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# **Integrated Stratigraphy of the Cenozoic Andean Foreland Basin (Northern Argentina)**

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Claudia Inés Galli, Ricardo Narciso Alonso and Lidia Beatriz Coira

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.69985>

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## **Abstract**

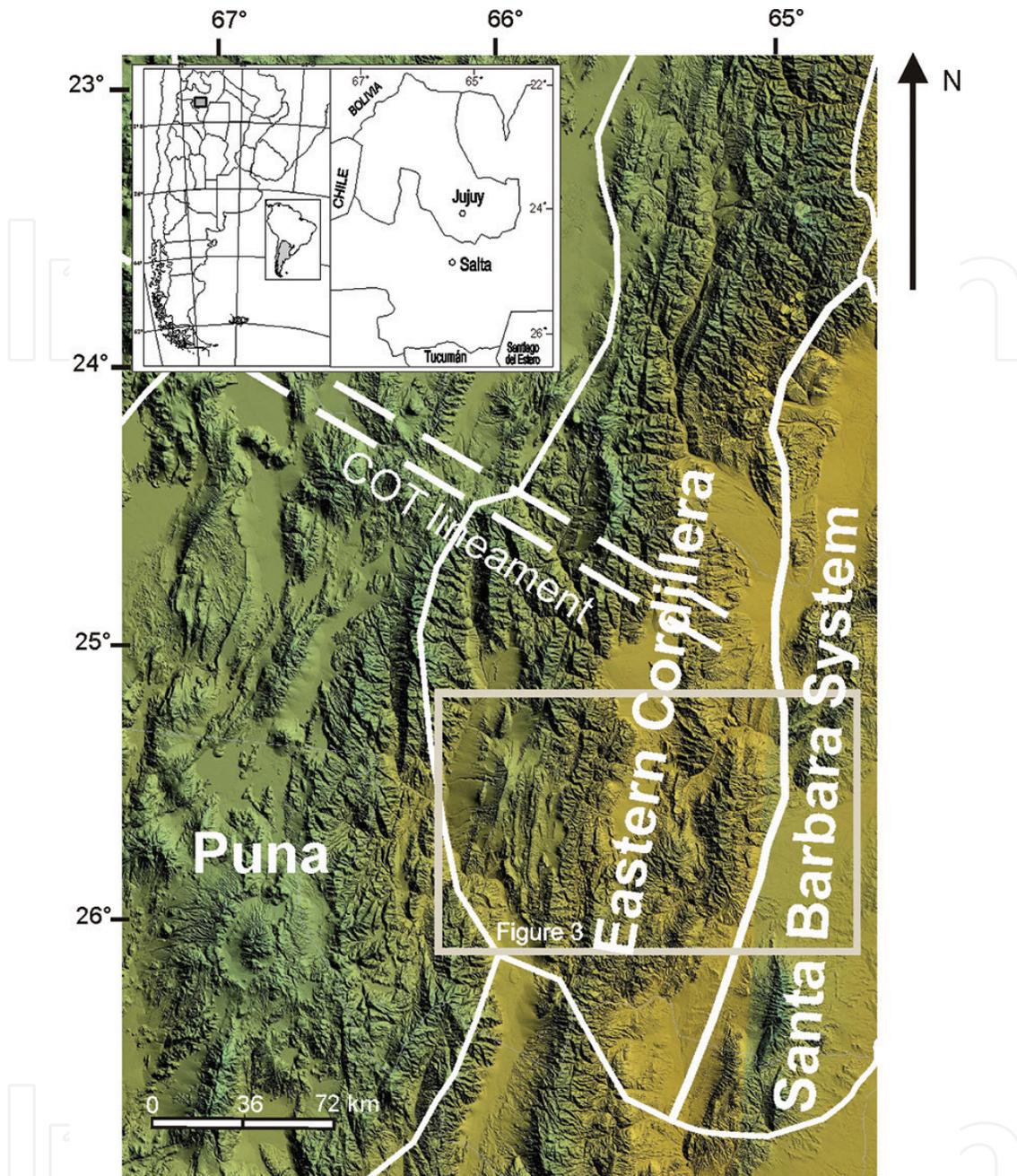
The stratigraphic and sedimentologic characteristics of Cenozoic deposits in north-western Argentina represent important tectono-sedimentary constraints on the evolution of the Andean foreland basin in this region. This nonmarine unit unconformably rests on the top of the postrift deposits of the middle Eocene Lumbreira Formation (Santa Bárbara Subgroup, Salta Group) or on older deposits. Eocene-Pliocene paleoenvironmental changes were the direct result of changes in the tectonic setting and accommodation space. This study describes the results of an integrated analysis of the middle-upper Eocene to Pliocene deposits filling the basins of the Cordillera Oriental. Fluvial deposits associated with different topographic slopes characterize the basins that formed in the Central Andes of north-western Argentina due to Cenozoic tectonic convergence. The formation of these basins led to the development of continental sedimentary environments, including an ephemeral fluvial system with aeolian dune fields; a sandy braided fluvial system; a playa lake; a sinuous gravelly sandy fluvial system with lagoons; and lagoons and marshes. These basins, which were probably connected during the first stage of their development, are characterized by different subsidence histories, sedimentary paleoenvironmental evolution patterns, topographic slopes, provenances, and paleocurrent directions, resulting in different tectono-sedimentary histories.

**Keywords:** Andean foreland basin, Payogastilla Group, Orán Group, provenance, stratigraphy, sequence stratigraphic, magnetostratigraphy

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## **1. Introduction**

The two-dimensional elastic model of the evolution of foreland basins, which proposes that the thrust load and the sedimentary load produce a wide deflection in the lithosphere [1, 2],



**Figure 1.** Satellite image of regional location of Cenozoic foreland basin.

has been widely applied to foreland basins [3–9]. These models show that the tectonic activity and the evolution of the fold and thrust belt are the drivers of subsidence in the associated foreland basins [10]. Sediment redistribution, autocyclic sedimentary processes, and eustatic baseline changes are important factors affecting the basin characteristics [2].

The main elements of “foreland basin systems” result from the accommodation created by the bending of the crust in response to the topographic load of the fold and thrust belt. This widely applied model includes four depozones: wedge-top, foredeep, forebulge, and back bulge [6].

Another model in the northern Argentina, the “broken foreland basin,” describes basins that form in retroarc zones that are largely influenced by basement structures. In these basins, the accommodation develops mainly along reactivated and inverted structures, thereby giving rise to relatively restricted basins with variable and laterally limited connections [10].

The clastic deposits of the Middle Eocene-Pliocene are excellent examples of the Cenozoic foreland basin, which is associated with Andean orogeny [11, 12] that evolved into intermontane basins (Figures 1 and 2). In north-western Argentina, the Cenozoic sediments reflect the passage of a “rift” basin during the Eocene. These deposits are associated with the Salta Group and the Andean foreland basin, which comprises extensive basins in which the Payogastilla

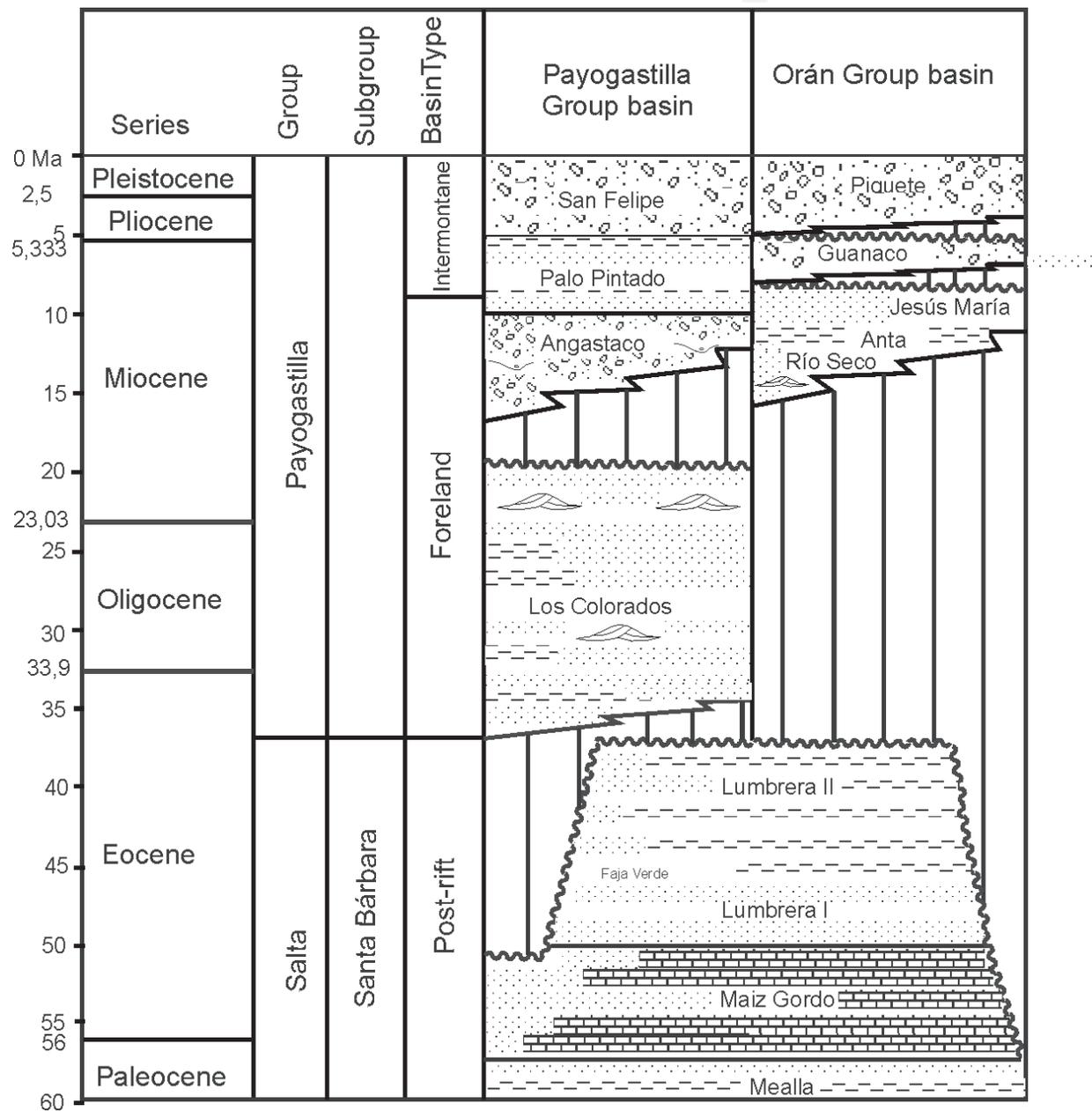


Figure 2. Stratigraphic chart of the units from Calchaquí basin and Orán basin.

Group (Valle Calchaquí) and the Orán Group (Lerma Valley, Sianca Valley, Santa Bárbara System, and Sierra de Zapla) accumulated (**Figures 1 and 2**).

The structural evolution of the Andean foreland basin was mainly controlled by the inversion of the extensional basins of the Cretaceous rift of the Salta Group, which overlaps with the general migration of the deformation toward the foreland. Some authors describe this as “broken foreland basin,” a view with widespread consensus today [13, 14], while others refer to it as a “foreland basin system” [6, 7].

The Cenozoic Andean foreland basin provides an excellent opportunity to define the relationships between tectonism and sedimentation because its geologic history is closely linked to the tectonic activity over the evolution of the river system in the basin. In this study, the paleoenvironmental characteristics, the types of contacts between units, the provenance of the deposits, and the geochronologic and paleomagnetic ages of the stratigraphic units in each basin are presented. The integration of these data has improved our understanding of the basin evolution during the Andean orogeny.

## 2. The pre-Andean basement

In Cordillera Oriental, the upper Neoproterozoic La Paya Formation basement unit contains low-grade metamorphosed sandstones and mudstones [15, 16] that grade southward into schists, gneisses, and migmatites [17, 18] in the Sierra de Quilmes and Cumbres Calchaquíes (**Figures 2 and 3**).

Marine quartzites of the Meson Group are arranged in angular unconformity on top of the previous deposits [19] (middle to upper Cambrian).

The marine deposits of the Silurian-Devonian basin are represented by deposits of an extensive marine platform environment whose greater thicknesses are developed east of the Cordillera Oriental [20].

The sedimentary succession that overlaps the Neoproterozoic to lower Paleozoic basement corresponds to the Cretaceous-Paleogene strata of the Salta Group [21] and the Paleogene-Neogene strata of the Payogastilla Group and Orán Group.

The Salta Group, in Cordillera Oriental and Santa Bárbara System, is present in three subbasins: Metán, Alemania, and Pucará-Brealito (**Figure 3**). The Salta Group deposits are divided into the following three subgroups (from base to top): Pirgua [22], Balbuena, and Santa Bárbara [23]. The Pirgua Subgroup is composed of sandstones, conglomerates, and siltstones at almost all localities and represents the syn-rift fill. The Balbuena Subgroup, which accumulated during the Maastrichtian to Early Paleocene, represents the early postrift stage and is composed of white sandstones (Lecho Formation) and gray to yellow limestones in the upper part (Yacoraite Formation). The Santa Bárbara Subgroup consists of the Mealla, Maíz Gordo, and Lumbrera formations [23] and is dominated by fine-grained red sandstone, siltstone, and green mudstone.

The Lumbrera Formation [23], which represents the uppermost part of the Salta Group (**Figure 2**) is composed of claystones and siltstones and is always reddish-brown to red. In the

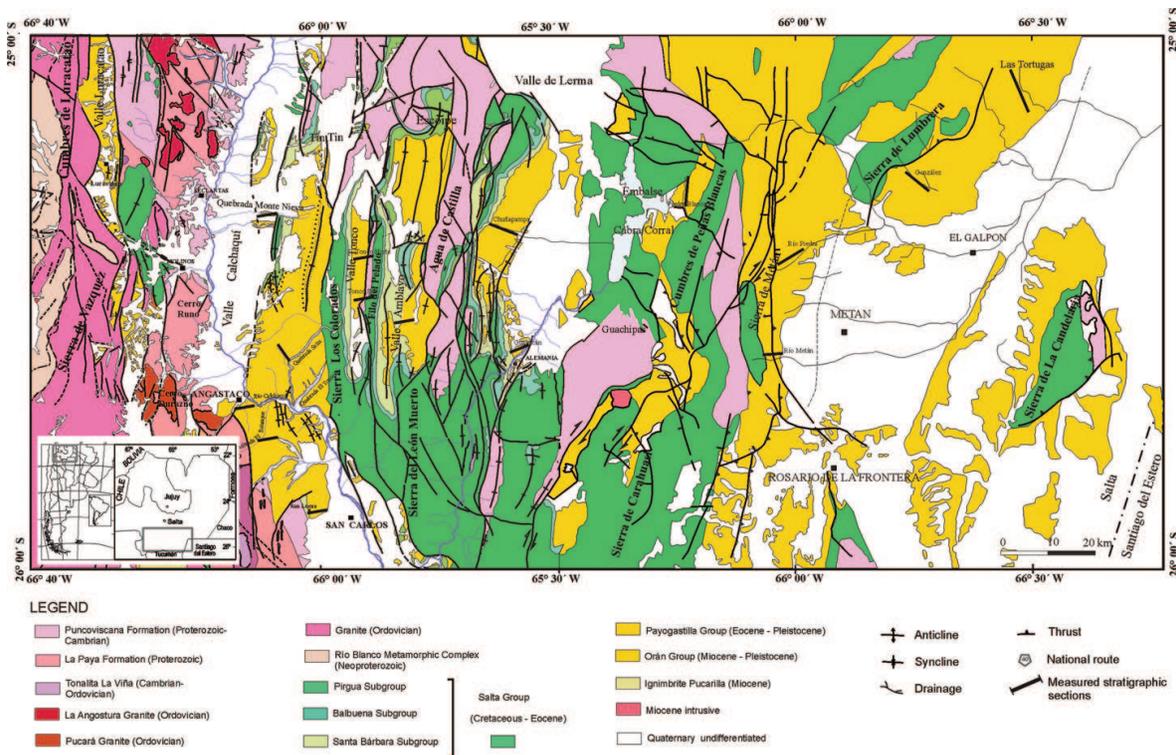


Figure 3. Geologic map of the region in southern Salta province, northwest Argentina. Adapted from [68, 69].

Lumbrera Formation, three units have been identified based on the contrasting characteristics of the facies groups: the lower Lumbrera Member, the *Faja Verde*, and the upper Lumbrera Member [24]. The lower part is fossil-rich [25–27] and was dated to the lower to middle Eocene based on vertebrate associations [28]. The top of the *Faja Verde* is an omission surface that marks the beginning of the sedimentary foreland basin for some authors [4, 29–31].

A clear paraconformity is located between the Lumbrera II Formation and the Los Colorados Formation. In parts of the foreland basin, a paraconformity between Lumbrera II Formation and Río Seco Formation corresponds to a hiatus from lower Eocene to middle Miocene.

The Orán Group [32] includes the Paleogene and Neogene deposits, which, in the Salta and Jujuy provinces and surrounding areas, overlie on the Salta Group (Cretaceous-Eocene, Figure 2). During the upper Neogene, several tectonic events related to the uplift of the Andes occurred and caused variations in the basins located to the east, consequently influencing the characteristics of the sediments, which can be divided into two sequences: the lower, Metán Subgroup, and the upper, Jujuy Subgroup (Figure 2).

### 3. Calchaquí Basin

#### 3.1. Los Colorados Formation

The middle to upper Eocene deposits of the Payogastilla Group, including the Los Colorados Formation, represents the initial stage in the evolution of the Andean foreland basin of

north-western Argentina (**Figure 2**). The area of Tin Tin, Tonco, and Calchaquí valleys feature outcrops with well-documented, complete profiles of the Los Colorados Formation (**Figure 4**).

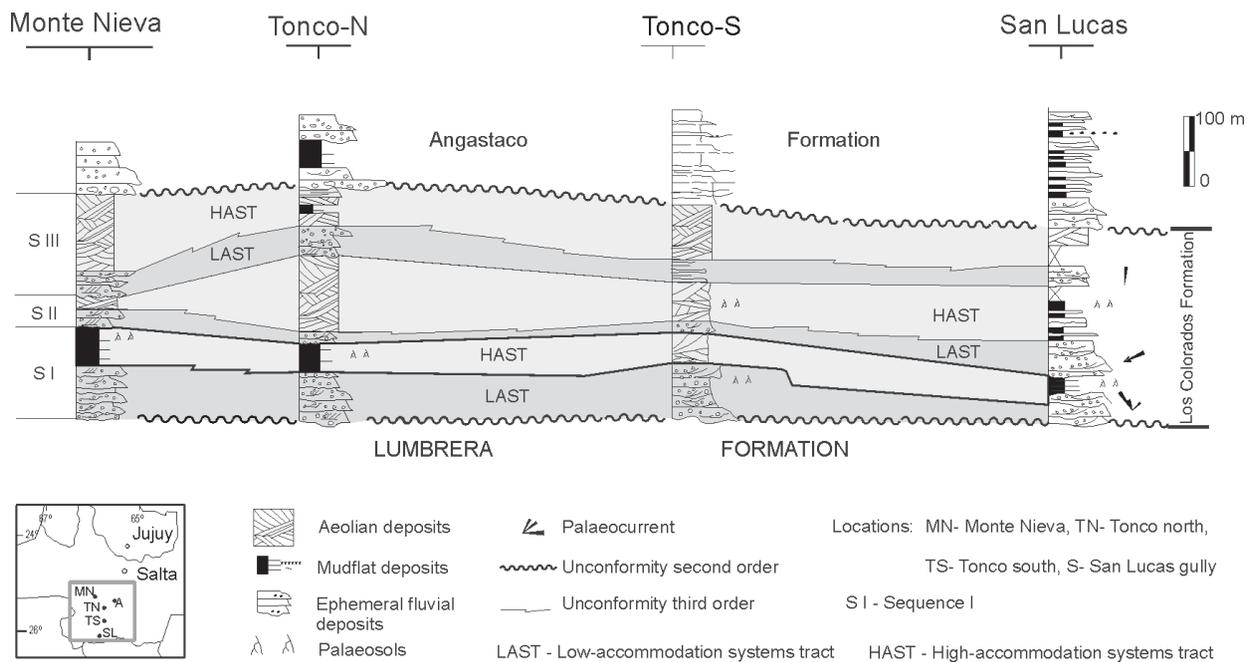
The first episode of filling of the basin started with the deposition of the Los Colorados Formation in the middle to upper Eocene [33, 34]. A clear second-order subaerial unconformity Type 2 [35, 36] is located between the Lumbrera Formation and Los Colorados Formation. This unconformity is also found in the Luracatao and Pucará valleys [13, 14, 31, 34].

Based on the fossil record, the initial development of the foreland basin, at least in the Luracatao Valley, occurred during the middle Eocene [34]. Sedimentary filling of the basin began with the deposition of the Los Colorados Formation and was characterized by sheet-flood ephemeral fluvial deposits formed by unconfined and confined channels within dune fields in an arid region. In some parts of the basin, aeolian deposits interfinger with ephemeral fluvial systems, such as those in the Tonco Valley (Sequences I and III).

Detrital zircons from the town of Angastaco have been dated to  $37.6 \pm 1.2$  Ma [37] and the apatites from Monte Nieva have been dated to  $28.7 \pm 1.9$  Ma [6]. This deposit is ~300 m thick and contains basal sandstone and siltstone facies of an ephemeral fluvial system and is associated with aeolian deposits [38]. A tuff horizon intercalated in the aeolian deposits in the Tin Tin section has provided an age of  $21.0 \pm 0.8$  Ma (U-Pb) [39].

3.1.1. Facies, depositional architecture, and sequence stratigraphy of the Los Colorados Formation

The Los Colorados Formation is an unconformity-bounded depositional sequence that corresponds to a major stratigraphic cycle in the evolution of the foreland basin in the Calchaquí



**Figure 4.** Correlation of Los Colorados Formation based on the sequence stratigraphy analysis.

Valley. The entire Payogastilla Group corresponds to a first-order sequence [35, 36], i.e., it is associated with one distinct tectonic setting. Hence, according to the hierarchy based on the magnitude of base-level changes that resulted in the formation of the sequence, the Los Colorados Formation can be assigned to a second-order level of stratigraphic cyclicity. In this context, the three depositional sequences that form its stratigraphic subdivisions can be considered third-order sequences. The correlations reveal that the deposits are separated at the base and top by second-order subaerial unconformities [35, 36].

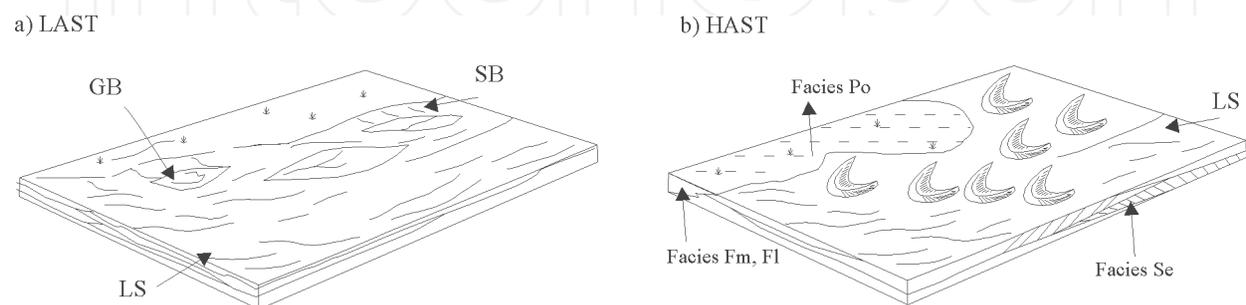
The lower boundary of the Los Colorados Formation is marked by an increase in the grain size, by a paleoenvironmental change from the mud flat deposits of the Lumbrera Formation to ephemeral fluvial systems with conglomerates and by a marked change in the sedimentary provenance. This unconformity is very clear in the northern part of Amblayo Valley. The controversial upper boundary is an erosional unconformity (Tonco Valley) and represents a change in depositional paleoenvironment from distal sandy ephemeral fluvial system and clay playa deposits or aeolian accumulations to a braided fluvial system (**Figures 4 and 5**).

The Los Colorados Formation deposits were identified as facies of an ephemeral fluvial system with flashy discharge, calcic paleosols, and dune fields, which are characteristic of arid regions.

Sequence stratigraphic concepts are applicable, with modifications, to the successions that are entirely nonmarine in origin, even where there are no marine surfaces with which to correlate them, such as in the Payogastilla Group basin. In a fully nonmarine environment, fluvial accommodation is created and destroyed by the following: (a) differential tectonic movement between basin and source areas, which can modify the amount of sediment supply and the gradient of the landscape profile and (b) cycles of climate change, which can alter the balance between fluvial discharge and sediment load [40].

### 3.2. Angastaco Formation

The thickness of the Angastaco Formation varies considerably between the sections in which it is fully exposed (e.g., from 4450 m at the Calchaquí River to 1500 m in the Tonco Valley, **Figure 6**). The depocenter of the basin between ~13.7 and 10 Ma was located in the area of Angastaco.



**Figure 5.** Palaeoenvironment with architectural elements illustrated using schematic diagrams of Los Colorados Formation. a) LAST (e.g. Sequence II), proximal ephemeral confined (SB element) in the base, b) unconfined ephemeral - mud flat (LS element) associated with aeolian deposits (HAST).

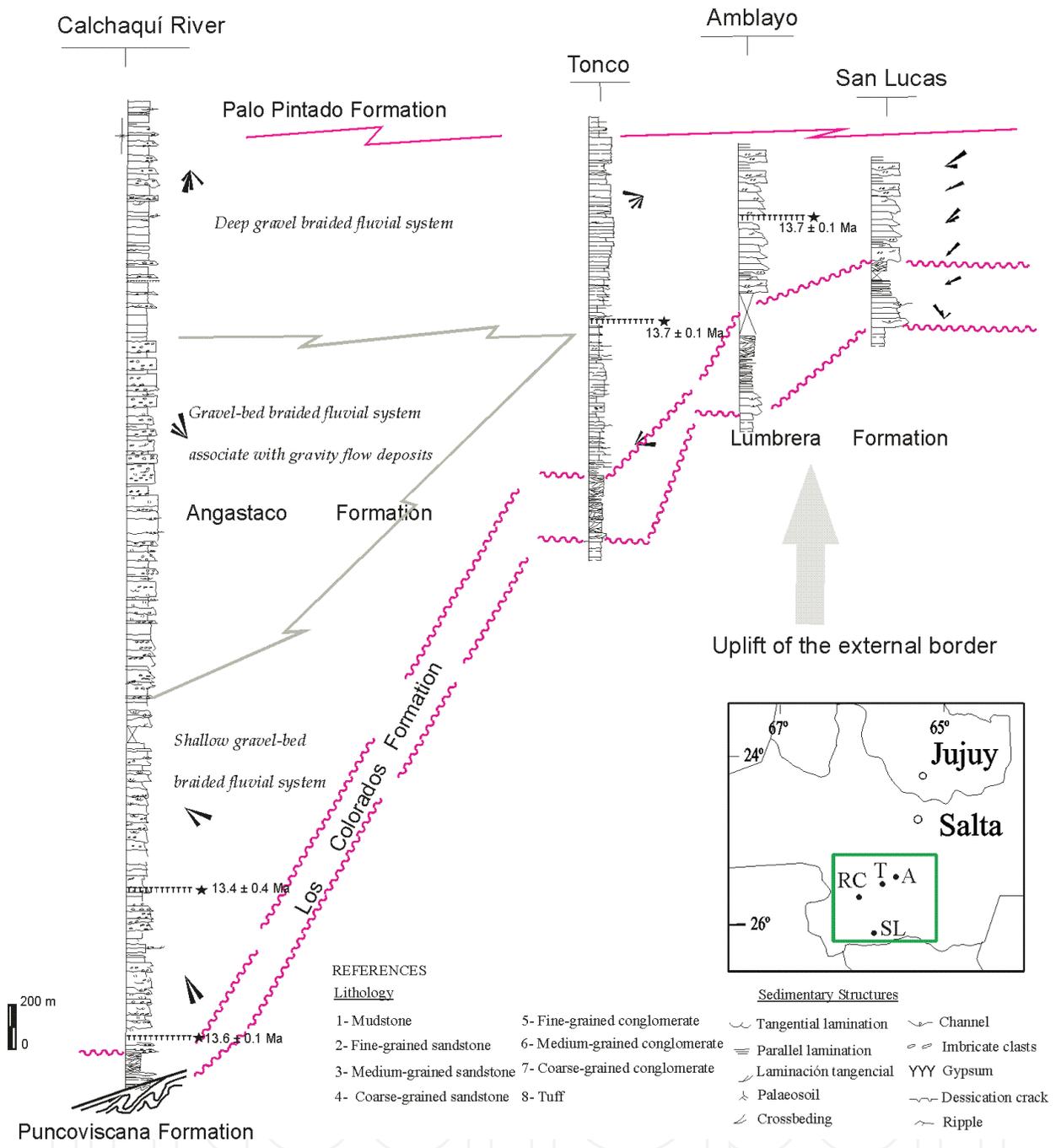
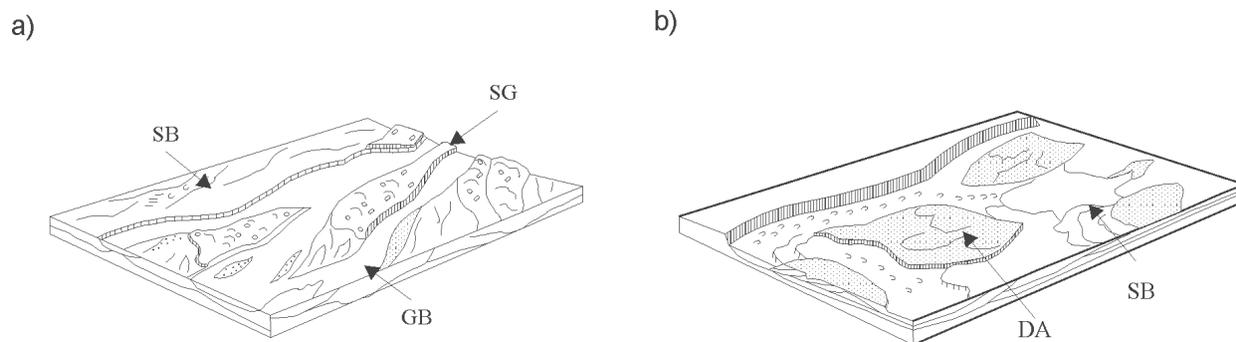


Figure 6. Stratigraphic correlation of the Los Colorados and Angastaco formations (base of Pavogastilla Group).

The structures are located on the western edge of the basin and are similar to those that created local accommodation space in other broken foreland settings [10, 13, 14, 41, 42].

### 3.2.1. Facies and depositional architecture of the Angastaco Formation

Several fluvial systems have been recognized based on the lithofacies and stratigraphic architectural. The lithofacies were characterized based on the deposits' properties (Table 1) and on the stratigraphic analysis (Figure 7, Table 2).



**Figure 7.** Description of the palaeoenvironment with architectural elements illustrated using schematic diagrams of Angastaco Formation. a) Gravel-bed braided river system associated with gravity flow deposits, Angastaco Formation of the middle part of the deposits with its architectural elements, b) Deep gravel-bed braided river at the top Angastaco Formation, with its architectural elements.

Code	Lithofacies	Interpretation
Gmm	Massive conglomerate, poorly sorted matrix-supported clasts, sandy matrix. Strata with abrupt lateral terminations.	Debris flow (high strength). Flows passively occupy preexisting alluvial topography and mold to the preexisting channel.
Gmg	Massive conglomerate, matrix-supported clasts with normal grading.	Pseudoplastic debris flow (low strength).
Gcm	Clast-supported, massive conglomerate, with poorly sorted, very angular clasts.	Pseudoplastic debris flow (inertial bedload).
Gh	Clast-supported conglomerate, crudely bedded, sandy matrix. Imbrication.	Longitudinal bars, lag deposits.
Gi	Conglomerate with well-sorted and rounded clasts, sparse matrix, imbrication.	Longitudinal bars.
Gt	Matrix-supported conglomerate with trough cross-bedding.	Minor channel fills.
Se	Sandstone with cosets of grouped trough cross-beds (10–20 m thick), very well-sorted, rounded grains.	Aeolian dune deposits.
St	Very coarse-grained sandstone, sets of trough cross-beds. Wedge-shaped strata with residual lag.	Linguoid (3D) dunes.
Sp	Very coarse-grained sandstone, sets of planar cross-beds, and lag deposits. Beds with erosional bases.	Transverse and linguoid bedforms (2D dunes).
Sl	Fine- to coarse-grained sandstone, planar lamination, lag deposits. Tabular beds.	High flow conditions. Flash flood.
Sm	Fine- to coarse-grained sandstone, poorly sorted, massive, with clastic wedges and beds with erosional bases.	Upper flow regime and poorly sorted deposits.

Code	Lithofacies	Interpretation
Fl	Very fine-grained sandstone, siltstone, and mudstone, fine lamination, desiccation cracks, roots, bioturbation.	Overbank, abandoned channel, or waning flood deposits.
Fm	Massive siltstone and mudstone, very thin beds.	Overbank or abandoned channel deposits.
Fo	Siltstone and mudstone, very small ripples and very thin laminations.	Swamp and lacustrine in the floodplain.
Po	Very fine-grained sandstone, siltstone and mudstone, massive with calcified rhizoliths penetrating down into sandstone of aeolian dune origin.	Paleosols. The rhizoliths emanate from the bases of damp and wet interdune units.

**Table 1.** Major lithofacies identified in the Payogastilla Group and Oran Group (modified from Ref. [47]).

Formation	Code	Architectural elements	Principal lithofacies
San	GB	Gravel bars	Gmg - Gi - Gt - Sm
Felipe	SB	Sandy bedforms	St - Sm - Fm
	GB	Gravel bars and bedforms	Gt - Gm
Palo	LA	Lateral-accretion macroform	Gt - Sm
	CS	Crevasse splay - Channel	Sp - Sl - Sm
Pintado	FF(CH)	Abandoned channel fills	Fl - Fm
	FF	Floodplain deposits	Fl - Fm - Fo - Po
	SB	Sandy bedforms	Sl - Sm - Fl
	GB	Gravel bars and bedforms	Gh - Sm
	DA	Downstream – accretion macroform	Gh - Gi - Gm - Sl - Sm - St
Angastaco	SB	Sandy bedforms	Sm - St - Sp - Sm
	GB	Gravel bars and bedforms	Gh - Gcm
			Gmg
	GB	Gravel bars and bedforms	Gh - St
			Gh - Gi - Sm
			Gh - Gt - Gmg
	SB	Sandy bedforms	Gh - Gt - Sl
Sl - St - Sp - Fl - Fm			
Los Colorados	LS	Laminated sand sheets associated with aeolian deposits	Sl - Fm - Fl - Se
	SB	Sandy bedforms	Gcm - Sm - St - Sp
	GB	Gravel bars and bedforms	Gm - Gt

**Table 2.** Codes of the major architectural elements defined for the Payogastilla Group with their characteristic lithofacies.

The Angastaco Formation conglomerates in the western part of the basin contain substantial amounts of plutonic rocks from the Oire Eruptive Belt. In the eastern part of the study area (Tonco profile), however, slates, phyllites, and schists from the Puncoviscana Formation are present. There are fewer paleovolcanic clasts from the Eruptive Belt of the eastern Puna (Calchaquí River) and neovolcanics in the San Lucas River and the Tonco south area, which are associated with paleocurrent directions from the north-west and west. In the San Lucas and the Tonco south River area, a small but significant component of red sandstone clasts from the Formation and gray sandstones from the Maíz Gordó Formation represent the Salta Group. These data suggest the tectonic uplift of the Sierra León Muerto in the eastern study area (**Figures 3 and 6**) [43].

In the upper section, the paleoenvironment changes to more erosional rivers with deep channels. The paleocurrents are from the north-west and are associated with neovolcanic clasts from the volcanic-sedimentary deposits of the Almagro-El Toro basin, which has a depositional and eruptive age between 14.3 and 6.4 Ma and synorogenic deposits dated at ~11 Ma [44].

### 3.3. Palo Pintado Formation

The Palo Pintado Formation is ~800 m thick and contains a tuff level that has been dated to  $10.29 \pm 0.11$  Ma (K/Ar) [45]. Near the top is another pyroclastic level that has been dated to  $5.27 \pm 0.28$  Ma ( $^{206}\text{Pb}/^{238}\text{U}$ ) [46] and  $5.98 \pm 0.32$  Ma [47] (**Figure 7**). The unit comprises thickening- and coarsening-upward cycles, including matrix-supported conglomerates, fine- to medium-grained sandstones, and fine-grained sublithic sandstones ending in green, brown, and gray siltstones levels (**Figure 8a**).

These deposits have been interpreted as wandering sand-gravel fluvial systems with small lakes [48]. The geometry and the fluvial architectural characteristics are a direct consequence of allogenic controls, such as tectonic activity, under constant climatic conditions.

During the upper Miocene, the uplift of the basin caused an increase in the sedimentary accommodation/deposition (A/D) rate and was also associated with a change in the petrologic composition of the deposits [48]. The resulting orographic barriers produced a warmer and wetter climate [49].

#### 3.3.1. Facies and depositional architecture of the Palo Pintado Formation

The fluvial architectural characteristics and associated lithofacies in the Palo Pintado Formation define a fluvial system with intrachannel and overbank deposits [43]. The intrachannel deposits include gravel bars and bedform deposits (GB) and sandy bedforms comprising transverse bars and sand waves formed by vertical accretion and downstream flow (SB) (**Table 2, Figure 8a**). In contrast, the overbank deposits are represented by three types of features: (a) lateral accretion macroforms, which are characterized by large-scale, gently dipping second-order bounding surfaces that correspond to successive increments of lateral growth, with erosional bases and gradational tops; (b) small crevasse splay channels resulting from erosion at

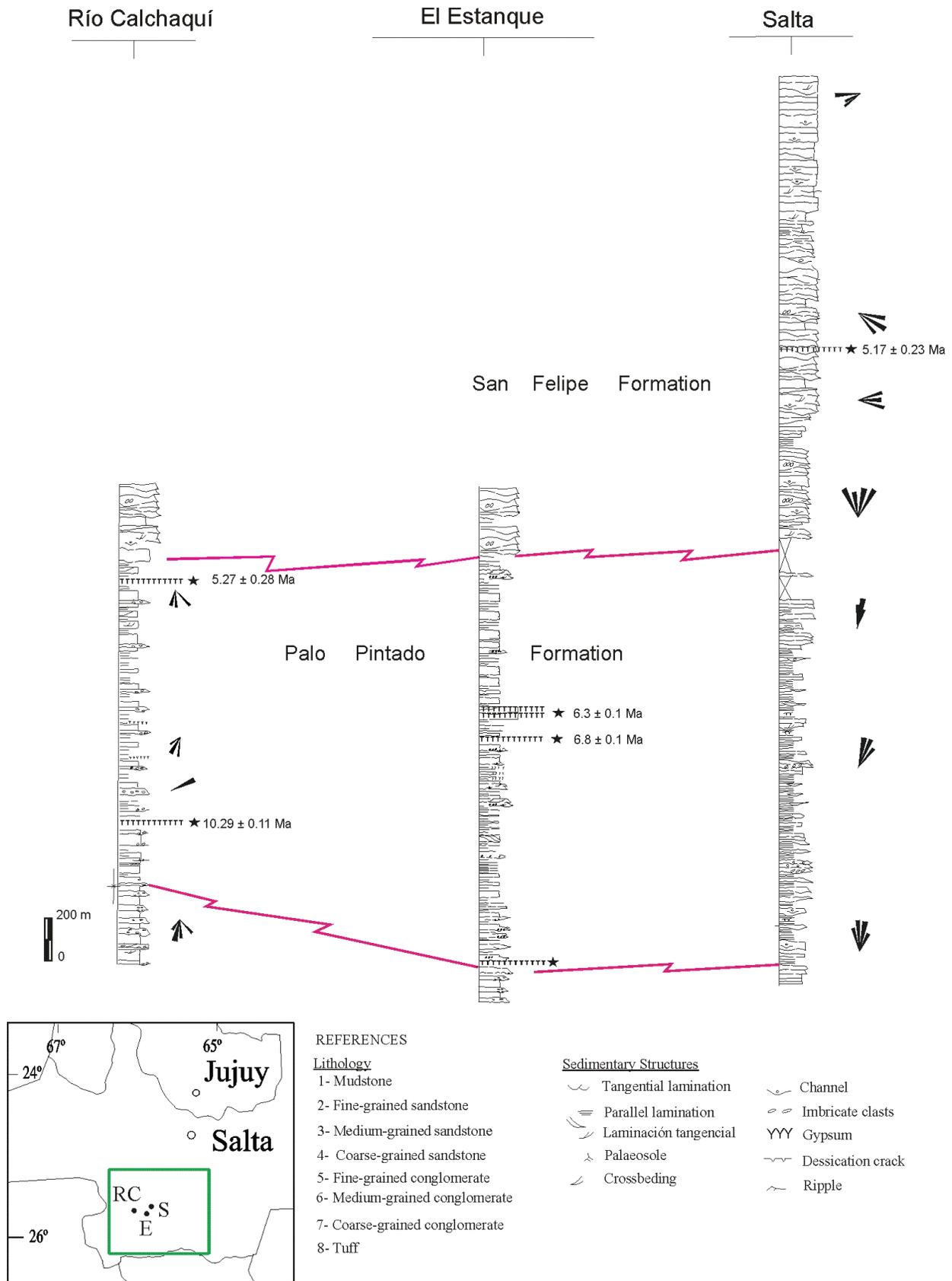


Figure 8. Stratigraphic correlation of the deposits of Palo Pintado and San Felipe Formations (top of Payogastilla Group).

the borders of the main channel during flood events, which correspond to crevasse channels (CS); and (c) the development of large floodplain deposits (FF) (**Figure 8a, Table 2**).

X-ray diffraction data from floodplain clay minerals revealed the presence of illite, montmorillonite, magnesium-rich smectite, and kaolinite generated by hydrolysis under a warm and humid climate [50].

The occurrence of *Caiman cf. latirostris* also supports the hypothesis that the climatic conditions in Valle Calchaquí during the upper Miocene were comparatively wetter than those inferred for contemporaneous units deposited to the east (Guanaco Formation, Orán Group) [51].

The paleomagnetic analysis reflects the increase in the sedimentation rate from 0.41 mm/year at the base, to 0.11 mm/year at the middle, to 0.66 mm/year in the top of the deposits, which is associated with a higher percentage of Salta Group clasts. Paleocurrent directions from the south and the south-east indicate the tectonic reactivation of the deposition area from the Sierra León Muerto (and its continuation to the north as the Sierra Los Colorados). The exhumation was registered before in the conglomerates of the Angastaco Formation [43, 52].

In the Quebrada Salta, quartzite clasts with *Skolithos* from the Mesón Group (upper Cambrian) and paleocurrents from the north and north-east suggest a provenance from Quebrada El Toro, where the Mesón Group (upper Cambrian) is well exposed.

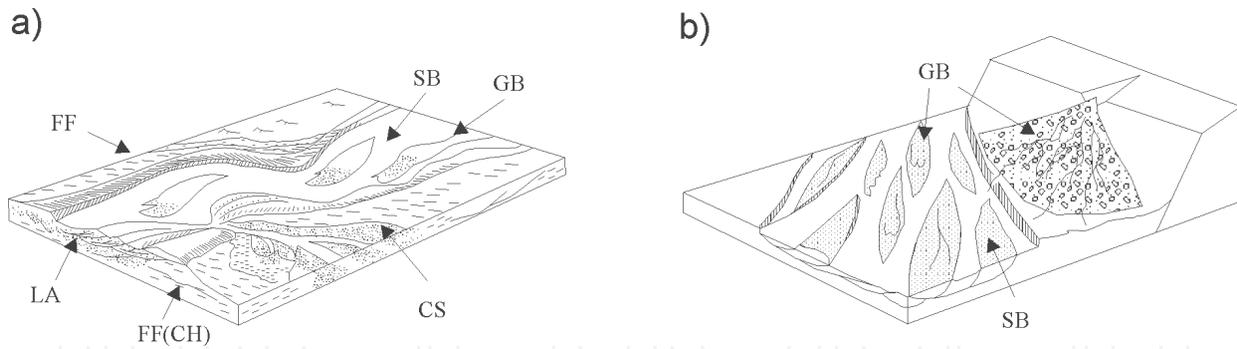
### 3.4. San Felipe Formation

The deposits of the San Felipe Formation at the top of the Payogastilla Group are more than 600 m thick in the south-eastern Calchaquí Valley and are affected by numerous faults and folds. The transition between the Palo Pintado Formation and the San Felipe Formation is sharp and unconformable. The outcrops of San Felipe Formation, present less areal distribution than the previous and are restricted to the south-eastern sector of the Calchaquí basin (**Figure 8**).

#### 3.4.1. Facies and depositional architecture of the San Felipe Formation

The San Felipe Formation is characterized by conglomerates deposited in low-sinuosity channels.

The well-sorted conglomerates lack of matrix, contain rounded clasts overlapping in thick tabular strata, are 2 to >7 m in thickness, and are found in longitudinal bar deposits (**Table 1, Figure 9b**). The unit also contains poorly sorted conglomerates, supported clasts, pseudoplastic debris flow, and massive coarse-grained wackes resulting from rapid accumulation and poorly sorted deposition. The origin of the conglomerates in the San Felipe Formation was analyzed in the Quebrada Salta, where there are also elements of the Puncoviscana Formation and the Oire Eruptive Complex. In addition, limestone clasts from the Yacoraite Formation (Salta Group) have been found and clasts from Pirgua Subgroup (Salta Group) in association with paleocurrent directions from the west and south-west. The San Felipe Formation deposits have been interpreted as braided alluvial fans associated with shallow gravelly braided fluvial system (**Figure 9b, Table 2**) [38].



**Figure 9.** Description of the palaeoenvironment with architectural elements illustrated using schematic diagrams. a) meandering fluvial sand-gravel system with small lakes of the Palo Pintado Formation with its architectural elements, and b) braided fluvial fan and river system of San Felipe Formation with its architectural elements.

## 4. Orán Group

### 4.1. Metán Subgroup (Río Seco, Anta, and Jesús María formations)

The basal contact of the Metán Subgroup deposits corresponds to a regional unconformity and is generally associated with the Lumbrera Formation (Santa Bárbara Subgroup, Salta Group). In the eastern part of the basin (Umbral de Los Gallos [53]), this subgroup lies on different units of the postrift deposits of the Salta Group, such as the Lumbrera, Maíz Gordo, Mealla, and Yacoraite formations (**Figure 7**). Although the distribution of the Metán Subgroup is broader than that of the Salta Group, its depocenters are generally the same as those existing during the accumulation of the Salta Group [54].

In this basin, a zircon fission-track sample from an intercalated tuff at Alemanía yielded an age of  $14.5 \pm 1.4$  Ma and hornblende crystals from a tuff collected in the lower part of the Anta Formation at Río Piedras produced a  $^{40}\text{Ar}/^{39}\text{Ar}$  date of  $13.95 \pm 0.72$  Ma. The age of the lowest exposed Anta Formation beds is 15.2 Ma at Río Piedras and 17.3 Ma at Río Metán based on magnetic stratigraphy [55, 56]. Other authors have placed the contact with the overlying Guanaco Formation at 12.3 Ma (Arroyo Piedra Blanca), 13.5 Ma (Río Metán), 13.1 Ma (Río Piedras), and 9.7 Ma (Arroyo González) [56, 57] (**Figure 7**). The paleomagnetic ages obtained from the contacts at the base and top of the Metán Subgroup vary in different parts of the basin, from between 17.3 and 12 Ma to between 15 and  $\sim 9$  Ma (**Figure 7**). These data reveal that an elongated initial depocenter developed parallel to the uplift zone at  $\sim 17$  Ma, migrated toward the eastern edge of the recent basin at  $\sim 15$  Ma and continued to fill with sediment until  $\sim 12$  Ma, when new basin structuring and the erosion of the Metán Subgroup deposits began.

#### 4.1.1. Facies and depositional architecture of the Metán Subgroup

The Río Seco, Anta, and Jesús María formations present interfingering stratigraphic relationships (**Figure 11**). The deposits of the Metán Subgroup (Río Seco and Jesús María formations)

are characterized by a succession of lithofacies from fine-grained to very coarse-grained sandstone, often with pelitic clasts (Table 3) and have been interpreted as the product of ephemeral flows that deposited sand sheet under high-flow regime conditions (Figures 10 and 11, Table 3).

The deposits of the Río Seco and Jesús María formations have been interpreted as accumulates in a paleoenvironment of a “sandy ephemeral fluvial system associated with dune fields” under arid climatic (Figure 11) [54, 56].

The Anta Formation is primarily composed of brown, green, and yellow mudstone and medium- to fine-grained sandstone. Gypsum layers, gypsum nodules, and pyroclastic layers are common throughout the basin. The oolitic limestones with foraminifera are found in the south-eastern sector of the basin. These limestones have been assigned to the Paraná marine ingression with 14.9 Ma in age, based on paleomagnetic data collected at the Piedras river (Miliolidos, Figure 10) [54, 56].

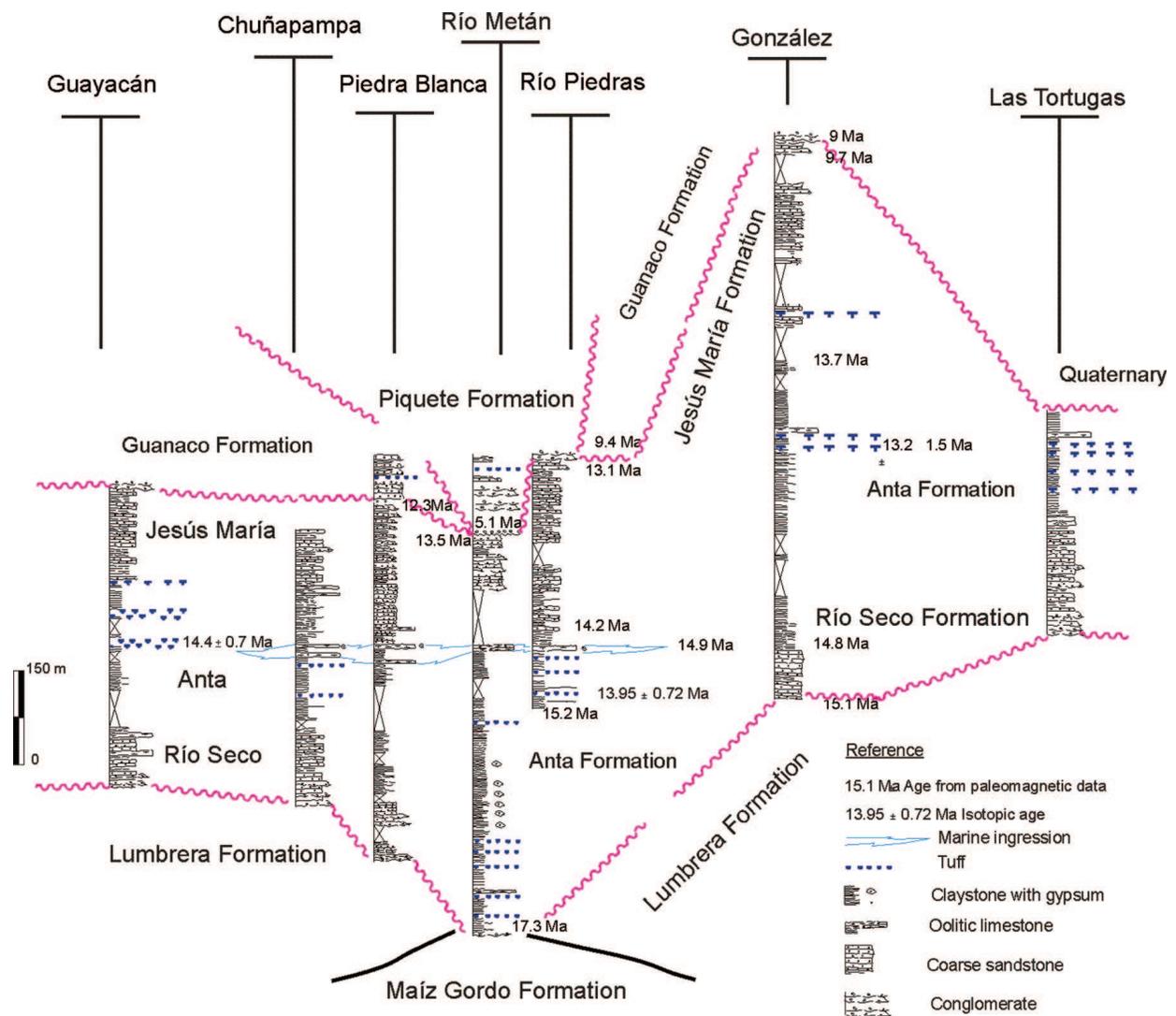
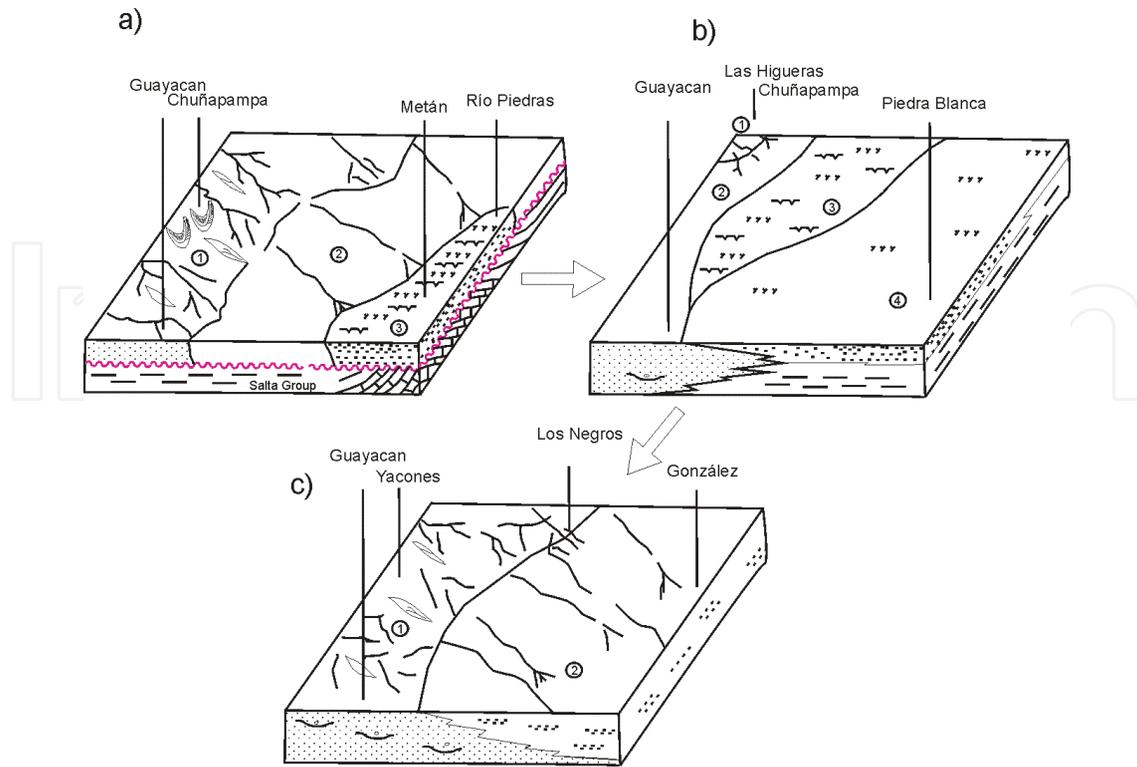


Figure 10. Stratigraphic correlation of the deposits of Metán Subgroup (base of Orán Group).



**Figure 11.** Description of the palaeoenvironment with architectural elements illustrated using schematic diagrams of Metán Subgroup a) 1 - proximal ephemeral sandy fluvial system associated with wind deposits, 2- distal ephemeral sandy fluvial system, 3- playa lake; b) 1- alluvial fan deposits, 2- sandy plain, 3- dry mud flat, 4- ephemeral saline lake; c) 1- proximal ephemeral fluvial system and, 2- distal ephemeral fluvial system.

Formation	Code	Architectural elements	Principal lithofacies
Piquete	SG	Sandy bedforms	Gcm - Sm - St - Sp
	GB	Gravel bars	Gmg - Gi - Gt - Sm
Guanaco	GB	Gravel bars	Gmg - Gi - Gt - Sm
	SB	Sandy bedforms	St - Sm - Fm
	CH	Channel	
Jesús	FF	Foodplain deposits	Fl - Fm - Fo - Po
María	LS	Laminated sand sheets	Sl - Fm - Fl - Se
	SB	Sandy bedforms	Gcm - Sm - St - Sp
	FL	Saline lake	Fl - Fm - Co
Anta	FF	Mud Flat	Fl - Fg - Fgr
	SB	Sand Flat	Sm - St - Sp - Sm
	FF	Foodplain deposits	Fl - Fm - Fo - Po
Río Seco	LS	Laminated sand sheets associated with aeolian deposits	Sl - Fm - Fl - Se
	SB	Sandy bedforms	Gcm - Sm - St - Sp

**Table 3.** Code of the major architectural elements defined for the Orán Group with their characteristic lithofacies.

The deposits of the Anta Formation have been defined as accumulates in a playa lake paleoenvironment, in which the following features have been recognized: sand flats, arid mud-flats, ephemeral saline lakes, and permanent saline lakes [54] (**Figure 11**).

The presence of zeolites (analcime) in the facies of laminated green pelite indicates that it formed in an environment such as alkaline lake in an arid to semiarid condition. In these basins with little or no drainage, evaporation would have increased the alkalinity of the waters and the reaction between the water and volcanic ash falling intermittently into the lake would have caused the zeolitization of the volcanic glass [56, 57].

The provenance of the Metán Subgroup in the area of maximum subsidence (Piedra Blanca, Río Metán, Arroyo González, **Figure 10**) most probably came from the west with sediments of the Salta Group, the Puncoviscana Formation, and granite from the border of Puna as a result of first- or second-order fluvial systems connected to the Calchaquí Basin.

The presence of *Riella* sp. (phylum Bryophyta, class Hepaticae, family Riellaceae) in the Anta Formation suggest that it is the only genus of the class Hepaticae whose present representatives develop in both purely alkaline salt waters and fresh water. Associated with *Pediastrum* sp. and *Phaeceros* sp., they are formed in lacustrine environments and reflect stenohaline conditions that are alkaline and rich in nutrients [54, 58].

#### 4.2. Guanaco Formation (base of Jujuy Subgroup)

The Jujuy Subgroup is widely distributed in the central and southern sector of the Cordillera Oriental and in the Santa Barbara System. It exhibits a general increasing grain-size trend, with cycles of 50–200 m in thickness and lateral extents of tens of kilometers. The cycles represent the progradation of the sediments at times of reduced accommodation space, whereas the cycles of decreasing grain-size represent periods of vertical aggradation associated with greater accommodation space [59] (**Figure 12**).

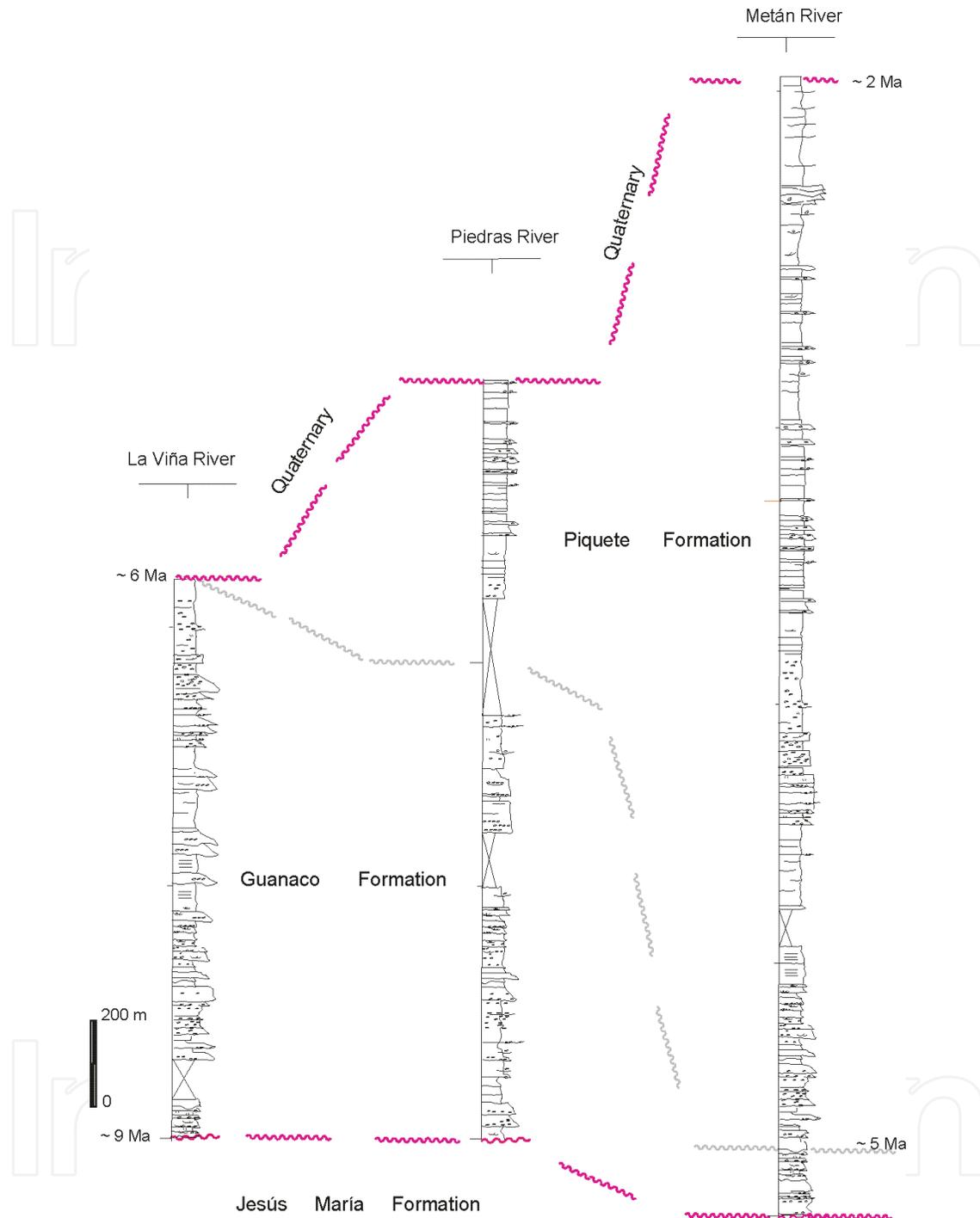
The basal contact between the Jesús María or older deposits and Guanaco formations is a paraconformity or unconformity and the contact at the top is an unconformity with the Piquete Formation or Quaternary deposits (**Figure 12**).

The Guanaco Formation has garnetiferous glassy tuff layers and is linked to the La Pava-Ramadas Caldera, whose volcanic activity has been dated to  $8.73 \pm 0.25$  Ma (K/Ar; [60]). Records of these tuffs have been found in San Antonio de los Cobres, Lerma Valley, and the valleys of Rio Grande of Jujuy and Juramento-Metán.

The Guanaco Formation was deposited between  $\sim 9$  and  $<6.9$  Ma [60], near Coronel Moldes, and it has an age of  $9.31 \pm 0.31$  Ma [57]. The thickness of the preserved Guanaco Formation deposits ranges between 0 and 900 m in the Cordillera Oriental and more is more than 2000 m in the Santa Bárbara System (**Figure 12**) [59, 61]. This variation reflects a deformation episode after the formation was deposited and a previous structuring at  $\sim 10$  Ma [31, 62].

##### 4.2.1. Facies and depositional architecture of the Guanaco Formation

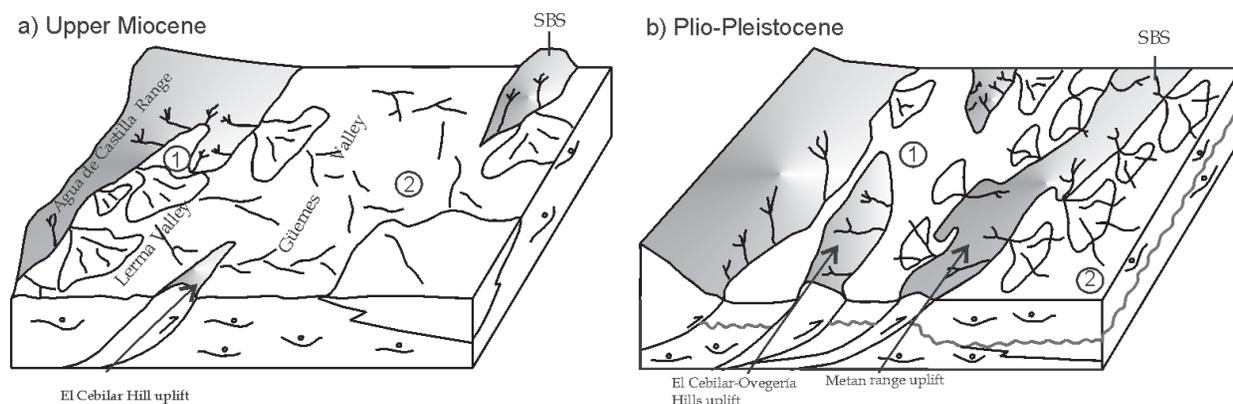
The Guanaco Formation is characterized by alluvial fans deposits dominated by: (1) conglomerate and sabulite with channeled bases and an upward fining arrangement, constituting



**Figure 12.** Stratigraphic correlation of the deposits of Jujuy Subgroup (top of Orán Group).

deposits of gravel bars; (2) facies of conglomerates accumulated by hyperconcentrated deposits; and (3) conglomerate sandstone with trough and planar stratification corresponding to lateral bar deposits and dune migration [59] (**Table 3, Figure 13a**).

This fluvial system is associated with an alluvial fan paleoenvironment dominated by braided stream. The proximal deposits are located in the western zone (the Lerma Valley) and the



**Figure 13.** Description of the paleoenvironment with architectural elements illustrated using schematic diagrams of Jujuy Subgroup. a) 1- alluvial fan deposits and, 2- braided fluvial systems deposits of Guanaco Formation, b) 1- and 2- alluvial fan deposits with braided fluvial systems of Piquete Formation.

middle and distal sectors are located in the central and distal zones [59] (**Figures 12 and 13**), which are associated with a large river system.

The conglomerate facies of the Guanaco Formation contain more than 15% high-grade metamorphic clasts (migmatites) and granitoids associated with paleocurrent directions from the west. These characteristics have been interpreted that the provenance sediments is from the eastern edge of the Puna.

The characteristics of the sedimentary paleoenvironment, the provenance data, and the paleocurrent directions from the west suggest that, between ~9 and 6 Ma, the foreland basin evolved independently from the Calchaquí Valley Basin and that the connection of first- and second-order fluvial systems transported material from the eastern edge of the Puna and from the El Toro Lineament.

### 4.3. Piquete Formation (top of Jujuy Subgroup)

The Piquete Formation is widespread in the Cordillera Oriental, the Santa Bárbara System, and the Sierra de Zapla (**Figures 3 and 12**). The base is characterized by an erosional unconformity or paraconformity on the deposits of the Guanaco Formation in the Santa Bárbara System [63]. In other areas, these units are separated by an angular unconformity, as in the Cordillera Oriental [59, 64] (**Figure 12**).

The measured partial thickness varies from 190 to over 2000 m. This unit features deposits of whitish, fine-grained vitrocrystalline, rhyodacitic to dacitic tuffs with thicknesses of 1.80 to 3 m. The Pliocene deposits of the Piquete Formation accumulated in response to the strong structuring that produced the upheaval of the Subandean ranges, the Santa Bárbara System, and part of the Cordillera Oriental, which also resulted in the formation of intermontane basins, such as the Lerma Valley and the Siancas Valley.

Paleomagnetic studies and ages from fission track dating in apatite from one tuff (Coronel Moldes) in the basal section of this unit yielded an age of 5 Ma [33, 57]. The upper third was dated based on a tuff that yielded an age of  $1.3 \pm 0.2$  Ma [65].

#### 4.3.1. Facies and depositional architecture of the Piquete Formation

The paleoenvironment of the Piquete Formation has been interpreted as relatively small alluvial fans distributed on the flanks of structural depressions and dominated by debris flows (**Table 3**). If these alluvial fans would have been more, had developed in the eastern sector, and away from the thrust fronts, flood plains with small lake systems would have developed [59] (**Figure 13**).

The conglomerates in the Piquete Formation contain slabs of limestone from the Yacoraite Formation, slate from the Precambrian basement of the Puncoviscana Formation, and clasts of reddish sandstone and limestone from the Salta Group. The change in the conglomeratic clast composition from the Guanaco Formation to the Piquete Formation suggests that between ~5 and 2 Ma, thick sediments from the eastern edge of the Puna were trapped in the intermontane Calchaquí Basin [42, 59].

The paleontological content of the Piquete Formation at present is very limited and includes fragmentary remains of vertebrates, notably including abrocomid rodents and plates of Dasypodidae. In the Xibi Xavi river, in the city of Jujuy, complete remains of a glyptodont (*Cranithlastus xibiensis*) and megatherium teeth [66] have been found. Alligatoroid remains from Rosario de la Frontera (south of Salta province), assigned to the species *Caiman latirostris* based on its morphology [67], have also been found.

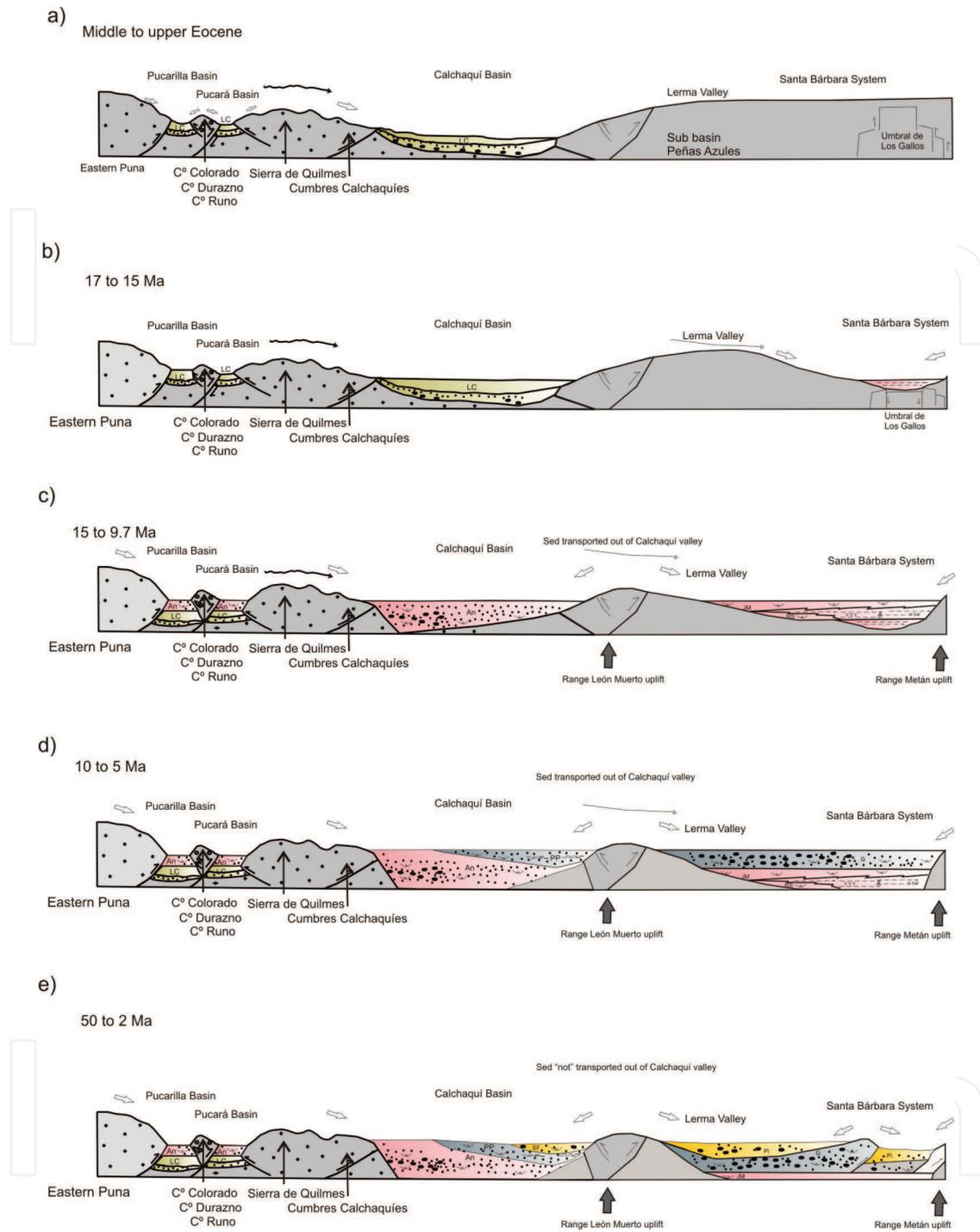
## 5. Conclusion

The complexity of tectonic processes controlling the evolution of foreland basins resulted in highly complex basins. The more that is known about these processes and their consequences, the more complex our models become and the more each basin appears to be unique [9].

During the first evolutionary stage of the foreland basin that developed during the middle to upper Eocene in north-western Argentina, the basin had an elongated configuration, was parallel to the Andean uplift, and did not extend to the external sector of the Cordillera Oriental (**Figure 14a**).

The uplift of the margins of the basin and the increase in the relief of the edge of the Puna plateau associated with the Leon Muerto Range are reflected in three depositional sequences that are interpreted to represent three tectonic episodes. Consequently, the main controls over the ephemeral fluvial system were the interactions between tectonics and basin subsidence and the constant arid climatic conditions (**Figure 14a**).

At the beginning of the second evolutionary stage of the foreland basin, an initial elongated depocenter parallel to the orogen developed at ~17 Ma. This depocenter featured the development of playa lake deposits and paleocurrent directions to the north (along the Umbral de Los Gallos). Over time, the depocenter migrated to the eastern edge of the basin by ~15 Ma (**Figure 14b**).



**Figure 14.** Schematic diagram models for Cenozoic foreland basins showing the evolution of the study area from Eocene (a) to Pliocene (d) time (not to scale).

The second evolutionary stage of the foreland basin (15–10 Ma) featured a new restructuring of the broken foreland basin with the development of thick sedimentary deposits in the Calchaquí basin area that thin toward the eastern basin margin. The same pattern in sedimentation and development is observed in the Metán Subgroup basin to the east (**Figure 14c**).

The contact between the Los Colorados and Angastaco formations is a paraconformity grading into an unconformity. Tectonics and subsidence were the fundamental controls on the evolution of the fluvial style, the deposit thickness, and the paleocurrent variability. The red sandstone clasts (Lumbrera Formation) and gray sandstone clasts (Maíz Gordo Formation) in the Tonco Valley, which are associated with easterly paleocurrents, suggest that the Sierra León Muerto to the east of the Angastaco basin was uplifted (**Figure 14c**).

The Metán Subgroup deposits are interpreted to have accumulated at ~14.9 Ma in an arid paleoenvironment characterized by a sandy ephemeral fluvial system associated with dune fields and playa lake deposits, with sand flats, mud flats, an ephemeral saline lake, and a permanent saline lake and sporadic marine incursions from the south-east (**Figure 14c**). At ~12 Ma, a new basin restructuring event began and the Metán Subgroup deposits began to be eroded.

During the third stage of evolution in the foreland basin (~10–5 Ma), the western part of the basin experienced at least three episodes of tectonic reactivation, which are reflected in variations in the rate of sedimentation in the Palo Pintado Formation. Paleocurrents from the south and south-east indicate tectonic reactivation of the depositional area from the Sierra León Muerto-Sierra Los Colorados (**Figure 14d**).

The Guanaco Formation is characterized by alluvial fans deposits dominated by flowing streams and a braided fluvial system. The sedimentary paleoenvironment, provenance, and paleocurrent data suggest that the foreland basin evolved at a different time and rhythm than the Calchaquí basin, with the connection of first- and second-order river systems transported material from the eastern edge of the Puna and the area of the El Toro Lineament (**Figure 14d**).

The San Felipe Formation is characterized by braided fluvial fan and a shallow gravel-braided fluvial system. The provenance and abundant clasts in different levels of the Salta Group and the association with paleocurrents from the north-east, east, and south-east suggest a reactivation of the Sierra León Muerto and the Sierra Los Colorados in the depositional area (**Figure 14e**).

The Piquete Formation lies in marked unconformity over the deposits of the Guanaco Formation or older deposits. They accumulated as a series of alluvial fans of limited dimensions and are distributed on the flanks of structural depressions and dominated by debris flows. The composition of the clasts of conglomerates from the Piquete Formation suggests that between ~5 and 2 Ma, the basin was isolated from the basin of the San Felipe Formation (**Figure 14d**).

## Acknowledgements

This research was funded by the projects: AGENCIA (PICT-2012-1984, PICT 2014-3654), UNJu (SECTER 08/E036 and 08/E037), UNSa (CI-UNSa 2287), and SuRfAce processes, TECTONICS and GEORESOURCES: The Andean foreland basin of Argentina (StRaTEGy).

## Author details

Claudia Inés Galli<sup>1,3\*</sup>, Ricardo Narciso Alonso<sup>2</sup> and Lidia Beatriz Coira<sup>3</sup>

\*Address all correspondence to: [claudiagalli@fibertel.com.ar](mailto:claudiagalli@fibertel.com.ar)

1 INECONA-Facultad de Ingeniería, Universidad Nacional de Jujuy, Facultad de Ciencias Naturales, Universidad Nacional de Salta, Argentina

2 CEGA-CONICET, Universidad Nacional de Salta, Salta, Argentina

3 INECONA-CONICET, Instituto de Geología y Minería, S.S. de Jujuy, Argentina

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