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New chronostratigraphy for a lower to upper Carboniferous strike-slip basin of W-Precordillera (Argentina): Paleogeographic, tectonic and glacial importance

Juan Pablo Milana[a,*], Mercedes Di Pasquo[b]

[a] CONICET and INGEO-Universidad Nacional de San Juan, Av. Ig. De la Roza y Meglioli, 5401, Rivadavia, San Juan, Argentina
[b] CICYTTP (CONICET-ProvER-UADER), Dr. Materi y España S/N, Diamante, E3105BWA, Entre Ríos, Argentina

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ABSTRACT

New biostratigraphic ages and the stratigraphic revision of a c. 4 km thick succession of Lower and Upper Carboniferous beds, exposed in the Del Salto creek, in the western Precordillera (San Juan, Argentina) are presented. Detailed mapping and analysis of the vertical and lateral variations of the sedimentary systems of the three units we are redefining here (El Planchón, Churupatí and Del Salto formations) allowed us to modify many pre-existing concepts. The palynological data provided for the El Planchón Formation corroborate it is not Devonian but Carboniferous, (mid-late Visean), since it conformably overlies the Del Ratón Formation (Early Visean). A distal glacial interval in El Planchón lower member, distal turbidites and hemipelagites in the middle member and non-glacial shallow-water heterolithics with small slumps and proximal turbidites for the upper member are interpreted. An angular unconformity defines the base of the alluvial conglomeratic Churupatí Formation (redefined herein), that shows dramatic lateral variations from a dominantly alluvial conglomeratic sequence to the north (green- purple conglomerates) and sandier fluvial to swampy sequences to the south. Chrupati palynological content suggests its late Visean – early Serpukhovian age. A new erosive unconformity separates Churupatí from Del Salto formations with an interpreted glacial origin, while the palynological content of basal Del Salto Fm indicates a Pennsylvanian (Bashkirian) age, not Permian. A dextral strike-slip basin is interpreted to explain this Carboniferous succession, based on geological, stratigraphical and sedimentological data. Evidence supporting this interpretation are: (1) its thickness (c. 4 Km) in a restricted geographical place as no traces of these units are found east or westwards except for Del Salto formation equivalents. (2) the amount of active-tectonically fed gravel, important lateral changes, and fast transitions to from gravel-to mud-dominated sequences, (3) the southward displacement of the entry-point from hinterland of coarse sediment observed between Churupatí and Del Salto formations, (4) the partial rotation of local structures, (5) its coincidence with the modern dextral Del Tigre fault. The entire sequence supports the existence of three main glacial episodes and does not support the existence of the Protoprecordillera, but a surrounding hummocky positive terrain that did not obstruct the drainage systems moving sediment eastwards.

1. Introduction

The Upper Paleozoic deposits exposed in the Del Salto creek, also known as IMSA creek or Km 114 of the San Juan-Calingasta road (Figs. 1 and 2) have been the subject of a long geological debate for more than 50 years. This debate has not yet been able to answer questions such as the stratigraphic and paleoenvironmental relationships between the El Planchón formation and surrounding units (Sessarego, 1983; Milana, 2000a; Milana et al., 2014; Colombo et al., 2014), its extent, paleoenvironment, tectostratigraphic significance and mainly, its age due to the lack of dating elements. This debate comes now to an end due to the palynomorphs recovered from the typical El Planchón F beds as litostragraphically defined by Quartino et al. (1971). The complex geology of this region mainly due to the superposition of several tectonic processes of different ages, reinforced by the difficulties of giving ages to this stratigraphic unit, has resulted in persistent uncertainties such as the supposed Devonian age of the El Planchón Formation (Baldis and Peralta, 2000). Some time ago, Milana (2000a) pointed out that El Planchón has to be Carboniferous due to its conformable base over Del Ratón Formation (Visean) which was later

* Corresponding author.
E-mail addresses: jpmilana@gmail.com (J.P. Milana), medipa@cicyttp.org.ar (M. Di Pasquo).

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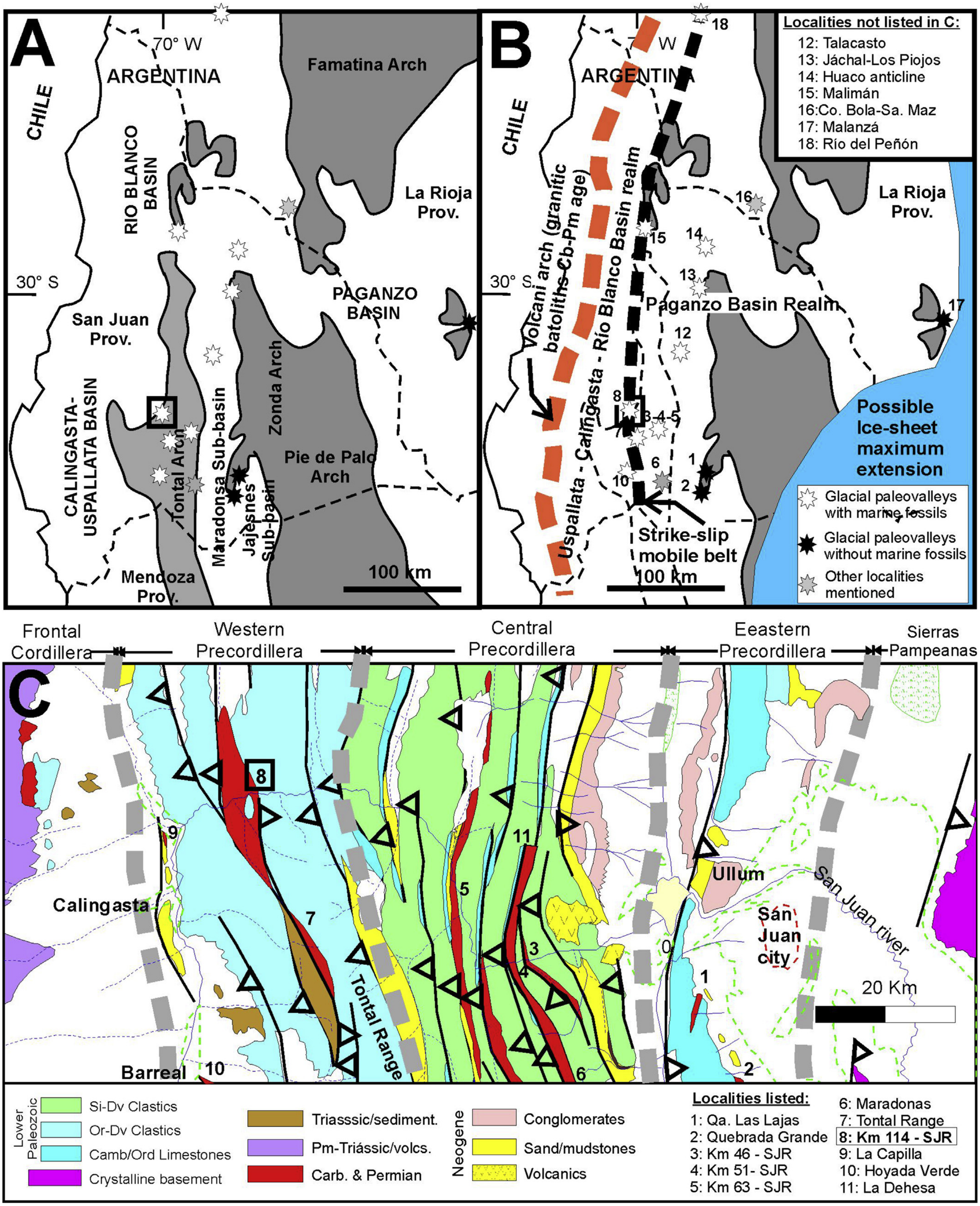


Fig. 1. General Maps. A) Most used paleogeographic map for the regional Carboniferous portraying the distribution of Late Paleozoic basins and positive areas (modified from Limarino et al., 2014, and other authors). Study area indicated by box. B) General paleogeographic map proposed, indicating the belt of basins created by el Tigre falt zone and the possible extension of the ice-sheet, from which outlet glaciers of variable lengths would be radiated. Localities mentioned in the text are also indicated. C) Geological map of the Precordillera at the working latitude belt showing geological province domains (separated by thick dashed gray lines) and Carboniferous localities mentioned in the text. SJR quotes for San Juan River. Study area highlighted with box.

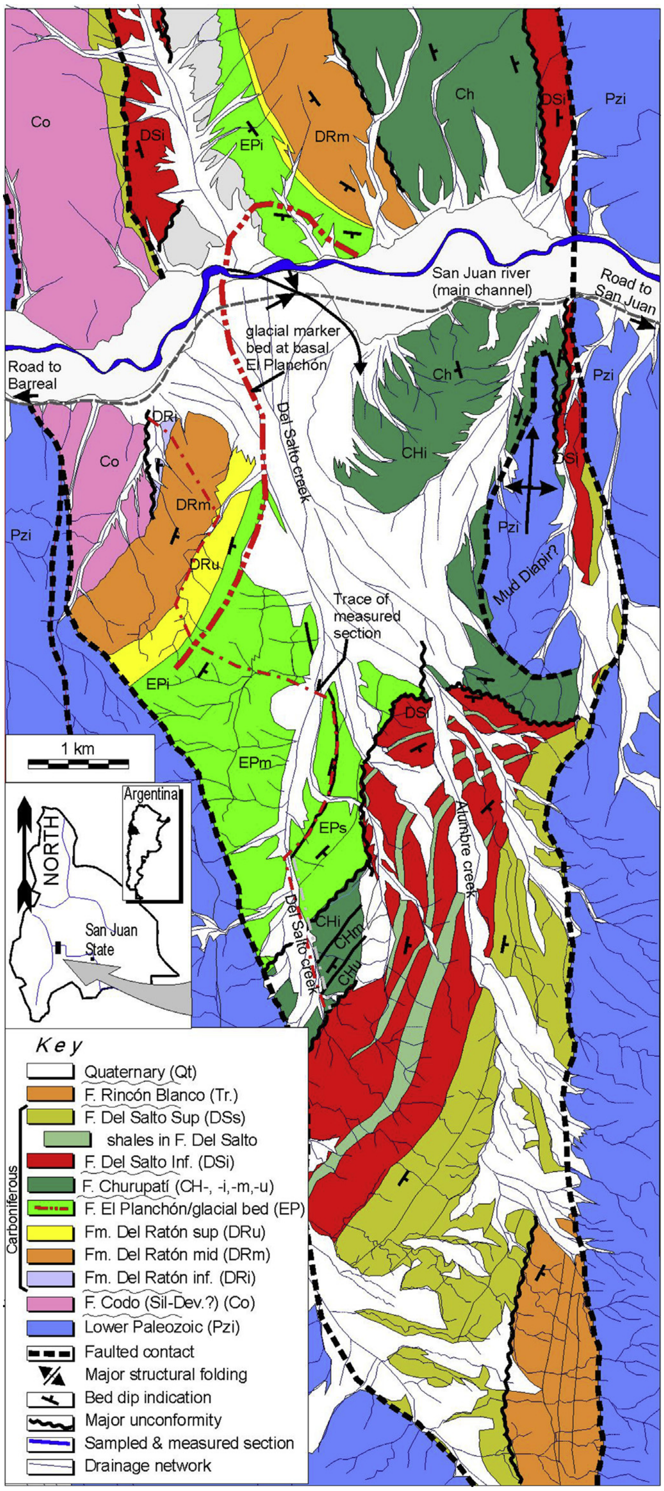


Fig. 2. Detailed geologic map of the study area with indication of measured sections that define the stratotypes of the enmended units considered (El Planchón and Churupatí Fm), discussed in the text. It is also indicated the interpreted projection of the glacial interval found at the base of El Planchón that was used to correlate units across the San Juan river Qt cover.

supported by other authors (cf. Colombo et al., 2014).

In order to solve these issues after recovering some key palynological information from the expected type section of El Planchón formation, we have produced a detailed geological map, measured new stratigraphic profiles of the Neopaleozoic units present in this area, and undertook a second exhaustive sampling to check the presence of microfossils. This work allowed us to present here, for the first time, detailed palynological material obtained from the El Planchón, Churupatí and Del Salto Formations that allow us now to define their ages. We have amended some stratigraphic definitions, established their relationships, and interpreted their palaeoenvironmental, paleoclimatic and paleogeographic setting.

The section studied was the basis on which some authors proposed the idea of a glaciated mountain chain –the Protoprecordillera-during part of the Carboniferous (Amos and Rolleri, 1965; Limarino et al., 2014). For this reason, it is of the utmost interest to understand this section, and the reason to carry out new geological and paleontological surveys of all the units deposited above the fossiliferous strata of the Del Ratón Formation, attributed to the Late Tournaisian-Early Visean (Amenábar and di Pasquo, 2008 and references). Our study allowed us to separate two clearly different units: El Planchón Formation, c. 1500 m thick and deposited entirely subaqueously, and the overlying Churupatí Formation, c. 700 m thick and mainly deposited subaerially.

This late Paleozoic succession culminates with the Del Salto Formation that was assigned to the upper Pennsylvanian-Cisuralian (Manceñido, 1973) based on invertebrate data (e.g. Manceñido and Sabattini, 1974; Colombo et al., 2014; Taboada, 2014). Its age, suggesting a long hiatus over most of the Carboniferous was also used to support the existence of a mountain chain. The analysis of this hypothesized range, called Acadic Precordillera or Protoprecordillera (Amos and Rolleri, 1965; Rolleri and Baldis, 1969; Limarino et al., 2014) is pertinent to this work, since this study area would have been located very close to its supposed axis. The new chrono- bio- and stratigraphic information of this site supplied here will help to understand this paleogeographic issue along with the extent and nature of the LPIA (Late Paleozoic Ice Age) in western Gondwana.

1.1. *Origin of the problem in this section*

The confusing stratigraphy of the upper Paleozoic succession in this locality, that created a debate that lasted more than half a century is due to a combination of several factors; (1) The first factor is the change in orientation of the traditional N–S precordilleran structures as in this locality there are many oblique structures that complicate the geological understanding (Fig. 2). (2) The second relates to the varied tectonic phases that suffered this strip that coincides with the Del Tigre fault, generating an intense deformation that prevents finding clean stratigraphic surfaces. The presence of stratigraphic units with dissimilar competences due to important lithological changes generated differential responses to the tectonic stress. As a result, most stratigraphic boundaries became natural planes of shearing, being necessary to survey these surfaces laterally for several kilometers to define their stratigraphic origin. In some cases, it was not possible to find clean stratigraphic surfaces, making the reconstruction of the original stratigraphic sequence very difficult (Fig. 3). (3). Third is the existence of large lateral facies changes in the Neopaleozoic, which further complicates the correlations between the exposed units. This aspect was already pointed out both by Milana (2000a) and Colombo et al. (2014), who agreed on the Carboniferous age of the El Planchón Formation given its stratigraphic relationships, but without providing chronostratigraphic data. (4) Fourth is the existence of a significant Quaternary cover that prevents constraint of the inferred lateral variations. Thus, interpretations made herein, especially for the Churupatí Formation, may need further revision. (5) A fifth problem is the relief of several hundred meters of the discordances associated with large erosive troughs, typical of the glacial events that occurred in this locality (Figs. 2 and 3).

Besides the problems detailed above, some erroneous interpretations of key geological elements added more confusion to this already complicated scenario, principally the incorrect mapping of the sedimentary contact between the Del Ratón and El Planchón formations as a reverse fault (Kerlleñevich, 1969; Quartino et al., 1971). This error was

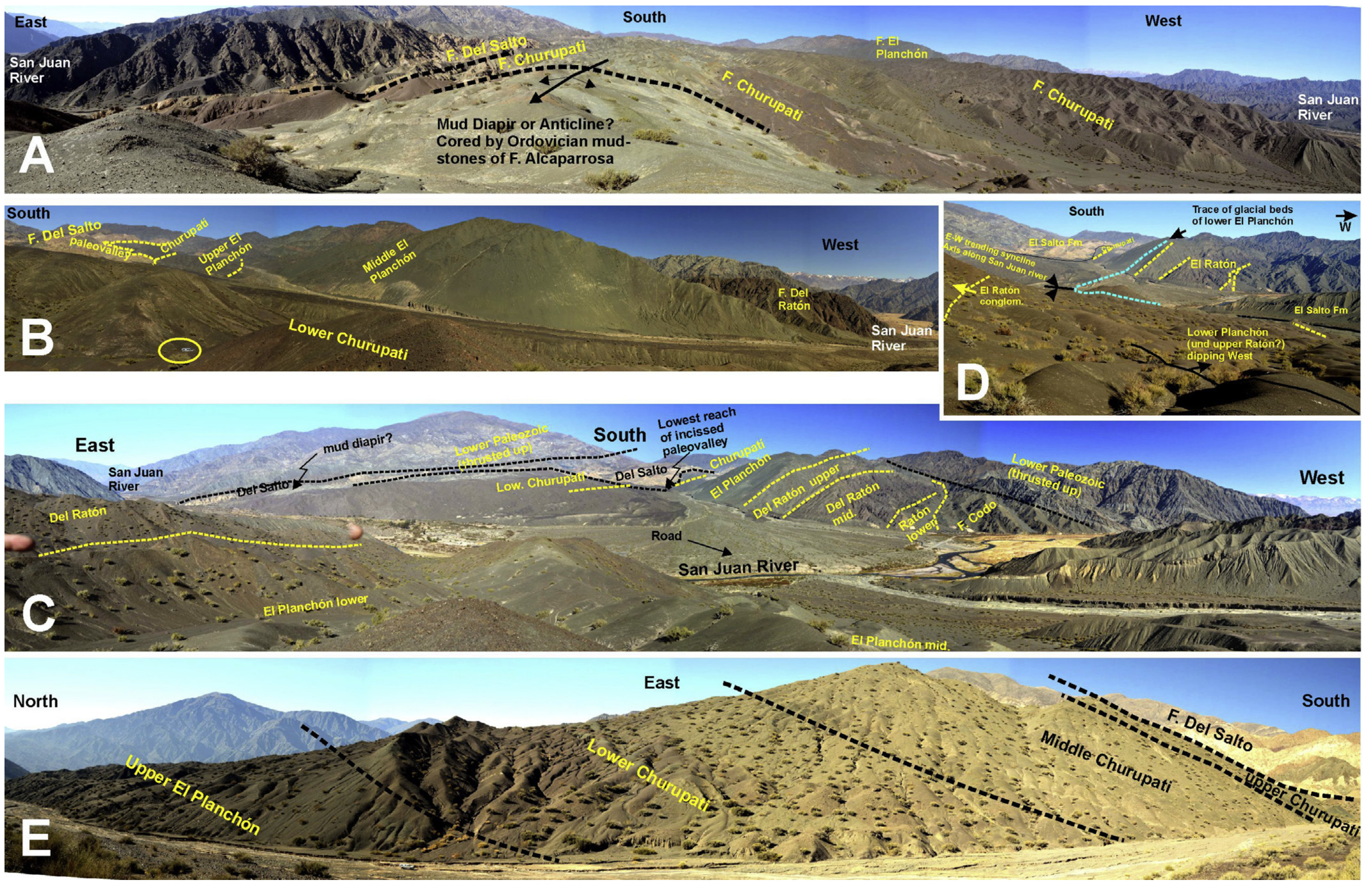


Fig. 3. Selected views using photomosaics of the Km 114 outcrop showing different structural and sedimentary characteristics discussed in the text. A) 180° view southward of the potential mud diaper cored in Alcaparrosa Fm, draped by the Churupatí Fm conglomerates, eroded then by the basal Del Salto unconformity. B) View to the southwest from the southern extreme of the braquianticline, suspected diapir, showing the sucession from Del Ratón, El Planchón, Chrupatí and Del Salto Formations. C) View southward taken north from the San Juan river showing in the foreground Del Ratón and El Planchón Fm dipping Wast, and the same units at the other side of the river dipping east. D) A detail of Photomosaic C, showing the correlation of the Glacial 2 marker bed at lower El Planchón traced through the San Juan river course. E) eastward view through Del Salto creek to the stratotype and sampled section of Churupatí Formation.

repeated by Sessarego (1983, 1988), Sellés Martínez (1985), Sessarego and Césari (1989) and Amenábar and di Pasquo (2008), maintaining this reverse fault between the top of the Del Ratón and the base of the El Planchón formations. Milana (2000a) reinterpreted this contact for the first time as a stratigraphic surface, and more recently, Colombo et al. (2014) reiterated this same geological observation. Given the need to define the age of the El Planchón Formation (also to confirm that it is not Devonian), a detailed palynological sampling of its fine-grained facies and overlying units was carried out.

2. Methodology

2.1. Stratigraphic sections and sampling

Detailed lithostratigraphic work was carried on outcrops that are partially exposed near the National highway N. 20 from Km 112 to Km 118, and extending south and north from the San Juan River (Figs. 1 and 2). The stratigraphic sections of the Del Ratón, El Planchón and Churupatí formations were measured with tape and Brunton compass, whereas the Del Salto Formation was not measured due to samples were taken along a several hundred meters incised basal trough (glacial paleovalley) and the initial filling of this paleotopographic low had intense refolding associated with numerous "slumps". Del Salto F thickness value depends heavily on logging location and readers are referred to published values of Manceñido (1973) and Colombo et al. (2014). The thickness of the middle and upper shaly sections of the El Planchón Formation was obtained using open polygonals as the surface creep processes affect the structural dip of these shales. The interpretation of the depositional paleoenvironments of each unit is based on the analysis of the facies surveyed along the main stratigraphic profiles and their lateral changes.

2.2. Laboratory

Fifty five samples were collected from gray and brown shaly-marly, carbonaceous-shales and diamictites with fine matrix of the Del Ratón, El Planchón, Churupatí and Del Salto formations, with the aim of studying their palynological content. Standard palynological methods remove carbonates and silicates using HCl (15%) and HF (40%) respectively. The organic residues were treated with hot HCl and the remaining material was mounted with jelly glycerin for a first palynofacies inspection of the kerogen. Three samples of El Planchón, two from Churupatí and two from Del Salto formations (Fig. 4) yielded palynomorphs (spores and pollen grains) mostly immersed in a carbonaceous-phytoclastic matrix. Other residues from the latter unit provided only phytoclasts and indeterminate remains. In addition, the degree of thermal alteration of the organic matter in the seven samples reached relatively high values measured in thin-walled spores (between −3 and +3/−4, dark brown and very dark, scale TAI of Utting and Wielens, 1992). Further, the residues were oxidized with HNO_3 for 3 min, neutralized with ammonia, washed with distilled water and filtered with 25 µm mesh. This procedure allowed the recovery of a greater number of determinable palynomorphs, illustrated with a Labomed 5.0 Mp digital video camera attached to a Nikon E200

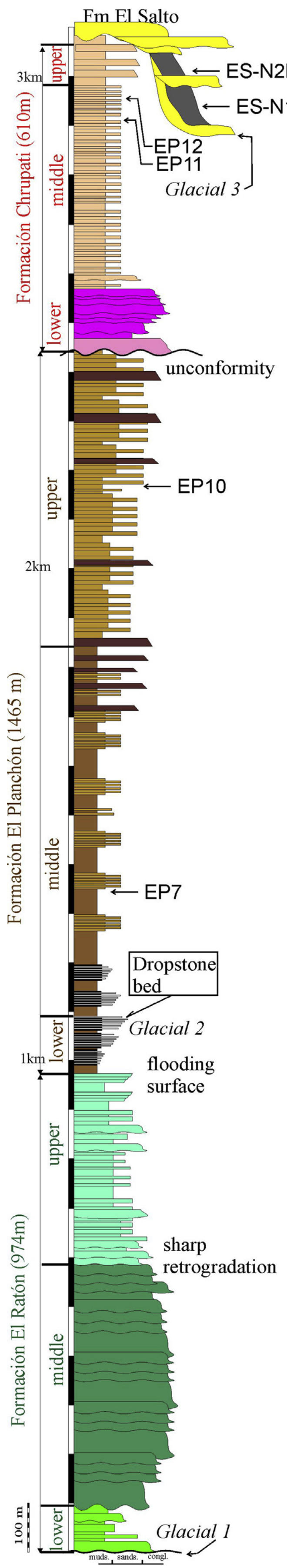


Fig. 4. Schematic sedimentary log for the studied sequence depicting the stratigraphic location of fertile palynological samples mentioned in the text and position of the three interpreted glacial events associated to this sequence. Grain size scale at the base of log.

microscope. The samples are housed at the Palynostratigraphy and Paleobotany Laboratory of the CICYTTP (CONICET-ER-UADER, Diamante, Entre Ríos, Argentina), under the acronym CICYTTP-Pl followed by the preparation number. Location of palynomorphs is stored with England Finder coordinates, and could be requested to the authors. For the list of recovered species with its authors see Appendix.

3. Results (stratigraphy and paleontology)

In this section we describe and interpret the depositional and tectono-stratigraphic setting of the Carboniferous Del Ratón, El Planchón, Churupatí and Del Salto Formations. The descriptions and interpretations are mainly arranged to explain why some of our interpretations differ from those previously published. Due to the uniqueness of this outcrop in the Carboniferous time (3 km thick for just the Mississippian, in a limited geographical area), we believe this section is of pivotal importance. As we will show, there are coarse grained systems that may look similar as both are alluvial, but the details shown here allow us to understand the evolution of this small basin as well as the possible evolution of the hinterland. Our proposed environmental and tectono-stratigraphic interpretation, sketched in the models of Fig. 5, is then matched with the age based on the novel palynological information supplied here.

3.1. *Del Ratón formation (Guerstein et al., 1965)*

3.1.1. *Basic data and distribution*

We suggest maintaining the traditional division of this unit into three members (see Amenábar and di Pasquo, 2008). Despite not being respected by all the authors (see Colombo et al., 2014), it is stratigraphically the most accurate. The three members are clearly distinguishable in the field, and with significant lithological and environmental differences, as described below. The three members observed in the geological map in Fig. 2 show very strong lateral variations of facies that cause the lower member to disappear southward and the upper member to become coarser northwards. Thus, the tripartite division is valid only for the profile immediately to the south of the San Juan river. Thicknesses given here were measured by an open polygonal, and only valid for the profile described here (Figs. 2 and 4).

3.1.2. *Lower member (91 m, greenish sandstones)*

This member is probably the best known to date given its palynological and megaflora contents, In its stratotype, this member is represented by fining upward cycles of 2–3 m thick, from medium-coarse sand to fine sand, with intercalations of silty fine sand, with erosive base with occasional gravel scours, and low-angle cross stratification. The basal gravel is the coarsest and shows crude stratification and intermediate roundness. The base of this member lies directly over the Codo (Devonian) Formation, through an angular unconformity (Amenábar and di Pasquo, 2008), and a basal conglomerate with pinkish syenite cobbles, over which some striations have been found (Cf. Colombo et al., 2014).

3.1.3. *Interpretation*

Some authors suggest that the basal conglomerate has possibly a glacial origin (cf. Colombo et al., 2014). We have observed delicate striae on some clasts but we interpret them as being inherited from a previous glacial cycle which is not preserved in this member, because we interpret the depositional environment of this unit as fluvial/alluvial, in agreement with most researchers (see Amenábar and di Pasquo,

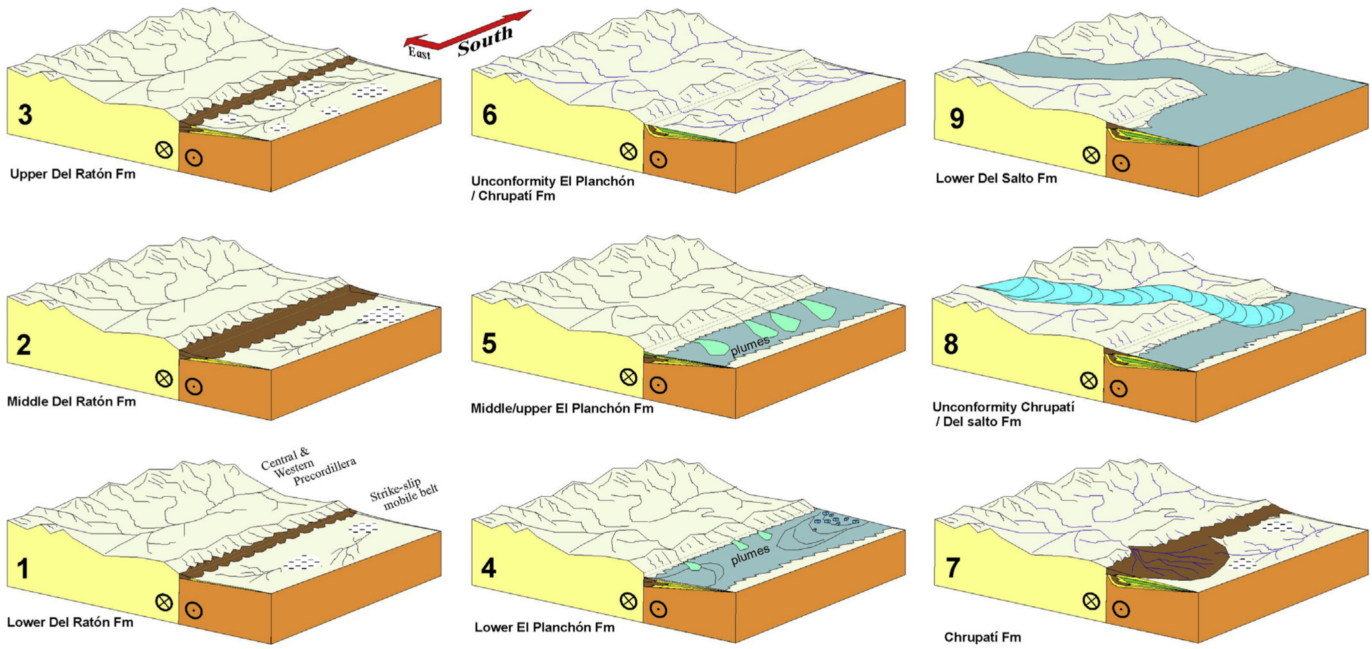


Fig. 5. Sedimentary depositional setting and their relation to an evolving hinterland within a strike-slip setting. El tigre dextral fault movement represented by the two circles (pint circled indicate movement towards observer). Dark color on blocks 1, 2, 3 and 7 are the alluvial gravels of Del Ratón and Churupatí Formations. Darker shading on blocks 4, 5, 8 and 0 indicate inundated areas, Intermediate color on Block 8 indicate the only moment glaciers reached location and excavated the observed U-shaped trough. Block 6 indicates a memento of no-deposition when the Churupatí basal unconformity was elaborated. A schematic bedding of this transtensional basin has been portrayed as well. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2008). Due to the thickness of the sandstone beds, the high range of grain size variations and the rapid lithological changes, we suggest that they were deposited by ephemeral rivers in a profan alluvial systems. The absence of deep erosive surfaces, bedforms of medium or large relief, and the limited lateral extent of the facies of this member support this interpretation.

3.1.4. Middle member (432 m, reddish-brown conglomerates)

It is a monotonous succession of red to green, medium to coarse conglomerates, with moderate to good sorting and rounded clasts. It is arranged in medium to thick strata, with many amalgamations revealed by the presence of few interbedded lenses of medium to coarse sand. The conglomerates are exclusively clast-supported and contain variable amounts of medium to coarse sands between clasts that do not qualify as matrix. The clasts are mostly of Paleozoic sandstones and some altered basalts, with a minor component of rhyolites and granites. Towards the top, the monotonous succession of conglomerates begins to split into two different types, one more greenish, with more clasts of lower to middle Paleozoic sediments, and minor volcanics, and another of more pinkish color, with a higher content of acid igneous rocks (rhyolites and granites). These conglomerates are normally overlaying the Lower member, although marginal discontinuities at the base are not ruled out (cf. Colombo et al., 2014), due to the particular tectono-stratigraphic regime of this basin.

3.1.5. Interpretation

In the profile surveyed, the base is a rapid gradation without an associated sedimentary discontinuity. We agree with previous interpretations of this system as alluvial gravels (see Milana, 2000a; Colombo et al., 2014), but we suggest that the depositional system is a *bajada* type (slope-apron) instead of an alluvial fan style, since no autocyclic processes were observed in this member. It is known that the process involving the relocation of the active lobes in alluvial fans produces distinctive sequences, up to seven levels of hierarchy, in proximal and distal parts of the fan (Decelles et al., 1991), which are absent in this member. In contrast, in bajadas, lateral facies do not change significantly laterally (nor vertically) because of the coalescence of many small fans causing continuous facies domains parallel to the active mountain front (fault) is very continuous (Milana, 2000b). The minor change in the clast-size evolution (maximum clast observed is c. 20 cm), the absence of mass-flow facies types, lack of erosive surfaces of over half meter of relief, absence of fine intervals, and a similar vertical facies evolution to pure gravel sequences of El Corral Formation (Neogene, Milana, 1997) support this interpretation.

Overall, the sedimentological features described suggest a system of small coalescent fans, in which gravels are mobilized by Newtonian fluid flows (dilute to hyperconcentrated), and with the contribution of previously rounded gravels. Therefore, this member suggests the beginning of tectonic activity along a nearby fault line, but without the need for it to be a significant orographic element due to the immaturity of the depositional system. If tectonic processes had continued to be active, an alluvial progradation would be observed due to the creation of higher relief, as well as the evolution of gravel to larger and less mature clasts (more angular, less sphericity). However, the opposite occurs and we interpret that this conglomerate is a phase of reactivation of the Tigre paleofault, and not an indication of tectonic processes associated with the formation of the Protoprecordillera. The paleocurrents observed come from the north, and not from the hypothetical Protoprecordillera towards the east. Comparable sequences do not occur in the other margin of this hypothetical paleomountain where the tectonic load should have created some accommodation space. Therefore, we interpret that this unit as simply the sedimentary product associated with the Tigre Fault reactivation. This explains the occurrence of conglomerates of similar age that have been observed in the Cortaderas Formation (Limarino et al., 2017) located along the trace of this fault to the north.

3.1.6. Upper member (410 m, sandstones, mud-limestones and greenish conglomerates)

A rapid transition initiates the deposition of this member over the

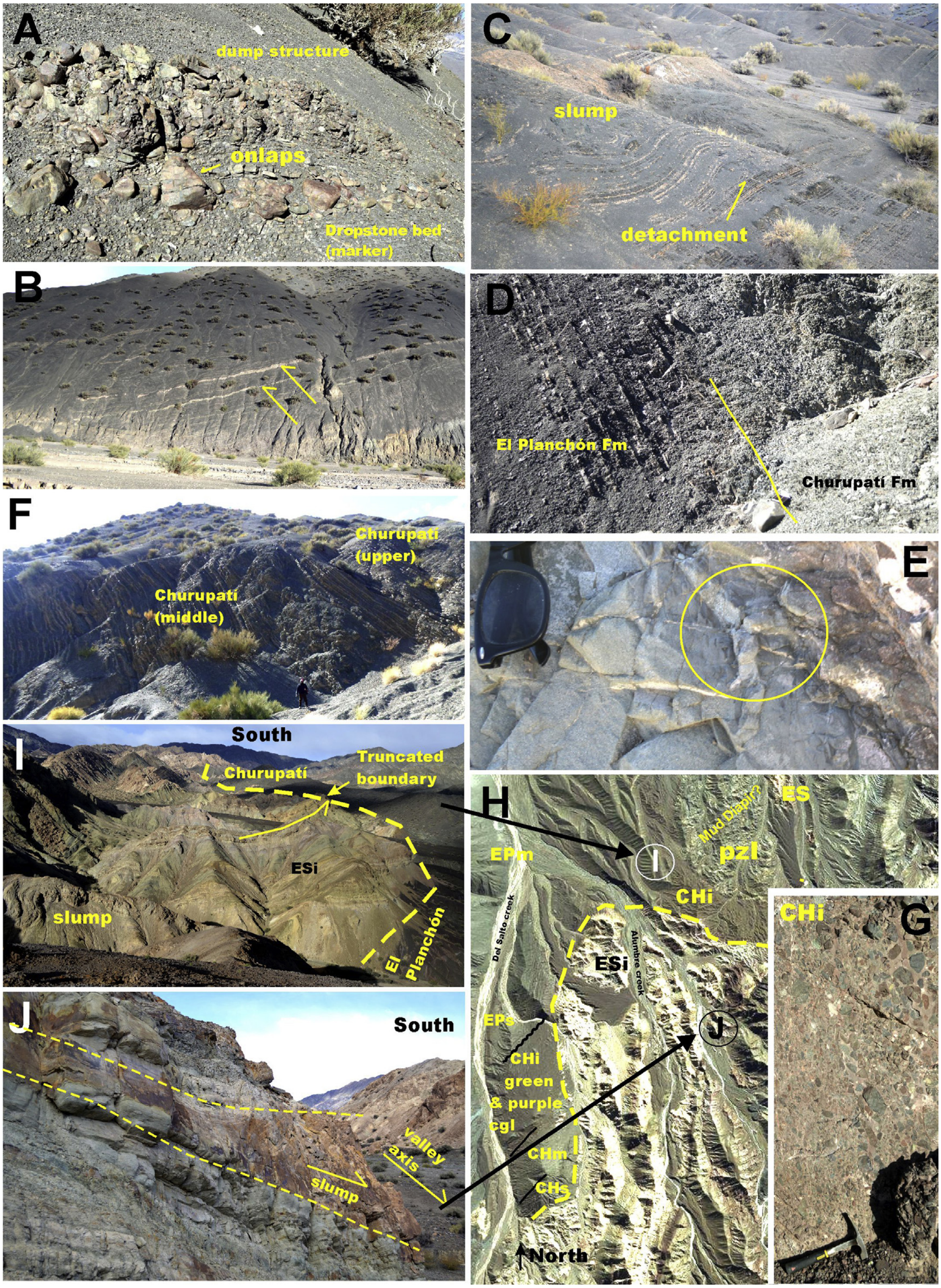


Fig. 6. Pictures of outcrops. Abbreviations of units as used in the Map of Fig. 2. **El Planchón Fm**: A) Lower Member showing a dropstone layer (lower gravelly bed) and a convex-upward dump structure, both product of floating ice meltout. B) Middle member shales with the two outstanding turbidites that allowed connecting logs across the El Salto creek. C) Middle member showing slumped heterolithics. Notice the detachment of underlying heterolithics (arrow) suggesting they were still soft due to rapid deposition. D) Upper heterolithics of El Planchón oxidized at the Churupatí base, defined by a diamictite. **Churupatí Fm**.: E) Mud cracks in the lower member, showing typical triple junctions (circle). F) Middle member medium-bedded heterolithics that gave some palynomorphs. G) Detail of low maturity of gravels of lower Churupatí, the well-known purple and green conglomerates. **El Salto Fm**.: H) Satellite vertical view of the paleovalley enclosing lower Del Salto beds that brought palynomorphs with indication of photoacquisition of I and G. I) Ground view from the deepest erosion of the paleovalley showing the truncation of El Planchón/Chrupatí boundary and slumped beds of lower El Salto, inside the trough. F) Slump surveyed at the northern side, showing sliding direction perpendicular to the paleovalley axis. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

middle one. Near its base, the interaction of two alluvial-fluvial systems of different composition was observed: the first, fed from the south-east is characterized by scarce pinkish igneous clasts and the other fed from the north contains these clasts in abundance. The system that prevails during this transition is the second, which seems associated with an axial drainage system. After this rapid transition, conditions return to those of the Lower Member: bodies with conglomeratic bases evolving into coarse sandstones with upwards fining into medium and fine sandstones, ending with a sharp top followed by fine-grained sediments (massive to laminated mudstones). In many cases, there are asymmetric ripples in the top of the beds together with numerous lycophytes and few other plant remains. Towards the top of the Del Ratón Formation, the lithology becomes finer and minor coarsening-upwards sand-dominated bodies appear. This section ends in a distinctive stratigraphic and laterally continuous surface (interpreted as a fault by several authors, see Sessarego, 1983), caused by the sharp change from the upper sandstones at the top of the Del Ratón Formation, to the dark shales of the El Planchón Formation (Fig. 6).

3.1.7. Interpretation

The environmental interpretation of this member is complex because it represents a transition from distinctly alluvial and subaerial conditions at the base to almost completely subaqueos conditions at the top. This transition occurs mostly in the last 80 m of this member where the coarsening upward sequences were only observed. The presence of deltaic sequences in this unit has been cited (Colombo et al., 2014), and we suggest the deltaic interpretation applies only to the uppermost 80 m of this member. The lower and middle intervals suggest a transition from an alluvial system of linear input (bajada) to an axial one, which would explain the progressive and rapid reduction of the conglomerates of the middle member, and its compositional change. The axial system would have been composed of ephemeral braided rivers of medium to small size, given the scale of the sandy packages. The change at the base of the middle member, defined by the rapid disappearance of the conglomerates, suggests steady active tectonics that increased the basin capacity and systems started to be unable to fill completely the basin. The sharp boundary from coarse to fine systems is typical of some strike-slip basins in which the rapid generation of accommodation space forces the sequences to show a clear upward decreasing grain size (as in the rifts). This continues, until a starved basin stage occurs due to the immature drainage network in the hinterland supplying insufficient sediment to balance subsidence, forcing eventually a sharp flooding. The evolution of this member evidences this, first with a passage from a gravelly to a more distal sandy fluvial system, followed by progressive flooding of the basin indicated by the appearance of deltaic facies developed in the last 80 m of the member and the final sharp flooding at the top of the member. We interpret the fine sandstone bodies as small braid-deltas, due to their moderate scale, dominated by sandstones and the lack of evidence of episodic flows in the observed coarsening-upwards sequences, not supporting the fan-delta model as suggested by Colombo et al. (2014).

3.1.8. Paleontological content of the Del Ratón formation

This unit has provided palynomorphs and remains of fossil plants studied by several authors (see Amenábar and di Pasquo, 2008, and their references). The palynological association found in the lower member by Amenábar and di Pasquo (2008) is composed of spores dominated by the genus *Cristatisporites* (lycophytes) and diagnostic species such as *Anapiculatisporites amplus* Playford and Powis, *Anapiculatisporites hystricosus* Playford, *Colatisporites decorus* (Bharadwaj and Venkatachala) Williams in Neves et al., *Verrucosisporites morulatus* Potonié and Kremp emend. Smith and Butterworth, of pteridophytic affinities. This association allows assigning the unit to the late Tournaisian-Early Visean, correlating it with the middle to upper part of the Malimán Formation (Fig. 11) (Amenábar and di Pasquo, 2008). On the other hand, stems of lycophytes and pteridosperms (e.g. *Diplothmema bodenbenderii* (Kurtz) Césari) predominate in the lower and upper members (Azcuy et al., 1981; Sessarego and Césari, 1989; Arrondo et al., 1991), attributed to the *Frenguellia-Paulophyton* Phytozone of the late Tournaisian-Visean (Carrizo and Azcuy, 2015). The vegetation in both lower and upper members developed in bars and levees of braided fluvial environments and mainly over floodplain swamps of the previously described depositional systems.

3.2. El Planchón formation (Quartino et al., 1971)

3.2.1. Basic data and distribution

This unit, defined by Quartino et al. (1971), has its type section located along the Del Salto creek (Figs. 1 and 2) where typical facies were portrayed (Quartino et al., 1971, Photograph 5). These heterolithic facies only characterize the upper member and differ from facies associations observed underlying beds, also belonging to this Formation but assigned here to the lower and middle members. The El Planchón Formation is 1465 m thick and crops out mainly to the south of the San Juan River, and a few km to the north. No other outcrops are known for this unit elsewhere. Its apparent absence northwards from the San Juan river appears to be the result of significant erosion at the base of the Churupatí Formation. In addition, an important lateral variation in this unit observed (Milana, 2000a; Milana et al., 2014; Colombo et al., 2014) causes its facies to be quite different to the north. The measured thickness of 1465 m, was along its stratotype that crosses the Del Salto creek, about 8 km to the south of the San Juan river (Fig. 2). To the south, a slightly oblique regional fault that thrusts up deposits from the Lower Paleozoic (Alcaparrosa Formation) over the local Neopaleozoic units (Quartino et al., 1971), progressively cut this formation and then the overlying Churupatí and Del Salto formations (Fig. 2).

3.2.2. Lower member (115 m, dark shales and thin bedded heterolithics with dropstones)

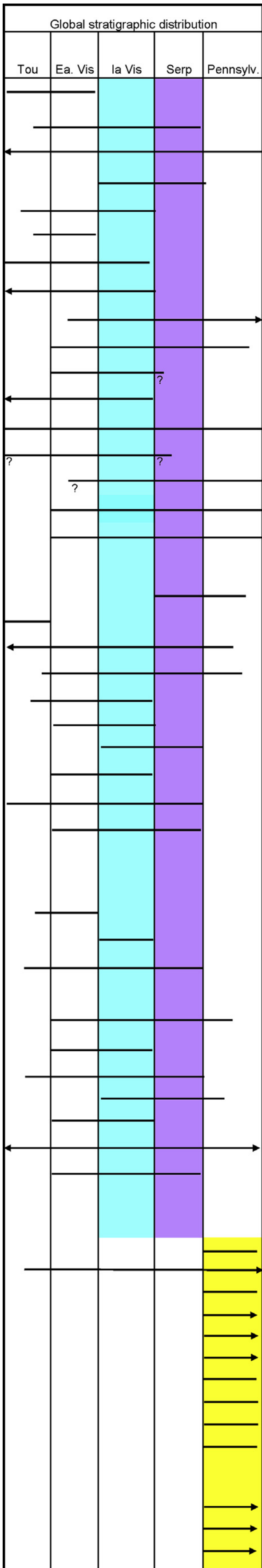
This member is the thinnest and is represented by silty shales abruptly overlaying the Del Ratón Formation. Towards its middle part there is an increase in the resistance of the outcrop, due to coarser lithologies intercalated with the shales (sandy silt). Three sedimentary cycles of thin-bedded heterolithics with a pseudo-varved appearance were surveyed and are defined by the rhythmic alternation of well-differentiated pairs of 1–2 cm thick mudstones and fine sandstones (couplets). These three packages of hetherolithic sedimentation are separated by homogeneous fine-grained zones. In the heterolithics, the coarsest bed observed reached up to medium sand with coarser grains dispersed. The packages of varve-like couplets are slightly asymmetric, most of their thickness is upward coarsening and thickening, with a less developed fining- and thinning upward upper interval. No primary sedimentary structure was observed, The last of the three packages defining the lower member contains a level of dropstones near the top, with clear structures of impact, and with the complete absence of conglomerates or sandstones showing any indication of tractive flows.

3.2.3. Interpretation

Suspension processes deposited hemipelagites characterized by cycles of finer (clay-silt) and coarser (silt-fine sand) material. The absence of any tractive structure in the heterolithics suggests that their rhythmic style was produced by deposition from buoyant proglacial plumes affected by seasonal meltwater cycles giving the classical varved outlook observed. The appearance of dropstones marks the top of this Lower Member suggesting the presence of floating glacial ice in this flooded basin which was deepened at the beginning of the deposition of the member. This apparent deepening is mainly the result of the passage from an overfed basin into a starved basin phase, produced by the transtensional activity, as indicated for the previous unit.

3.2.4. Middle member (752 m, rhythmic to uniform dark shales)

It lies in continuity over the Lower Member, starting just above the



Stratigraphic units	El Planchón		Churupatí		Del Salto			El Ratón	Malimán	Cortaderas	Guandacol	Guandacol
species/samples (Collection CYCYTTP-PI)	EP7 (931, 1010)	EP10 (934)	EP11 (935)	EP12 (936)	ES-N1 (1187)	ES-N2B (1189)	Botanic affinity	1	2	3	4	5
Anapiculatisporites hystricosus	X						F	X	X			
Apiculiretusispora semisenta	X						F, P		X	X		
Bascaudaspora collicula	X		X				L			X		
Bascaudaspora sp. P.Loinaze	X						L			X		
Crassispora scrupulosa	X		X				L		X			
Crassispora sp. Amenábar et al.	X						L		X			
Cristatisporites aculeatus	X						L					
Cristatisporites echinatus	X						L					
Cristatisporites inconstans	X		X				L	X				X
Cristatisporites indignabundus	X			X			L		X			
Cristatisporites indolatus	X						L		X	X		
Cristatisporites matthewsii	X	X					L	X	X	X	X	
Cristatisporites menendezii	X	X				X	L			X		X
Cristatisporites peruvianus	X	X	X				L		X		X	
Cristatisporites scabiosus	X						L	X				X
Cristatisporites spinosus	X					X	L					X
Cristatisporites stellatus	X	X					L	X			X	X
Cristatisporites spp.	X		X				L					
Cristatisporites verrucosus	X						L					X
Cymbosporites loboziakii	X						L					
Densosporites annulatus	X	X	X				L		X			
Densosporites sp. cf. *D. rarispinosus*	X						L					
Densosporites secundus	X						L		X			
Densosporites steinii	X						L					
Dibolisporites insolitus	X	X					F			X		
Dibolisporites microspicatus	X	X	X				F	X	X			
Knoxisporites pristinus	X						F					
Kraeuselisporites tedantus	X						L			X		
Laevigatosporites-Latosporites	X						F					
Lophozonotriletes sp.	X						F					
Pustulatisporites malimanensis	X	X					F		X			
Retusotriletes sp. cf. *R. mirabilis*	X	X					F, S			X		
Tholisporites scoticus	X	X					D	X				
Vallatisporites sp.	X						L					
Verrucosisporites morulatus	X	X				X	F	X	X			
Densosporites gracilis		X					L		X			
Densosporites pseudoannulatus			X				L				X	
Spinozotriletes hirsutus			X				L	X		X		X
Reticulatisporites vitiosus			X				F					
Vallatisporites vallatus			X				L					X
Densosporites triangularis				X			L		X			
Knoxisporites sp.				X			L					
Punctatisporites spp.						X	F, S					X
Kraeuselisporites malanzanensis					X		L					X
Vallatisporites ciliaris					X	X	L			CF.		X
Velamisporites cortaderensis					X		F					X
Calamospora hartungiana						X	S					X
Lundbladispora riobonitensis						X	L					X
Lundbladispora braziliensis						X	L					X
Retusotriletes anfractus						X	S, F			X		X
Apiculiretusispora tuberculata						X	F					X
Apiculatasporites parviapiculatus						X	F					X
Apiculatasporites caperatus						X	F					X
Leiotriletes sp.						X	F					X
Apiculatisporis sp.						X	F					X
Cannanoropollis janakii						X	G					X
Potonieisporites cf. *barrelis*						X	G					X
Potonieisporites novicus						X	G					X
Potonieisporites magnus						X	G					X

(caption on next page)

Fig. 7. Stratigraphic distribution of the species present in the El Planchón, Churupatí and Del Salto formations obtained in this study and their comparison with neighbouring units: Del Ratón (1: Tournaisian-Visean, Amenábar and di Pasquo, 2008), Malimán (2: Tournaisian -Visean, Amenábar, 2006; Amenábar et al., 2006, 2007, 2009), Cortaderas (3: late Visean, Pérez Loinaze, 2007), Guandacol (4: Visean, Valdez et al., 2014; 5: Serpukhovian - early Bashkirian, Valdez et al., 2015, 2017). Global stratigraphic ranges based on the mentioned works among others (e.g., di Pasquo et al., 2010; Playford and Melo, 2012; di Pasquo and Iannuzzi, 2014). Botanical affinity (Balme, 1995) = F: Pteridophyte, L: Lycophyte, S: Sphenophyte, P: Progymnosperms, G: Cordaitales/Coniferales, D: unknown, A: algal.

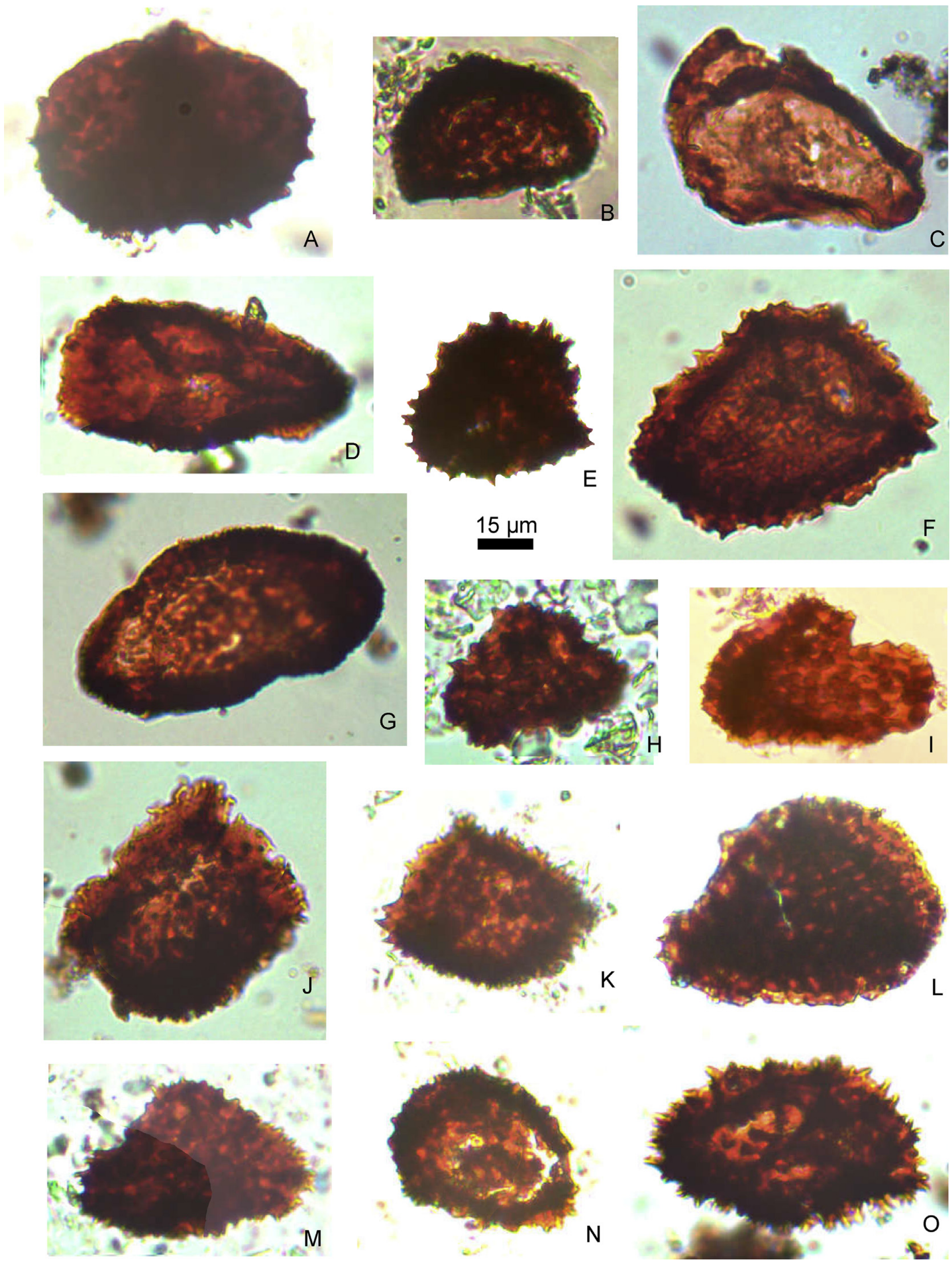


Fig. 8. Palynomorphs from the El Planchón Formation, stored in the collection CICYTTP-Pl (code that adds to sample number), including coordinates. A. *Anapiculatisporites hystricosus* Playford; 931-1 R23/4 (half tetrad). B. *Bascaudaspora* sp. Pérez Loinaze; 931-5 K50/3. C. *Apiculiretusispora semisenta* (Playford) Massa et al.; 1010-1 J25. D. *Crassispora scrupulosa* Playford emend. Playford and Satterthwait; 1010-2 Q32/1. E. *Cristatisporites indignabundus* (Loose) Potonié, Kremp *emend.* Staplin and Jansonius; 931-8 Q44/1. F. *Bascaudaspora collicula* (Playford) Higgs, Clayton and Keegan; 1010-2 G29/4. G. *Crassispora* sp. Amenábar et al.; 1010-2 V40. H. *Cristatisporites spinosus* (Menéndez, Azcuy) Playford; 1010-2 T40. I. *Cristatisporites menendezii* (Menéndez, Azcuy) Playford; 934-3 T55. J. *Cristatisporites aculeatus* (Hacquebard) Potonié; 1010-2 Q57. K. *Cristatisporites inconstans* Archangelsky and Gamerro; 931-1 M51/2. L. *Cristatisporites indolatus* Playford and Satterthwait; 931-2 X36/2. M. *Cristatisporites echinatus* Playford; 1010-3 S34. N. *Cristatisporites stellatus* (Azcuy) Gutiérrez and Limarino; 931-10 G29/4. O. *Cristatisporites verrucosus* González Amicón; 1010-2 R31.

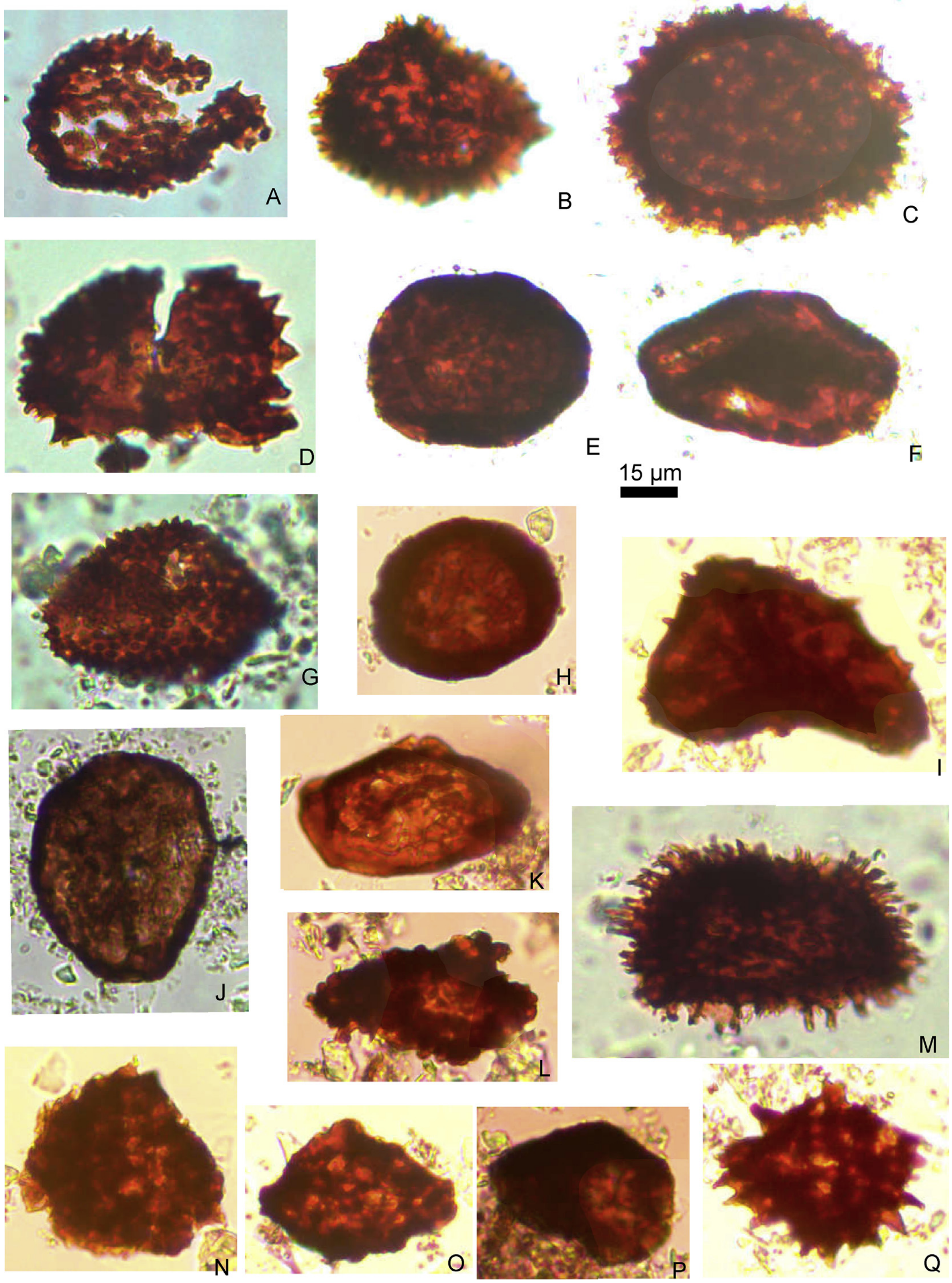


Fig. 9. Palynomorphs from the El Planchón and Churupatí formations, stored in the collection CICYTTP-Pl (code that adds to sample number), including coordinates. A. *Cristatisporites peruvianus* Azcuy and di Pasquo; 1010-1 D25/2. B. *Cristatisporites scabiosus* Menéndez; 931-2 N29/3. C. *Cristatisporites* sp.; 931-1 R46. D. *Densosporites secundus* Playford and Satterthwait; 1010-2 O55/3. E. *Densosporites annulatus* (Loose) Schopf, Wilson and Bentall; 931-1 N46/4. F. *Knoxisporites pristinus* Sullivan; 931-1 Q50. G. *Dibolisporites microspicatus* Playford; 1010-3 O50/4. H. *Densosporites triangularis* Kosanke; 936-3 S46/2. I. *Pustulatisporites malimanensis* Amenábar et al.; 934-3 L49. J. *Latosporites* sp.; 931-1 H29/3. K. *Retusotriletes* sp. cf. *R. mirabilis* (Neville) Playford; 934-3 T46. L. *Verrucosisporites morulatus* (Knox) Potonié, Kremp *emend.* Smith, Butterworth; 934-2 G38/4. M. *Densosporites steinii* Ravn; 1010-2 F46/2. N. *Dibolisporites insolitus* Pérez Loinaze; 934-4 O34/2. O. *Reticulatisporites vitiosus* Playford; 935-6 Y48. P. *Tholisporites scoticus* Buttherworth and Williams; 934-4 O37/2. Q. *Spinozotriletes hirsutus* Azcuy; 935-5 T43/4.

layer with dropstones. At its base, a notable sedimentary change occurs, from the heterolithics of the previous member (alternation of fine sandy-to massive silty mudstones) into a homogeneous muddy interval. This basal interval is marked by the absence of fine and very fine sandstones. The depositional conditions in this member do not change much, since in the lower section, there are two cycles of heterolithics observed in the basal 100 m of this member. In the following part of this member, coarser grain size intervals of sandy silt stand out from the fine-grained shaly sequence but without the presence of heterolithics. At about 500 m over the base of this member, layers of fine to medium sand start to occur showing evidence of traction currents, initially plane lamination and rare ripples towards the top. These layers stand out

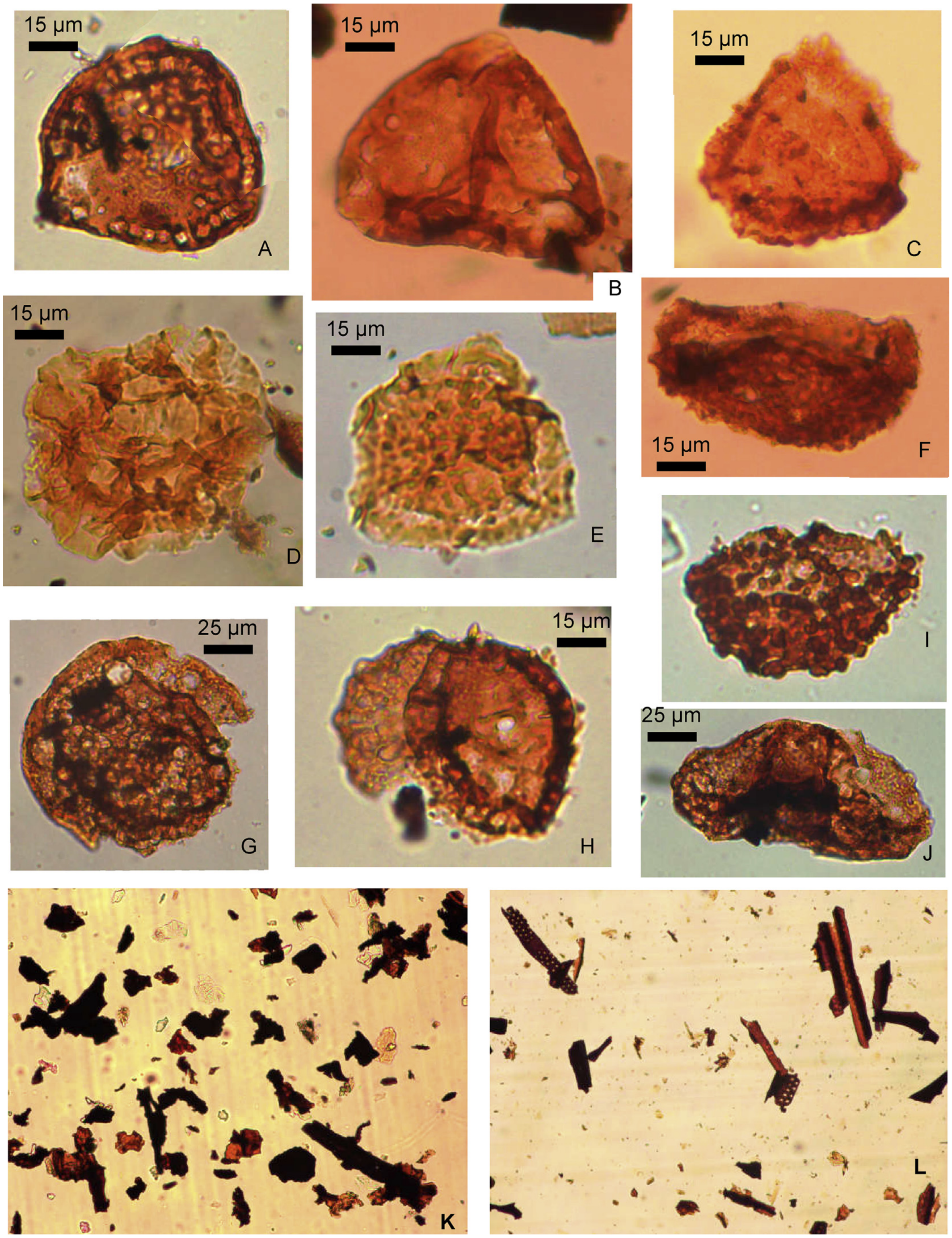


Fig. 10. Palynomorphs from the Del Salto Formation, stored in the collection CICYTTP-Pl (code that adds to sample number), including coordinates. A, B. *Lundbladispora riobonitensis* Marques Toigo and Picarelli; A. 1189-4 L48, showing pyrite. B. 1189-1 M18/3. C, E. *Vallatisporites ciliaris* (Luber) Sullivan; D. 1187-1 T28/4. E. 1189-1 26/103,5. D. *Velamisporites cortaderensis* (Césari and Limarino) Playford; 1187-1 O22/2. F. *Cristatisporites menendezii* (Menéndez and Azcuy) Playford; 1189-1 L18. G. Monosaccate pollen grain with framboidal pyrite; 1189-4 G32. H. *Potonieisporites magnus* Lele and Karim 1971, monosaccate with framboidal and euhedral pyrite; 1189-4 J50/3. I. *Verrucosisporites morulatus* (Knox) Potonié and Kremp emend. Smith and Butterworth; 1189-3 R27. J. *Potonieisporites barrelis* Tiwari; 1189-2 J38/3. K. Palynofacies, 1189-2 G31/3. Tracheids and other components of terrestrial origin with different sizes and shapes. L. Palynofacies, 1187-2 Q32. Idem in K.

because they are 10–20 cm thick, with planar contacts at the base. Towards the top of this member these sandy layers are thicker, may reach 1 m thick, presenting an irregular base, partly channeled. The fine deposits, silty-sandy shales, compose at least 95% of this member, giving it a monotonous appearance.

3.2.5. Interpretation

The depositional environment is very similar to the Lower Member, but its development suggests an initial short period of non-deposition (hiatus), followed by a gradual loss of proglacial influence, an intermediate stage of suspension-dominated sedimentation until in the upper sector distal turbidites start appearing which pass into medium to thick-bedded turbidites. This member suggests the passage from a suspension-dominated depositional system (hemipelagic settling) into a progradation of a gravitational-driven depositional system formed by lobes of occasional distal turbidites. The contact between the two

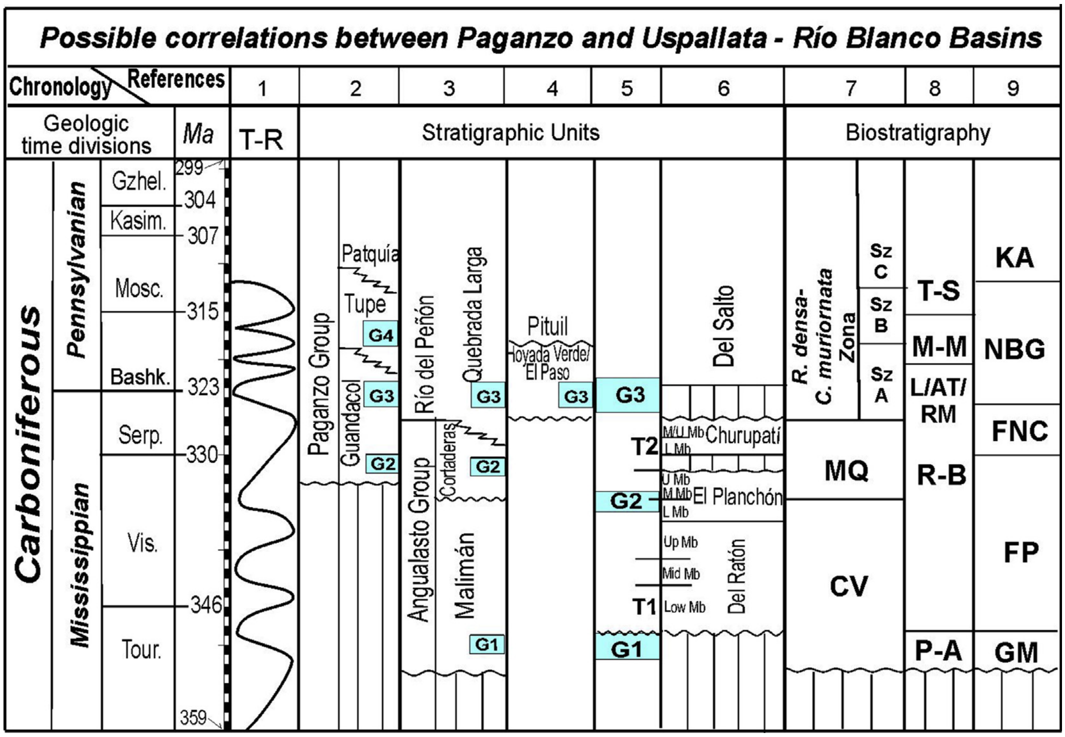


Fig. 11. Stratigraphic and biostratigraphic correlation of the Carboniferous units discussed in this work and major regional glaciations (referred as G1, G2, G3, G4, according to our interpretation). The mismatch of Glacial 2 between sections, could be related to the use of different biostratigraphic elements used as discussed in the text, and should be a matter of future studies. Numbers refer to: 1: T–R: Transgressive-Regressive cycles, Gradstein et al. (2012), 2: Valdez et al. (2015, 2017), 3: Amenábar and di Pasquo (2008), Pérez Loinaze et al. (2010), 4: Vergel et al. (2015), 5 and 6: This work, 7: Pérez Loinaze et al. (2014), Valdez et al. (2015, 2017), 8: Taboada (2010, 2014), Vergel et al. (2015), 9: Carrizo and Azcuy (2015). Abbreviations: *C–V. Convolutispora-Verrucosisporites. M-Q. Reticulatisporites magnidictyus-Verrucosisporites quasigobbetti P-A. Protocanites-Azurduya. R–B. Rugosochonetes-Bulahdelia. L. Levipustula levis. A-T. Aseptella-Tuberculatella. R-M. Rhipidomella-Micraphelia. M-M. Marginovatia-Maemia. T-S. Tivertonia-Streptorhynchus. G-M. Gilbophyton-Malimanium. F–P. Frenguellia-Paulophyton. FNC. Frenguellia-Nothorhacopteris-Cordaicarpus. NBG. Nothorhacopteris-Botrychiopsis-Gingophyllum. KA. Kraeuselcladus-Asterotheca.*

members is located on the level of maximum glacial advance, evidenced by the presence of dropstones. This conspicuous level of dropstones has been recognized laterally in all the revised outcrops of the El Planchón Formation and is a marker bed to correlate sections from south and north of the San Juan River. Evidences of proglacial effects disappear in the first 100 m of the Middle Member.

3.2.6. *Upper member (medium-bedded heterolithics, fine conglomerates and meso-slumps)*

It overlies the previous member via a lithological transition. It is characterized by its heterolitic facies typically described and pictured by Quartino et al. (1971). The lithological change from the middle member occurs mainly in the stratigraphic strip along the Del Salto creek, so it is partially cover by modern sediments, and thus the boundary between this member and the previous one is difficult to evaluate. However, the obliquity between the bed strike and the creek trace, allowed us to correlate two marker beds (outstanding turbidites) from one margin to the other. This correlation allowed us to estimate the thickness of this unit very confidently. This member shows the continuation of the upwards progradation observed in the upper part of the underlying member. The fine-grained hemipelagites of the Middle Member are progressively replaced by the well-known medium-bedded heterolithics of Quartino et al. (1971, Photo 5). These heterolithics show continuous and consistent rhythmicity, in couplets alternating laminated medium-fine silt with fine sands, the latter laminated to massive with rare ripples, in sets of 10 cm average thickness. The heterolithics make up 90% of the outcrop, with random beds of up to 2 m, composed of medium to coarse sandstones, sometimes fine conglomerates, showing tractive evidences and normal gradation, with similar coloration and composition than the turbidites of the Middle Member. Numerous levels of micro to meso slumping are also present.

3.2.7. *Interpretation*

Heterolithics are interpreted as annual deposition of layers mainly formed by settling combined with low energy flows of hyperpycnal type. These rhythmites might be comparable to thick varves, but we do not suggest a proglacial influence but instead a regime of seasonal fluvial discharges due to: 1) The whole sequence lacks dropstones, 2) the lower boundaries of the sandy part of the couplet are not as sharp as in proglacial deposits, where spring melt-out creates a strongly asymmetric sand couplet. Some beds with clast concentrations draw attention due to their rather coarse grained for their small thickness, which is interpreted by the action of sustained diluted hyperpycnal flows that acted to winnow and “clean” the muddier sediment of the initial deposit. These deposits accumulated subaqueously in a moderate depositional slope, indicated by the medium to coarse turbidites and to the presence of deformed layers that indicate the plastic deformation downslope of packages of heterolithics. The layers of medium to thick sandstones, sometimes conglomeratic, with traction evidence and normal grading, suggest the presence of expanding density flows of low to high flow regimes. We interpret this environment as a shallow prodelta of possibly a braid-delta.

3.2.8. *Paleontological content of the El Planchón formation*

The lower and upper members were palynologically barren, whereas three productive samples of the Middle Member allowed the recognition of 32 spore species (31 trilete and one monolete) with a regular to good preservation (fragmented and complete). The three associations are composed mainly of species whose ranges extend between the Tournaisian and Visean (e.g. *Anapiculatisporites hystricosus,* *Apiculiretusispora semisenta, Cristatisporites aculeatus, Cristatisporites echinatus, Cristatisporites peruvianus, Crassispora scrupulosa, Densosporites secundus, Pustulatisporites malimanensis, Crassispora* sp. Amenábar et al., *Knoxisporites pristinus, Tholisporites scoticus*). Other species indicate a Visean age according to their stratigraphic distribution recorded in Mississippian associations (Figs. 7–9) of south America and other regions of the world (e.g. *Cristatisporites inconstans, Cristatisporites indignabundus, Cristatisporites indolatus, Cristatisporites scabiosus, Cristatisporites stellatus, Densosporites steinii, Dibolisporites microspicatus, Verrucosisporites morulatus*). There are poorly represented species ranging from the late Visean to Serpukhovian (e.g. *Bascaudaspora* sp. Pérez Loinaze, *Cristatisporites verrucosus, Dibolisporites insolitus, Retusotriletes* sp. cf. *R. mirabilis*). Hence, the combined data of these three associations allows an attribution of El Planchón Formation to the late Visean.

3.2.9. General interpretation and discussion

This unit deposited in a local high-stand system, high subsidence rate (due to the interpretation of basin starving stage) and significant input of detrital material that eventually marches subsidence in spite of the initial over deepening. These conclusions are consistent with a relatively small basin close to a low orographic relief with a large amount of varied sediment available. We can reach this conclusion due to the immaturity of the drainage systems indicated mainly by Del Ratón Formation analysis and that persists through the El Planchón Formation. The presence of alluvial bajadas in the middle member of Del Ratón Fm, suggests deposits generated by the coalescence of many small alluvial fans each generated by a small entry point indicating an immature drainage network in the hinterland. At the end of Del Ratón, these immature systems are replaced by large alluvial fans or axial drainage systems, a feature observed in the transition from the Middle to Upper members of the Del Ratón Formation but not in the El Planchón Formation. This suggests ongoing subsidence without the creation of significant positive relief, fitting well with a transtensional basin (Fig. 5). This scenario caused a long phase of starvation during which an apparent flooding occurred, then a glacial event, followed by almost one km of suspension-dominated shales. Finally, progradation takes over the sedimentation in the upper member of El Planchón.

The cyclicity registered in the Lower and Middle members of the El Planchón Formation with the presence of thin-bedded heterolithics is explained by the preservation of a complete glacial cycle (Fig. 6). The flooding surface at the base of this unit was probably partially forced by subsidence due to a regional glacio-isostatic loading, or due to a tectonic event in the basin. We are inclined towards the first alternative (glacio-isostasy) given the close relationship with the immediately following glacial interval. The first part of the El Planchón Formation is hemipelagic, with heterolithics that could be interpreted as varves, carrying a classic interval with dropstones at the glacial maximum. A Visean calving glacier system, located at a relatively far distance, would have contributed with clasts of several decimeters. Therefore, the glacier tongues would not have reached the study area but probably were located in a range of 50–100 km away. This glacial event is quite symmetrical as above the dropstone layer, varves appear once again fading in the first 100 m of the seemingly thick middle El Planchón member. The flora preserved in the samples of the Middle Member indicates favorable conditions for the development of herbaceous lycophytes (*Cristatisporites, Densosporites*) mainly in lacustrine environments and floodplains with higher areas and/or with better drainage colonized by pteridophytes (*Verrucosisporites, Pustulatisporites, Dibolisporites*) and pteridosperms (*Crassispora*). Thus, we support an interpretation of a narrow but long and deep basin surrounded by seasonally flooded areas where these plants could live and plumes would distribute their spores. Curiously, there are no preserved plant remains (palynomorphs nor leaf fragments) in the upper member in spite of the apparent coaly nature of some back shales, while they were preserved in the middle member, further downstream from the plant source. We interpret this to be the effect of a strong seasonal regime in the upper member causing the well-known water column overturning that results in oxidation of plant remains. When lowering the average temperature below 4 °C, the oxygenated surface waters reach a maximum density and begin to sink, oxygenating the bottom and restricting the capacity of preservation of organic matter. This process would indicate that the basin was quite restricted and that the process of oxygenation at the bottom was not disturbed by currents. This interpretation is supported by the absence of significant wave action at the shallower Upper Member.

On the other hand, rapid sedimentation in the middle member or the presence of a deep thermocline, would prevent the oxidative effect of the sinking surface water. Medium-bedded heterolithics in the upper El Planchón member do not seem glacially related, since they do not show evidence of proglacial varves as elsewhere in the region (cf. Milana and López, 1998). We interpret them as the effect of a strong seasonality of the climate and the change of the waters ("turn-over") without any glacial influence.

3.3. Churupatí Formation (Kerlleñevich, 1969) emend

3.3.1. Basic data and distribution

This unit was included in the Stratigraphic Lexicons of the Devonian (Rubinstein, 2014) and Carboniferous (Gutiérrez, 2012), and was defined by Kerlleñevich (1969) to join under a new formational entity the conglomerates of the Del Ratón Formation (Guerstein et al., 1965) along with the "green and purple conglomerates" that crop out on the route to Calingasta, east of the Del Salto creek. This formational denomination is accepted here but is restricted only to the "green and purple conglomerates" and associated beds, because they do not belong to the Del Ratón Formation (cf. Quartino et al., 1971), nor are they part of the El Planchón Formation, as suggested by some authors (Sessarego, 1983; Colombo et al., 2014). The geological review carried out in this study allows us to recognize and redefine this stratigraphic unit, which does not solely include the well-known conglomerates, but also sandy and muddy units above them. The amendment proposed may help to avoid the proliferation of formational names.

The Churupatí Formation is 610 m thick at its stratotype as proposed here (along the El Salto creek) and crops out discontinuously between the underlying El Planchón Formation to the west, and the overlying Del Salto Formation to the east. An erosive and angular discordance defines its base, which explains the strong lateral changes in the subcrop to the Churupatí and the local stratigraphy. This formation is the most heterogeneous unit with strong lateral changes: in its southernmost profile it is dominated by sandstones with few conglomerates, while to the north of the Alumbre creek it turns into conglomerates almost entirely. This lateral facies change cannot be seen because most of this unit was eroded at the Alumbre and Del Salto creek junction where coincides with the deepest excavation of the following unconformity, which constitutes the paleovalley enclosing the oldest deposits of Del Salto Formation (Figs. 2 and 3).

As part of the amendment, we suggest a division into three members based on the proposed stratotype, as it is the most complete section and on which the only existing biostratigraphic information was obtained. The basal angular unconformity also explains the presence of the Churupatí Formation in direct and unfaulted contact on the Alcaparrosa Formation (Ordovician), a few hundred meters far from where the Churupatí overlies the El Planchón Formation (Figs. 2 and 3). This fact suggests the disappearance of c. 2.5 km of Mississippian sediments in matter of meters, indicating how complex is the structure and stratigraphy of this location.

Noteworthy is the anticline structure observed near the Del Salto Formation on the route to Calingasta, cored by the Alcaparrosa Formation and normally draped by the Churupatí Formation. The conglomerates of the Churupatí Formation are smoothly arched in a double-plunging brachianticline, but the core is quite massive and homogeneous, without visible traces of bedding at the Alcaparrosa

Formation and with numerous mineralized veins. We suggest this structure could be interpreted alternatively mud diapir.

Another important issue related to the distribution of the Churupatí Formation is the change of bed-dip between the south and north of the San Juan River. To the south of the Alumbre creek slopes dip between 40 and 50° eastward (except in the near of the hypothetical mud diapir), while to the north of the San Juan River, the conglomerates tilt at different angles to the west. This structural change is interpreted as being due to the presence of a syncline which is not visible due to the Quaternary cover, but it is suggested by the progressive changes of inclination of the strata, and mainly by the tracking of the proglacial marker beds of El Planchón Fm.

3.3.2. Lower member (120 m, green and purple conglomerates)

This member overlies the El Planchón Formation on an erosive and angular discordance that is subtle to the south and quite marked to the north. Its base along the stratotype of Del Salto creek is characterized by the strong change in coloration, and the appearance of massive diamictites for the first time in this Neopaleozoic sequence. The coloration at the base is reddish-purple, contrasting with the dark greenish and dark gray of the lower unit, although the few upper meters of the El Planchón Formation have violet colors probably due to staining by the subaerial exposure of these beds. The diamictite beds are several meters thick, contain green-purple sandy silt matrix at the base and a higher concentration of dispersed pebbles and cobbles, and sometimes distorted beds. Several packages of medium-grained sandstones and intercalations of coarse-grained pebbly sandstones with low-angle cross-bedding are observed, all separated by green-purple massive mudstones. At the top of the sandstone beds desiccation cracks (Fig. 6) were observed. The conglomerates show a provenance quite similar to those of the Del Ratón Formation with Paleozoic green sandstones and altered basalt clasts, but with fewer clasts of acid igneous rocks.

Another feature that allows the differentiation of the thick conglomerates succession of the Churupatí Formation and the comparable one of Del Ratón formation is the general immaturity of those of Churupatí. This could be interpreted from the higher grain-size contrasts (poorer sorting in Churupatí) and higher range of maximum particle size (MPS) in Churupatí that contains blocks up to 60–70 cm long while in the Middle Member of the Del Ratón Formation the MPS is c. 20 cm and very monotonous. The higher angularity and lower sphericity of Churupatí clasts also point to less mature sediment. Towards north of Churupatí stratotype, progressively more conglomerate facies appear rapidly, and before reaching the Alumbre creek, this lower unit is entirely conglomeratic, explaining the composition of the outcrops exposed along the road from San Juan to Calingasta. The interpretation of this lateral facies change is based on the most likely stratigraphic correlation of this lower member, being no physical connection between the outcrops from the south and north of the Alumbre creek, as it is covered.

3.3.3. Interpretation

The reddish, purple and violet colors of the conglomerates, slightly reddish color of the sandstones and some mudstones, and the tops of the sandstone beds with desiccation cracks imply a subaerial deposition, unlike conglomerates of the top of the El Planchón Formation interpreted as resedimented deposits in subaqueous environments. The diamictites are debris flow deposits unrelated to glacial processes. The significant amount of mudstones observed in the region probably favored these dense flows. Towards the north, and in stratigraphic continuity, there is an increase in the amount of hyperpycnal, non-cohesive deposits, which suggests that debris flows were mainly associated with the first stage of deposition of Churupatí Fm. All these elements suggest an alluvial fan environment with a very extensive profan with swampy characteristics indicated by the occurrence of green mudstone layers and the occurrence of dense flow deposits with both subaqueous (as the distorted bedding within some diamictites) and subaerial features observed.

3.3.4. Middle member (410 m, green sandstones and rhythmites)

This member is transitional over the previous one, it is composed mainly of sandstones, and is only observed to the south of the outcrops mapped as Churupatí Formation. Massive beds of sandstones, up to 10–30 cm thick, separated by thin intervals of mudstones occur. In some sandstones, rippled tops, mainly symmetrical, were observed suggesting wave action. Externally, both the lithology and color are very similar to the Upper Member of the Del Ratón Formation, although the sandy beds are much thinner in this member. Megafloral remains are not present but two samples provided palynomorphs (Figs. 4, 7 and 9). In the uppermost beds, the fine-grained sandstones embedded in a well bedded fine grained sequence give a similar aspect to the Upper Member of the El Planchón Formation with its typical heterolithics. However, this unit is greener and the heterolitic layers are slightly coarser grained.

3.3.5. Interpretation

The continuity over the underlying member and the lithologies described suggest a deposition on a flooded profan, in which the main alluvial flows ended forming the prominent sandy deposits observed, while the occurrence of heterolithics would be the result of minor floods entering the profan. The greenish colors of this unit would suggest that in spite of the important oxidation of the more proximal beds of the lower member, the water table was not so deep, allowing to keep the floodplain inundated and prevent oxidation. This points to a temperate climate for the Churupatí unit, and not desertic. The permanent water at the lowlands, supported by the presence of wave reworked tops, would have allowed the development of a hydrophilous megaflora composed mostly of herbaceous lycophytes as inferred from the botanical affinities of the documented species of palynomorphs (Fig. 7).

3.3.6. Upper member (80 m, mudstones)

It transitionally overlies the middle member and the heterolithics of the middle member disappear to give rise to a succession of non-rhythmic alternation of fine sand and mudstones layers of varied colors, ranging from greenish to reddish and gray. As in the previous interval, there are some ripples within the sandier intervals, as an effect of the rework of their tops.

3.3.7. Interpretation

This member is part of the same depositional system described for the lower and middle members of the Churupatí Formation. In this case, the environment seems to be quite similar to that of the middle member, but with lesser permanence of the water bodies, that gave rise to some reddish colors and the absence of any plant or palynological remains. The textural variations observed could correspond to changing conditions of the profan swamps, that may seasonally exposed subaerially, explaining the absence of organic material remains in this member that would be oxidized during episodes of exposition.

3.3.8. Palynological content

Two fertile levels yielded palynological material from the Middle Member of this unit, in which 14 species of trilete spores were recognized and mostly complete specimens are well-preserved. However, their high degree of thermal alteration (Fig. 7, see item methods), despite the oxidation applied to the samples prevented an adequate determination of all the specimens recorded in both associations. Eight species are shared with the El Planchón Formation while six are exclusive to this unit (Fig. 7). Among the latter, *Spinozonotriletes hirsutus* (= *Spinozonotriletes* sp. in Sessarego and Césari, 1989), whose range extends between the late Visean and early Pennsylvanian is found in the Del Ratón Formation (Amenábar and di Pasquo, 2008). Other species are characteristic of the Visean (*Densosporites triangularis, Reticulatisporites vitiosus, Cristatisporites indignabundus, C. peruvianus,* *Densosporites pseudoannulatus*). Therefore, we suggest a latest Visean – early Serpukhovian age (Fig. 7), matching the late Visean age assigned to the middle member of El Planchón Formation. One needs to consider that between these fertile intervals two barren members (upper member of El Planchón and lower member of Churupatí) and an angular unconformity occur Hence, the Churupatí Formation is attributed to the early Serpukhovian.

3.3.9. General interpretation and discussion

Separated from the El Planchón Formation by an angular unconformity, the Churupatí F was deposited in a proximal alluvial system evolving to a distal alluvial fan and culminating as a lacustrine profan, being completely different to the subaqueous environment of the underlying unit. Therefore, the unification proposed by Sessarego (1983, 1988) of these conglomerates with the typical facies of the El Planchón Formation according to the original description by Quartino et al. (1971), has no geological support in our opinion. There are partly similar facies between the Churupatí and El Planchón which are the sandy members (middle of Churupatí and upper of El Planchón), and such similarity is due to a shared environment but not to a similar depositional setting given the fact they are laterally and vertically related to different depositional environments that define different depositional systems according to Walther's law, and different evolution. The El Planchón Formation is purely subaqueous, progradational and shallowing up, while the Churupatí Formation is subaerial (except in its middle-upper part), retrogradational and deepening except for the upper member in which this tendency is reversed. The palynological composition found at Churupatí indicate that the floras throughout the Mississippian were maintained (Fig. 7), and agrees with the inclusion of this unit in the Phytozone *Frenguellia-Paulophyton* assigned to the Tournaisian - early Serpukhovian (Carrizo and Azcuy, 2015).

The Churupatí Formation was deposited in a proximal alluvial fan that evolved (retrogradation) to a middle-distal alluvial fan and finally to a profan, probably partially inundated (swamps) as indicated by a lack of oxidation of the profan beds and the wave action. An important stratigraphic discontinuity defined at its base implies some tectonic activity that allowed the erosion of several hundred meters of the upper part of the El Planchón Formation, only a few kilometers to the north of its stratotype located to the south of the Alumbre creek. To the east, Churupatí lies directly on the lower Paleozoic Alcaparrosa Fm, indicating the importance of the event between El Planchón and Churupatí. This intra-Lower Carboniferous unconformity is not abnormal considering the interpreted strike-slip basin interpretation already suggested for this locality. The continuous lateral movement of the adjacent blocks may cause transtensional basins to transform rapidly into transpressional. When this occurs, subsidence is sharply limited and a compressional regime may prevail for s given period (Christie Blick and Biddle, 1985) explaining the folding of previously deposited beds. Therefore, the basal unconformity does not imply a regional tectonic phase *per se*, but just a local effect implying El Tigre fault may experience a compressive phase in a regime of continuous tectonism. This local phase could be the result of movement through a restraining bend, or a temporal change in the relative stress direction of the two sliding blocks. The evidence supporting a compressive local tectonic phase within a strike-slip realm are: 1) The erosive contact at the base of the Churupatí Formation that is recorded over different terms of the El Planchón Formation and other units such as the Alcaparrosa Formation. 2) The basal member of Churupatí is conglomeratic and more immature than the conglomerates of the Del Ratón Formation suggesting a more active tectonic process than the previous one, with generation of relief and traction-power in the hinterland. 3) A stratal angularity observed between the layers of the El Planchón and Churupatí formations (both Mississippian).

Another argument helping to differentiate the conglomerates of Churupatí and Del Ratón is the presence of autocycles in the first that are absent in the second. The latter unit is interpreted as an alluvial bajada typical of an immature hinterland, whereas Churupatí shows visible autocycles in the middle to distal areas that suggest an alluvial fan with active and inactive lobes, and therefore a more mature drainage network developed in the source areas that created larger contrast between the size of fans of the different entry points to the basin. This occurs in spite of the fact that gravels are less mature in Churupatí. In the most proximal areas (outcropping area along the route to Calingasta) these autocycles can be defined by the variations in maximum particle size. Also, the scarcity of fragments of acid igneous rocks in Churupatí suggests that the tectonic reactivation occurred in the hinterland and was located towards east or west, but not axially due to the tendency of MPS along N–S. The inspection of the MPS across most exposures mapped in Churupatí suggests it reaches a maximum at a couple of km north of the San Juan River. This finding together with all indications pointing to an alluvial fan environment, leaves no doubt there was a gravel entry point little distance north of the San Juan River that explains the impressive lateral facies change of this unit. During the intervening time between Del Ratón and Churupatí, the hinterland drainage network evolved into a better-organized drainage, that occurs by the progressive capture of small streams by the main drainage courses, creating a main point-entry to the basin little north of the San Juan river, to the south intermediate alluvial fan facies start to occur south of the Alumbre creek while to the north, only a decrease of the MPS was observed, allowing us to interpret that an N–S transect along Chrupatí lower member goes from distal to proximal and starts going distal suggesting the transect is parallel to the basin margin, and that the entry direction was perpendicular to such a transect.

The Churupatí Formation evidences the presence of a topographically positive element towards the east (and perhaps towards west), although the size of it needs some debate. An important tectonic phase creating a significant mountain would have generated a large relief and a great rejuvenation of all the drainage systems. The Churupatí Formation demonstrates indeed an initial rejuvenation of the transport system of short duration that seems to be quite local given the oligomictic composition of the conglomerates: almost all its clasts come from units now belonging to the western Precordillera. However, conditions rapidly returned to the previous situation, as evidenced by the similarity between the Upper Member of the El Planchón Formation and the Middle Member of Churupatí. Therefore, our observations support again the development of a tectonic process that generated this thick basin fill within a small areal extent, being mainly related to a strike-slip system associated with the Tigre fault that is mentioned to have crustal importance (cf. Siame et al., 1996). This mechanism, also explains the absence of comparable sequences east- and westwards from the studied location, and the fact comparable sedimentary sequences are only found cropping out closely related to the trace of this fault, such as occurs with the outcrops of the Angualasto Group in the Malimán area (Limarino et al., 2017).

3.4. Del Salto formation (Quartino et al., 1971)

In this contribution we only focus on the basal section, its stratigraphic relationships with the underlying units, and its lower litho-palynological content, pointing out the need for further detailed geological and biostratigraphic work in this Formation.

3.4.1. Basal stratigraphic characteristics

The first aspect to consider is the characteristics of the basal erosive surface of the Del Salto Formation (Figs. 2 and 6) as it allowed us to understand some anomalies that exist in this locality. The mapping of this unconformity and the onlaps of basal beds in opposite directions from the section along the Alumbre creek demonstrated it has a deep and continuous curved shape. The deepest point of this megaerosion coincides with the Alumbre creek. Given the tectonic complexity, it looked initially like a folded unconformity. However, the mapping of the enclosed Del Salto strata shows a lateral onlap onto the unconformity formed by the deep carving into the Churupatí Formation (Figs. 2 and 6). The revision of this curved unconformity suggests it is a deep paleovalley that divides the outcrops of the Churupatí Formation as its level of erosion reaches the upper levels of El Planchón Formation. The careful survey and the restoration of this tilted surface revealed a U-valley shape, typical of those excavated by glacial processes. The detailed review of the deposits directly overlying the base of this paleovalley did not demonstrate the presence of preserved glacial nor proglacial deposits. However, there are numerous cases of paleovalleys in the neighbouring Paganzo basin, also related to the LPIA, in which primary basal glacial deposits have not been preserved, such as the paleovalleys of the Quebrada Grande (Kneller et al., 2004; Valdez et al., 2015), Lajas (Dykstra et al., 2006) and Talacasto creeks (Aquino et al., 2014) and Malanzán (Moxness et al., 2018). Therefore, the presence of glacial deposits is not a necessary condition to interpret the glacial origin of a paleovalley carved in the Carboniferous.

It is worth mentioning the change in the bed dip of the Del Salto Formation to the north of the San Juan River, as also observed for the El Planchón and Churupatí Formations through a broad syncline oblique to the trace of the San Juan River. For this reason, the basal unconformity of the Del Salto Formation is located on the western margin of the outcrops northwards from the river, and not in the eastern margin as it is to the south of the river.

3.4.2. Palynological content

From the lower part of this unit, some dark shales, mudstones, marls and fine sandstones were sampled near the Alumbre creek section (Fig. 2). Of eleven samples taken, two yielded palynomorphs (1187 and 1189), whereas the other four samples provided only phytoclasts (1185 with brachiopods, 1188, 1190–1192). The characteristics of the phytoclastic content in the six samples are very similar, in which larger tracheids (sharp rectangular) predominate over other sizes, while cuticles and other particles are less frequent. The palynomorphs obtained are relatively diverse and better preserved than in the underlying units. The palynological association of the 1187 sample provided few trilete spores (5%) and abundant phytoclasts (95%), and pyrite is not present. The sample 1189 contains monosaccate pollen grains and trilete spores (15%) together with abundant phytoclasts (85%) and the presence of pyrite (mainly framboidal) in palynomorphs and phytoclasts (Fig. 10). The appearance of monosaccates and typical spores of the Pennsylvanian (*Velamisporites cortaderensis* (= *Reticulatisporites passaspectus*), *Lundbladispora riobonitensis*, *L. braziliensis, Retusotriletes anfractus*) allows assignment of this association to the late Serpukhovian-Bashkirian (Fig. 7) and to be correlated to the DMa palynozone (Fig. 11).

3.4.3. General interpretation and discussion

The Del Salto Formation was originally divided into six members (Manceñido, 1973), and attributed to the Early Permian due to the finding of *Cancrinella* aff. *farleyensis* among other marine fossils of its lower section (Manceñido and Sabattini, 1974; Manceñido et al., 1976a, 1976b). Later, Lech and Aceñolaza (1990) and Lech (1993, 1995), suggested that the basal terms of this unit might be late Pennsylvanian in agreement with Taboada (1997), who included the same invertebrate fauna in the oldest zone of *Trivertonia jachalensis-Streptorhynchus inaequiornatus* (Sabattini et al., 1991) of the late Ghzelian? Taboada (2014) discarded the presence of *Costatumulus amosi* (= *Cancrinella* aff. *farleyensis*) in this association and confirmed a Moscovian age (up to Kasimovian) based on its correlation with different stratigraphic units of western Argentina (Fig. 11). However, the new biostratigraphic elements shown here suggest a much older age, although still in the Pennsylvanian Most of the palynological species found in both productive levels of the Del Salto Formation (Fig. 5) are absent in the underlying units and the appearance of monosaccate pollen grains supports their correlation with the DMa Zone widely documented in Paganzo and western basins (Fig. 11), supporting a Bashkirian age for the lower parts of Del Salto Formation.

Our observations support the interpretation that the paleovalley enclosing the older beds of Del Salto Fm. (the only deep erosion observed in this sequence) was created during the glacial maximum occurred near the Mississippian-Pennsylvanian boundary. Therefore its filling is also likely to be Bashkirian in age (Figs. 10 and 11). The depositional system preserved within this paleovalley suggests the existence of important but limited lateral slopes, which caused the collapse of some layers towards the center of the paleofjord, producing a thickening of some sand beds in the central areas of the paleovalley along with the beds strongly folded by synsedimentary deformation processes. In some cases, we could observe that the slumping direction was towards the center of the paleotrough that had an approximately East-West elongation, as also observed in comparable paleovalleys of Central Precordillera (Milana, 1988. As well known, glacial valleys tend to evolve over pre-existing drainage lines (valleys). In our case, we can demonstrate that there was a single entry point of the coarse gravels that fed the previous depositional system of Churupatí Formation, and located a couple of km north from the trace of the San Juan River. However, the dominant single entry for this basin during the lower Del Salto Formation time was c. 4 km further south. We interpret that the location of the paleovalley of the Del Salto Formation, c. 6 km south of the entry point of Churupatí alluvial fan, is due to the translation of the hinterland in relation to the basin (Fig. 5), along the El Tigre Fault traditionally considered dextral (Siame et al., 1996) which could easily displace the valley entry point by several kilometers southwards in the intervening time between Churupatí and Del Salto Formations deposition.

The palynofacies differences between the two samples obtained in the lower part of the paleovalley filling (Fig. 4) allow us to infer two types of depositional environments. The lower sample (1187) contains spores of herbaceous lycophytes that lived in humid environments whereas in the upper sample (1189) the cordaitalean and coniferalean (monosaccate pollen grains) and pteridophytes (Fig. 7) represent better-drained areas, possibly a bit further away from water bodies with lycophytes (Fig. 5). The absence of monosaccates in the lower sample is likely due to a very low density of palynomorphs in the sample, so the chance to find them was low. Sample 1189 presents palynomorphs and pyritized phytoclasts (framboidal and euhedral pyrite types, see Fig. 10), which is evidence to support a marginal marine environment of deposition in agreement with the brachiopods we recovered at the sampling sites (Figs. 2 and 4).

The formation of pyrite occurs in the water-sediment interface of marine shelf to brackish environments, and requires organic matter and seawater due to the high sulphate content for allowing the sulforeductive bacteria to reduce the sulphate into sulfide phases. This process requires anoxic-dysoxic conditions in a stable bottom surface with relatively low sedimentation rates where the organic matter deposited by decantation (Tyson, 1995). The framboidal type normally occurs in euxinic waters and brackish-type areas where the formation of framboidal pyrite in the suspended organic matter starts in the water column always in anoxic conditions (Sawlowicz, 2003; Mozer, 2010). The pyrite does not develop in highly modified refractory or black organic matter highly oxidized or thermally altered, so the pyritization process is mainly synsedimentary (Tyson, 1995, p. 78).

Samples bearing solely terrestrial phytoclasts (tracheids, cuticles, indeterminate black and brown particles) suggest a strong fluvial connection with the marine depocenter and rapid deposition of organic matter in shallower or marginal areas (Tyson, 1995). The analysis of the palynofacies supports, therefore, a depositional model of a flooded paleovalley, comparable to modern fjords in which it is not difficult to think in a deepened segment of the glacial trough due to the softer sediments in this basin, with respect to surrounding positive areas.

This paleovalley is another element against the Protoprecordillera model. An alpine glaciation model sourced from the Protoprecordillera as suggested (cf. Limarino et al., 2014), would have been no just a few kilometers long, quite steep and accompanied by a large amount of tilloid deposits coming from western Precordillera, due to our close position to the expected Protoprecordillera axis. On the other hand, if we use an ice-cap glaciation model with outlet glaciers evacuating the ice, depositional models suggest limited or almost absence of primary glacial deposits (see Eyles et al., 1985). An outlet glacial model has been proposed by authors who worked in the Central Precordillera (see Milana and Bercowski, 1987a, 1987b, 1990), in sections located only 25 km to the east of the study section, where a flooded glacial valley of comparable age was also described. The most logical solution to this scenario is tracing a line between the described single paleovalley that was facing westwards, and the Del Salto paleovalley that clearly is fed from the east. In the outlet glaciers, the supraglacial deposits are almost non-existent and subglacial deposits are very scarce and are often bulldozed by the glacier itself, leaving the base of the valleys almost completely devoid of primary glacial deposits, as is commonly observed in Paganzo Basin paleovalleys as mentioned above.

Our new findings also suggests a strong affinity of the marine beds of the Del Salto Formation with others in marine deposits immediately to the west (San Eduardo Group and La Capilla Formation) given the similarities in the palynological content as described by Vergel et al. (2015) for the Hoyada Verde and El Paso formations of the San Eduardo Group. We, therefore, suggest that there was a direct physical connection between the Del Salto paleovalley and the continuous E-W paleovalley that can be recognized in three successive thrust sheets of the Central Precordillera, along the San Juan river valley (Milana et al., 1987: Milana, 1988; Milana and Bercowski, 1987a, 1990). We also suggest also a potential connection with the Carboniferous deposits described over the Tontal range, laying directly at the core of the hypothetical Protopreordillera (Lech et al., 1998; Lech and Milana, 2006). The information provided here adds another paleofjord point to the network of glacial paleovalleys in the region of the modern Precordillera.

4. Discussion

4.1. The Mid-Carboniferous unconformity

It is widely known that in the central-western Argentina a hiatus is recognized between the depositional sequences of the Mississippian and Pennsylvanian in the Paganzo and Barreal-Uspallata basins. Despite almost a century of research over numerous outcrops known of the “tillitic” (cf. Keidel, 1921), now the LPIA, of the Precordillera, no clear evidence of glacial deposits were documented in the study area (cf. Colombo et al., 2014). However, glacial evidences are subtle, but present: modern high definition satellite images allow now to establish a possible glacial relief below the Del Salto Formation, which defines the boundary between the lower and upper Carboniferous series. The previously assigned Permian age for Del Salto Formation and the lack of precise chronological data in the underlying units prevented an accurate interpretation of the Carboniferous succession in this area. The mid-Carboniferous stratigraphic discontinuity and its associated hiatus it is now supported by the palynological determinations in this study for the first time, and it shows that it is not possible to know the complete evolution of the intra-Carboniferous boundary (Fig. 11) due to its erosive nature. Our study rules out a tectonic origin for this discontinuity, but we interpret a paleoclimate origin, as it coincides with the LPIA glacial maximum in this area which was the only time when glaciers carved valleys up to the western Precordillera rim.

4.2. Timing of local tectonic and glacial events

a) *Glacial 1 (late Tournaisian-Early Visean)*: As discussed above, the Del Ratón Formation is the result of a rapid deposition product of active tectonics. The thin but coarse conglomerates of the Lower Member do not show evidence of direct glacial effects but inherited features suggesting there was a glacial episode between the age of the glacially abraded rock fragments (dated as 348 ± 2 Ma, Gallastegui et al., 2014), and the age of deposition of the Lower member. Besides some igneous dykes intruding a comparable sedimentary cycle of the Del Ratón Formation are dated as 337 ± 10 Ma (Sessarego and Césari, 1989; Sessarego et al., 1990). These two isotopic ages define an interval equivalent to the late Tournaisian-early Visean age based on palynomorphs recovered from Del Ratón Lower member (Fig. 11; Amenábar and di Pasquo, 2008, and references). A transgression event occurred in the earliest Visean in concordance with the global T-R events in Gradstein et al. (2012) during which this unit was deposited in agreement with the palynological and fossil plant data for deposition of this unit (Fig. 11). This transgressive event might be the product of the post-glacial rise of sea-level, creating some accommodation space although not letting the sea level to reach this location,

b) *Glacial 2 (late Visean)*: The hemipelagic deposits with thin-bedded heterolithics carrying dropstones of the Lower Member of the El Planchón Formation would represent the second glacial event recorded in this section. In this member, only suspension-dominated deposition was recorded so it is likely that the varve-type heterolithics were produced by processes associated with cycles of seasonal melting due to their association to dropstones. Three glacial advances were probably recorded in the lower member and two in the lower part of the middle member of El Planchón, as these are the asymmetric cycles characterized by the thin-bedded heterolithics (inverse and then normal bed-thickening and upward grain-size evolution) that interrupt the monotonous shales of lower and middle El Planchón. This glacial event would be dated as late Visean given the palynomorphs recovered (Figs. 7 and 11). The sharp flooding at the top of Del Ratón Formation might be related, besides the tectonic process of opening this transtensional basin, to general subsidence due to glacioisostatic load, that might have amplified the flooding effect. The following postglacial transgression due to the ice-melting is represented in the shales of the Middle Member of the El Planchón Formation where a flora of herbaceous lycophytes, pteridophytes and pteridosperms of late Visean age was preserved.

This second glacial event can be correlated with some early glacial deposits (diamictites) in Guandacol and those of the Cortaderas formations (Fig. 11, and references therein), which partially coincides with a global regressive phase (335 Ma) according to Gradstein et al. (2012). The correlative event with the Guandacol Fm. is found only in the area of Villa Unión (MTD1 of Sierra de Maz and Cerro Bola), where the glacial and postglacial sediments yielded a palynoassemblage of Serpukhovian age corresponding to the DMa (Valdez et al., 2015), which allows us to correlate Guandacol MTD1 glacial beds and those from the Cortaderas to the glacial event recorded at El Planchón formation (Fig. 11).

c) *Visean-Serpukhovian tectonic phase:* The Churupatí Formation between the underlying El Planchón and the overlying Del Salto Formation in the new stratigraphic scheme proposed here evidences an important tectosedimentary reactivation of the basin. The important basal discontinuity over the El Planchón Formation, marked by the appearance of the green-purple conglomerates of the Lower Member and by an angular unconformity leaves no doubt it was related to a tectonic process. The marked Churupatí lateral facies change, however, it is not tectonic but the effect of the depositional alluvial system fed from one point and grading laterally and distally into ephemeral fluvial deposits passing into a swampy floodplain with permanent water. Thus, the well-known green and purple conglomerates would not correlate with any eustatic cycle but to a forced regression triggered by a tectonic event associated with the evolution of this strike-slip basin, added to a possible isostatic readjustment in the late Visean-Serpukhovian due the to ice unloading. The palynological content of the El Planchón and Churupatí formations shows only minor compositional differences (Figs. 7 and 8), which indicates that the floras developed under similar physiographic conditions in the surroundings of this small basin, and were maintained throughout the Mississippian in accordance with the extent of the *Frenguellia-Paulophyton* Phytozone (Tournaisian - early Serpukhovian, Carrizo and Azcuy, 2015). This also demonstrates that the unconformity developed at the base of Churupatí does not involve a long time gap, and supports our interpretation that it was mainly forced by a minor change of the strike-slip basin such as the passage of one block through a restraining bend.

d) *Glacial 3 (Serpukhovian-Bashkirian)*: Above the Churupatí Formation, the Del Salto Formation overlies a is deeply carved (c. 700 m) unconformity interpreted as a U-shaped paleovalley produced by glacial action. As mentioned, two palynological associations yielded species characteristic of the subzone A of the *Raistrickia densa-Convolutispora muriornata* (DMa) Zone. The appearance of monosaccate pollen grains, not recorded in the lower three units, is known to occur in the late Serpukhovian-Bashkirian (cf. Valdez et al., 2017). With respect to the invertebrates both Lech (1990, 2002) and Taboada (2014) interpreted that species of the *Tivertonia-Streptorhynchus* association (T-S) determined for the Del Salto Formation are present in units such as the Hoyada Verde and Río del Peñón formations (Fig. 11). Also, the *Levipustula* fauna of the glaciomarine sequences Hoyada Verde and the *Rhipidomella-Micraphelia* fauna of the El Paso formations were reassigned to the late Serpukhovian–early Bashkirian based on the association with monosaccate pollen grains documented by Vergel et al. (2015) suggesting El Salto Fm. would partly coeval to the Hoyada Vrede Fm. The mapping and correlation of El Paso and Hoyada Verde Formations also indicate they are part of the same sequence that was deposited within a paleorelief of possible glacial origin (Milana and Banchig, 1997).

All this suggests that both Del Salto and Hoyada Verde/El Paso paleovalleys were carved by the same event that probably coincided with the Serpukhovian–Bashkirian boundary. However, given the absence of glacial or proglacial sediments at our section, it is logical to consider Del Salto Fm, slightly younger than Hoyada Verde/El Paso complex as it is postglacial. In the light of our findings the conclusion of Taboada (2010) that established a Pennsylvanian – early Cisuralian age for the Del Salto formations on the basis of the associated T-S fauna, needs revision. Our palynological study allows us to restrict the hiatus between the Churupatí and Del Salto formations and hence the glacial erosion to the late Serpukhovian and to consider the El Paso, Hoyada Verde, Guandacol (middle), Río del Peñón and other Bashkirian units of western Argentina to be partially time-equivalent over this unconformity.

Therefore, the discontinuity defined here between the Mississippian and Pennsylvanian reinforces the existence of an important period of erosion when many paleovalleys of the LPIA of western Argentina were probably carved. It also points to the time of LPIA glacial maximum as it is the only time when glaciers reached the western Precordillera and created the largest suite of glacial deposits (Bashkirian in age) recognized in this and other Late Paleozoic basins such as the Paganzo. Remarkably, the first appearance of monosaccate pollen grains derived from cordaitalean and coniferalean (gymnosperms) also follow this, the most important glacial event (Glacial 3), suggesting it probably reshaped the vegetation regionally. This strong glacial event is widely documented in W-Argentina and elsewhere in South America.

4.3. Implications for the regional tectosedimentary regime of the Carboniferous

For the first time, chrono-palynological information of the El Planchón, Churupatí and Del Salto formations, complemented with field observations, allows us to propose a new stratigraphic and structural approach for this region. The present stratigraphic review reaffirms previous hypotheses that suggest that Neopaleozoic deposits at Km 114 were deposited in a transtensional basin (Milana, 2000a), during a period of significant tectonic activity that occurred mainly in the Mississippian. The geological complexity of this area has caused much stratigraphic and structural confusion, due to the localized behavior of this belt due to its relation to the crustal-scale El Tigre dextral strike-slip fault. There are elements yet to be reviewed, such as the middle and upper part of the Del Salto Formation, but the post-Bashkirian evolution will not be tackled here, only the events and paleogeographic elements related to the Del Ratón, El Planchón Churupatí and lower Del Salto Formations.

A) *The hypothetical Protoprecordillera*: The section studied is a key point for the paleogeography of the Carboniferous of Argentina as it is almost at the axis of what it is called Protoprecordillera (Fig. 1). In all the paleogeographic maps including the hypothetical Protoprecordillera, N–S paleo-orographic belt is modified with an engulfment due to this outcrop (cf. Salfity and Gorustovich, 1983, and further works based on their map). According to the Protoprecordillera model retained by many authors (see Gulbranson et al., 2010; Limarino et al., 2014), this mountain chain created a core from which valley glaciers flowed both to the so-called Maradonas sub-basin of the Paganzo Basin, and westwards to the Barreal-Calingasta Basin, as originally proposed by Amos and Rolleri (1965) and Rolleri and Baldis (1969). In such a model, it was assumed that this orographic chain separated continental basins eastwards and marine ones westwards. The proximity of our study area with the Protoprecordillera agreed with the supposed absence of sedimentation from the Visean to the Lower Permian (hiatus assumed between Formation Del Ratón and Del Salto as explained above), a hiatus that supported the existence of this tectonic positive element. However, data presented here suggest there was not a significant hiatus, and that actually the mid-Carboniferous unconformity is a paleovalley that owes its origin to a deep glacial scour. We agree that a tectonic process needed to open this basin and to accommodate 4 km of sediment, and c. 900 m of conglomerates, with many internal unconformities. However, all these units are adequately explained by a tectonic regime ascribed to a strike-slip-dominated setting, without the need of a nearby intermittently glaciated mountain.

The Protoprecordillera hypothesis also falls if we consider the connection between this locality, lying in the central strip of the western Precordillera and those cropping out at the Central Precordillera, only 25 km distant. If we consider 60% of shortening of the Precordillera during the Andean shortening (Allmendinger et al., 1990) we arrive to only 40 km of separation. Outcrops of the Central Precordillera are proved as marine due to their marine invertebrates (Milana and Bercowski, 1987a; Milana et al., 1987) that are comparable to Del Salto ones. These marine fossils were found in the supposedly continental and intermontane Maradonas sub-basin (Fig. 1, Rolleri and Baldis, 1969; Salfity and Gorustovich, 1983). Subsequent works determined defined a marine flooded paleovalley, with some primary glacial deposits with a well documented glacially striated pavement and overall and with paleocurrents pointing to the west (Milana, 1988; Milana and Bercowski, 1990). The projection of this fjord recorded in three thrust sheets of the Central Precordillera matches perfectly with the paleovalley defined for basal Del Salto Fm. Lateral inspection of the Central Precordillera thrust slices showed that no marine nor glacial deposits are nearby, suggesting initial glaciomarine sedimentation during the Carboniferous occurred only within excavated valleys. Only c. 100 km northwards at Talacasto creek, a paleovalley is mentioned, and interpreted as a tributary of the one located along the San Juan river trace (Aquino et al., 2014).

In considering the existence of the Protoprecordillera, the key outcrop on the Tontal range needs to be considered (Lech et al., 1998; Lech and Milana, 2006), as it lies just at the axis of the Proto-precordillera (the Tontal range, Fig. 1). In the Tontal section, five fossiliferous intervals with marine invertebrates were described in a section that probably includes both a Mississippian and Pennsylvanian sections according to the paleontological content. In that outcrop, a unique development of marine shelf carbonates including hydrodynamic shell accumulations (Lech and Milana, 2006) suggests again the absence of such a positive element as the Protoprecordillera.

A third element that also rules out the Protoprecordillera as a continuous mountain chain is given by the two paleovalleys of Talacasto; progradation direction of the subaqueous outwash deltas to the north, the orientations of the paleovalleys and their marine content led to interpret that glaciers flowed southward from Talacasto to the San Juan river paleovalley (Aquino et al., 2014). This suggest that the avenue for marine ingressions that could have reached the Eastern Precordillera judging for the strong eustatic control of the paleofjord deposition (Kneller et al., 2004; Dykstra et al., 2006), would have been located coinciding the present trace of the San Juan River, where deposits show the strongest marine affinity (Milana et al., 1987a). Conversely, the paleovalley defined in the Central Precordillera (Milana, 1988) would be also the main avenue to evacuate large amounts of ice from an ice-cap located southeastwards as previously suggested by some authors (cf. Milana et al., 1987; Kneller et al., 2004; Dykstra et al., 2006; Aquino et al., 2014), being Del Salto paleovalley the best potential candidate to continue that evacuating glacier. The fact marine ingressions entered no less than 100 km inland along the glacially excavated paleovalleys only, conspires against the idea of alpine glaciers, and reinforces the interpretation of this glacial network as outlet glacier valleys. In summary, the hypothesis of the Acadic Protoprecordillera proposed by Amos and Rolleri (1965), cannot be supported in the light if the new facts brought here and we suggest the paleogeography and evolution of this margin of the Gondwana needs to be adjusted.

B) *Neopaleozoic tectonism:* While we do not support the existence of the Protoprecordillera *per se*, we do support an active tectonic regime in the western Precordillera. Tectonism is the main generator of accommodation space, and the Carboniferous sequence accumulated in the Del Salto creek, reaches ca. 4 km thick, being the thickest known in the Precordillera, supporting the existence of active tectonism. The two continuous successions of conglomerates also imply an active and nearby tectonic process. The 500 m of continuous conglomerates without sandy intercalations of the Middle Member of the Del Ratón Formation are only comparable to the Neogene bajada conglomerates formed by the Andean tectonics (Milana, 1997). However, bajadas in the Andean basins occur at the top, while Del Raton bajadas occur at the base typifying the opposite tectonic regime, i.e. extensional tectonics. Thus, the initial deposition of the Del Ratón Formation followed by El Planchón typify a syntectonic graben with a high degree of local subsidence that has not been documented in nearby locations, which would actually be transtensional.

The second conglomeratic sequence, corresponding to the lower Churupatí Fm, indicates the onset of a new active tectonic process. In this case, the lower Churupatí is also associated with an angular unconformity of variable erosional relief reinforcing the active tectonism. We suggest that this was produced by a transient transformation of the basin from transtensional into transpressional due to a change of stress directions or because the basin moved through a restraining bend. Additional evidence of tectonism is the existence of marked facies lateral variations (Milana, 2000a; Colombo et al., 2014) of the Churupatí Formation. These lateral variations are often the result of immature basins with rapid subsidence, where the depositional systems are more segmented or restricted geographically.

This tectonic imprint, unique in the basins of central-western Argentina. Is the reason we propose that deposition in this Carboniferous basin was driven by El Tigre meagfault, with whose trace it coincides. This feature partially coincides with the area interpreted as the suture zone between Chilenia and South America (Gondwana), which collided and docked in the Middle Paleozoic (Ramos et al., 1984). However, the El Tigre fault is today described as a crustal-scale fault and suggested to be the most active in the region (Siame et al., 1996; Fazzito et al., 2013). We believe it is not a coincidence that this important structure of the W-Precordillera shows a large number of oblique structures to the general N–S trending structure. Therefore, we interpret that the El Tigre fault activation during the Lower Carboniferous was the main basin-forming element for the studied deposits as it explains the large thickness observed, given that accommodation space generation might be exceptionally fast in strike-slip basins. Numerous examples exist, particularly in the southwest of the USA and north-western Mexico, of transtensional basins that accumulated several km of sediment in small areas (Christie Blick and Biddle, 1985) as in our case.

Most evolutionary characteristics observed in this basin support the strike-slip hypothesis: 1) the sedimentary fill suggests that the accommodation space increased very fast causing the rapid gradation from the thick conglomerates of Middle Del Ratón Formation, to the shales of the lower El Planchón Formation. This rapid transition from coarse-to fine sediments also occurs in rift basins, and when the accommodation space exceeds the rate of sedimentation, a “stasis” moment can occur of sediment starvation. This stasis of starvation stage that develops during the syn-rift phase causes no sedimentation at basin mid and central zones because sediment is trapped at its edges, as shown for the Triassic Ischigualasto rift basin (Milana and Alcober, 1994), but in our case the presence of sediment-laden plumes prevented this stasis stage, and instead a suspension-dominated depositional interval prevails such as that observed in the lower El Planchón Fm. Thus, the sharp contact between Del Ratón and El Planchón formations is attributed to the transformation from an overfed to a starved basin, as rift and transtensional basins follow similar trends of creation of accommodation space. When interpreting this as a strike-slip basin associated with the El Tigre fault, the basin accommodation space will depend on the curves of the fault trace or irregularities of the blocks that are sheared one against the other. Thus subsidence doesn't depend on isostatic loading, thermotectonic processes, or situations of crustal attenuation as in other basins (see Christie Blick and Biddle, 1985).

This strike-slip model could be tested against some chrono-stratigraphical facts. The lateral transport of the hinterland respect to the basin would have affected also the entry of sediment to the basin. The displacing of the main entry points that form a bajada as that of Del Ratón Fm, would be difficult to track down but it is not the case during more mature basin stages. We demonstrated the lack of coincidence in c. 6 km between the entry point of the alluvial fan of the lower Churupatí Formation (north of the San Juan River) and the entry of the glacial flow that carved the Del Salto paleovalley. The displacement of 5–7 km southwards of the valley that fed the Churupatí alluvial fan to the position of the paleovalley of the Del Salto, could have last 5–7 Ma according to the upper Serpukhovian-lower Bashkirian hiatus defined herein between the Churupatí and Del Salto formations (Fig. 11). Today, the calculated movement rate range for the El Tigre fault based on the cosmogenic dating of the displaced quaternary terraces is 0.5–5 mm/year (Siame et al., 1996). Thus, the displacement rate for the Churupatí/Del Salto entry point indicates a displacement at a rate of 1 mm/yr that it is in the lower range of displacement today when no basin or positive elements are clearly formed along this fault trace. These considerations show there was enough time for the basin to have changed transiently from a transtensional into a transpressional regime, without the need of a specific tectonic phase, but just as the evolution of a basin moving along an unknown design of curves of the strike-slip system.

To the north, the traditional outcrops of the Angualasto Group

(Fig. 1) seems to be associated with this megafault as they lie along its trace and further north, this fault trace could be extended even to the Agua del Peñón outcrop area where Mississippian deposits are again recorded (Agua de Lucho and Tres Cóndores formations, González and Bossi, 1986). Several authors have recognized the correlation of units in Agua del Peñón with the Angualasto Group (Azcuy et al., 2000; Limarino and Césari, 1993). Therefore, we suggest that the Del Ratón, El Planchón and Churupatí formations might be part of the Angualasto Group (Fig. 11), as they have been deposition by same tectonic regime driven by El Tigre fault.

5. Conclusions

The new palynological information obtained in this study clearly defines a Mississippian age for the El Planchón (late Visean) and Churupatí (Early Serpukhovian) formations and Bashkirian for Del Salto. Our litho-stratigraphic information provided evidences of three glacial events at this locality, not previously recorded despite the great sedimentary thickness (ca. 3000 m) of the Carboniferous succession. The first glacial event already mentioned predating the Del Ratón lower member of late Tournaisian-Early Visean age, the second preserved at lower El Planchón of late Visean age, and the third and defining the local glacial maximum as located at the Serpukhovian-Bashkirian boundary. The third event that carved a paleovalley which can be tied to marine flooded paleovalleys entering the Central Precordillera for more than 100 km, rules out the alpine glacier hypothesis due to their higher slopes would inhibit such deep penetration of the sea into the continent along the fjord systems. Instead, it reinforces a previous idea that the carving was generated by outlet glaciers draining a large ice cap located to the east.

The stratigraphic affiliation of the green and purple conglomerates, assigned here to the Churupatí Formation was determined, amending previous definitions. The new stratigraphic scheme of the local Carboniferous beds allows better correlations to the Angualasto group. We support the correlation between Del Ratón and Malimán formations although their lower and upper limits might not be synchronous (Amenábar and di Pasquo, 2008; Amenábar et al., 2009). We do not agree with the correlation of the Middle Member conglomerates of the Del Ratón Formation and the Cortaderas Formation (Limarino et al., 2017) and instead we suggest a partial correlation of the El Planchón to the Cortaderas formations (Pérez Loinaze et al., 2010) given comparable palynological content and that both units show glacio-related deposits.

The two thick conglomeratic sequences surveyed were differentiated and they suggest two different stages of strike-slip activity rather than the hypothetical Protoprecordillera. Del Ratón conglomerates are syntectonic, product of a transtensional basin opening, a process that explains well their abrupt termination and the fast evolution to the shaly El Planchón Fm. The second set of conglomerates is linked to a transpressional transient stage due to geometrical effects of the dextral fault system, explaining also the irregular unconformity at the base of Churupatí Fm. The impact of this crustal-scale strike-slip dextral El Tigre fault on the evolution of this western margin of the Gondwana needs to be reassessed in the light of more data, as it might challenge concepts as the Chilenia allochtony and its interpreted collision due to the close association between El Tigre fault trace and the proposed suture zone between Precordillera and Chilenia.

The unconformity at the base of Del Salto Fm, is the product of the strongest glacial event that was responsible for the erosion of an important U-shaped paleovalley cutting down through the entire Churupatí formation at the deepest erosion levels, placing Del Salto in direct contact with El Planchón. The palynomorphs recovered from Del Salto paleovalley fill indicate it has a Bashkirian age (Figs. 7 and 11) and not Permian as suggested previously. The hiatus between Churupatí and Del Salto would comprise locally the latest Serpukhovian and this climate event (maximum glacial of the local LPIA) would have favored the introduction of monosaccate pollen grains from the Cordaitalean and Coniferalean groups of gymnosperms that inhabited mixed marine fjord environments. This is in concert with other paleobiological changes documented in the Serpukhovian-Bashkirian associated with the glacial maximum of the LPIA in W-Gondwana.

This glacial carving also provides some control on the strike-slip hypothesis, by comparing the displacement of the sediment entry point of Churupatí and Del Salto Formations. A rough estimate suggests a displacement rate on the order of 1 mm/yr, which is within the present-day displacement range of El Tigre dextral fault. Thus, we conclude that the El Tigre fault was very active during the Lower Carboniferous, being responsible for the local basin evolution. This model permits the generation of accommodation space that allowed accumulation of more than 4 km of Late Paleozoic sediments in a very small basin.

Despite the large amount of conglomerates observed, the influence of an orographic element comparable to that indicated for the Protoprecordillera was not recognized, but a rather continuously positive area (hinterland) to the west and/or east. We interpret that the Del Salto paleovalley is the continuation of the marine flooded paleovalley described in Central Precordillera (Milana et al., 1987) and rather than a mountain change in between, we propose a continuously positive area, carved by glacial valleys that then was the avenue for the marine transgressions from east from the study location.

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Declaration of competing interest

We declare hereby that there are no conflicts of interest in relation of the article published and that authors have all the rights to use the original data supplied in this article.

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Appendix 1

List of palynomorphs identified for each Formation, with authors (references are not included)

Spores from El Planchón Formation

Anapiculatisporites hystricosus Playford 1964
Apiculiretusispora semisenta (Playford) Massa et al., 1980
Bascaudaspora collicula (Playford) Higgs, Clayton and Keegan 1988
Bascaudaspora sp. P. Loinaze 2008
Crassispora scrupulosa Playford 1971 emend. Playford and Satterthwait 1988
Crassispora sp. Amenábar et al., (2007).
**Cristatisporites aculeatus* (Hacquebard) Potonié 1960
**Cristatisporites echinatus* Playford 1962
Cristatisporites inconstans Archangelsky and Gamerro 1979
Cristatisporites indignabundus (Loose) Potonié and Kremp 1954 emend. Staplin and Jansonius 1964
Cristatisporites indolatus Playford and Satterthwait 1988

Cristatisporites matthewsii Higgs, Clayton, Keegan 1988
Cristatisporites menendezii (Menéndez, Azcuy) Playford 1978
Cristatisporites peruvianus Azcuy and di Pasquo 2005
Cristatisporites scabiosus Menéndez 1965
Cristatisporites spinosus (Menéndez, Azcuy) Playford 1978
Cristatisporites spp.
Cristatisporites stellatus (Azcuy) Gutiérrez and Limarino 2001
Cristatisporites verrucosus González Amicón 1973
**Cymbosporites loboziakii* Melo, Playford 2012
Densosporites annulatus (Loose) Schopf, Wilson and Bentall 1944
Densosporites gracilis Smith and Butterworth 1967
Densosporites secundus Playford and Satterthwait 1988
**Densosporites* sp. cf. *D. rarispinosus* Playford 1963
**Densosporites steinii* Ravn 1991
Dibolisporites insolitus P. Loinaze 2008
Dibolisporites microspicatus Playford 1978
Kraeuselisporites tedantus Playford, Satterthwait 1988
**Knoxisporites pristinus* Sullivan 1968
Knoxisporites sp.
Laevigatosporites-Latosporites
Lophozonotriletes sp.
Pustulatisporites malimanensis Amenábar et al. (2006).
Retusotriletes sp. cf. *R. mirabilis* (Neville) Playford 1978
Tholisporites scoticus Buttherworth and Williams 1958
Vallatisporites sp.
Verrucosisporites morulatus (Knox) Potonié and Kremp 1955 emend. Smith and Butterworth 1967

Spores from Churupatí Formation
Bascaudaspora collicula (Playford) Higgs, Clayton and Keegan 1988
Crassispora scrupulosa Playford 1971 emend. Playford and Satterthwait 1988
Cristatisporites inconstans Archangelsky and Gamerro 1979
Cristatisporites indignabundus (Loose) Potonié and Kremp 1954 *emend.* Staplin and Jansonius 1964
Cristatisporites peruvianus Azcuy and di Pasquo 2005
Cristatisporites spp.
Densosporites annulatus (Loose) Schopf, Wilson and Bentall 1944
Densosporites pseudoannulatus Butterworth and Williams 1958
Dibolisporites microspicatus Playford 1978
**Reticulatisporites vitiosus* Playford 1978
Spinozotriletes hirsutus Azcuy 1975
Vallatisporites vallatus Hacquebard 1957
Densosporites triangularis Kosanke 1950
Knoxisporites sp.
Punctatisporites spp.

Palynomorphs from the Del Salto Formation
Spores. Apiculatasporites caperatus Menéndez and Azcuy 1969
Apiculatasporites parviapiculatus Azcuy 1975
Apiculatisporis sp.
Apiculiretusispora tuberculata Azcuy 1975
Botryococcus braunii Kützing 1849
Calamospora hartungiana Schopf in Schopf, Wilson and Bentall 1944
Kraeuselisporites malanzanensis Azcuy 1975
Leiotriletes sp.
Lundbladispora braziliensis (Pant and Srivastava) Marques Toigo and Pons, 1974 emend. M. Toigo and Picarelli 1984
Lundbladispora riobonitensis Marques Toigo and Picarelli 1984
Retusotriletes anfractus Menéndez and Azcuy 1969
Vallatisporites ciliaris (Luber) Sullivan 1964
Velamisporites cortaderensis (Césari and Gutiérrez) Playford 2015 (=*Reticulatisporites passaspectus* in Playford 2015)

Monosaccate pollen grains
Cannanoropollis janakii Potonié and Sah 1960
Potonieisporites barrelis Tiwari 1965
Potonieisporites magnus Lele and Karim 1971
Potonieisporites novicus Bhardwaj 1954 emend. Poort and Veld 1996

Appendix A. Supplementary data

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