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The latest Carboniferous-earliest Permian palynological assemblage from the Sauce Grande Formation, Claromecó Basin, Argentina: Implications for the local palynostratigraphic scheme and correlations in Western Gondwana

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ABSTRACT

The Sauce Grande Formation of the Ventania System and Claromecó Basin, east-central Argentina, is a geological unit of glaciomarine origin showing evidence of the glaciation that affected the supercontinent of Gondwana during the late Paleozoic. The age of this unit was previously determined from scarce and poorly preserved fossils, but mainly from radiometric dating and the fossil content of the overlying geological units. This study presents a palynological assemblage obtained from the Sauce Grande Formation in the PANG 0002 borehole, drilled in the Upper Paleozoic Claromecó Basin. Based on the identification of key species, such as *Converrucosisporites confluens*, *Pakhapites ovatus*, *P. fusus*, *Vittatina* spp., and *Weylandites magmus*, an age no older than Gzhelian is inferred for the interval studied. The inferred age allows us to relate the glaciomarine deposits of the Sauce Grande Formation to the last episode of the late Paleozoic Ice Age. The palynological assemblage of the Sauce Grande Formation is correlated with the *Converrucosisporites confluens-Vittatina vittifera* (CV) Biozone of the Claromecó Basin. Based on updated information and new correlations of the CV Biozone with palynostratigraphic schemes established in neighboring basins (Chacoparaná, Paraná, and central-western Argentina), its age is adjusted to the Gzhelian-late Artinskian interval, encompassing the Carboniferous-Permian boundary. This new information contributes to refining the current biostratigraphic scheme of the late Paleozoic Claromecó Basin.

1. Introduction

The glaciomarine Sauce Grande Formation (Harrington, 1947, 1970) is the lowest unit of the late Paleozoic Pillahuincó Group, which outcrops in the eastern Sierras Australes, Buenos Aires Province, Argentina, and extends over the subsurface in the adjacent Claromecó Basin. Since the beginning of the 20th century, the Sauce Grande Formation has been assigned to the Upper Paleozoic based on correlation with the diamictites of the Dwyka Group in South Africa (Keidel, 1916). Subsequently, mainly indirect evidence has been used to infer the age of the Sauce Grande Formation, including radiometric dating and fossil content of the overlying Piedra Azul, Bonete, and Tunas formations, as no well-preserved fossils had been found within this unit that led to refining its age (cf. di Pasquo et al., 2008).

The main palynological studies in the Claromecó Basin were carried out by di Pasquo et al. (2008) with surface samples of the Sauce Grande Formation and by Balarino (2009, 2012, and 2014) with subsurface cutting and core samples from the Piedra Azul, Bonete, and Tunas formations. di Pasquo et al. (2008) analyzed outcrop samples of the Sauce Grande Formation and assigned the recovered palynological assemblage to the Late Pennsylvanian-Cisuralian. Balarino (2014) established the local palynostratigraphic scheme based on samples from the La Estrella x-1 and Cruz del Sur X-1 boreholes (Fig. 1b), identifying two palynozones: 1- the *Converrucosisporites confluens- Vittatina vittifera* (CV)

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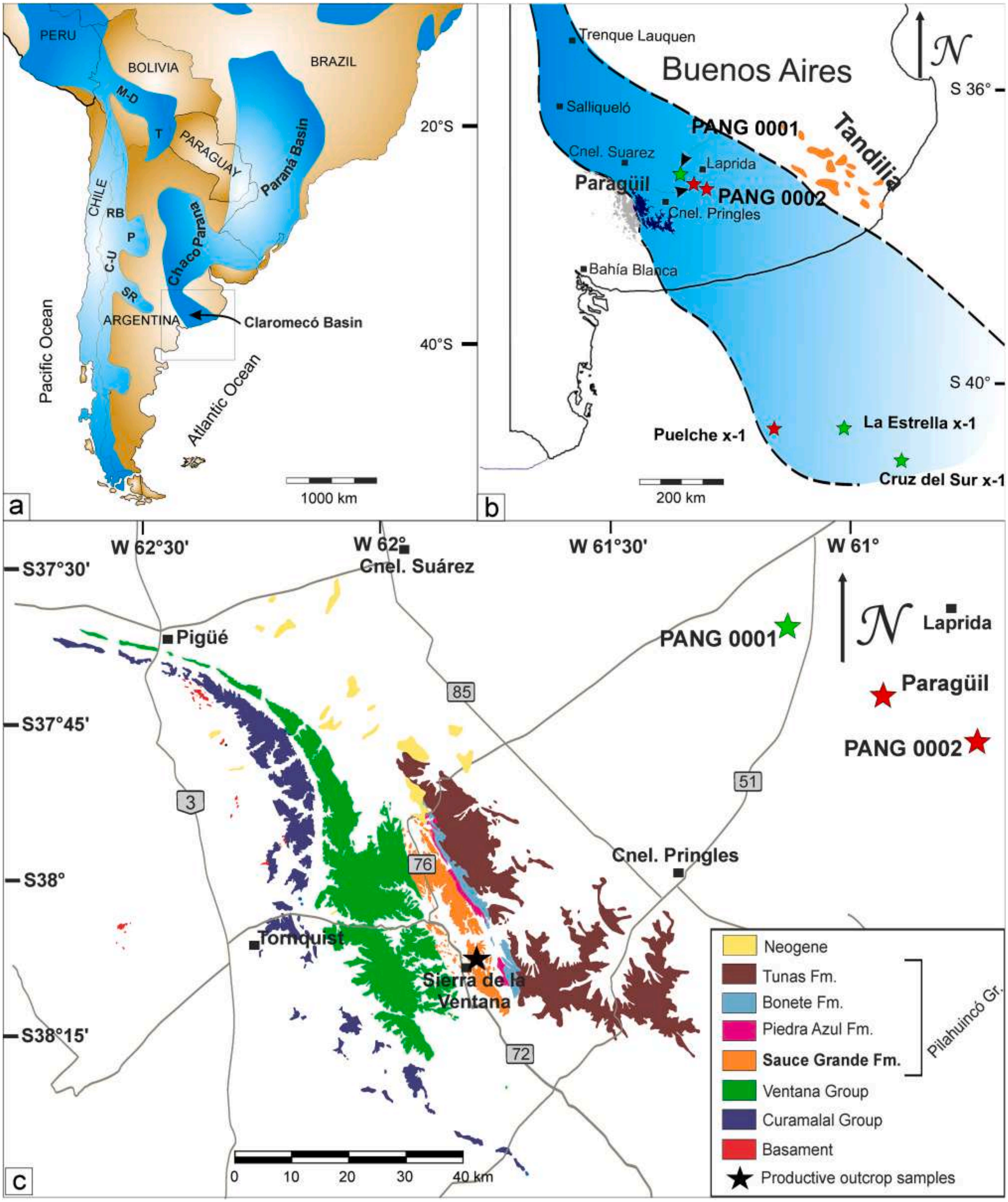

Fig. 1. a. Geographic location of late Paleozoic Gondwanan basins (modified from Azcuy et al., 2007) in South America. B. Boundaries of the Claromecó Basin in the continental area of Buenos Aires province and its extension on the Argentine Continental Shelf during the late Paleozoic. The location of boreholes that yielded palynomorphs is indicated by stars and names: Puelches x-1 (Archangelsky and Gamerro, 1980; Archangelsky, 1996), Paragüil (Archangelsky, 1999 in Lesta and Sylwan, 2005), La Estrella x-1 and Cruz del Sur x-1 (Balarino, 2012, 2014); PANG 0001 (di Pasquo et al., 2018), and PANG 0002 (Di Nardo et al., 2021, 2022, and this contribution). Boreholes drilled into the Sauce Grande Formation are indicated with red stars. Green stars indicate the locations of boreholes that did not reach the Sauce Grande Formation. c. Geological map of the Sierras Australes modified after Harrington (1947) and Furque (1973, 1979). The black star indicates the location of the only Paleozoic palynologically fertile outcrop of the entire Sierras Australes area (di Pasquo et al., 2008). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Biozone, recognized in the Piedra Azul and Bonete formations, and 2- the *Tornopollenites toreutos-Reduviasporonites chalastus* (TC) Zone, identified in the Tunas Formation. The palynology of the lowermost Sauce Grande Formation was not included in this palynozonation because the La Estrella x-1 and Cruz del Sur x-1 boreholes did not reach this unit.

This study aims to present a new palynological record from the Sauce Grande Formation in the subsurface of the Claromecó Basin, where the PANG 0002 exploration borehole was drilled (Fig. 1). For the first time, a reliable age for the deposition of the unit is presented based on its fossil content, which helps to delimit the age of the late Paleozoic Ice Age in the Claromecó Basin. In addition, the age of the CV Biozone is refined considering the new palynological data presented here its correlations with recently updated palynozonations from southwestern Gondwana, and additional age proxies.

2. Geological setting

The Upper Paleozoic Claromecó Basin covers an area of approximately 50,000 km^2 in Buenos Aires Province (Lesta and Sylwan, 2005). The Basin is considered a foredeep associated with the Ventania fold and thrust belt (Ramos, 1984; López-Gamundí and Rossello, 1992; Ramos and Kostadinoff, 2005). More recently, Pángaro et al. (2016) interpreted the Claromecó depocenter as part of the Hespérides Basin, in lateral continuity with the Karoo, Kalahari, and Chacoparaná basins. The Hespérides Basin is believed to be one of the largest Pennsylvanian-Lower Triassic basins in the southwestern region of Gondwana.

The Pillahuincó Group (Harrington, 1947, 1970) outcrops in the Sierras Australes area (Fig. 1) and constitutes the infill of the late Paleozoic Claromecó Basin. This group includes the Sauce Grande, Piedra Azul, Bonete, and Tunas formations, in ascending order. The glaciomarine Sauce Grande Formation (Harrington, 1947, 1970) overlies the Devonian Lolén Formation. The contact between these two units is controversial. However, there is consensus that a regional unconformity and a hiatus spanning the Upper Devonian to the middle Pennsylvanian exist between the Lolén and Sauce Grande formations (Tomezzoli et al., 2023, and references therein). The upper boundary of the Sauce Grande Formation with the Piedra Azul Formation is transitional, marked by a gradual decrease in the abundance of diamictites and an increase in shale (Harrington, 1947, 1970).

Andreis and Torres Ribeiro (2003) analyzed two sections in the Sauce Grande Formation and identified three megacycles. The lower megacycle (∼400–700 m) is composed mainly of diamictites with few sandstones and conglomerates. It was interpreted as a slope apron located near the continental slope. The middle megacycle (∼40–50 m) comprises sandstones and conglomerates. It was interpreted as a rapid phase of glacial advance related to isostatic shallowing. The upper megacycle (∼350 m), in which the abundance of sandstones and shales increases, was related to the transgression that continued in the Piedra Azul Formation. López-Gamundí et al. (2021, 2023) reinterpreted the three megacycles of Andreis and Torres Ribeiro (2003) as two deglaciation sequences (DS) sensu Visser (1996, 1997): the lower DS includes the lower and middle megacycle, and the upper DS includes the upper megacycle, ending with the marine transgression of the Piedra Azul Formation.

The Sauce Grande Formation has also been identified in the Puelches x-1, Paragüil x-1, and PANG 0002 boreholes (Fig. 1b–c). The PANG 0002 borehole (S 37°46′58.50″, W 60°44′34.86″) is composed of a continuous sequence (219 m) of matrix-supported diamictites, and subordinated sandstones and mudstones (Fig. 2). The entire borehole is correlatable with the Sauce Grande Formation and may represent the uppermost section of the unit (Zavala et al., 2008).

The first references to the age of the Sauce Grande Formation can be attributed to Keidel (1913, 1916), who correlated “the conglomerates that outcrop all along the Sauce Grande River and in the Pillahuincó Ranges” with the Dwyka Group in South Africa, concluding that the

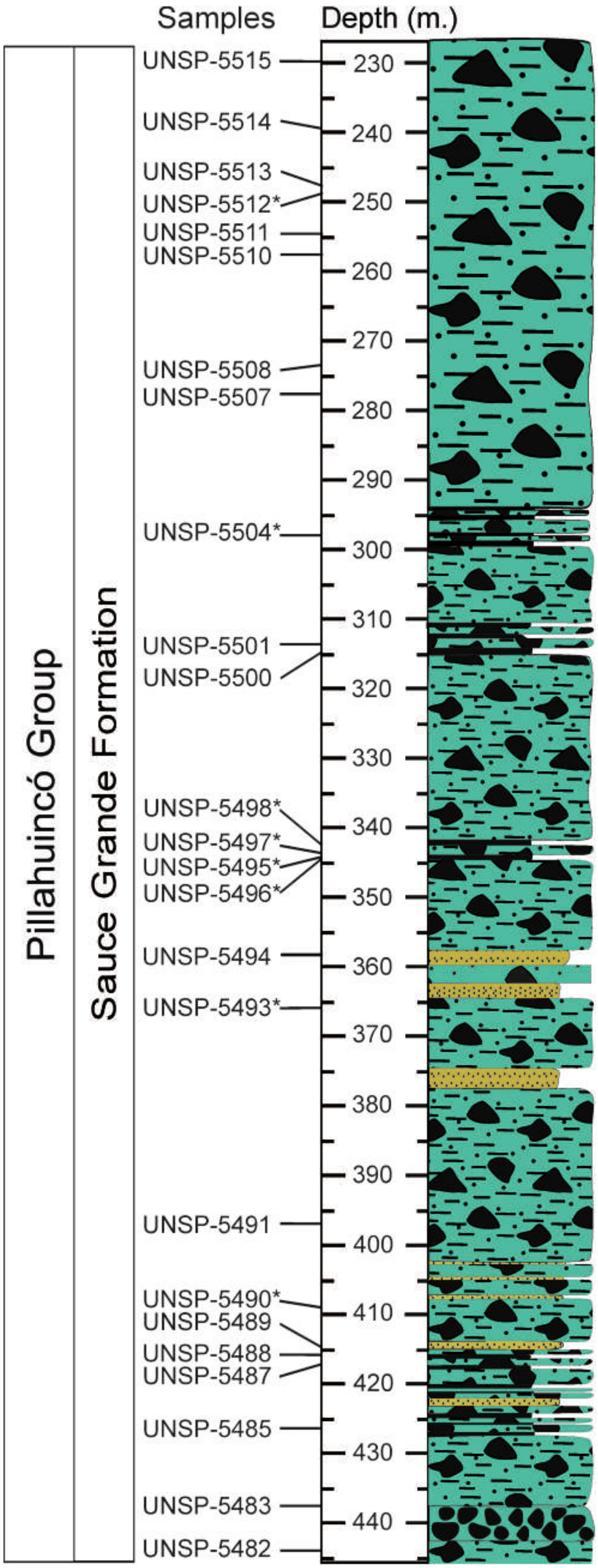

Fig. 2. Generalized stratigraphic column of PANG 0002 borehole, with indication of fertile palynological samples. Samples marked with an asterisk correspond to the most productive levels.

former could not be older than the latter. The palynological content also provided a broad Pennsylvanian-Cisuralian age delimitation for the Sauce Grande Formation (di Pasquo et al., 2008; Di Nardo et al., 2022).

According to Morel and Gutiérrez (2000), plant remains from the *Nothorhacopteris-Botrychiopsis-Ginkgophyllum* (NBG) Biozone or the Interval (=*Krauselcladus-Asterotheca* Biozone Carrizo and Azcuy) have been found in sandstones of the 'Interserrana area', suggesting a Late Carboniferous age, and therefore a probable correlation between these rocks and the Sauce Grande Formation.

The fossil content of the overlying Piedra Azul, Bonete, and Tunas formations, as well as radiometric dating in the Tunas Formation, has also indirectly helped to delimit the age of the Sauce Grande Formation to the Asselian or pre-late Asselian (e.g., López-Gamundí et al., 2021, 2023).

3. Paleontology of the Sauce Grande Formation

Palynomorphs, plants, and marine invertebrates have been reported in the Sauce Grande Formation. The first palynological data of this unit were obtained from cutting samples of the offshore Puelches x-1 borehole (Archangelsky and Gamerro, 1980; also reproduced in Archangelsky, 1996; Fig. 1b), with imprecise reference to the stratigraphic position of the samples studied. Unpublished reports on the palynological content of the onshore Paragüil x-1 borehole have also been mentioned in the literature (Archangelsky, 1998, in Lesta and Sylwan, 2005; Fig. 1b–c), where the assemblage recovered in the middle member of the unit was attributed to the *Potonieisporites-Lundbladispora* Biozone of the Chacoparaná Basin. The unique palynological assemblage from outcrop samples, also in the middle section of the unit, was attributed to the broad range of the Late Pennsylvanian-Cisuralian age (di Pasquo et al., 2008; Fig. 1c). More recently, an association of acritarchs recovered from core samples from the PANG 0002 borehole was referred to as the Pennsylvanian-Cisuralian interval (Di Nardo et al., 2021, 2022).

Poorly preserved remains of a sphenophyte and two lycophyte axes have been found in isolated outcrops of fine-grained sedimentary rocks in the "Interserrana area" near Lumb, Buenos Aires Province. However, there is no consensus regarding the stratigraphic position of these levels, which have been correlated with the Sauce Grande (e.g., Andreis et al., 1987) or Tunas (e.g., Andreis et al., 1990; Andreis and Japas, 1996) formations. According to various authors, these plant remains have been referred to as different taxa. In particular, the lycophyte axes were described as *Cyclostigma* sp. by Terraza and Deguillén (1973), as *Lycopodiopsis* cf. *millani* by Arrondo and Petriella (1982), and as *Bumbudendron* sp. cf. *B. millani* by Andreis and Japas (1996). Later, Morel and Gutiérrez (2000) reassigned these lycophytes to *Malanzania nana* Archangelsky, Azcuy and Wagner, an element of the NBG Biozone (late Serpukhovian- earliest Moscovian, according to Césari, 2023), or the *Krauselcladus-Asterotheca* Biozone Carrizo and Azcuy, previously known as the "Interval" (late Kasimovian-Gzhelian, according to Carrizo and Azcuy, 2015).

The paleontological record of the unit is completed by only one closed bivalve, referred to as *Astartella*? *pusilla* by Harrington (1955), found in the uppermost beds of the Sauce Grande Formation in the Abra Fea area, Sierra de las Tunas. The presence of poorly preserved, reworked Cambrian archaeocyathids in limestone clasts is also noteworthy, which may correspond to the corals mentioned by Keidel in 1916 (González et al., 2013).

4. Materials and methods

Sixteen core samples of laminated mudstones and matrix-supported diamictites of the Sauce Grande Formation (PANG 0002 borehole; interval 445.7–227.50 m) were studied (Fig. 2). Palynological organic matter was extracted at the Laboratory of Palynology of the Instituto Geológico del Sur-Universidad Nacional del Sur (Bahía Blanca, Buenos Aires Province, Argentina) by applying conventional techniques with hydrochloric and hydrofluoric acids, as described by Volkheimer and Melendi (1976) and Riding (2021). To clarify dark palynomorphs, oxidative techniques using Schulze's solution were applied, with reaction times ranging from 5 to 30 min depending on the opacity and state of preservation of the palynomorphs. The productive residues were mounted using UV-curable acrylate (Trabasil ® NR2) media (Noetinger et al., 2017). Slides were observed under a Nikon eclipse50i transmitted white light microscope. A minimum of 200 palynomorphs were counted from the 8 most productive samples and grouped according to morphological categories. For biostratigraphic purposes, samples with sporadic occurrences of palynomorphs were also examined. The illustrated specimens were captured with a microscope digital camera Amscope MU Series 14.0 MP and are located with England Finder coordinates. The rock samples, residues, and slides are housed at the Instituto Geológico del Sur, Universidad Nacional del Sur, Bahía Blanca, Buenos Aires, Argentina. They are identified by catalog numbers preceded by the acronym UNSP (Universidad Nacional del Sur, Palynology).

5. Results

5.1. Composition of the palynological assemblage

Nineteen spore genera, 25 pollen grain genera, 9 microplankton genera, and one fungal spore genus were recovered (Tables 1, 2). The preservation of palynomorphs is poor to moderate. Their Thermal Alteration Index ranges from 3 to −4, according to Utting and Wielens (1992), and they do not exhibit autofluorescence. Considering the main deterioration classes proposed by Delcourt and Delcourt (1980), the palynomorphs recovered from the PANG 0002 borehole show degradation mainly due to chemical oxidation, as evidenced by the fusion of sculptural features or thinning of the exine. Mechanical damage (e.g., Plate I, figs. 6, 11, and 29; Plate II, fig. 7; Plate V, fig. 4), probably due to post-depositional compaction, is also common. Other types of deterioration are present to a lesser extent and include corrosion due to biochemical oxidation, indicated by locally perforated exines (e.g., Plate I, fig. 14), and evidence of pyrite crystal growth (concealment by authigenic minerals), recognized as cubic cavities (e.g., Plate IV, fig. 4) due to the removal of the original crystals by exposure to oxidative conditions.

Although several specimens show poor preservation or high opacity, a quali-quantitative assessment of the relative abundances of the major palynomorph groups was performed at the most productive levels: UNSP-5490, UNSP-5493, UNSP-5496, UNSP-5495, UNSP-5497, UNSP-5498, UNSP-5504, and UNSP-5512 (Fig. 3). Specimens were classified as indeterminate palynomorphs, acritarchs, psilate, ornamented, or cinguli-zonate spores, and monosaccate, taeniate, non-taeniate, or colpate pollen grains. The recovered assemblage at these levels is characterized by a predominance of degraded spheroidal palynomorphs (17.1–49.7%), which might correspond to terrestrial palynomorphs (e.g. psilate spores with circular amb, such as *Punctatisporites* spp.) or aquatic palynomorphs (algae and acritarchs, such as sphaeromorphs and *Leiosphaeridia* spp.). Ornamented trilete spores (17.1–53.7%) related to Filicopsida are also abundant, with a predominance of morphotypes belonging to the genera *Converrucosisporites* and *Granulatisporites*. Non-taeniate (1.2–12.6%), taeniate (1.1–8.3%) and monosaccate (1.5–5.3%) pollen grains are less abundant, and colpate (0–2%) pollen grains are very rare. Acritarchs (9.2–27.5%) are mainly represented by *Lancettopsis harringtonii* and related sphaeromorphs (cf. Di Nardo et al., 2022). Terrestrial palynomorphs are dominated by pteridophytes, indicating a paleoflora of humid environments. The presence of acritarchs and one scolecodont (Plate V, fig. 11) suggests transitional to marine environments, and terrestrial spores indicate fluvial influx, representing provenances from lowland landscapes. The lower proportion of gymnosperm pollen grains (e.g., coniferaleans, cordaitaleans, Peltaspermaceae, and Glossopteridales) suggests distal forest

Table 1
Distribution of spores, algae, fungi, and *Incertae sedis* species identified in the samples of PANG 00002 borehole (Sauce Grande Formation).

	Samples (prefixes UNSP)																								
	5482	5483	5485	5487	5488	5489	5490	5491	5493	5494	5496	5495	5497	5498	5500	5501	5504	5507	5508	5510	5511	5512	5513	5514	5515
Spores																									
Brevitriletes cornutus									•					•											
Brevitriletes levis							•			•	•				•										
Brevitriletes sp. cf. *B. parmatus*									•																
Brevitriletes spp.							•		•		•						•					•			
Calamospora spp.											•			•		•	•								
Converrucosisporites sp. cf. *C. micronodosus*							•		•		•	•	•									•			
Converrucosisporites confluens	•	•	cf	•		•	•		•	•	•	•	•	•	•		•			•		•		•	•
Converrucosisporites Morphon							•				•	•	•	•							•	•			
Convolutispora spp.									•																
Cristatisporites spp.		•	•		•		•		•		•			•	•		•							•	•
Cyclogranisporites spp.	•	•				•	•				•		•	•	•		•				•			•	•
Dictyotriletes sp. cf. *D. aules*		•					•										•								
Gondisporites serrulatus									•																
Granulatisporites austroamericanus							•		•		•	•	•	•	•						•	•			
Granulatisporites spp.		•					•		•		•	•	•	•		•	•			•					
Horriditriletes ramosus							•				•		•							•					
Horriditriletes uruguaiensis													•												
Horriditriletes spp.							•		•		•	•	•	•	•		•					•			•
Leiotriletes directus							•																		
Leiotriletes ulutus																	•								
Lophotriletes spp.							•	•	•		•		•		•										
Lundbladispora areolata							•																		
Lundbladispora braziliensis						cf					•						•								
Lundbladispora sp. cf. *L. riobonitensis*									•																
Lundbladispora spp.	•	•					•		•				•	•			•								
Punctatisporites spp.						•	•		•								•								
Raistrickia spp.									•		•														
cf. *Spelaeotriletes ybertii*							•		•					•	•					•					
Striatosporites heyleri														•											
Vallatisporites spp.															•		•								
Verrucosisporites andersonii														•			•								
Verrucosisporites spp.		•					•	•	•		•			•	•		•								
Algae + Fungi + Incertae sedis																									
Brazilea scissa (=*Ovoidites scissus*)											•		•	•			•								
Cymatiosphaera sp. cf. *C. gondwanensis*								•	•																
Deusilites tenuistriatus									•		•		cf	•	•		•					•		•	
Gorgonisphaeridium sp.									•																
Lancettopsis harringtonii	•						•	•	•	•	•	•	•	•			•	•		•	•	•	•	•	
Leiosphaeridia crescentica											•			•											
Leiosphaeridia simplex									•																
Leiosphaeridia talchirensis											•			•			•								
Leiosphaeridia spp.							•	•	•		•	•	•	•			•			•		•			
Pilasporites sp. B Stephenson & Osterloff						•																			
Portalites confertus						•																			
Sphaeromorph gen. et sp. indet. Di Nardo et al.							•		•		•			•			•			•		•			
Acritarch gen. et sp. indet.														•											

Table 2
Distribution of pollen grains species identified in the samples of PANG 00002 borehole (Sauce Grande Formation).

	Samples (prefixes UNSP)																								
	5482	5483	5485	5487	5488	5489	5490	5491	5493	5494	5496	5495	5497	5498	5500	5501	5504	5507	5508	5510	5511	5512	5513	5514	5515
Monosaccate pollen grains																									
Caheniasaccites flavatus											•	•		•		•									
Caheniasaccites spp.														•											
Mabuitasaccites crucistriatus																				•		•			
Meristocorpuss spp.											•														
Plicatipollenites malabarensis									•																
Plicatipollenites sp. cf. *P. gondwanensis*														•											
Plicatipollenites spp.													•											•	
Potonieisporites lelei							•																		
Potonieisporites sp. cf. *P. novicus*							•																		
Potonieisporites spp.							•				•			•											
Tuberisaccites lobatus														•											
Non-taenniate bissacate pollen grains																									
Alisporites/Falcisporites spp.							•				•		•	•			•			•		•			
Alisporites splendens																						•			
Colpisaccites granulosus		•					•		•		•			•			•								
Falcisporites similis														•											
Limitisporites hexagonalis													•												
Limitisporites spp.						•																			
Scheuringipollenites circularis											•			•											
Scheuringipollenites ovatus											•														
Scheuringipollenites spp.											•														
Pteruchipollenites gracilis														•								cf			
Platysaccus spp.											•			•											
Vitreisporites signatus														•											
Indeterminate non-striate						•	•				•	•	•	•	•							•		•	
Striate pollen grains																									
?*Staurosaccites* sp.									•																
cf. *Striatoabieites multistriatus*																	•								
Hamiapollenites fusiformis											•		•	•	•							•			
Illinites talchirensis											•														
Illinites unicus							•				•			•			•					•			
cf. *Lunatisporites variesectus*											•														
Lunatisporites spp.						•	•																		
Marsupipollenites striatus							•				•			•								•			
Marsupipollenites triradiatus							•				•														
Pakhapites fusus														•											
Pakhapites ovatus																						•			
Protohaploxypinus limpidus											•			•											
Protohaploxypinus perfectus														•											
Protohaploxypinus spp.												•	•	•								•			
Vittatina costabilis							•				•			•	•		•								
Vittatina subsaccata											•			•											
Vittatina vittifera		•												•											
Vittatina spp.						•	•				•	•		•								•			
Weylandites magmus														•											
Weylandites spp.						•					•			•											
Indeterminate striate pollen grains		•			•		•	•	•			•	•	•			•					•			
Monocolpate pollen grains																									
Cycadopites spp.							•				•		•	•										•	•

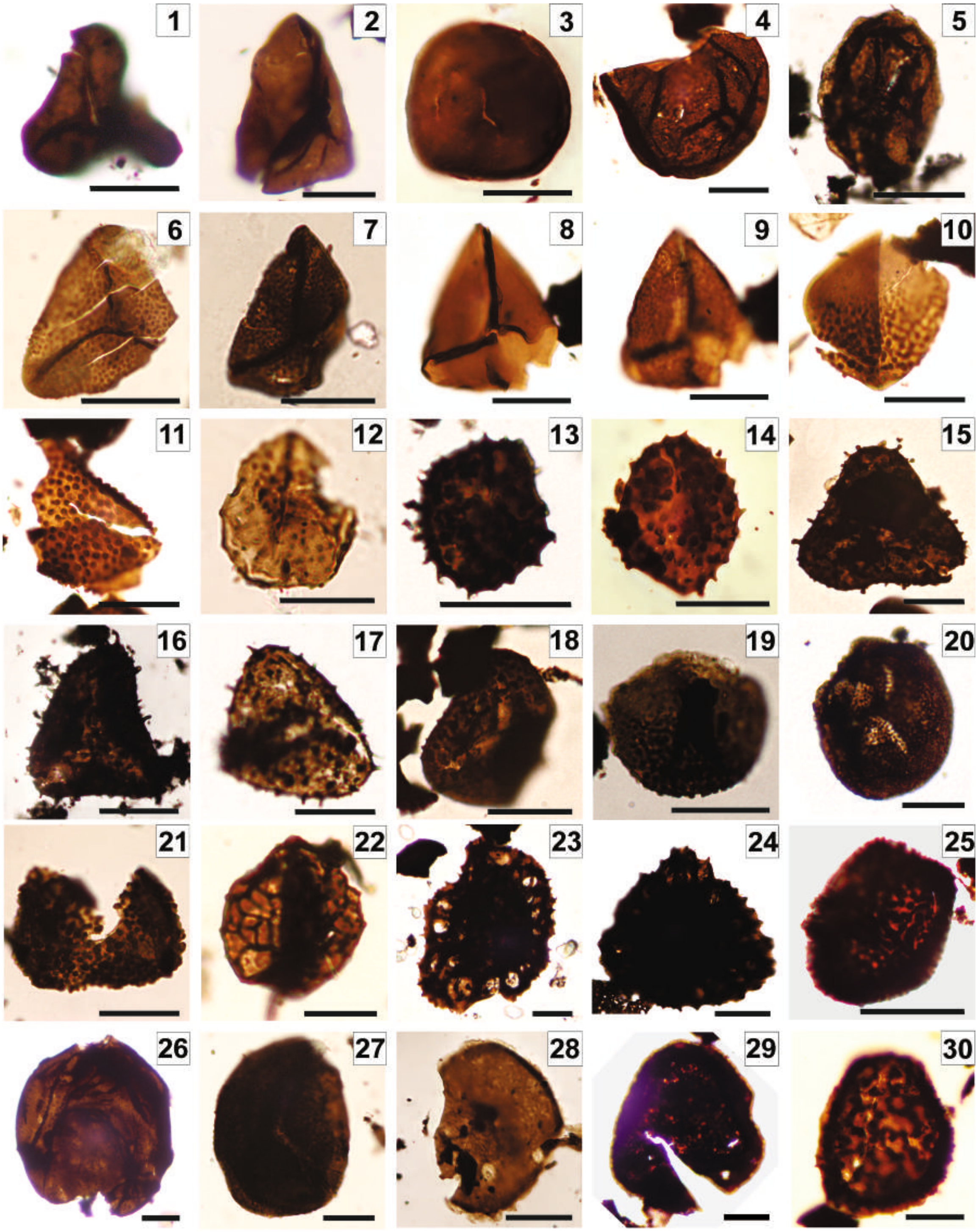

Plate I. Selected spores of the Sauce Grande Formation (PANG 0002). 1. *Leiotriletes ulutus* Utting, 1994, UNSP-5504 N18/2. 2. *Leiotriletes directus* Balme and Hennelly, 1956a UNSP-5490-C C23/0. 3. *Punctatisporites* sp. UNSP-5490-C B15/0. 4. *Calamospora* sp. UNSP-5501 Y7/0. 5. *Cyclogranisporites* sp. UNSP-5497 M34/0. 6. *Granulatisporites austroamericanus* Archangelsky and Gamerro, 1979, UNSP-5493-C F29/2. 7–10. *Converrucosisporites confluens* (Archangelsky and Gamerro) Playford and Dino, 2002; 7. UNSP-5494-C C40/0, 8–9. UNSP-5493-C B44/3 (proximal and distal surface, respectively), 10. UNSP-5493-C C31/2. 11. *Converrucosisporites* sp. cf. *C. micronodosus* (Balme and Hennelly) Playford and Dino, 2002, UNSP-5493-C B36/0. 12. *Brevitriletes* sp. cf. *B. parmatus* (Balme and Hennelly) Backhouse, 1991, UNSP-5493-C X40/1. 13–14. *Brevitriletes cornutus* (Balme and Hennelly) Backhouse, 1991; 13. UNSP-5498 Y25/3; 14. UNSP-5493-C B43/1. 15. *Horriditriletes ramosus* (Balme and Hennelly) Bharadwaj and Salujha, 1964, UNSP-5510-C X25/0. 16. *Horriditriletes uruguaiensis* (Marques-Toigo) Archangelsky and Gamerro, 1979, UNSP-5497 N25/1. 17–18. *Lophotriletes* spp.;17. UNSP-5496 Z37/0. 18. UNSP-5490 T18/4. 19. *Verrucosisporites andersonii* (Anderson) Backhouse, 1988, UNSP-5498 L22/0. 20–21. *Verrucosisporites* spp.; 20. UNSP-5498-2 T21/1; 21. UNSP-5393-C B23/3. 22. *Dictyotriletes* sp. cf. *D. aules* Rigby 1977, UNSP-5504-1 F27/0. 23. *Vallatisporites* sp., UNSP-5504-C X34/0. 24–25. *Cristatisporites* spp.; 24. UNSP-5500-2 W24/4; 25. 5498–2 E24/2. 26. *Striatosporites heyleri* (Doubinger) Playford and Dino 2000, UNSP-5498-5 R36/0. 27. *Gondisporites serrulatus* Césari et al., 1995, UNSP-5493-C E42/0. 28. *Lundbladispora* sp. cf. *L. riobonitensis* Marques-Toigo and Picarelli 1984, UNSP-5493 D25/2. 29. *Lundbladispora braziliensis* (Pant and Srivastava) Marques-Toigo and Pons emend. Marques-Toigo and Picarelli 1984, UNSP-5496 N25/1. 30. *Lundbladispora areolata* Césari et al., 1995, UNSP-5490-C O25/3. Scale bar =20 μm, except for figs. 1 and 22 (scale bar =10 μm).

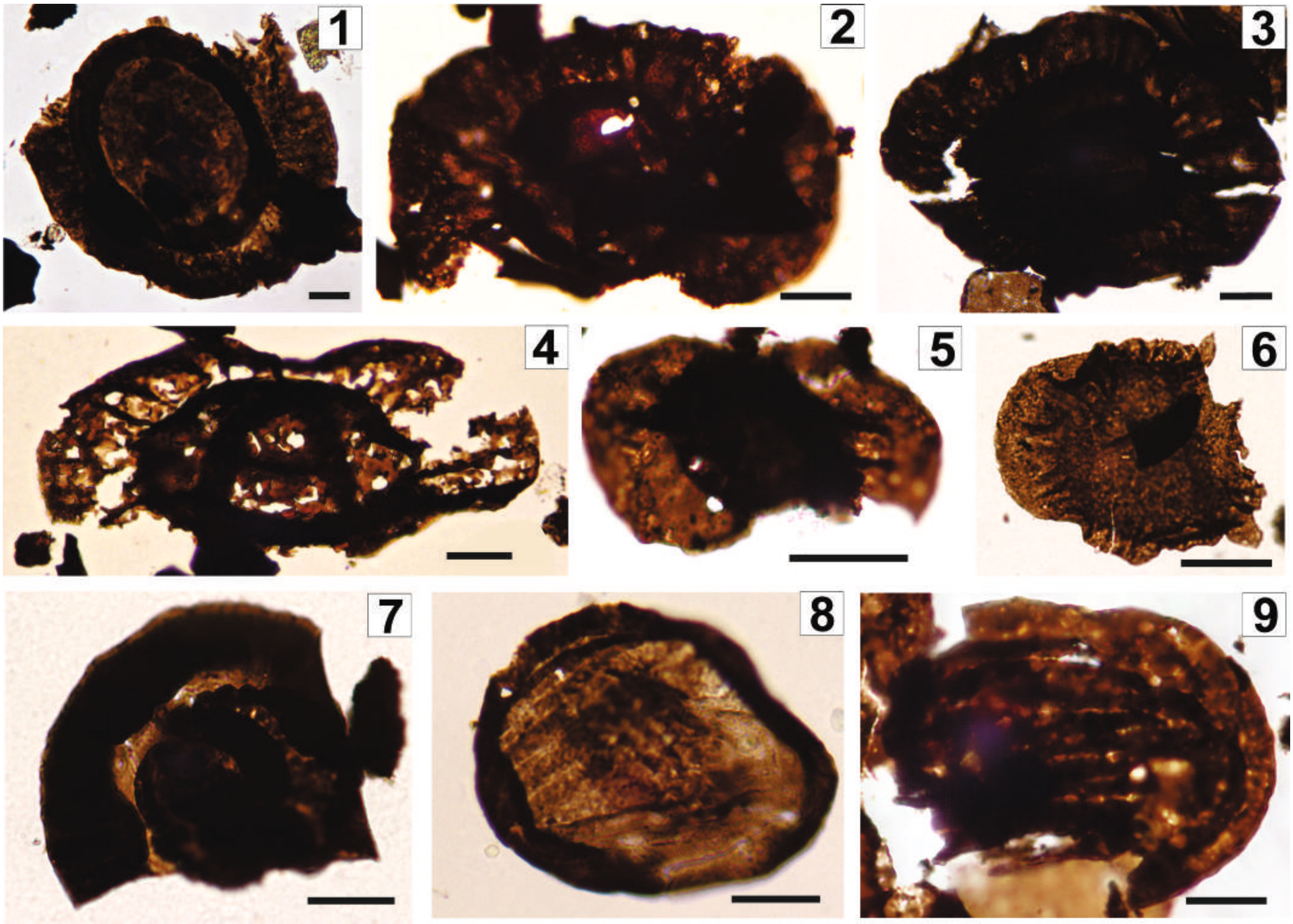

Plate II. Selected striate and non-striate monosaccate pollen grains of the Sauce Grande Formation (PANG 0002). 1. *Plicatipollenites malabarensis* (Potonié and Sah) Foster, 1975, UNSP-5493-C K29/4. 2. *Potonieisporites lelei* Maheshwari, 1967, UNSP-5490-2 O39/2. 3. *Plicatipollenites* sp. cf. *P. gondwanensis* (Balme and Hennelly) Lele, 1964, UNSP-5498-2 Y43/2. 4. *Potonieisporites* sp. cf. *P. novicus* Bharadwaj, 1954, UNSP-5490-C M33/0. 5–6. *Caheniassaccites flavatus* Bose and Kar *emend.* Azcuy and di Pasquo, 2000; 5. UNSP-5496 U42/1; 6. UNSP-5498-2 D43/2. 7. *Tuberisaccites lobatus* Lele and Makada, 1972*,* UNSP-5498-2 U33/3. 8. *Mabuitasaccites crucistriatus* (Ybert) Playford and Dino 2000, UNSP-5510-C D19/1. 9. *Meristocorpus* sp., UNSP-5496 P33/2. Scale bar = 20 μm.

landscapes.

5.2. Systematic paleontology

Most of the recognized species are well known in several Pennsylvanian or Cisuralian palynofloras of South America and elsewhere. Therefore, descriptions, ranges, previous synonym lists, and occurrences of these taxa are avoided here. The reader is referred to Foster (1979), Archangelsky and Gamerro (1979), Césari et al. (1995), García (1995, 1996), Azcuy and di Pasquo (2000), Playford and Dino (2000a, 2000b, 2002), Souza et al. (2003), Beri et al. (2006), Balarino and Gutiérrez (2006), Gutiérrez et al. (2006, 2010), di Pasquo and Grader (2012), Balarino (2012), di Pasquo et al. (2021), and references therein. Additional taxonomic considerations are given only when necessary. The taxa recovered from the samples studied are selectively illustrated in Plates I–V and listed below following the systematical order of Potonié (1970) and others. Lanceolate morphotypes and sphaeromorphs follow the designation given by Di Nardo et al. (2022). Species with few, poorly preserved specimens were assigned to the genus level and were mostly not illustrated.

Anteturma PROXIMEGERMINANTES Potonié, 1970.

Turma TRILETES (Reinsch) Dettmann, 1963.

Suprasubturma ACAVATITRILETES Dettmann, 1963.

Subturma AZONOTRILETES (Luber) Dettmann, 1963.

Infraturma LAEVIGATI (Bennie and Kidston) Potonié, 1956.

Genus: **Calamospora** Schopf et al., 1944.

Type species: *Calamospora hartungiana* Schopf in Schopf et al., 1944.

Calamospora sp. (Plate I, fig. 4).

Genus: **Leiotriletes** Naumova emend. Potonié and Kremp, 1954.

Type species: *Leiotriletes sphaerotriangulus* (Loose) Potonié and Kremp, 1954.

Leiotriletes directus Balme and Hennelly, 1956a (Plate I, fig. 2).

Leiotriletes ulutus Utting, 1994 (Plate I, fig. 1).

2006. *Waltzispora?* sp. A Beri et al., p. 231, Fig. 2D.

Remarks: *Leiotriletes ulutus* has been reported in the *Tornopollenites toreutos–Reduviasporonites chalastus* Biozone Balarino, 2014, whose first occurrence (FO) denotes its basal limit. The specimen illustrated and described as *Waltzispora* sp. A Beri et al. (2006) in the San Gregorio Formation may correspond to this species, as pointed out by Balarino (2009).

Genus: **Punctatisporites** Ibrahim emend. Potonié and Kremp, 1954.

Type species: *Punctatisporites punctatus* (Ibrahim) Ibrahim, 1933.

Punctatisporites sp. (Plate I, fig. 3).

Infraturma APICULATI Bennie and Kidston emend. Potonié, 1956.

Subinfraturma GRANULATI Dybová and Jachowicz, 1957.

Genus: **Cyclogranisporites** Potonié and Kremp, 1954.

Type species: *Cyclogranisporites leopoldi* (Kremp) Potonié and Kremp, 1954.

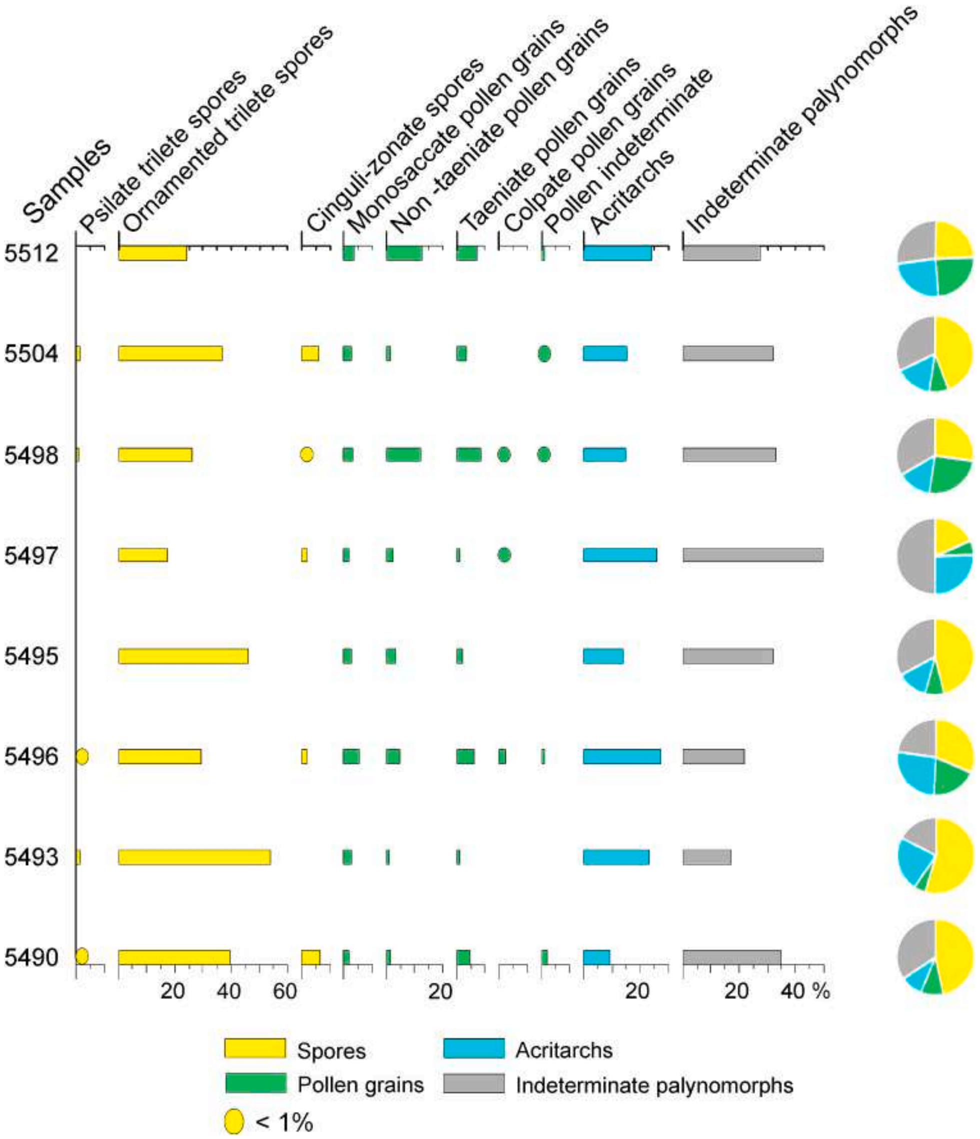

Fig. 3. Semi-quantitative distribution of major palynomorph groups in the Sauce Grande Formation (PANG 0002 borehole), expressed in percentages of total palynoflora, based on a total count of at least 200 palynomorphs.

Cyclogranisporites sp. (Plate I, fig. 5).

Genus: **Granulatisporites** Ibrahim emend. Potonié and Kremp 1954.

Type species: *Granulatisporites granulatus* Ibrahim, 1933.

Granulatisporites austroamericanus Archangelsky and Gamerro, 1979 (Plate I, fig. 6).

Subinfraturma NODATI Dybová and Jachowicz, 1957.

Genus: **Brevitriletes** Bharadwaj and Srivastava, 1969.

Type species: *Brevitriletes communis* Bharadwaj and Srivastava, 1969.

Brevitriletes cornutus (Balme and Hennelly) Backhouse, 1991 (Plate I, figs. 13–14).

Brevitriletes levis (Balme and Hennelly) Bharadwaj and Srivastava, 1969.

Brevitriles sp. cf. *B. parmatus* (Balme and Hennelly) Backhouse, 1991 (Plate I, fig. 12).

Subinfraturma VERRUCATI Dybová and Jachowicz, 1957.

Genus: **Converrucosisporites** Potonié and Kremp, 1954.

Type species: *Converrucosisporites triquetrus* (Ibrahim) Potonié and Kremp, 1954.

Converrucosisporites confluens (Archangelsky and Gamerro) Playford and Dino, 2002 (Plate I, fig. 7–10).

Remarks: Some specimens assigned to this species are smaller than those established in the original diagnosis. Smaller specimens have also been described by Balarino (2009) from the CV Biozone Balarino, 2014. Based on the recognition of an intergradational morphological variation in specimens of *Granulatisporites austroamericanus*, *Converrucosisporites confluens,* and *C. micronodosus*, Playford and Dino (2002) proposed using the term Morphon, following Van der Zwan (1979). The specific intergradation was also recognized by Césari et al. (2013) and Césari and Chiesa (2017). Many intermediate morphotypes between *G. austroamericanus* and *C. confluens* are present in the samples from the Sauce Grande Formation. However, the intergradation with *C. micronodosus* is not clearly evident.

cf. *Converrucosisporites micronodosus* (Balme and Hennelly) Playford and Dino, 2002 (Plate I, fig. 11).

Remarks: Poorly preserved spores with a verrucate exine may correspond to *C. micronodosus*.

Genus: **Verrucosisporites** Ibrahim emend. Smith and Butterworth, 1967

Type species: *Verrucosisporites verrucosus* (Ibrahim) Ibrahim, 1933.

Verrucosisporites andersonii (Anderson) Backhouse, 1988 (Plate I, fig. 19).

Verrucosisporites spp. (Plate I, fig. 20–21).

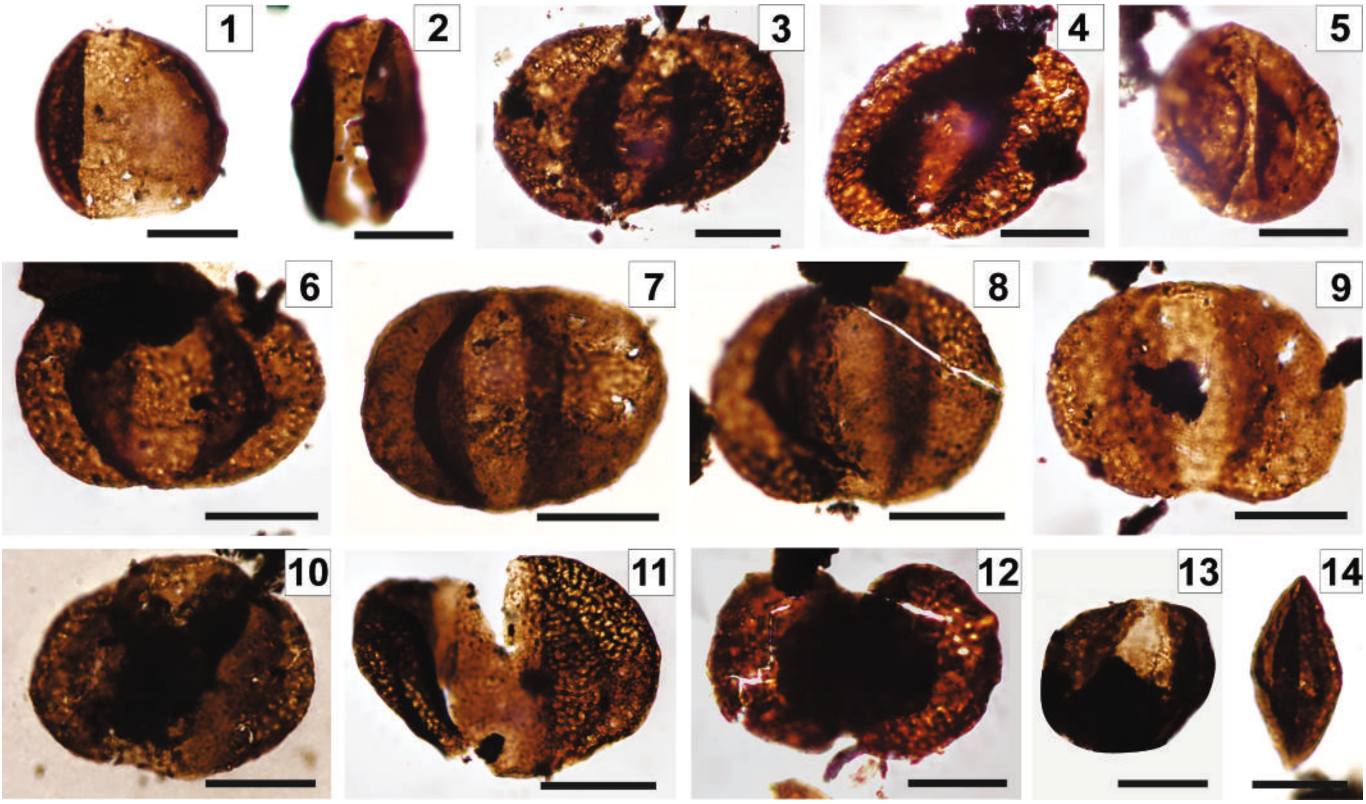

Plate III. Selected non-striate and colpate pollen grains of the Sauce Grande Formation (PANG 0002). 1–2. *Colpisaccites granulosus* Archangelsky and Gamerro, 1979; 1. UNSP-5498 J23/2; 2. UNSP-5504-2 H29/0. 3. *Limitisporites hexagonalis* Bose and Maheshwari, 1968 UNSP-5497 W24/2. 4. *Alisporites splendens* (Leschik) Foster, 1979 UNSP-5512-3026/2. 5. *Scheuringipollenites ovatus* (Balme and Hennelly) Foster, 1975, UNSP-5496 O36/2. 6–9. *Falcisporites similis* (Balme) Balarino, 2012; 6. UNSP-5498 F24/0; 7. UNSP-5498 Q21/1, 8. UNSP-5498 N12/1, 9. UNSP-5498 V11/1. 10. *Pteruchipollenites gracilis* (Segroves) Foster, 1979, UNSP-5498-2 G38/1. 11. *Scheuringipollenites circularis* Césari et al., 1995, UNSP-5510-C W20/0. 12. *Platysaccus* sp., UNSP-5498 Y18/4. 13. *Vitreisporites signatus* Leschik, 1955, UNSP-5498-2 K41/2. 14. *Cycadopites* sp., UNSP-5498G15/0. Scale bar = 20 μm.

Subinfraturma BACULATI Dybová and Jachowicz, 1957.

Genus: **Horriditriletes** Bharadwaj and Salujha, 1964.

Type species: *Horriditriletes curvibaculosus* Bharadwaj and Salujha, 1964.

Horriditriletes ramosus (Balme and Hennelly) Bharadwaj and Salujha, 1964 (Plate I, fig. 15).

Horriditriletes uruguaiensis (Marques-Toigo) Archangelsky and Gamerro, 1979 (Plate I, fig. 16).

Genus: **Lophotriletes** Naumova ex Ischenko emend. Potonié and Kremp, 1954.

Type species: *Lophotriletes gibbosus* (Ibrahim) Potonié and Kremp, 1955.

Lophotriletes spp. (Plate I, fig. 17–18).

Genus: **Raistrickia** Schopf, Wilson and Bentall emend. Potonié and Kremp, 1954.

Type species: ***Raistrickia grovensis*** Schopf in Schopf et al., 1944.

Raistrickia sp.

Infraturma MURORNATI Potonié and Kremp, 1954.

Genus: **Convolutispora** Hoffmeister et al., 1955.

Type species: *Convolutispora florida* Hoffmeister et al., 1955.

Convolutispora sp.

Genus: **Dictyotriletes** Naumova emend. Potonié and Kremp, 1955.

Type species: *Dictyotriletes bireticulatus* (lbrahim) Potonié and Kremp, 1954.

Dictyotriletes sp. cf. *D. aules* Rigby and Hekel, 1977 (Plate I, fig. 22).

Remarks: Two moderately preserved specimens were recovered, similar to those reported from the Sachayoj Formation by Vergel (1998).

Suprasubturma LAMINATRITRILETES Smith and Butterworth, 1967.

Subturma ZONOLAMINATITRILETES Smith and Butterworth, 1967.

Infraturma CINGULICAVATI Smith and Butterworth, 1967.

Cristatisporites spp. (Plate I, figs. 24–25).

Remarks: We include several dark-colored and poorly preserved specimens that cannot be accurately referred to the species level.

Genus: **Gondisporites** Bharadwaj, 1962.

Type species: *Gondisporites raniganjensis* Bharadwaj, 1962.

Gondisporites serrulatus Césari et al., 1995 (Plate I, fig. 27).

Genus: **Lundbladispora** (Balme) Playford, 1965.

Type species: *Lundbladispora wilmontti* Balme, 1963.

Lundbladispora areolata Césari et al., 1995 (Plate I, fig. 30).

Lundbladispora braziliensis (Pant and Srivastava) Marques-Toigo and Pons emend. Marques Toigo and Picarelli, 1984 (Plate I, fig. 29).

Lundbladispora sp. cf. *L. riobonitensis* Marques Toigo and Picarelli, 1984 (Plate I, fig. 28).

Genus: **Vallatisporites** Hacquebard, 1957.

Type species: *Vallatisporites vallatus* Hacquebard, 1957.

Vallatisporites sp. (Plate I, fig. 23).

Suprasubturma PSEUDOSACCITRILETES Richardson, 1965.

Infraturma MONOPSEUDOSACCITI Smith and Butterworth, 1967.

Genus: **Spelaeotriletes** Neves and Owens, 1966.

Type species: *Spelaeotriletes triangulus* Neves and Owens, 1966.

cf. *Spelaeotriletes ybertii* (Marques-Toigo) Playford and Powis, 1979.

Turma MONOLETES Ibrahim, 1933.

Suprasubturma ACAVATOMONOLETES Dettmann, 1963.

Subturma AZONOMONOLETES Luber, 1935.

Infraturma SCULPTATOMONOLETI Dybová and Jachowicz, 1957.

Genus: **Striatosporites** Bharadwaj, 1954.

Type species: *Striatosporites major* Bharadwaj, 1954.

Striatosporites heyleri (Doubinger) Playford and Dino, 2000a (Plate I,

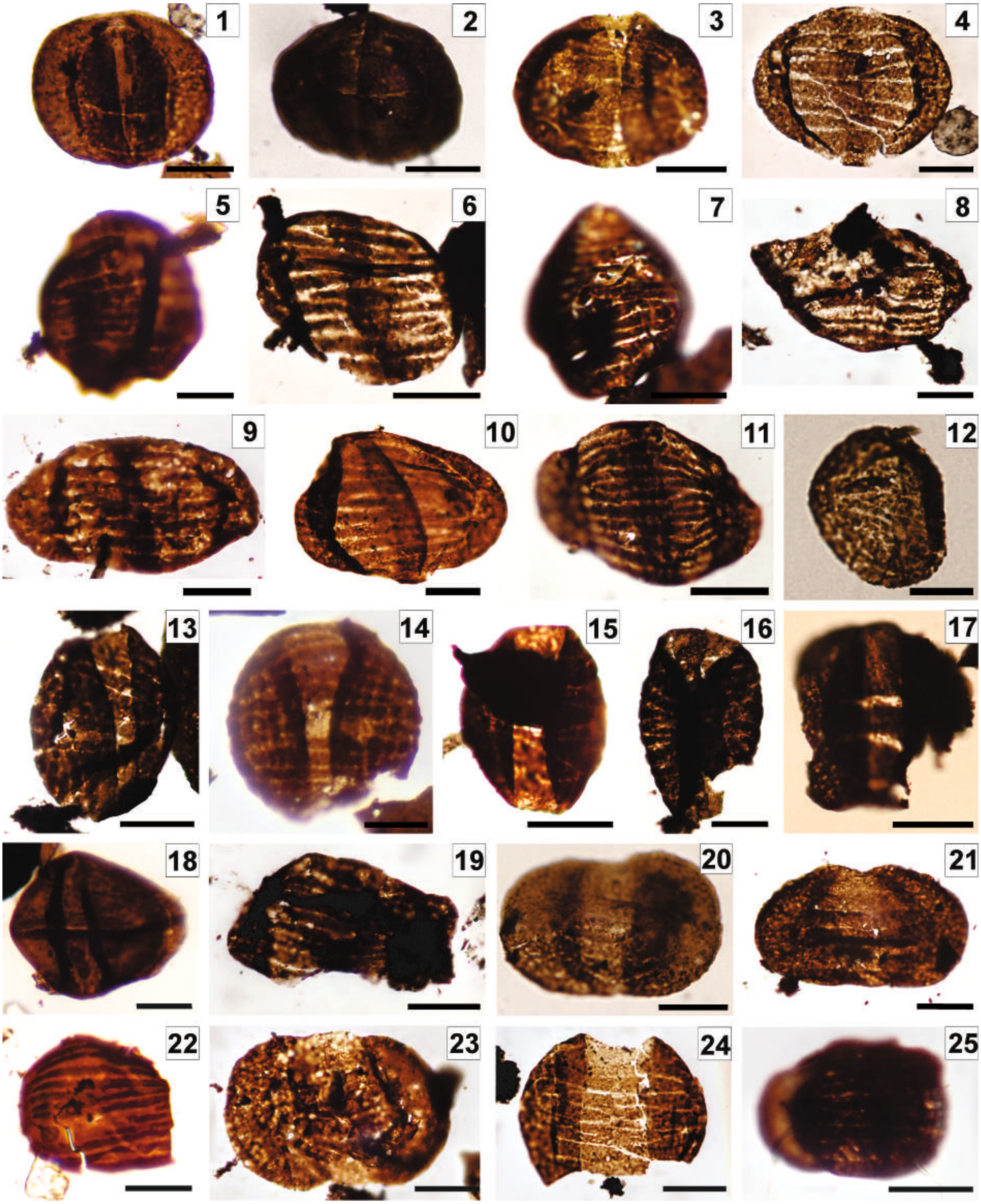

Plate IV. Selected striate pollen grains of the Sauce Grande Formation (PANG 0002). 1–2. *Illinites unicus* Kosanke *emend.* Jansonius and Hills, 1976; 1. UNSP-5498-2 O30/0; 2. UNSP-5512-3 J42/4. 3. *Illinites talchirensis* (Lele and Makada) Azcuy et al., 2002, UNSP-5496-1 F28/0. 4, 9. *Vittatina subsaccata* Samoilovich, 1953; 4. UNSP-5498-1 T38/0. 9. UNSP-5496-1 V16/0. 5–6. *Vittatina costabilis* Wilson, 1962; 5. UNSP-5490-C F21/4; 6. UNSP-5498-1 Z23/2. 7, 22. *Vittatina vittifera* (Luber and Waltz) Samoilovich, 1953; 7. UNSP-5498-1 Y34/1; 22. UNSP-5483-C B31/2. 8. *Vittatina* sp., UNSP-5498-1 F32/2. 10–11. *Hamiapollenites fusiformis* Marques-Toigo *emend.* Archangelsky and Gamerro, 1979; 10. UNSP-5512 Z36/0; 11. UNSP-5496-3 D17/3. 12. *Marsupipollenites striatus* (Balme and Hennelly) Foster, 1975, UNSP-5498-2 B35/0. 13–14. *Weylandites magmus* (Bose and Kar) Backhouse, 1991; 13. UNSP-5498-2 P27/0; 14. UNSP-5498-5 R48/0. 15. *Pakhapites ovatus* (Bose and Kar) García, 1996, UNSP-5512 026/0. 16. *Pakhapites fusus* (Bose and Kar) Menéndez, 1971, UNSP-5498-2 X39/4. 17. *Lunatisporites* sp., UNSP-5490-2 A32/3. 18.?*Staurosaccites* sp., UNSP-5493-C L47/2. 19. *Vittatina* sp., UNSP-5496 R35/2. 20. *Protohaploxypinus perfectus* (Naumova) Samoilovich, 1953 sensu di Pasquo et al., 2021, UNSP-5498-1 P33/3. 21. *Protohaploxypinus limpidus*, UNSP-5498-2 D15/1. 23. cf. *Lunatisporites variesectus* Archangelsky and Gamerro, 1979, UNSP-5496-2 C38/2. 24. *Weylandites* sp., UNSP-5498-1 Y33/0. 25. cf. *Striatoabieites multistriatus* (Balme and Hennelly) Hart, 1964, UNSP-5504-1 H37/1. Scale bar = 20 μm.

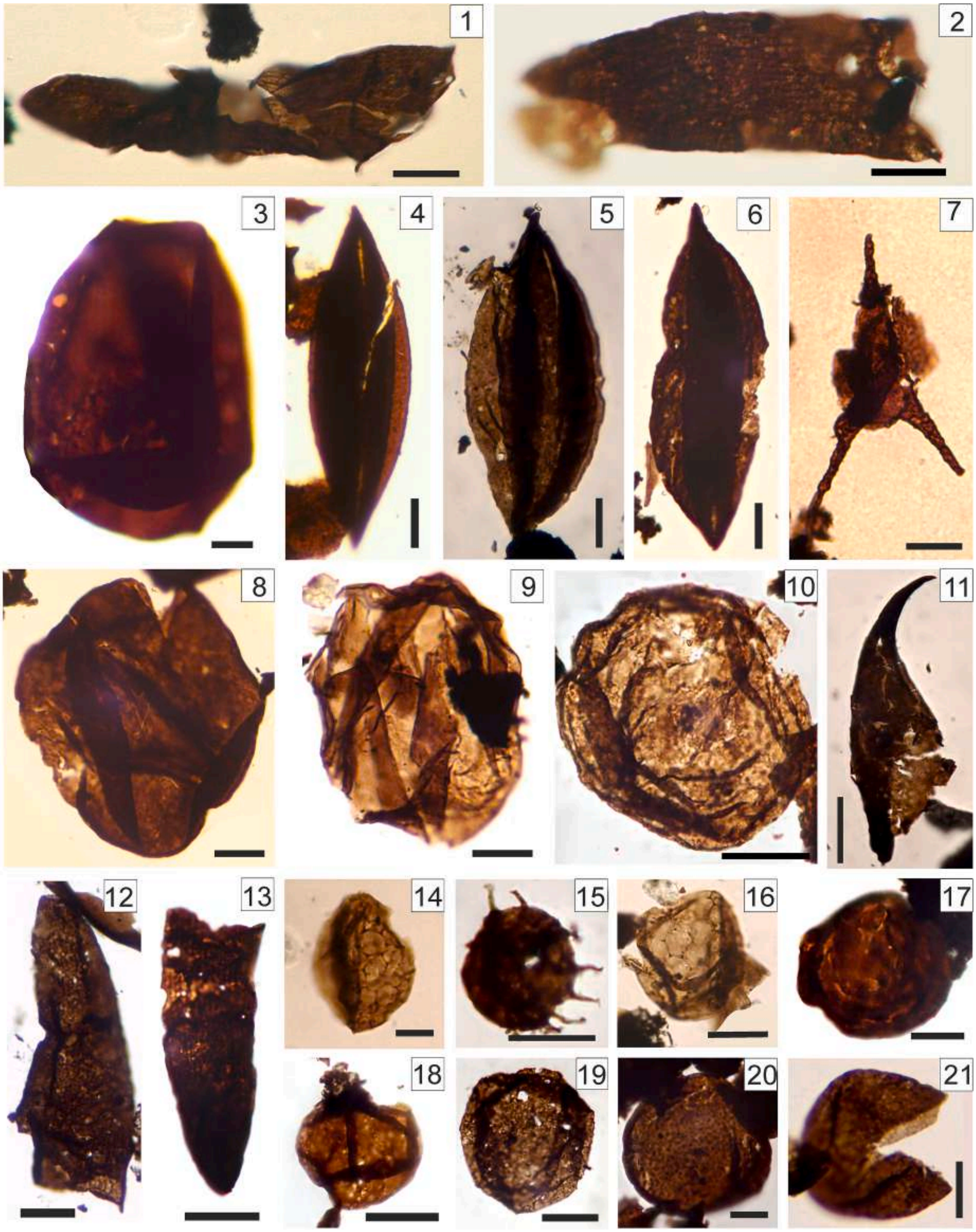

Plate V. Selected algae, fungal spores, and *incertae sedis* of the Sauce Grande Formation. One scolecodont is also illustrated. 1–2, 12–13. *Deusilites tenuistriatus* Gutiérrez et al., 1997. 1. UNSP-5498-2 O30/0; 2. UNSP-5512-1 E36/0; 12. UNSP-5496-1 G16/0; 13. UNSP-5500 W15/3. 3, 8. Sphaeromorph gen. et sp. indet. Di Nardo et al., 2022; 3. UNSP-5498-5 C45/2; 8. UNSP-5493-C D43/O. 4–6. *Lancettopsis harringtonii* Di Nardo et al., 2022; 4. UNSP-5498-2 Z39/0; 5. UNSP-5493-C J27/3; 6. UNSP-5510-C P19/0. 7. Acritarch indet., UNSP-5498-2 L28/2. 9. *Leiosphaeridia simplex* Sinha, 1969, UNSP-5493-C B35/2. 10, 19. *Leiosphaeridia crescentica* Sinha, 1969; 10. UNSP-5498-1 P23/4; 19. UNSP-5496 J36/4. 11. Scolecodont gen. et sp. indet., UNSP-5500 P18/3. 14, 16. *Cymatiosphaera* sp. cf. *C. gondwanensis* (Tiwari) Backhouse, 1991; 14. UNSP-5491-C B19/1; 16. UNSP-5493-C J22/1. 15. *Gorgonisphaeridium* sp., UNSP-5493 R30/2. 17. *Portalites confertus* Hemer and Nygreen, 1967, UNSP-5489 L29/1. 18. *Leiosphaeridia talchirensis* Lele and Karim, 1971, UNSP-5496 T22/1. 20. *Pilasporites* sp. B Stephenson and Osterloff, 2002, UNSP-5489 R40/4. 21. *Ovoidites scissus* (Balme and Hennelly) Zavattieri et al., 2020, UNSP-5498-2 M20/0. Scale bar =20 μm.

fig. 26).

Anteturma VARIEGERMINANTES Potonié, 1970.

Turma SACCITES Erdtman, 1947.

Subturma MONOSACCITES Chitaley emend. Potonié and Kremp, 1954.

Infraturma DIPOLSACCITI Hart emend. Dibner, 1971

Subinfraturma APERTACORPINI Dibner, 1971.

Genus: **Plicatipollenites** Lele, 1964.

Type species: *Plicatipollenites malabarensis* (Potonié and Sah) Foster, 1975.

Plicatipollenites malabarensis (Potonié and Sah) Foster, 1975 (Plate II, fig. 1).

Plicatipollenites sp. (Plate II, fig. 3).

Genus: **Potonieisporites** Bharadwaj emend. Bharadwaj, 1964

Type species: *Potonieisporites novicus* Bharadwaj, 1954.

Potonieisporites lelei Maheshwari, 1967 (Plate II, fig. 2).

Potonieisporites sp. cf. *P. novicus* Bharadwaj, 1954 (Plate II, fig. 4).

Subinfraturma CLAUSICORPINI Dibner, 1971.

Genus: **Caheniasaccites** Bose and Kar emend. Azcuy and di Pasquo, 2000

Type species: *Caheniasaccites flavatus* Bose and Kar emend. Azcuy and di Pasquo, 2000.

Caheniasaccites flavatus (Bose and Kar) Azcuy and di Pasquo, 2000 (Plate II, figs. 5–6).

Genus: **Tuberisaccites** Lele and Makada, 1972.

Type species: *Tuberisaccites varius* Lele and Makada, 1972.

Tuberisaccites lobatus Lele and Makada, 1972 (Plate II, fig. 7).

Infraturma STRIASACCITES Bharadwaj, 1962.

Genus: **Mabuitasaccites** Bose and Kar, 1966.

Type species: *Mabuitasaccites ovatus* Bose and Kar, 1966.

Mabuitasaccites crucistriatus (Ybert) Playford and Dino, 2000a (Plate II, fig. 8).

Genus: **Meristocorpus** Playford and Dino, 2000a.

Type species: *Meristocorpus explicatus* Playford and Dino, 2000a.

Meristocorpus sp. (Plate II, fig. 9).

Subturma DISACCITES Cookson, 1947.

Infraturma DIASACCITRILETES Leschik emend. Potonié, 1958.

Genus: **Alisporites** Daugherty emend. Jansonius, 1971

Type species: *Alisporites opii* Daugherty, 1941.

Alisporites splendens (Leschik) Foster, 1979 (Plate III, fig. 4).

Genus: **Falcisporites** (Leschik) Klaus, 1963.

Type species: *Falcisporites zapfei* Potonié and Klaus, 1954.

Falcisporites similis (Balme) Balarino, 2012 (Plate III, figs. 6–9).

Remarks: This species is characterized by exinal folds on the proximal base of the sacci and a rectangular cappula. These morphological features distinguish it from *Pteruchipollenites indarraensis* (Segroves) Foster, 1979 and *Alisporites tenuicorpus* Balme, 1970, which have thickenings at the distal base of the sacci and a more oval-shaped cappula. The presence of exinal folds at the proximal base of the sacci is a distinguishing character that has been used by some authors (e.g., Foster, 1979; Balarino, 2012) as one of the criteria to separate the genera *Alisporites* and *Falcisporites*. However, it is important to note that in the specimens studied, proximal exinal folds were either only partially preserved or completely absent (Plate III, figs. 6–9) due to taphonomic processes affecting their preservation.

Genus: **Platysaccus** Naumova, 1939.

Type species: *Platysaccus papilionis* Potonié and Klaus, 1954.

Platysaccus sp. (Plate III, fig. 12).

Genus: **Pteruchipollenites** Couper, 1958.

Type species: *Pteruchipollenites thomassi* Couper, 1958.

Pteruchipollenites gracilis (Segroves) Foster, 1979 (Plate III, fig. 10).

Genus: **Scheuringipollenites** Tiwari, 1973.

Type species: *Scheuringipollenites maximus* (Hart) Tiwari, 1973.

Scheuringipollenites circularis Césari et al., 1995 (Plate III, fig. 11).

Scheuringipollenites ovatus (Balme and Hennelly) Foster, 1975 (Plate III, fig. 5).

Genus: **Vitreisporites** Leschik emend. Jansonius, 1962

Type species: *Vitreisporites signatus* Leschik, 1955.

Vitreisporites signatus Leschik, 1955 (Plate III, fig. 13).

Subturma DISSACCITRILETI Leschik, 1955.

Genus: **Colpisaccites** Archangelsky and Gamerro, 1979.

Type species: *Colpisaccites granulosus* Archangelsky and Gamerro, 1979.

Colpisaccites granulosus Archangelsky and Gamerro, 1979 (Plate III, figs. 1–2).

Genus: **Limitisporites** Leschik emend. Klaus, 1963.

Type species: *Limitisporites rectus* Leschik, 1956.

Limitisporites hexagonalis Bose and Maheshwari, 1968 (Plate III, fig. 3).

Subturma STRIATITI Pant, 1954.

Genus: **Hamiapollenites** Wilson emend. Tschudy and Kosanke, 1966.

Type species: *Hamiapollenites saccatus* Wilson, 1962.

Hamiapollenites fusiformis Marques-Toigo emend. Archangelsky and Gamerro, 1979 (Plate IV, fig. 11).

Genus: **Illinites** Kosanke emend. Jansonius and Hills, 1976

Type species: *Illinites unicus* Kosanke emend. Jansonius and Hills, 1976.

Illinites talchirensis (Lele and Makada) Azcuy et al., 2002 (Plate IV, fig. 3).

Illinites unicus Kosanke emend. Jansonius and Hills, 1976 (Plate IV, figs. 1–2).

Genus: **Lunatisporites** Leschik emend. Scheuring, 1970

Type species: *Lunatisporites acutus* Leschik, 1955.

Lunatisporites sp. cf. *L. variesectus*. Archangelsky and Gamerro, 1979 (Plate IV, fig. 23).

Lunatisporites sp. (Plate IV, fig. 17).

Genus: **Protohaploxypinus** Samoilovich emend. Morbey, 1975

Type species: *Protohaploxypinus latissimus* (Luber) Samoilovich, 1953.

Protohaploxypinus limpidus (Balme and Hennelly) Balme and Playford, 1967 (Plate IV, fig. 21).

Protohaploxypinus perfectus (Naumova) Samoilovich, 1953 (Plate IV, fig. 20).

Remarks: We concur with the synonymy list by di Pasquo et al. (2021).

Genus: **Staurosaccites** Dolby *in* Dolby and Balme, 1976.

Type species: *Staurosaccites quadrifidus* Dolby *in* Dolby and Balme, 1976.

? *Staurosaccites* sp. (Plate IV, fig. 18).

Genus: **Striatoabieites** Zoricheva and Sedova ex Sedova emend. Hart, 1964

Type species: *Striatoabieites brickii* Sedova, 1956.

cf. *Striatoabieites multistriatus* (Balme and Hennelly) Hart, 1964 (Plate IV, fig. 25).

Turma PLICATES Naumova emend. Potonié, 1960

Subturma POLYPLICATES Erdtman, 1952.

Genus: **Vittatina** Luber *ex* Samoilovich emend. Wilson, 1962

Type species: *Vittatina subsaccata* Samoilovich, 1953.

Vittatina costabilis Wilson, 1962 (Plate IV, figs. 5–6).

Vittatina subsaccata Samoilovich, 1953 (Plate IV, figs. 4, 9).

Vittatina vittifera (Luber) Samoilovich, 1953 (Plate IV, figs. 19, 22).

Genus: **Weylandites** Bharadwaj and Srivastava, 1969.

Type species: *Weylandites lucifer* (Bharadwaj and Salujha) Foster, 1975.

Weylandites magmus (Bose and Kar) Backhouse, 1991 (Plate IV, figs. 13–14).

Weylandites sp. (Plate IV, fig. 24).

Subturma PRAECOLPATES Potonié and Kremp, 1954.

Genus: **Marsupipollenites** Balme and Hennelly emend. Balme, 1970

Type species: *Marsupipollenites triradiatus* Balme and Hennelly, 1956b.

Marsupipollenites triradiatus.Balme and Hennelly, 1956b

Marsupipollenites striatus (Balme and Hennelly) Foster, 1975 (Plate

IV, fig. 12).

Subturma MONOCOLPATES (Wodehouse) Iversen and Tröels-Smith, 1950.

Genus: **Cycadopites** Wodehouse, 1933.

Type species: *Cycadopites follicularis* Wilson and Webster, 1946.

Cycadopites sp. (Plate III, fig. 14).

Genus: **Pakhapites** Hart, 1965.

Type species: *Pakhapites fasciolatus* (Balme and Hennelly) Hart, 1965.

Pakhapites ovatus (Bose and Kar) García, 1996 (Plate IV, fig. 15).

Pakhapites fusus (Bose and Kar) Menéndez, 1971 (Plate IV, fig. 16).

Algae

Division: CHAROPHYTA Migula, 1897.

Class: ZYGNEMATOPHYCEAE (Round) Guiry, 2013.

Order: Zygnematales Bessey, 1907.

Family: Zygnemataceae Kützing, 1843.

Genus: **Ovoidites** Potonié ex Thomson and Pflug emend. Krutzsch, 1959

Type species: *Ovoidites ligneolus* Potonié ex Krutzsch, 1959.

Ovoidites scissus (Balme and Hennelly) Zavattieri et al., 2020 (Plate V, fig. 21).

Division: CHLOROPHYTA Pascher, 1914.

Subdivision: PRASINOPHYTINA Round, 1963.

Class: PYRAMIMONADOPHYCEAE Moestrup and Daugbjerg in Daugbjerg et al., 2019.

Order: Pyramimonadales Chadefaud, 1950.

Family: Cymatiosphaeraceae Mädler, 1963.

Genus: **Cymatiosphaera** Wetzel emend. Deflandre, 1954

Type species: *Cymatiosphaera radiata* Wetzel, 1933.

Cymatiosphaera sp. cf. *C. gondwanensis* (Tiwari) Backhouse, 1991 (Plate V, figs. 14, 16).

Kingdom: FUNGI Moore, 1980.

Genus: **Portalites** Hemer and Nygreen emend. Souza et al., 2016

Type species: *Portalites confertus* Hemer and Nygreen, 1967.

Portalites confertus Hemer and Nygreen, 1967 (Plate V, fig. 17).

Incertae sedis.

Acritarch gen. et sp. indet. (Plate V, fig. 7).

Genus: **Deusilites** Hemer and Nygreen, 1967.

Type species: *Deusilites tentus* Hemer and Nygreen, 1967.

Deusilites tenuistriatus Gutiérrez et al., 1997 (Plate V, figs. 1–2, 12–13).

Genus: **Gorgonisphaeridium** Staplin et al., 1965.

Type species: *Gorgonisphaeridium winslowiae* Staplin et al., 1965.

Gorgonisphaeridium sp. (Plate IV, fig. 15).

Genus: **Lancettopsis** Mädler emend. Di Nardo et al., 2022.

Type species: *Lancettopsis lanceolata* Mädler, 1963.

Lancettopsis harringtoni Di Nardo et al., 2022 (Plate V, figs. 4–6).

Genus: **Leiosphaeridia** Eisenack emend. Downie and Sarjeant, 1963

Type species: *Leiosphaeridia baltica* Eisenack, 1958.

Leiosphaeridia crescentica Sinha, 1969 (Plate V, figs. 10, 19).

Leiosphaeridia talchirensis Lele and Karim, 1971 (Plate V, fig. 18).

Leiosphaeridia simplex Sinha, 1969 (Plate V, fig. 9).

Genus: **Pilasporites.**Balme and Hennelly, 1956b

Type species: *Pilasporites calculus.*Balme and Hennelly, 1956b

Pilasporites sp. B Stephenson and Osterloff, 2002 (Plate V, fig. 20).

Remarks: This species has been previously recorded in the Gharif Formation (Stephenson and Osterloff, 2002), the San Gregorio Formation (Beri et al., 2006), and in cuttings from the La Estrella x-1 borehole assigned to the *Converrucosisporites confluens-Vittatina vittifera* Biozone (Balarino, 2009, 2012, 2014).

Sphaeromorph gen. et sp. indet. Di Nardo et al., 2022 (Plate V, figs. 3, 8).

Scolecodonts

Phylum: ANNELIDA Lamarck, 1809.

Class: POLYCHAETA Grube, 1850.

Order: Eunicida Dales, 1963.

Scolecont gen. et sp. indet. (Plate V, fig. 11).

6. Comparisons with biostratigraphic schemes from South-Western Gondwana

The identification of key species in the palynological associations from the Sauce Grande Formation presented here supports their comparison with the local biostratigraphic scheme defined by Balarino (2014) in the Claromecó Basin and with the recently updated palynostratigraphic schemes of the neighboring late Paleozoic Chacoparaná and central-western basins of Argentina (Césari and Chiesa, 2017; Gutiérrez and Balarino, 2019; Césari and Perez Loinaze, 2021) and Paraná in Brazil and Uruguay (Beri et al., 2011; Souza et al., 2021).

6.1. Brazil and Uruguay, Paraná Basin

Four interval zones characterize the Upper Paleozoic of the Paraná Basin in Brazil: *Ahrensisporites cristatus*, *Crucisaccites monoletus*, *Vittatina costabilis* (VcZ), and *Lueckisporites virkkiae* (LvZ) (Souza and Marques-Toigo, 2001, 2003). Souza et al. (2021) proposed a new characterization of the VcZ, delimiting its age to the Gzhelian-Artinskian interval based on numerous radiometric dating information. In this new characterization, the lower limit of the VcZ is established by the FO of several species of *Vittatina* (*V. saccata, V. subsacatta, V. vittifera,* and *V. costabilis*), together with *Converrucosisporites confluens*, *Stellapollenites talchirensis*, *Protohaploxypinus goraiensis* (= *P. pennatulus* following di Pasquo et al., 2021), *P. hartii* and *Illinites unicus*. The *Protohaploxypinus goraiensis* and *Hamiapollenites karroensis* subzones previously established by Souza and Marques-Toigo (2003, 2005) were also discarded.

Some species previously considered restricted to the LvZ, such as *Weylandites lucifer, Marsupipollenites striatus, Lunatisporites variesectus,* and *Lueckisporites virkkiae* have also been found in the VcZ (Souza et al., 2021, and references therein). Monosaccate pollen grains of bilateral and radial symmetry predominate, although spores may constitute up to 80–90% of the association due to local paleoenvironment conditions (Souza et al., 2021). The upper limit is marked by quantitatively well-represented species of *Lueckisporites*, *Weylandites*, *Lunatisporites*, and *Corisaccites* characterizing the upper LvZ.

The Sauce Grande Formation assemblage shares diagnostic key species, such as *Vittatina subsacatta*, *V. costabilis*, *V. vittifera*, *Illinites unicus,* and *Converrucosisporites confluens,* with the VcZ. The absence of highly represented species of *Weylandites* and *Lunatisporites*, along with the absence of species of *Lueckisporites* and *Corisaccites* precludes its correlation with the LvZ.

In the Paraná Basin in Uruguay, preliminary and informal palynozonations were first proposed by Beri et al. (2004), Azcuy et al. (2007), and Souza et al. (2007), and later formalized by Beri et al. (2011). Beri et al. (2011) differentiated the *Cristatisporites inconstans-Vittatina saccata* (IS) Biozone, correlated with the VcZ, and the *Striatoabieites anaverrucosus-Staurosaccites cordubensis* (AC) Biozone, correlated with the LvZ.

The Sauce Grande Formation assemblage exhibits similarities with the IS Biozone, such as a dominance of trilete spores and lower proportions of monosaccate, bisaccate, taeniate, and plicate pollen grains, and they share the following species: *Brevitriletes cornutus*, *B. levis*, *Converrucosisporites confluens*, *C. micronodosus,* and *Mabuitasaccites crucistriatus*. Minor differences in the Sauce Grande Formation assemblage compared with those of the IS Biozone, such as lower proportions of monosaccate pollen grains and a less conspicuous presence of *Cristatisporites* spp., can be attributed to local variations in paleofloristic composition. Besides, we cannot disregard the impact of taphonomical effects on the composition of the palynofloras of the Sauce Grande Formation.

The predominance of trilete spores instead of bisaccate taeniate and non-taeniate pollen grains, and mainly the absence of *Lueckisporites* spp., *Striatoabieites anaverrucosus*, *Staurosaccites cordubensis*, *S. quadrifidus*, *Lunatisporites paliensis*, *Protohaploxypinus samoilovichii*, *Striatopodocarpites gondwanensis*, *Corisaccites alutas*, *Alisporites parvus*, and

Platysaccus leschikii preclude its correlation with the younger AC Assemblage Zone.

6.2. Argentine basins

6.2.1. Chacoparaná Basin

The biostratigraphic scheme of the Chacoparaná Basin was originally proposed by Russo et al. (1980) based on samples from the Ordoñez borehole, located in the San Cristobal-Las Breñas Oriental Sub-basin. They recognized three palynozones: the *Potonieisporites-Lundbladispora* (PL), the *Cristatisporites* (Cr), and the *Striatites* (S). Subsequent palynological studies of samples from boreholes located in the San Cristobal-Las Breñas Oriental and Alhuampa sub-basins incorporated some modifications (Vergel, 1993; Césari et al., 1995; Archangelsky and Vergel, 1996), although the tripartite division was recognized and the validity of the scheme at a regional scale was confirmed. More recently, Gutiérrez and Balarino (2019) re-characterized the previously established biozones for the Chacoparaná Basin based on a revision of previous borehole information and proposed the new *Anapiculatisporites concinnus* (Ac) Biozone of upper Serpukhovian-Bashkirian age, based on palynological assemblages from Santiago Temple boreholes.

The PL Biozone, originally defined by Russo et al. (1980), is characterized by the predominance of monosaccate and bisaccate pollen grains (*Potonieisporites* spp., *Plicatipollenites* spp., *Caheniasaccites* spp., *Limitisporites* spp.), the occasional presence or absence of striate pollen grains in the upper levels and the presence of *Lundbladispora braziliensis*, *Punctatisporites gretensis*, *Vallatisporites arcuatus*, *Cyclogranisporites microgranulatus,* and *Cristatisporites inconstans* (Gutiérrez et al., 2003). The base of the Cr Biozone is marked by the beginning of persistent records of *Hamiapollenites fusiformis* and *Protohaploxypinus limpidus*. A dominance of monosaccate pollen grains and apiculate and zonate trilete spores characterizes this biozone, along with species diversification of the genus *Cristatisporites*. In addition, *Brevitriletes cornutus*, *Converrucosisporites micronodosus,* and *C. confluens* are recorded for the first time in the Cr Biozone (Russo et al., 1980; Gutiérrez et al., 2003). The lower limit of the S Biozone is defined by the beginning of the predominance of striate pollen grains. Within this biozone, some species, such as *Marsupipollenites striatus*, *Lunatisporites variesectus*, *Staurosaccites cordubensis*, and *Lueckisporites virkkiae*, dominate or are recorded for the first time (Russo et al., 1980; Gutiérrez et al., 2003).

In the Sauce Grande Formation, the presence of *Converrucosisporites confluens* in the lowermost sample (UNSP-5482) from the PANG 0002 borehole, together with the lack of predominance of striate pollen grains and the absence of important key species of the S Biozone in the whole palynological assemblage, enables us to correlate the entire succession with the Cr Biozone. The poor state of preservation of palynomorphs at this level does not allow us to confirm accurately the presence of other key taxa.

Considering the stratigraphic ranges of taxa in the re-characterization by Gutiérrez and Balarino (2019), the presence of *Colpisaccites granulosus* in UNS-5483 also indicates a correlation of the almost complete succession in PANG 0002 with the Cr Biozone. However, the presence of *Verrucosisporites andersonii* in the upper levels (UNSP-5498) is incongruent with its LO in the PL Zone in the Chacoparaná Basin. This situation highlights a limitation in using long-ranging taxa or endemics to establish biozonation schemes, as they can hinder the precise correlation of biozones across different basins. On the other hand, none of the exclusive species of the S Biozone mentioned by Gutiérrez and Balarino (2019) were recorded in the Sauce Grande Formation.

Gutiérrez and Balarino (2019) interpreted the existence of two glacial events in the Ordoñez Formation of the Chacoparaná Basin. The youngest event is recorded in the Ordoñez borehole, evidenced by the presence of diamictites containing palynological assemblages referring to the *Cristatisporites* Biozone (Archangelsky and Gamerro, 1979; Russo et al., 1980). The oldest event is recorded in the Santiago Temple boreholes, evidenced by the diamictites containing palynological assemblages referred to, as the Ac Zone (late Serpukhovian–early Bashkirian). However, in the Ac Biozone, it is important to note the presence of some taxa identified in younger strata throughout Gondwana, including *Converrucosisporites confluens*, *Deusilites tenuistriatus*, *Stellapollenites talchirensis, Brevitriletes cornutus*, and *Dictyotriletes aules,* among others (fig. 8, p. 12 and Supplementary File 2 in Gutiérrez and Balarino, 2019). As an example, the FO of *Converrucosisporites confluens,* among others, indicates the base of the *Vittatina costabilis* Biozone in the Paraná Basin (Souza et al., 2021), and the base of the *Pahkapites fusus-Vittatina subsacatta* Biozone in the central-western basins (Césari and Perez Loinaze, 2021). Both biozones were isotopically calibrated, spanning from the Gzhelian to Asselian. *Stellapollenites talchirensis* occurs in the VcZ of the Paraná Basin in Brazil (Félix and Souza, 2008; Souza et al., 2021). Specimens comparable to *S. talchirensis* have also been recorded in the IS Zone of the Paraná Basin in Uruguay (Gutiérrez et al., 2006).

As the levels studied come from cores and not from drill cuttings, artificial contamination from the upper levels (caving) is discarded. The process of stratigraphic leakage, which produces the downwashing of palynomorphs (e.g., Gupta et al., 2023), can occur in carbonate lithologies, but it is not likely in clastic rocks. Therefore, those taxa with younger ranges than the age given to the AcZ (late Serpukhovian–early Bashkirian), even mentioned at the base, imply an extension of its FO, at least, up to the Serpukhovian. Owing to the absence of radiometric calibration of the biozones defined in the Chacoparaná Basin, we suggest that the biochronology of taxa should not be extended up to the uppermost Mississippian. An alternative explanation could be an intense reworking process (plausible in glaciogenic rocks), which may have mixed older materials with younger ones. This process has already been identified in the Sachayoj Formation (El Caburé borehole), an equivalent unit of the Ordoñez Formation spanning from the Late Carboniferous to the Early Permian (Vergel, 1998) in the Alhuampa Sub-basin, where palynomorphs of the Devonian age have been recognized (Antonelli and Ottone, 2006).

Considering the youngest taxa recovered in the levels of the Ordoñez Formation in the Santiago Temple boreholes studied by Gutiérrez and Balarino (2019), we suggest that the lowermost diamictites of this unit may be temporally equivalent to the Sauce Grande Formation in PANG 0002 borehole. This interpretation agrees with previous preliminary palynological studies of the same intervals in the Santiago Temple boreholes conducted by Archangelsky et al. (1980), who suggested a correlation of these levels with both the upper part of the PL Biozone and the lower part of the Cr Biozone.

6.2.2. Central-western basins

Four biozones characterize the Upper Paleozoic in central–western Argentina: The *Cordylosporites magnidictyus–Verrucosisporites quasigobbetti*, the *Raistrickia densa– Convolutispora muriornata* (DM), the *Pakhapites fusus–Vittatina subsaccata* (FS), and the *Lueckisporites–Weylandites* (LW) biozones (Césari and Gutiérrez, 2001; Césari et al., 2011).

The DM Biozone is subdivided into subzones A, B, and C. In brief, DM Subzone A was characterized by a consistent presence of monosaccate pollen grains, with its base defined by the FO of *Plicatipollenites* spp. DM Subzone B was defined by the FO of *Protohaploxypinus* spp., while DM Subzone C was marked by the inception of *Quadrisporites* spp., scolecodonts, and acritarchs, such as *Micrhystridium* sp. and *Verhyachium* sp. (Césari and Gutiérrez, 2001; Césari et al., 2011).

The base of the *Pakhapites fusus* Interval Zone was defined by the FO of *Pakhapites fusus* and an increase in striate pollen grains (Césari and Gutiérrez, 2001). This biozone is characterized by the abundance of bisaccate striate (*Protohaploxypinus*, *Vittatina*, *Hamiapollenites*, and *Striatopodocarpites*), plicate (*Pakhapites* and *Marsupipollenites*) pollen, and some spores referred to *Converrucosisporites confluens* (Césari et al., 2011). *Granulatisporites* sp. cf. *G. trisinus*, a typical taxa of FS Biozone (Césari and Gutiérrez, 2001), was later referred to *Converrucosisporites* *confluens* Morphon by Césari and Chiesa (2017). The top of the FS Biozone was defined by the FO of *Lueckisporites* spp. (Césari and Gutiérrez, 2001; Césari et al., 2011).

Césari and Perez Loinaze (2021) redefined the boundaries of the aforementioned Pennsylvanian biozones. The upper limit of Subzone C of DM (Moscovian-Kasimovian?) was established by the FO of *Converrucosisporites confluens*, *Pakhapites fusus*, *Vittatina costabilis,* and *Weylandites* spp.

The palynological assemblage recovered in the Sauce Grande Formation shows clear similarities with the FS Biozone, based on the presence of key taxa such as *Converrucosisporites confluens*, *Vittatina costabilis*, and *Weylandites magmus*. The base of the FS Biozone was originally considered to be of earliest Permian age (Césari and Gutiérrez, 2001), and later, with more certainty, was attributed to the post-Moscovian based on absolute dates (e.g., Césari et al., 2013; Césari and Chiesa, 2017). The absence of *Lueckisporites* spp. and the low frequency of striate pollen grains in the Sauce Grande Formation precludes its correlation with the LW Biozone.

6.2.3. *Claromecó Basin*

The first references to a palynozonation in the Late Paleozoic Claromecó Basin can be traced back to Archangelsky and Gamerro (1980) and Archangelsky (1996). These authors correlated the samples from the Puelches X-1 borehole (Fig. 1b), drilled in the Argentine continental shelf, with the PL, Cr, and S biozones of the Chacoparaná Basin.

The informal palynozonation initially described by Balarino (2009, 2012) was later formalized by the same author in 2014, where a local palynostratigraphic scheme was proposed based on the analysis of core and cutting samples from two boreholes (La Estrella x-1 and Cruz del Sur x-1), also located on the Argentine continental shelf (Fig. 1b). The biozonation included the Piedra Azul, Bonete, and Tunas formations. As the Sauce Grande Formation was not drilled in the aforementioned boreholes, this unit could not be included in the Balarino palynostratigraphic scheme.

Balarino (2014) established two palynozones: the *Converrucosisporites confluens-Vittatina vittifera* (CV) Assemblage Zone, which occurs in the Piedra Azul and Bonete formations, and the *Tornopollenites toreutos–Reduviasporonites chalastus* Assemblage Zone (TC), in the Tunas Formation (detailed information in the next section).

In a first approach, the palynological assemblage recovered in the Sauce Grande Formation reported here can be ascribed to the CV Biozone based on the presence of some exclusive species, such as *Vittatina vittifera*, *Converrucosisporites confluens*, and *Gondisporites serrulatus.* Species that have their FO in the CV Biozone are also present in the Sauce Grande Formation, specifically *Horriditriletes uruguaiensis*, *Falcisporites similis*, *Colpisaccites granulosus*, *Vittatina costabilis*, and *Leiosphaeridia talchirensis*. As in the CV Biozone, spores of the genus *Cristatisporites* and monosaccate pollen grains are not abundant in the Sauce Grande Formation. Differences in the relative abundance of palynomorphs can be explained in paleoenvironmental and paleoclimatic terms and do not justify their separation from the CV Biozone. Furthermore, relative abundances of sporomorphs that characterize the CV Biozone have been determined from samples in the interval 3428–3231 mbgl (meters below ground level) of the La Estrella x-1, referred to as the Bonete Formation. The assemblages obtained from cuttings at intervals 3549–3450 mbgl (Piedra Azul Formation) were not used to characterize this biozone, indicating a lack of information between the Sauce Grande and the Bonete formations. Despite this lack of information, the relative abundances of the different groups of palynomorphs found in the Sauce Grande Formation are consistent with the general trend recorded in the La Estrella x-1 borehole, not only in the CV Biozone, but also in the overlying TC Biozone, and suggest a progressive change in vegetation associated with environmental and climatic changes throughout the evolution of the Claromecó Basin.

7. Discussion

7.1. *Characterizing the CV Biozone*

The new palynological data from the Sauce Grande Formation presented here help us make some comments and improve the current biostratigraphic scheme in the Claromecó Basin, mainly in the CV Biozone.

The CV Biozone was informally divided into a lower and an upper subzone, with the boundary marked at 3380 mbsl (the middle part of the Bonete Formation) by the FO of fifteen species (see Balarino, 2014, p. 4). Six of these taxa, namely *Brevitriletes cornutus, Brazilea scissa* (=*Ovoidites scissus*), *Leiosphaeridia talchirensis*, *Colpisaccites granulosus, Hamiapollenites fusiformis*, and *Vittatina vittifera,* are reported here for the first time in the underlying Sauce Grande Formation (Fig. 4). The absence of these species in the lower CV subzone could be related to specific paleoenvironmental conditions (e.g., *Brazilea scissa*, and *Leiosphaeridia talchirensis,* which are paleoenvironmental indicators) or biases due to sampling or differential preservation. These species should therefore be discarded to delimit the lower and upper subzones.

On the other hand, Vázquez and Césari (2017) suggested that the boundary between the lower and upper CV Biozone would be better placed at the boundary between the Piedra Azul and the Bonete formations at 3428 mbsl and in the deepest core sample in the La Estrella X-1 borehole, where the FO of *Lueckisporites* occurs, along with the FO of other species, such as *Thymospora criciumensis*, *Vittatina costabilis*, *Hamiapollenites andiraensis*, *Striatoabieites anaverrucosus* (FO in core samples at 3380, but not at 3428 mbsl), and *Lunatisporites variesectus*. All these taxa are found at greater depths in the La Estrella x-1 borehole,

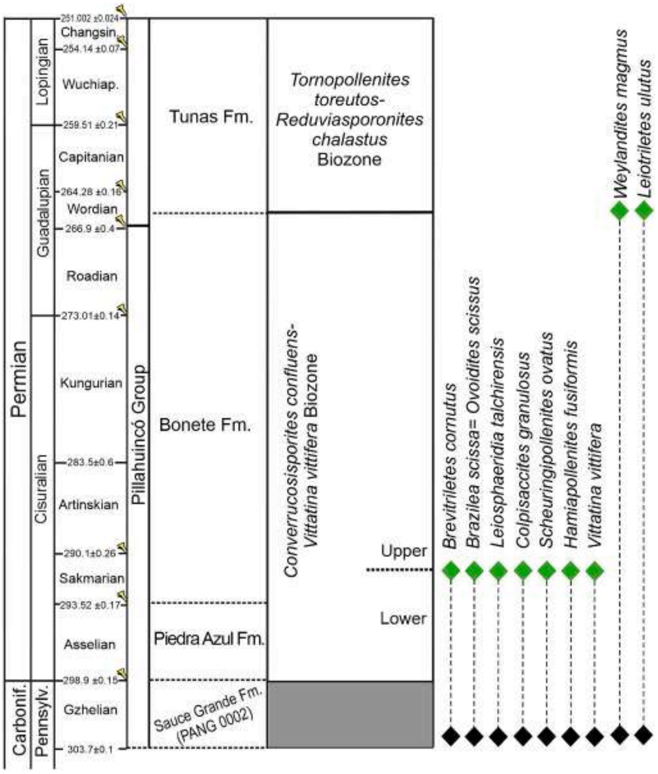

Fig. 4. Palynomorphs recovered in the Sauce Grande Formation in PANG 0002 (black diamonds) used by Balarino (2012 and 2014) to delimit the lower and upper CV Biozone, and the CV and TC biozones (green diamonds). The ages of the CV lower and upper boundary and the CV- TC boundary are in agreement with Gutiérrez and Balarino (2019). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

although they are from cutting samples.

The TC Biozone was marked by the LO of 18 species together with the FO of *Tornopollenites toreutos*, *Weylandites magmus*, *Leiotriletes ulutus*, *Pseudoreticulatispora pseudoreticulata*, *Gondwanapollis frenguelli*, *Vallatisporites arcuatus*, *Laevigatosporites flexus*, *Reduviasporonites chalastus*, *Leiosphaeridia crescentica*, and *Portalites gondwanensis* (Balarino, 2009, 2012, and 2014). Although the discussion of the TC Biozone is beyond the scope of this paper, it should be noted that, among these taxa, *Leiotriletes ulutus*, *Weylandites magmus,* and *Leiosphaeridia crescentica* are reported here in the Sauce Grande Formation, so they should no longer be considered for delimiting the boundary between the CV and TC biozones (Fig. 4).

7.2. Correlations of the CV Biozone and age

Balarino (2014) correlated most of the CV Zone with the Vc and IS biozones of the Paraná Basin -in Brazil and Uruguay, respectively-, the Cr Biozone of the Chacoparaná Basin, and the FS Biozone of the central-western basins of Argentina. Furthermore, a partial overlap with the Lv and AC biozones (Paraná Basin), S (Chacoparaná Basin), and LW Biozone (central-western basins of Argentina) was suggested. However, updated information allows us to discard the overlap with the younger biozones, in agreement with fig. 7 of Gutiérrez and Balarino (2019).

The partial overlap of the CV with the Lv and AC biozones (Paraná Basin) was based on the presence of species, such as *Lueckisporites virkkiae*, *Lunatisporites variesectus, Vittatina vittifera,* and *Pakhapites ovatus* (Balarino, 2014, p. 11). As recently summarized by Souza et al. (2021), *Lueckisporites virkkiae* and *Lunatisporites variesectus*, first considered restricted to the Lv Zone of the Paraná Basin by Souza and Marques-Toigo (2005), have been recorded in the VcZ (cf. Boardman et al., 2012; Leite, 2017), although their presence is limited to only one or a few specimens. Similarly, in the CV Biozone of the Claromecó Basin (La Estrella x-1), *Lueckisporites* spp. and *Lunatisporites* spp. are present at a very low frequency (less than 0.006%), as can be inferred from the taxa distribution at the genus level in Balarino (2009, p. 493). The low frequency of these genera is also maintained in the TC zone and characterizes the palynological assemblages recovered from the entire Pillahuincó Group. The discovery of *Lueckisporites virkkiae* in isotopically calibrated strata of the Copacabana Formation in Bolivia would indicate the presence of this taxon since the Asselian. The time span for the migration of its parent plant in the South American basins is the main explanation given to support the different temporal ages of this taxon (di Pasquo et al., 2015, 2024).

The species *Vittatina vittifera*, which is exclusive of the CV zone (Balarino, 2012, 2014), also characterizes the VcZ in Brazil, together with other species of *Vittatina* (Souza and Marques-Toigo, 2005; Souza et al., 2021).

In the Paraná Basin of Uruguay, *Pakhapites ovatus* has been reported in the San Gregorio Formation (Gutiérrez et al., 2006), attributed to the *Cristatisporites inconstans–Vittatina saccata* Biozone (Beri et al., 2011). This taxon is also present in the FS Biozone (Patquía Formation) and in the Sauce Grande Formation (this contribution).

The partial overlap between the CV Biozone of the Claromecó Basin and the S Biozone of the Chacoparaná Basin is supported by shared species, such as *Convolutispora archangelskyi*, *Scheuringipollenites ovatus*, *Corisaccites alutas*, *Lueckisporites virkkiae*, and *Tiwariasporis* (*Striatoabieites*) *anaverrucosus* (Balarino, 2014). Except for *Convolutispora archangelskyi*, which has also been reported in the *Cristatisporites* Biozone in the Cd O-es (Ordoñez) borehole (Playford and Dino, 2002), the remaining species are considered exclusive to the Striatites (S) Biozone, together with *Lueckisporites angoulaensis* and *L. latisaccus*, as recently characterized by Gutiérrez and Balarino (2019). Although *Scheuringipollenites ovatus* would be exclusive to the S Biozone, it has older records in the neighboring Paraná Basin in Uruguay, as it has been found in the San Gregorio Formation - in the lowest sample (14.9 m) in the CLS-24 borehole-, which is assigned to the IS Biozone (cf. Gutiérrez et al., 2006; Beri et al., 2006).

Even if this correlation is stronger when considering key species, it is also worth mentioning that the lower limit of the S Biozone was first characterized by a substantial increase in striate pollen grains, which can reach up to 80% of the association (Vergel, 1993). As in the S Biozone, the LW Biozone of the central-western basins of Argentina is characterized by dominance of taeniate and plicate pollen, such as *Lunatisporites* spp., *Marsupipollenites* spp., *Vittatina* spp., and *Weylandites* spp. (Césari and Gutiérrez, 2001). In contrast to the assemblages from the CV Biozone, which include a few occurrences of *Lueckisporites virkkae* as seen in the Vc Zone of Brazil, striate pollen grains are not present in high frequencies.

These correlations illustrate that key taxa, useful for local correlations, are influenced by ecological and environmental factors, among others, which may limit their effectiveness in achieving high-resolution regional and global stratigraphic correlations. However, they can still provide valuable information on the migration of parent plants.

From the above observations, we propose to maintain the correlation of the CV Biozone with the VcZ and the IS biozones of the Paraná Basin and to discard its overlap with the earlier Lv and AC biozones. Likewise, we also propose its correlation with the FS Biozone and discard its partial overlap with the *Lueckisporites* Biozone of the central-western Argentine basins, as shown in Gutiérrez and Balarino (2019; p. 10) (Fig. 5). If these correlations are accepted as valid, two species may have their oldest record in the CV Biozone: *Tiwariasporis* (*Striatoabieites*) *anaverrucosus*, recovered in the core sample at 3380 mbsl in the La Estrella x-1 by Balarino (2012, 2014) in the Bonete Formation, and *Corisaccites alutas* recovered in the lowest core sample (3428 mbsl) in the La Estrella x-1 borehole by Balarino (2012, 2014), also in the Bonete Formation.

The new palynostratigraphic correlations proposed here (Fig. 6), along with radiometric dating in the Tunas Formation and the fauna and flora recovered in the Bonete and Tunas formations, provide ample evidence that makes it possible to refine the age of the Sauce Grande Formation and the timespan of the CV Biozone in the Claromecó Basin. Several authors have performed radiometric dating on zircons in tuff levels of the Tunas Formation, helping to delimit the age of the late Paleozoic Pillahuincó Group. At the Abra del Despeñadero locality (upper section of the Tunas Formation), Tohver et al. (2008) reported an Ar-Ar age of 282.4 ± 2.8 Ma, Alessandretti et al. (2013) obtained a U–Pb (LA-ICP-MS) zircon age of 284 ± 15 Ma, and López-Gamundí et al. (2013) reported a U–Pb (SHRIMP) zircon age of 280.8 ± 1.9 m.a. More recently, Arzadún et al. (2018) obtained a U–Pb (SHRIMP) zircon age of 291.7 ± 2.9 Ma from tuff levels at the base of the Tunas Formation (road 76 locality) and a U–Pb (SHRIMP) zircon age of 295.5 ± 8.0 Ma, in tuff levels of the PANG 0001 borehole (Tunas Formation).

The *Eurydesma* Fauna in the Bonete Formation has been referred to as different ages in the Cisuralian. Recently, Cisterna and Sterren (2022) included this fauna in the *Tomiopsis harringtonii* Zone, which was initially considered Artinskian-Kungurian in age and then restricted to the Asselian by López-Gamundí et al. (2023).

Macrofloral remains of the Bonete Formation, described by Harrington (1933 and 1934) and Menéndez (1966), were assigned to the *Glossopteris* Flora (Sakmarian- Artinskian) by Archangelsky and Cúneo (1984), and to the Permian Stage III (~Artinskian-Kungurian) by Cúneo (1996). Cleal (2018) redefined the global biostratigraphical schemes for Permian macrofloras and recognized four biozones in the Gondwana province: the *Botrychiopsis* Zone, which encompasses the Permo-Carboniferous boundary and may extend to the top of the Asselian stage, the *Gangamopteris* Zone (Permian Stage III of Cúneo, 1996) referred to the Sakmarian-Kungurian, the *Glossopteris* Zone (=Zone IV of Cúneo, 1996) with a probable late Kungurian age, and the Zone V of Cúneo, 1996. Considering this scheme, macrofloral remains from the Bonete Formation have been included in either the *Botrychiopsis* Zone or the *Gangamopteris* Zone, while the macrofloral remains from the Tunas Formation have been attributed to the *Gangamopteris* Zone (Otero, 2019;

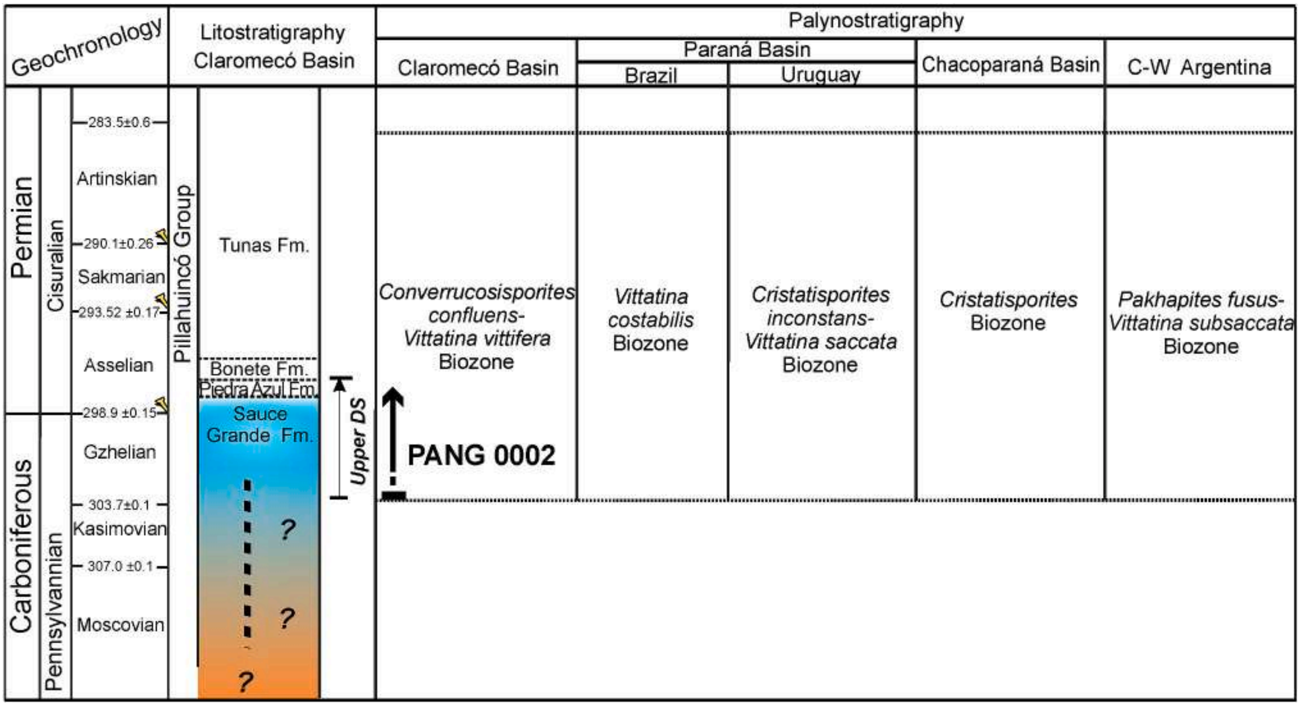

Fig. 5. Regional palynostratigraphic correlations proposed for selected South American late Paleozoic basins.

Ballivián Justiniano et al., 2020). The new findings will contribute to improving their definitions.

The presence of two lycophyte axes in fine-grained, quartz-rich sandstones and siltstone outcropping in the "Interserrana area" referred to *Malanzania nana* by Morel and Gutiérrez (2000) would suggest a late Serpukhovian-Bashkirian or late Kasimovian-Gzhelian sedimentation in the Claromecó Basin (see Section 3). However, the stratigraphic position of these levels is uncertain and its assignment to the Sauce Grande Formation is speculative.

Based on an initial assessment, we conclude that the new palynological assemblage of the Sauce Grande Formation can be correlated with the *Converrucosisporites confluens- Vittatina vittifera* Biozone described by Balarino (2009, 2012, and 2014). This biozone correlates with the Vc (Brazil) and IS biozones (Uruguay) of the Paraná Basin, and with the FS Biozone of central-western basins in Argentina. The age of this biozone can be adjusted to the Gzhelian-late Artinskian interval, encompassing the Permo-Carboniferous boundary,

The present analysis shows that a revision and redefinition of the whole palynostratigraphic scheme of the Claromecó Basin is required. Future contributions of the palynology of the Tunas Formation will contribute to this purpose.

8. Conclusions

In this contribution, we report a diverse palynological association from samples of the glaciomarine Sauce Grande Formation in the PANG 0002 borehole, consisting of 19 spore genera, 25 pollen grain genera, 9 microplankton genera, and one fungal spore genus.

The presence of key species, such as *Converrucosisporites confluens*, *Pakhapites ovatus*, *P. fusus*, *Vittatina* spp., and *Weylandites magmus* indicates an age not older than the Gzhelian for the interval studied. For the first time, a reliable age is assigned to the Sauce Grande Formation based on its fossil content, confirming the Event 5 of the late Paleozoic Ice Age in the Claromecó Basin as suggested by López-Gamundí et al. (2021).

The palynological assemblage of the Sauce Grande Formation is included in the *Converrucosisporites confluens-Vittatina vittifera* Biozone of the Claromecó Basin.

The *Converrucosisporites confluens-Vittatina vittifera* Biozone correlates with the *Vittatina costabilis* and the *Cristatisporites inconstans- Vittatina saccata* biozones of the Paraná Basin, disregarding its partial overlap with the *Lueckisporites virkkiae* and *Striatoabieites anaverrucosus-Staurosaccites cordubensis* biozones. We also propose its correlation with the *Pakhapites fusus-Vittatina subsacatta* Biozone of the central-western Argentine basins and reject its partial overlap with the *Lueckisporites* Biozone.

Considering these new correlations and the isotopically calibrated biozones of the Paraná Basin and central-western basins of Argentina, the age of the *Converrucosisporites confluens- Vittatina vittifera* Biozone can be adjusted to the Gzhelian-late Artinskian interval, encompassing the Permo-Carboniferous boundary. This age agrees with the palynological association obtained from the Sauce Grande Formation in concordance with the *Eurydesma* fauna, Glossopteridalean paleoflora, and radiometric dating of the overlying Bonete and Tunas formations.

These new palynological results from the Sauce Grande Formation combined with unpublished data from the Tunas Formation will enable us to refine the current biostratigraphic scheme of the Upper Paleozoic Claromecó Basin.

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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.

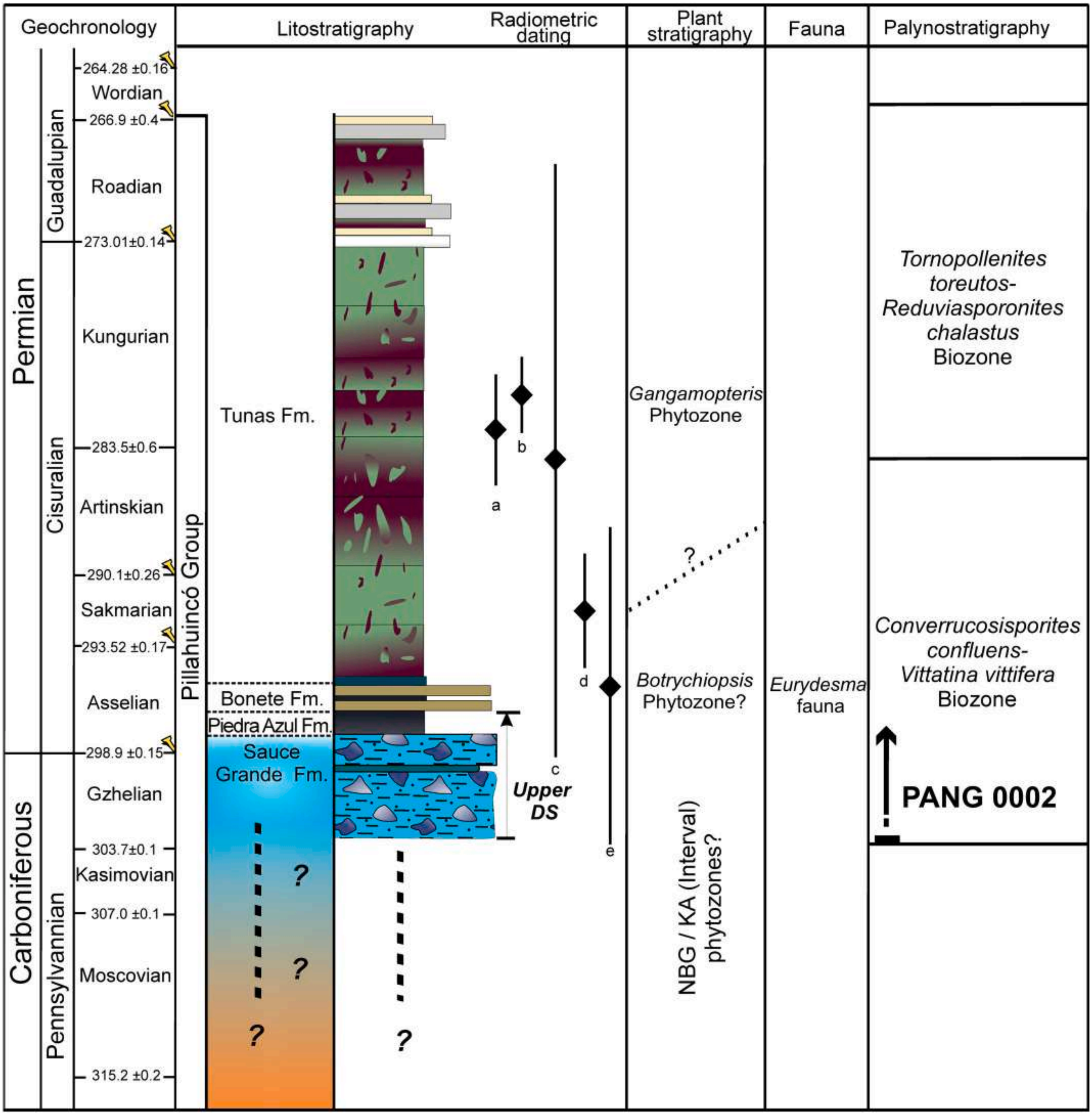

Fig. 6. Age constraints of the Sauce Grande Formation. Time span of radiometric data obtained from tuffs of the Tunas Formation: a: 282.4 ± 2.8 Ma (Tohver et al., 2008) b: 280.8 ± 1.9 Ma (López-Gamundí et al., 2013); c: 284 ± 15 Ma (Alessandretti et al., 2013) d: 291.7 ± 2.9 (Arzadún et al., 2018); e: 295.5 ± 8.0 Ma (Arzadún et al., 2018). 2. Plant stratigraphy of the Bonete and Tunas formations (Ballivián Justiniano et al., 2020), and the Sauce Grande Formation (Morel and Gutiérrez, 2000). 3. *Eurydesma* fauna in the Bonete Formation. Ages are in agreement with Cisterna and Sterren (2022) and López-Gamundí et al. (2023); and palynostratigraphy (Balarino, 2014; this article).

Data availability

Data will be made available on request.

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