

New age, stratigraphic and paleoenvironmental interpretation of the Loma de los Piojos Formation (San Juan Province, Argentina) based on new palynologic and stratigraphic information

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ABSTRACT

A physical stratigraphic study of the Loma de los Piojos Formation (LPF) and related units at the homonymous locality (5 km north of Jachal city, San Juan Province, Argentina) was carried out. The first palynologic result is presented herein from the shale beds of the Loma de los Piojos Formation, just below the deposits bearing floral remains of the *Frenguella eximia*–*Nothorhacopteris kellybelenensis*–*Cordaicarpus cesarii* (FNC) informal zone of Balseiro et al. (Serpukhovian sensu lato). The Loma de los Piojos does not have an exposed base, and the Guandacol Formation (late Serpukhovian–early Pennsylvanian) overlies it. Also, the field work analysis allowed the association of LPF shales with the last depositional sequence of the recently defined and underlying Don Buenaventura Formation, of late Mississippian–earliest Pennsylvanian age. The four fertile samples obtained from the shale beds of the LPF yielded 45 species of terrestrial plants. Monosaccate pollen grains (*Cannanoropollis janakii*, *Cannanoropollis mehtae*, *Circumplicatipollis plicatus*, *Crucisaccites monoletus*) represent the Cordaitalean and Coniferalean that varied in their frequency c. 25 % in the lower two samples to 34 % and 7 % in the other two. Spore species of lycophytes dominate in all samples (ca. 50–80 %) along with other spores that appeared in the late Serpukhovian–Bashkirian subzone A of the *Raistrickia densa*–*Convolutispora muriornata* Palynozone (DMZ). However, in the lowest sample the key spore *Spelaeotriletes ybertii* and a well-preserved specimen of the striate bisaccate pollen *Illinites unicus* allowed the correlation with the late Bashkirian–Moscovian Subzone B of DMZ. Therefore, the informal floral zone *Frenguella eximia*–*Nothorhacopteris kellybelenensis*–*Cordaicarpus cesarii* is here reallocated to the *Nothorhacopteris*–*Botrychiopsis*–*Ginkgophyllum* (NBG) Zone, which is relevant in the global context of the evolution of the plant groups involved. This dark shale section would correspond to a warmer interval during which the maximum flooding zone was dated c. 320 Ma locally at the Huaco section (also close to Jachal city), also documented across the Paganzo Basin up to the Paraná Basin in Brazil. The three Late Paleozoic mentioned units were deposited within the largest incised valley complex of this region based on the amount of preserved depositional sequences (7), thickness (>1 km), and time span (from Late Mississippian to lower Pennsylvanian). This complex stratigraphic succession formed within a large paleovalley probably acted as a trunk drainage system connecting depositional areas from the continental interior with coastal areas of the Gondwanan continental western margin.

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1. Introduction

The Serpukhovian sensu lato age attributed to the Loma de los Piojos Formation (Balseiro et al., 2009) located in the homonymous creek of the Precordillera range in San Juan Province (Argentina) is revised in this study. It is important for a better understanding of the Late Paleozoic paleogeography of this region of the western Gondwana

margin and the global record of the gymnosperm groups Cordaitalean and Coniferalean. In the context of the Late Paleozoic ice age (370 to 260 Ma), the Carboniferous and Permian fossiliferous sequences of central-western Argentina (Paganzo, Río Blanco, Calingasta–Uspallata, and San Rafael basins) yielded abundant plant remains, palynomorphs and invertebrates studied by different groups of researchers (see Azcuy et al., 2007; Césari et al., 2007; Limarino et al., 2014a; Cisterna and Sterren, 2022). The late Mississippian–Pennsylvanian biostratigraphic framework in this region is currently a focus of debate especially concerning the appearance of Cordaitalean and primitive Coniferalean plants known through their record of leaves

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(e.g. *Cordaites*), monosaccate pollen grains (e.g. *Plicatipollenites*, *Potoniaisporites*), and platyspermic seeds (e.g. *Cordaicarpus*). The inception of the monosaccate pollen grains used to mark the base of the *Raistrickia densa*–*Convolutispora muriornata* (DMZ) Assemblage Zone established by Césari and Gutiérrez (2001), was recognized in the Guandacol and Tupe formations of the Paganzo Basin and equivalent units of central-western Argentina. The Subzone A of DMZ (DMA) is characterized by the first record of monosaccate pollen genera *Plicatipollenites* and *Potoniaisporites* and the absence of bisaccate striated pollen grains, usually *Protohaploxylinus limpidus*, which starts to occur in the overlying Subzone B of DMZ (DMb).

Césari and Pérez Loinaze (2021) updated the chronostratigraphic distribution of species and improved the boundaries of this scheme. The base of the DMA is defined by the first appearance datum (FAD) of *Lundbladispota* and monosaccate pollen grains, and it is equivalent to the appearance of the *Nothorhacopteris*–*Botrychiopsis*–*Ginkgophyllum*–NGB floral Zone. *Ahrensia* *crustatus* and *Horriditriletes* appear upward below the boundary with the DMb. The latter subzone (DMb) is marked by the FAD of *Spelaeotriletes ybertii* and striate bisaccate pollen grains (*Protohaploxylinus*, *Striatoabeites*). Gulbranson et al. (2010) provided absolute $^{206}\text{Pb}/^{238}\text{U}$ ages of 319.57 ± 0.09 Ma and 318.79 ± 0.10 Ma from post-glacial transgressive facies of the Guandacol Formation, confirmed (320 ± 3 Ma) by Valdez et al. (2020), who added an age of 326 ± 3 Ma (late Serpukhovian–Bashkirian) from glacial deposits (Pre-MTD1/Cycle 0 at Sierra de Maz). From these deposits, Valdez et al. (2020) obtained palynological assemblages correlated to the base of DMA.

On the other hand, Balseiro et al. (2009) carried out the first study of the outcrops at Loma de los Piojos that allowed them the recognition of a sandy-mudstone interval unconformably overlain by basal diamictite of the Guandacol Formation. Mediating an unconformity, the Talacasto (Lower Devonian) and Los Piojos formations are physically, laterally equivalent at this location, suggesting prima-facie that Los Piojos was also deposited within a paleorelief excavated onto the Talacasto Formation, as occurs with the lower part of the Guandacol Formation at this location (Alonso-Muruaga et al., 2018). This becomes well-proved by the fact the underlying Don Buenaventura Formation deposits recently described and nominated by Milana and di Pasquo (2021), were deposited entirely within a paleorelief and show at its top the lowstand deposits corresponding to the lower part of the depositional sequence that

continues with Loma de los Piojos shales as the transgressive and highstand intervals. The Don Buenaventura Formation is a geological unit earlier recognized by Balseiro et al. (2009, unknown formation in their Fig. 1) and also mapped as undefined by Alonso-Muruaga et al. (2018), in which Serpukhovian palynomorphs were found recently (Milana and di Pasquo, 2021), proving it was mostly deposited before Loma de los Piojos (Fig. 1).

The shales of the basal Loma de los Piojos Formation lack macrofloral remains, whereas in its upper part, three fossiliferous levels (LM1, LP9 and LM2) allowed Balseiro et al. (2009) to define the informal plant zone *Frenguellia eximia*–*Nothorhacopteris kellybelebensis*–*Cordaicarpus cesarii* (FNC). The lower LM1 yielded seeds, small and fragmentary fronds and sphenophyte remains preserved as adpressions, LP9 characterized by the abundance of sphenophytes, together with lycopsids and scarce pinnules of *Nothorhacopteris* (as molds or reddish impressions–compressions) and LM2 with remains of *Diplothmema*, *Cordaicarpus* and *Nothorhacopteris* as the only identified fossils.

The Serpukhovian (sensu lato) FNC informal plant zone shared Cordaitalean seeds with the late Serpukhovian–early Pennsylvanian *Nothorhacopteris*–*Botrychiopsis*–*Ginkgophyllum* (NGB) Zone. The Cordaitalean's FAD also involves the FAD of monosaccate pollen grains, which are documented in the base of the DMA as aforementioned. Despite this information, Balseiro et al. (2009) used an erosive surface between Loma de los Piojos and Guandacol formations as a significant time-gap to support their separation.

The geologic survey of this area and sampling for palynology (Figs. 1 and 2) are our tools to provide new insights into the age of the Loma de los Piojos Formation bearing the FNC flora. Palynological results obtained from this formation (di Pasquo and Milana, 2021) plus palynological results from the underlying Don Buenaventura Formation (Milana and di Pasquo, 2021) are used to discuss the age assigned to this flora due to the importance of this record in terms of the FAD of Cordaitalean and Coniferalean groups. A reappraisal of its age in terms of new stratigraphic correlation and paleogeographic and paleoclimatic interpretations is also addressed.

2. Brief geologic description of the area

The Loma de los Piojos Formation crops out at the homonymous locality, located approximately 5 km north of Jachal city (Fig. 1). The

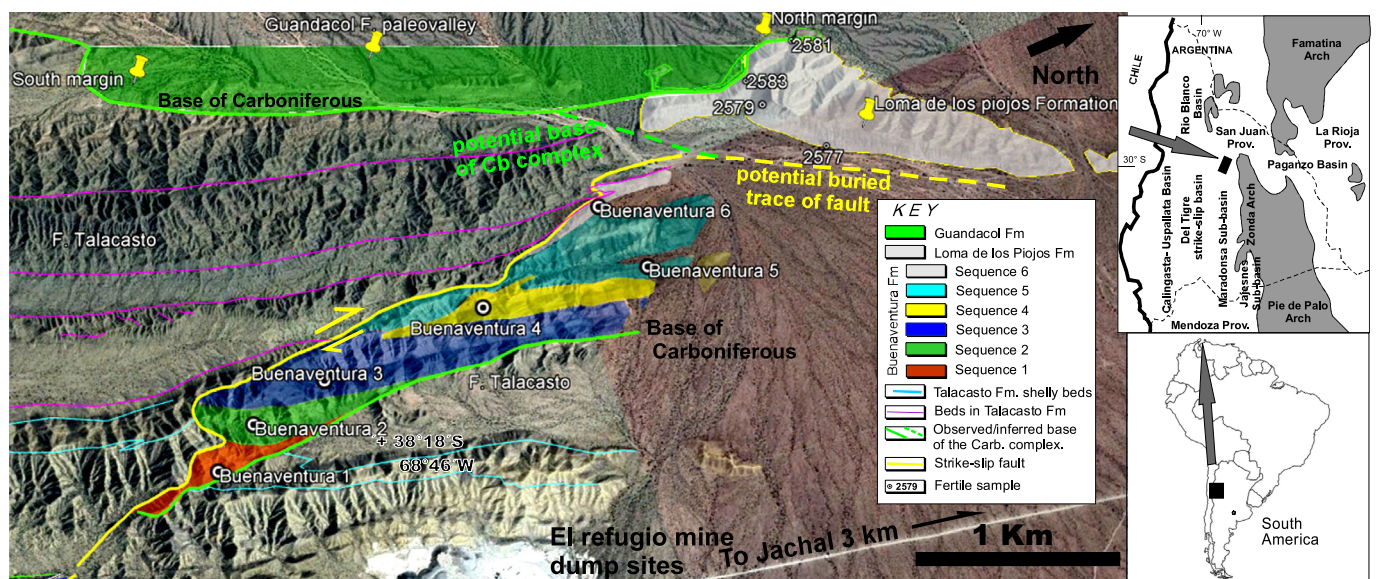


Fig. 1. Geological map overlaid to the aerial image showing the different units mentioned in the text, and the location of the four fertile palynological samples of the Loma de los Piojos Formation (indicated under the collection numbers cited in Table 1). Last sequence of Don Buenaventura Formation shown in same color as Loma de los Piojos Formation because they are associated as part of a thick glacial-eustatic depositional sequence.

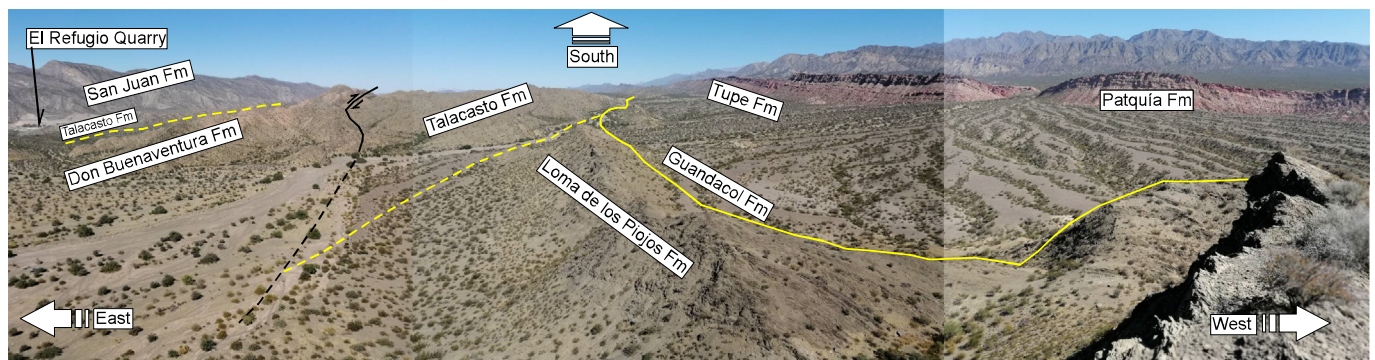


Fig. 2. Photomosaic showing the complex interrelation of Late Paleozoic units at Loma de los Piojos area. This complexity is the result of two important surfaces that are not exposed, the strike-slip fault moving the western block (right handed) toward observer that becomes buried (black hatched line). The base of Loma de los Piojos Formation would define a margin of a larger paleovalley (yellow hatched line) that encloses the smaller paleovalley elaborated on top of this unit, and hosting the lower Guandacol Formation. The paleovalley base is cut and repeated by the fault in the eastern block marked by the left yellow hatched line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Guandacol Formation erosively overlies the Loma de los Piojos Formation while to the south (Fig. 2), it overlies Lower Devonian sandstones and shales of the Talacasto Formation making the two latter units laterally correspondent, although the surface separating Talacasto and Loma de los Piojos formations is not exposed. Thus, the explanation of the Loma de los Piojos Formation stratigraphic context requires the understanding of the role of the previously unnamed unit, which was recently defined as the Don Buenaventura Formation (Milana and di Pasquo, 2021). The Loma de los Piojos Formation forms a stratigraphical wedge with its lateral and lower boundaries that are not visible (covered by Quaternary fans and stream deposits). The contact between Loma de los Piojos and Don Buenaventura Formations is completely covered by a modern wash that also covers the projection of an important strike-slip fault that cuts obliquely the top of the Don Buenaventura Formation as shown in Fig. 1. In spite of the disconnection of the Loma de los Piojos Formation from Don Buenaventura and Talacasto Formations (Fig. 2), there is no doubt that the floral remains of the *Frenguella eximia*–*Nothorhacopteris kellybelenensis*–*Cordaicarpus cesarii* (FNC) informal zone Balseiro et al. (2009) are part of this former unit.

The field survey of the Don Buenaventura Formation indicated that it was deposited within a very large paleovalley, initially narrow and becoming c. 2 km wide at its halfway, and probably reaching 4 to 5 km wide at Loma de los Piojos time of deposition. This paleovalley was initially filled by six glacial-related depositional sequences described for the Don Buenaventura Formation (Milana and di Pasquo, 2021), each one soled by an important erosive surface, suggesting two conclusions: 1) Loma de los Piojos Formation thick shale deposits are probably composing the middle and upper parts of the sixth depositional sequence of the Don Buenaventura Formation; and 2) the lower part of the so-called Guandacol Formation by Alonso-Muruaga et al. (2018), characterized by an incised system, would represent the seventh glacial-related depositional sequence.

While the depth of incision of the Guandacol paleovalley is only 60 m (Alonso-Muruaga et al., 2018), the entire incision associated with the Don-Buenaventura–Loma de los Piojos complex amounts over 1 km, indicating this paleovalley was >1 km deep and a few km wide. The fact that Don Buenaventura, Loma de los Piojos and lower Guandacol formations deposited within a paleorelief that seems to be unique for this area of the Central Precordillera (no other paleovalley reaches 1 km deep and several km wide), explains why the lower two units have not been recognized elsewhere. The size of the paleovalley enclosing the aforementioned units suggests this valley would have been the main sedimentary avenue connecting Sierras Pampeanas depocenters with the western coastal ones, before the generalized

subsidence associated with the Paganzo Basin turned this area into a depositional basin (cf. Milana and di Pasquo, 2023, this volume).

3. Material and methods

A palynologic study of this section carried out in the Loma de los Piojos Formation was based on six samples collected across the entire unit and processed following standard methods (Traverse, 2007), at the *Laboratorio de Palinestratigrafía y Paleobotánica* (LPP) of the CICYTTP (CONICET-ENTRE RÍOS-UADER, Diamante, Entre Ríos). Four samples (CICYTTP-PI 2577, 2583, 2579, 2581) collected below the plant beds resulted fertile (Figs. 2 and 3). The material was analyzed using a Leica DM 500 microscope bearing LED white and fluorescence lamps, a fluorescein filter and an AmScope 14 Mp video camera, and housed under the acronym CICYTTP-PI (di Pasquo and Silvestri, 2014). Residues were also revised in Petri dishes under a Leica EC3 stereomicroscope and selected palynomorphs manually picked and temporarily mounted in slides with water and illustrated in the microscope. After the transfer of some palynomorphs and other organic particles to stubs, illustrations were taken without coating using low vacuum energy in a SEM Phenom Pro (di Pasquo and Vilá, 2019) belonging to the same institution. Three main groups of the kerogen characterized the palynofacies composition mainly following Tyson (1995). The frequency of the mentioned groups, palynomorphs, amorphous organic matter (AOM), and structured (cuticles and tracheids)/non-structured organic remains (brown and black particles) was calculated (c. 400 organic particles including palynomorphs) and their paleoenvironmental significance addressed below.

4. Results

4.1. Palynofacies features and botanical composition of the assemblages

From the four productive samples (Figs. 2 and 3) of the Loma de los Piojos Formation, 45 species of spores and pollen grains, phytodebris and amorphous organic matter (AOM) are the components recorded. Preservation varied from fairly-good for most spores to poor especially for pollen grains, being mostly corroded, abraded and/or fragmented. Thermal alteration index (TAI in Utting and Wielens, 1992) ranges between +2 and 3– (orange to light brown).

The quantitative trends observed of the palynofacies components indicate (Fig. 4, Table 1): 1) a peak of 80 % of AOM in the third sample (CICYTTP-PI 2579) and around 50 % in the remaining; 2) phytoclasts (tracheids, cuticles, brown and black particles), poorly represented in the two upper samples; and 3) palynomorphs exhibiting a peak of

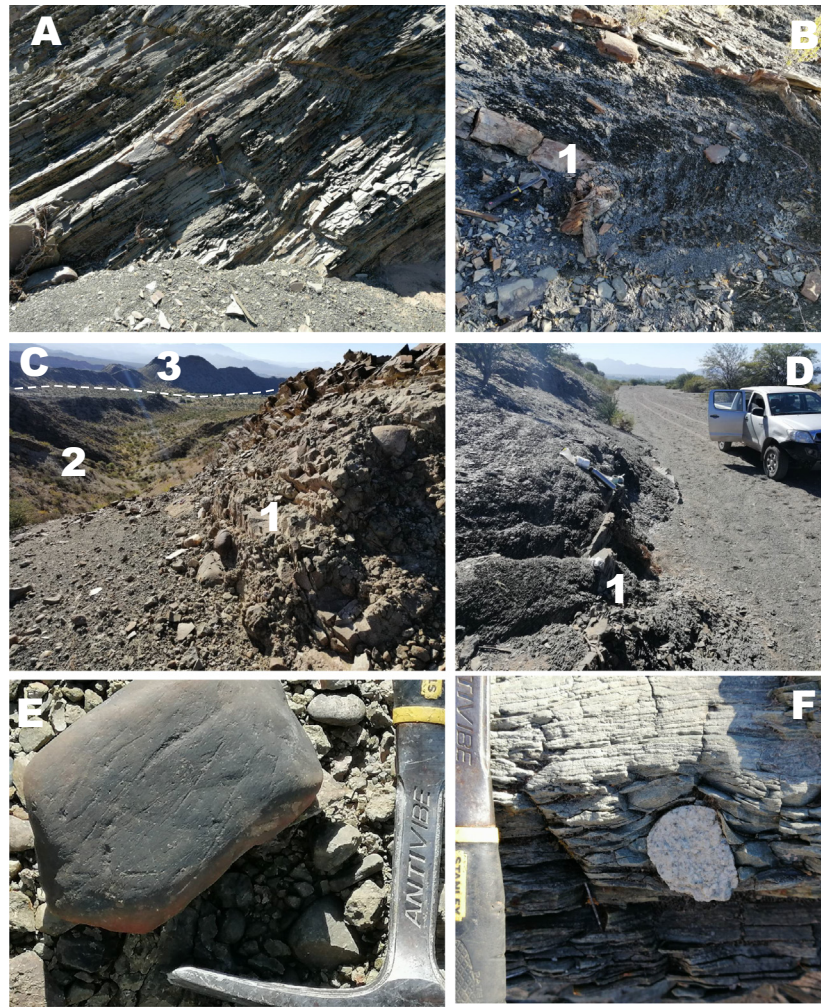


Fig. 3. Field photographs of Loma de los Piojos and Don Buenaventura Formations. A) Silty shales of middle Loma de los Piojos Formation, cropping out at the western part of the outcrop, hosting one of the fertile samples. B) Lower shales of Loma de los Piojos with carbonate interbeds (1). C) View of relationships between the upper Don Buenaventura cycle showing the basal diamictites (1) and a following MTD (2), while Loma de los Piojos would represent the fine grained part of this sedimentary cycle (3), with a fault separating these units (white dashed line). D) Lowest exposed beds of Loma de los Piojos Formation showing fine grained shales and carbonate beds (1), the latter resulted fertile. E) Glacially striated clasts present at the top of Don Buenaventura Formation. F) Dropstones present on shales interbedded with diamictites and sandstones of Don Buenaventura Formation indicating proglacial conditions that disappear in Loma de los Piojos Formation.

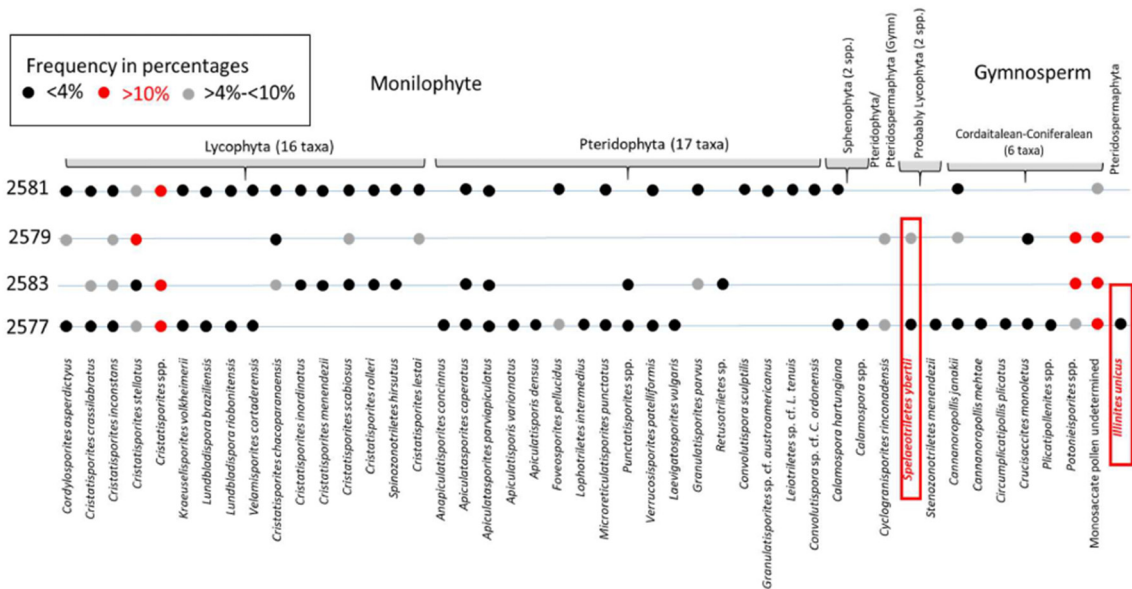


Fig. 4. Stratigraphic distribution and frequency of taxa documented in the Loma de los Piojos Formation, organized by main botanical groups. The two species highlighted in red are diagnostic for biostratigraphic correlation with the DMbZ. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1 (continued)

Spores/samples (CICYTP-PI)	2577	2583	2579	2581	Plates	Western Argentina biozones			Global range Gondwana	El Planchón Fm	Churupatí Fm	Del Salto Fm	Guandacol Formation					Tuminico Fm	El Paso Fm	Jejenes Fm	
						CV	MQ	DM/FS					1. Pre-DMa (MQ zone)	1. DMA	2. DMA	3. DMA	4. DMA				5. DMA
<i>Apiculatasporites caperatus</i> Menéndez & Azcuy 1969	1 %	1 %		2 %	2.6						X			X	X			X			
<i>Apiculatasporites parviapiculatus</i> Azcuy 1975	1 %	1 %		1 %	2.7						X		X								
<i>Apiculatisporis variornatus</i> di Pasquo, Azcuy & Souza 2003	2 %				2.8	X							X	X			X				
<i>Apiculatisporis densus</i> Pérez Loinaze and Césari, 2004 In Césari et al., 2019	1 %				2.9								X								
<i>Foveosporites pellucidus</i> Playford & Helby 1968	4 %			3 %	2.10	X															
<i>Lophotriletes intermedius</i> Azcuy 1975	1 %				2.11									X	X						
<i>Microreticulatisporites punctatus</i> Knox 1950 (= <i>M. microreticulatus</i> Knox 1950)	1 %			3 %	2.12, 4.2, 4.4								X	X	X		X				
<i>Punctatisporites</i> spp.	1 %	1 %																			
<i>Verrucosporites patelliformis</i> (Menéndez) Limarino & Gutiérrez 1990	1 %			2 %	2.13								X	X	X						
<i>Laevigatosporites vulgaris</i> (Ibrahim 1933, Potonié & Kremp 1956) Alpern & Doubinger 1973	1 %				2.14									X	X						
<i>Granulatisporites parvus</i> (Ibrahim) Schopf et al. 1944		4 %		2 %	2.15													X			
<i>Retusotriletes</i> sp.		1 %																			
<i>Convolutispora sculptilis</i> Felix & Burbridge 1967				2 %	2.16	X							X		X						
<i>Granulatisporites</i> sp. cf. <i>austroamericanus</i> Archangelsky & Gamarro 1979				2 %	2.17												X				
<i>Leiotriletes</i> sp. cf. <i>L. tenuis</i> Azcuy 1975				1 %	2.4												X				
<i>Convolutispora</i> sp. cf. <i>C. ordonensis</i> Archangelsky & Gamarro 1979				1 %	2.19								X		X						
Sphenophyta	3 %	2 %	0 %	2 %																	
<i>Calamospora hartungiana</i>	1 %			2 %	2.18						X		X	X	X		X				

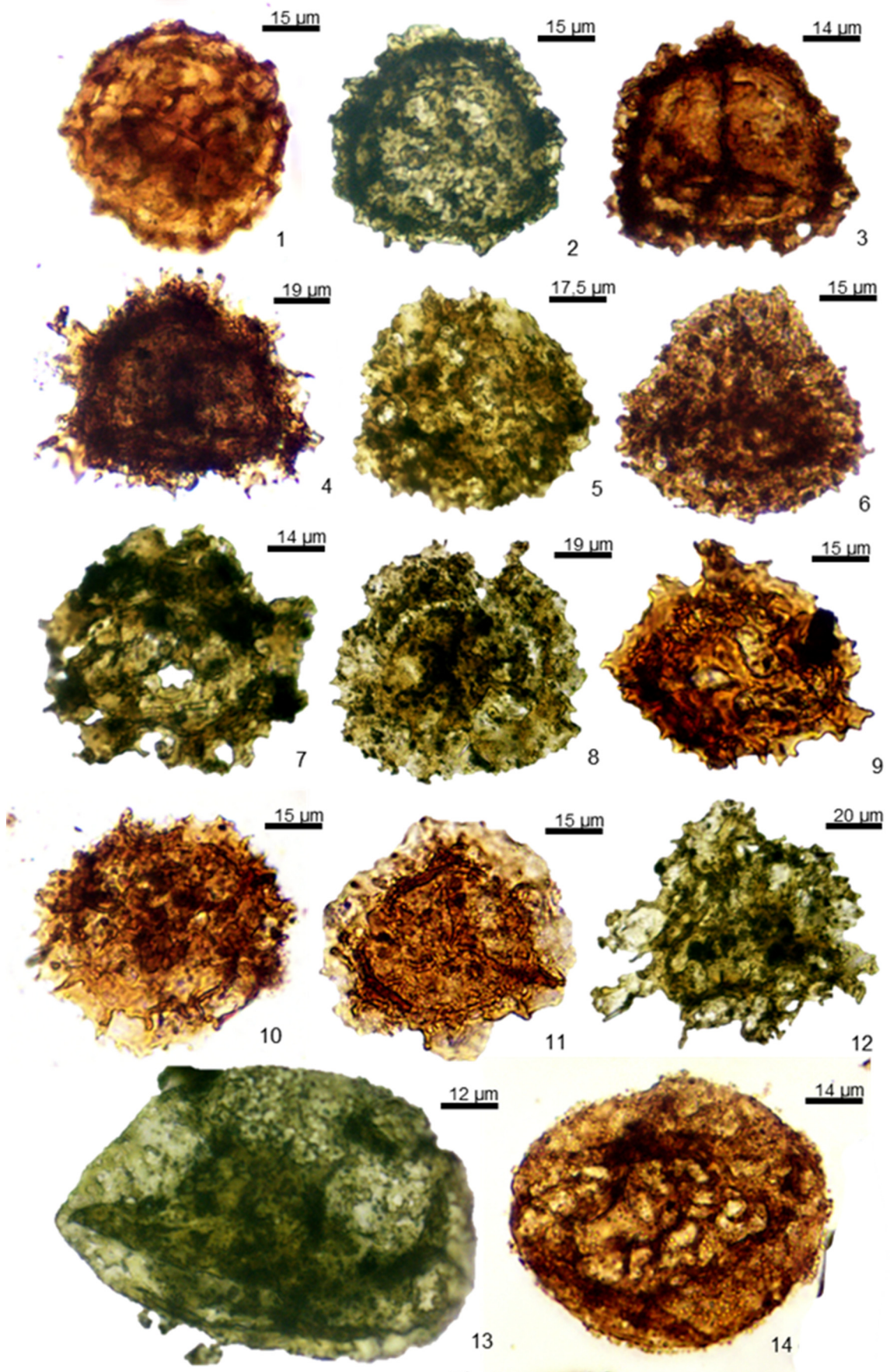


Plate 1

40 % in the upper sample (CICYTTP-PI 2581) and around 20 % in the remaining. The AOM is composed of non-fluorescent fine black particulate matter derived from terrestrial materials, and tracheids and less frequent cuticles are brown and black, with variable sizes and shapes except in sample CICYTTP-PI 2579, in which they are in small sizes (lesser than 40 µm) and AOM dominates. Furthermore, palynofacies of the lower sample (CICYTTP-PI 2577) differs from the other samples due to the abundance of phytodebris with a higher frequency of black tracheids (charcoal from fire?), and finely divided amorphous organic matter. Also, the presence of few reworked spores (poorly preserved) from Devonian deposits, such as *Retispora lepidophyta* (Kedo) Playford (biochron late Famennian, latest Devonian) and possibly, from Mississippian rocks is distinctive.

The documented taxa in the four samples are listed in alphabetical order by botanical affinities as illustrated in Figs. 5–9 and addressed in Fig. 4 and Table 1 along with biostratigraphic records and global range. Concerning the major groups of plants represented in these samples based on the most probable botanical affinities of taxa (e.g. Balme, 1995), 18 spore species of lycophytes (*Cristatisporites*, *Kraeuselisporites*, *Lundbladispota*, *Spelaeotriletes*, *Velamisporites*), 17 pteridophytes (*Anapiculatisporites*, *Apiculatisporis*, *Convolutispora*, *Granulatisporites*, *Leiotriletes*, *Lophotriletes*, *Punctatisporites*), two sphenophytes, one Pteridospermaphyta, six monosaccate pollen grains of Cordaitalean and Coniferalean and one striated bisaccate are identified (Fig. 4 and Table 1). Lycophytes dominate in all samples (ca. 50–80 %), being the most frequent of them, species of *Cristatisporites* (>15 %), *Cristatisporites crassilabratus*, *Cristatisporites inconstans* and *Cristatisporites stellatus*, followed by Cordaitalean and Coniferalean (26 %–24 %–34 %–7 %). Despite many of the specimens of monosaccate pollen grains are degraded, the external morphology (barely smooth) and internal morphology (filled with ectexinal partitions) of the saccus illustrated with SEM in Figs. 8 and 9 are in agreement with the SEM and TEM description of *Plicatipollenites* published by Zavialova and Stephenson (2006).

4.2. Age of the assemblage

Most of the species documented from the lower sample (Fig. 4 and Table 1) appeared in the late Serpukhovian–Bashkirian subzone A of the *Raistrickia densa*–*Convolutispora muriornata* Zone (DMZ) and especially, supported by the presence of monosaccate pollen grains in the lower sample (e.g. *Cannanoropollis janakii*, *Cannanoropollis mehtae*, *Circumplicatipollis plicatus*, *Crucisaccites monoletus*) give support to this correlation (cf. Césari and Pérez Loinaze, 2021 and references therein). Spore species present at least in the lower sample (*Anapiculatisporites concinnus*, *Cyclogranisporites rinconadensis*, *Lophotriletes intermedius*, *Lundbladispota braziliensis*, *Lundbladispota riobonitensis*, *Microreticulatisporites punctatus*, *Spelaeotriletes ybertii*, *Velamisporites cortaderensis*, *Verrucosiporites patelliformis*) are characteristic of the DMZ. As aforementioned, the presence of *Spelaeotriletes ybertii*, a key taxon of the Subzone B of DMZ (Césari and Pérez Loinaze, 2021) along with the striate bisaccate pollen grain *Illinites unicus* documented in the lower sample (see di Pasquo and Milana, 2021) is allowing us to propose the reassignment of the Loma de los Piojos Formation to the late Bashkirian (Fig. 10).

5. Discussion

5.1. Sedimentary and stratigraphic revision and importance of a new age for the FNC flora

Alonso-Muruaga et al. (2018) described the Guandacol Formation at the Loma de los Piojos locality, where it sharply overlies Lower Devonian sandstones and shales of the Talacasto Formation and, locally, Mississippian marginal marine siliciclastic deposits of the Loma de los Piojos Formation (López-Gamundí and Martínez, 2000). From the latter formation, floral remains were studied in detail by Balseiro et al. (2009), who characterized the assemblages as unique due to the presence of *Tomiodendron* and *Nothorhacopteris kellyabelenensis*, leading them to the creation of the FNC zone based on this single floral record. The presence of Cordaitalean seeds, which are also coeval with the FAD of monosaccate pollen grains appearing in the DMA was disregarded.

An important argument to support the creation of the FNC zone was the stratigraphic position below an apparent important erosive surface separating Loma de los Piojos from the Guandacol Formation. This was mandatory for Balseiro et al. (2009) to discard its inclusion in the NBG Zone. However, it is important to indicate that the overlying “Guandacol Formation” described by Alonso-Muruaga et al. (2018) does not show the typical thick dark shale interval corresponding to the maximum flooding zone recognized across the Paganzo Basin realm (cf. Valdez et al., 2020, 2021). Instead, the Loma de los Piojos Formation does, and it also, shows the typical carbonate-rich beds that usually appear interbedded with the dark shales that define the postglacial flooding that followed the mid-Carboniferous glacial event widely recorded in the western Gondwana Late Paleozoic Ice Age (LPIA). On the other hand, the significant erosion described by Alonso-Muruaga et al. (2018) that reaches c. 60 m of incision as measured by those authors, is minor if compared to the c. 1 km deep incision associated with the Don Buenaventura–Loma de los Piojos depositional complex (Milana and di Pasquo, 2021). Another element that suggests that the local Guandacol Formation is not related to the local maximum glacial and postglacial after our revision of the incised valley is related to the maximum particle size of basal diamictites and conglomerates. They reach up to 15–20 cm of largest size whereas some boulders up to 3 m in diameter found in the Don Buenaventura Formation are showing metamorphic composition attesting for a long-distance transport.

Hence, sedimentary evidences from nearby Late Paleozoic units suggest the following conclusions. A) The deposition of the Guandacol Formation starts at this location much later than at other localities as it does not contain the shales of the maximum flooding interval associated with the postglacial transgression following the largest LPIA glaciation correlated to the mid-Carboniferous boundary (e.g. Milana and di Pasquo, 2019; Valdez et al., 2020). B) The finest grained and more euxinic Late Paleozoic unit in this area is the Loma de los Piojos Formation that also shows the typical carbonatic beds associated with the aforementioned maximum transgression. C) Deposits that could be correlated to the glacial maximum are not those of the base of the Guandacol Formation but are likely to be those of the Don Buenaventura Formation given the presence of large boulders of exotic composition, some of

Fig. 5. 1. *Cordylosporites asperdictyus* (Playford & Helby) Dino & Playford. CICYTTP-PI 2577-1 England Finder coordinates (EF) Z40/3. 2–3. *Cristatisporites stellatus* (Azcuay) Gutiérrez & Limarino. 2. CICYTTP-PI 2577 (residue). 3. CICYTTP-PI 2577-2 EF O33/2. 4. *Cristatisporites crassilabratus* Archangelsky & Gámerro. CICYTTP-PI 2577-1 EF Q26/1. 5. *Cristatisporites chacoparanaensis* Ottone. CICYTTP-PI 2583-2 EF T17/2. 6. *Cristatisporites lestai* Archangelsky & Gámerro. CICYTTP-PI 2581-2 EF T26/1. 7. *Cristatisporites inordinatus* (Menéndez & Azcuay) Playford. CICYTTP-PI 2583-1 EF O30/0. 8. *Cristatisporites scabiosus* Menéndez. CICYTTP-PI 2583-1 EF O30/4. 9. *Cristatisporites inconstans* Archangelsky & Gámerro. CICYTTP-PI 2581-R1 EF P36/3. 10. *Cristatisporites rolleri* Ottone. CICYTTP-PI 2583-1 EF Z54/1. 11. *Kraeuselisporites volkheimerii* Azcuay. CICYTTP-PI 2581-1 E59/4. 12. *Spinozonotriletes hirsutus* Azcuay. CICYTTP-PI 2583-2 EF R53/2. 13–14. *Spelaeotriletes ybertii* (Marques Toigo) Playford & Powis emend. Playford et al. 13. CICYTTP-PI 2577 (residue). 14. CICYTTP-PI 2577-1 EF Y57/3.

them showing glacial striations (Fig. 3, cf. Milana and di Pasquo, 2021). Given these physical stratigraphic facts that suggest the Guandacol Formation base is locally younger than the same unit at other localities, plus the biostratigraphic content recovered from the Don Buenaventura Formation that suggests its upper part is correlative with lower intervals of the Guandacol Formation (Milana and di Pasquo, 2021), as dated in Cerro Bola–Sierra de Maz sections (Valdez et al., 2020), we interpret that the Loma de los Piojos Formation is biostratigraphically correlative with the Guandacol Formation in spite of the clear erosive surface separating it from the local Guandacol Formation.

A consequence of the late Bashkirian age given to the Loma de los Piojos Formation involves the reallocation of the *Frenguella eximia*–*Nothorhacopteris kellybelenensis*–*Cordaicarpus cesarii* informal floral zone documented by Balseiro et al. (2009) just over the shales bearing our palynoassemblages in the early Pennsylvanian NBG Zone (Fig. 10). We therefore expect that future misinterpretations on the FAD of different components of the Gymnosperm groups related to Cordaitalean and Coniferalean (e.g. seeds, pollen grains, cones, tracheids, cuticles, leaves, trunks and others; Archangelsky, 1999; Azcuy and di Pasquo, 2000; Falcon-Lang and Bashforth, 2005; Šimůnek and Libertín, 2006; Taylor

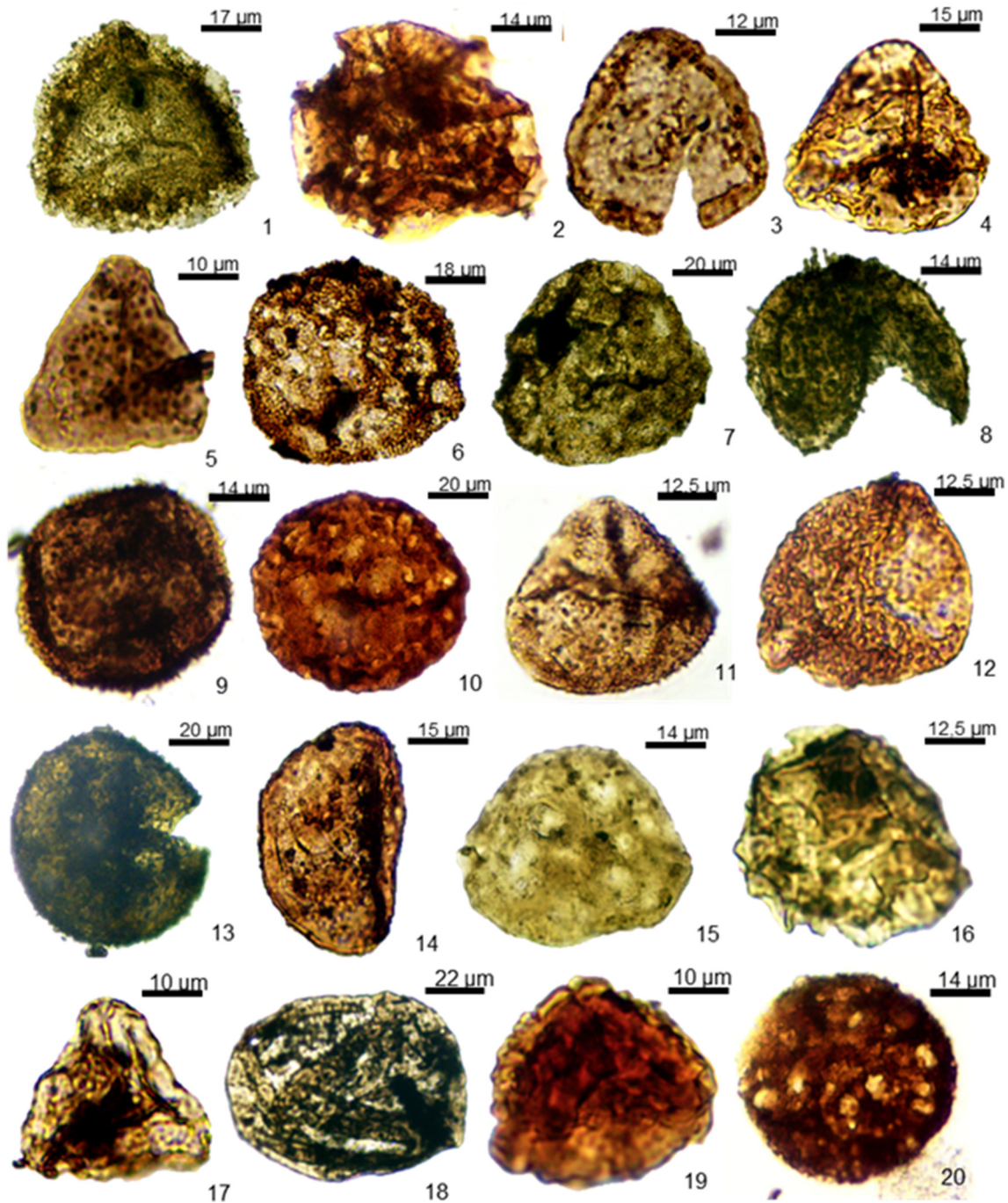


Plate 2

et al., 2009; Césari and Hünicken, 2013; Wang et al., 2016), considering the previously Serpukhovian age assigned to the FNC single record will not occur.

5.2. Approaches on the FAD of *Illinites unicus* and other striated pollen grains and their importance for correlations in South America

Azcuy et al. (2002) reviewed the taxonomic status of *Illinites unicus* (Voltziales, Gymnosperm) due to the high frequency of specimens documented in the Moscovian Tarma Formation of Peru. This Peruvian assemblage correlated with the *Illinites unicus* palynozone defined in the Amazonas Basin (see Fig. 10; Playford and Dino, 2000b) and documented in the Parnaiba Basin as well (Dino and Playford, 2002). Instead, younger records of this taxon are found in the *Pakhapites fusus*–*Vittatina subsaccata* (FS) Zone of Paganzo and San Rafael basins (see di Pasquo et al., 2010; Correa et al., 2012; Vázquez et al., 2020) and in the Kasimovian–Ghzelian of the Chacoparaná Basin (Gutiérrez and Balarín, 2018) (Fig. 11).

In the Paraná Basin of Brazil, the inception of *I. unicus* coincides with the inception of *Vittatina* species, which defined the base of the latest Pennsylvanian/Asselian–Artinskian *Vittatina costabilis* Zone of Souza (2006). This cosmopolitan taxon is also documented in Moscovian to Permian strata outside South America as for example, in U.S.A. (Kosanke, 1950; Jizba, 1962; Traverse and Ash, 1999), Europe (Helby, 1966), and many more references from Russia, India, Nigeria, Libya and other countries (see Palynodata website). Although, the taxonomic assignment of this taxon in each work cited in Palynodata should need to be checked and confirmed.

On the other hand, other striate–taeniate mono- and bisaccate pollen grains (*Meristocarpus*, *Protohaploxylinus*) are documented in low frequency since the late Bashkirian in Pennsylvanian deposits of Argentina, Bolivia and Brazil (Loboziak et al., 1997; di Pasquo, 2002, 2003, 2009b, 2022; Azcuy et al., 2002; Melo and Loboziak, 2003; Souza, 2006; Césari and Pérez Loinaze, 2021, and their references). In western Argentina, the inception of striate bisaccate pollen grains allows the differentiation of the DMA SZ and DMb SZ (Césari and Pérez Loinaze, 2021). Their frequency is always low, and may vary along an outcrop in which DMb SZ palynofloras are documented especially across the western Paganzo Basin whereas the striate pollen grains increase slightly in those palynofloras assigned to the younger DMc SZ present in eastern Paganzo (Fig. 11.B). Among those records mainly in the Paganzo Basin, palynological assemblages in the Jejenes (=Retamito) Formation at the Río del Agua site containing bisaccate taeniate pollen *Protohaploxylinus* and *Striatoabieites*, and spores (e.g. *Striatosporites heyleri*) were attributed to the early Moscovian within the DMb SZ by Correa and Césari (2019). In this succession diagnostic plant components

of the NBG Zone of fluvial–deltaic origin and shallow marine deposits were also documented.

At La Herradura creek Pérez Loinaze et al. (2014) recorded palynoassemblages assigned to the DMb SZ despite lacking striate pollen grains, which first appear in the DMc SZ over short-lived transgressive deposits bearing the invertebrate fauna *Tivertonia jachalensis*–*Streptorhynchus inaequiornatus*. The palynoassemblage yielded spores, non-striate mono- and bisaccate pollen grains (e.g. *Cannanoropollis trilobatus*, *Potonieisporites marleniae*, *Limitisporites monosaccoides*) and the first appearances of the striate pollen *Hamiapollenites insolitus*, *Protohaploxylinus amplus*, *Protohaploxylinus limpidus*, *Protohaploxylinus* sp. cf. *P. haigii*, and *Striatoabieites multistriatus*. The appearance of *Illinites unicus* was documented upwardly in the same succession at this locality associated with the *Pakhapites fusus*–*Vittatina subsaccata* (FS) Zone Césari and Gutiérrez (2001).

In the Las Angosturas area of Catamarca province, Césari et al. (2019) analyzed palynofloras and plant remains of the Agua Colorada Formation, and recovered from fluvial and estuarine–fluvial deposits (stages 4 and 5) striate pollen of *Protohaploxylinus* sp., together with spores (*Apiculatisporites variornatus*, *Cristatisporites menendezii*, *Lundbladispora braziliensis*, *Spelaeotriletes ybertii*) that were referred to the DMb SZ. Upwardly, from the basal section of the De la Cuesta Formation zircons from a tuff intercalated with mudstones and sandstones of a marine interval provided an age of 311.89 ± 0.21 Ma (CA-TIMS technique weighted average of $^{206}\text{Pb}/^{238}\text{U}$ dates) that confirms previous isotopic ages obtained from different successions in the Paganzo Basin (Fig. 10).

Therefore, our record of *Illinites unicus* in the Loma de los Piojos Formation most likely attributed to the late Bashkirian (Figs. 10 and 11.A), would be somewhat slightly older than the aforementioned documentation and it is the first record for the early Pennsylvanian in western Precordillera.

5.3. Palynofacies, the environment of deposition and glacial–deglacial cycles

Considering the palynofacies features and floristic composition of the Loma de los Piojos Formation, we interpret the microflora was preserved in a water body under low energy bottom conditions during a warm and humid interval. This environment of deposition was surrounded by lycophytes (ca. 50–80 %), and Cordaitalean and Coniferalean monosaccate pollen grains (26%–24%–34%–7 %), which are more widely distributed from up- to lowlands. The variations of the frequency of spores/pollen depend on the floristic composition while factors that can influence this composition are the main characteristics of the vegetation surrounding the environment of deposition, the dispersal mode of plants and paleogeographic and paleoclimatic

Fig. 6. 1. *Lundbladispora braziliensis* (Pant & Srivastava) Marques-Toigo & Pons. CICYTTP-PI 2581 (residue).

2. *Velamisporites cortaderensis* (Césari & Limarino) Playford. CICYTTP-PI 2577-1 EF Y24/2.
3. *Stenozonotriletes menendezii* Azcuy. CICYTTP-PI 2577-1 EF Z60/3.
4. *Leiotriletes* sp. cf. *L. tenuis* Azcuy. CICYTTP-PI 2581-R1 EF D42/0.
5. *Anapiculatisporites concinnus* Playford. CICYTTP-PI 2577-2 EF Z61/0.
6. *Apiculatisporites caperatus* Menéndez & Azcuy. CICYTTP-PI 2581-R1 EF L36/2.
7. *Apiculatisporites parviapiculatus* Azcuy 1975. CICYTTP-PI 2581 (residue).
8. *Apiculatisporites variornatus* di Pasquo, Azcuy & Souza. CICYTTP-PI 2577 (residue).
9. *Apiculatisporites densus* Pérez Loinaze & Césari in Césari et al. CICYTTP-PI 2577-3 EF Q16/1.
10. *Foveosporites pellucidus* Playford & Helby. CICYTTP-PI 2577-2 EF G62/0.
11. *Lophotriletes intermedius* Azcuy. CICYTTP-PI 2577-4 EF E24/3.
12. *Microreticulatisporites punctatus* Knox (= *M. microreticulatus* Knox). CICYTTP-PI 2581-1 EF S47/1.
13. *Verrucosporites patelliformis* (Menéndez) Limarino & Gutiérrez. CICYTTP-PI 2577 (residue).
14. *Laevigatosporites vulgaris* (Ibrahim/Potonié & Kremp) Alpern & Doubinger. CICYTTP-PI 2577-4 EF M53/4.
15. *Granulatisporites parvus* (Ibrahim) Schopf et al. CICYTTP-PI 2583 (residue).
16. *Convolutispora sculptilis* Felix & Burbridge. CICYTTP-PI 2581 (residue).
17. *Granulatisporites* sp. cf. *G. austroamericanus* Archangelsky & Gamero. CICYTTP-PI 2581-R1 EF S17/1.
18. *Calamospora hartungiana* Schopf in Schopf, Wilson & Bentall. CICYTTP-PI 2577-1 EF Q41/3.
19. *Convolutispora* sp. cf. *C. ordonensis* Archangelsky & Gamero. CICYTTP-PI 2581-2 EF M18/0.
20. *Cyclogranisporites rinconadensis* Césari & Limarino. CICYTTP-PI 2577-2 R47/3.

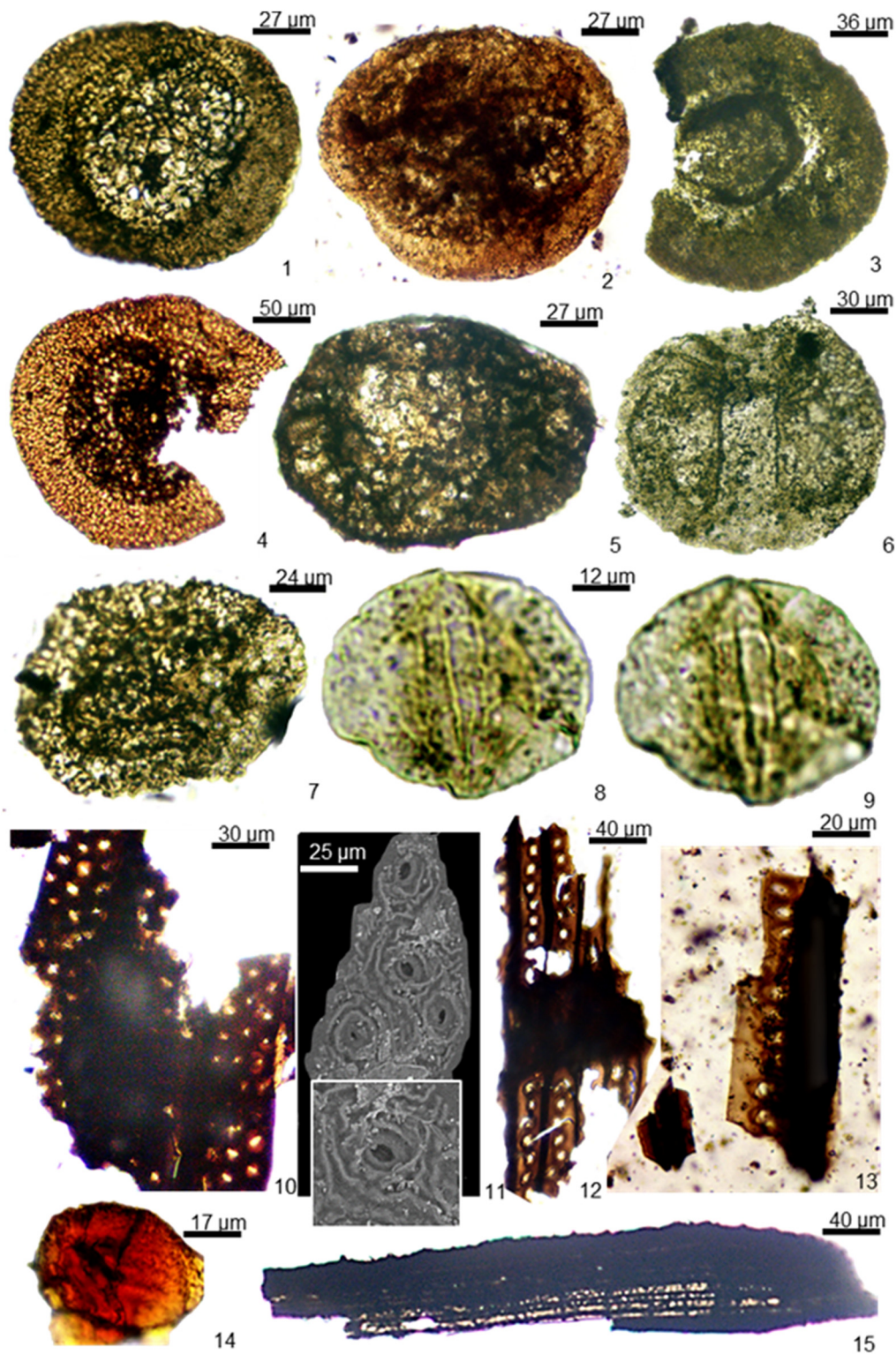


Plate 3

Fig. 7. 1. *Cannanoropollis janakii* Potonié & Sah. CICYTTP-PI 2577-1 EF K33/1.
 2, 5, 7. *Potoniopsisporites* spp. 2. CICYTTP-PI 2577-4 EF Q44/0. 5. CICYTTP-PI 2579-1 EF J43/2. 7. CICYTTP-PI 2583-1 V49/0.
 3-4. *Circumplicatipollis plicatus* Ottone & Azcuy. 3. CICYTTP-PI 2577 (residue). 4. CICYTTP-PI 2577-4 EF W33/0.
 6. *Crucisaccites monoletus* Maithy. CICYTTP-PI 2577 (residue).
 8-9. *Illinites unicus* Kosanke emend. Jansonius & Hills. CICYTTP-PI 2577-1 EF Z67/0.
 10-15. Phytodebris.
 10, 12, 13, 15. Tracheids. 10. CICYTTP-PI 2577-4 EF L20/0. 12. CICYTTP-PI 2577-4 EF G60/0. 13. CICYTTP-PI 2577-1 EF P40/2.
 15. CICYTTP-PI 2581 (residue).
 11. SEM image of a cuticle with stomata. CICYTTP-PI 2577 (residue).
 14. Resinite. CICYTTP-PI 2581-R1 EF Z57/0.

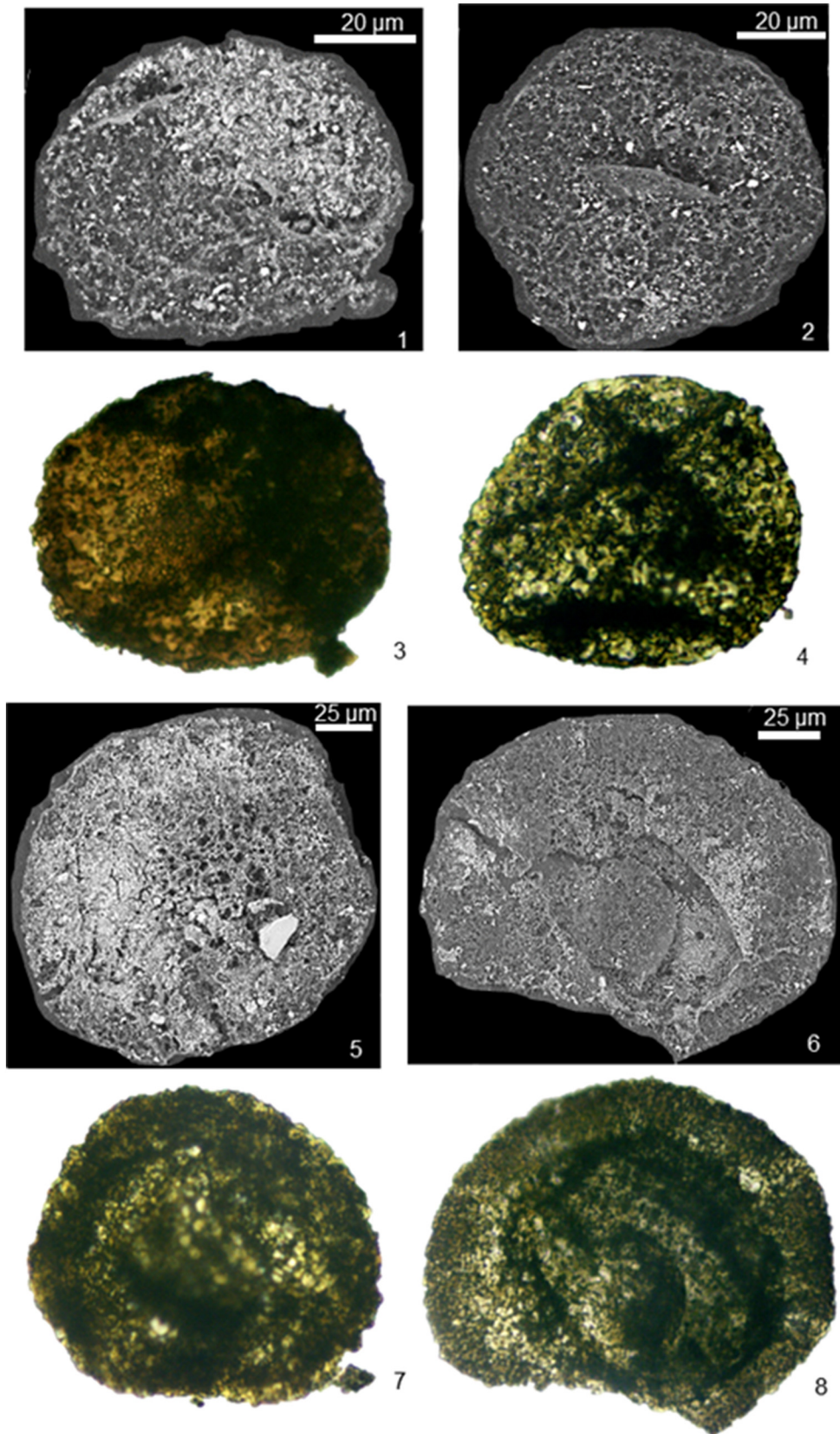


Plate 4

Fig. 8. The same specimen of each species illustrated under light and SEM microscopes.
 1, 3. *Lundbladispora braziliensis* (Pant & Srivastava) Marques-Toigo & Pons. CICYTTP-PI 2577 (residue).
 2, 4. *Microreticulatisporites punctatus* Knox. CICYTTP-PI 2577 (residue).
 5, 7. *Cannanoropollis mehtae* (Lele) Bose & Maheshwari. CICYTTP-PI 2577 (residue).
 6, 8. *Circumplicatipollis plicatus* Ottone & Azcuy. CICYTTP-PI 2577 (residue).

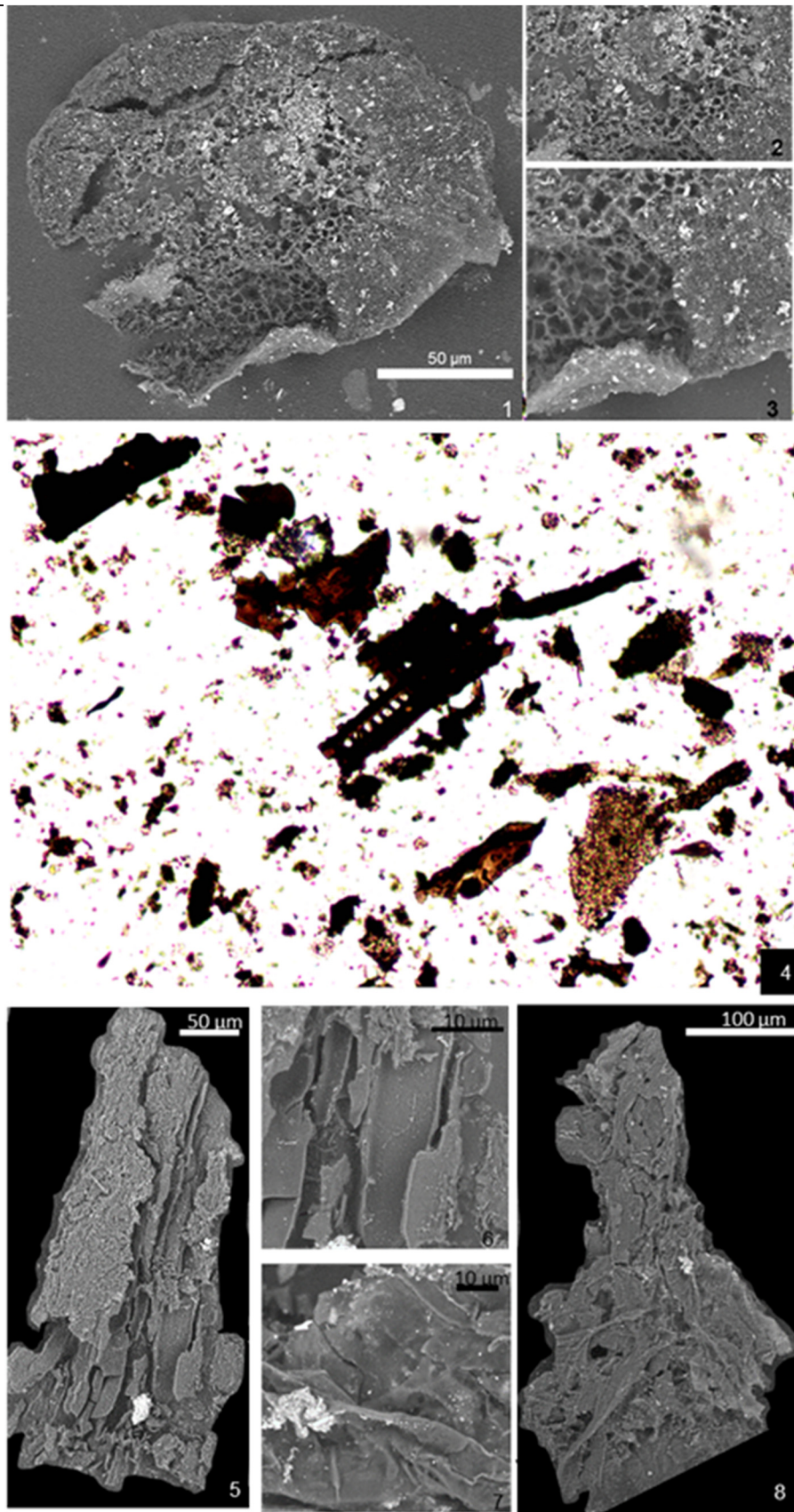
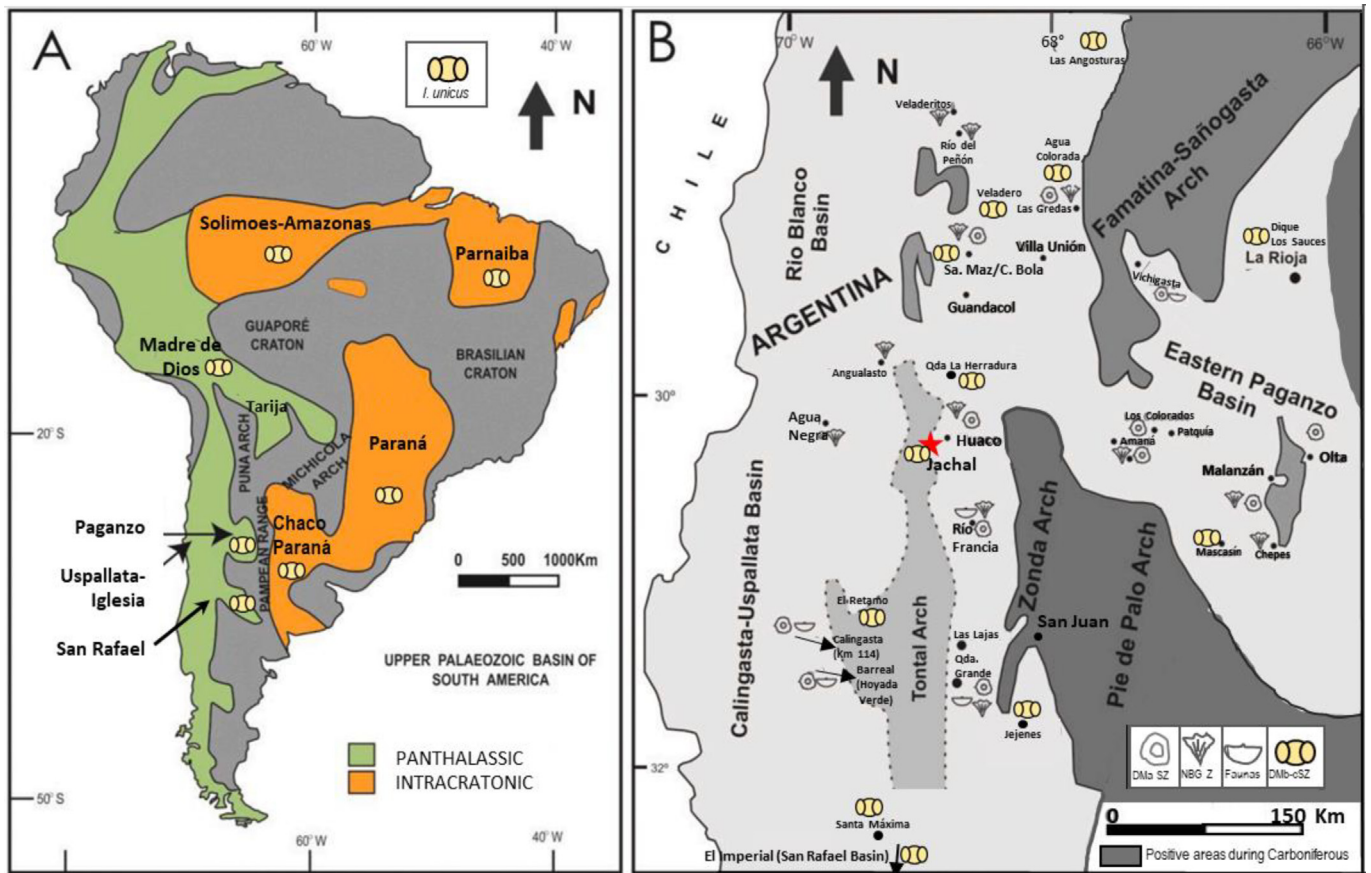


Plate 5

Fig. 9. Monosaccate pollen grain and phytodebris picked from CICYTTP-PI 2577 residue. 1–3. SEM image showing the external and internal structure of the exine of a monosaccate pollen grain. 4. Picture of slide under light microscope. 5–8. SEM images of phytodebris specimens.



References (from Césari and Pérez Loinaze, 2021, supplm.)	SUBZONE B												SUBZONE C			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
<i>Striatoabieites</i> spp.	X															
<i>Striomonosaccites</i> sp.																
<i>Protohaploxypinus limpidus</i> (Balme and Hennelly) Balme and Playford 1967																
<i>Protohaploxypinus perfectus</i> (Naumova ex Kara-Murza 1952) Samoilovich 1953																
<i>Protohaploxypinus</i> sp.		X														
<i>Striatoabieites multistriatus</i> (Balme and Hennelly) Hart 1964																
<i>Protohaploxypinus amplius</i> (Balme and Hennelly) 1955) Hart 1964																
<i>Protohaploxypinus bharadwajii</i> Foster 1979																
<i>Protohaploxypinus clarensis</i> Menéndez 1976																
<i>Hamiapollenites insolitus</i> (Bharadwaj and Saluja) Balme 1970																
<i>Lunatisporites varisectus</i> Archangelsky and Gamero 1979																
<i>Protohaploxypinus haigii</i> Foster 1979																
<i>Vittatina</i> sp.																
Number of species	1	1	3	2	1	1	1	1	1	1	5	4	4			

Fig. 11. A. Paleogeographic map showing the presence of *Illinites unicus* in different Pennsylvanian–Cisuralian deposits of South American basins. References: late Bashkirian, Paganzo Basin (di Pasquo and Milana, 2021, and this work). Moscovian–Ghzelian, Perú (Azcuy et al., 2002), Brazil, Amazonas (Playford and Dino, 2000b), Parnaíba (Dino and Playford, 2002; Souza et al., 2010). Kasimovian–Ghzelian, Argentina, Chacoparaná Basin (Gutiérrez and Balarino, 2018). Ghzelian–Artinskian, Brazil, Paraná Basin (Souza, 2006; Rischbieter et al., 2022), Uruguay, (Gutiérrez et al., 2010), Argentina, Paganzo Basin (di Pasquo et al., 2010; Correa et al., 2012), San Rafael Basin (Vázquez et al., 2020). B. Western Argentinian Range (taken/modified from Valdez et al., 2020), in which localities with striate pollen taxa (C) are documented. DMb SZ references after Césari and Pérez Loinaze (2021): 1. Minas Victoria and La Negra, Sierra de Maz, Tupe Formation (Césari, 1984, 1986). 2. Las Angosturas, Stage 4 and 5 Agua Colorada Formation (upper levels, Césari et al., 2019). 3. Agua Colorada, Agua Colorada Formation (upper levels, Vergel and Lech, 2001). 4. Agua Colorada, Agua Colorada Formation (upper fluvial levels, Gutiérrez, 1993). 5. Jejenes, Jejenes Formation (upper levels, Vázquez et al., 2017). 6. Santa Máxima, Lower association Santa Máxima Formation (Ottone, 1989). 7. Retamo, El Retamo Formation (Carrizo, 1992). 8. Veladero, Deltic platform and fluvial deposits of Quebrada Larga Formation (Limarino et al., 2014b). 9. El Imperial Formation (Vázquez et al., 2020). (DMc SZ) 10. Quebrada La Herradura, FA5 Tupe Formation (Pérez Loinaze et al., 2014). 11. Mascasín, Mascasín Formation (Pérez Loinaze and Césari, 2004). 12. Dique Los Sauces, Libertad Formation (di Pasquo et al., 2010). For references of DMA SZ see Valdez et al. (2020, 2021) and Césari and Pérez Loinaze (2021), and for localities of Serpukhovian–Moscovian invertebrate zones see Cisterna and Sterren (2022). Note: The Uspallata–Iglesia Basin includes those Río Blanco and Calingasta–Uspallata ones. C. Distribution of striate pollen grain taxa in DMb and DMc zones after Césari and Pérez Loinaze (2021).

Earth’s climate change to relatively warm and humid conditions extended between ca. 320 and 316 Ma according to absolute ages (Fig. 10).

6. Conclusions

The palynologic analysis of the lower shales of the Loma de los Piojos Formation carried out at the homonymous locality yielded two diagnostic taxa, the spore *Spelaeotriletes ybertii* and the striate bisaccate pollen

Illinites unicus that allowed the correlation with the late Bashkirian–Moscovian B Subzone of the DMZ. This subzone is distinguished of the underlying (late Serpukhovian–mid Bashkirian) DMA SZ due to the appearance of striate bisaccate pollen grains. Moreover, the *Illinites unicus* recovered from the Loma de los Piojos Formation is the oldest record for the early Pennsylvanian of South America (Fig. 11).

This new age is important because it allows us to support the inclusion of the informal flora *Frenguellia eximia*–*Nothorhacopteris kellybelenensis*–*Cordaicarpus cesarii* (FNC) that Balseiro et al. previously

described in the overlying beds of our same outcrop, into the early Pennsylvanian *Nothorhacopteris–Botrychiopsis–Ginkgophyllum* NBG Zone (Fig. 10). The palynofacies and floristic composition of the Loma de los Piojos Formation support that warm and humid conditions prevailed during its deposition in a water body under low energy conditions, for the shale interval.

The analysis of the stratigraphic interrelations of the late Paleozoic units in this locality of western Precordillera suggests that the Loma de los Piojos Formation was deposited within a series of superimposed incised valleys, initiated in the Don Buenaventura Formation as recently described, and ending with the Guandacol Formation paleovalley in this area of the western Paganzo Basin. The Loma de los Piojos Formation corresponds to the evolution of the last depositional sequence of the Don Buenaventura Formation. Also, in this same locality, the Guandacol Formation is another glacial-related depositional sequence associated with a major sedimentary conduit (a paleovalley) connecting two contrasting areas, the internal continental area of the Paganzo Basin realm and marine dominant basins to the west (e.g. Río Blanco Basin, Fig. 11). The fine grained interval of the Loma de los Piojos Formation is part of the Warm Humid Interval during which deglaciation processes prevailed. A regional maximum flooding event documented in the early Bashkirian of western Argentina is traced across South America up to the Paraná Basin (Fig. 10).

Data availability

Data will be made available on request.

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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