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SCIENCE

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# Geomorphological evolution of the western piedmont of Cumbres Calchaquíes (Tucumán Province, NW Argentina)

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**ABSTRACT**
The aim of this paper is to present a detailed geomorphological map of the western piedmont of Cumbres Calchaquíes (Tucumán Province, NW Argentina) bounded by the Amaicha River to the south and the administrative border with Salta Province to the north. It contains information about geomorphological units, their relative ages, and morphogenetic processes. The main map shows the presence of seven aggradation stages separated by incision phases. The first three stages (St1, St2, and St3) were modeled on a thick accumulation located in the upper piedmont from the Late Pliocene and Early Pleistocene. Intermediate stages (St4 and St5) are alluvial fans and pediments with less thickness and gradient. They cover the Early Pleistocene (St4) and the Late Pleistocene-Middle Holocene (St5). Finally, stages St6 and St7 are from the Upper Holocene.

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Quaternary; alluvial fans; pediments; Sierras Pampeanas; neotectonic

## 1. Introduction

The study of piedmonts in arid areas of NW Argentina is of great interest for the reconstruction of Quaternary paleoenvironments at the regional level. An important aspect of such reconstruction involves developing detailed geomorphological maps, providing information about geomorphological units, morphogenetic and morphodynamic processes, chronological sequences, and past human occupations (Peña-Monné & Sampietro-Vattuone, 2016; Sampietro-Vattuone & Peña-Monné, 2016, 2019).

The Santa María valley, one of the arid valleys in the region, is a tectonic depression located between Sierra de Aconquija (5500 m) and Cumbres Calchaquíes (4700 m) to the east and Sierra de Quilmes (5500 m) to the west. It is crossed by the Santa María River with a floodplain located between 2100 m a.s.l. in the south and 1550 m a.s.l. in the north, at the confluence with the Calchaquí River (Figure 1). The average annual rainfall of about 200 mm and temperature of 17°C (Peña-Monné et al., 2015). According to Köppen classification, the climate is arid, Bwk type (Minetti et al., 2005). Most rain (85%) falls in the summer (December-March), while the winters are dry. Dominant winds come from the N and NE, reaching 100 km/h (Peña-Monné et al., 2015). The study area includes the Monte and the Prepuna phytogeographycal provinces (Cabrera, 1971). In the piedmonts there are two main plant communities: the shrub steppes of xerophytes and cacti and *Prosopis* forest that grow only where water table is available. Sandy and salty soils are occupied by other edaphic communities (Bisigato et al., 2009; Cabrera, 1971; Morello, 1951).

Due to litho-structural factors, the valley exhibits a strong dissymmetry between both margins (Figure 1): the piedmonts of Cumbres Calchaquíes and Sierra de Aconquija are very long, with a complex system of pediments and alluvial fans (Sampietro Vattuone & Neder, 2011; Strecker, 1987; Strecker et al., 1987), while the piedmont of Sierra de Quilmes is shorter, steeped, and formed by a less complex system of alluvial fans that reach the Santa María River (Peña Monné et al., 2016; Peña-Monné & Sampietro-Vattuone, 2016, 2018a).

The aims of this paper are (a) to present the detailed geomorphological map of the western piedmont of Cumbres Calchaquíes bounded by the Amaicha River to the south and the administrative border with Salta Province to the north; (b) to provide geochronological and morphogenetic information; and finally (c) to propose a paleoenvironmental reconstruction of the region.

## 2. Geological settings

The Cumbres Calchaquíes, like other reliefs bordering the Santa María graben (Aconquija and Sierra de Quilmes), are composed of Upper Precambiran-

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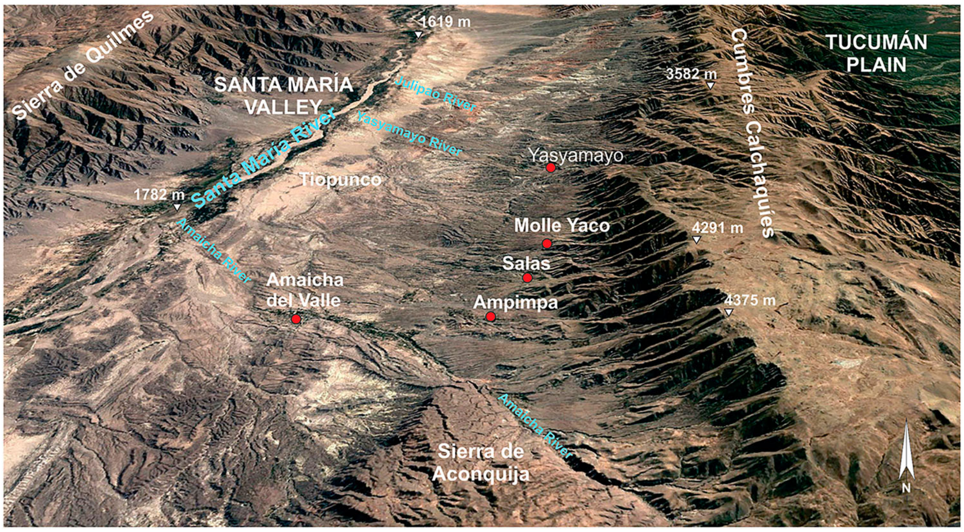


**Figure 1.** Oblique view of the study area taken from Google Earth (2019) showing main human settlements, rivers, and ranges.

Lower Cambrian metamorphic rocks of the Puncoviscana Group with intrusions of Ordovician granitoids (González et al., 2000). It is a low-degree metamorphism dominated by banded quartz-micaceous schists, metaquartzites, phyllites, and migmatites (Galván, 1981; Ruiz Huidobro, 1972).

An extensional phase around 13 Ma (Bossi et al., 1984; Strecker, 1987) developed a graben where the continental Pirgua Fm (Cretaceous) (Ruíz Huidobro, 1966) and the Santa María Group sedimented (Galván & Ruiz Huidobro, 1965). Compressive phases around 5.2 Ma (Strecker, 1987) uplifted the marginal mountains, produced thrusts in the graben borders by reactivation of the Paleozoic faults (Mon et al., 2012), and intensively faulted and folded the Mesozoic-Neogene sediments. The Cenozoic formations of the Santa María Group were described by Galván and Ruiz Huidobro (1965) and Ruiz Huidobro (1972). Later, descriptions were partially modified by González et al. (2000), Bossi et al. (2001), and Mon et al. (2012), among others. The Santa María Group is formed by detritic sediments, generally erodible (lutites and siltstones of different colors), although some harder levels (sandstones and conglomerates) are interbedded. Bossi et al. (2001) and Mon et al. (2012) grouped these formations into four sequences separated by discontinuities. The oldest one (Sequence I) is formed by Paleogene conglomerates and sandstones (Saladillo and Yacomisqui Fms.). It is followed by Sequence II, formed during the Miocene and integrated by San José, Las Arcas, Chiquimil, Ampajango, and Andahuala Fms. Sequence III was formed during the Pliocene, after the large intra-Andalhuala disconformity. Its upper section contains the Andalhuala and Corral Quemado Fms. Sequence IV, or Yasyamayo Fm., is deposited above a new disconformity. It spans the period between the end of the Pliocene and Lower Pleistocene (Bossi et al., 2001). Quaternary sediments extend on large surfaces partially covering the Neogene sequences.

## 3. Methodology

To make the geomorphological study and the map we follow the next steps:

1. The geomorphological map was drawn by using black and white aerial photographs (scale 1:50.000) (SPARTAM 1969) and a Google Earth satellite image (2019), according to the criteria proposed by Peña Monné (1997). Complementary oblique photographs were taken from DJI Phantom 4, Phantom 4 Pro, and a private flight.
2. After photointerpretation, the intensive field work (2014–2019) was made, complemented with outcrop descriptions of the representative landforms and features. Special attention was given to the recognition and mapping of the different Quaternary pediment levels, the morphogenetic processes, the establishment of their relative chronological sequence, and the neotectonic influence on landscape morphology.
3. The final map was drawn using QGIS v. 3.16, and the final graphical edition was made using FreeHand 11. The working scale was around 1:10000. The edited map was reduced to 1:27000 scale to fit into A0 format.

The map is composed of a base layer corresponding to the bedrock expressed by two contrasting colors. Other colored layers overlie previous units, corresponding to Quaternary accumulations (pediments and alluvial fans, floodplains, fluvial-eolian mantles).

Finally, symbols and lines are superimposed to define different geomorphological features, such as fluvial networks, glacial landforms, faults, tors, etc., as well as roads, archaeological sites, and present human settlements.

## 4. Results and discussion

The great lithological and structural contrast between Cumbres Calchaquíes and the graben of Santa María is reflected in the pronounced topographic unevenness created by tectonic deformations and geomorphological features. Arid conditions promoted intense erosion and, together with the continued Quaternary uplift (Strecker et al., 1989) of the ranges, drove the formation of a very complex landscape.

## 5. Geomorphology of the mountainous framework

The set of metamorphic rocks and granitoids of Cumbres Calchaquíes forms a broad, NS elongated horst showing flattened summits (Figures 1 and 2a). This large peneplain was formed *ca.* 13 Ma (Bossi et al., 2001) before the first Cenozoic materials (Santa María Group) sedimented, since they uncomformably overlie the basement. The uplift of Cumbres Calchaquíes began at that time and accelerated by *ca.* 4 Ma (Strecker, 1987; Strecker et al., 1987) to reach their current height during the Quaternary. Some residual reliefs, especially formed by granitoids, together with tor groups, are higher (4700 m) (Figure 3). Glacial and periglacial modeling created more surficial irregularity. Moreover, the erosion of the headwaters of the


Figure 2. (a) Frontal view of the western side of Cumbres Calchaquíes and its erosive flattening. At its foot, Cenozoic formations in the Santa María piedmont. In the foreground, alluvial fans and aeolian mantles close to Santa María River showing typical *Monte* vegetation; (b) aerial view of structural reliefs of Santa María Group exposed after the erosion of Quaternary pediments; (c) layer alignments on folded Neogene sandstones, silts, and clays; in the background, Quaternary pediments of stage St4; (d) aerial view of the fold of Santa María Group sediments in the north of Amaicha del Valle village and remains of stage St4; (e) detail of cuesta reliefs on Cenozoic sandstones in the NW sector of the Main Map.

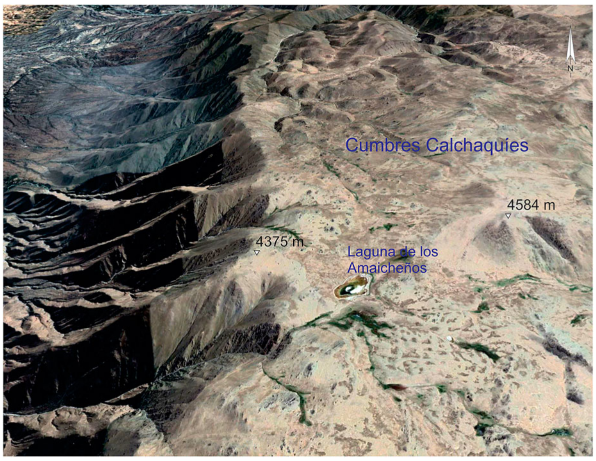


**Figure 3.** Google Earth (2019) oblique image of the general flattened summits of Cumbres Calchaquíes towards the east of Amaicha del Valle village. See some residual reliefs of granitic rocks and tors of metamorphic rocks. Remains of old glacial cirques and depressions occupied by lakes. Observe towards the east the pronounced unevenness between the range and the piedmont.

fluvial network opened valleys following the fracture network with different orientations.

Heights between 4000 and 4761 m a.s.l. of the Cumbres Calchaquíes favored climate conditions for the development of glacial and, in particular, periglacial features. There were well-developed glaciers on the east side of the range, where moraines from different cold stages are preserved. This is the case of Huaca Huasi basin and Minas and Matadero valleys (Arcuri, 1998; Halloy, 1982). On the western side, many fluvial heads of the Amaicha River tributaries show morphologies of glacial cirques and probably nivation hollows, highly modified by subsequent erosion processes (Figure 3). Some moraine arches are preserved over the peneplain and probably some inactive rock glaciers (Ahumada et al., 2017), together with till deposits forming discontinuous surfaces (main map). There are also overdeepening depressions occupied by lakes, like Laguna de los Amaicheños (Figure 3), partially filled with fine sediments forming highland wetlands (locally named *vegas*). Cold processes are still active over 4000 m a.s.l. (Ahumada, 2002; Ahumada et al., 2017; Halloy, 1982). Previous research found that cold events belong to the Final Pleistocene-Holocene. Peña-Monné and Sampietro-Vattuone (2019) showed that there were phases of glacier and/or rock glacier advances during the Late Glacial-Early Holocene (13–10 ky BP), the Early-Middle Holocene (ca. 10 ky–4.2 ky), and the LIA on the east side of Sierra de Aconquija (Alto Muñoz).

## 6. Piedmont of Cumbres Calchaquíes

A continuous N-S trending fault marks the border between Cumbres Calchaquíes and the Cenozoic deposits of Santa María valley. It is not visible on the surface due to the thick overlapping Quaternary deposits. Many fluvial courses -most of them temporary- with a base level on the Santa María or Amaicha rivers traverse, from E to W, the folded Cenozoic deposits. Their heads are on the scarp and highlands of the Cumbres Calchaquíes. During the Quaternary, these courses formed several stages of accumulation, giving rise to alluvial fans and pediments on the Cenozoic structures. At present, incision processes and many piracies between basins promote the development of a complex landscape formed by the remains of different accumulation stages among structural reliefs crossed by a segmented network (Main Map). The complexity of this piedmont contrasts with the simple evolution of the piedmont of Sierra de Quilmes, on the other side of the Santa María River, dominated by Holocene alluvial fans (Peña-Monné & Sampietro-Vattuone, 2016).

Alluvial fans had been preferred for human settlements due to the easy access and management of water resources. There are references to old human occupations in the area (Sampietro-Vattuone et al., 2020a) but only disperse sedentary settlements are visible from the air (Main Map). They belong to Early and Late periods described in the region by Rivolta (2007), Sosa (1996–97, 1999), and Sampietro Vattuone and Neder (2011), among others.

Between the high water divides (3500–4500 m a.s.l.) and our section of the Santa María River, located between 1780 and 1650 m a.s.l., unevenness promotes the high gradients of rivers and streams, favoring high erosion and transport capacity. Most upper basins are small; they barely penetrate into the Paleozoic relief of Cumbres Calchaquíes, except for the large Amaicha River upper course (214 km$^2$), which course extends SE through the summits of Sierra de Aconquija (Main Map). Other large upper basins in the area are Yasyamayo (66.5 km$^2$) and Julipao (65.4 km$^2$). The longitudinal profiles of these rivers (Figure 4) show the pronounced gradient diminishing after they reach the piedmont. The Julipao River has a gradient of 9.6% on its head but an average of 3.7% in the piedmont, while the Yasyamayo River gradient is over 11.7% in the ranges and 4% in the piedmont. Other rivers have similar profiles, but Amaicha River, with the largest basin, has a 6% gradient in the mountainous section and 2.3% in the piedmont.

Strecker (1987) conducted the first study on the Quaternary accumulations in the piedmont of Cumbres Calchaquíes, including the piedmonts of Sierra de Aconquija and Quilmes. He identified a system of pediments with five stages (Pediments I to V) dated by fission-track in tephras and by measuring carbonate buildup stages. Later, Sampietro Vattuone and Neder (2011) produced cartography of a large part of the piedmont of Cumbres Calchaquíes identifying

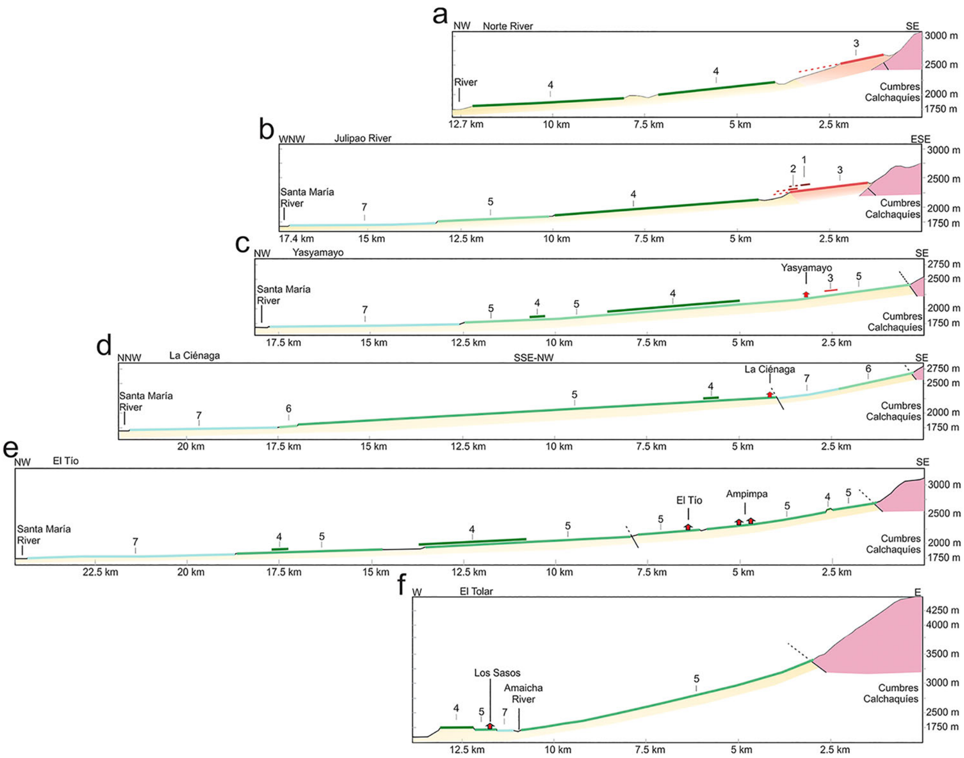

Figure 4. Longitudinal profiles of the different stages of Quaternary alluvial fans/pediments from the western piedmont of Cumbres Calchaquíes ordered from N to S.

three Pleistocene pediments and three Holocene alluvial fan stages related to those previously described by Strecker (1987). Our map (Main Map) shows two groups of deposits, mainly alluvial fans. However, alluvial fans and pediments are sometimes difficult to differentiate.

The first group of deposits is formed by Stages 1, 2, and 3. From a sedimentological point of view, the set partially corresponds to Yasyamayo Fm, formed by fanglomerates eroded from the eastern side of the Santa María basin. This formation was defined by Galván and Ruiz Huidobro (1965) and described by Bossi et al. (2001) as Sequence IV. Its age is later than 2.9 Ma, covering the Late Pliocene and Early Pleistocene, contemporary with the highest uplift of Cumbres Calchaquíes (Bossi et al., 2001). This formation is about 50–100 m thick, formed by gravels and semi-rounded blocks of granitic and metamorphic rocks. The internal structure is chaotic, formed by debris flow, and it represents the upper sections of alluvial fans. Geomorphologically, it was modeled on three stepped surfaces. The oldest ones (St1 and St2) have only residual character, while St3 (the youngest) still has an alluvial fan shape with depth incisions (Main map). In the upper section of the Cumbres Calchaquíes piedmont, crossed by the Julipao River, the three well-represented stages are visible (Figure 5a). There are St3 remains in the Yasyamayo sector (Figure 5b) and towards the N of Amaicha del Valle village. The longitudinal gradients of the surfaces of the three stages are between 6% and 8% and W-oriented

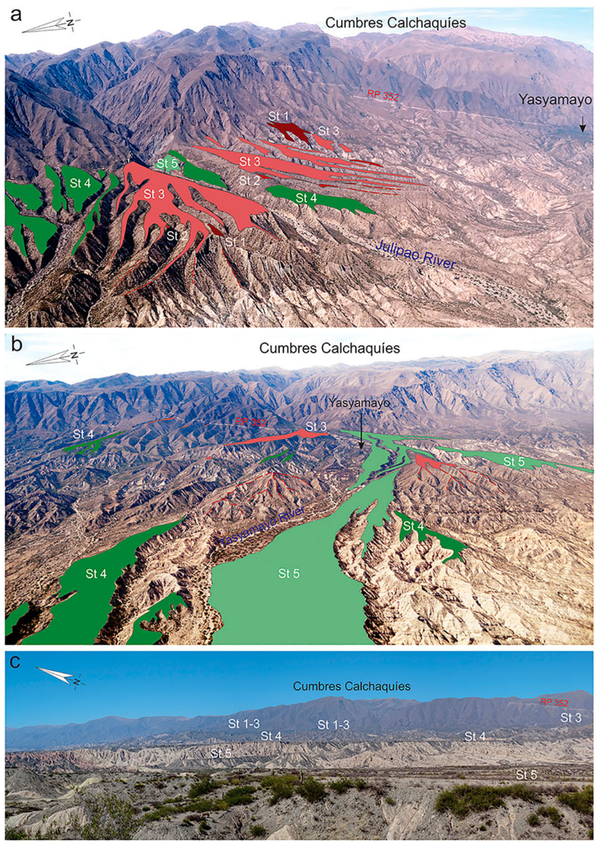

Figure 5. (a) Oldest stages (St1, St2, and St3) of the alluvial fans formed by Julipao River on its outlet from the range; (b) remains of stage St3 and middle stages (St4 and St5) in the Yasyamayo River; (c) panoramic view of stages St4 and St5 on the Mio-Pliocene formations from La Ciénaga sector; observe their continuity. In the background, residual reliefs of older stages and Cumbres Calchaquíes in the back.

(Figure 4a,b); due to the distance between these units and the base level of Santa María River, it is difficult to reconstruct their gradients in the middle and distal sections of the longitudinal profiles. Stages St1 to St3 may correspond to Pediments I to III established by Strecker (1987), although this cannot be ascertained because the author only observed Pediment I in the piedmont of Sierra de Aconquija. If this correspondence is correct, according to Strecker's (1987) chronology, St1 to St3 ages might be between 2.9 and 0.6 Ma.

The second group is formed by Stages St4 and St5, located at an intermediate height of the piedmont (Main Map). Large surfaces are preserved between the old stages (St1 to St3) and those closer to Santa María River (Figure 5c). They are discordant deposits, 4–6 m in thickness, occurring on the folded Mio-Pliocene formations with an irregular base (Figure 6a). The longitudinal gradient of their surfaces is around 3–5% (Figure 4a–d), with stage St4 being more pronounced. Unlike the older stages, the deposits of stages St4 and St5 are rounded gravels and well-stratified, and they show fluvial imbrication (Figure 6b). The development of carbonate coatings over gravels and calcitic speleothems is frequent (Figure 6c), hardening the deposit.

Stage St4 shows digitate morphologies, as narrow water divides among fluvial courses, and forms the highest reliefs in the middle sector of the piedmont. One of the wider surfaces of St4 is located between the Julipao and Yasyamayo rivers, showing the shape of an alluvial fan. There are large accumulations of this stage between Los Corpitos and Los Cardones (Main Map), on the north side of the Amaicha River (Figure 6d). This sector also features some relicts of older stages (St2 and St3) and other more recent ones, such as St5 (Figure 6d, Main map). The

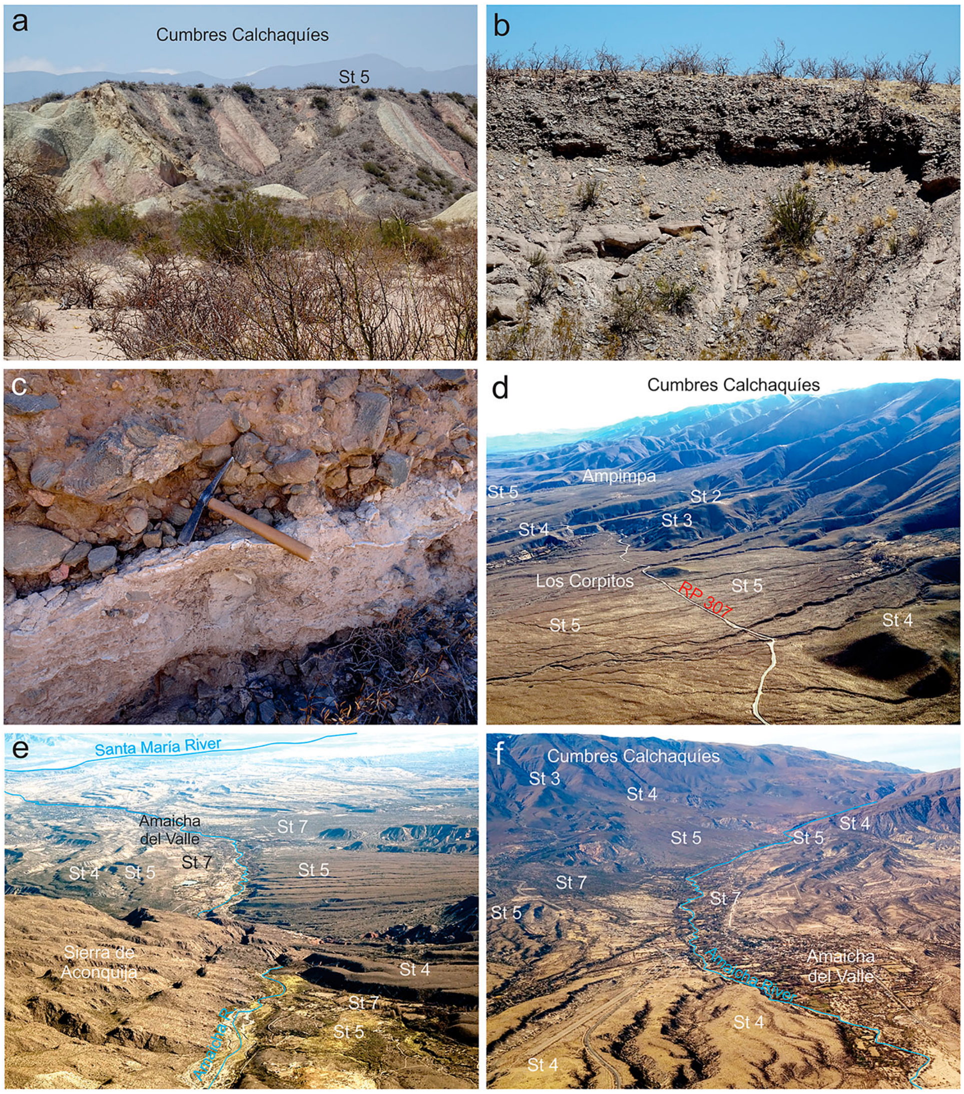


**Figure 6.** (a) Stage St5 leveling sandstone and pelite layers in the Yasyamayo area; (b) detail of the imbricate gravels of stage St5 from Yasyamayo area; (c) detail of carbonate speleothems and coatings from stage St5 of Los Cardones; (d) aerial view of different stages from Ampimpa and Los Corpitos; (e) aerial view of the Amaicha River valley from its headwater area (Sierra de Aconquija) in the southern sector of the study area. Quaternary accumulations around Amaicha del Valle village. In the background, Santa María River; (f) upper section of the Amaicha River between Cumbres Calchaquíes and Sierra de Aconquija showing different Quaternary stages.

longitudinal continuity of St4 stands out in the area of La Ciénaga (Figure 5c). Stage St5 occupies a large area in the middle sector of the piedmont, at the margins of the main streams. St5 maintains digitate forms that are sometimes entrenched among St4 remains, as fluvial terraces. This is the case of the alluvial fans of Yasyamayo (Figure 5b) and La Ciénaga (Figure 5c). Towards the southeast of the study area (Los Corpitos and Los Cardones), St5 forms large and continuous accumulations (Figure 6c,d, Main Map).

A special case is the deposits of the Amaicha River, towards its left margin, after it leaves the Sierra de Aconquija (South of Main Map; Figure 6e,f). Although they are represented as stages St4 and St5 on the Main Map to relate them to other alluvial fans in the piedmont, it is a stepped system following a fluvial terrace model. The set is composed of three sub-levels belonging to St4 and two other sub-levels belonging to St5. This set forms the water divide between the main channel of Amaicha River and other southern tributaries (Main Map). On the right margin, the two stages (St4 and St5) border the river and an abandoned channel that previously flowed north.

Stages St4 and St5 may correspond to Strecker's (1987) Pediments IV and V, respectively, the former dated between 0.6 and 0.3 Ma and the latter dated after 0.3 Ma. However, according to regional data, especially from Tafí valley (Sampietro Vattuone & Peña-Monné, 2016; Sampietro-Vattuone et al., 2020b), St5 must be younger and may correspond to H1 Unit (between 13 and 4.2 ky BP), based on tephras dating.

The third group of accumulations is formed by stages St6 and St7. They are Holocene stages and recent morphologies corresponding to fluvial terraces and alluvial fans around active fluvial courses. Thus, on the eastern margin of Santa María River, all tributaries develop wide alluvial fans (Main Map) located only 2–4 m above the present channel. They connect the last Mio-Pliocene structures with the floodplain (Figure 7a). Stage St6 has a 2–2.3% gradient and the accumulation can reach up to 4–5 m in thickness. These stages were stratigraphically described by Sampietro-Vattuone et al. (2020a) in La Sala alluvial fan, on the north side of Amaicha River. Figure 7b displays a stratigraphic profile of stage St6, with interbedded peats in the lower section (1528–1280 cal BP), a layer of tephra (V2) dated to *ca.* 600 cal BP, and after a gravel layer, an upper section dated to 550–454 cal BP. The outcrop ends with a soil dated to 350–310 cal BP. Therefore, the accumulation belongs to the Upper Holocene. This stage corresponds to the H2 Unit identified by Sampietro-Vattuone and Peña-Monné and Sampietro-Vattuone (2016) and Sampietro-Vattuone et al. (2020b) in neighboring Tafí valley.

Composed of pebbles, sands, and silts, St7 is the youngest stage. It reaches 2 m in thickness in the secondary ephemeral streams and wadi channels (Figure

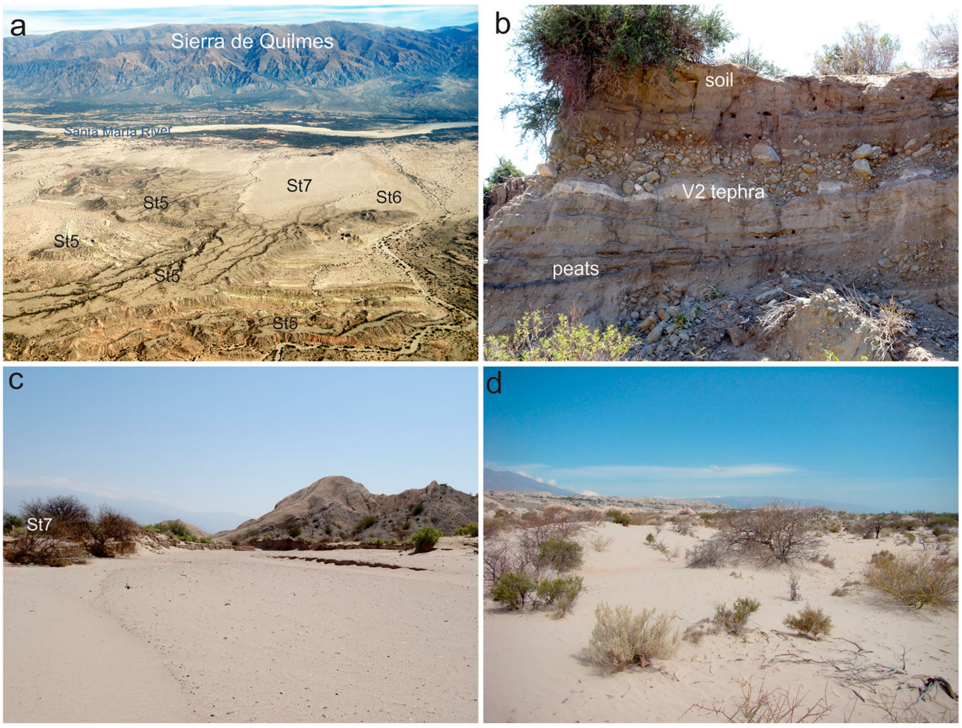


**Figure 7.** (a) Aerial view of the distal sector of the piedmont with younger stages (St5, St6, and St7) and the Santa María floodplain. In the background, Sierra de Quilmes; (b) outcrop of stage St6 from Campo Blanco; see the stratigraphic levels (explanation in the text); (c) ephemeral stream (type wadis) from the north of the study area with the floodplain partially covered with aeolian mantles; (d) small dune over the surface of stage St7 in the confluence between Yasyamayo and Santa María rivers.

7c), as well as the main streams. The gradient is around 1–1.1%. In many areas, finer materials are moved by dominant NNE winds (Peña-Monné et al., 2015; Peña-Monné & Sampietro-Vattuone, 2018b), forming aeolian mantles and small dunes (Figure 7d; Main Map), which are sometimes fixed by vegetation.

Lastly, it is noteworthy that the middle and lower stages (St4, St5, and St6) show deformations due to faults, with slight inner unevenness. Many of these faults are represented on the Main Map. More important faults are located between Molle Yaco and La Ciénaga and in a wide sector in the north and south of Amaicha del Valle village. In the first case (Figure 8a), faults are affecting stages St4 and St5, creating ruptures that favor erosion and allow the exposure of Mio-Pliocene soft materials. In the case of the area of Amaicha del Valle-El Tío, faults are affecting St6 and St7 stages and creating a sub-parallel fault network (Main Map), easily identifiable from the air. Scarcely entrenched small gullies that cross the surface of the landform change their direction to adapt to the tectonic alignment (Figure 8b). Finally, there is another functional fault described by Strecker (1987) at El Bañado. It traverses the Santa María River from NNW to SSE, at the confluence with the Amaicha River (Main map).

These examples of recent tectonic activity, in addition to the presence of several fluvial piracies and others in progress, indicate that this is a young relief resulting from the recent uplift of Cumbres Calchaquíes, as pointed out by several authors (Bossi et al., 2001; Strecker, 1987). The fluvial network on recent reliefs needs time to adapt and does so by network re-organization through fluvial piracies and neotectonics (Lavé, 2015). Both processes have also been related in other cases studied in the region (Gutiérrez et al., 2003; Peña-Monné & Sampietro-Vattuone, 2020; Perucca et al., 2018). Moreover, the longitudinal profiles shown in Figure 4, together with the gradients determined for each stage, show that the heights estimated for the Santa María River are under the present river base level. This phenomenon may be attributed to the continued fill of the central sector of the valley floor through which the river flows and/or a continued uplift of the Cumbres Calchaquíes during the Quaternary. The uplift could explain why older stages (St1 to St3) have higher gradients (8%), diminishing in the middle stages to 4–5% (St4 and St5), 2.3% in St6, and 1.1% in St7.

To completely understand the genesis of this piedmont, Quaternary climate changes must be considered in addition to the neotectonic processes. On the NE side of Sierra de Aconquija, in Tafí valley, Peña-Monné and Sampietro-Vattuone (2019) pointed out the geomorphological and chronological relationships with glacial advances at the end of the Pleistocene and Holocene (equivalent to stages St5 and St6) and the formation of the alluvial fans developed on this valley. These relationships may also influence the genesis of older stages from the western piedmont of Cumbres Calchaquíes, although there is no information available on the subject.

## 7. Conclusions

The geomorphological landscape of the western side of Cumbres Calchaquíes is the result of a long evolutionary process due to the combination of neotectonics and climate changes. There is a strong topographic and morphological contrast between the flattened surfaces affected by cold Quaternary environments of the Cumbres Calchaquíes summits and the structural reliefs of the Mio-Pliocene partially covered with Quaternary deposits. The geomorphological map shows the presence of seven aggradational stages separated by incision phases. The first three stages (St1, St2, and St3) are the product of the modeling of a large accumulation located in the upper

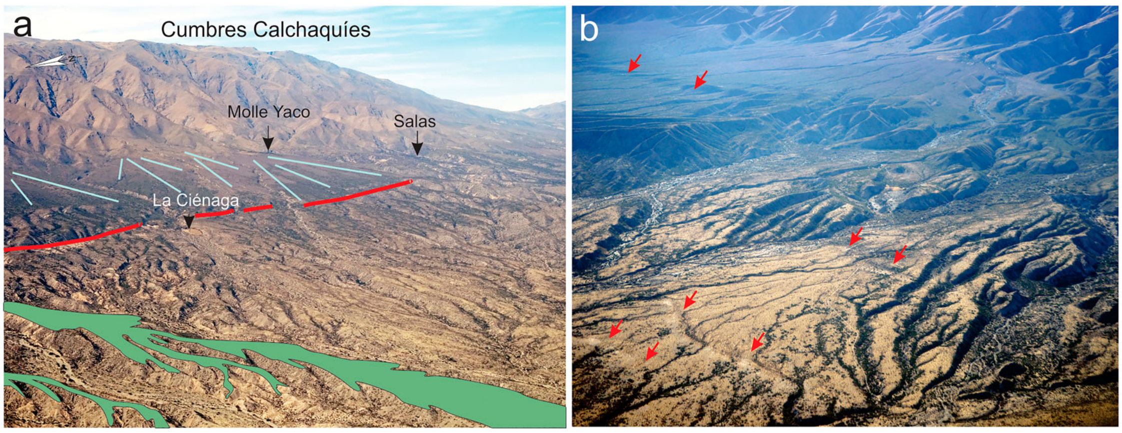


Figure 8. (a) Aerial view of the alluvial fans of La Ciénaga and Molle Yaco (stages St5, St6, and St7) affected by a Quaternary fault; (b) alluvial fans from the north of Amaicha del Valle village belonging to stage St5, uneven due to Quaternary faults. The fluvial network turns to adapt to new faults. Rearward the alluvial fans of Molle Yaco from the previous image (Figure 8a). Red arrows show the fault lines.

piedmont belonging to the Late Pliocene and Early Pleistocene. Intermediate stages (St4 and St5) are alluvial fans and pediments with less thickness and gradient. They cover the Early Pleistocene (St4) to the Late Pleistocene-Middle Holocene (St5). Finally, stages St6 and St7 are from the Upper Holocene.

## Software

QGIS 3.16 was used for processing and interpreting the spatial data, and the final version of the map was produced using Freehand 11.


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## Disclosure statement

No potential conflict of interest was reported by the author(s).

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## Data availability statement

The data that support the findings of this study are available from the corresponding author, MMSV, upon reasonable request.

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