of the southern Central Andes have shown that the reactivation and inversion of major fault systems that currently delimit many of the intermontane basins of the Puna-Eastern Cordillera transition zone was controlled either by contractionally reactivated Cretaceous extensional structures, or by Paleozoic shear zones and metamorphic fabrics.

3. In summary, we present robust new evidence which, together with previously published results from northwestern Argentina and southern Bolivia, shows that the early Cenozoic Andean deformation was remarkably diachronous, persistent and irregularly distributed across a wide belt in the backarc. The basal and intra-formational unconformities in the Casa Grande Formation imply that the Andean shortening in the Puna-Eastern Cordillera region occurred both before and during its deposition, i.e. during the middle Eocene, at the very least. Regional
plateau-building processes that were ultimately responsible for the final uplift of these highlands, subsequently affected this proto-landscape. In this context our results support models that the present-day Andean plateau corresponds to a pre-strained area of basins and intervening ranges with medium elevations that was affected by wholesale regional uplift during the Neogene.

ACKNOWLEDGEMENTS
The authors acknowledge financial support by FONCyT-ANPCyT (PICT-0432, PICT-1928) and CONICET (PUE-IBIGEO) from Argentina. Additional support came from DFG grant STR 373/34-1 and the Brandenburg Ministry of Sciences, Research and Cultural Affairs, Germany, within the framework of the international IGK2018 research training group “SuRFace processes, TECTonics and GEoresources: The Andean foreland basin of Argentina (StRATEGy)”. We are grateful to Humberto Tolaba and his family (Laguna Colorada area, Jujuy province) for their hospitality and to A. Scanferla and R.N. Alonso for constructive discussions. We thank T. Jordan, A. Stevens Goddard and D. Pearson for helpful comments that improved the manuscript and N. McQuarrie for editorial handling.

CONFLICT OF INTEREST
There is no conflict of interest concerning this contribution.

PEER REVIEW
The peer review history for this article is available at https://publons.com/publon/10.1111/bre.12510.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are provided in the Supplementary Material.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

**How to cite this article:** Montero-López C, Hongn F, López Steinmetz RL, et al. Development of an incipient Paleogene topography between the present-day Eastern Andean Plateau (Puna) and the Eastern Cordillera, southern Central Andes, NW Argentina. *Basin Res.* 2021;33:1194–1217. https://doi.org/10.1111/bre.12510