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New palynostratigraphic data of the Irati (Assistência Member) and the Corumbataí formations, Paraná Basin, Brazil, and correlation with other south American basins

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ABSTRACT

This research presents the palynostratigraphy of organic-rich shales from the Irati and the Corumbataí formations, Paraná Basin (PB), Southeastern Brazil, as part of an unconventional hydrocarbon source rock and CO_2 reservoir assessment study. Thirty-four samples from the Corumbataí Formation and the Assistência Member of the Irati Formation were collected in the states of Goiás (northern border of the PB), São Paulo and Paraná (eastern and southern border of the PB, respectively). The acquired data allowed to establish a comprehensive palynostratigraphic study across the basin where a total of 18 pollen genera (34 pollen species), seven spore genera, four microplankton genera (1 species), and Chlorophyceae algae species where identified. The palynostratigraphic analysis also reveals a clear dominance of bisaccate pollen grains such as *Corisaccites alutas*, *Lueckisporites virkkiae*, and *Weylandites lucifer*. The *Lueckisporites virkkiae* zone was identified in the upper part of the Irati Formation (Assistência Member) and the lowermost part of the Corumbataí Formation, indicating a Kungurian to Roadian age for this part of the succession. Differences in the *Guttulapollenites hannonicus* and T*ornopollenites toreutos* biostratigraphic ranges, recovered in the Corumbataí Formation, suggest an earlier development of these species in the Paraná Basin during the middle Permian. Therefore, to evaluate the differences in the first occurrences of key species within the Paraná Basin, a close palynostratigraphic correlation between the main Guadalupian-Lopingian South American Gondwana basins is tentatively established.

1. Introduction

Organic-rich shales are the main conventional source rocks found in petroleum systems. However, with the growing importance of unconventional hydrocarbon resources for the future of fossil fuel supply, such as shale gas and shale oil, these organic-rich rock formations gained even more relevance in the global energy scenario. Brazil ranks in the 10th position of countries with technically recoverable shale gas resources, estimated in 245 Tcf (EIA, 2015). Furthermore, estimates made by the National Petroleum, Gas and Biofuels Agency indicate more auspicious numbers for the country: attributing 226 Tcf of estimated shale gas reserves to the Paraná Basin (EIA, 2015), due mostly to the extensive occurrence of black shales within the Passa Dois Group (Milani et al., 2007; Santos et al., 2006; Mateus et al., 2014).

Despite these estimates, the potential for shale gas and CO_2 geological storage in the Paraná Basin remains unclear. As part of a more comprehensive study aiming for a detailed characterization of the Irati Formation oil shales in order to determine its potential for unconventional hydrocarbons source rock and CO_2 geological storage, palynostratigraphy will be used in a multidisciplinary approach that also includes the analysis of vitrinite reflectance, maceral composition, organic geochemistry (proximate and ultimate analyses, pyrolysis - Rock-Eval), and sorption isotherms.

This work presents a detailed palynostratigraphic study of the basal formations of Passa Dois Group, providing a more comprehensive cross-basin correlation for the unconventional economic hydrocarbon-bearing units in the Paraná Basin.

The Passa Dois Group has been extensively studied, including its

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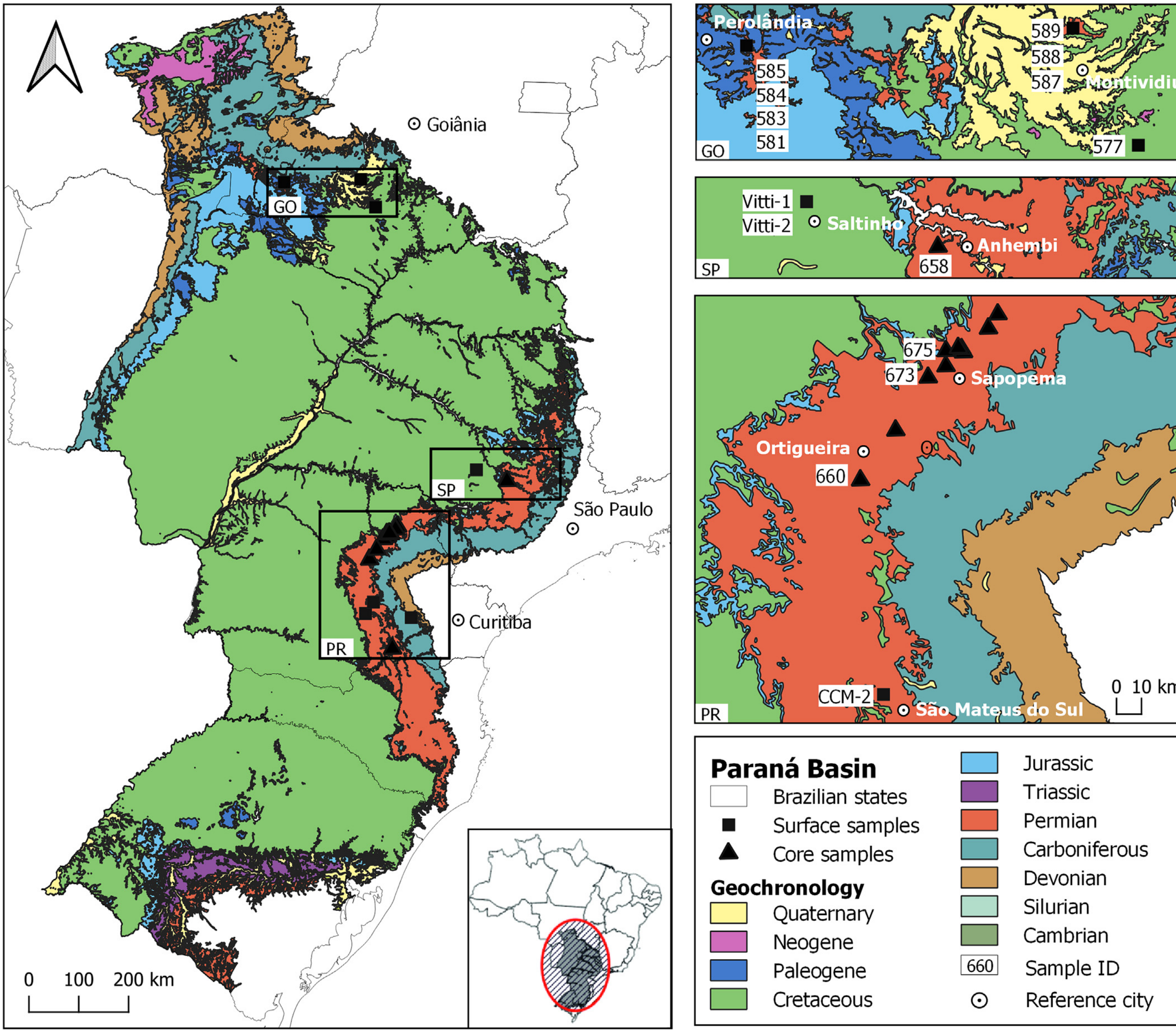

Fig. 1. Map of the Paraná Basin showing the chronostratigraphy and samples location.

paleoflora and palynostratigraphy (Daemon and Quadros, 1970; Marques-Toigo, 1988, 1991; Souza and Marques-Toigo, 2003, 2005; di Pasquo and Souza, 2014; di Pasquo et al., 2018; Premaor et al., 2006; Neregato et al., 2008; Mori and Souza, 2012). Even so, this paper focuses on the palynostratigraphy and environmental analysis of new outcrop and borehole data collected in the Goiás, Paraná and São Paulo regions, which includes from base to top: the Irati, Serra Alta, Teresina, and Rio do Rasto formations, as well as their lateral equivalent occurring in São Paulo State, the Corumbataí Formation (Figs. 1 and 2). This paper focuses on the uppermost Irati and the lowermost Corumbataí formations.

2. Geological setting

Located in the central-eastern part of the South American Platform, the Paraná Basin is the largest South American intracratonic basin. Comprising territorial areas in southern Brazil, eastern Paraguay, northeastern Argentina, and northern Uruguay, this basin covers an area of approximately 1.4 million square kilometers, from which 1.1 million square kilometers are located in Brazil. With an outline configuring an erosive border reaching approximately 5.500 kilometers in diameter, geographically it includes most of the south and southeast regions of Brazil (Milani, 1997; Zalán et al., 1990) (Fig. 1).

The geological evolution of the Paraná Basin is closely linked to the geological history of Gondwana, dating from the Paleozoic and Mesozoic, and varying from the Upper Ordovician to the Upper Cretaceous. In Brazil, the stratigraphic studies of the Paraná Basin started with White, 1908, being followed by Schneider et al. (1974), Zalán et al. (1990), Milani (1997, 2004), and Milani et al. (2007). The two most recent works cited herein, established the current stratigraphic scheme in use for this basin. The basin contains a sedimentary and magmatic stratigraphic column of approximately seven thousand meters of maximum thickness at the structural depocenter of the syncline. During this long-time interval, its tectonic-stratigraphic evolution encompassed continental distension, thermal subsidence, and isostatic adjustment processes (Maack, 1947; Milani, 2004; Zalán et al., 1990).

Six large-scale stratigraphic units, or super-sequences, were identified by Milani (1997) in the Paraná basin: Rio Ivaí (Ordovician-Silurian), Paraná (Devonian), Gondwana I (Carboniferous to Eotriassic), Gondwana II (Medium to Neotriassic), Gondwana III (Neojurassic to

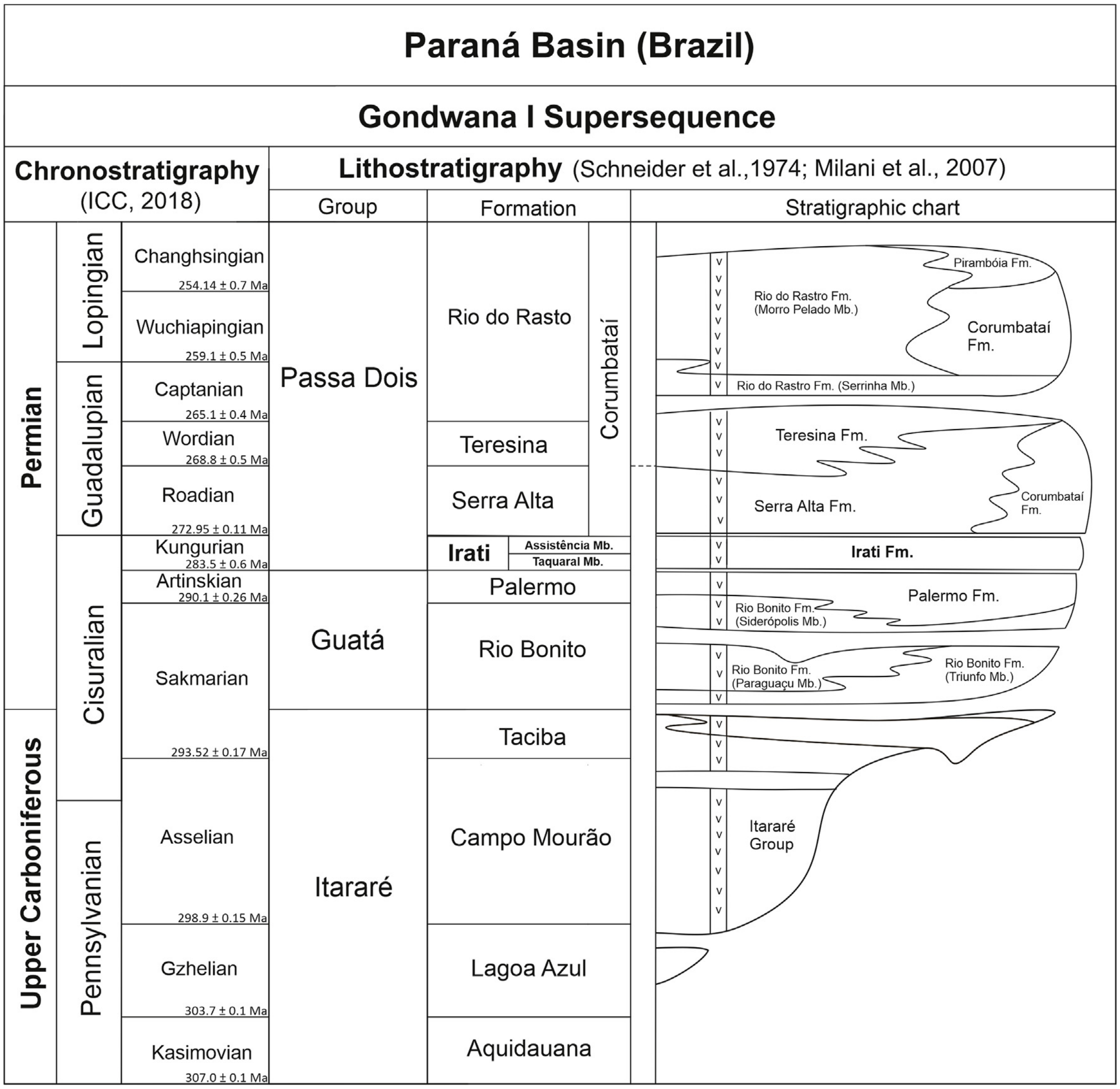

Fig. 2. Stratigraphic succession of the Gondwana I super-sequence, defined by Milani (1997) (Modified from Santos et al., 2006).

Eocretaceous), and Bauru (Neocretaceous). According to the author, the first three super-sequences – Rio Ivaí, Paraná and Gondwana I, represent transgressive-regressive cycles associated with sea-level oscillations that occurred during the Paleozoic. The other super-sequences - Gondwana II, Gondwana III, and Bauru, of Mesozoic age, are characterized as continental sedimentary packages associated with igneous intrusions (Milani, 1997, 2004; Milani et al., 2007).

Due to its economic potential for conventional and unconventional hydrocarbons source rocks, the Passa Dois Group, Gondwana I supersequence, has been the focus of several studies throughout the years (e.g., Milani et al., 2007; Santos et al., 2006; Mateus et al., 2014), including the Irati, Serra Alta, Teresina, and Rio do Rasto formations (Fig. 2). The lowermost unit of the Passa Dois Group, the Irati Formation, is one of the most studied Brazilian geological formations due to its unique fossil-bearing content and potential on hydrocarbons exploitation, being considered one of world's largest oil-shale deposit (e.g., Padula, 1969; Tissot and Welt, 1984; Oelofsen and Araújo, 1987; França et al., 1995; Goldberg and Humayun, 2016). This unit is divided into two distinctive members, the Taquaral Member, located in the lower part of the Irati Formation, which includes dark-grey non-bituminous shales (Barbosa and Gomes, 1958), followed upwards by the Assistência Member comprising bituminous black shales intercalated with dolomites (Barbosa and Gomes, 1958). The intercalation between dolomite and shale beds has higher rhythmicity in the northern and eastern parts of the Paraná Basin, being less predominant in the southern part of the Ponta Grossa arch (Hachiro et al., 1993; Hachiro, 1996). According to Holz et al. (2010), the Taquaral Member was deposited in a marine epicontinental to restricted environment (Reis et al., 2018), while the Assistência Member was originated in a vast and shallow sea where there was an influx of continental waters in some marginal areas of the basin (e.g., presence of *Botryococcus* -brackish to freshwater algae) or hypersaline conditions in other sections.

Several palynological studies performed in the Irati Formation assigned an Artinskian to Roadian age to this unit, based on the identification of the *Lueckisporites virkkiae* zone (Daemon and Quadros, 1970; Menéndez, 1976; Burjack, 1984; Marques-Toigo, 1988; Souza and Marques-Toigo, 2003, 2005; Felix et al., 2006; Santos et al., 2006; Premaor et al., 2006; Calça and Fairchild, 2012). Macrofossils are also recorded in this unit, for instance, mesosaurid reptiles, plants, and crustaceous fossils (Vasconcelos, 1973; Vieira et al., 1991; Ricardi-Branco et al., 2008). The age of the Irati Formation is also constrained by absolute dating, indicating a Kungurian age (e.g., 278.4 ± 2.2 Ma, 276.4 ± 3.7 Ma, 279.9 ± 4.8 Ma, 278.1 ± 3.4 Ma - SHRIMP zircon ages; Santos et al., 2006; Rocha-Campos et al., 2006, 2019).

The upper units of the Passa Dois Group are described in detail by Krebs and Menezes Filho (1984), Castro et al. (1994), and Holz et al.

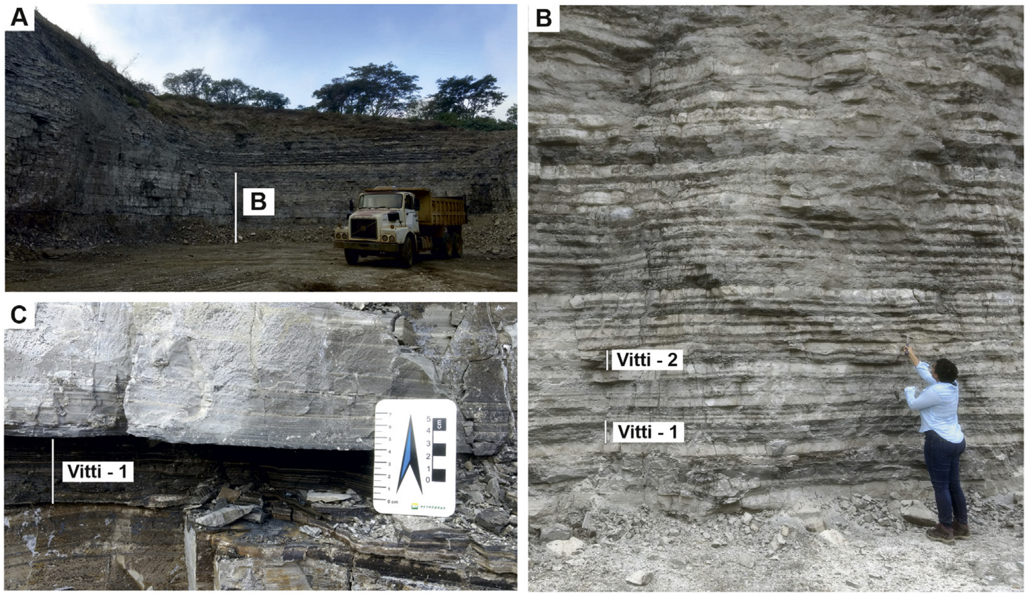

Fig. 3. Vitti Quarry with Corumbataí Formation sample's location. A: Overview of open-pit mining front, where the Corumbataí Formation is exposed. B: Vertical sequence with the location of samples Vitti 1 and Vitti 2. C: Detail of sampled levels - centimetric shales interbedded with carbonates.

(2010). Black shales and siltstones with local calcareous lenses, concretions, and fossil-rich content composed of fish, pelecypods, and conchostrachans specimens comprise the Serra Alta Formation rocks which were conformably deposited over the Irati Formation. This unit was deposited in a calm marine environment below the fairweather wave base. The Teresina Formation was conformably deposited over the Serra Alta Formation and comprehends mudstones and shales, interbedded with sandstone beds, calcareous lenses, and concretions. This unit fossil content includes plant debris, lamellibranch, and palynomorphs (Neregato et al., 2008). The Teresina Formation was deposited in a marine environment marked by high energy shallow waters, which were dominated by wave and tidal processes. The following unit, the Rio do Rasto Formation, comprehends two members, the oldest Serrinha Member, consisting of fine-grained sandstones and interbedded grey to red siltstones, mudstones, and local limestone lenses; and the Morro Pelado Member, consisting of red beds deposited in a continental environment. The fossil content includes pelecypods, conchostracans, plant remains, and vertebrates, reaching the basal Lopingian age (Holz et al., 2010). At the top of the Rio do Rasto Formation, an erosive surface marks the passage to the overlying Botucatu Formation (Krebs and Menezes Filho, 1984; Castro et al., 1994; Holz et al., 2010).

The Teresina and Rio do Rasto formations were previously studied for palynology, and provided assemblages assigned to the *Lueckisporites virkkiae* Zone of Kungurian/Roadian age (common Laevigatosporites vulgaris) and Roadian/Wordian age (abundance of *Thymospora* spp.). Recent research published by di Pasquo et al. (2018) confirmed the Roadian/Wordian age for the Teresina Formation (Serra do Rio Rasto region, Santa Catarina State), indicating a Capitanian (?Lopingian) age for the Rio do Rasto Formation (Urubici region, southern Santa Catarina State). For the first time in the Paraná Basin, these authors identified palynomorph assemblages that include the following taxa: *Cladaitina veteadensis*, *Guttulapollenites hannonicus*, *Lophotriletes parryensis*, *Protohaploxypinus microcorpus*, *Staurosaccites quadrifidus*, and *Weylandites cincinnatus*, extending the age range of the Rio do Rasto Formation to the earliest Lopingian.

The Corumbataí Formation, recognized in the northern part of the basin in the S. Paulo State, is considered an equivalent to the Serra Alta and Teresina formations (southern PB). This unit is fossil-rich, containing different fossil groups, such as pelecypods, conchostracans, ostracods, macroflora remains (Cordaitales), bivalves (Pinzonella neotropica), scales and fish teeth. The palynostratigraphic studies in this unit are scarce and indicate the *Lueckisporites virkkiae* Zone of Kungurian/Roadian age based on the presence of the taxa *Alisporites* cf. *nuthalensis*, *Corisaccites vanus*, *Limitisporites* sp., *Lueckisporites virkkiae*, and *Vittatina*? sp. (Daemon and Quadros, 1970; Maranhão, 1995).

In general, the Irati Formation presents a low degree of thermal evolution, ranging from 0.34% to 0.40% R_0 (Corrêa da Silva and Cornford, 1985); except in the basin depocenter where it can reach high values of maturation, ranging from 1.1 to 1.6% R_0 (Córdova-González et al., 2016; Souzade et al., 2008) due to the influence of intrusive magmatic bodies (Arthur and Soares, 2002; Goldberg and Humayun, 2016; Hachiro, 1996; Milani et al., 2007; Silva, 2007).

3. Materials and methods

A total of thirty-four shale samples from the Irati Formation (Assistência Member) and from the lowermost part of Corumbataí Formation were collected and analyzed in this study (Fig. 1). The Irati Formation was sampled in detail, and thirty-two samples were collected from several outcrops (open-pit mines) and boreholes (core material) belonging to the Brazilian Geological Survey (*Companhia de Pesquisa de Recursos Minerais* – CPRM). The Corumbataí Formation was sampled in the Vitti Quarry in the São Paulo State (two samples). The sample's location is detailed below and its geographic coordinates are available in Fig. 1 and Appendix A.

3.1. Goiás State (GO)

In the northern part of the Paraná Basin, the Irati Formation outcrops in the State of Goiás (GO). A total of six samples were collected in two Montividiu municipality mining areas, Rio Verde (samples 572 to 579) and ELBA (samples 587 to 590), as well as from the Perolândia municipality, SUCAL mining area (samples 580 to 586). These samples comprise black shales with pyrite and silex nodules, which are intercalated by 10–30 cm dolomite beds. An igneous intrusion is also present in the sampled successions (Fig. 1).

3.2. São Paulo state (SP)

In the eastern part of the Paraná Basin in the São Paulo State, borehole FP-12-SP comprising the uppermost part of the Irati Formation (Assistência Member, Fig. 1), was selected for palynostratigraphic sampling. The sampled lithologies are characterized by bituminous black shales, dark grey argillites, and grey shales intercalated by limestone beds.

In the São Paulo State, the Corumbataí Formation was also sampled in the Vitti Quarry (Figs. 1 and 3, samples Vitti-1, Vitti-2). In this region, this unit consists of mudstones, siltstones, and fine sandstones intercalated with dolomitic limestones.

3.3. Paraná State (PR)

In the southern part of the Paraná Basin, in the Paraná State, the Irati Formation was sampled in an open-pit mine in the São Mateus do Sul municipality (samples CCM-1, CCM-2, and CCM-3). The upper part of this unit in this area comprises bituminous black shales, dark grey shales, and associated limestones. The Irati Formation was sampled in the following boreholes: FP-01-PR, FP-02-PR, FP-03-PR, FP-04-PR, FP-07-PR, FP-11-PR, SP-29-PR, SP-37-PR, SP-47-PR, SP-49-PR, SP-55-PR (Fig. 1, Appendix A).

The analyzed palynological samples were treated with standard palynological laboratory procedures to extract and concentrate the organic residues (Wood et al., 1996; Riding and Warny, 2008). Fifteen of the thirty-four samples processed proved productive and were studied for palynology. The slides were analyzed using an optical light BX40 Olympus microscope equipped with an Olympus C5050 digital camera, as well as a Nikon eclipse Ci microscope. The palynomorph identification was based on its morphological features, and qualitative and quantitative analysis was carried out in this study. A total of 250 palynomorph specimens were counted per slide and the complete slide was scanned for rare taxa, which were then recorded as present but outside of the count. All samples, residues, and slides are held in the Palynological Collection of the Portuguese Geological Survey, LNEG, S. Mamede de Infesta, Portugal.

4. Palynological results

Biostratigraphic schemes used herein follow previous palynostratigraphic works of Souza and Marques-Toigo (2003, 2005), and Souza (2006). The recovered palynomorph assemblages are presented in Fig. 4, and stratigraphically significant palynomorphs are illustrated in Plates 1-3. Relative frequencies of selected groups obtained for each sample are presented in Fig. 5.

The quantitative and qualitative distribution of palynomorphs in the studied samples allow the identification of several assemblages based on the relative abundance of common taxa and the first occurrence of selected taxa distributed by the different states, Goiás State, Assemblage 1 (samples 583, 584, 589, 577, 581, 585, 587, 588), São Paulo State, Assemblage 1 (sample 658) and Assemblage 2 (sample Vitti-1), and Paraná State, Assemblage 1 (samples 660, 673, 675 and CCM-2) (Figs. 1 and 3, and Appendix A).

4.1. Goiás State

4.1.1. Assemblage 1 (samples 583, 584, 589, 577, 581, 585, 587, 588)

In general, the assemblage is characterized by a clear dominance of bisaccate taeniate pollen grains, excepting for sample 0588 where non-taeniate bisaccate pollen are prevailing. Pollen grains are very well preserved, in particular in samples 585 and 587.

The abundant and well preserved taeniate bisaccate pollen grains assemblage (35.3–90%) include the coniferopsida *Lueckisporites* complex (according to Vázquez and Césari, 2017 includes the genus *Lueckisporites*, *Corisaccites* and *Staurosaccites* and presents a wide morphological variation) that comprises in the studied assemblage, the taxa *Lueckisporites agoulaensis*, *L. densicorpus*, *L. latisaccus*, *L. stenotaeniatus*, *L. virkkiae*, *Corisaccites alutas*, *C. vanus*, *Staurosaccites cordubensis*, and *S. quadrifidus*), and the lyginopteridopsida *Protohaploxypinus* spp. (*P. amplus*, *P. bharadwajii*, *P. hartii*), Other abundant and complementary species are present in the assemblage: *Lunatisporites variesectus*, *Lunatisporites* sp., *Marsupipollenites striatus*, *M. triradiatus*, *Striatoabieites multistriatus*, *Striatopodocarpites cancelatus*, *S. fusus*, *Tiwarisporites simplex*, *Vittatina* spp. (*V. costabilis, V. fasciolata, V. subsaccata, V. vittifera*), *Weylandites lucifer*, and *Weylandites magmus*.

The monosaccate pollen *Plicatipollenites gondwanensis* and *Potonieisporites novicus* are rare and are only present in samples 585 and 587 (0.7%). However, the percentage of non-taeniate bisaccate gymnosperm pollen like *Alisporites nuthallensis*, *Alisporites* sp., *Caheniasaccites flavatus*, *C. ovatus*, *Limitisporites hexagonalis*, *L. rectus*, and *Limitisporites* sp., varies more intensely throughout the samples (3.0%–62.5%) and is dominant in sample 588 (62.5%). Spores are very rare in this assemblage (0–0.7%) and include the pteridophyte fern *Convolutispora* sp. (samples 585 and 587, Fig. 4). Also, microplanktonic Chlorophyceae algae (e.g., *Brazilea scissa*, *Leiosphaeridia* sp., and algae clusters) are present in several samples and vary from rare to common (0.0–18.5%) (samples 583 and 587, Figs. 4 and 5).

4.2. Paulo State

4.2.1. Assemblage 1 (sample 658)

Sample 658 presents a very poorly preserved assemblage with a clear dominance of microplanktonic specimens which comprise approximately 70.8% of the assemblage (e.g., *Brazilea scissa*, *Leiosphaeridia* sp., and algae clusters). Important taxa include poorly preserved taeniate bisaccate pollen grains (29%), such as *Lueckisporites* spp., *Protohaploxypinus amplus*, *Staurosaccites quadrifidus*, and *Staurosaccites* spp., as well as scarce asaccate pollen grains like *Vittatina costabilis* (0.2%). Spores are absent in this assemblage, and very abundant amorphous organic matter was observed.

4.2.2. Assemblage 2 (sample Vitti-1)

This assemblage contains well preserved and characteristic taeniate bisaccate pollen grains (64.3%–82.7%), such as *Lueckisporites* complex (including *Lueckisporites agoulaensis*, *L. densicorpus*, *L. latisaccus*, *L. stenotaeniatus*, and *L. virkkiae*), *Protohaploxypinus* spp. (*P. amplus, P. bharadwajii, P. hartii*), and asaccate pollen grains (9.0%–15%) including, *Vittatina* spp. (*V. costabilis*, *V. fasciolata*, *V. subsaccata*, *V. vittifera*) and *Weylandites* spp. (*W. lucifer, W. magmus*). The following common taxa complete the assemblage: *Lunatisporites variesectus*, *Lunatisporites* sp., *Marsupipollenites striatus*, *Marsupipollenites triradiatus*, *Pakhapites fusus*, *Striatoabieites multistriatus*, *Striatopodocarpites cancellatus*, *Striatopodocarpites fusus*, and *Tiwarisporites simplex*. Scarce *Guttulapollenites hannonicus* and Tornopollenites toreutos are observed in sample Vitti-1. Monosaccate pollen are rare to absent (0%–1.3%), and bisaccate non-taeniate pollen grains (6.2%–13.3%) also occur in this assemblage (e.g., *Alisporites nuthallensis*, *Alisporites* sp., *Caheniasaccites flavatus*, *C. ovatus*, *Limitisporites hexagonalis*, *L. rectus,* and *Limitisporites* sp.). Fern spores are rare to absent (0%–0.7% of Convolutispora sp. in sample Vitti-1, Figs. 4 and 5), while microplanktonic and Chlorophyceae algae represent 2.1%–5.3% of the assemblage content, including *Brazilea scissa*, *Leiosphaeridia* sp., and indeterminate algae clusters (Figs. 4 and 5).

4.3. Paraná State

4.3.1. Assemblage 1 (samples 660, 673, 675, CCM-2)

The Paraná State palynological assemblages reveal poorly preserved material with a distinctive dominance of taeniate bisaccate pollen grains (57.4%–75.0%), excepting for sample 660 (17.5%) where Chlorophyceae algae dominate (82.5%). Only a few important specimens are identified, for instance the *Lueckisporites* complex (including *Lueckisporites densicorpus*, *L. latisaccus*, *L. virkkiae*, *Lueckisporites* spp., *Corisaccites alutas*, *Staurosaccites cordubensis*, *S. quadrifidus*, and *Staurosaccites* spp.), *Protohaploxypinus amplus*, as well as the asaccate pollen grains *Vittatina costabilis*, *V. subsaccata*, and *Weylandites lucifer.*

	Irati Fm.								Irati Fm.	Corumbataí Fm.	Irati Fm.			
States	Góias								S. Paulo		Paraná			
Assemblages	Assemblage 1								Assemblage 1	Assemblage 2	Assemblage 1			
Samples	583	584	589	577	581	585	587	588	658	Vitti-1	660	673	675	CCM-2
Pollen Grains														
Alisporites nuthallensis		•	•			•	•	•		•		•		
Alisporites sp.		•	•		•	•	•	•		•		•		•
Caheniasaccites flavatus							•			•				
Caheniasaccites ovatus							•			•				
Corisaccites alutas	•		•	•	•	•	•			•			•	•
Corisaccites vanus						•	•			•				
Corisaccites spp.						•	•			•				
Guttulapollenites hannonicus										•				
Limistisporites hexagonalis						•	•			•				
Limitisporites rectus						•	•			•				
Limistisporites sp.	•	•	•			•	•			•	•			
Lueckisporites agoulaensis						•	•			•				
Lueckisporites densicorpus												•		
Lueckisporites latisaccus						•	•	•		•				•
Lueckisporites stenotaeniatus														
Lueckisporites virkkiae	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Lueckisporites spp.	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Lunatisporites variesectus						•	•			•				
Lunatisporites sp.						•	•			•				
Marsupipollenites striatus						•	•			•				
Marsupipollenites triradiatus						•	•			•				
Plicatipollenites gondwanensis							•							
Plicatipollenites sp.												•		
Protohaploxypinus amplus	•	•	•	•		•	•	•	•	•		•	•	•
Protohaploxypinus bharadwajii						•	•			•				
Protohaploxypinus hartii						•	•			•				
Protohaploxypinus goraiesis														
Protohaploxypinus sp.						•	•			•				
Staurosaccites cordubensis		•	•		•	•	•			•	•	•	•	•
Staurosaccites quadrifidus			•		•	•	•		•	•	•	•		•
Staurosaccites spp.	•	•	•	•	•	•	•	•	•	•	•			•
Striatoabieites multistriatus						•	•			•				
Striatopodocarpites cancelatus						•	•			•				
Striatopodocarpites fusus						•	•			•				
Striatopodocarpites cf. *gondwanensis*														
Pakhapites fusus										•				
Potonieisporites novicus							•					•		
Potonieisporites sp.												•		
Tiwarisporites simplex						•	•			•				
Tornopollenites toreutos										•				
Vittatina costabilis	•	•	•			•	•	•	•	•		•		•
Vittatina fasciolata						•	•			•				•
Vittatina subsaccata		•				•	•			•		•		•
Vittatina vittifera						•	•			•				
Vittatina spp.						•	•			•				
Weylandites lucifer			•			•	•	•		•		•		•
Weylandites magmus						•	•			•				
Weylandites spp.						•	•			•				
Spore														
Convolutispora spp.						•	•			•		•		•
Cristatisporites sp.												•		
Kraeuselisporites sp.												•		
Leiotriletes sp.												•		
Lundbladispora sp.												•		
Punctatisporites sp.												•		
Verrucosisporites sp.												•		
Algae														
Botryococcus braunii												•		
Brazilea scissa	•				•	•	•		•	•		•	•	•
Leiosphaeridia sp.	•	•	•		•	•	•		•	•	•			•
Algae cluster			•						•		•			

Fig. 4. Palynomorph assemblages recovered from the studied Irati Formation, Assistência Member, and Corumbataí Formation (Paraná Basin, Brazil).

The following non-taeniate bisaccate pollen grains are also present in this assemblage (9.0%–20.7%, samples 673, 675, and CCM-2, Figs. 4 and 5), *Alisporites nuthallensis*, *Alisporites* sp., and *Limistisporites* sp., and rare monosaccate pollen were identified in sample 673, including *Plicatipollenites* sp., *Potonieisporites novicus*, and *Potonieisporites* sp.. Rare to common trilete spores could be identified in samples 673 and CCM-2 (0.7%–6.7%), including the pteridopsida *Leiotriletes* sp., *Punctatisporites* sp., *Verrucosisporites* sp., and *Convolutispora* spp., as well as the lycopodiopsida *Cristatisporites* sp., *Kraeuselisporites* sp., and *Lundbladispora* sp. (Figs. 4 and 5).

Microplanktonic elements like Chlorophyceae algae and incertae algae clusters are common to abundant in all samples (6.7%–82.5%),

States	Goiás								S. Paulo		Paraná			
Formations	Irati Fm.								Irati. Fm.	Corumbataí Fm.	Irati Fm.			
Assemblages	Assemblage 1								Assemblage 1	Assemblage 2	Assemblage 1			
Samples	583	584	589	577	581	585	587	588	658	Vitti-1	660	673	675	CCM-2
Spores	0.0	0.0	0.0	0.0	0.0	0.7	0.7	0.0	0.0	0.7	0.0	6.7	0.0	0.7
Monosaccate pollen	0.7	0.7	0.7	0.0	0.0	0.7	0.7	0.0	0.0	1.3	0.0	1.3	0.0	0.0
Non-taeniate bisaccate pollen	7.8	9.3	20.0	3.0	20.0	23.3	32.7	62.5	0.0	13.3	0.0	20.7	15.6	9.0
Taeniate bisaccate pollen	70.0	85.0	72.3	90.0	70.5	58.0	47.3	35.3	29.0	64.3	17.5	57.4	70.5	75.0
Assacate/Colpate pollen	3.0	4.3	3.0	0.0	0.0	11.3	8.0	2.2	0.2	15.0	0.0	5.3	0.0	5.3
Chlorophycean algae	18.5	0.7	4.0	7.0	9.5	6.0	10.7	0.0	70.8	5.3	82.5	6.7	14.0	10.0
↘*Botryococcus braunii*	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0

Fig. 5. Relative frequencies of selected palynomorph groups in the studied assemblages (in %).

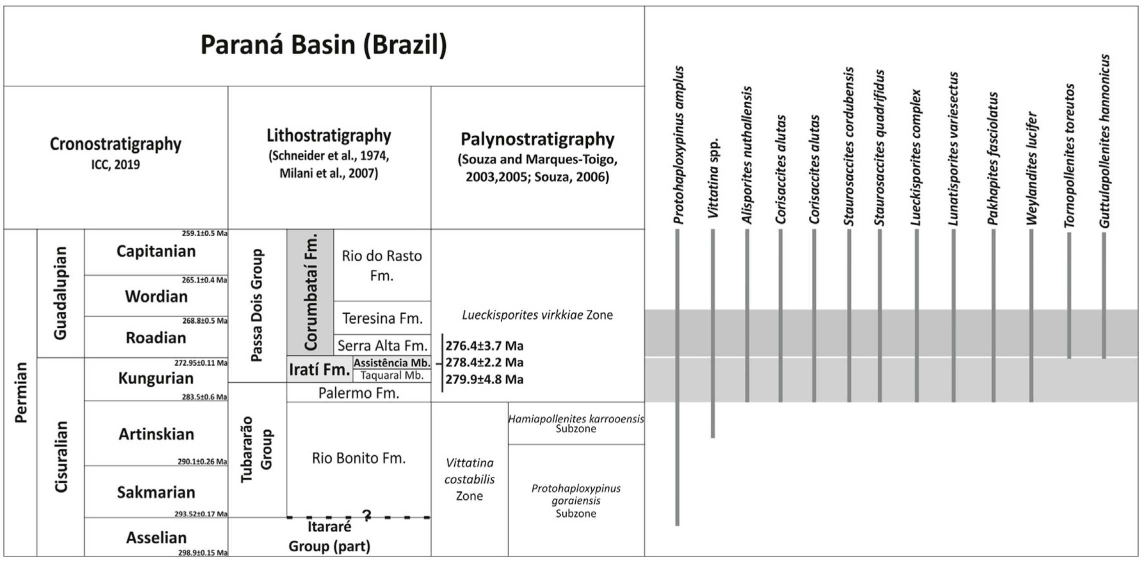

Fig. 6. Lithostratigraphic and palynostratigraphic taxa distribution of *Lueckisporites virkkiae* Zone established by Souza and Marques-Toigo (2005), and the selected species (bold) obtained in the studied Assistência Member (Irati Formation, Paraná Basin, Brazil). International Chronostratigraphic Chart (ICC), International Commission on Stratigraphy 2019/05.

and the occurrence of *Botryococcus braunii* (about 2%), in sample 673, is also worth noting. Phytoclasts and amorphous organic matter dominate the palynodebris recovered in samples 660 and 675.

5. Palynostratigraphic age interpretations

Assemblage 1, identified in this study for the Irati Formation (Assistência Member) in the Goiás, S. Paulo, and Paraná states, can be assigned to the *Lueckisporites virkkiae* Zone defined for the Paraná Basin by Souza and Marques-Toigo (2005) (Fig. 6). The assemblage indicates a Kungurian to Roadian age and is characterized by abundant taxa assigned to the *Lueckisporites* complex (including *Lueckisporites virkkiae*, *L. densicorpus*, *L. stenotaeniatus*, *Corisaccites* spp. and *Staurosaccites* spp.) and *Protohaploxypinus hartii*, together with common *Alisporites nuthallensis*, *Lunatisporites variesectus*, and *Weylandites lucifer*. Other stratigraphically important taxa such as *Lunatisporites, Protohaploxypinus*, and *Pakhapites* are present. The Goiás State palynological results confirm previous ages established by Premaor et al. (2006).

The palynological data gathered in this study correlates well with the geochronological ages previously obtained for the Irati Formation (Paraná Basin), confirming that the base of the *Lueckisporites virkkiae* Zone is no older than Kungurian in age (e.g., 278.4 ± 2.2 Ma, 276.4 ± 3.7 Ma, 279.9 ± 4.8 Ma, 278.1 ± 3.4 Ma) (Santos et al., 2006; Rocha-Campos et al., 2006, 2019, Fig. 6), and can reach the Capitanian.

The palynological assemblage identified in the Corumbataí Formation (Assemblage 2), S. Paulo State, presents the typical species of the *Lueckisporites virkkiae* Zone, displaying a dominance of taeniate pollen grains of the following genera: *Lueckisporites* complex (*Lueckisporites*, *Corisaccites*, and *Staurosaccites*), *Lunatisporites*, *Protohaploxypinus*, *Pakhapites* and *Weylandites*. Furthermore, *Tornopollenites toreutos* and *Guttulapollenites hannonicus* are rarely identified in this formation, and its occurrence could also be assigned to the *Lueckisporites virkkiae* Zone (Menéndez, 1976; Quadros et al., 1995; Mori, 2010; Mori and Souza, 2012, Fig. 6), confirming a Cisuralian-Guadalupian age for this formation.

The occurrence of *Tornopollenites toreutos* was already known from palynoassemblages of the Amazonas Basin, Brazil (*Tornopollenites toreutos* Zone; Playford and Dino, 2000a, 2000b), the Claromecó Basin, Argentina (*Tornopollenites toreutos–Reduviasporonites chalastus* Zone, Balarino, 2014; Gutiérrez et al., 2011), and Paraguay (Perez Loinaze et al., 2010, Figs. 6 and 7).), to which it was assigned a Roadian to Guadalupian age.

The recognition of *Guttulapollenites hannonicus* in the Irati, Serra Alta, Teresina, and Rio do Rasto formations (Mori, 2010; Mori and Souza, 2012) highlights the stratigraphic difficulties and complexities of the Paraná Basin. Considering this work and related researches, the similarity of the palynoflora identified in the Irati and Corumbataí formations could suggest a lateral age correlation between the two formations.

6. Stratigraphical significance of the palynoflora and correlation with other main south American gondwana basins

In South American Gondwana basins, several palynostratigraphic studies were already developed throughout the years, resulting in well-established palynological schemes (e.g., Playford and Dino, 2000a, 2000b; Gutiérrez et al., 2003, 2011; 2018; Beri et al., 2011; Balarino, 2014; di Pasquo et al., 2015, 2018; Vázquez and Césari, 2017; Zavattieri et al., 2018). Moreover, recent data obtained by

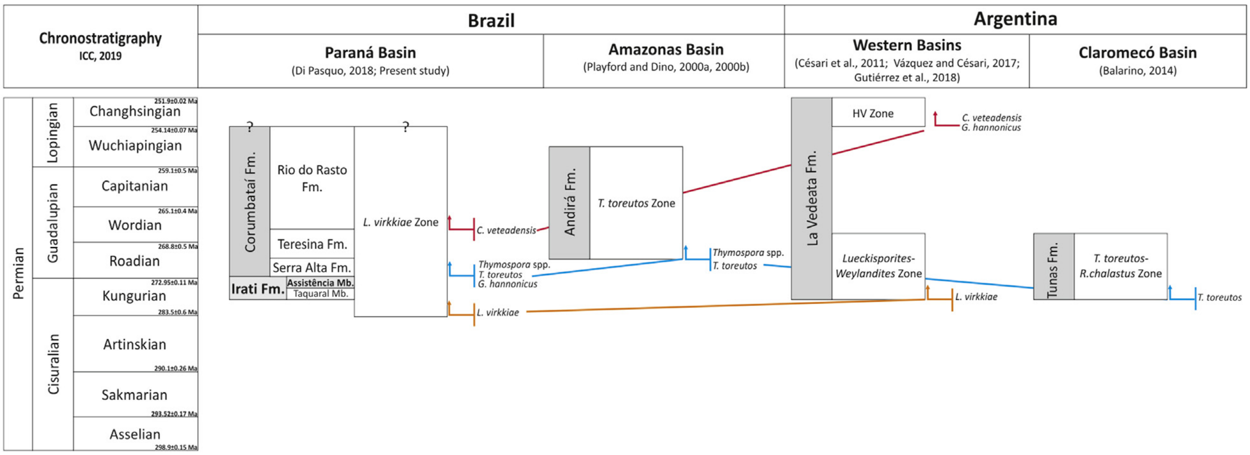

Fig. 7. Palynological correlation with South American Gondwana basins. International Chronostratigraphic Chart (ICC), International Commission on Stratigraphy 2019/05.

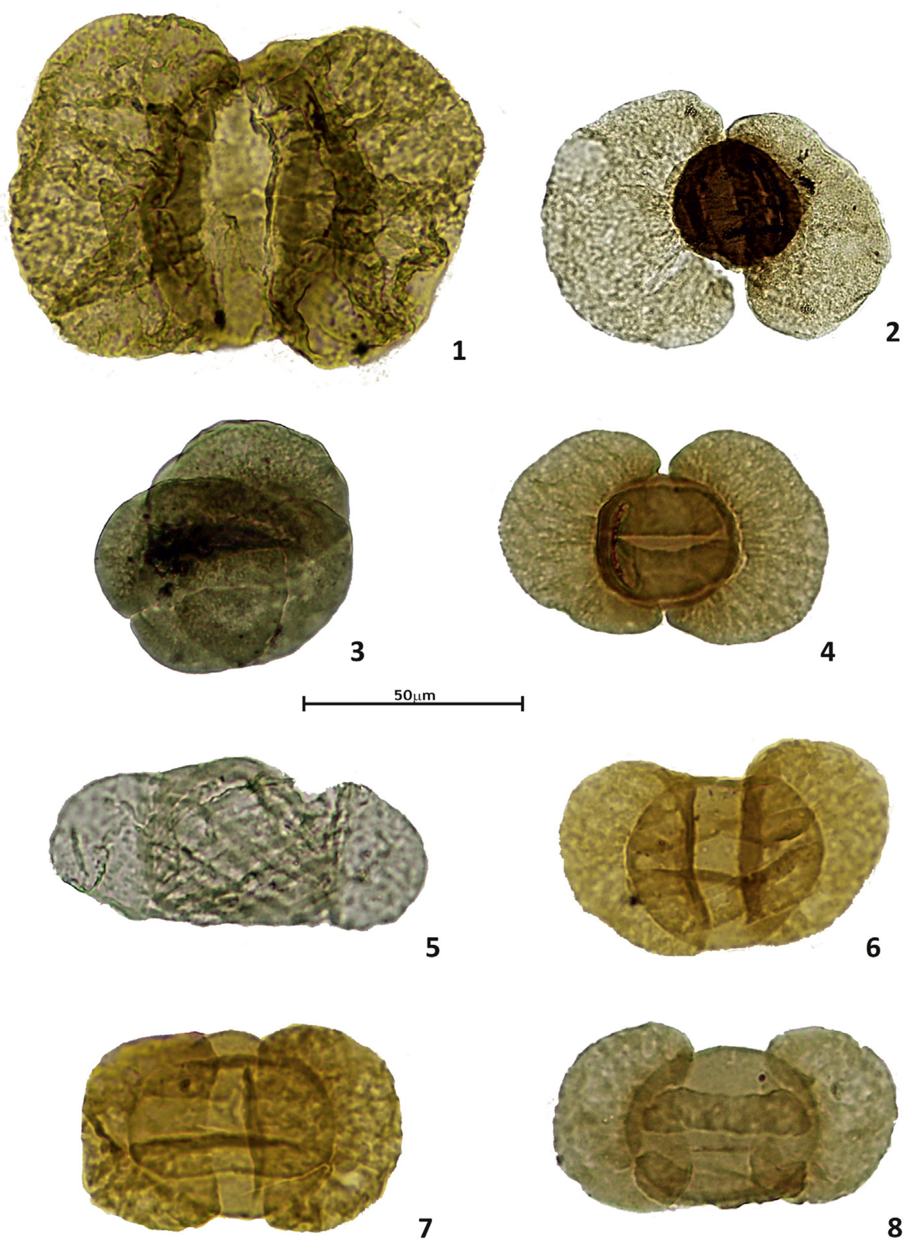

Plate 1. 1. *Limitisporites hexagonalis* Bose and Maheshwari 1968; sample vitti, slide 2A_104, MC 1118/454;
2. *Striatopodocarpites fusus* (Balme and Hennelly) Potonié 1958; sample 587, slide F3_108, MC 1157/170;
3. *Guttulapollenites* cf. *hannonicus* Balme 1970; sample Vitti 1, slide D_54, MC 1165/100;
4. *Lueckisporites agoulaensis* Jardiné 1974; sample 587, slide F2_121, MC 1296/134;
5. *Tornopollenites toreutos* Morgan 1972; sample Vitti 1, slide E4_96, MC 1353/100;
6. *Lueckisporites stenotaeniatus* Menéndez (1976); sample 587, slide 1_49, MC 973/388;
7. *Lueckisporites stenotaeniatus* Menéndez (1976); sample 587, slide 1_55; MC 1046/390;
8. *Lueckisporites stenotaeniatus* Menéndez (1976); sample 587, slide F1_55, MC 1407/207.

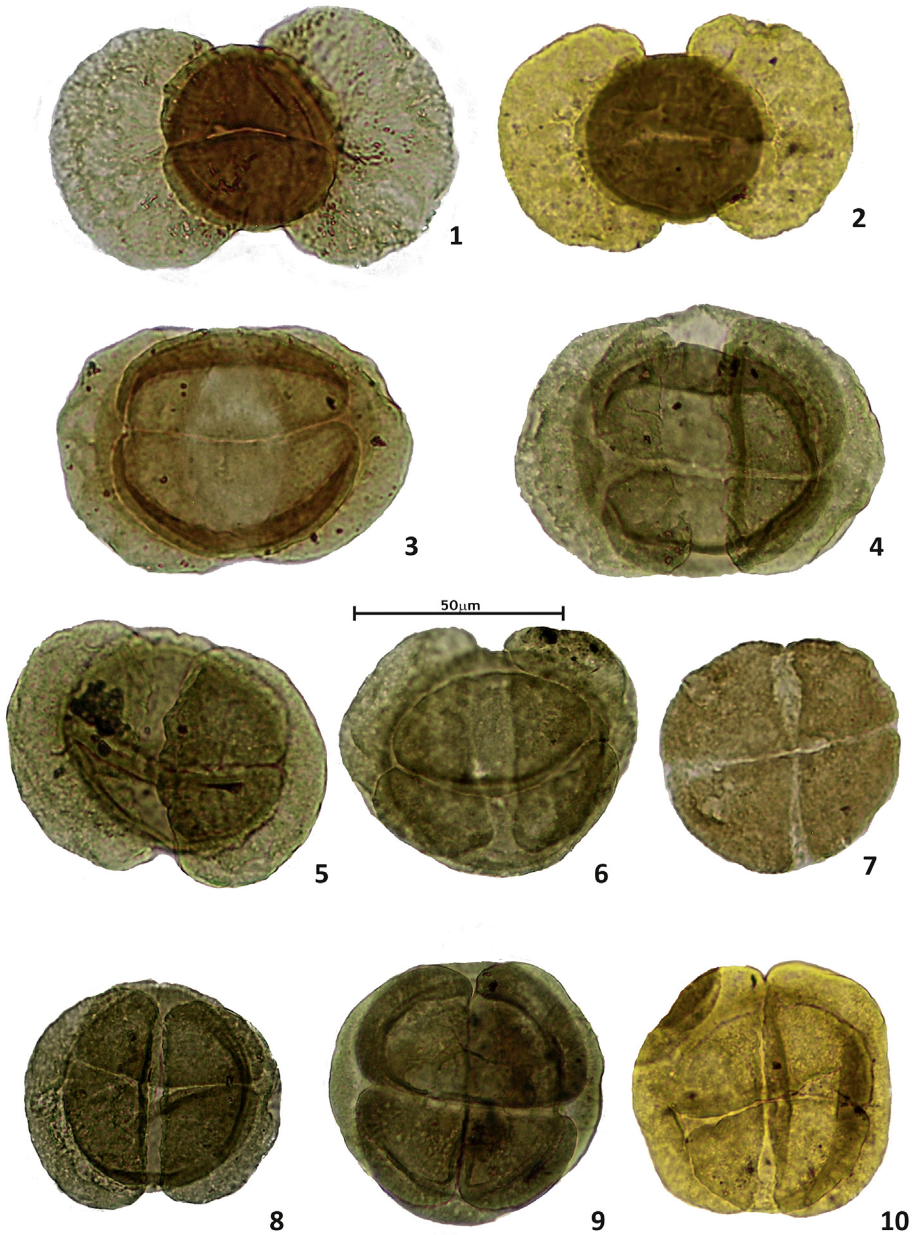

Plate 2. 1. *Lueckisporites densicorpus* Archangelsky and Gamerro 1979; sample 587, slide F1_136, MC 1355/180;
2 - *Lueckisporites densicorpus* Archangelsky and Gamerro 1979; sample Vitti 1, slide 2a_15, MC 1046/512;
3 - *Lueckisporites virkkiae* (Potonié and Klaus) Klaus 1963; sample 587, slide F2_25, MC 1340/198;
4 - *Lueckisporites virkkiae* (Potonié and Klaus) Klaus 1963; sample Vitti 1, slide 7D, MC 1275/68;
5 - *Lueckisporites virkkiae* (Potonié and Klaus) Klaus 1963; sample Vitti 1, slide F1_142, MC 1405/233;
6 - *Lueckisporites virkkiae* (Potonié and Klaus) Klaus 1963; sample Vitti 1, slide D_50, MC 1450/99;
7 - *Staurosaccites cordubensis* Archangelsky and Gamerro 1979; sample vitti, slide cF2_159, MC 1225/75;
8 - *Staurosaccites quadrifidus* (Dolby) Dolby and Balme 1976; sample 587, slide F3_60, MC 1185/101;
9 - *Staurosaccites quadrifidus* (Dolby) Dolby and Balme 1976; sample Vitti 1, slide D_81, MC 1090/115;
10 - *Staurosaccites quadrifidus* (Dolby) Dolby and Balme 1976; sample Vitti 1, slide 2b_40, MC 1117/347.

geochronology has provided the basis to better constrain the Gondwana palynozones established for example in Brazil (following Souza and Marques-Toigo, 2005; Santos et al., 2006; Mori et al., 2012) and in Argentina (following Césari et al., 2011; Vázquez and Césari, 2017). Therefore, the assemblages characterized in this work can be correlated with palynological assemblages known for other Gondwana basins. This correlation is based on the first occurrence (FO) of selected taxa and abundances of characteristic species, in particular for the Kungurian-Roadian age interval (Fig. 7).

The most important palynoevents with a regional expression that are known for this age interval include, from base to top: the FO of Lueckisporites virkkiae of Kungurian/Roadian age, which is followed by the FO of *Tornopollenites toreutos*, *G. hannonicus*, and *Thymospora* spp., in the early Gualadupian, and finally, the abundant presence of *G. hannonicus* and *Cladaitina veteadensis*, which is recognized in palynological assemblages of late Guadalupian/early Lopingian age.

G. hannonicus was described in South America Gondwana basins ranging from the Guadalupian to the Lopingian. More specifically in Brazil, its base range has been recorded since the middle Permian, in the Serra Alta and Rio do Rasto formations (Mori and Souza, 2012; di Pasquo et al., 2018). In this study, *G. hannonicus* was recorded together with *T. toreutos* (Assemblage 2) in the Corumbataí Formation assemblage, suggesting an earlier occurrence of these taxa during the Kungurian/Roadian (Mori, 2010; Mori and Souza, 2012).

Nevertheless, in Western Argentina, La Veteada Formation, the presence of *G. hannonicus* constitutes a well-defined Lopingian age stratigraphic record (Gutiérrez et al., 2018; Zavattieri et al., 2017, 2018). Even if the assemblages described from the La Veteada Formation also contain *Cladaitina veteadensis* and several other taxa that indicate an end-Permian palynofloral signature, these are not totally recognized in the Irati and the Corumbataí assemblages, suggesting an older age for the Paraná formations.

Likewise, *T. toreutos* was previously recognized in the Amazonas Basin by Playford and Dino (2000a, 2000b), in assemblages assigned a Guadalupian (Capitanian) to Lopingian age. This taxon is also documented from palynological assemblages recovered in the Tunas

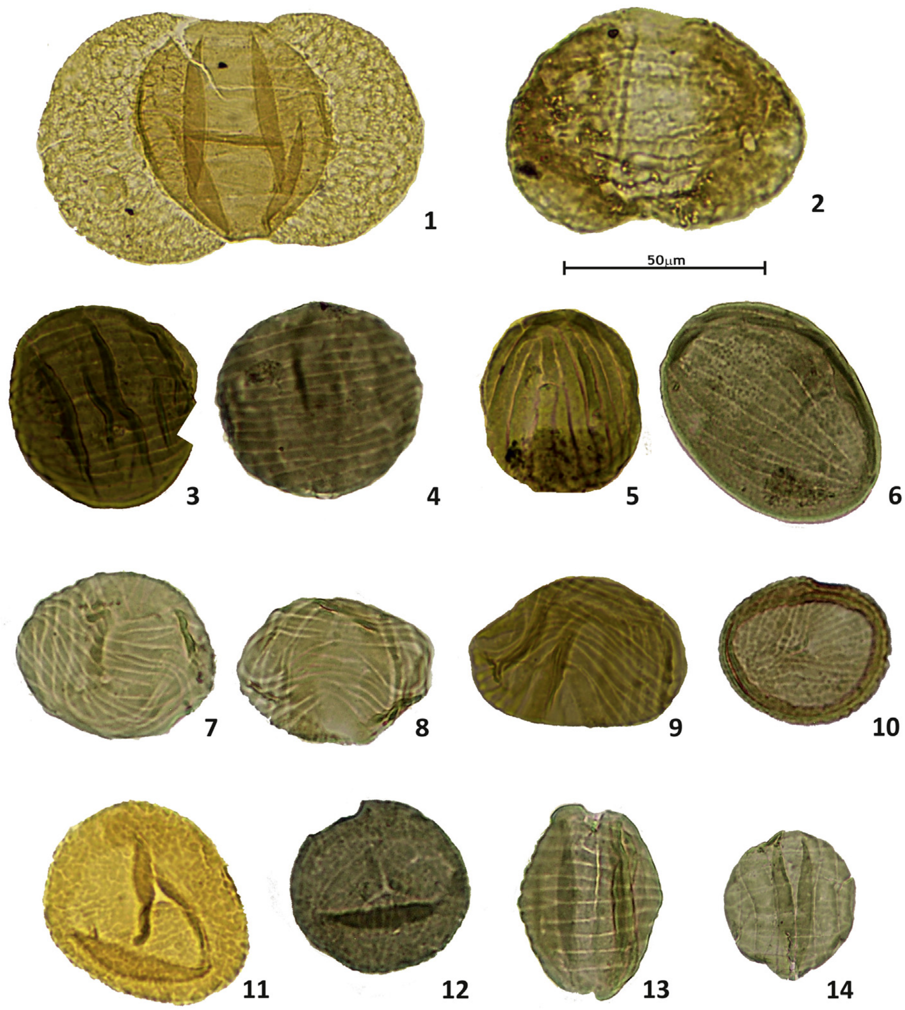

Plate 3. 1 - *Protohaploxypinus amplus* (Balme and Hennelly) Hart 1964; sample 587, slide 1_22, MC 1004/413;
2 - *Protohaploxypinus goraiensis* (Potonié and Lele) Hart 1964; sample 673, slide 9B3_4, MC 935/130;
3 - *Vittatina costabilis* Wilson 1962; sample Vitti 1, slide 2a_142, MC 1014/449;
4 - *Vittatina costabilis* Wilson 1962; sample Vitti 1, slide c3_42, MC 1192/55;
5 - *Vittatina fasciolata* (Balme y Hennelly) Bharadwaj 1962; sample Vitti 1, slide 2a_13, MC 1062/522;
6 - *Vittatina vittifera* (Luber and Waltz) Samoilovich 1953; sample Vitti 1, slide F3_28, MC 1371/135;
7 - *Weylandites lucifer* (Bharadwaj and Srivastava) Foster 1975; sample 587, slide F2_16, MC 1350/178;
8 - *Weylandites lucifer* (Bharadwaj and Srivastava) Foster 1975; sample 587, slide F1_111, MC 1430/150;
9 - *Weylandites lucifer* (Bharadwaj and Srivastava) Foster 1975; sample 587, slide 1_63, MC 1063/389;
10 - *Marsupipollenites striatus* (Balme and Hennelly) Foster 1975; sample 587, slide F2_28, MC 1340/198;
11 - *Marsupipollenites striatus* (Balme and Hennelly) Foster 1975; sample 587, slide 1_38, MC 1058/409;
12 - *Marsupipollenites triradiatus* Balme and Hennelly 1956; sample Vitti 1, slide c3_76, MC 1122/80;
13 - *Pakhapites fusus* (Bose and Kar) Menéndez 1971; sample Vitti 1, slide E/F2_87, MC 1444/90;
14 - *Pakhapites fusus* (Bose and Kar) Menéndez 1971; sample 9B, slide F2_166, MC 1331/275.

Formation, Claromecó Basin, Argentina (Balarino, 2014), where the FO of *T. toreutos* marks the base of the *Tornopollenites toreutos-Reduviasporonites chalastus* Zone, of lower Guadalupian age. However, radiometric dating obtained from the Tunas Formation (280.8 ± 1.9 Ma, López-Gamundí et al., 2013; 282.4 ± 2.8 Ma, Tohver et al., 2008; 291.7 ± 2.9 Ma and 295.5 ± 8.0 Ma, Arzadún et al., 2018) raises doubts regarding the Guadalupian age assigned by the palynological data, as already suggested by Vázquez and Césari (2017). In the Paraná Basin, the occurrence of this taxon could suggest an earlier occurrence during the Cisuralian/Guadalupian boundary, since it is rare in the studied samples and the lithostratigraphic information of Quadros et al. (1995) is uncertain.

7. Irati and Corumbataí formations environmental interpretation

Schneider et al. (1974) suggest a marine environment below the fairweather wave base for the deposition of the Irati Formation. However, in this study, the absence of marine palynomorphs, as well as the dominance of taeniate pollen grains, the presence of fresh to brackish water algae specimens, and scarce spores in the studied samples suggest deposition in a shallow marine environment close to the shoreline as the influx of freshwater and terrestrial material in the assemblages is considerable. The record of *Botryococcus braunii*, already described by Corrêa da Silva and Cornford (1985) and De Castro (1988) for the Irati Formation (Paraná Basin) can also support these authors interpretation of a shallow and low energy lacustrine depositional regime (following Traverse, 1992). The record of amorphous organic matter and framboidal pyrite in the studied samples also supports the idea of deposition in shallow and anoxic environments.

Deposition in a shallow marine environment in anoxic conditions for the lowermost part of the Corumbataí Formation is the interpretation provided by Schneider et al. (1974). This interpretation highlights the similitude between the depositional environments and the palynofloras found in the Irati and the Corumbataí formations, pointing a dominance of taeniate bisaccate pollen grains (e.g., *Protohaploxypinus*, *Striatopodocarpites*, *Guttulapollenites hannonicus*, and *Tornopollenites toreutos*), scarce spores and rare fresh to brackish water algae elements.

8. Conclusions

The palynostratigraphic data from the Paraná Basin, Brazil, obtained for the Irati Formation in the Goiás, S. Paulo, and the Paraná states can be correlated with the *Lueckisporites virkkiae* Zone of Kungurian to Roadian age (Cisuralian/Guadalupian age). These data confirm previous palynological studies done in the Paraná Basin, as well as previous U–Pb geochronology ages obtained for this unit. Likewise, the lowermost part of the Corumbataí Formation, in the Paraná Basin, allowed the identification of the *Lueckisporites virkkiae* Zone of Kungurian/Roadian age. These assemblages are similar to the palynofloras recorded from the Irati Formation, with rare exceptions of *Guttulapollenites hannonicus* and *Tornopollenites toreutos*.

The dominance of taeniate pollen grains and the presence of fresh to brackish water algae specimens, suggests a deposition in a shallow marine environment, close to the shoreline, highlighted by the influx of freshwater and the presence of considerable terrestrial material in the assemblages.

The new palynological data contributes to the development of a better stratigraphic framework for future unconventional hydrocarbons source rocks and CO_2 geological storage assessment and exploitation in the Paraná Basin.

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.

List of taxa

Spores
Convolutispora spp.
Cristatisporites sp.
Kraeuselisporites sp.
Leiotriletes sp.
Lundbladispora sp.
Punctatisporites sp.
Verrucosisporites sp.
Pollen grains
Alisporites nuthallensis Clarke 1965
Alisporites sp.
Caheniasaccites flavatus Bose and Kar emend. Azcuy and di Pasquo 2000
Caheniasaccites ovatus Bose and Kar 1966
Corisaccites alutas Venkatachala and Kar 1966
Corisaccites vanus Venkatachala and Kar 1966
Corisaccites spp.
Guttulapollenites hannonicus Balme 1970
Limitisporites hexagonalis Bose and Maheshwari 1968
Limitisporites rectus Leschik 1956
Limitisporites sp.
Lueckisporites agoulaensis Jardiné 1974
Lueckisporites densicorpus Archangelsky and Gamerro 1979
Lueckisporites latisaccus Archangelsky and Gamerro 1979
Lueckisporites stenotaeniatus Menéndez 1976
Lueckisporites virkkiae (Potonié and Klaus) Klaus 1963
Lueckisporites spp.
Lunatisporites variesectus Archangelsky and Gamerro 1979
Lunatisporites sp.
Marsupipollenites striatus (Balme and Hennelly) Foster 1975
Marsupipollenites triradiatus Balme and Hennelly 1956
Pakhapites fusus (Bose and Kar) Lele 1964
Plicatipollenites sp.
Potonieisporites novicus Bhardwaj emend. Poort and Veld 1997
Potonieisporites sp.
Protohaploxypinus amplus (Balme and Hennelly) Hart 1964
Protohaploxypinus bharadwajii Foster 1979
Protohaploxypinus hartii Foster 1979
Protohaploxypinus goraiensis (Potonié and Lele) Hart 1964
Protohaploxypinus spp.
Staurosaccites cordubensis Archangelsky and Gamerro 1979
Staurosaccites quadrifidus Dolby in Dolby and Balme 1976
Staurosaccites spp.
Striatoabieites multistriatus (Balme and Hennelly) Hart 1964
Striatopodocarpites cancellatus (Balme and Hennelly) Hart 1964
Striatopodocarpites fusus (Balme and Hennelly) Potonié 1958
Tiwarisporites simplex (Tiwari) Maheshwari and Kar 1967
Tornopollenites toreutos Morgan 1972
Vittatina costabilis Wilson 1962
Vittatina fasciolata (Balme and Hennelly) Bharadwaj 1962
Vittatina subsaccata Samoilovich 1953
Vittatina vittifera (Luber and Waltz) Samoilovich 1953
Vittatina spp.

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Weylandites lucifer (Bharadwaj and Srivastava) Foster 1975
Weylandites magmus (Bose and Kar) Backhouse 1991
Weylandites spp.
Chlorophycean algae
Botryococcus braunii Kützing 1849
Brazilea scissa (Balme and Hennelly) Foster 1975
Leiosphaeridia sp.

Appendix A. Sample locations list description (State, Municipality and UTM Coordinates). Bold sample references indicates the productive samples for palynology

Lab ID	Sample ID	Outcrop Sample	Borehole	Depth (m)	Formation	State	Municipality	Coordinates (E, N)	
								UTM ZONE 22 L	
15	**583**	x			Irati	Goiás (GO)	Perolândia	393552.3	8120173.4
16	**584**	x			Irati	Goiás (GO)	Perolândia	393552.3	8120173.4
22	**581**	x			Irati	Goiás (GO)	Perolândia	393552.3	8120173.4
23	582	x			Irati	Goiás (GO)	Perolândia	393552.3	8120173.4
24	**585**	x			Irati	Goiás (GO)	Perolândia	393552.3	8120173.4
14	579	x			Irati	Goiás (GO)	Montividiu	606447.7	8120173.4
17	**589**	x			Irati	Goiás (GO)	Montividiu	500000	8120445
20	574	x			Irati	Goiás (GO)	Montividiu	606447.7	8120173.4
21	**577**	x			Irati	Goiás (GO)	Montividiu	606447.7	8120173.4
25	**587**	x			Irati	Goiás (GO)	Montividiu	500000	8120445
26	**588**	x			Irati	Goiás (GO)	Montividiu	500000	8120445
								UTM ZONE 22 K	
1	**658**		FP-12-SP	274.2	Irati	São Paulo (SP)	Anhembi	780500	7480600
27	659		FP-12-SP	274.38	Irati	São Paulo (SP)	Anhembi	780500	7480600
19	**Vitti-1**	x			Corumbataí	São Paulo (SP)	Saltinho	423974.7	4794350.7
34	Vitti-2	x			Corumbataí	São Paulo (SP)	Saltinho	423974.7	4794350.7
								UTM ZONE 22 J	
2	**660**		FP-11-PR	351.34	Irati	Paraná (PR)	Ortigueira	52110	733800
7	668		FP-04-PR	185.61	Irati	Paraná (PR)	Ortigueira	507000	7318000
3	662		FP-01-PR	194.5	Irati	Paraná (PR)	Ibati	562000	7384500
4	663		FP-01-PR	195.07	Irati	Paraná (PR)	Ibati	562000	7384500
30	664		FP-01-PR	196.95	Irati	Paraná (PR)	Ibati	562000	7384500
31	665		FP-01-PR	197.45	Irati	Paraná (PR)	Ibati	562000	7384500
5	666		FP-02-PR	122.8	Irati	Paraná (PR)	Sapopema	541200	7363700
6	667		FP-03-PR	227.16	Irati	Paraná (PR)	Sapopema	534100	7359200
9	**673**		SP-29-PR	340.65	Irati	Paraná (PR)	Sapopema	541258	7369810
10	**675**		SP-37-PR	213.72	Irati	Paraná (PR)	Sapopema	548201	7369295
11	676		SP-47-PR	241.74	Irati	Paraná (PR)	Sapopema	547500	7370615
12	679		SP-49-PR	373.27	Irati	Paraná (PR)	Sapopema	558189	7378836
13	681		SP-55-PR	477	Irati	Paraná (PR)	Sapopema	546150	7371080
33	680		SP-49-PR	373.4	Irati	Paraná (PR)	Sapopema	558189	7378836
8	669		FP-07-PR	81.07	Irati	Paraná (PR)	S. Mateus do Sul	55610	713930
18	**CCM-2**	x			Irati	Paraná (PR)	S. Mateus do Sul	562239	7136074
28	CCM-1	x			Irati	Paraná (PR)	S. Mateus do Sul	559453	7142580
29	CCM-3	x			Irati	Paraná (PR)	S. Mateus do Sul	557652	7147058
32	672		FP-07-PR	95.45	Irati	Paraná (PR)	S. Mateus do Sul	55610	713930

Authorship statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in the Journal of South American Earth Sciences.

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