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STRATIGRAPHY AND SEDIMENTARY ENVIRONMENTS OF THE VILLA MARÍA AND PEÑA COLORADA FORMATIONS (PALEOGENE), WESTERNMOST ARGENTINE PLATEAU

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ABSTRACT

The Peña Colorada Formation records the early stage of Andean foreland sedimentation over ~1,000 km^2 in the north westernmost Argentine plateau (21°51' S - 66°12' W). The aim of the present contribution is to provide a detailed stratigraphic characterization of these deposits and the description of their sedimentary environments. Detailed stratigraphic observations conducted to the division of the Peña Colorada Formation in two formal units, the Villa María and Peña Colorada formations. Subsequently, these two formations were divided into members according to sedimentary facies, textural tendencies, the alternating presence of quartz, carbonate and gypsum veins, and the distinctive cementation of deposits by iron carbonate, silica, and calcium carbonate. Data suggest that sedimentation would have taken place in alluvial plains near sourcing sediments that were being actively uplifted.

INTRODUCTION

The Puna plateau is emplaced at the north westernmost Argentine Andes, being the southern continuation of the Bolivian Altiplano. During the early Cenozoic, thick continental red beds were deposited in several depocenters across the incipient foreland. Many sedimentological, stratigraphic and structural studies have been conducted in basins of the Altiplano, the Southern Puna, and the Eastern Cordillera (*e.g.* Allmendinger *et al.*,1997; Lamb and Hoke, 1997; Coutand *et al.*, 2001; Jordan *et al.*, 2010; del Papa *et al.*, 2013; Aramayo *et al.*, 2017). However, little is still known about deposition in the northwesternmost Puna. This region located at the transition between the two major segments of the Andean Plateau, the Puna and the Altiplano, is today the westernmost area of the plateau with exorheic drainage to the east, which defines a peculiar zone in order to conduct basin studies.

Thick synorogenic deposits are covering ~1,000 km^2 in the north western sector of the Argentine Puna plateau (Turner, 1964a; Coira *et al.*, 2004). The Paleogene section of these sedimentary units is known as the Peña Colorada Formation (Bellman and Chomnales, 1960; *nom. transl*. Turner, 1966, 1978, 1982). This unit can be correlated with the Paleogene units cropping out along the Puna and Eastern Cordillera of Argentina, which are key for unravelling the initial sedimentation and deformation during the Andean orogeny.

The Peña Colorada Formation is composed of >1,000 m-thick continental conglomerates and red beds, and it was divided into the Villa María and the San Isidro members (Viera, 1984). The Peña Colorada Formation lies over the middle and upper

Salta Group (Navarini *et al.*, 1973) and is covered by the Cabrería Formation (early Oligocene - Miocene; Viera, 1984). According to its position within the stratigraphic framework, the Peña Colorada Formation has been assigned to the early Eocene - early Oligocene (Viera, 1984).

The aim of the present contribution is to provide a detailed stratigraphic characterization of these lithostratigraphic units. This article summarizes unpublished data previously reported on the considered units, and introduces new field observations collected during field surveys, as detailed descriptions and photographs of the sedimentary facies and stratigraphic relationships. Main features characterizing the lower and upper formal units, and the subdivision of these into members are proposed and stated through detailed litho-stratigraphic descriptions.

METHODS

Field works have focused on stratigraphic descriptions, and collecting data of the strata orientation. The thickness of outcropping sections has been measured using a Jacob's staff. Lithologic characteristics of the outcropping units have been photographed in detail, and stratigraphic columns have been described in detail. Counting clast in conglomeratic levels is being reported and referred to as predominant due to major lithotypes always represent ≥95%. The facies analysis follows the criteria presented by Miall (2006) and Fielding (2006). The sedimentary facies are summarized in Table 1 and facies assemblages are presented in Table 2. The location of outcropping units and orientation of strata are shown in Figure 1, and the reported data and the stratigraphic column are presented in subsequent Figures.

REGIONAL SETTING

The study area is located in north westernmost Argentina; it is delimited by the Cerro Negro to the west, the Argentina-Bolivia frontier to the north, the Sierra de Rinconada to the east; and extends southwards up to the latitude of the town of La Ciénaga (~80 inhabitants). El Angosto (3,580 m asl) is the other town in this area, which consist of a scattered, rural settlement including a few (~40) families. Field observations have been conducted covering an area of ~85 km^2 (21°51' S - 21°58'30" S and 66°09' W - 66°16'20" W; Fig. 1).

The basin substrate is composed of meta-sedimentary marine rocks of the Ordovician Santa Victoria Group (Acoite Formation, Harrington, 1957; Turner, 1964 a), and the Cretaceous - Paleocene Salta Group (Brackebusch, 1883, 1891; *nom. transl.* Turner, 1959). The Acoite Formation (Arenigian - Llanvirnian, Turner, 1964 b; Bahlburg *et al.*, 1990) largely outcrops in mountain-ranges that array longitudinally: the Sierra de Rinconada, Cerro Chaupiorco, Cerro Buena Esperanza, and the Cerro Negro (Fig. 1). Outcrops of the Salta Group are reduced and consist of few meters-thick, thin belts disposed along major thrusts that delimit ranges (Turner, 1964a; Navarini *et al.*, 1973; Viera, 1984; Coira *et al.*, 2004). The Salta Group consists of sedimentary units formed under marine and continental conditions in a rift-related basin (Salfity and Marquillas, 1994; Marquillas *et al.*, 2005) and includes partial sections of the Balbuena (Moreno, 1970) and Santa Bárbara Subgroups (Vilela, 1956; *nom. transl.* Moreno, 1970).

At the study area, the Balbuena Subgroup is represented by the Yacoraite Formation (Moreno, 1970 - Maastrichtian – Danian, Marquillas *et al.*, 2005) that crops out along the western side of the Río Grande de San Juan, and in El Angosto anticline (Fig. 1). The Yacoraite Formation lies unconformably over the Acoite Formation, and locally involves white-grayish to green-yellowish, up to 5 m-thick, calcareous limestones, lumachellas, oolitic sandstones, and conglomeratic sandstones, containing abundant veins of carbonate up to 5 cm-thick, and intercalated levels of euhedral crystals of calcite sizing 1 cm-long (Fig. 2). Strata are tabular and range from a few centimeters up to ~1 m-thick. Beds contain laminations, ripples, and marks of bioturbation. Fossils within lumachella levels include shells of undetermined brachiopods and/or bivalves.

The Santa Bárbara Subgroup (Vilela, 1956; *nom. transl.* Moreno, 1970 – middle Paleocene - middle Eocene, Carabajal *et al.,* 1977; Pascual *et al.,* 1978, 1981) crops out along the Río Grande de San Juan (a ~30 m-thick section that includes the basal contact), and along the anticline axis running through El Angosto (the uppermost 15 m including the upper contact, Fig. 1). In the study area, the Santa Bárbara Subgroup consist of gray to greenish limestones and

Facies code	Lithology	Sedimentary structures	Interpretation
Gcm	Clast-supported conglomerate	Massive tabular bedding delimited by marked erosive surfaces	Pseudoplastic debris flow (inertial bedload, turbulent flow)
Gt	Matrix-supported conglomerate	Through cross-bedding, lateral wedging, tabular bedding	Mud flow (high flow regime)
Gmg	Matrix-supported conglomerate	Normal grading Tabular bedding delimited by marked erosive surfaces	Pseudoplastic debris flow (low flow regime, low strength, viscous)
Gmm	Matrix-supported, massive conglomerate and sandstone	Massive Planar cross-bedded Lateral wedging Marked erosive bounding surfaces Quadrangular meshwork of quartz veins	Plastic debris flow (low flow regime, high-strength, viscous)
Sp	Pebbly sandstone	Planar cross-beds, linguoid bedforms, marks of bioturbation (undetermined tubes)	Plastic debris flow (low flow regime, high-strength, viscous)
Sm	Muddy to coarse sandstone	Massive Mottles and marks of bioturbation (undetermined tubes)	Sediment-gravity flow deposits or massive structure due to bioturbation and soil development
Sr	Muddy to coarse sandstone	Parallel and ripple cross laminations Mottles and marks of bioturbation (undetermined tubes)	Fluvial transitional flow regime from the dune stability field into the upper plane bed field
Sl	Muddy to coarse sandstone	Thin and planar lamination Low-angle (<15°) cross-beds Marks of bioturbation (undetermined tubes)	Fluvial transitional flow regime from the dune stability field into the upper plane bed field
St	Medium sandstone	High-angle (~45°) planar and trough cross-beds	Aeolian 2-D and 3-D dunes
Sh	Fine to medium-grained sandstone	Parallel and planar lamination, planar bedding	Fluvial (high flow strength)
Fl	Muddy sandstone	Lenticular strata Fine lamination Marks of bioturbation (undetermined tubes)	Overbanks in the flood plain
Fsm	Mudstone	Massive Cataphylar disjunction	Backswamp

Table 1. Sedimentary facies described in the study area for the Villa María and Peña Colorada formations.

sandstones, yellow, purple and green claystones and mudstones. Strata often contain laminations and cross stratifications. The uppermost Santa Bárbara Subgroup consists of non-calcareous, fine-grained deposits, mainly including red-purple mudstones and sandstones containing abundant marks of bioturbation. The upper section begins with alternating purple fine-grained sandstones containing whitish mottles of bioturbated mudstones, which are overlain by whitish claystones with mottles of purple mudstones containing intraclasts of the precedent claystone. Upwards, the muddy fraction and bioturbation increase. The top of the unit (Mealla Formation?) corresponds to a 7.70 m-thick gray-greenish to light blue paleosol that is truncated by a highly developed, erosive surface (Fig. 3).

The Andean Cenozoic record in the study area is represented by the Peña Colorada Formation (Bellman and Chomnales, 1960; *nom. transl.* Turner, 1966, 1978, 1982) and the Cabrería Formation (Viera, 1984). These units extend beyond of the study area, across the entire valley of the Río Grande de San Juan (Turner, 1978; Viera, 1984; Coira *et al.*, 2004; Prezzi *et al.*, 2011; Fig. 1).

Viera (1984) reported that the Peña Colorada Formation lies paraconformable over the Salta

Stratigraphic unit		Facies associations	Geometry and relationships	Interpretation
Peña Colorada Formation	Upper member	Fl, Sm, Gt	Tabular bodies with erosional surfaces, strata are up to 8-m thick, w/d*<5, upward coarsening, laminations, gypsum veins, cross-bedding, wedges, marks of bioturbation	Overbank, flood deposits, sediment-gravity flow deposits, and mud flow in a braided plain, soil development
	Middle member	Fl, Sh, Fsm	the thickness of strata and the ratio are highly variable, parallel laminations, oblique gypsum veins	Overbank, wash out sediments under upper flow regime, and backswamp in a meandering plain
	Lower member	Fl	strata are up to 1-m thick, w/d>5, parallel laminations, veins of carbonate	Overbank, abandoned channel or waning flood deposits in a meandering plain
Villa Maria Formation	Upper member	Gmm	strata are up to 1.5-m thick, w/d*<10, massive bedded, wedges, cross-beds, marks of bioturbation	Lobes, sheets, coarse bars and bedforms deposited by flash flows, in a braided river plain near a piedmont
		Fsm, Fl	w/d highly variable, wedges, cross-beds, laminations, marks of bioturbation	Abandoned channels in a braided plain
		St	w/d highly variable, high angle (45°) planar and trough cross-beds, laminations, wedges	Aeolian dunes associated to ephemeral channels, and formed under semiarid conditions
	Middle member	Sm, Sr, Sp, Sl	strata are up to 2-m thick, w/d <10, Wedge, cross-beds, laminations, ripples, marks of bioturbation	Mobile channel beds, channel fills, bars deposited by flash flows through a braided river plain, soil development
	Lower member	Gcm, Gmg	Tabular bodies with erosional surfaces, strata are ~2-m thick, w/d<10, massive to poorly graded, marks of bioturbation	Flood plain bedforms deposited by alluvial fans, and flash flows. (piedmonts are near the flood plain)

* w/d is the descriptor of the channel perimeter, w: width, d: depth

Table 2. Facies associations and interpreted paleo-environment of the Villa María and Peña Colorada formations.

Group, and assigned the Peña Colorada Formation to the early Eocene - early Oligocene based on its stratigraphic position (Viera, 1984). The Peña Colorada Formation comprises two members named Villa María and San Isidro members by Viera (1984). The basal Villa María Member consists of up to 170 m-thick, reddish-yellow succession, predominantly composed of psephites, while the upper San Isidro Member is a 1,000 m-thick succession that mainly comprises reddish-orange psamites and pelites with abundant gypsum veins (Viera, 1984).

The Peña Colorada Formation is covered by the overlying Cabrería Formation that has been assigned to the early Oligocene - Miocene by Viera (1984). Later on, Caffe and Coira (2002) have reported a K/Ar age of 17.40 ± 0.80 Ma for a tuff at the top of this unit. The Cabrería Formation is composed of three members: Vallecito, Eureka and Quebrada Grande; but only the Vallecito Member crops out in the study area. The Vallecito Member is a 50 to 60 m-thick upward coarsening succession, mainly composed of conglomerates, with abundant sandy matrix, and cemented by carbonate (Viera, 1984).

The study area is bounded east and west by basement-cored ranges, delimited by thrusts. The Ordovician basement thrusts over younger units along the mountain ranges, leading to the tectonic wedging of the Salta Group, and to the loss of some sections of the Peña Colorada and Cabrería formations (Viera, 1984). Distinctive structural features of the Peña Colorada Formation consist of asymmetric, and open folding, with N-S trending axis (Viera, 1984).

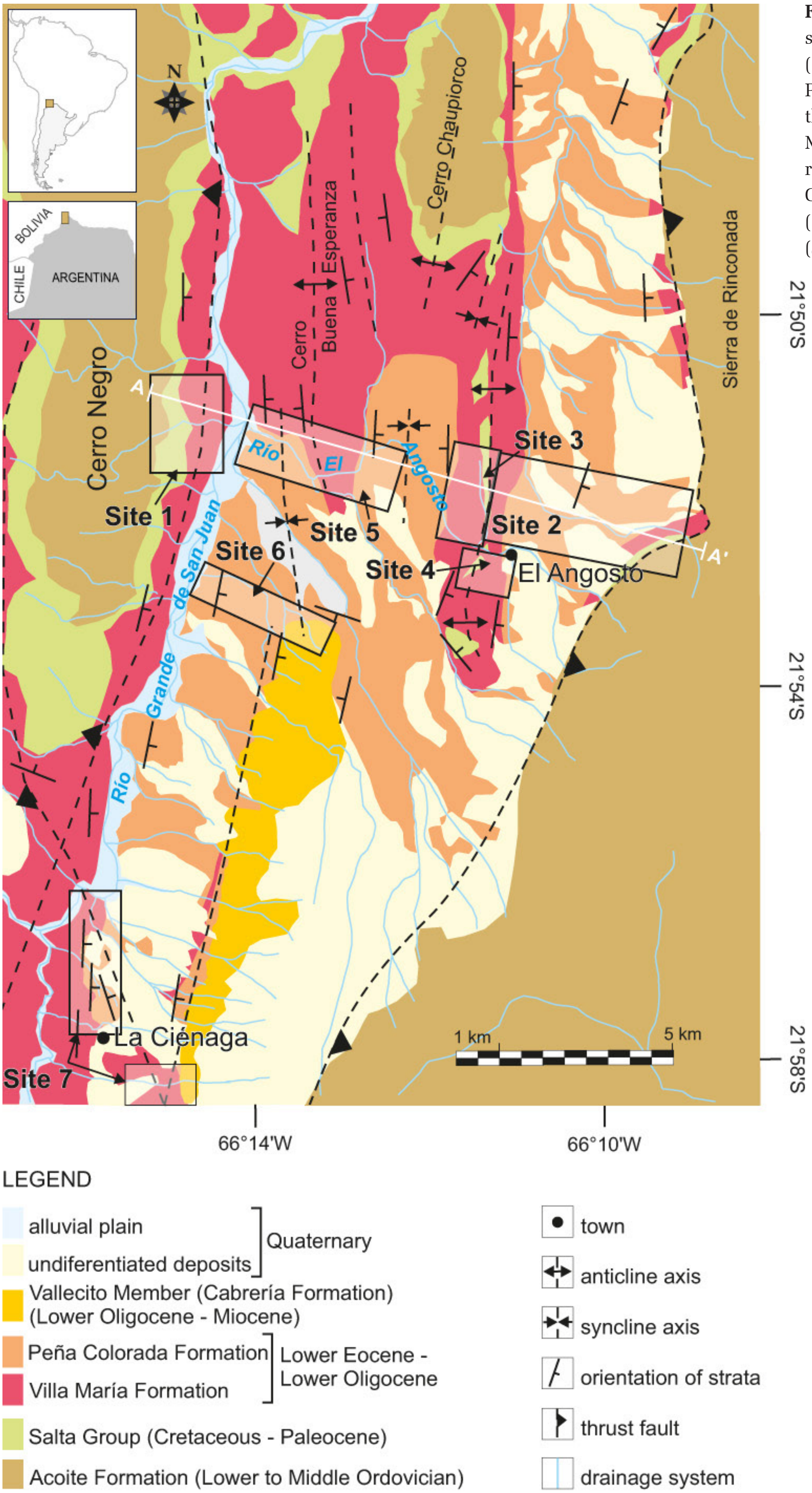


Figure 1. Geologic map of the study area modified from Viera (1984). The Villa María and Peña Colorada formations in the map correspond to the Villa María and San Isidro members, respectively, of the Peña Colorada Formation of Viera (1984). A-A': structural transect (shown in Fig. 10).

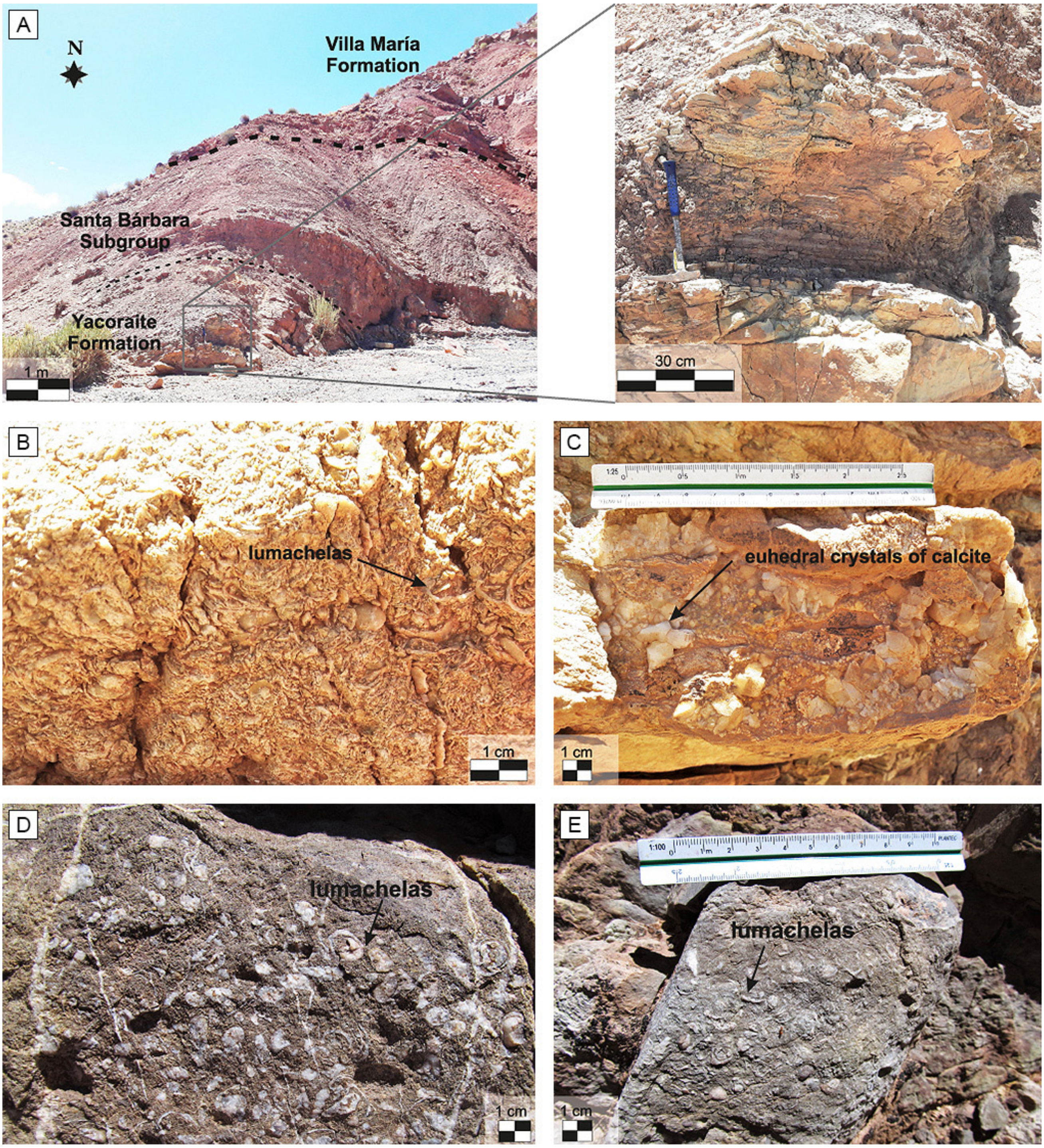


Figure 2. The Yacoraite Formation outcropping at El Angosto (site 2; panel **a)** is characterized by fossiliferous calcareous sandstones and limestones containing lumachellas **(b)** and euhedral crystals of calcite **(c)**. Similar facies of the Yacoraite Formation are observed in Site 1, where fossils within lumachella levels include shells of undetermined brachiopods and/or bivalves **(d** and **e)**.

RESULTS

The Peña Colorada Formation (Bellman and Chomnales, 1960; *nom. transl*. Turner, 1966, 1978, 1982) was previously separated in two members: the Villa Maria and the San Isidro members (Viera, 1984). The nature of the bounding surfaces and the observed lithological contrasts (see below) allow us to redefine these formal lithostratigraphic units and to assign them to separated formations as the

Villa María (nom. nov.) and the Peña Colorada formations. It is important to note that the Peña Colorada Formation now includes exclusively the lithostratigraphic unit that Viera (1984) previously assigned as the San Isidro Member.

In the study area, the Villa María Formation overlies the middle Paleocene - middle Eocene Santa Bárbara Subgroup (Carabajal *et al.*, 1977; Pascual *et al.*, 1978, 1981), and the overlying Peña Colorada Formation is covered by the early Oligocene - Miocene Cabrería Formation (Caffe and Coira, 2002). According to its stratigraphic relationships, the sedimentation of these units would have taken place between the early Eocene and the early Oligocene (Viera, 1984).

The Villa María Formation

Field observations of the Villa María Formation have been focused in two outcrops located along the Río El Angosto. These outcrops correspond to cross-sections caused by the river through the anticlines of El Angosto (site 4) and Buena Esperanza (site 5; Fig. 1).

Stratigraphic relationships. The stratigraphic boundaries of the Villa María Formation correspond to erosive unconformities defining the contact with the Salta Group, and the overlying Peña Colorada Formation (Fig. 4). The basal contact of the Villa María Formation locally involves an angular unconformity, according to the section outcropping along the Río Grande de San Juan (in site 1), where the Villa María Formation dips 50° E over the Salta Group dipping 74º E. The upper bounding surface of the Villa María Formation corresponds to an erosive unconformity in all outcrops, with the exception of the western flank of the Buena Esperanza anticline, where an angular unconformity was observed between the Villa María Formation that is dipping steeper (60° W) than the Peña Colorada Formation (26° S; Fig. 5).

Stratigraphic characteristics. The Villa María Formation consists of a 170 m-thick succession, composed of gray-whitish to pink-yellowish coarse sandstones and conglomerates that alternates with reddish-purple muddy sandstones (Figs. 4 and 6). Strata are tabular, delimited by highly erosive surfaces, and thickness is reaching up to 2 m. Lateral wedging and cross-beds are very distinctive features

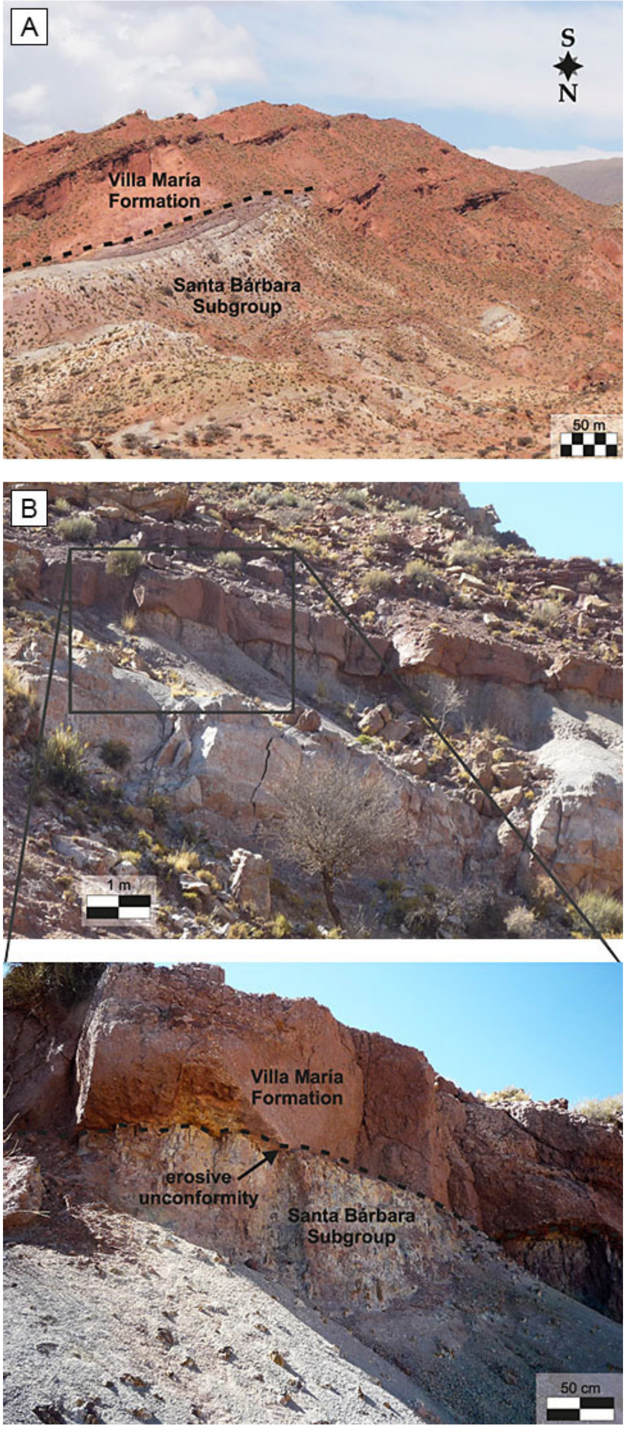
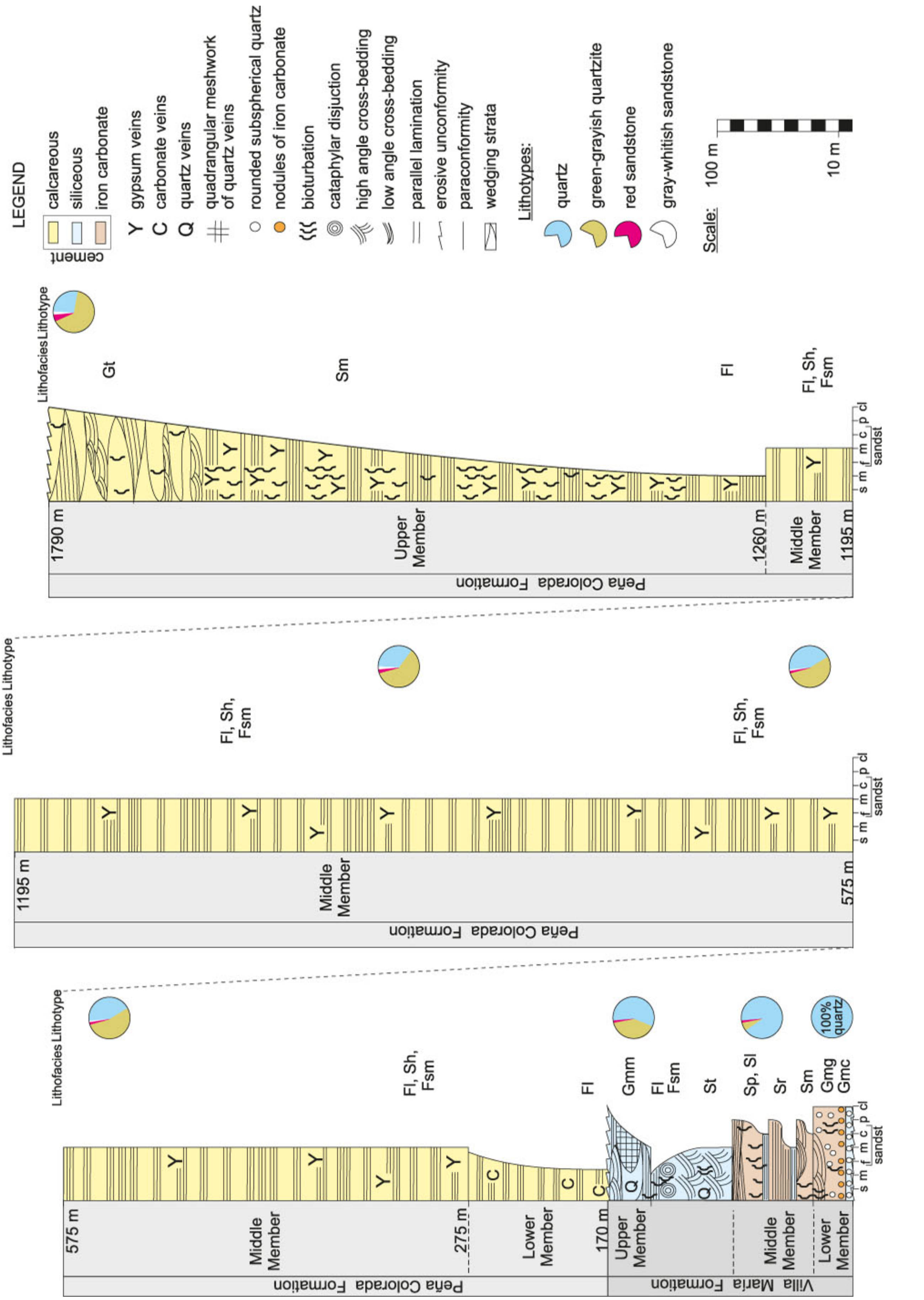


Figure 3. Picture of the Santa Bárbara Subgroup outcropping at El Angosto (site 4, panel **a)**. The top of the unit corresponds to a 7.70 m-thick gray-greenish to light blue paleosol that is truncated by a highly developed, erosive surface **(b)**.

of the Villa María Formation (Fig. 7). According to their facies associations (Table 2), we propose divide this formation in three members:

The lower member is 23 m-thick and consists of


LEGEND
cement
calcareous
siliceous
iron carbonate
Y gypsum veins
C carbonate veins
Q quartz veins
quadrangular meshwork of quartz veins
rounded subspherical quartz
nodules of iron carbonate
bioturbation
cataphylar disjuction
high angle cross-bedding
low angle cross-bedding
parallel lamination
erosive unconformity
paraconformity
wedging strata
Lithotypes:
quartz
green-grayish quartzite
red sandstone
gray-whitish sandstone
Scale:
100 m
10 m
Lithofacies Lithotype
Peña Colorada Formation
Villa María Formation
Upper Member
Middle Member
Lower Member
1790 m
1260 m
1195 m
575 m
275 m
170 m
Gt
Sm
Fl
Fl, Sh, Fsm
Gmm
Fl Fsm
St
Sp, Sl
Sr
Sm Gmg Gmc
100% quartz
s m f m c p cl
sandst

coarse-grained strata (facies Gcm and Gmg; Table 1), containing veins of quartz, and, with the exception of the basal level, this member is mainly cemented by iron carbonate. The lowermost stratum consists of a 2 m-thick, gray-whitish, massive clast-supported conglomerate, cemented by silica, composed of subrounded and polish clasts of white quartz sizing up to 7 cm-long. This is a very distinctive layer locally indicating the base of the Villa María Formation (i.e., lower limit stratotype; Fig. 6 A). The lower member also contains brown-reddish conglomerates cemented by iron carbonate, and dark nodules of iron carbonate sizing up to 5 cm within a sandy matrix that increases upwards (Fig. 6 B). A single lithotype is present through the lower member, and it is composed of rounded and sub spherical quartz clasts sizing up to 5 cm.

The middle member consists of sand-dominated facies (facies Sp, Sr, Sl, and Sm; Table 1), mainly cemented by iron carbonate with minor alternating levels cemented by silica (Fig. 4). This member includes an alternation of pink-yellowish massive muddy sandstones, coarse sandstones, and rippled laminated mudstones containing purple mottles and marks of bioturbation (facies Sm and Sr, respectively; Fig. 6 C and D). Bioturbation consist of undetermined tubes. There are also medium to coarse-grained, micaceous, sandstones with parallel and ripple cross laminations. These deposits are followed by brown-reddish, cross-bedded, rippled medium to coarse sandstones cemented by iron carbonate (facies Sr) that alternate with brown-reddish to purple pebble layers, cemented by iron carbonate, containing marks of bioturbation and highly developed planar cross-bedding (facies Sp). These pebbles have an aspect quite similar to accretionary bodies (pisolite) but are instead composed of highly well sorted lithic clasts (Fig. 6 E). Predominant lithotypes in pebbles include white quartz (≥95%), and minor proportions (<5%) of green-grayish quartzites, crystalline pink quartz, and red fine sandstones. Pebble layers intercalate with finely laminated, and low angle cross-bedded micaceous, purple muddy sandstones, sandstones, and grayish coarse sandstones, cemented by silica and containing marks of bioturbation (facies Sl; Fig. 6 F).

The upper member consists of a fine-to-coarse facies assemblage cemented by silica (St, Fsm, Fl and Gmm; Table 1), and contains abundant veins of quartz. This member involves pink to whitish, siliceous, laminated, medium sandstones with cross stratification dipping ~45º (facies St; Fig. 6 G and H). These sandstones are overlain by siliceous, brown-reddish mudstones with cataphylar disjunction (facies Fsm; Fig. 6 I) and containing abundant post-sedimentary (i.e., oblique to the stratification) gypsum veins up to 10 cm-thick. These mudstones alternate with light brown-pink, micaceous, laminated muddy sandstones with marks of bioturbation (facies Fl). The overlying units consist of a 30 m-thick succession of gray-whitish to pink-yellowish, sandstones and matrix-supported massive conglomerates cemented by silica (facies Gmm). Sandstones are often mottled and contain abundant marks of bioturbation. Fine-grained sandstones are micaceous, laminated, and rippled. Cross-bedded coarse sandstones are characterized by a distinctive quadrangular meshwork of quartz veins (Fig. 6 J). The uppermost strata consist of pink-yellowish, polymictic, massive and consolidated conglomerates (upper limit stratotype), containing rounded and polish clasts sizing up to 15 cm. Predominant lithotypes (≥95%) include quartz and green-grayish quartzites, with a minor fraction (≤5%) composed of red fine sandstones. Strata wedge laterally, and are bounded by highly erosive surfaces (Fig. 7).

Depositional environment. We interpret an initial alluvial fan environment with flood plain deposits during flash-flows events, in a landscape that would have been characterized by a flood plain located near the piedmonts (Table 2). The characteristics of the middle member could be interpreted as mobile channel beds, downstream-accretion macroforms,

Figure 4. Idealized stratigraphic column of the Villa María and Peña Colorada formations. Summarized data correspond to field observations in sites 1 and 2 for the Salta Group, sites 2, 3 and 4 for the lower and middle members of the Villa María Formation, sites 4 and 5 for the middle and upper members of the Villa María Formation, site 5 for the lowermost Peña Colorada Formation, and site 6 for the entire Peña Colorada Formation excepting its basal contact. Horizontal axe: texture. Legend: s: siltstone; m: mudstone; sandst: sandstone; f: fine sandstone; m: medium sandstone; c: coarse sandstone; p: pebble; cl: conglomerate. Lithofacies code as in Table 1.

channel fills, and bars through a braided river plain.

The upper member starts with high angle (45°) cross-bedded sandstones that are assigned to aeolian dunes associated to ephemeral channels. The overlaying facies (wedging, cross-bedding, and laminated sandstones) may correspond to abandoned channels in a braided plain. The uppermost facies (wedging and cross-bedded conglomerates) are interpreted as lobes, sheets, coarse-grained bars and bedforms deposited by flash flows, in a braided river plain located near a piedmont.

The widespread marks of bioturbation through the Villa María Formation indicate some degree of water availability. Bedforms most likely to be preserved in gradually changing flows are those formed under the most tranquil conditions, and, conversely, in rapidly changing flows there is much greater potential for preventing bedforms characteristic of strong flow (Fielding, 2006). The prevalence of low energy flow regime elements such as ripples and cross-bedding in fluvial successions of the Villa María Formation indicate sediment might accumulate in an ephemeral river system with flashy discharges under semiarid conditions associated to gradual seasonal variations in rainfalls.

The Peña Colorada Formation

The Peña Colorada Formation offers many outcropping sections in the study area that are shown in Figure 1.

Stratigraphic relationships. The stratigraphic boundaries of the Peña Colorada Formation correspond to erosive unconformities defining the contact with the Villa María Formation, and the overlying Cabrería Formation. Despite that the most complete section of the Peña Colorada Formation is cropping out at the Peña Colorada site (site 6, for location see Fig. 1), the basal section is missing due to the incision of the Río Grande de San Juan. This basal contact is instead outcropping on both east and west sides of the El Angosto and Buena Esperanza anticlines (sites 4 and 5; Figs. 5 and 8), and in the La Ciénaga area (site 7). The basal contact can be recognized due to the presence of an evident erosive unconformity separating the underlying yellowish, consolidated, siliceous conglomerates of the uppermost Villa Maria Formation from the basal section of the Peña Colorada Formation that is made of friable reddish calcareous muddy sandstones (Fig. 5). The upper limit of the Peña Colorada Formation consists of an erosive unconformity that demarcates the onset of the brownish conglomeratic thick successions of the Vallecito Member (lower Cabrería Formation) (Fig. 9).

Stratigraphic characteristics. The Peña Colorada Formation consists of a 1,620 m-thick, calcareous succession cemented by carbonate that presents a gradual transition from muddy sandstones to sandy conglomerates (Fig. 4). According to their facies associations (Table 2) this unit is separated in three members:

The basal member involves the lowermost 105 m of the unit, and is represented by facies Fl containing veins of carbonate (Tables 1 and 2). This member consists of purple-reddish to light orange-reddish, friable, calcareous muddy sandstones and sandstones, showing parallel laminations and abundant grains of crystalline quartz (lower limit stratotype). These strata alternate with friable, calcareous whitish to light pink sandstones. Abundant fine (up to 3-cm thick) veins of carbonate arrange parallel to the stratification. Strata thickness is typically between 0.10 and 1 m (Fig. 8 A).

The middle member involves 985 m of muddy sandstones containing gypsum veins, abundant fine laminations, and little ripples (facies Fl). Additional distinctive features are the emergence of a new lithotype in pebbly layers, consisting of gray-whitish, micaceous fine to medium-grained sandstones, and the increase of parallel laminated facies (facies Sh). Veins of gypsum display oblique to the stratification and are up to 3 cm-thick (Fig. 8 B). Fine-grained 5 cm-thick layers of whitish and greenish muddy claystones, gypsum-free, are frequent intercalations through the calcareous and friable deposits of the middle member (facies Fsm; Fig. 8 C).

The upper member is 530 m-thick, coarsening upward and cross-bedded succession containing veins of carbonate. This member is characterized by the increasing presence of coarser and thicker strata that reach up to 8 m-thick. The color gets darker, changing from the light orange-reddish in the basal and middle members to become brown-reddish. The upper Peña Colorada Formation starts with facies Fl that includes alternating orange-reddish bioturbated muddy sandstones containing gypsum veins, abundant fine laminations, little ripples and

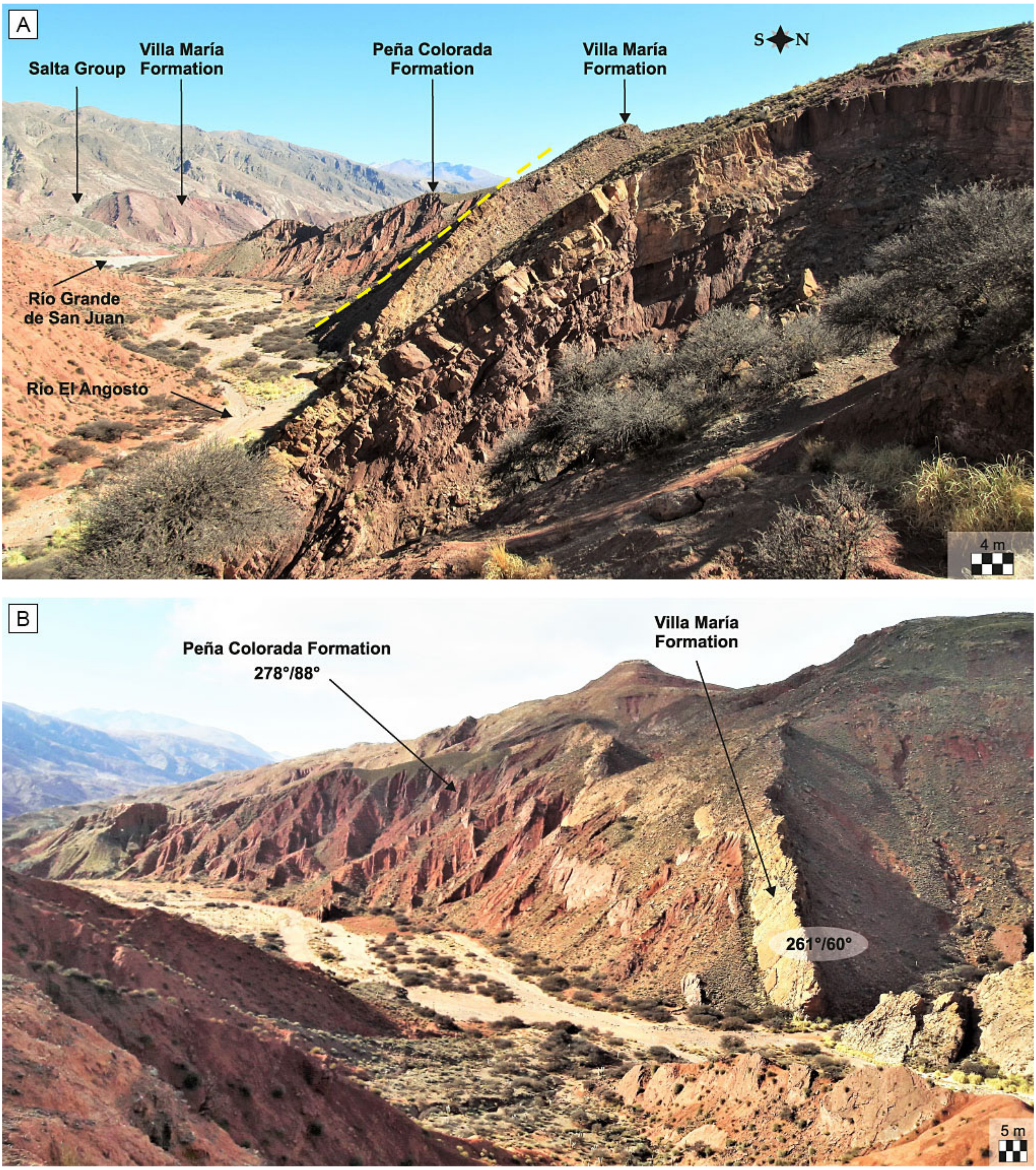
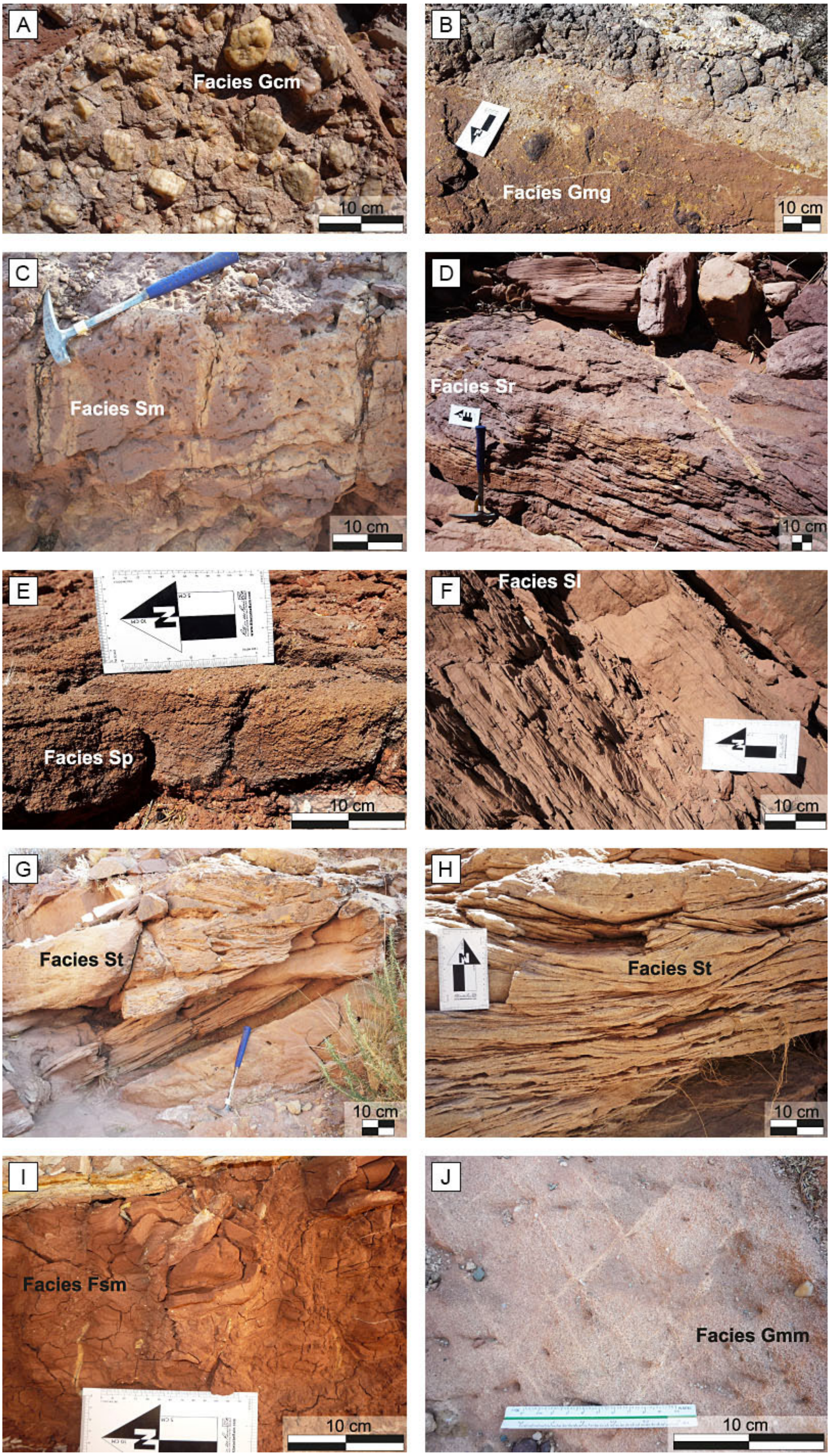


Figure 5. **a)** The contact (yellow dashed line) between the Villa María and Peña Colorada formations outcropping on the western side of the Buena Esperanza anticline (site 5). **b)** The uppermost conglomeratic strata of the Villa María Formation are disposed 261°/60°, whereas the lower Peña Colorada Formation is tilted 278°/88°.

associated with whitish, laminated, fine-grained sandstones. This succession is followed by facies Sm that involves brown-reddish pebbly sandstones, muddy sandstones, and conglomeratic sandstones. The proportion of conglomerates increases upwards. Uppermost conglomerates, with abundant sandy matrix, are characterized by cross-bedding and clasts sizing up to 10 cm (facies Gt, upper limit


A
Facies Gcm
10 cm
B
Facies Gmg
10 cm
C
Facies Sm
10 cm
D
Facies Sr
10 cm
E
Facies Sp
10 cm
F
Facies Sl
10 cm
G
Facies St
10 cm
H
Facies St
10 cm
I
Facies Fsm
10 cm
J
Facies Gmm
10 cm

stratotype; Fig. 8 D and E). Predominant lithotypes (≥95%) consist of subangular clasts of green-grayish quartzites and white quartz, with minor proportions (≤5%) of red sandstones and gray-whitish micaceous sandstones.

Depositional environment. The facies associations can be assigned to overbank, flood plain deposits, and backswamp, transitionally to meander river system with plane-bed flows with soil development.

In the upper member, facies Sm suggest the occurrence of sediment-gravity flow events, whereas cross-bedding and wedging strata of facies Gt would correspond to minor channel infilling in a braided plain with flashy discharges due to seasonal variations in rainfalls. The prevalence of flat and planar laminations in fluvial successions of the Peña Colorada Formation indicate sediment accumulation under upper flow regimes (i.e., rapid changes in flow strength; Fielding, 2006) and strongly seasonal rainfalls. Paleo-environmental conditions would have been then characterized by pronounced seasonal peaks in precipitation and runoff.

LITHOSTRATIGRAPHIC CONSIDERATIONS

Lithological Variations

The textural shifting through the considered deposits involves basal conglomerates that are overlain by aeolian and sandy to conglomeratic strata belonging to the Villa María Formation. These deposits are followed by the sandy lower and middle members of the Peña Colorada Formation that ends with an upper member grading from muddy sandstones to very coarse conglomerates (Fig. 4). According to the dominant textures, the Villa María Formation is, in general, coarser than the Peña Colorada Formation, and only the uppermost conglomerates of the Peña Colorada Formation are similar-to-coarser than those of the Villa María Formation. Therefore, no clear upward coarsening tendency is observed through the early Cenozoic record. Despite this, the Peña Colorada Formation clearly revealed getting coarser upward.

The color of the deposits changes from reddish-purple (muddy sandstones) and gray-whitish to pink-yellowish (coarse sandstones and conglomerates) in the Villa María Formation; to light orange-reddish and light pink (muddy sandstones and sandstones) and brown-reddish (coarse sandstones and conglomerates) in the Peña Colorada Formation. This purple - pale - orange-brown chromatic transition seems being simultaneous with major changes in rock cement: reddish-purple strata in the lower Villa María Formation are often cemented by iron carbonate, pale rocks of the upper Villa María Formation are cemented by silica, and strata of the Peña Colorada Formation are exclusively cemented by carbonate. Notwithstanding the relation between the cement and color of rocks would coincide with major shifting features of the considered deposits, some strata in the Villa María Formation (*e.g.*, see facies Sl: finely laminated, micaceous, muddy sandstones and sandstones shown in Fig. 6 F) are purple despite having a siliceous cement.

The presence of quartz, carbonate, and gypsum veins are additional distinctive features of the different members constituting the Villa María and Peña Colorada formations. The veins of quartz are widely distributed in the Villa María Formation; carbonate veins are present in the lower member of the Peña Colorada Formation, whereas gypsum veins are a characteristic feature of its middle and upper parts.

An additional feature that gradually changes throughout the considered deposits is the proportion between lithotypes. Quartz and green-grayish

Figure 6. Lithofacies of the Villa María Formation. Lower member: **a)** basal conglomerate composed of spherical and polish clasts of white quartz (facies Gcm, lower limit stratotype); **b)** brown-reddish conglomerates cemented by iron carbonate, containing dark nodules of iron carbonate (facies Gmg). Middle member: **c)** pink-yellowish, frequently laminated **(d)**, muddy sandstones containing purple mottles and marks of bioturbation (facies Sm and Sr, respectively); **e)** brown-reddish, cross-bedded, medium to coarse sandstones and pebble layers, cemented by iron carbonate, having an aspect similar to pisolite but composed of highly well sorted lithic clasts (facies Sp); **f)** finely laminated, micaceous, siliceous, purple muddy sandstones, sandstones (facies Sl). Upper member: **g)** and **h)** pink to whitish, siliceous, laminated, medium sandstones (facies St) with cross stratification (planar cross-bed in panel g and trough cross-beds in panel h) dipping ~45 (indicated by hummer in panel **g)**; **i)** brown-reddish mudstones with cataphylar disjunction and containing abundant gypsum veins oblique to the stratification (facies Fsm); **j)** massive conglomeratic coarse sandstones containing a distinctive quadrangular meshwork of quartz veins (facies Gmm).

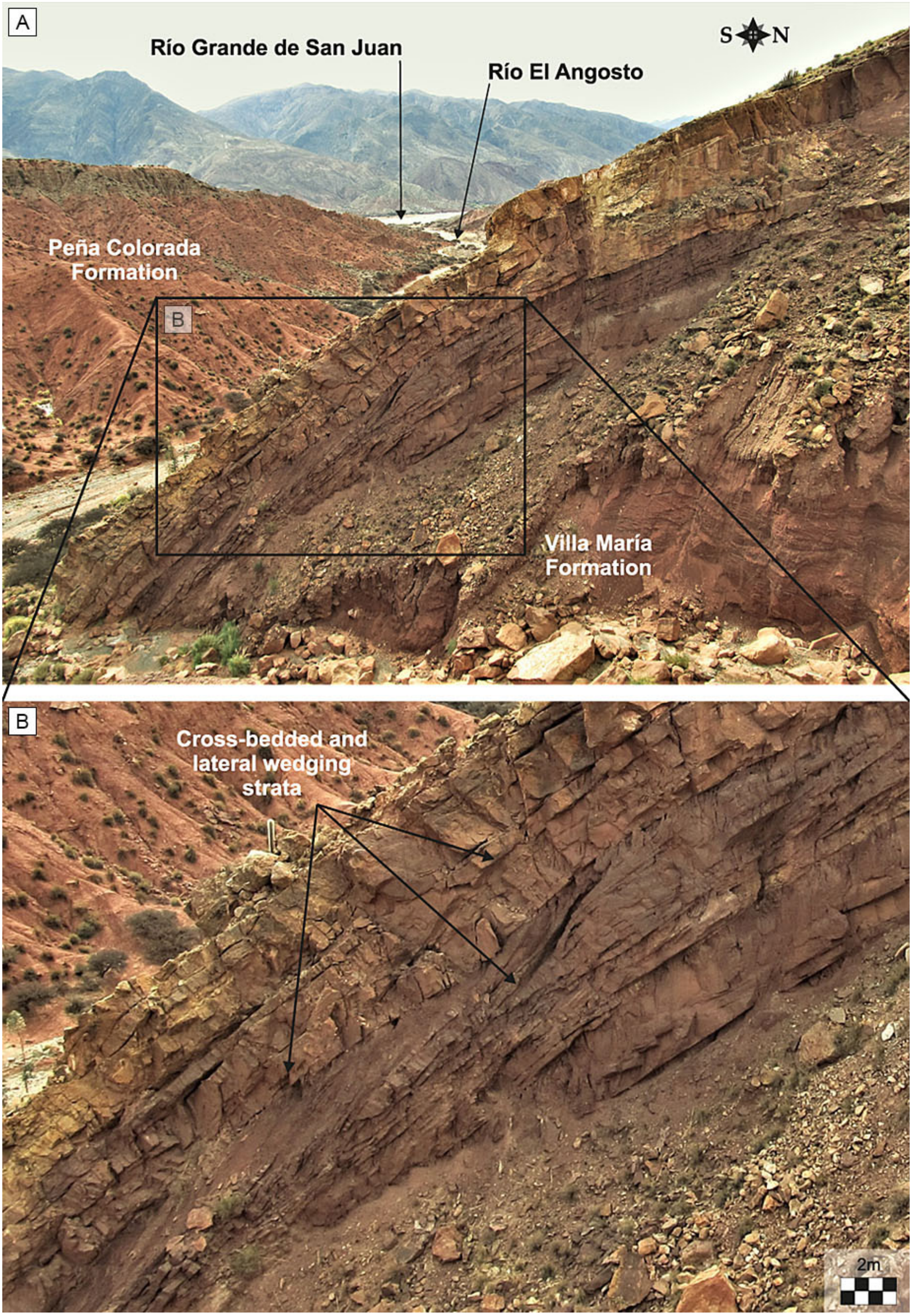


Figure 7. Cross-bedded, purple sandstones (facies Gmm) of the uppermost Villa María Formation at the Buena Esperanza anticline (site 5). The overlying yellowish strata correspond to the massive and consolidated conglomerates defining the upper limit stratotype of the Villa Maria Formation.

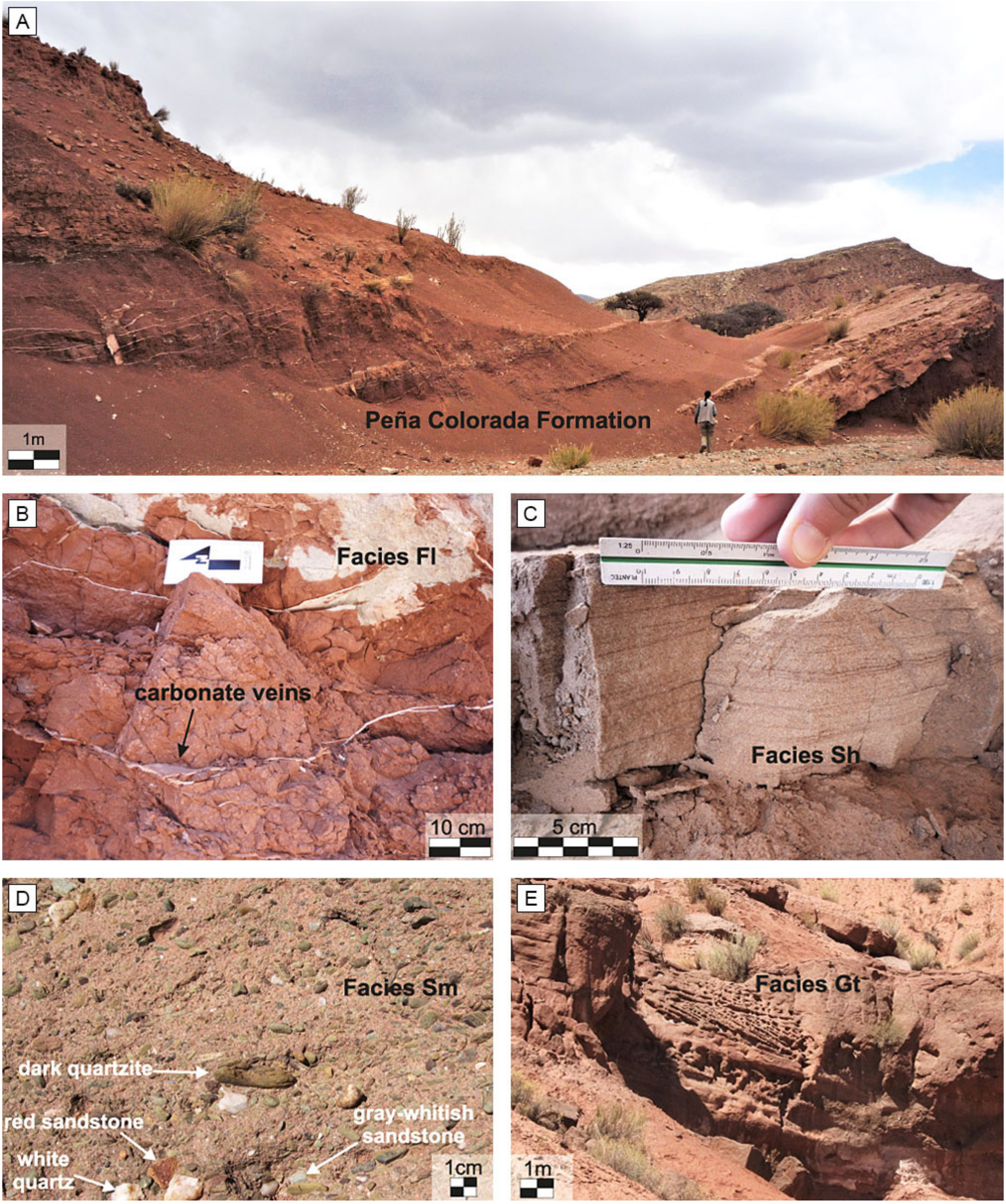


Figure 8. Lithofacies of the Peña Colorada Formation. The basal member involves the lowermost 105 m of the unit, and consists of facies Fl: purple-reddish to light orange-reddish, friable, calcareous muddy sandstones and sandstones containing abundant carbonate veins, fine laminations and little ripples **(a)**. Orange-reddish, friable, calcareous muddy sandstones containing carbonate veins (facies Fl, lower limit stratotype) **(b)**. Strata consisting of whitish fine to medium-grained sandstones (facies Sh) in the middle member **(c)**. The upper member is characterized by increasing proportions of pebbly sandstones and, conglomeratic sandstones (facies Sm) where the predominant lithotype consists of subangular clasts of green-grayish quartzites, white quartz, and minor red sandstones and gray-whitish micaceous sandstones **(d)**. Sedimentary structures are widespread in the upper coarser member (facies Gt, upper limit stratotype) and mainly include crossbedding **(e)**.

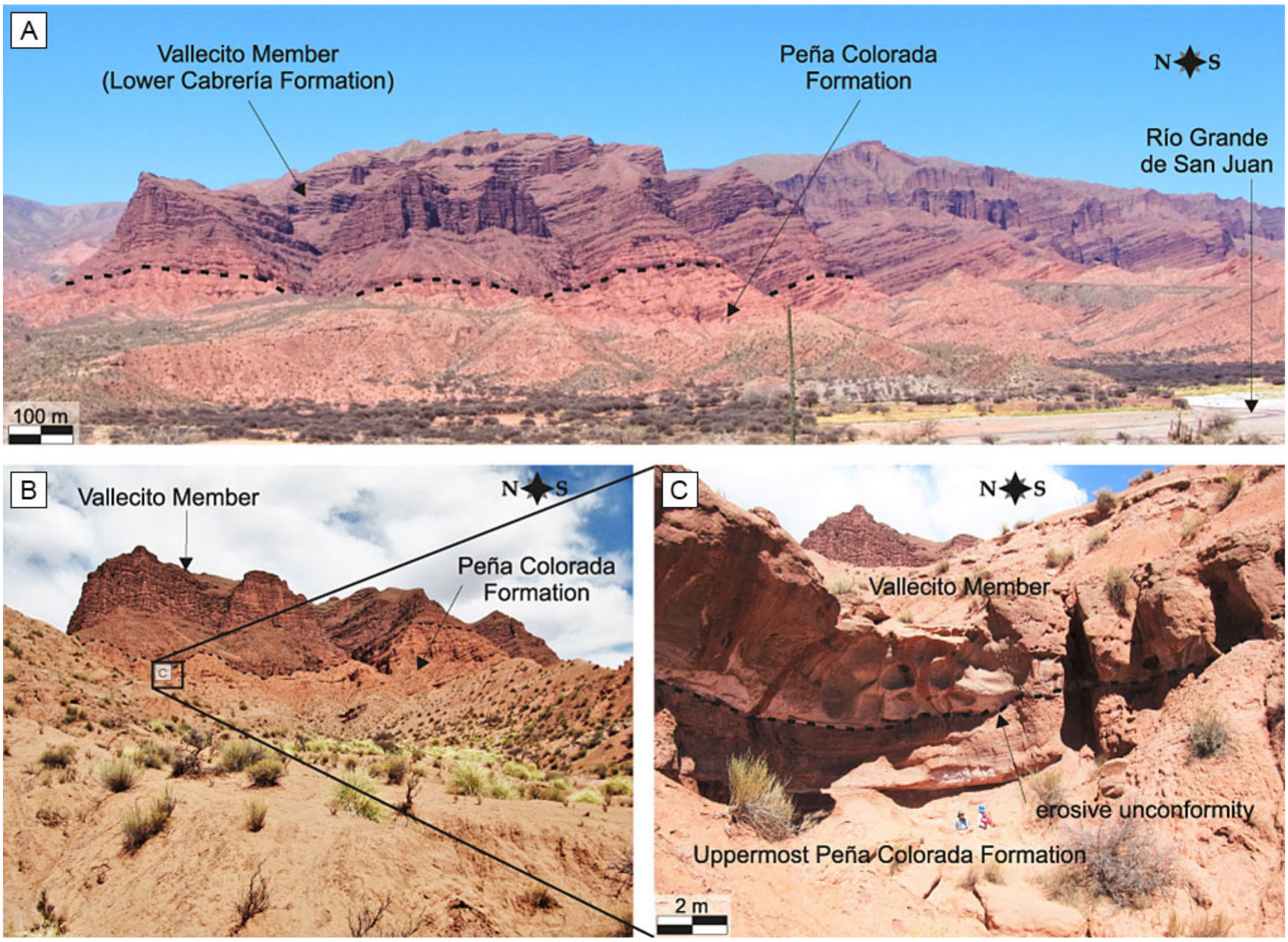


Figure 9. In picture **a)** and **b)** the contact between the Peña Colorada and the Cabrería formations at the Peña Colorada site corresponds to an erosive unconformity between the orange-reddish to brown-reddish sandy conglomerates of the Peña Colorada Formation and the brown, conglomeratic thick succession of the Vallecito Member. **c)** Thick conglomeratic strata at the lowermost Vallecito Member.

quartzite are steady representing more than 95% of clasts in pebbles and conglomerates through the two stratigraphic units. Even though that these two lithotypes would have sourced from the Acoite Formation, the proportion of Ordovician quartzites increases upwards with respect to quartz, and became majoritarian from the middle member of the Peña Colorada Formation. This change could be interpreted as a shift in the source area or the increase in the erosion of uplifted deposits of the Acoite Formation. Minor proportions of red and gray-whitish sandstones remain less than 5% throughout the Villa María and Peña Colorada formations. These lithotypes are assimilated to clastic supply sourced from the Salta Group. Red sandstones are persistent through the stratigraphic record, meanwhile gray-whitish sandstones are restricted to the Peña Colorada Formation. These variations between the proportions of lithotypes would be related to the landscape evolution, as the location and exhumation of the source areas.

Paleo-landscape Evolution

The basal contact of the early Cenozoic deposits includes the angular unconformity measured with the underlying Salta Group in the western side of the Río Grande de San Juan (site 1), and the highly developed erosive surface observed at El Angosto (Fig. 1). Accordingly, the basal contact of the Villa María Formation would be pointing to a disconformity (hiatus plus erosion). These evidences, together with the textural characteristics of the lower Villa María Formation (that mainly involves coarse conglomerates and the prevalence of the quartzitic lithotype), suggest previous exhumation and deformation

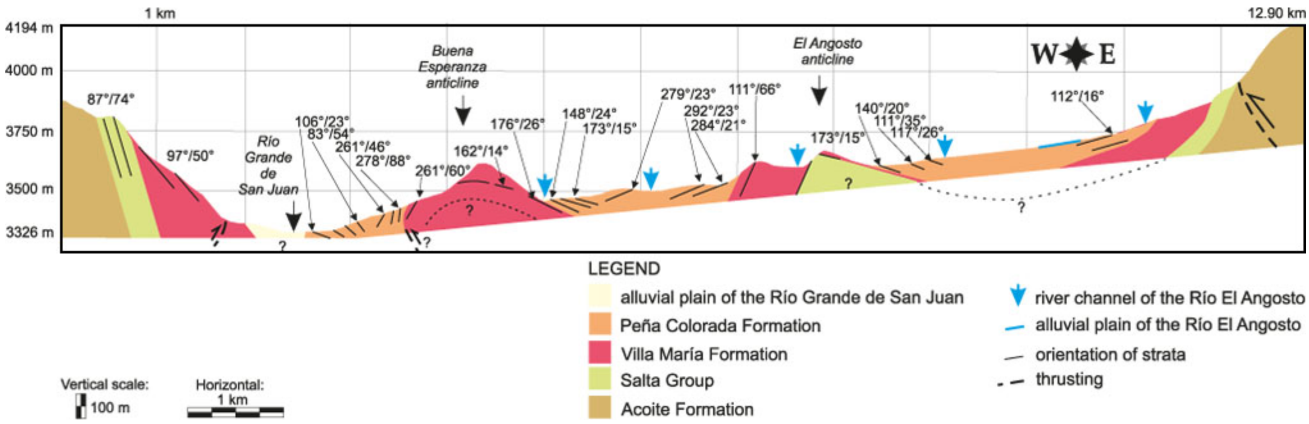


Figure 10. Structural transect across the study area, displaying WNW-ESE at the latitude of El Angosto (for location see Fig. 1). The vertical scale is exaggerated 2.5 times relative to the horizontal scale.

resulting in a paleotopography sculpted in the rocks of the Acoite Formation, with minor exposures of the Salta Group. This paleotopography would have been subsequently eroded and covered by the continental deposits of the Peña Colorada Formation. According to this, thrusting along the Cerro Negro could have been already active during this initial basin stage. Furthermore, facies assemblages in the Villa María Formation are consistent with alluvial fans and flash flows flooding a braided plain near the piedmonts, which involve proximal facies in mountainous settings (Table 2). The erosive unconformity in the upper limit of the Peña Colorada Formation reveals the existence of active exhumation at the headwaters, and the proximity to the areas sourcing sediments.

The contact between the Villa María and Peña Colorada formations is likely paraconcordant along the eastern side of the El Angosto and Buena Esperanza anticlines (Fig. 10). Almost vertical strata of the Villa María Formation overlie the western flank of the Buena Esperanza anticline, where the Peña Colorada Formation tilts 60° (see Figure 5). This pattern of younger strata steeply dipping than the older ones is probably the result of post-sedimentary faulting driven by the propagation of Andean compressive deformation.

CONCLUSIONS

The Peña Colorada Formation has been divided in two distinctive formal units according to their internal bounding surfaces and sedimentological characteristics. The Villa María and Peña Colorada formations record the early Eocene - early Oligocene continental sedimentation over ~1,000 km^2 in the north westernmost Argentine Puna plateau. Our new data show an unconformable contact between these deposits and the underlying Cretaceous-Paleogene Salta Group instead of a paraconformity as had been previously reported. The upper contact with the early Oligocene-Miocene Cabrería Formation is an erosional unconformity. The early Cenozoic record starts with the 170 m-thick Villa María Formation that comprises a lower member mainly characterized by the predominance of conglomerates and coarse sandstones cemented by iron carbonate, which is followed by the middle and upper members composed by alluvial and aeolian deposits mainly cemented by silica. The overlying Peña Colorada Formation consists of a 1,620 m-thick, calcareous, upwards coarsening succession. We identified three well defined members: a- the lower member involves purple-reddish to light orange-reddish, friable, muddy sandstones containing veins of carbonate, b- the middle member is characterized by the presence of gypsum veins, and c- the upper member involves an upwards coarsening alternation of brown-reddish sandstones and cross-bedded sandy conglomerates.

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REFERENCES

Allmendinger, R.W., T.E. Jordan, S.M. Kay and **B.L. Isacks,** 1997. The evolution of the Altiplano-Puna Plateau of the Central Andes. *Annual Review Earth Planetary Sciences* 25:139-174.

Aramayo, A., F. Hongn and **C. del Papa,** 2017. Acortamiento paleógeno en el tramo medio de los Valles Calchaquíes: depositación sintectónica de la Formación Quebrada de los Colorados. *Revista de la Asociación Geológica Argentina* 74 (4):524-536.

Bahlburg, H., C. Breitkreuz, J. Maletz, M.C. Moya and **J.A. Salfity,** 1990. The Ordovician sedimentary rocks in the northern Puna of Argentina and Chile: New stratigraphical data based on graptolites. *Newsletters on Stratigraphy* 23(2):69-89.

Bellman, R. and **R. Chomnales,** 1960. Estudio hidrogeológico del Valle Puesto Viejo y sus posibilidades económicas, Provincia de Jujuy. *Acta Geológica Lilloana* 3:59-84.

Brackebusch, L., 1883. Estudios sobre la Formación Petrolífera de Jujuy. *Boletín de la Academia Nacional de Ciencias de Córdoba* 5:137-252.

Brackebusch, L. 1891. *Mapa geológico del interior de la República Argentina*, escala 1:1.000.000. Gotha.

Caffe, P.J. and **B. Coira,** 2002. Chronostratigraphy of the San Juan de Oro Basin and its tectonic implications for the Northern Puna during the Miocene. *Proceedings 5th International Symposium of Andean Geodynamics*, Toulouse, France.

Carabajal, E., R. Pascual, R. Pinedo, J.A. Salfity and **N. Vucetich,** 1977. Un nuevo mamífero de la Formación Lumbrera (Grupo Salta) de la comarca de Carahuasi (Salta, Argentina). Edad y correlaciones. *Museo Municipal de Ciencias Naturales Lorenzo Scaglia* 2(7):148-163. Mar del Plata.

Coira, B., P.J. Caffe, A. Ramírez, W. Chayle, A. Díaz, S. Rosas, E. Pérez, O. Orosco and **M. Martínez,** 2004. *Hoja Geológica 2366-I/2166-III Mina Pirquitas*, Provincia de Jujuy (escala 1:250.000). Servicio Geológico Minero Argentino. Instituto de Geología y Recursos Minerales. Boletín 269: 1-123.

Coutand, I., P.R. Cobbold, M. de Urreiztieta, P. Gautier, A. Chauvin, D. Gapais, E.A. Rossello and **O. López-Gamundi,** 2001. Style and history of Andean deformation, Puna plateau, northwestern Argentina. *Tectonics* 20 (2):210-234.

del Papa, C., F. Hongn, J. Powell, P. Payrola, M. Do Campo, M. Strecker, I. Petrinovic, A. Schmitt and **R. Pereyra,** 2013. Middle Eocene-Oligocene broken-foreland evolution in the Andean Calchaquí Valley, NW Argentina: insights from stratigraphic, structural and provenance studies. *Basin Research* 25:574-593.

Fielding, C.R., 2006. Upper flow regime sheets, lenses and scour fills: Extending the range of architectural elements for fluvial sediment bodies. *Sedimentary Geology* 190: 227-240, doi: 10.1016/j.sedgeo.2006.05.009.

Harrington, H.J., 1957. Ordovician formations of Argentina. In Harrington H.J. and A.F. Leanza (Eds.), *Ordovician trilobites of Argentina*. Department of Geology, University Kansas Special Publication 1:1-59.

Jordan, T.E., P.L. Nester, N. Blanco, G.D. Hoke, F. Dávila and **A.J. Tomlinson,** 2010. Uplift of the Altiplano-Puna plateau: a view from the west. *Tectonics* 29, TC5007, doi: 10.1029/2010TC002661.

Lamb, S. and **L. Hoke,** 1997. Origin of the high plateau in the Central Andes, Bolivia, South America. *Tectonics* 16:623-649.

Marquillas, R.A., C. del Papa and **I.F. Sabino,** 2005. Sedimentary aspects and paleoenvironmental evolution of a rift basin: Salta Group (Cretaceous-Paleogene), northwestern Argentina. *International Journal of Earth Sciences* 94:94-113.

Miall, A.D., 2006. The Geology of Fluvial Deposits Sedimentary facies, basin analysis, and petroleum geology. 4th ed. Springer, Berlin, 582 pp.

Moreno, J.A., 1970. Estratigrafía y paleogeografía del Cretácico superior de la cuenca del Noroeste Argentino, con especial mención a los Subgrupos Balbuena y Santa Bárbara. *Revista Asociación Geológica Argentina* 25 (1):9-44.

Navarini, A., V. Méndez and **J.C. Zanettini,** 1973. Sobre la presencia de la Formación Yacoraite en el anticlinal del Cerro Chaupiorco. Departamento Santa Catalina, Provincia de Jujuy. *Revista de la Asociación Geológica Argentina* 28 (1):88-90.

Pascual, R., M.G. Vucetich and **J. Fernández,** 1978. Los primeros mamíferos (Notoungulata Henricosborniidae) de la Formación Mealla (Grupo Salta, Subgrupo Santa Bárbara). Sus implicancias filogenéticas, taxonémicas y cronológicas. *Ameghiniana* 15:366-390.

Pascual, R., M. Bond and **M. Vucetich,** 1981. El Subgrupo Santa Bárbara (Grupo Salta) y sus vertebrados, cronología, paleoambientes y paleobiogeografía. *Congreso Geológico Argentino*, Actas 3:743-178.

Prezzi, C., J.P. Caffe and **M.P. Iglesia Llanos,** 2011. Paleogene-Lower Miocene local clockwise vertical axis tectonic rotations in the northern Argentina Puna: new data. *Proceedings Biennial of Latinmag, Latinmag Letters* 1(17): 1-7. Tandil, Argentina.

Salfity J.A. and **R.A. Marquillas,** 1994. Tectonic and sedimentary evolution of the Cretaceous-Eocene Salta Group Basin, Argentina. In: Salfity J.A. (ed.), *Cretaceous Tectonics of the Andes*. Earth Evolution Sciences, Friedr. Vieweg & Sohn, pp 266-315.

Turner, J.C., 1959. Estratigrafía del cordón de Escaya y de la Sierra de Rinconada (Jujuy). *Revista de la Asociación Geológica Argentina* 13 (1-2):15-39.

Turner, J.C., 1964a. *Descripción Geológica de la Hoja 2c Santa Victoria* (Provincias de Salta y Jujuy). Boletín del Instituto Nacional de Geología y Minería 104: 83 p.

Turner, J.C., 1964b. *Descripción Geológica de la Hoja 2b La Quiaca* (Provincia de Jujuy). Boletín del Instituto Nacional de Geología y Minería 103:109 p.

Turner, J.C., 1966. Estratigrafía de la Comarca de Santa Catalina, Jujuy. *Acta Geológica Lilloana* 8:33-47.

Turner, J.C., 1978. *Descripción Geológica de las Hojas 1a y b. Santa Catalina y 2a San Juan de Oro*. Provincia de Jujuy. Boletín del Servicio Geológico Nacional 156 (7): 1-56 p.

Turner, J.C., 1982. *Descripción Geológica de la Hoja 3b, Mina Pirquitas, Jujuy*. Servicio Geológico Nacional. Secretaría de Industria y Minería. Boletín 187:1-56.

Viera, O.V., 1984. Geología de la comarca de Eureka. Departamento Santa Catalina, Provincia de Jujuy. Plan NOA-I. Dirección Provincial de Minería y Recursos Energéticos de Jujuy. Informe 574, Carpeta 214:1-183, Jujuy (inédito).

Vilela, C.R., 1956. *Descripción Geológica de la Hoja 7d, Rosario de Lerma* (Provincia de Salta). Boletín de la Dirección Nacional de Geología y Minería 84.