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Carboniferous marine deposits of the Tontal section suggest that no Protoprecordillera existed along the Western Gondwana margin

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A B S T R A C T

We present new palaeontological and stratigraphic data from a poorly known section located in the Tontal Range, Argentina, whose importance is key to defining the character of a hypothetical Carboniferous mountain chain, the Protoprecordillera. The Tontal Range composed the core of the hypothetical Protoprecordillera, also called the Tontal arch. The section described here comprises Mississippian and Pennsylvanian marine and mixed marine–terrestrial units that were deposited within a proglacial (non-fjord) environment. A new correlating scheme of Tontal section units is brought based on new biostratigraphic data plus the recent development of a stratigraphic order of Carboniferous units cropping out only 15 km away. The lowermost unit in the Tontal section is Del Ratón Formation conglomerate, which passes upwards into glaciomarine shales correlated with the El Planchón Formation that bears marine bivalves and palynomorphs suggesting a Serpukhovian (Upper Mississippian) age. El Planchón is overlain by the barren Churupatí Formation, with lower units of shallow marine, fan-deltaic conglomerate, passing to fluvial redbeds. The overlying Del Salto Formation has intense intraformational folding due to slumping at its base, and consists of sandstone, organic-rich shale, and shelf carbonate, the latter containing marine invertebrates and palynomorphs that suggest a Bashkirian (Lower Pennsylvanian) age. The Tontal section represents a marginal position within a previously defined strike-slip basin (Milana and Di Pasquo, 2019) that was active during most of the Carboniferous. It was deposited in a shallow marine shelf beside a hummocky coastal landscape, the erosion of which provided rounded gravels deposited in Gilbert-type deltas with associated slumps. We found no indication this area hosted any kind of glaciers, and most of the time it was below sea level. These observations, along with the lack of any mountain-side complex or any alpine-valley glacio-related depositional features remain at this, or any neighbouring sections; suggest that there was no Protoprecordillera mountain chain. Correlation with nearby sections also suggests this margin was not influenced by any prominent topographic highs during the depositional time of the Tontal section (upper Mississipian to Pennsylvanian), but rather that this area was located near sea level, potentially with emergent and positive areas along both margins of the strike-slip basin that allowed preservation of the oldest Carboniferous units of this region. On the other hand, the tendency for generalised subsidence during the Upper Carboniferous over most of the Precordillera, may respond to the development of a volcanic arc westwards over the present Cordillera, associated with the activation of a subduction zone in the present-day Chile, turning most of the area into retroarc basins.

1. Introduction

A key element for the understanding of palaeogeographical and palaeoclimatological controls of western Gondwana sequences during the Carboniferous Period is the Protoprecordillera hypothesis, a concept that is developed in the following item. However, none of the studies alluding to the Protoprecordillera mentions the actual existence of Lower and Upper Carboniferous beds cropping out at the expected top of this palaeomountain range. Part of this detachment between the hypothesis and the true data, is owed to the fact geological exploration that supplied the key outcrops that are closest to the Protoprecordillera axis, occurred several decades after the hypothesis was proposed, allowing the deep establishment of the hypothetical mountain chain in the scientific community. However, after Amos and Rolleri (1965) proposed it, several obstacles to their hypothesis suggested an alternate hypothesis might be required. The first problem was the discovery of marine elements in the Maradonas sub-basin in 1987 (Milana et al., 1987) just to the east side of the palaeomountain range, in an area that should be purely continental, and fed from the western flank of it. Palaeocurrents also indicated

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westwards flow, suggesting an open connection to the west that facilitated the marine ingression. The second challenge was the discovery, in 1997 (Banchig et al., 1997), of a marine section just atop the expected palaeomountain range including lower and upper Carboniferous deposits, some of which suggest the development of a carbonate platform (Lech et al., 1998; Lech and Milana, 2006). The third dilemma was related to the Carboniferous microfossils extracted from the alleged Devonian El Planchón Formation (Milana and Di Pasquo, 2019), whose detailed study allowed separating it from the conglomeratic Churupatí Fm, and creating a new stratigraphic order. Given that the most important section to resolve the Protoprecordillera enigma was the El Tontal section, we undertook an intensive biostratigraphic sampling and a more detailed sedimentological analysis with the objective to bring more elements to judge the Protoprecordillera hypothesis.

New sedimentological and biostratigraphical data for the Tontal Range section is presented here including (1) new palynomorphs that corroborate the presence of lower and upper Carboniferous at El Tontal, (2) new plant fragments from this section, (3) improved sedimentological analysis of each stratigraphical interval of this section, (4) new stratigraphic correlations based on recent re-evaluations of nearby sections, (5) a revision of glacial evidences to the east and west of this section to check the nature and palaeocurrent of glacial systems, and (6) a re-evaluation of the palaeogeography of this Western Gondwana margin and its role associated with the largest glacial episode recorded locally for the Late Palaeozoic Ice Age (LPIA).

2. Geological context

2.1. The Tontal section and its basin

Carboniferous deposits near the axis of the Tontal Range have been known for more than 20 years (Banchig et al., 1997), and marine invertebrate fauna from both lower and upper Carboniferous units were described by Lech et al. (1998) and Lech and Milana (2006). Barredo and Ottone (2003) published palynological data based on samples from the upper section and named the entire unit as the Ciénaga Larga Del Tontal Formation.

In spite of the fact that these four studies, produced c. 2 decades ago, mentioned that Tontal section was a dominantly marine section and that developed a mixed carbonate shelf, that is incompatible of being at the axis of the hypothetical Protoprecordillera, a plethora of subsequent works (e.g., cf. Limarino et al., 2014b and references therein) still mention the Protoprecordillera not only as a positive topographic element (which would be impossible given the fact there was marine sedimentation) but also as a climatological barrier trapping east directed moisture and generating glaciers over a hypothetical ELA (Elevation Line Altitude) that were descending both eastwards and westwards to Rio Blanco–Calingasta and Paganzo–Maradonas basins respectively (Limarino et al., 2014b). Therefore, instead of trying to conciliate new data product of the geological exploration of this previously unexplored region, many authors insisted on keeping the same geological model adding new roles for this challenged mountain as being a palaeoclimate controlling agent added to its role as a glacier-bearing positive element.

In order to present a better idea of the interrelation of the poorly known outcrops that occur near the Tontal section, we included a section comparing Tontal and the neighbouring sections that clearly demonstrates the free movement of rivers, and glaciers from east to west.

2.2. The importance of defining the type of glaciation affecting the W Gondwana margin

The Late Palaeozoic Ice Age (LPIA) in South America has been a matter of debate for more than half a century. Evidence for glaciation from Carboniferous strata has been presented for different sections across southern South America, yet reviews were mixed. Frakes and Crowell (1969) discussed the idea of a positive glaciated terrain coinciding with the Precordillera, concluding that evidence did not support the hypothesis. However, recent papers use the hypothetical Protoprecordillera to develop alpine glacial and palaeoclimatological models (Limarino et al., 2014b; Moxness et al., 2018; Pauls et al., 2019), without any supporting evidence for those potential alpine glaciers. The full-marine fossil association published for the Mississippian and Pennsylvanian Tontal section strata for the last 20 years (Lech et al., 1998; Lech and Milana, 2006) should preclude the existence of a mountain chain at this location during the Carboniferous. We believe the Protoprecordillera might have existed during the Devonian, due to the generation of extensive low-grade metamorphism over most of the western Precordillera (Baldis et al., 1982), but certainly not during the LPIA.

In this context, the new data supplied for the Km 114 section by Milana and Di Pasquo (2019) is a key for the understanding of this margin as it allows a new interpretation of the Tontal section stratigraphy due to the fact it is the nearest outcrop. The Km 114 section is located only 15 km to the NNW of the Tontal section (Fig. 1), and its stratigraphy has changed due to the discovery of several palynological associations that served to end a 60 year-long discussion about the correct age of some units that were assigned alternatively to the Devonian and Carboniferous. The section shows more than 4 km of Late Palaeozoic sediments accumulated at this location whilst no sedimentation was recorded both westwards and eastwards, for the lower two thirds of the total thickness, and also shows that glaciers only reached this basin during the middle Carboniferous advance, when a glacial valley that holds the lower El Salto Formation was excavated. One of the most important outcomes of the Km 114 section reappraisal was the discovery of evidence suggesting strike-slip basin dynamics. Lateral displacement of the main feeding valley provides the strongest evidence. Given the almost physical connection between Km 114 and Tontal outcrops, we assume that the Tontal section was deposited in a strike-slip basin environment.

We will not discuss in this contribution the basin dynamics associated with the Tontal section as due to its almost physical connection (only 15 km apart) that it belonged to the same tectonostratigraphic environment as the Km 114 section. We therefore refer the reader to that extensive analysis of Milana and Di Pasquo (2019) if a doubt arises in relation to basin dynamics and bio and physical stratigraphical aspects, as we adopt here the stratigraphic scheme already developed and discussed for the Km 114 section. It is emphasised in this study that we consider a "sedimentary basin" as an area characterised by accommodation space produced by some tectonic process. In other words, the carving of a valley and its subsequent fill, do not qualify as "sedimentary basin". However, many palaeovalley fills have been used to demark boundaries of alleged basins, creating very complex palaeogeographic maps, which are difficult to interpret from a basin-forming point of view. The Tontal section may not qualify as a basin given a palaeofjord setting was suggested for this site (Barredo and Ottone, 2003; Lech and Milana, 2006). However, the present study in which a lateral survey of the section was made, suggests this section was not deposited in such setting, but that it was a peripheral sector of the strike slip basin defined for the Km 114 section. In the vicinity, most sections containing glacial and postglacial transgressive deposits were found to be forming palaeovalley fills, such as the Jejenes Formation within the Las Lajas (Dykstra et al., 2006) and Quebrada Grande (Kneller et al., 2004) palaeovalleys, the San Juan river Palaeovalley (Milana et al., 1987; Milana and Bercowski, 1990; Milana, 1988), The Hoyada Verde complex (Milana and Banchig, 1997) and the Talacasto North and South palaeovalleys (Aquino et al., 2014). Thus, most glacio-related deposits surveyed near the Tontal section beyond this strike-slip basin cannot be considered depositional basins as they are preserved within palaeovalleys that were carved directly on a pre-Carboniferous subcrop.

Therefore, at the time of the largest glacial advance, available data suggest there was not a single positive element as the Precordillera, but a generalised emergent area that implied the entire Precordillera,

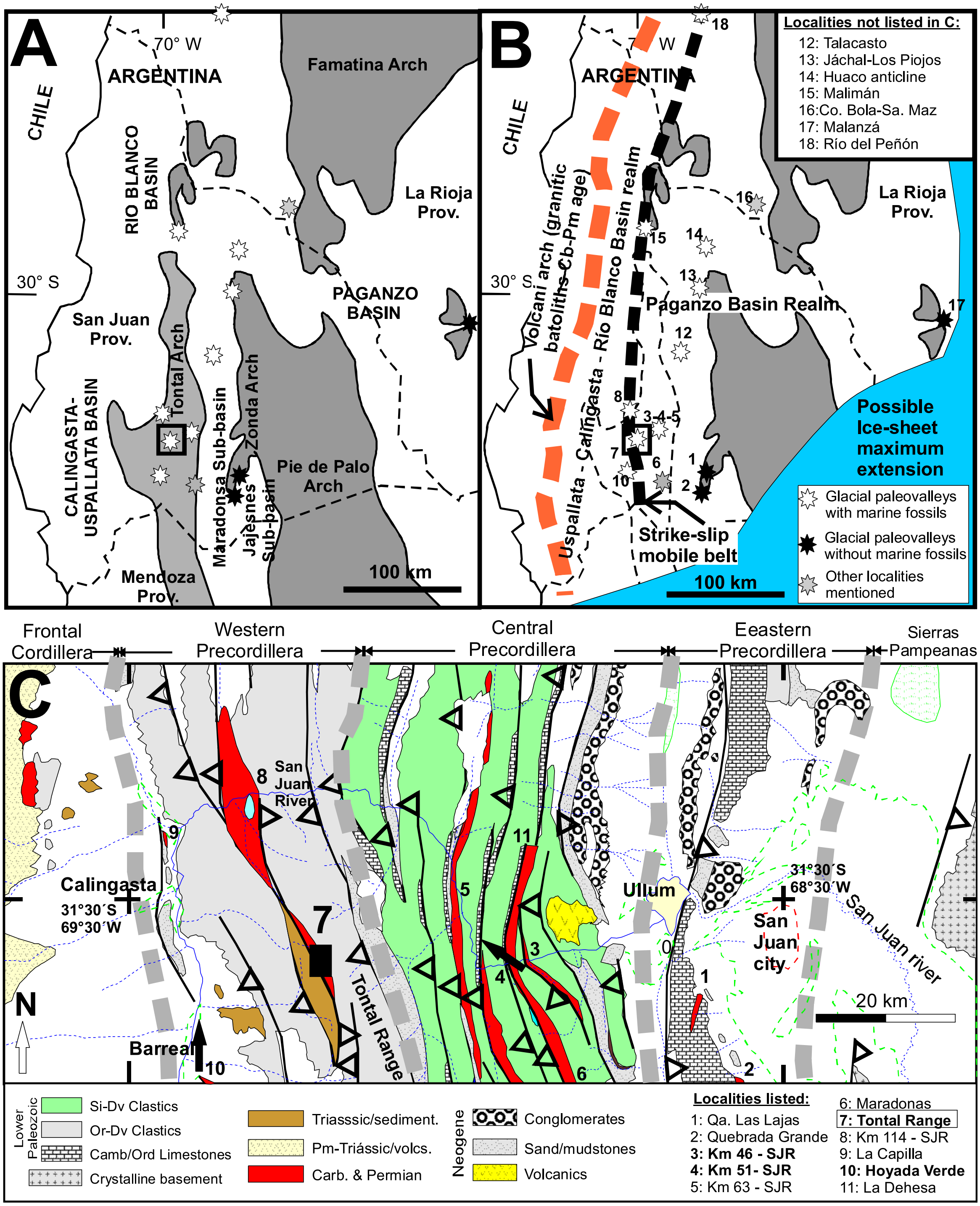

Fig. 1. General maps. A) Most used palaeogeographic map for the Carboniferous of this region (cf. Limarino et al., 2014b), portraying distribution of basins and positive areas (modified from Limarino et al., 2014b, and other authors). B) General palaeogeography proposed, emphasising that lower and upper Carboniferous scenarios are radically different. C) Geological map of the Precordillera at the latitude of this work. The two main glacial striated pavements are indicated and palaeoflow indicated by black arrows. SJR quotes San Juan River. Study area (locality 7), shown by box. Locations indicated in the text are shown in this and previous map.

that became cut down by the long, separated palaeovalleys, mentioned above. This context cannot be explained by localised alpine glacier centres. Instead, a large ice cap located eastwards from the Precordillera and feeding ice to these long outlet glacial valleys, explains most of the field evidence. This scenario can explain how it is possible that the marine postglacial transgression had brought bivalves to places located almost 200 km inland and generate transgressive shales up to 350 km inland.

2.3. Origin of the Protoprecordillera hypothesis

The idea of the Protoprecordillera was inspired almost exclusively from Carboniferous outcrops exposed along the San Juan River section and neighbouring localities, when geological exploration was very rudimentary and several Carboniferous beds were considered to be Devonian (cf. Milana and Di Pasquo, 2019). The Protoprecordillera hypothesis was initially published by Amos and Rolleri (1965) and Rolleri and Baldis

(1969) postulating an N–S elongated palaeomountain coinciding with the Tontal range, sourcing alpine glaciers to the west and east. They based their hypotheses on: 1) the presence of dominantly marine carboniferous successions to the west (Barreal–Calingasta basin), with glaciomarine deposits at the Hoyada Verde section (cf. López Gamundí, 1991); 2) the presence of exclusively continental deposits to the east in the Maradonas sub-basin, which belongs to the Paganzo Basin (cf. Salfity and y Gorustovich, 1983); and 3) the absence of upper Palaeozoic deposits along the hypothetical palaeomountains, the Tontal Range.

This hypothesis fuelled a revision of this glaciation by Frakes and Crowell (1969) who supported true glacial remains from the Río Blanco basin (west of the Protoprecordillera), whereas at continental parts of the basin no convincing evidence was found. Frakes and Crowell (1969, p. 1009), suggested a possible glaciated narrow coastal *cordillera*, which captured humidity from the ocean, mentioning "initial deposition was, therefore, probably by alpine or piedmont glaciers debouching on a narrow, rugged coast from sources high in elevated Cordilleras". They concluded "with this picture, perhaps only high parts of the cordillera were glaciated" (Frakes and Crowell, 1969, p. 1035), adding that Calingasta–Uspallata basins lay "quite near and to the east of glaciated source areas". This revision already suggested a mountain between western and central Precordillera areas was not possible, and that if an alpine glacier model had to be used, it could be only with a glaciated centre where the present Cordillera is located; so to the west of Precordillera. Indeed, the presence of positive elements to the west has recently been suggested based on provenance study of igneous clasts in some Western Precordillera Mississippian units (Gallastegui et al., 2014).

The Protoprecordillera debate should have ended two decades after Amos and Rolleri (1965) proposed it, given the marine brachiopods *Nudirostra cuyana* (Amos), *Septosyringothyris* sp. and *Cancrinella* sp. were found within the "continental" Maradonas sub-basin at the Km 63 locality near the San Juan River (Fig. 1, Milana et al., 1987). Later, Lech et al. (1990) added *Septosyringothyris* aff. *amosi*, *Punctothyris* aff. *sanjuanensis*, *Neospirifer* sp., to this locality along with the lamellibranches *Stutchburia* sp., *Vacunella* sp. and *Edmondia* sp. all of which have undoubted marine affinity. Sedimentological studies indicated deposition within a palaeofjord environment (Milana, 1988) and some remnant glaciogenic deposits were found along the southern margin of this palaeovalley, which was carved a few hundred metres into the upper Devonian subcrop (Milana and Bercowski, 1990). This marine flooded glacial valley, lies only 21 km east of the Tontal section today, and most reconstructions suggest less than 100 % of Neogene shortening (Allmendinger et al., 1990), thus the original distance was no more than 40 km. A connection of the central Precordillera palaeofjord of Milana (1988) with a glacial palaeovalley carved at the Km 114 locality, hosting the lowest Del Salto Formation, was recently suggested (Milana and Di Pasquo, 2019). It could be possible that a trunk glacial valley cut through a glaciated palaeomountain chain, but how could it be possible that 20 km south of such a deepened trunk valley, and over the expected axis of the palaeomountain, marine deposits still accumulated, as those from the Tontal section?

A fatal problem of the Protoprecordillera hypothesis relates to the existence of a glacial striated pavement supplying flow directional marks in the Maradonas sub-basin. This glacial pavement was found at the Km 46 outcrop (Fig. 1, Milana et al., 1987; Milana and Bercowski, 1987a, 1987b) and was connected to another glacial pavement found in the next thrust slice (Km 51 outcrop, Milana and Bercowski, 1993). This glacial erosive complex includes areas with abrasion zones over the subcrop, as it is usual on protruding parts of the valley flow, such as *roches moutonées*, which produce rock flour and large intact boulders by plucking (or quarrying) (Fig. 2). Subglacial striations and grooves occur together with directional nailhead and crescentic marks on the top surface of the Devonian Punta Negra Formation, indicating glacial flow to the WNW. These glacial flow features described from three different thrust slices contradict, again, the Protoprecordillera model that requires eastwards ice flow.

On the other hand, all evidence found points to a trunk glacial valley in which ice flowed westwards, as recorded in four different thrust slices: three in Central Precordillera, and Km 114 in the Western Precordillera. There is no evidence in the Maradonas sub-basin supporting the Protoprecordillera model of Amos and Rolleri (1965).

2.4. The Protoprecordillera hypothesis today

In spite of a significant amount of published evidence indicating this palaeomountain did not exist during the Carboniferous, or that at least, it did not affect the depositional history of Carboniferous basins, most authors continue to include this particular positive element. Thus, the Protoprecordillera potentially has the responsibility to constitute: (a) a glacier emitting centre, and (b) an active element defining the palaeoclimate history of this continental margin as its indirect climatic effects are called to explain the evolution of depositional sequences located more than 300 km towards the continental interior (cf. Moxness et al., 2018; Pauls et al., 2019). Some authors suggested potential equilibrium line altitude (ELA) fluctuations over the Protoprecordillera slopes, to explain the evolution of glacial and interglacial episodes in Western Gondwana (cf. Limarino et al., 2014a), without considering the type of strata deposited atop the hypothetical palaeomountain range. In some cases, it has been suggested Zonda and Tontal may form a continuous positive element (cf. Henry et al., 2008), eliminating the existence of the Maradonas sub-basin.

As indicated above, many of these palaeographic reconstructions do not consider the depositional setting that is correlated. It is possible to measure a ~1 km thick succession within the Eastern Precordillera palaeovalleys (Kneller et al., 2004; Dykstra et al., 2006); however, they do not determine any depositional basin. The same can be extracted from gloriorelated deposits in the Central Precordillera: they are found exclusively within the only two recognised carved palaeovalleys, the Río San Juan (Milana et al., 1987; Milana, 1988) and the Talacasto (Aquino et al., 2014). Therefore, published evidence suggests:

1) The Talacasto palaeovalley contributed ice to the Río San Juan valley, given the palaeocurrents measured at Talacasto (Aquino et al., 2014) and the stronger marine signal in the second: Three different marine levels with diverse brachiopods and pelecipods vs. the absence of marine fossils in Talacasto.
2) None of the glacio-related Eastern and Central Precordillera deposits formed near the Serphurkovian/Bashkirian boundary, were associated with a depositional basin, but they are fills of carved glacial valleys, given the glacial pavements found over several subcrops (cf. Milana and Bercowski, 1993, Aquino et al., 2014).
3) The two previous points suggest no-basin forming processes before the Bashkirian at Eastern and Central Precordillera. Therefore, it is unlikely that a mountain-forming process took place at the same spatial-temporal frame.
4) The glacial flow, also documented graphically here, within the Río San Juan trunk palaeovalley (from WNE to WSW), matches perfectly the Lower Del Salto Formation palaeovalley position and palaeocurrents. This palaeovalley is the only one carved into Carboniferous deposits indicating it was the only active basin of the region, whose dynamics have been discussed by Milana and Di Pasquo (2019).
5) The analysis of glacial deposits and sequences of the Río San Juan palaeovalley (Km 46, 51 and 63 outcrops, Fig. 1), allowed an interpretation related to an outlet glacier draining an ice sheet located to the east (Milana and Bercowski, 1990, 1993), using the models of Eyles et al. (1985). This conclusion was published more than 3 decades ago, but is not referred to in any subsequent contribution.

Based on all of these reasons, we present new data from the Tontal section to eradicate the Protoprecordillera model from the regional palaeographic scheme, and establish a new frame in which all the

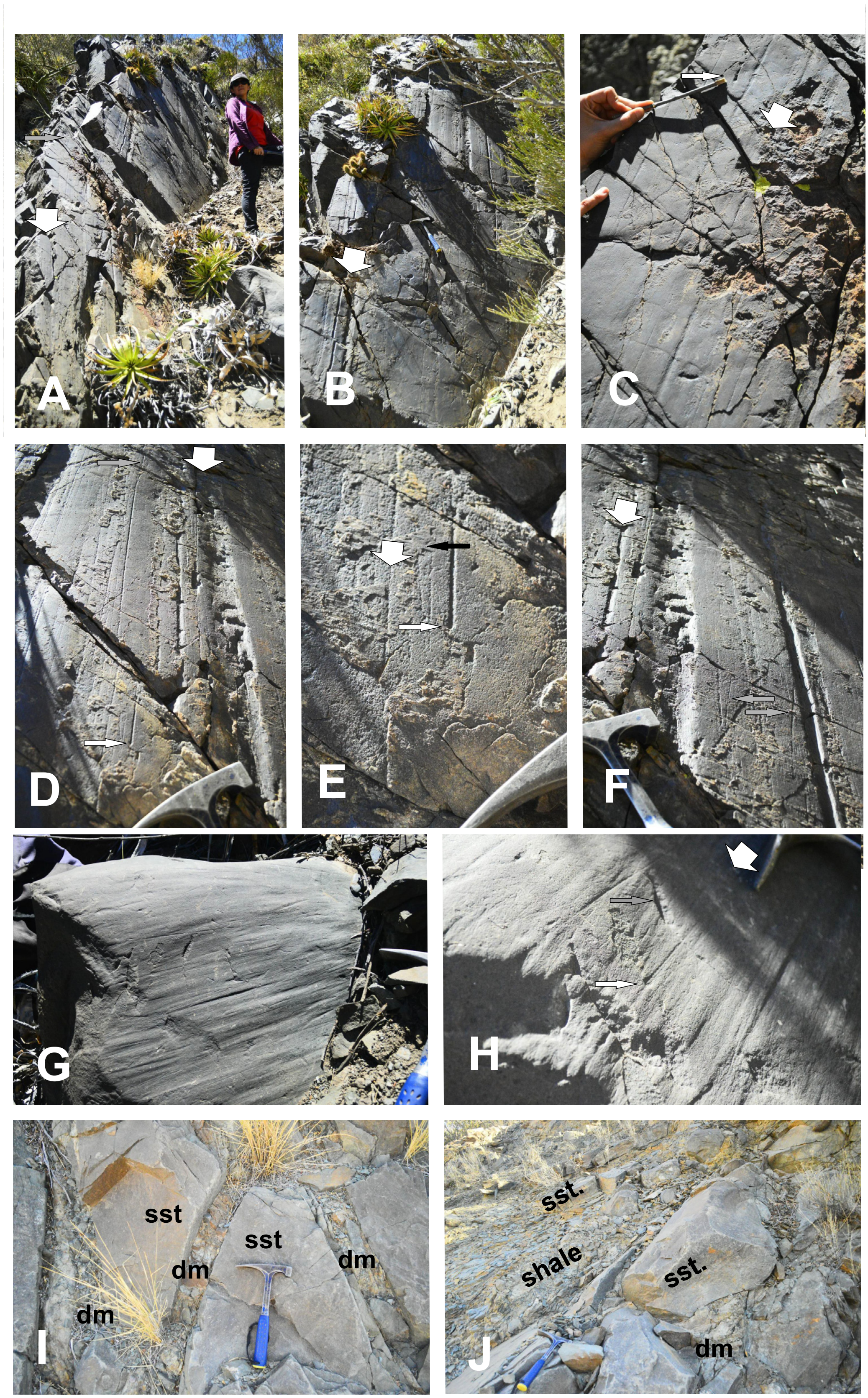

Fig. 2. Evidence of glacial flow to the east. A–F) Different views of the glacially striated and grooved pavement of Km 51 locality (see Fig. 1). Wide arrows indicate glacial flow sense, narrow white arrows point to nail heads, which are directional glacial marks, grey arrows point curved striations and black arrow on E, slickensides perpendicular to glacial striae. E) Detail of D. G and H are views of a striated boulder few decimetres above the glacial pavement in a diamictite interpreted as lodgement till (Milana and Bercowski, 1987a, 1987b). Note the irregular striae, the nailheads (white arrow) and the crescentic cracks (grey arrow) typical of glacial abrasion effect. I and J, portray a plan and section view of the quarrying surface, where the Devonian beds of sandstones and shales (sst. and shales) are still in position of extraction, surrounded by the basal massive diamictite (dm) injected in the process of extraction.

“hard” data matches into an integrative scenario, that will improve the understanding of the western Gondwana margin.

3. Materials and methods

3.1. The Tontal section

The Tontal section can only be reached by foot or horse either from the north or west. The north access involves a 6-hour walk from El Salto, a small creek-step that restricts 4WD advance. El Salto Creek, tributary of the Río San Juan, is where most of the Km 114 section crops out (cf. Milana and Di Pasquo, 2019). From the west, a rough 4WD trail is used to reach the old Rincón Blanco exploration camp, from which the Tontal section can be reached after a ~5-hour walk.

During field-work we collected biostratigraphic, sedimentological, and stratigraphic data, focusing on defining the 3D spatial distributions of lithosomes within the Carboniferous deposits in order to reconstruct palaeoenvironmental interpretations of these alleged palaeofjord deposits (Lech and Milana, 2006). We also focused on improving stratigraphic correlations, using the recently defined units of Km 114 (Milana and Di Pasquo, 2019) and applying sequence stratigraphy concepts. We resampled the entire section for palynological remains, in two campaigns: the first one as a strategic sampling and the second for a detailed sampling of prospective intervals.

3.2. Previous palaeontological work and methods

Several authors investigated the biostratigraphy of the Tontal section. Lech et al. (1998) and Lech and Milana (2006) studied marine invertebrates collected from five fossiliferous levels from the lower and upper Carboniferous El Planchón and Del Salto formations at this section. Barredo and Ottone (2003) obtained palynomorphs only from the Del Salto Formation, confirming its Upper Carboniferous age. Besides our palynological sampling we recovered plant fragments from carbonate silty shales of the upper member of El Planchón, which also yielded palynomorphs (Fig. 3).

Only eight samples proved to be fertile, and these were processed following the standard methodology of maceration with HCl and HF. Organic residues were mounted with jelly glycerine and observed preliminarily to discard the barren samples. The yield from fertile samples was improved by applying new HF for enough time to eliminate most of the remnant quartz. After neutralisation with distilled water, samples were boiled in HCl and sieved with 25 μm mesh and mounted with Trabasil (Noetinger et al., 2017). Due to the very low recovery, poor preservation, and high grade of thermal alteration, a lot of samples needed to be processed. Part of the residues were oxidised using sanitary water in a Petri-box, checking under a microstereoscope Leica DM500 in order to stop the process when spores changed to a brown colour. At that point, residues were neutralised with distilled water in a centrifuge, sieved, and mounted (see Traverse, 2007). The palynological analysis was performed using Nikon E200 and Leica DM500 (with a fluorescence device) transmitted light microscopes, each one bearing a video camera Amuscope 14 Mpx for illustrations. Plant fossils were studied and illustrated with the stereoscope and video camera Leica EC3 (3 Mpx), and with a cell-phone camera with 13 Mpx.

Plants and palynologic slides and residues are catalogued with specific acronyms and numbers corresponding to the collections housed at the Laboratory of Palynostratigraphy and Paleobotany of the Centro de Investigaciones Científicas y Tecnológicas de Transferencia a la Producción (CICYTTP-CONICET-ER-UADER) at Diamante, Entre Ríos (Di Pasquo and Silvestri, 2014). Sedimentary organic matter (palynomacerals) of the kerogen here identified is in agreement with Tyson (1995) as follows: phytoclasts (tracheids, cuticles), opaques (non-structured brown and black particles), amorphous organic matter (AOM), and palynomorphs. Quantitative and geo-stratigraphic distribution of species (with their authorities) and illustration of selected species are addressed below.

4. Stratigraphy and palaeontology

The Carboniferous succession of the Tontal Range lies unconformably above the Ordovician Portezuelo del Tontal Formation, across an irregular erosive unconformity surface. Both the Ordovician and the Carboniferous have a strong and quite similar diagenetic imprint, and there is not a perceived angularity between these two sedimentary units, suggesting a lack of strong tectonic activity between these units' deposition (i.e., in the middle Palaeozoic). The stratigraphic units exposed are Del Ratón, El Planchón, Churupatí and Del Salto formations (Figs. 1 and 3). Specific information for each of these units is supplied in Table 1. We suggest the use of the stratigraphic name Ciénaga Larga Del Tontal Formation (Barredo and Ottone, 2003) or other previous names should be abandoned.

4.1. Del Ratón Formation

The Carboniferous Tontal succession initiated with an irregular basal conglomerate. This conglomerate is absent in some parts and reaches a maximum thickness of 50 m. It fills up irregularities of the unconformity surface on the Ordovician Portezuelo del Tontal Formation, which was proposed to be a glacially excavated trough (Lech and Milana, 2006). In this work we followed this unconformity laterally. We did not find compelling evidence that this surface represents a glacially carved palaeovalley (Table 1). Del Raton conglomerates change irregularly its thickness laterally, suggesting the base was irregular, as with a hummocky design, but no evidence of a deepened trough was found when this basal surface was inspected laterally.

4.2. El Planchón Formation

Similar to its stratotype, described by Milana and Di Pasquo (2019), this formation consists of: (a) a basal shale unit that rests on a marine flooding surface, (b) a thin glaciomarine interval deposited shortly after flooding, (c) a dark shale unit, and (d) a coarsening-up succession with resedimented conglomerates near the top. Specific data on each member is provided in Table 1. The presence of marine invertebrate fossils indicates a marine environment, and although the El Planchón Formation at its stratotype lacks marine invertebrate fossils this correlation suggests the El Planchón Fm at Km 114 is marine. There is a significant difference in thickness and lithofacies between the two sites, indicating rapid lateral changes of palaeoenvironments over short distances (Table 1), which is very common in geographically restricted strike-slip basins.

4.2.1. Fossil content, age and correlations

The upper member yielded the marine brachiopods *Productella* sp., *Lissochonetes* sp. (Lech et al., 1998) and the molluscs *Nuculopsis*? sp. and *Peruvispira* aff. ‘*P*’. *sueroi* Sabattini and Noirat (Lech and Milana, 2006). We sampled at several levels in the upper member shales, but only one sample yielded identifiable palynomorphs (31°26′50.68″ S, 69°14′20.83″ W; CICYTTP-Pl 2293; Table 2) in the first campaign. Resampling provided two more fertile samples (M3/4 31°26′51.28″ S, 69°14′21.53″ W, M4 31°26′51.30″ S, 69°14′22.49″ W) and another fertile sample bore identifiable plant fragments (31°27′3.64″ S, 69°14′ 21.11″ W) and palynomorphs (CICYTTP-2494).

4.2.1.1. Plant assemblage. The assemblage is composed of leaves and stems, and one cupule-like specimen. These are mostly preserved as moulds, although a few are compressions (Fig. 6). The leaf specimens are assigned to *Nothorhacopteris kellaybellenensis* Azcuy and Suárez-Soruco emend. by Azcuy et al. (2011) due to their main morphological characters of cuneiform shape and size, with distinct short petiole and distal margin lobulate. One specimen (Fig. 6C) is connected to the stem and possibly a second (Fig. 6E). There are dispersed stems finely striated (Fig. 6F) of different sizes preserved as moulds and compressions as well. Moreover, the internal morphology of venation is visible in the specimens illustrated (Fig. 6) and in a fourth one as well, and it agrees with the description and illustrations provided by Azcuy et al. (2011) and Carrizo and Azcuy (2015) based on material from the upper Visean of northern Bolivia and Peru. The plant assemblage illustrated by Balseiro et al. (2009), recovered from the Lomas de los Piojos Formation in Precordillera, is the only one up to now that contains pinnules assigned to this species. A single compression of an isolated cupule-like (Fig. 6H–I) is similar to *Austrocalyx jejenensis* Vega and Archangelsky (1996), found in connection with *Nothorhacopteris argentinica* branches in the Jejenes Formation at La Rinconada in San Juan. Both have two main erect to sub-erect lobes fused at their base (like a petiole) and a fibrous internal pattern. Our specimen differs in having both lobes similar and symmetrical bearing a fibrous distal flabelliform shape. Hence, these differences allowed us to assign the specimen to the genus.

4.2.1.2. Palynology. One palynoassemblage is exclusively composed of spore species with high thermal alteration index c. 3+ and 4− (dark brown to black after TAI scale in Utting and Wielens, 1992). They are represented by c. 60 % of lycophyte (*Cristatisporites*, *Vallatisporites*, *Cordylosporites*, *Spinozonotriletes*, *Spelaeotriletes*) and pteridophyte (e.g., *Brochotriletes Convolutispora*, *Dibolisporites*, *Leiotriletes*, *Punctatisporites*) species (Table 2). Cuticles and tracheids are abundant and there are a subordinate number of brown and black particles in all the samples (between 80 and 90 %) with irregular shapes, variable sizes with the same TAI. Slightly less mature (3/3+) palynomorphs were recovered from the same beds that carried the palaeoflora (Fig. 3), in which there are also fine particles and AOM (not fluorescent).

The relative frequency and order of appearance of species are variable (Table 2) and several are present in all or almost all samples (e.g., *Bascaudaspora submarginata*, *Bascaudaspora* sp. Pérez Loinaze, *Brochotriletes diversifoveatus*, *Cristatisporites peruvianus*, *Cristatisporites stellatus*, *Convolutispora ampla*, *Dibolisporites insolitus*, *Dibolisporites microspicatus*, *Foveosporites pellucidus*, *Microreticulatisporites microreticulatus*, and probably a new species of *Cordylosporites*). Less abundant species, restricted to one or two samples (*Densosporites intermedius*, *Densosporites annulatus*, *Spelaeotriletes arenaceous*, *Crassispora scrupulosa*, *Ahrensisporites cristatus*), do not occur in the Del Salto Formation (see below). The exceptions are the species *Cristatisporites stellatus*, *C. inconstans*, *C. menendezii* and *Vallatisporites arcuatus*, which are generally abundant in both Mississippian and Pennsylvanian assemblages herein and in western Argentina (Table 2).

The pollen stratigraphic distribution reveals two groups with biostratigraphic importance for comparisons and correlations (Table 2). One group corresponds to species with their last occurrences in the late Visean (e.g., *Bascaudaspora submarginata*, *Bascaudaspora* sp. Pérez Loinaze, *Crassispora scrupulosa*, *Cristatisporites peruvianus*, *Dibolisporites insolitus*, *Dibolisporites microspicatus*, *Dibolisporites malimanensis*, *Pustulatisporites malimanensis*). Specially, it is defined by the first appearance of *Brochotriletes diversifoveatus*, due to its shorter range from mid Visean to early Serpukhovian. The second group includes *Ahrensisporites cristatus*, *Apiculatisporis variornatus*, *Convolutispora sculptilis*, *Cristatisporites scabiosus*, *Cristatisporites inordinatus Raistrickia accinta* and *Spelaeotriletes arenaceous*, and this group appears in the late Visean. *Microreticulatisporites microreticulatus* first record appears in the Serpukhovian. Palynoassemblages of El Planchon are illustrated in Figs. 7 and 8.

4.2.1.3. Age and correlation. A late Visean to lower Serpukhovian age is assigned for these El Planchón strata, similar to the Km 114 section (Milana and Di Pasquo, 2019). The assemblage in the upper member of El Planchón at Tontal is assigned to the MQ Zone (Table 2) based on several common species, confirming the biostratigraphic scheme of Milana and Di Pasquo (2019). However, there is an absence of diagnostic species, such as *Reticulatisporites magnidictyus* Playford and Helby and *Verrucosisporites quassigobbetti* Jones and Truswell, at both Tontal and Km 114. The recovery of *Nothorhacopteris kellaybelenensis* and palynomorphs in the same sample represents the oldest record of co-occurrence of these fossils in Argentina. The *Frenguellia eximia*–*Nothorhacopteris kellaybelenensis*–*Cordaicarpus cesarii* flora of Balseiro et al. (2009), known from a single locality Lomas de los Piojos, was re-assigned to the late Bashkirian B Subzone of the DM Zone (Table 2), based on the recovery of monosaccate pollen grains and the first appearance of striate bisaccate pollen *Illinites unicus* (Di Pasquo and Milana, 2021). Hence, this flora was also attributed to the late Serpukhovian–Moscovian *Notorhacopteris*–*Botrychiopsis*–*Ginkgophyllum* (NBG) Zone, which is associated with the DM Palynozone (Table 2). The lack of platyspermic seeds, leaves, and pollen grains of cordaitean–coniferalean affinity in our interval and the main diagnostic species of the MQ Zone (mentioned below), support a lower Serpukhovian age for the El Planchón Formation at this section, in agreement with Milana and Di Pasquo (2019). There are currently few Mid-Mississippian deposits in central western Argentina that have yielded palaeontologic data, especially those with more than one group of fossils, as we present here (Figs. 3 and 6). Hence, for a better understanding of the floral differences between our assemblages and others, more studies are required on beds of expected late Visean and Serpukhovian age. Such studies would help solving the debate concerning the first appearance of those gymnosperm groups (see Valdez et al., 2017, 2020 and references therein).

4.3. Churupatí Formation

This unit shows variable thickness due to its erosive base with a documented relief of 20–30 m, and its top is cut by a slumping surface, which is well recorded at the Del Salto Fm (Fig. 9B). It shows a lower conglomeratic member and an upper sandy member. The upper member disappears to the north as a result of its cut-off by the lower Del Salto Fm slide scar. Interesting features of the lower member are the well-preserved clinoforms suggesting small high-energy Gilbert deltas prograding into a shallow sea (see Fig. 9A and Table 1, for a description and interpretation). No fossils have been recovered from this unit, but due to palaeontological data in underlying and overlying units, lithological characteristics, and sequence stratigraphic evolution, we find no doubts to correlate this unit to the Churupatí Formation, as redefined by Milana and Di Pasquo (2019).

4.4. Del Salto Formation

This unit may reach up to 500 m thick in Tontal, but its true thickness is undefined, due to partial removal of the base and top. The base appears to be a slump detachment surface (as indicated above); an interpretation extracted from the fact the base of the Del Salto Fm shows intense folding, whilst the top of the underlying Churupatí Formation (Fig. 9) is not. Additionally, the reddish upper member of the Churupatí is progressively cut down by that surface, until it disappears over the northern part of the outcrop. Thus, we suggest the lower 200 m of the Del Salto Formation slid northwards and piled up as a wedge of deformed strata (Fig. 9). It is not within the scope here to depict the specific process of this potential Mass Transport Deposit (MTD), but to order the local stratigraphy with the objective of understanding the regional evolution of the area during the Carboniferous.

Reconstructing the true depositional history of the Churupatí and Del Salto formations will require a careful lateral survey of this contact. In the meantime, we interpret that there is an important sedimentary discontinuity along this formational contact, that, in addition to the slide scar, a sharp lithofacies change is observed as subaerial facies of the upper Churupatí are followed by marine (bivalve-bearing) deposits of the lower Del Salto Formation, suggesting a transgressive event in between. A comparable discontinuity was mentioned c. 17 km north

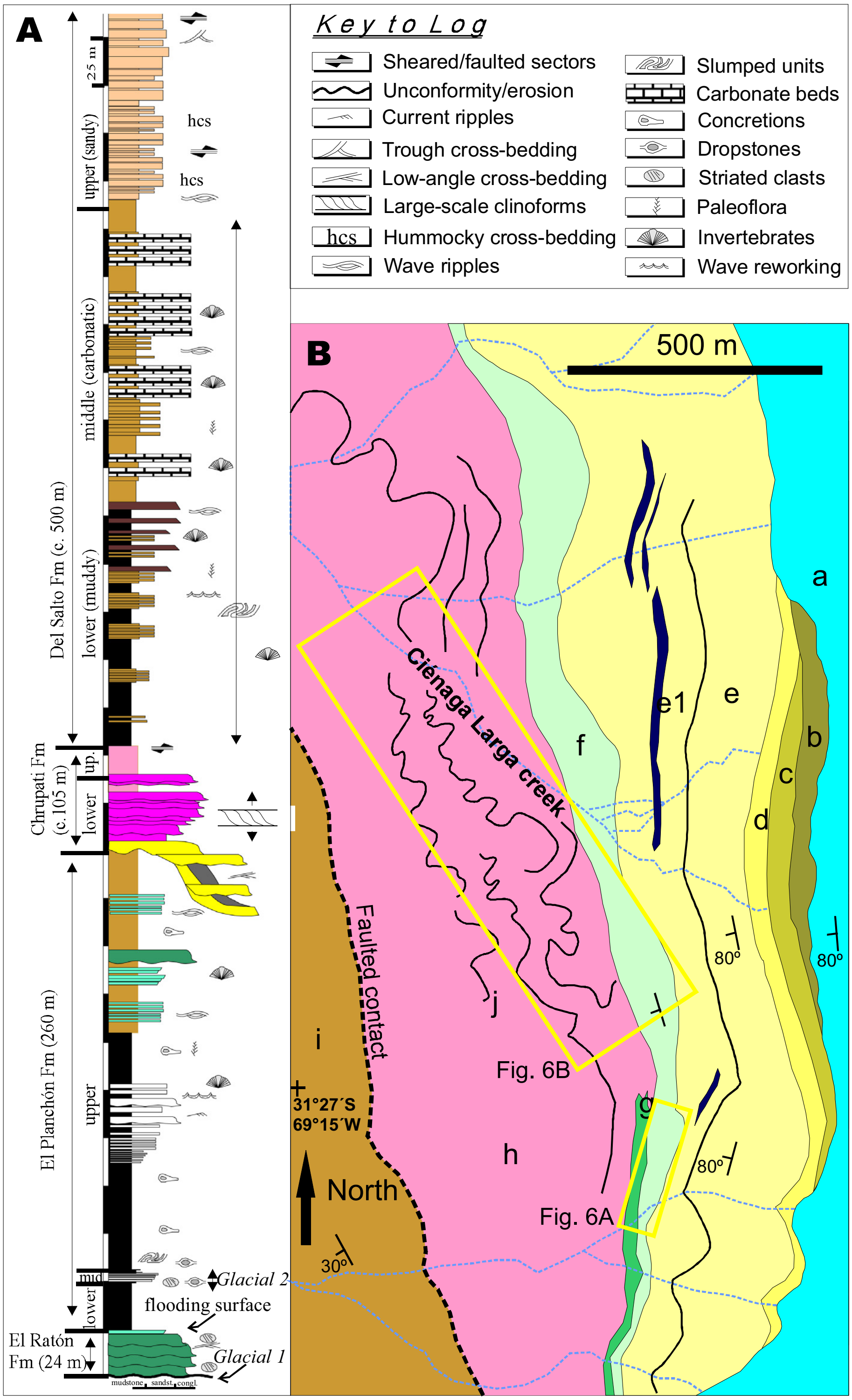

Fig. 3. A) Sedimentary log of the Carboniferous section along the Ciénaga Larga Creek, with indication of deformed areas. Not all Del Salto Formation was measured. B) Detailed geologic map of the study area with indication of position of the two photomosaics of Fig. 8: a) Lower Palaeozoic rocks, b) Del Ratón Fm, c) Lower El Planchón Fm., d) Middle El Planchón Fm., e) Upper El Planchón Fm, e1) Gravelly bodies within (e), f) Lower Churupatí Fm., g) Upper Churupatí Fm., h) Del Salto Fm., i) Rincón Blanco Group (Triassic), j) tracing of deformed beds on satellite image.

within this basin by Milana and Di Pasquo (2019), who interpreted this formational change was associated with the local LPIA glacial maximum (cf. Valdez et al., 2020), as shales from the base of El Salto Fm, are well correlated to the postglacial Bashkirian cycle (and transgression event). To the south, a minor unconformity was also described, suggesting a local tectonic process interpreted as a transient shift from transtensional to transpressional tectonics. Thus, the contact between Churupatí and Del Salto formations probably shows the combined effects of climatic and tectonic processes. The top of the Del Salto Formation is cut by the main trace of the Del Tigre Fault, which places the Carboniferous outcrop in contact with both the Triassic beds of the Rincón Blanco Group, and lower Palaeozoic units (generally the Ordovician Portezuelo del Tontal Formation). Deformation near this fault is very intense.

Table 1
Description and interpretation of Carboniferous units cropping out at Tontal section.

Unit	Description	Interpretation
Del Raton Fm	This basal coarse-grained unit consists of a poorly sorted, clast-supported, poorly bedded conglomerate. Clasts are moderately round with maximum size reaching 40 cm, and showing a composition of sedimentary rocks (sandstones and mudstones) and basaltic fragments. In a few cases, very faint striations were identified suggesting an inherited glacial history. There are not many sedimentary structures visible, or evidence of the original depositional process, due to the strong diagenetic overprint, but a fluvio/alluvial filling of irregularities of the subcrop interpreted. These irregularities do not look to follow an organised scheme (as a palaeovalley) although the conglomerates tend to thicken to the north, until the end of the outcrop. The thickness of this unit is 3–4 m in the southern area and reaches up to 24 m in the northern part of the revised outcrop. It is assigned to Del Ratón Formation based on stratigraphical relationships and depositional similitude.	Similar to its type section, Del Ratón Formation is fluvio–alluvial (although more mature) and shows a minor glacial inheritance as indicated by scarce faintly striated clasts (cf. Colombo et al., 2014; Milana and di Pasquo, 2019).
El Plan-chón Fm. Lower Member	It is composed of silty shales that drape over the basal conglomerates making a sharp marine flooding surface. In many cases, these lower member shales are not present due to the effect of localised erosion on the following interval (proglacial) causing amalgamation of the middle member with the Del Ratón conglomerates. These shales were barren of palynomorphs but indicate that an important marine flooding predated the following glacial interval as observed at Km 114 section. The maximum thickness of this unit is 35 m. The depositional environment is marine due to its continuity with the upper shale member, but there are no diagnostic elements to decide about the sedimentation conditions, as only suspensive sedimentation fallout occurred in this interval.	Lower member starts deposition after an important marine flooding of the basin that restricted the potential entry of other than suspended sediments. After this transgression, a highstand condition is sustained that fosters a slow progradation of a siliciclastic wedge. The entire unit is deposited in marine conditions, at moderate depths in spite of the turbiditic flows recorded by facies c2 as they show wave-action on the bed tops. Occasional removal of coarse-grained deposits, probably located at coastal or even subaerial places is indicated by the redeposited ribbon-like conglomerates (facies c3). The glaciomarine section of middle member seems to be deposited entirely by suspension and rafting, with a minor amount of resedimented processes generating the deformed and massive beds of facies c4. The glaciomarine facies c1, c2 and c3 suggest that glaciers reached a position quite close to the location due to the thick couplets associated with dropstones with clear glacial striae. However, this advance seems it was short-lived given the limited thickness of the glacially related package. When compared to the homologous glacial level at Km 114 (much finer grained), it becomes evident the glaciers advanced towards north. The glacial advance direction is similar to that observed in Hoyada Verde Formation (López Gamundí, 1991; Milana and Banchig, 1997), although we remark this glacial episode would be the previous one to the Hoyada Verde glacial episode, according to the biostratigraphic content discussed below.
El Plan-chón Fm. Middle Member	It was indicated in the first publications the presence of glacial elements near the base of this sequence (Banchig et al., 1997; Lech et al., 1998; Lech and Milana, 2006), a fact that corroborated in this work. The glaciomarine suite here is relatively thin, and amounts for a maximum thickness of 4 m, but quite varied. Facies are described as follows: b1) Shales with dropstones. These are homogeneous shales with dispersed clasts between 2–3 cm and 35 cm, without any organisation or bedding type, except at the normal lamination of shales (Fig. 4). b2) Heterolithes of alternating shales (80–90 %) and granule-rich layers with larger dropstones (Figs. 4F, 5A, and D). Shales are silty, homogeneous to laminated, and granule-rich intervals are irregular containing granules up to 5 mm in a disorganised packing. Dropstones are 2–3 cm to 35 cm, usually faceted and may show glacially striated faces, with symmetric and asymmetric marks as nailheads (Fig. 4E). b3) Coarse-grained heterolithes with dropstones. This unit bears shales similar to facies b2 but it is rhythmically alternating with thicker coarse-grained intervals accounting for c. 80 % of the couplet. The coarser interval is made of massive fine-grained conglomerates with a muddy matrix and faint bedding distinguishable at the boundary of each element of the couplet. Muds separating them are massive to laminate. Couplets are c. 7–12 cm thick and bedding disrupted by occasional large dropstones of up to 50 cm large. Due to the poor outcrop quality and intense diagenesis, this unit may look sometimes as a conglomerate, and only clean faces along joints allow the observation of rhythmical internal structure. b4) Any of the above facies description could be contorted and some beds could turn to be completely massive composing facies b4.	
El Plan-chón Fm. Upper Member	This interval is the thickest and attains up to 220 m thick. It is dominantly composed of silty shales with random levels of carbonate-cemented shales composing its 3 % of facies c1. In some of these carbonatic shales (Fig. 3), plant fragments were observed and palynomorphs were later recovered in lab. Marine invertebrates were documented in two different levels of this unit (cf. Lech and Milana, 2006). Besides the monotonous shales and carbonatic levels of facies c1, two other distinct facies groups are present: c2) tabular to sheet-like fine sandstones with ripples: A particular unit south of the Cienaga Larga creek (Fig. 3), shows tabular, 30–50 cm thick, massive fine sandstones, alternating with thin 2–7 cm thick fine sandstones (Fig. 5B and C). In all cases it was possible to see ripple rework at the bed top, both symmetric and asymmetric. Plan view of ripple crests showed interference patterns. c3) Ribbon-like conglomerates: these are massive, clast-supported medium to coarse conglomerates with maximum particle size (MPS) of 15 cm. We surveyed two conglomerate bodies (we surveyed 2 bodies) only at the upper third of this member, being up to 3–4 m thick and with limited lateral extent. No diagnostic sedimentary structures were found due to the intense diagenesis, making them look massive.	

(continued on next page)

Table 1 (*continued*)

Unit	Description	Interpretation
Churu-patí Fm. Lower Member	This unit is 70 m thick and mainly composed by conglomerates with a MPS of c. 20 cm. Conglomerates stand out in the outcrop helping to mark the difference between the lower and upper Carboniferous sections. The base of this unit is clearly erosive, and to the southern part of the outcrop, it erodes a large part of the underlying El Planchón Formation. Between conglomerates, massive dark greenish silty–sandy mudstones occur. The contact between conglomerates and mudstones is sharp, but not erosional, and it is remarkable the scarcity of sand in this unit. The irregular and erosive base of the unit hosts massive conglomerates as those observed near the top of El Planchón Formation, but the following conglomerates are different. The middle part of this member is the most resistant and composed almost purely of conglomerates that form a single package showing internal sigmoidal stratification. This package is c. 20 m thick, and clinoforms are very planar, with steeply inclined surfaces, reaching up to 25° of inclination, although tectonism may partly distort this inclination. Conglomerate packages within the main clinoform end downslope sharply as wedges in a muddy basal unit. In some cases, clinoform bed-sets are separated by muddy breaks that cross 80 % of the entire clinoform. The sedimentation over the clinoform is also conglomeratic, in a well-organised horizontal bedding and low-angle cross stratification with shallow cut and fill structures. Sorting and roundness are intermediate, suggesting similar maturity of the basal conglomerates assigned to Del Ratón Formation.	There is no doubt this unit was deposited initially at shallow depths due to the presence of Gilbert-like deltas, defined by very planar and highly inclined foresets. The thickness of the clinoform of c. 20 m indicates the water depth that is compatible with the depth suggested for the upper interval of El Planchón wave reworked sandstone tops. The presence of mud breaks occasionally digitated up to 80 % into the clinoform also suggests an episodic nature of the bed-load dominated discharge. The scarcity of sand suggests an immature coastline probably associated with a submerged hilly terrain. The upper member suggests the development of a typical braid-plain depositional environment developed under subaerial conditions.
Churu-patí Fm. Upper Member	This shows a maximum thickness of 35 m and was not surveyed previously at the Ciénaga Larga creek as it does not crop out clearly there. It overlies in a rapid transition to the lower member. It is composed of redbeds and occurs only at the southern parts of the outcrop. It is not clearly present in the northern area due to the fact it might be involved in a contorted slump (Fig. 9B), in which there is no clear indication of the original stratigraphical order. The remaining parts of this member suggest a time of subaerial exposure and developments of a muddy–sandy floodplain with minor fluvial terminal systems as sand bodies are thin and restricted. More field- work is required to solve the contact between the top of this unit and the overlying Del Salto Formation in order to understand better the geological characteristics of this surface that would help to understand the Mississippian/Pennsylvanian local boundary.	
Del Salto Fm	There is an upwards tendency within Del Salto Formation to become more carbonatic until its middle reach, and then turning back to dominantly siliciclastic. Four main facies groups were defined here for the Del Salto Formation; D1) massive mudstones and rippled sands: these facies are mainly observed in the lower part of the unit, and composed of centimetric to decimetric fine-grained sandstone beds with asymmetric current ripples and symmetrical ripples of varied origin, whilst wave action usually is observed on sandstone tops. Mudstones are grey and yellowish in colour and quite affected by the deformation and thus, no primary stratification is visible. Scarce marine invertebrates were observed. D2) Stromatolitic limestones with shelly beds: composed of quite pure limestones arranged in beds of 50 cm to 2 m that occur mainly at the middle part of this formation. Limestones are light blue, a little darker in fresh cut and flat stromatolites are observed mostly near the top of carbonatic beds. In many cases, an irregular mottling associated with massive beds observed, suggests important bioturbation degree. In some levels, bioclastic accumulations occur defined by shell fragments of brachiopods being frequent large valves of *Septosyringothiris* sp. Limestone beds are separated by siliciclastic intervals of massive mudstones with minor participation of thin structureless sandy beds. D3) Coarsening up sandstone beds with HCS: these are thick bedsets forming coarsening up cycles of 2–4 m thick, from mudstones up to medium sand, usually without sedimentary structures due to the intense deformation This facies tends to dominate the section overlying the dominantly carbonate section. D4) Massive quartz sandstones: this facies is located at the exposed top of this unit and the intense deformation obscures all potential diagnostic sedimentary structures.	The geological evidence (Fig. 9) suggests that most of the lower part of Del Salto Formation is a Mass Transport Complex (MTC or MTD). Hence, there is a gap of information between the subaerial top of Churupatí, and the apparent marine base of Del Salto Formation. All facies groups suggest deposition in different parts of the same environment, which would be a shallow mixed siliciclastic–carbonatic shelf. The upwards tendency suggests an initial process of cutting off the siliciclastic supply to the area that could have been related to a temporal basin starvation. If we compare the Tontal section with the Km 114, no similar carbonate facies occur there, but a significant moment of starvation was observed near the base (black shales, marls and palynofossils with framboidal pyrite require euxinic conditions and low detrital input).

4.4.1. Fossil content and correlations

Several samples were collected for this study from the base to the top of this unit, but only one yielded palynomorphs (from the lower part) (31°26′39.84″ S, 69°14′42.69″ W). Four intervals previously studied from its lower (siliciclastic) and upper part (mixed carbonate–siliciclastic) yielded invertebrate fossils, such as the brachiopods *Cancrinella?* sp., *Septosyringothyris* aff. *S. saltensis* Lech, several undetermined spiriferids (Lech et al., 1998), and the bivalve *Limipecten* sp. (see Lech and Milana, 2006).

The palynoassemblage recovered from above the first layer bearing invertebrate fossils (Fig. 3) is composed of poorly preserved palynomorphs (10 %) with relatively high TAI 3 and 3+ (light to dark

Table 2
Distribution in percentages of the species documented in the Tontal section organised in alphabetic order by major botanical groups. Their biostratigraphic records are based on the following references: 1. Malimán Formation (Amenábar et al., 2006, 2007), 2. Del Ratón Formation (Amenábar and Di Pasquo, 2008), 3. El Planchón Formation (Milana and Di Pasquo, 2019), 4. Churupatí Formation (Milana and Di Pasquo, 2019), 5. (Cortaderas, Pérez Loinaze, 2008), 6. Guandacol (Valdez et al., 2020), and 7. DMa Zone (Césari and Gutierrez, 2001; Limarino et al., 2014a; Milana and Di Pasquo, 2019; Valdez et al., 2020). These references as well as Playford (2019) among others support global ranges. Asterisk marks first record of species in Mississippian of Argentina.

Collection number (CICYTTP-Pl)	2293	2495	2496	2494	2296	Global range	Western Argentina biozones		
Species (44 species in total) sample	MO3	M3–4	M4	PLANTAS	MO7	Gondwana	CV	MQ	DMa
Pteridophyta (20 species)	22 %	22 %	28 %	17 %	18 %		1, 2	3, 4, 5, 6	7
Brochotriletes diversifoveatus Playford & Satterthwait	3 %	2 %	3 %	3 %		Mid Visean–early Serpuk.			
Dibolisporites insolitus Pérez Loinaze	3 %	3 %	3 %	2 %		Late Visean		3, 5	
Dibolisporites microspicatus Playford	1 %	2 %	2 %	1 %		Late Visean	1, 2	3, 4, 5	
**Foveosporites pellucidus* Playford & Helby	4 %	4 %	10 %	2 %		Visean–Bashkirian			X
Convolutispora spp.	4 %	2 %	2 %		1 %			5	X
**Microreticulatisporites microreticulatus* Knox	1 %	2 %	1 %			Serp–Pennsylvanian			
Verrucosisporites spp.	1 %	2 %						5	X
Punctatisporites spp. (*P. pseudofoveosus*, others)	3 %							5	X
Pustulatisporites malimanensis Amenabar et al.	1 %					Early Visean	1	3	
Apiculatisporis variornatus di Pasquo, Azcuy & Souza		2 %	2 %	2 %		Late Vis–Pennsylvanian		5	X
Convolutispora ampla Hoffmeister, Staplin & Malloy		1 %	2 %	2 %		Latest Dev–early Pennsyl		5	
**Raistrickia accinta* Playford & Helby		1 %	1 %	2 %		Mid Visean–Bashkirian			X
Convolutispora sculptilis Felix & Burbridge		2 %				Late Visean–Pennsylvanian		CF	X
**Ahrensisporites cristatus* Playford & Powis			2 %			Mid/late Vis–Moscovian			X
Dibolisporites malimanensis Pérez Loinaze				1 %		Late Visean		5	
Apiculatasporites caperatus Menéndez & Azcuy					1 %	Late Visean–Pennsylvanian			X
Apiculatasporites parviapiculatus Azcuy					3 %	La Visean–Pennsylvanian			X
Foveosporites hortonensis (Playford) Azcuy					6 %	?Tourn.–Moscovian			X
Leiotriletes spp. (*L. tenuis*, others)					3 %				X
Punctatisporites spp.					4 %			5	X
Sphenophyta					1 %				
Calamospora hartungiana Schopf in Schopf, Wilson & Bentall					1 %	La Serp.–Pennsyl/Perm			X
Lycophyta (20 species)	57 %	60 %	48 %	61 %	31 %				
Cristatisporites peruvianus Azcuy & di Pasquo	4 %	5 %	2 %	3 %		?Stru.–late Visean	1	3, 4, 6	
Cristatisporites scabiosus Menéndez	1 %	6 %	1 %	3 %		Late Visean–Pennsylvanian	2	3	X
Cristatisporites spp.	14 %	18 %	8 %	22 %	6 %		2	3, 4, 5, 6	X
Cristatisporites stellatus (Azcuy) Limarino & Gutiérrez	14 %	12 %	11 %	11 %	14 %	Visean–Permian	2	3, 6	X
Cordylosporites asperdictyus (Playford & Helby) Dino & Playford	1 %	1 %	2 %			Visean–Bashkirian		5	X
Cordylosporites sp. (?nov. Sp.)	14 %	4 %	3 %						
Cristatisporites inconstans Archangelsky & Gamerro	2 %	0 %	3 %		1 %	Visean–Permian	2	3	X
**Densosporites intermedius* Butterworth & Williams	1 %	2 %				Tourn–ea Bashk			
Cristatisporites inordinatus (Menéndez & Azcuy) Playford	1 %	2 %				Late Visean–Pennsylvanian		5	X
Bascaudaspora submarginata (Playford) Higgs et al.	3 %	1 %	2 %	2 %		Stru–late Visean	1	5	
Bascaudaspora sp. Pérez Loinaze	3 %	1 %	2 %	2 %		Late Visean		3, 5	
Vallatisporites arcuatus (Marques-Toigo) Archangelsky & Gamerro		4 %		3 %	4 %	Visean–Permian		6	X
Cristatisporites menendezii (Menéndez & Azcuy) Playford emend. Césari		4 %	5 %		4 %	Stru–Visean–Permian		3, 5	X
Densosporites annulatus (Loose) Smith & Butterworth		1 %				Strunian–Pennsylvanian	1	3, 4	
Spelaeotriletes arenaceous Neves & Owens			2 %	6 %		Visean–Pennsylvanian	1		
Vallatisporites ciliaris (Luber) Sullivan			2 %			Tournais–Pennsylvanian		CF	X
Spinozonotriletes hirsutus Azcuy			2 %	2 %		Visean–Pennsylvanian	2	5	X
Crassispora scrupulosa Playford emend. Playford & Satterthwait				4 %		Late Tourn.–late Visean	1	3, 4	
Lundbladispora riobonitensis Marques Toigo & Picarelli					1 %	Late Serp–Permian			X
Pteridophyta/Pteridospermaphyta					8 %				
Cyclogranisporites australis Azcuy					4 %	Late Serp–early Pennsylvanian			X
Cyclogranisporites rinconadensis Césari and Limarino					3 %	Late Serp–early Pennsylvanian			X
Cyclogranisporites spp. (*C. lasius*, others)					1 %			5	X
Spores poorly preserved	21 %	18 %	25 %	22 %	28 %				
Cordaitalean-Coniferalean Monosaccate pollen grains (poorly preserved)					14 %	Late Serp–Pennsylvanian			X
Palynofacies = Phytoclasts/palynomorphs	80 %–20 %	80 %–20 %	85 %–15 %	90 %–10 %	90 %–10 %				
Plants						CICYTTP-Pb			
Nothorhacopteris kellaybellenensis				4		150 to 152			
Indet form (cupulae?)				1		154			
Stems				8		153			

brown). It also yielded phytoclasts (cuticles and tracheids) and abundant brown/black particles. Monosaccate pollen grains (14 %) of Cordaitean–Coniferalean affinity, and trilete spores derived from the Lycophyta (6 species, 31 %), Pteridophyta (6 species, 18 %), one sphenophyte (1 %) and gymnosperms Pteridospermaphyta (3 species, 8 %) were identified. Well-represented species in decreasing order of abundance are *Cristatisporites stellatus*, *Foveosporites hortonensis*, *Cristatisporites menendezii*, *Vallatisporites arcuatus*, *Cyclogranisporites australis* and *Cyclogranisporites rinconadensis* (Table 2 and Fig. 10). These species, together with *Lundbladispora riobonitensis*, documented in the late Serpukhovian–Bashkirian DMa palynozone, are widely registered in western Argentina (Table 2). This age is in agreement with

Barredo and Ottone (2003), who studied the palynological content of a single sample from the top of the unit. It is composed of poorly preserved monosaccate pollen grains of the genera *Plicatipollenites* and *Potonieisporites* (e.g., *Plicatipollenites* cf. *malabarensis* (Potonié and Sah) Foster, *Potonieisporites* cf. *triangulatus* Tiwari), and spores such as *Cristatisporites inconstans* and indeterminate species of *Lundbladispora*, *Horriditriletes*, *Spelaeotriletes* and *Vallatisporites*. Both the marine invertebrate fossils and palynoassemblages indicate an overall transgressive character for the lower and middle Del Salto Formation. There is a strong terrestrial influence both in facies and palynofacies during the Bashkirian of the Del Salto Fm, as described by Milana and Di Pasquo (2019) considering Km 114 (Del Salto Formation stratotype) is only c.17 km north from the Tontal section.

The shaly character in the lower Del Salto Formation could be part of a maximum flooding interval caused by the rapid glacial retreat that occurred during the lower Bashkirian in agreement with other records in Western Precordillera (cf. Valdez et al., 2017, 2020). The black shale unit is widespread and recognised from ancient coastal areas to far into the continental realm, usually within glacially carved palaeovalleys that were then flooded, such as those in Las Lajas (Dykstra et al., 2006), Quebrada Grande (Kneller et al., 2004; Valdez et al., 2017), Malanzán (Enkelmann et al., 2014), and Vichigasta (Valdez et al., 2021). At the Tontal section, however, transgressive facies differ from other sections in that it has: 1) some sandy interbeds and 2) some thinly bedded carbonate-rock intervals (see Table 1, Fig. 9). This could be explained by the fact the Tontal section was located at a more marginal basin position with a lower subsidence rate than at the Km 114 section. Sandy beds would reflect the occasional input of basin-margin systems, whilst the carbonate production would have been fostered during times of low detrital sediment input. Milana and Di Pasquo (2019) described large-scale erosion interpreted as a valley carving at a specific place of the Del Salto Formation base. However, at Tontal, no evidence of glacial activity was detected at the base of the Del Salto Formation. The increase in sandstone content in the upper Del Salto section (facies D4, Table 1), probably represents progradation of a siliciclastic wedge that covered the fine-grained, shelf deposits.

5. Discussion

5.1. Did the Protoprecordillera exist?

The Tontal section crops out at the core of the expected Protoprecordillera range. The dominantly marine environment recorded at Tontal, during the early Serpukhovian to the late Bashkirian, at a minimum precludes, in our view, the existence of the palaeomountain. Therefore, we may explore different options. It was mentioned this section may have been deposited within a deep valley connecting coastal and continental areas. However, the extensive lateral survey of the Tontal section base we undertook for this work indicated that the relief involved in that palaeosurface is in the range of tens of metres and it does not follow a coherent tendency as it would happen in the case of a palaeovalley as was mentioned earlier (Lech et al., 1998). Second, the depositional environments surveyed in more detail for this work, suggest shelf conditions and the few conglomerates present suggest reasonable maturity, which is not congruent with the presence of a mountain near this site. Third, Tontal section stratigraphy is intimately related to the strike-slip basin defined for Km 114, located directly southwards and formed by a north–south trending structure. This precludes the alternative interpretation Tontal marine sediments were deposited along a dissected valley crossing the Protoprecordillera. Present day reconstruction of this glaciated palaeomountain does not even show possible gaps across it but portrays the Precordillera as a continuous and elevated mountain that would not allow any marine incursion to move over or across it (cf. Limarino et al., 2014b). Fourth, all of the closest Late Palaeozoic sections to the Tontal show important marine influence, suggesting most nearby areas capable of preserving sediments, were lying near or below the sea level.

Fifth, the only proven glacial flow evidence immediately to the east, in the Maradonas sub-basin, indicates clear and coherent flow to the WNW, contrary to what is predicted by the Protoprecordillera models. As this element is so important, given the fact some authors interpreted that local glaciers were fed from the Protoprecordillera higher terrain, we supply original photographic documentation of the large quantity of directional marks Carboniferous glaciers left only 25 km eastwards from the Tontal section. Thus, direct observation indicates that many assumptions of the Protoprecordillera model are incorrect, and if proponents of that model wish to persist, a new model needs to be developed that includes all the field evidence.

It is important to mention glacial flow marks were only preserved along the Río San Juan glacial palaeovalley (Central Precordillera), as it matches with the only described glacially carved palaeovalley in coincidence with the position of the expected Protoprecordillera, at the base of the Del Salto Formation in the Km 114 locality (Milana and Di Pasquo, 2019). It is important therefore to mention the importance of the Hoyada Verde locality as it also shows an evident palaeorelief, but flow marks preserved in the well-known boulder striated pavement (López Gamundí, 1991) suggest glaciers locally displaced northwards.

5.2. Sedimentary basins vs. palaeorelief fills

An important source of palaeogeographic confusion might be that some Carboniferous deposits are preserved exclusively within glacial carved valleys. Deposits within palaeovalleys can reach more than 1000 m at some localities but cannot be used to define depositional basins as they are the fill of erosional pockets. They are not related to any basin forming process. Existing palaeogeographic maps do not show these aspects, and therefore, a detailed work identifying areas with accommodation space created by true basin forming processes from that created by random erosional processes should be done before producing any Carboniferous basin distribution map.

A second aspect to consider is the validity of the concept of the "Barreal–Calingasta basin". The definition of the Tigre strike-slip basin (Milana and Di Pasquo, 2019) that now includes the Tontal section suggests that two different tectonostratigraphic elements are mixed in the definition of the Barreal–Calingasta basin. The study of the Tontal and Km 114 localities indicates that Lower Carboniferous sedimentation was only occurring in the strike-slip basin that developed along the Tigre fault. Both northwards and southwards, Lower Carboniferous units are only present in close association with the fault trace, as is the Malimán (cf. Pérez Loinaze, 2008) locality to the north and the Agua del Peñon section even further north (cf. González and y Bossi, 1986). In contrast, westwards from this strike-slip belt (see Fig. 1B), sedimentation started after the mid-Carboniferous boundary, as observed to the east, with a few exceptions, such as the Guandacol Formation section at Co. Bola (Valdez et al., 2015), and Loma de los Piojos Formation at Jachal (Di Pasquo and Milana, 2021). Revision of the stratigraphy at several sections of the Barreal–Calingasta basin (Milana and Banchig, 1997) suggests that deposition during the LPIA glacial and postglacial maximum was enclosed within palaeovalleys, and hence predates the basin stage units. A similar stratigraphic history that is initial glacio-related accumulation only restricted to palaeoreliefs, and later spreading to wider areas as an effect of a basin-forming process, has been documented in Central and Eastern Precordillera, and parts of the Pampean ranges (Fig. 1). These are the San Juan River Valley (Milana and Bercowski, 1987a, 1987b, 1990, 1993); Quebrada Las Lajas valley (Dykstra et al., 2006); Quebrada Grande valley (Kneller et al., 2004); Río Francia locality (Milana and Lopez, 1998); Veladero palaeovalley (Limarino et al., 2014a, 2014b); Malanzán palaeovalley, (Enkelmann et al., 2014); Talacasto palaeovalley (Aquino et al., 2014); Los Piojos palaeovalley (Alonso-Muruaga et al., 2018); and Vichigasta palaeovalley (Valdez et al., 2021).

The Hoyada Verde–El Paso depositional complex case is portrayed here due to the importance of separating it from the Del Tigre strike-slip basin. The revision and correlation of sedimentary logs between the Hoyada Verde and El Paso anticlines show a significant thickening to the north suggesting the existence of a highland to the south and a potential basin to the north (Fig. 11). Taking in consideration all geologic evidence presented herein, we suggest a new palaeogeographic scheme (Fig. 12; valid only for this latitude), as the only Mississipian basinal area formed in the Precordillera is that of the Del Tigre strike-slip basin. The Central and westernmost Western Precordillera became depositional basins during or soon after the Bashkirian postglacial main flooding. The remaining outcrops seem to have been the fill of erosional features and would not qualify as depositional basins. Thus, the Paganzo basin-forming processes in the Precordillera at this latitude only started after the mid-Carboniferous glaciation, which was responsible for carving, deepening, and partial filling of these large glacial valleys. This interpretation fits with the fact most transgressive postglacial shale deposits drape glacial and proglacial units within these valleys and share the same DMa palynological signature, in spite of age problems generated by the less exact marine invertebrate biozones.

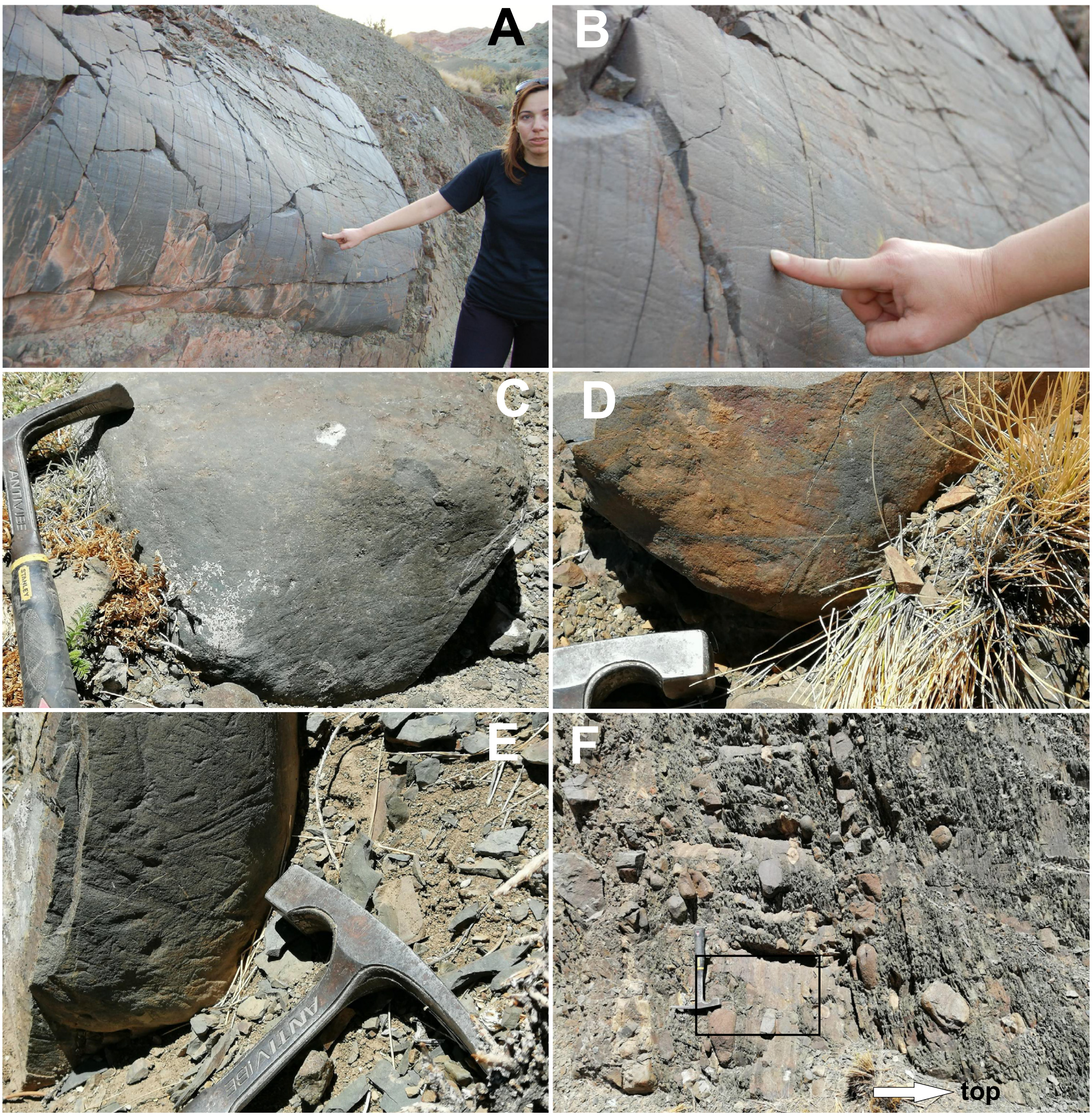

Fig. 4. Evidence of glacial flow to the west and locally. A, B) Largest striated boulder (c. 3 m long) composing the striated boulder pavement of Hoyada Verde Fm, which correlates with the glacial event that at Tontal is absent as it occurs between Churupatí and Del Salto Fm (cf. Milana and Di Pasquo, 2019). Note oblique nail head pointed in B. C) Faint striations on clasts at Del Ratón basal unit. D, E) Striations on clasts of middle El Planchon Fm. Note the striated plane of clast on E is faulted, displaced and re-cemented. F) Development of Glacial 2 in middle El Planchón made entirely of rafting suspended deposition. Box indicates rhythmite detail shown in Fig. 5D. Note the fast transition of coarse-grained rhythmites to dominantly shales with dropstones, suggesting Glacial 2 was a short event locally.

This model explains how post- and non-glacial Tupe and Patquía formations bearing microfloras of DM b–c signature (Table 2), and its equivalent stratigraphic units, spread out over previously positive areas (interfluves), and buried the deep glacial palaeorelief generated during the lower and mid-Carboniferous boundary intervals. Therefore, we propose here to separate those basins aligned along the Del Tigre

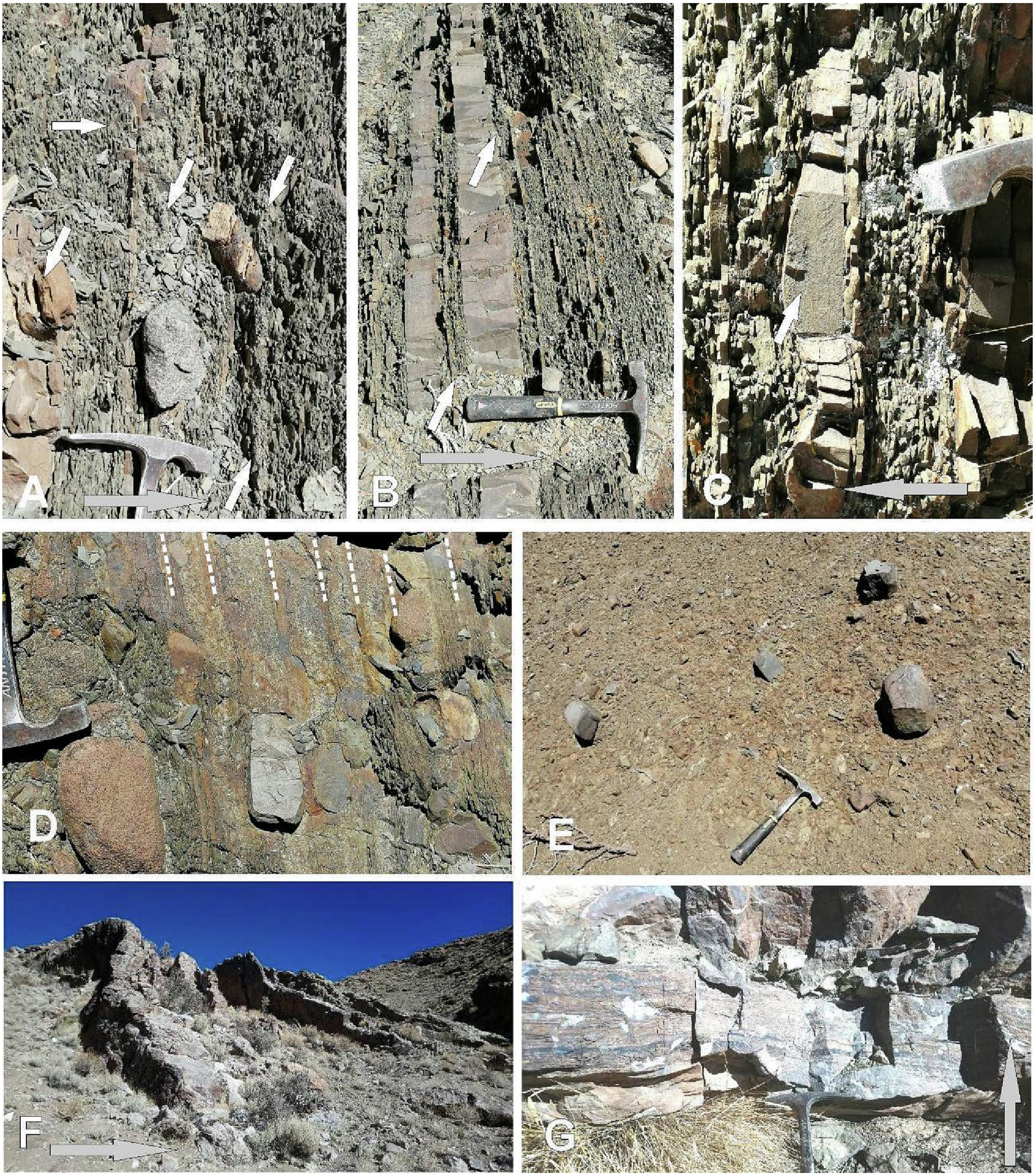

Fig. 5. Photos of more outstanding facies of the Tontal lower section. Grey arrow indicates bedding top. A) Facies B2 of middle El Planchon Fm. Granule rich levels indicated by white arrows. Note the limestone dropstone, aligned with the granule-rich bed. B) Intermediate and distal turbidites with wave top reworking (arrows) of upper El Planchón member. C) Detail of one thin bed showing wave reworking cuts internal lamination of bed (arrow). D) Detail of coarse-grained rhythmites of middle El Planchón member portrayed in Fig. 4F. Dashed line marks the shale part of the couplet. E) Lower Churupatí conglomerate showing the poor textural maturity of clasts and bad sorting, suggesting a local derivation of clasts. F) View of the limestone-dominated middle interval of Del Salto Formation. G) Detail of limestone bed with stromatolite-like bedding of the lower part that usually evolve upwards into massively or mottled stratification types.

fault, as a series of strike-slip basins, from those of upper Carboniferous age, whose tectonic regimes are likely different and presently unsolved. We also propose to consider that the Protoprecordillera was not an active palaeomountain as previously described, during the depositional time of the Del Tigre and Paganzo basins.

5.3. A need for a new Carboniferous palaeogeographical scenario

We emphasise that the Protoprecordillera hypothesis was a theory that was born and grew without sufficient stratigraphic, sedimentological, and palaeontological data. Perhaps a palaeomountain existed in coincidence with the Protoprecordillera, but it did not exist during the Carboniferous stages represented by the Del Tigre strike-slip and Paganzo basins, as the existing biostratigraphic and sedimentological evidence, and new data presented here, demonstrates.

When the Protoprecordillera hypothesis was introduced, half century ago (Amos and Rolleri, 1965; Frakes and Crowell, 1969), there was insufficient information to test it. Although geological knowledge is still incomplete, half century of added data is enough to discredit that hypothesis and begin working on new models that fit the data better. We hope this contribution will motivate future researchers to refine or rebate the palaeogeographic model presented here. However, we believe it is mandatory to reevaluate existing palaeogeographic and palaeoclimatic models that were developed using the Protoprecordillera hypothesis as a palaeomountain sourcing glaciers in opposite directions (cf. Limarino et al., 2014a, 2014b, Moxness et al., 2018; Pauls et al., 2019). Glacially striated pavements below marine Carboniferous outcrops within the Maradonas sub-basin, proving ice flow towards WNW (Fig. 4), are eloquent about how the glaciers flowed at the westernmost Central Precordillera, which lies immediately to the east of the hypothetical Protoprecordillera.

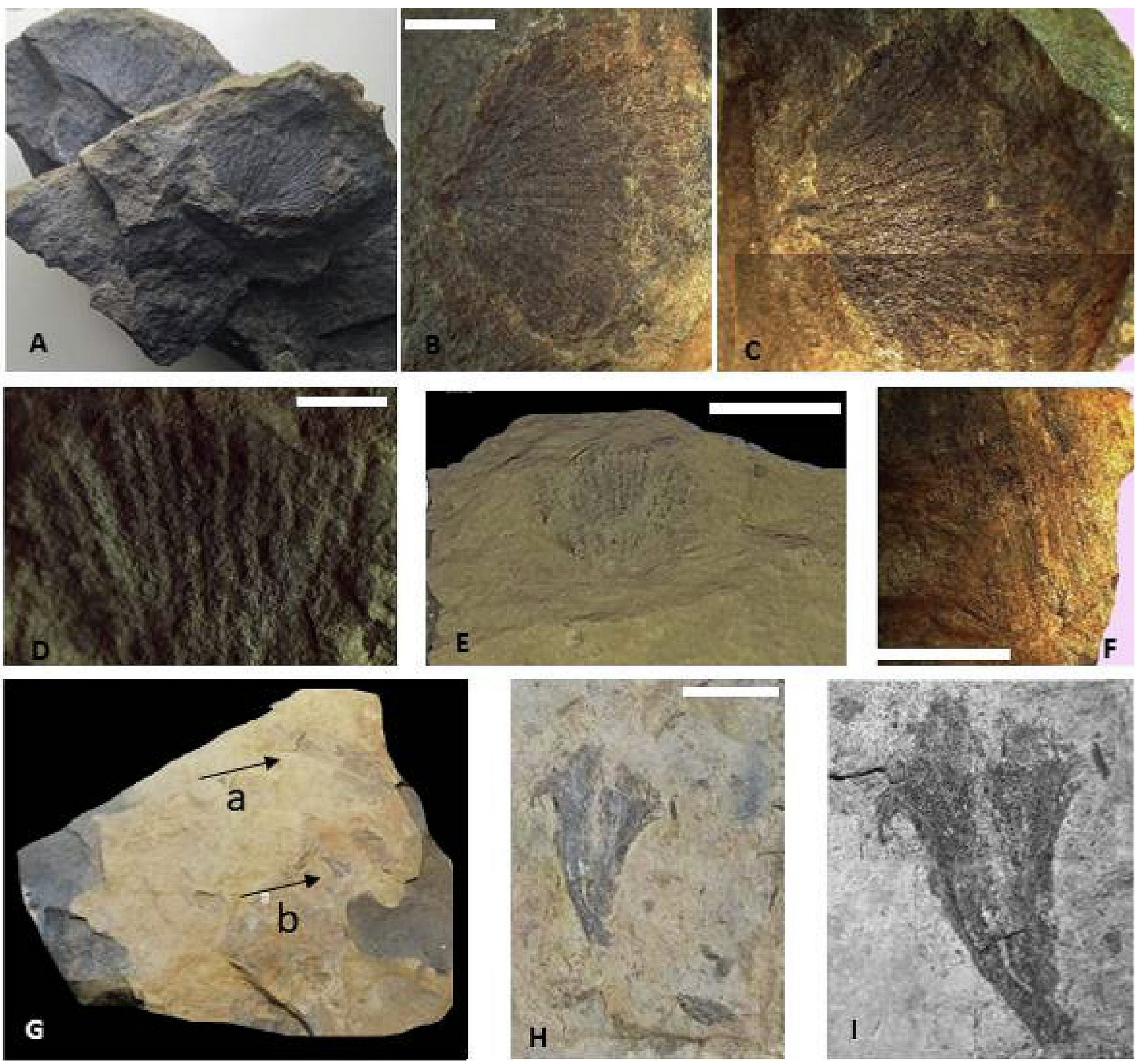

Fig. 6. Palaeoflora of El Planchon Fm at Tontal. A–E. *Nothorhacopteris kellaybellenensis* Azcuy and Suárez emend Azcuy et al. A–C) Two external moulds (CICYTTP-PB 150, specimens a and b in both sides of the slab). Scale bar 5 mm. D) CICYTTP-Pb 151. Scale bar 2.5 mm. E) CICYTTP-Pb 152. Scale bar 1.5 mm. F) Striated stem (CICYTTP-Pb 153). Scale bar 1 cm. G) Sample with striated stems (a) and *Austrocalyx* sp. (cupule in b, H–I) and organic matter remains. H) CICYTTP-Pb 154. Scale bar 1 cm.

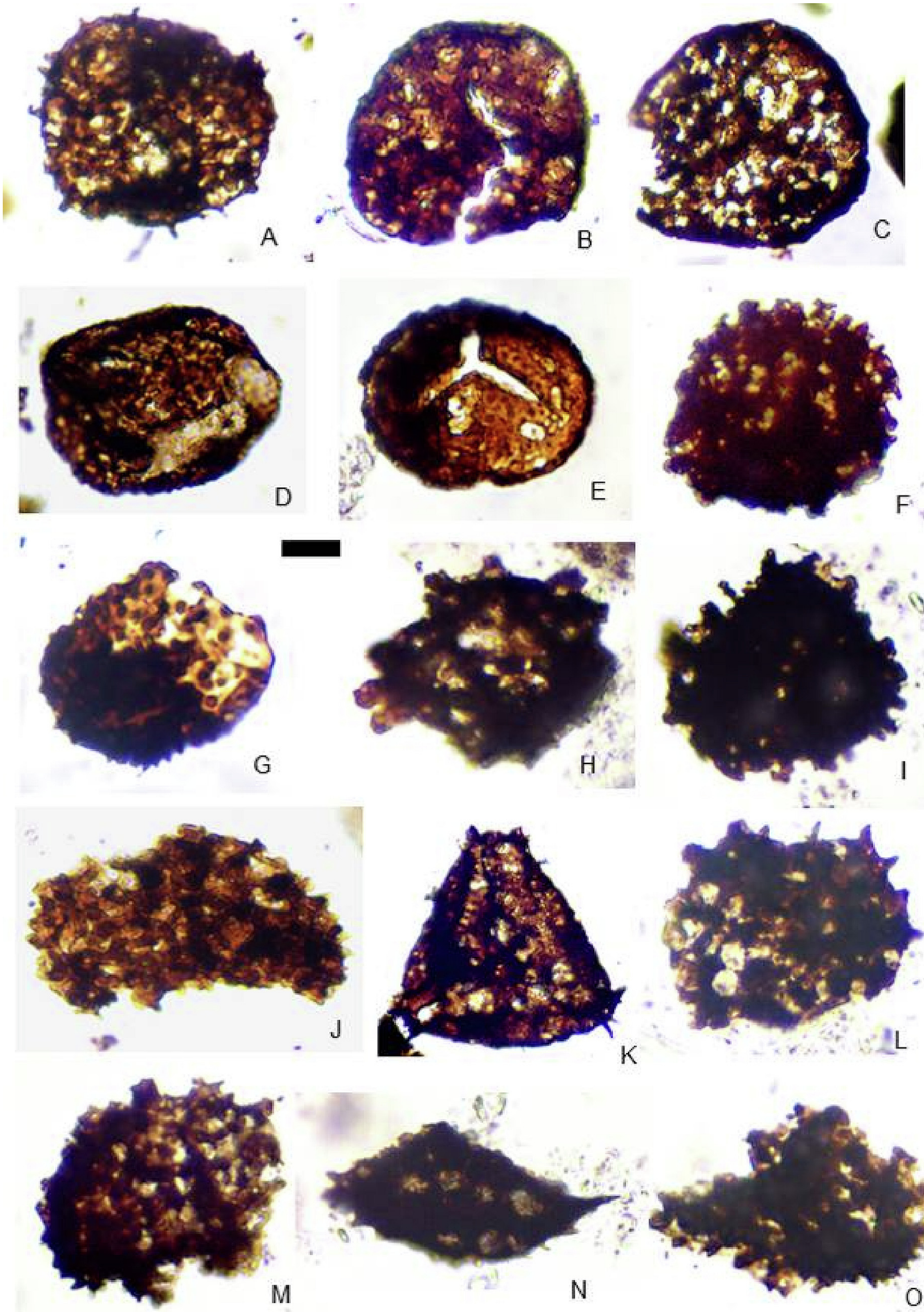

Fig. 7. Palynomorphs of the assemblage from El Planchón Formation. A) *Apiculatisporis variornatus* DiPasquo, Azcuy and Souza. CICYTTP-Pl 2495-D Q34. Scale bar 10 μm. B) *Foveosporites pellucidus* Playford and Helby. CICYTTP-Pl 2496-D Y57/1. Scale bar 13.5 μm. C) *Brochotriletes diversifoveatus* Playford and Satterthwait. CICYTTP-Pl 2494-A Q34/4. Scale bar 13 μm. D) *Convolutispora ampla* Hoffmeister, Staplin and Malloy. CICYTTP-Pl 2494-C Z51/1. Scale bar 13 μm. E) *Microreticulatisporites microreticulatus* Knox. CICYTTP-Pl 2495-2-LAV R34/3. Scale bar 14 μm. F) *Raistrickia accinta* Playford and Helby. CICYTTP-Pl 2496-2 F51/1. Scale bar 10 μm. G) *Dibolisporites microspicatus* Playford. CICYTTP-Pl 2496-2-LAV K57/1. Scale bar 10 μm. H–I. *Dibolisporites insolitus* Pérez Loinaze. H) CICYTTP-Pl 2293-2A V34/2. Scale bar 10 μm. I) CICYTTP-Pl 2293-2A Z54/2. Scale bar 12 μm. J) *Cordylosporites asperdictyus* (Playford and Helby) Dino and Playford. CICYTTP-Pl 2496-2-LAV S21/2. Scale bar 14 μm. K) *Ahrensisporites cristatus* Playford and Powis. CICYTTP-Pl 2496-2 N59/1. Scale bar 20 μm. L–O. *Cordylosporites* sp. L) CICYTTP-Pl 2293-2 K57/1. Scale bar 12 μm. M) CICYTTP-Pl 2293-1 V58. Scale bar 12 μm. N. CICYTTP-Pl 2293-3 B36/3. Scale bar 17 μm. O) CICYTTP-Pl 2293-2 X55. Scale bar 12 μm.

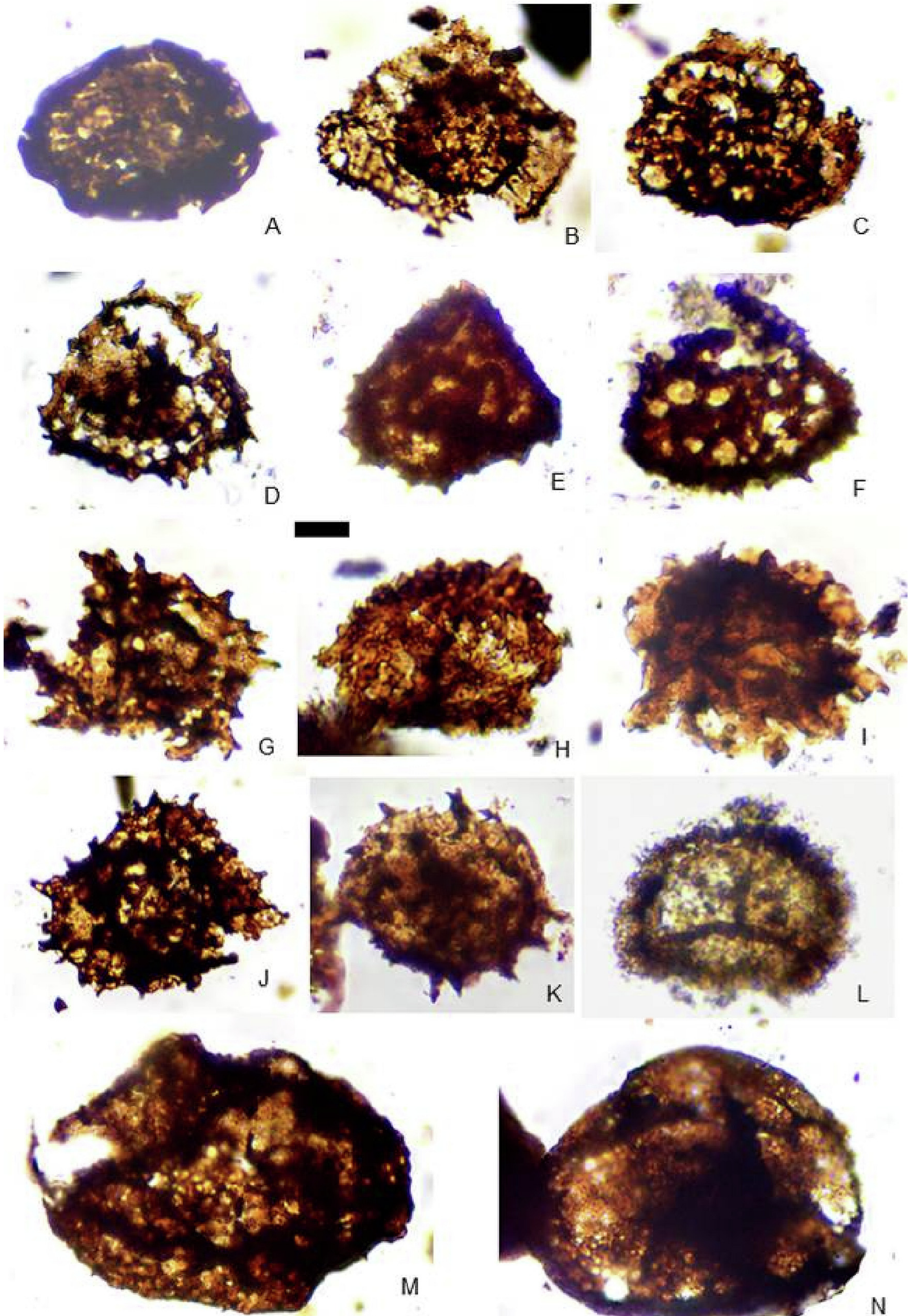

Fig. 8. Palynomorphs of the assemblage from El Planchón Formation. A) *Bascaudaspora* sp. Pérez Loinaze. CICYTTP-Pl 2293-1 T48/4. Scale bar 13 μm. B) *Vallatisporites ciliaris* (Luber) Sullivan. CICYTTP-Pl 2496-2 Q42/1. Scale bar 13 μm. C) *Vallatisporites arcuatus* (Marques-Toigo) Archangelsky and Gamerro. CICYTTP-Pl 2494-A S41. Scale bar 12 μm. D–E) *Cristatisporites stellatus* (Azcuy) Limarino and Gutiérrez. CICYTTP-Pl 2496-2-LAV L48/1. Scale bar 15 μm. CICYTTP-Pl 2495-2 G31/1. Scale bar 12 μm. F) *Cristatisporites peruvianus* Azcuy and DiPasquo. CICYTTP-Pl 2495-2 S47/3. Scale bar 10 μm. G. *Cristatisporites inconstans* Archangelsky and Gamerro. CICYTTP-Pl 2496-2 U45. Scale bar 12 μm. H. *Cristatisporites menendezii* (Menéndez and Azcuy) Playford emend. Césari. CICYTTP-Pl 2496-1-LAV P53/4. Scale bar (SB) 12 μm. I. *Cristatisporites scabiosus* Menéndez. CICYTTP-Pl 2496-1-LAV R20. Scale bar 14 μm. J-K. *Spinozonotriletes hirsutus* Azcuy. J. CICYTTP-Pl 2496-1 E55/3. Scale bar 20 μm. K. CICYTTP-Pl 2494-2 P39. Scale bar 12 μm. L. *Densosporites intermedius* Butterworth and Williams. CICYTTP-Pl 2495-2-LAV J24. Scale bar 14 μm. M-N. *Spelaeotriletes arenaceous* Neves and Owens. M. CICYTTP-Pl 2496-2 D46/2. Scale bar 20 μm. N. CICYTTP-Pl 2494-A M31/3. Scale bar 16 μm.

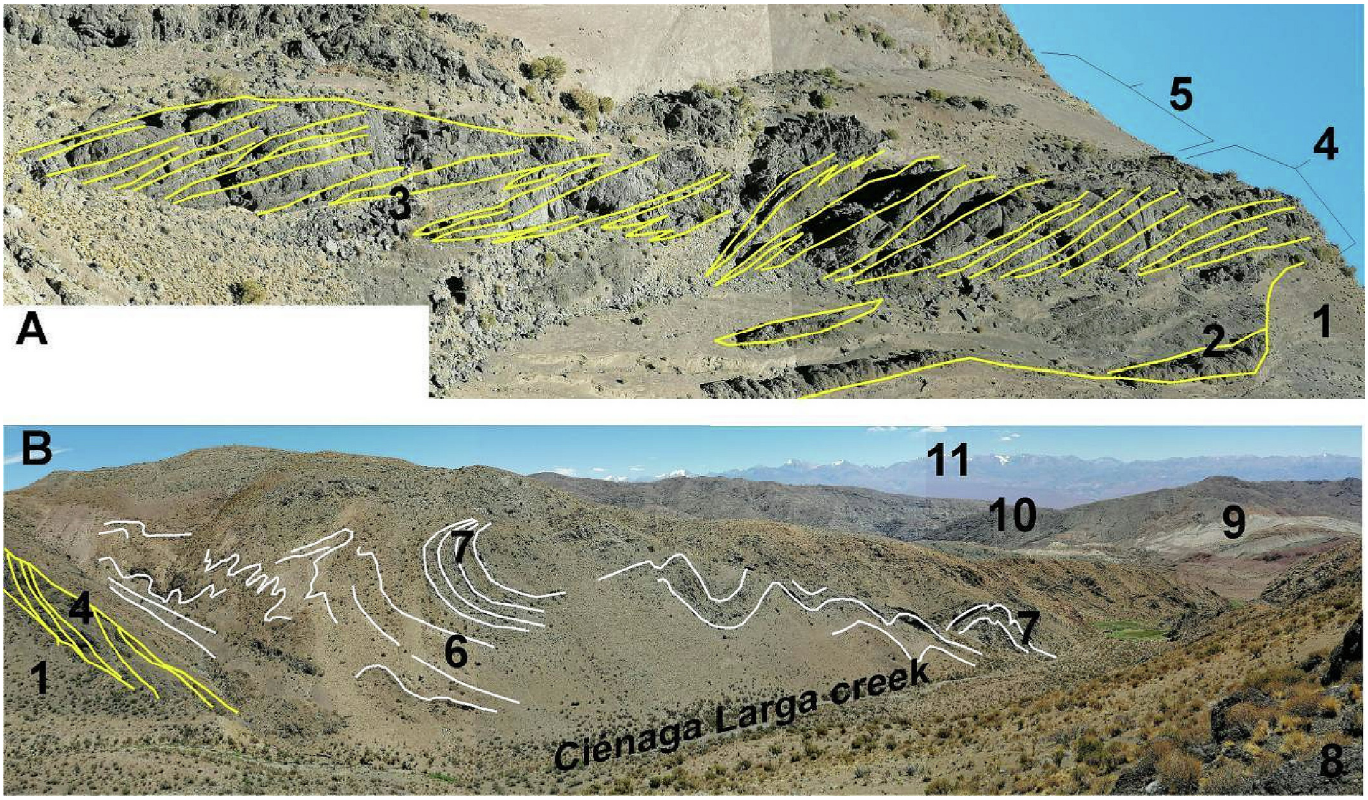

Fig. 9. Two photomosaics of Tontal outcrop. A) Inclined mosaic to capture the maximum development of Gilbert-like clinoforms (3) at lower Churupatí Fm (4), followed by redbeds of upper Churupatí (5). View from the south, suggesting progradation to the NW. Note the erosive base (2) of Churupatí over upper El Planchón (1). B) Photomosaic showing the large-scale folding at the base of Del Salto Fm, suggesting its lower muddy interval (6) and middle limestone-rich interval (7) were involved in a large-scale slump, whilst the top seems to be folded by the effect of the El Tigre Fault. Note the clinoforms in Churupatí (4) over El Planchón (1), suggesting progradation to the SW, which combined with Fig. 6A, indicate a main progradation to the West. Lower right angle shows one of the upper El Planchón ribbon-like conglomerates (8). In the background, the Triassic Rincón Blanco group (9), the lower Palaeozoic Alcaparrosa Fm (10) and the main Andes Cordillera (11) after the hidden Barreal–Calingasta Valley.

6. Conclusions

6.1. Local stratigraphy

Revision of the Tontal section allowed us to recognise the presence of Del Ratón, El Planchón, Churupatí and Del Salto formations, which have stratotypes only 15 km northwards. Significant lateral lithological changes between the Tontal and adjacent sections, corroborate that they were deposited in a narrow basin, elongated N–S, in which lateral facies changes are common. This supports the previous interpretation that this is a transtensional strike-slip basin and it was created along the Del Tigre fault that included the Tontal locality. The studied section confirms a marine environment for the El Planchón Formation, whilst its evident glaciomarine deposits corroborate the suggested glacial interval described near the base of the El Planchón Fm in the Km 114 locality.

6.2. Biostratigraphy

Based on the flora of the El Planchón Formation, we recommend a biostratigraphic revision of the ages of the invertebrate assemblages of this locality (see Lech and Milana, 2006). The age revision made here will allow better correlations with other sections, especially for strata bearing the *Rugosochonetes–Buhladelia* and *Levipustula* zones of western Argentina.

6.3. Basin implications

The sedimentary evolution, the new palaeontological material studied, including first appearances of several plant and palynomorph species for Argentina; and the previously documented invertebrate fossils and palynomorphs, suggest a comparable basin evolution to the Km 114 locality, although pointing a marginal position for the Tontal locality. This marginality explains the reduced thicknesses of coarse-grained units of the Ratón and Churupatí formations. This marginality enhanced the shelf carbonate deposition that stands out in comparison to coeval nearby sections, indicating moments of quite limited detrital sediment supply, a situation incompatible with the presence of nearby elevated terrain.

6.4. Protoprecordillera

The Tontal section that crops out at the axis of this expected palaeomountain exhibits marine deposition during both the late Early and the Late Carboniferous. It could not be deposited along a trough of the hypothetical range as the depositional system was elongated N–S. Besides, the important and unique development of carbonate sedimentation in the Bashkirian is incompatible with the presence of a nearby palaeohigh, whose erosion would have provided enough detrital input to drown carbonate production. On the contrary, there is a remarkable shortage of sand throughout the section, until the upper part, probably post-Bashkirian in age (barren) at the upper Del Salto Formation. At least seven different lines of evidence suggest the nonexistence of this palaeomountain: 1) A lack of palaeovalley relief that would make possible a trough crossing this hypothetical mountain, 2) marine deposition throughout the entire lower and upper Carboniferous sections, 3) shelf environments with restricted detrital input, 4) rounded coarse grained deposits suggesting maturity, incompatible with a nearby glaciated mountain, 5) deposition in a strike-slip basin elongated in coincidence with the postulated palaeomountain, 6) all nearby sections showing marine deposits without any evidence of mountain-side deposits, and

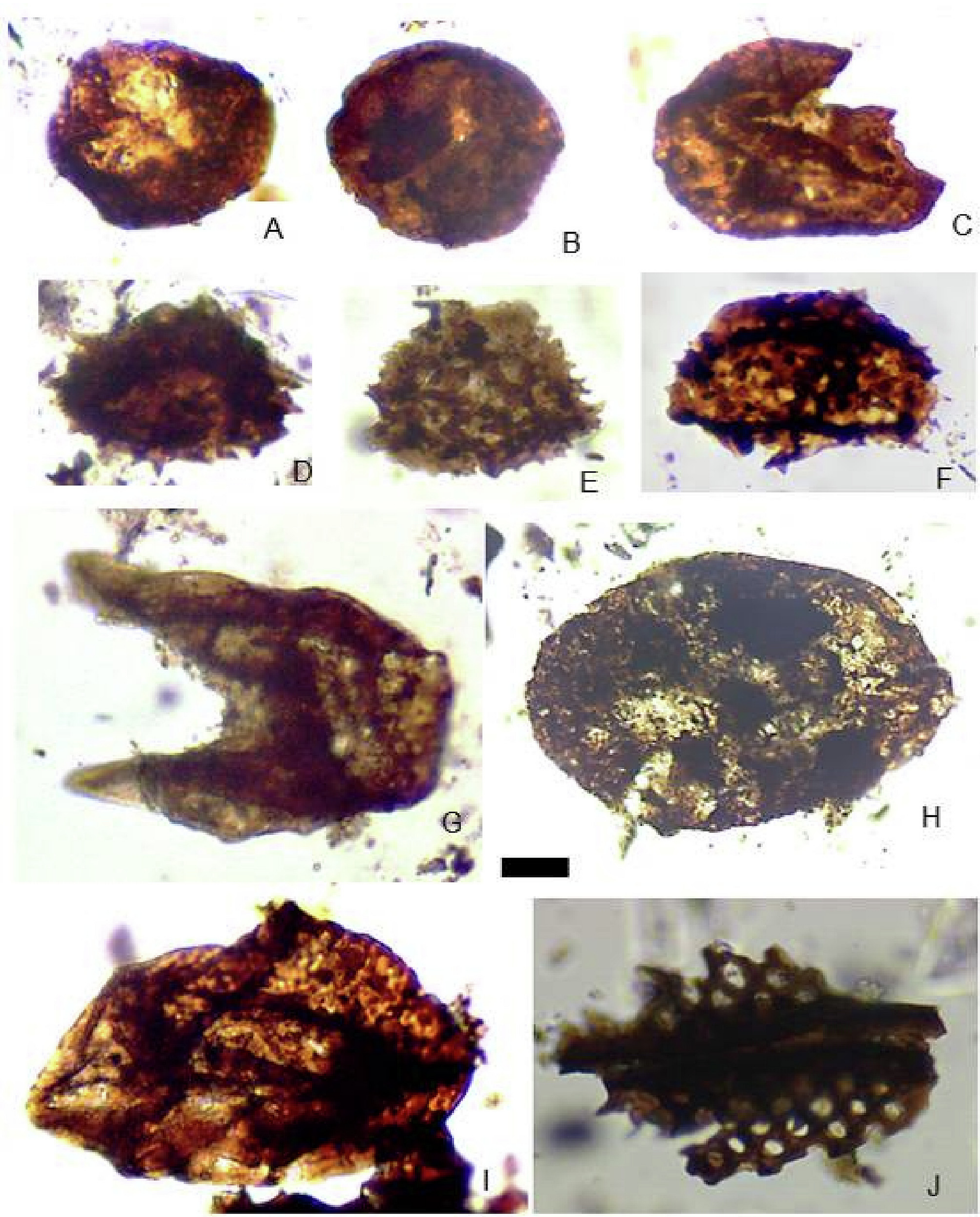

Fig. 10. Palynomorphs of the assemblage from Del Salto Formation. A) *Foveosporites hortonensis* (Playford) Azcuy. CICYTTP-Pl 2296-2A H60/3. Scale bar 12 μm. B) *Cyclogranisporites rinconadensis* Césari and Limarino. CICYTTP-Pl 2296-D H31/1. Scale bar 16 μm. C) *Apiculatasporites caperatus* Menéndez and Azcuy. CICYTTP-Pl 2296-A Q61/2. Scale bar 16 μm. D, E) *Cristatisporites stellatus* (Azcuy) Limarino and Gutiérrez. CICYTTP-Pl 2296-2A Y50/3. E. 2296-2A H25. Scale bar 15 μm. F) *Cristatisporites menendezii* (Menéndez and Azcuy) Playford emend. Césari. CICYTTP-Pl 2296-1A L35/1. Scale bar 13 μm. G–I. Monosaccate pollen grains. G) CICYTTP-Pl 2296-2A T37/3. Scale bar (SB) 12 μm. H) CICYTTP-Pl 2296-picking. Scale bar (SB) 26 μm. I) CICYTTP-Pl 2296-D H31/1. Scale bar (SB) 14 μm. J) Tracheid (gymnosperm- affinity). CICYTTP-Pl 2296-2A N26/4. Scale bar (SB) 15 μm.

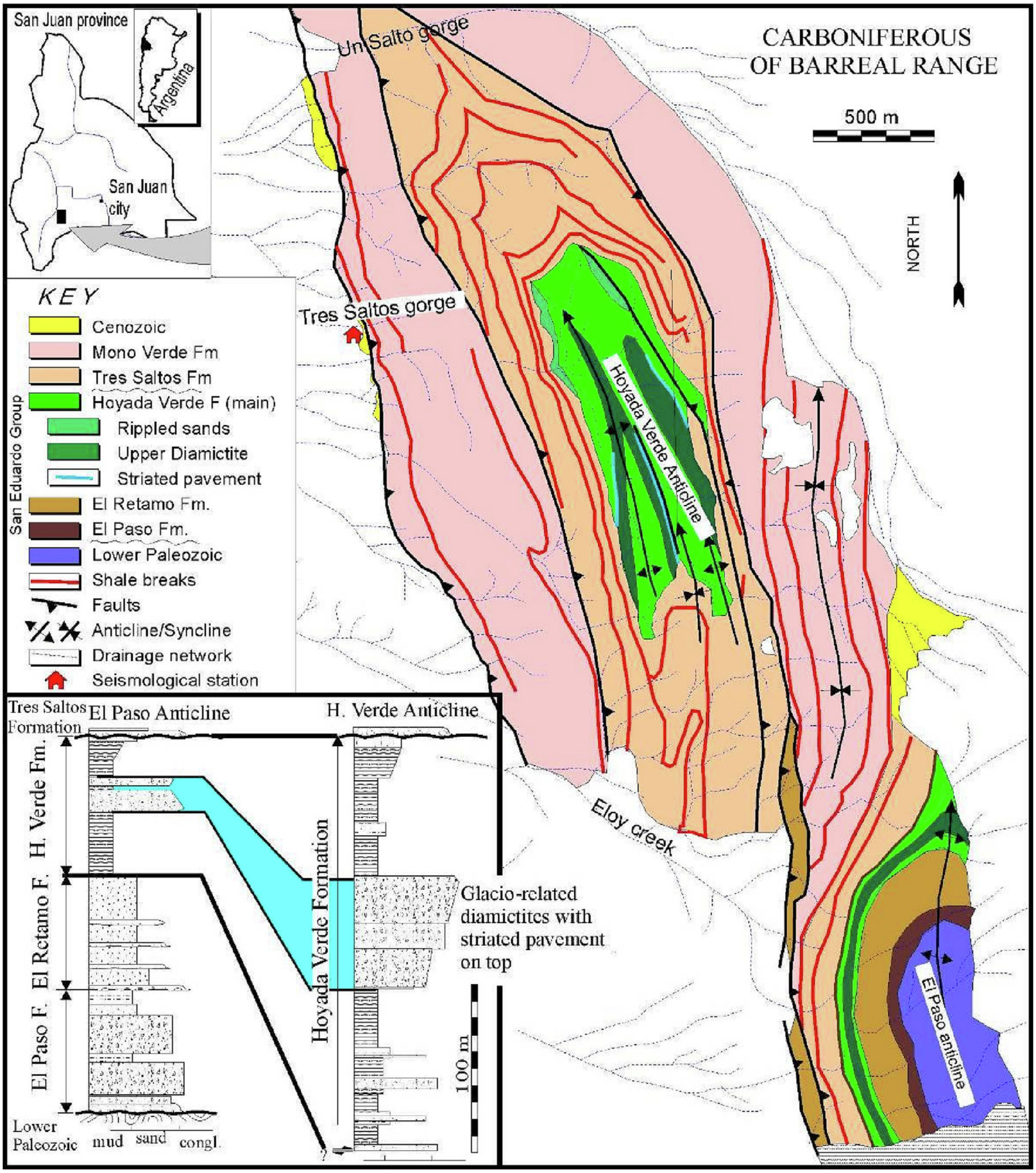

Fig. 11. Map of Barreal range outcrops with location and correlation of sections of the Hoyada Verde and El Paso anticlines showing that the glacio-related Hoyada Verde Formation was probably deposited entirely enclosed within a palaeovalley.

7) palaeoglacial flow, if present, is opposite or transverse to the hypothesised flow. On the other hand, we did not find any evidence supporting a nearby mountain, suggesting the so-called Protoprecordillera did not exist in the upper Early or Late Carboniferous.

6.5. W-Gondwana palaeogeography

This contribution suggests that palaeogeographic maps that include a mountain chain or elevated arch, called either Protoprecordillera or Tontal Arch, placed in coincidence with the core of the Western Precordillera, locally made by the present-day Tontal Range, are incorrect. Existing palaeogeographic maps need to be reappraised separating sedimentary basins from sedimentary sections preserved within deeply carved palaeovalleys. A section within a carved palaeorelief does not imply any tecto-sedimentary process of accommodation-space creation, does not rank as sedimentary basins, and tends to confuse the scenario of the western Gondwana during the Late Palaeozoic. In particular, the extent of Calingasta–Río Blanco basins needs revision due to the fact that Mississippian sedimentation over this area only occurred in relation to the Del Tigre strike-slip basin, whilst many classical glacio-related sections (as Hoyada Verde–El Paso) are apparently confined to carved palaeovalleys.

Data availability

No data was used for the research described in the article.

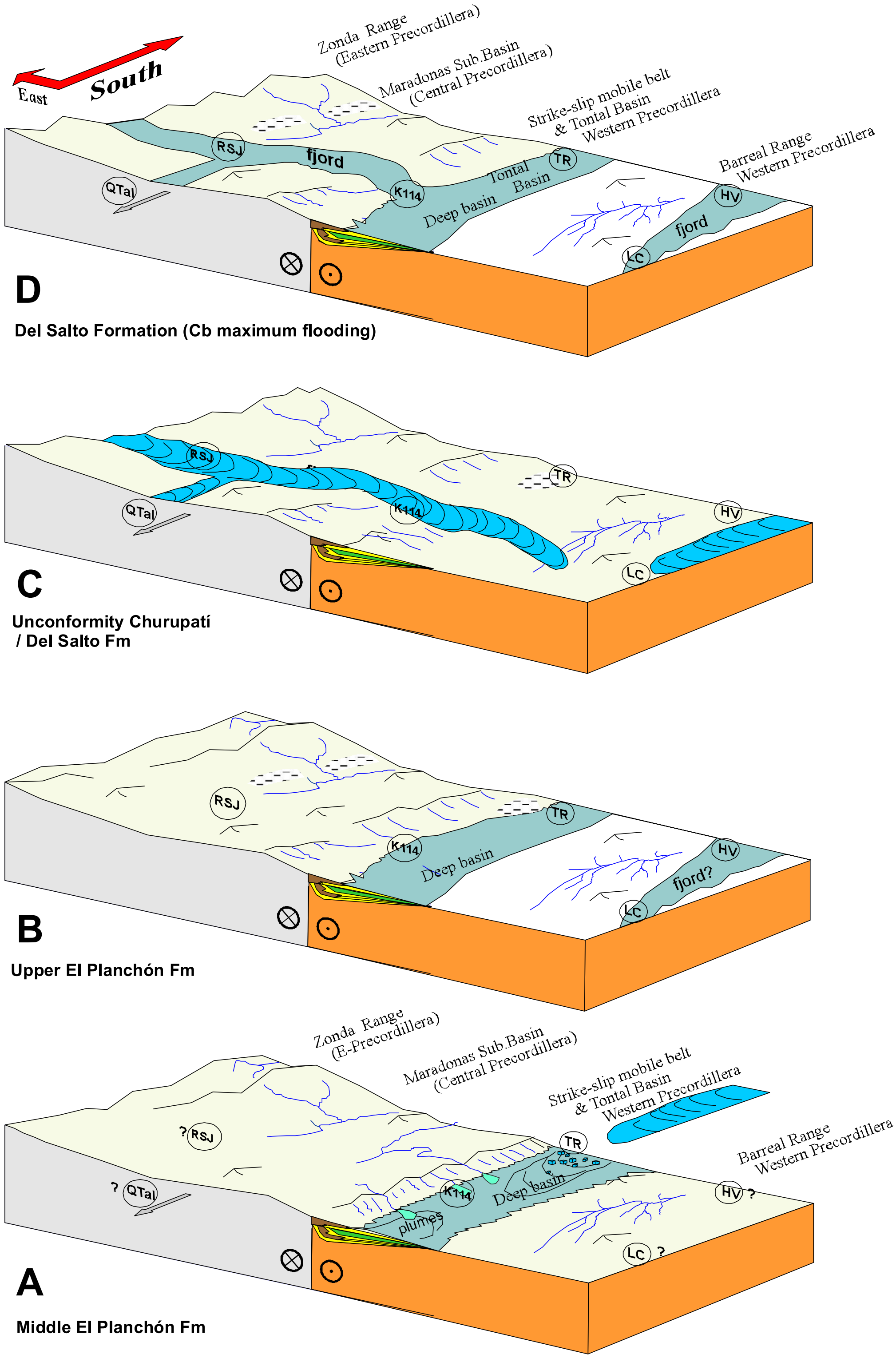

Fig. 12. Blocks suggesting the possible palaeogeographic scheme according to data presented here. Notice the represented area is beyond the ice sheet maximum extension and only few outlet glacier tongues reached the area portrayed (Central and Western Precordillera). Encircled acronyms refer to localities mentioned in the text and shown on map (Fig. 1) as: QTal; Quebrada de Talacasto, RSJ; Río San Juan, K114: Km 114, TR; Tontal Range, LC; La Capilla, HV; Hoyada Verde. A) Represents Glacial 2 maximum (Glacial 1 would be that made striations of Del Raton clasts). B) Represents postglacial maximum flooding, C) Represents Glacial 3 maximum at mid-Carboniferous boundary. D) Represents post Glacial 3 maximum flooding.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at https://doi.org/10.1016/j.sedgeo.2023.106458. These data include the Google map of the most important areas described in this article.

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