Journal of South American Earth Sciences 91 (2019) 27–35

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Palynology of Bonito and Barro Branco coal seams from Rio Bonito Formation (Lower Permian of Paraná Basin) in the Criciúma coal region, southernmost Brazil

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A R T I C L E I N F O

Keywords:
Spores
Pollen
Palynostratigraphy
Cisuralian
Criciúma coal seams
Brazil

A B S T R A C T

Seven coal seams were sampled from several mines and outcrops of the Rio Bonito Formation, Bonito and Barro Branco coal seams, in the coal mining region of Criciúma, Paraná Basin, Santa Catarina State (Brazil), for a detailed palynostratigraphic study. The coal seams sampled yield abundant, diverse and moderately to well preserved palynological assemblages. A total of twenty-seven spore species, fourteen pollen species and four microplanktonic or clorophyceae algae and fungi species were identified. The palyno-assemblages recovered in the Bonito and Barro Branco coal seams are assigned to the *Vittatina costabilis* Interval Zone, *Protohaploxypinus goraiensis* Subzone of the Paraná Basin, of Asselian? to Artinskian age (Lower Permian). The microflora assemblages identified in these coal seams are very similar in composition, presenting a dominance of arborescent and herbaceous lycophytes. The Barro Branco coal seam shows a relatively higher frequency of algae like composition than in the Bonito coal seam, suggesting a possible fluvial or lagoonal facies influence.

1. Introduction

The Paraná is a large intracratonic basin in Brazil and bears important coal seams within the Permian Rio Bonito Formation. The present contribution is a detailed study of the Bonito and Barro Branco coal seams at the Criciúma coal region, southern area of Santa Catarina State (Fig. 1). In Criciúma region, the main coal seams are assigned to the Tubarão Supergroup that includes the Guatá Subgroup: the Rio Bonito Formation (Paraguaçu Member - Bonito coal seam and Siderópolis Member - Barro Branco Coal seam) (Fig. 1).

The Tubarão Supergroup, in the southern Paraná Basin (PB), has been intensely studied by means of paleoflora (Iannuzzi, 2010; Bernardes-de-Oliveira et al., 2016) and palynostratigraphy (Daemon and Quadros, 1970; Marques-Toigo, 1988, 1991; Souza et al., 2003; Souza and Marques-Toigo, 2003, 2005; Souza, 2006; Boardman et al., 2012a, 2012b; di Pasquo et al., 2018) amongst others.

The main target of the present project is characterizing the potential of coal seams from Rio Bonito Formation for CO_2 sequestration, using a multidisciplinary approach that includes vitrinite reflectance, maceral composition, organic geochemistry (proximate and ultimate analyses, pyrolysis (Rock-Eval), sorption isotherms and palynostratigraphy. The World Energy Strategy new scenario is facing several demanding challenges to ensure the three main targets, a secure, competitive and sustainable energy, although supported by a climate strategy.

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https://doi.org/10.1016/j.jsames.2019.01.009
Received 27 November 2018; Received in revised form 11 January 2019; Accepted 11 January 2019
Available online 15 January 2019
0895-9811/

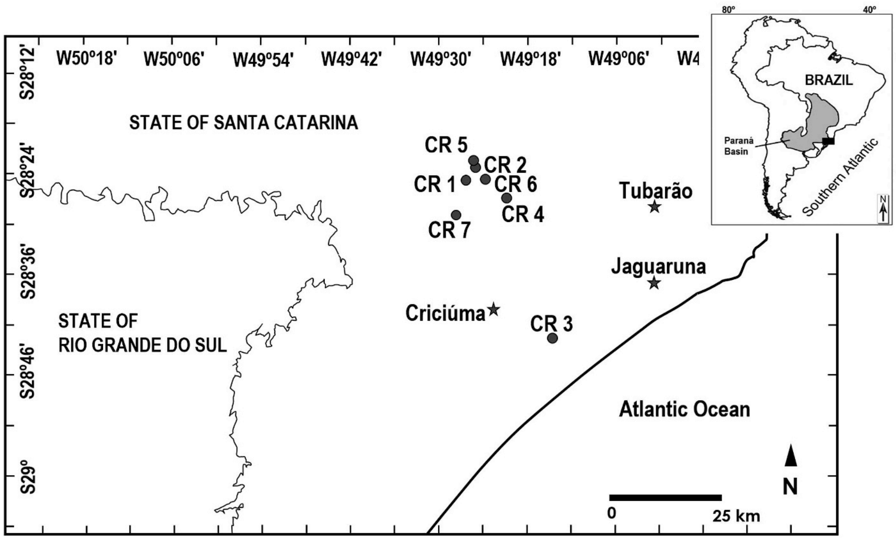

Fig. 1. a. Map of the studied area with location of studied sections and samples. b. Stratigraphic log with studied samples at the Siderópolis Member coal beds (Rio Bonito Formation) in Santa Catarina. Modified from Iannuzzi (2010) and Bernardes-de-Oliveira et al., 2016.

Nevertheless, in 2015 COP21 (2015 Paris Climate Conference), it was stated that this climate strategy can only be overcome by applying the CCS (Carbon Capture and Storage) Technologies. In this context, Brazil, due to their internationally well-known coalfields, can play a major role in the CCS technologies scope, which is the ultimate goal of this project, but not the main objective of the present study.

A total of 7 coal seams were sampled, from several mines and outcrops of the Criciúma coal region, Santa Catarina State for the detailed studies above mentioned. This work is the first contribution to these studies, where is presented a comprehensive study of the Cisuralian (Lower Permian) palynology of the key samples collected in the Bonito and Barro Branco coal seams at Rio Bonito Formation, with emphasis on spores and pollen assemblages significant for establishment the biostratigraphic setting, age correlations and environmental interpretations.

2. Geological setting

The PB is a large elongated intracratonic Paleozoic basin (ca. 1,700,000 km^2), located in central-southeastern South America with portions of the basin found in Brazil, Uruguay, Argentina and Paraguay (Zalán et al., 1990). PB contains upwards to 8000 m thickness of sedimentary and igneous rocks. Stratigraphic studies of the PB began, in Brazil, with the study of White (1908). Since then, several lithostratigraphic works were published, but only in 1974 and onwards comprehensive compilations of the stratigraphic column of PB were published by Schneider et al. (1974), Zalán et al. (1990) and the last stratigraphic review was done by Milani et al. (2007).

According to Zalán et al. (1990) and Milani et al. (2007), the PB was established over a cooling continental crust after the Brasiliano Orogenic Cycle (700-450 Ma). The resulting thermal subsidence, which began between the Cambrian and Ordovician Periods, caused sedimentation to begin in the Silurian and finishing in the Cretaceous with several breaks or unconformities in the sedimentary record.

Milani (1997) applying sequence stratigraphic concepts to PB have identified 6 s order sequences and has named them from the bottom to the top as: Rio Ivaí (Ordovician-Silurian), Paraná (Devonian), Gondwana I (late Carboniferous - early Triassic), Gondwana II (Triassic), Gondwana III (late Triassic - early Cretaceous) and Baurú (late Cretaceous), which were incorporated in the stratigraphic chart erected by Milani et al. (2007).

The South Brazilian coal measures occur in the Gondwana I Supersequence, lithostratigraphically corresponding to Rio Bonito Formation, which includes, in ascending stratigraphic order, the Triunfo, Paraguassu and Sinderópolis members. The Rio Bonito Formation overlies the Itararé Group, and is overlain by the Palermo Formation. These three lithostratigraphical units conform the Tubarão Supergroup, representing, in general aspect, a major transgressive and regressive cycle in the PB.

The main coal seams, in Santa Catarina State and Criciúma region, from bottom to top, include Bonito, Rio Bonito, Ponte Alta, Irapuá, Barro Branco and Treviso coal seams and are assigned to Rio Bonito Formation, Siderópolis Member and subordinately in the Triunfo Member, being associated to fluvio-deltaic (Triunfo Member) and lagoon-barrier to estuarine (Paraguaçú Member) systems according to White (1908), Medeiros and Thomas Filho (1973), Krebs and Menezes Filho (1984, unpublished data), Aboarrage and Lopes (1986), Della Fávera et al. (1992, 1994), Holz et al. (2010) and Iannuzzi (2010). These coal seams are interbedded with shale and siltstone layers and they are defined by different authors (Marques-Toigo and Corrêa da Silva, 1984; Miltzarek and Corrêa da Silva, 1992) as impure coals, due to their high mineral matter contents which are related to their estuarine-barrier shoreface depositional environment conditions.

3. Material and methods

For this study two coal seams from the Criciúma coal region were selected, including several mines and outcrops for a detailed study (see Fig. 1): Bonito coal seam (recorded as samples CR2, CR5 and CR7) and Barro Branco coal seam (recorded as samples CR1, CR3, CR4 and CR6), in a total of 7 coal seams.

The sample CR1 was collected in an outcrop of Barro Branco coal seam, near from Rio Bonito River, which is characterized by coal beds thickness of 40–50 cm interbedded with thin beds of siltstone and shale. In the Lauro Muller Mine, it was collected the sample CR2 from the Bonito coal seam, which is mainly characterized by thin coal beds 5–15 cm thick interbedded with shale and siltstone. The sample CR3 was collected in the 101 Mine from Barro Branco coal seam represented by coal beds of 20–30 cm of thickness interbedded by silty and shaly deposits. The sample CR4 was collected in an outcrop from the Barro Branco coal seam in the Carbonífera Siderópolis Mine and the coal bed sampled has a thickness of 2 m. In Bonito I Mine, it was collected the sample CR5 from Bonito coal seam, which is characterized by thin interbedding layers of coal, siltstone, shale and occasionally sandstone. The sample CR6 collected in an outcrop near from Salame River showed high levels of weathering however this outcrop is represented by a thick coal bed of, approximately, 1 m and thin layers of siltstone and shale. The sample CR7 was collected in the Bonito coal seam at Fontanela Mine, which is represented by thin interbedded coal, siltstone and shale layers. Coal seams from the South Brazil are mainly characterized by sequences of thin coal layers interbedded by siltstone and shale, which was defined as banded (barcode) coals by Marques-Toigo and Corrêa da Silva (1984) and Miltzarek and Corrêa da Silva (1992).

The palynological samples were treated with standard palynological laboratory procedures to extract and concentrate the organic residues. The organic residues were oxidized using fuming nitric acid for about 1–2 min (Wood et al., 1996; Riding and Warny, 2008). Residues were mounted in slides and subsequently examined, where taxonomic study and photomicrographs are made using optical light BX40 Olympus microscope equipped with an Olympus C5050 digital camera facility. Selected palynomorphs are illustrated in Plates I to III. All samples, residues, and slides are held in the Collection of the Geological Survey of Portugal, LNEG, S. Mamede de Infesta.

For biostratigraphic interpretations were used previous palynostratigraphy scheme of Souza and Marques-Toigo (2003, 2005) and Souza (2006).

4. Palynostratigraphy

In this section, the palynomorph assemblages from the two studied coal seams Bonito and Barro Branco assigned to the Rio Bonito Formation, Criciúma region, southern PB, sampled for this study are described. Relative frequencies of selected groups were obtained for each sample, after counting at least 200 palynomorphs and are presented in Fig. 2. Stratigraphic relevant taxa studied are presented in Fig. 3 and in Plates I to III.

The analysed samples yield abundant, diverse and moderately to well preserved palynological assemblages. A total of 24 spore species, 14 pollen species and 4 microplanktonic or clorophyceae algae species were identified.

The recovered assemblages are subdivided in two assemblages assigned to each coal seam studied. In general, the spore-pollen assemblages are very similar however a few differences are described below, from base to top:

4.1. Bonito coal seam

The three palynological samples analysed show a relative similarity to each other, with dominance of spores when compare with pollen grains. CR5 sample is the most productive level, with the most well preserved palynomorphs.

Assemblage recovered in CR2, CR5 and CR7 is dominated by a trilete spore palynoflora (89.3–96.6%), with some arborescent and herbaceous lycopsida such as *Cristatisporites inconstans*, *C. lestai*, *Cristatisporites* spp., *Kraeuselisporites* sp. and dominant *Lundbladispora* genus (*L. braziliensis, L. riobonitensis* and *Lundbladispora* spp.). *Spelaeotriletes triangulus*, *Vallatisporites arcuatus* and *Vallatisporites* spp. also occur.

Frequent spore tetrad occurs, mainly those of *Lundbladispora*. Filicopsida vegetation group (24.7–31.3%) is represented by *Apiculatisporites* spp., *Brevitriletes cornutus, Cyclogranisporites* spp., *Diatomozonotriletes subbaculiferus*, *Leiotriletes directus Leiotriletes virkii, Leiotriletes* spp., *Lophotriletes* spp., *Granulatisporites austroamericanus, Horriditriletes filiformis H. gondwanensis, H. ramosus, H. spinobaculosus, H. uruguaiensis, Horriditriletes* spp., *Microbaculatispora trisina, Punctatisporites gretensis, Retusotriletes nigritellus* and *Retusotriletes* sp. are common to abundant. *Calamospora sinuosa* and *Calamospora* spp. are also present and assigned to Sphenosida vegetation group.

Gymnospermic pollen grains are subsidiary (2–8%) and are assigned to the Glossopteridophyta group, including the monosaccate pollen *Florinites* spp. *Cannanoropollis janakii, C.* cf. *triangulatus*, *Cannanoropollis* spp., *Plicatipollenites malabarensis, Potoniesporites novicus, Scheuringipollenites maximus, Scheuringipollenites* spp., *Vesicaspora* sp. and the bisaccate pollen *Alisporites* spp., *Limitisporites rectus, Limitisporites* spp. Striate and polyplicate pollen grains (1.3–2.0%) related to certain Conifers are represented by *Protohaploxypinus amplus, P. goraiensis, Protohaploxypinus* sp., *Vittatina costabilis, V. subsaccata* and *Vittatina* spp.

In addition, chlorophyceae algae like or microplanktonic elements are very rare (0,7–1,3%), such as Leiosphaeridia sp., *Quadrisporites* sp., *Tasmanites* sp., *Tetraporina puctata, Tetraporina* sp. as well as fungi (*Portalites gondwanensis* and spores clusters).

Lundbladispora is dominant in all of Bonito coal seam samples, in association with *Horriditriletes* and *Punctatisporites* genus. Pollen grains are uncommon and poorly preserved, particularly in the sample CR2.

The occurrence of *Vittatina* genus, which have first occurrence in the base of *Vittatina costabilis* Zone, in particularly association with *Protohaploxypinus goraiensis* and abundant *Granulatisporites austroamericanus,* whose last event occurs in the top of the *Protohaploxypinus goraiensis* Subzone. The absence of *Hamiapollenites karrooensis* allows to stablish the *Protohaploxypinus goraiensis* Subzone.

4.2. Barro Branco coal seam

The four palynological samples studied show a relative similarity to each other, with a dominance of spores compared to pollen grains. CR1 sample is the most productive sample, with the most well preserved palynomorphs.

Samples CR1, CR3, CR4 and CR6 are dominated by trilete spores (89.3–93.3%) of the species *Cristatisporites inconstans*, *C. lestai, Cristatisporites* spp., *Kraeuselisporites* spp., *Lundbladispora braziliensis*, *Lundbladispora riobonitensis*, *Lundbladispora* spp., *Vallatisporites arcuatus*, *V. splendens* and *Vallatisporites* spp.

Apiculatisporites spp., *Brevitriletes cornutus*, *Cyclogranisporites parvigranulosus*, *Cyclogranisporites* spp., *Diatomozonotriletes subbaculiferus*, *Laevigatosporites vulgaris Leiotriletes virkii*, *Leiotriletes* spp., *Lophotriletes* spp., *Granulatisporites austroamericanus*, *Horriditriletes gondwanensis*, *Horriditriletes* spp. and *Punctatisporites gretensis* represent the Filicopsida

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	Bonito Coal Seam			Barro Branco Coal Seam			
Class/ sample number	CR2	CR5	CR7	CR1	CR3	CR4	CR6
Laevigate spores	18,0	14,7	19,3	29,3	36,0	30,0	15,3
Apiculate spores	13,3	10,0	12,0	13,3	26,0	14,7	6,7
Cingulizonate spores	65,3	65,3	58,0	46,7	31,3	36,0	68,7
Monossacate pollen	0,7	1,3	0,7	2,7	0,0	0,7	0,0
Bissacate pollen	1,3	5,3	7,3	2,7	4,0	9,3	8,0
Striate pollen	1,3	2,0	2,0	2,7	2,0	4,0	1,3
Chlorophycean algae	0,0	1,3	0,7	2,7	0,7	5,3	0,0
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Fig. 2. Relative frequencies of selected palynomorph groups in the studied samples (in %).

	Studied samples						
	Bonito Coal Seam			Barro Branco Coal Seam			
Species list	**CR2**	**CR5**	**CR7**	**CR1**	**CR3**	**CR4**	**CR6**
Spores							
Apiculatisporites spp.			●		●		
Brevitriletes cornutus	●	●	●	●	●	●	●
Calamospora plicata						●	
Calamospora liquida				●			
Calamospora sinuosa		●					
Calamospora spp.	●	●	●	●	●	●	●
Cristatisporites lestai				●			
Cristatisporites inconstans	●			●		●	
Cristatisporites spp.	●	●	●	●	●	●	●
Cyclogranisporites parvigranulosus		●	●			●	
Cyclogranisporites spp.		●	●	●		●	
Diatomonozonotriletes subbaculiferous	●	●		●	●	●	●
Granulatisporites austroamericanus		●	●	●	●	●	●
Horriditriletes gondwanensis				●			
Horriditriletes filiformis		●					
Horriditriletes ramosus	●	●					●
Horriditriletes spinobaculosus		●					
Horriditriletes uruguaiensis		●					
Horriditriletes spp.		●	●	●			
Kraeuselisporites spp.		●		●		●	
Laevigatosporites vulgaris				●			
Leiotriletes directus		●					
Leiotriletes virkii	●	●		●		●	●
Leiotriletes spp.	●	●	●	●		●	●
Lophotriletes spp.		●		●			
Lundbladispora braziliensis	●	●	●	●		●	●
Lundbladispora riobonitensis	●	●	●	●		●	●
Lundbladispora spp.	●	●	●	●		●	
Microbaculatispora trisina		●					
Punctatisporites gretensis	●	●		●		●	●
Raistrickia spp.		●					
Retusotriletes nigritellus	●			●			
Retusotriletes spp.					●		
Spelaeotriletes triangulus		●					
Vallatisporites arcuatus		●		●			●
Vallatisporites splendens				●		●	●
Vallatisporites spp.		●	●	●	●		●
Pollen grains							
Alisporites spp.	●	●		●		●	
Cannanoropollis janaki		●		●			
Cannanoropollis cf. *triangulatus*		●		●			
Cannanoropollis spp.		●			●		
Florinites spp.		●			●		
Limitisporites rectus		●				●	
Limitisporites cf. *rectus*		●					
Limitisporites spp.		●	●				
Plicatipollenites malabarensis		●		●			
Potonieisporites novicus		●		●			
Protohaploxypinus amplus		●				●	
Protohaploxypinus goraiensis		●		●			●
Protohaploxypinus limpidus					●		
Protohaploxypinus sp.		●	●	●			●
Pteruchipollenites indarraensis				●	●	●	
Pteruchipollenites sp.		●	●	●	●	●	●
Scheuringipollenites maximus		●		●			
Scheuringipollenites spp.	●	●		●			
Vesicaspora sp.		●		●			
Vittatina costabilis		●					
Vittatina subsaccata		●		●			
Vittatina vittifera		●		●			
Vittatina spp.		●	●	●			
Chlorophycean algae and Fungi							
Leiosphaeridia sp.	●	●		●		●	●
Portalites gondwanensis		●		●		●	●
Quadrisporites sp.		●					
Tasmanites sp.		●					
Tetraporina punctata		●		●			
Tetraporina spp.		●		●			
Algae cluster		●		●			

Fig. 3. Palynomorph assemblages recovered from the studied Bonito and Barro Branco Coal Seams, Rio Bonito Formation in the Criciúma coal region, Brazil.

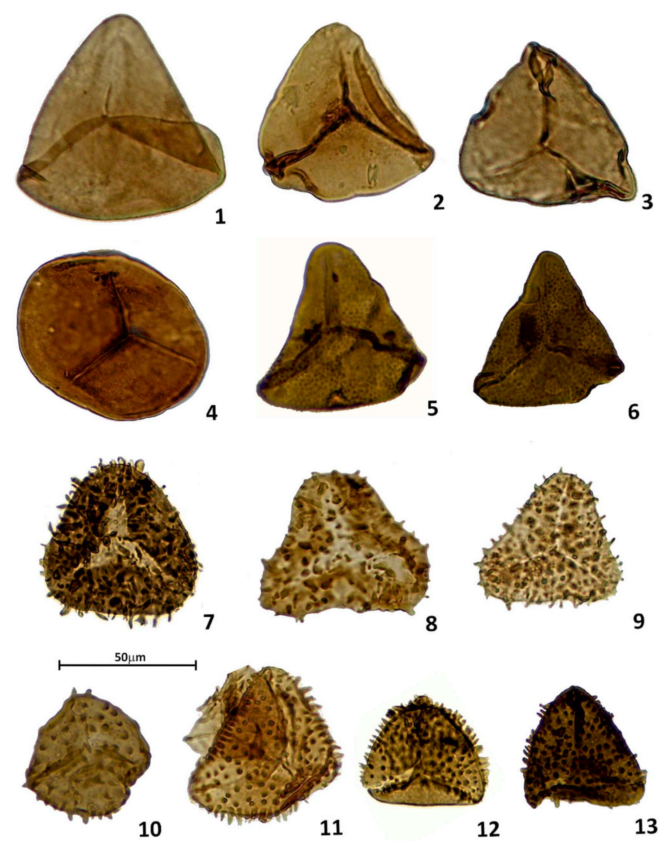

Plate 1. 1. *Leiotriletes directus* Balme and Hennelly 1956; Bonito coal seam, Sample CR5, slide 3b, 1310–95; 2. *Leiotriletes virkii* Tiwari 1965; Bonito coal seam, Sample CR5, slide4a, MC 1450–75; 3. *Leiotriletes virkii* Tiwari 1965; Bonito coal seam, Sample CR5, slide 3a, MC 1200–155; 4. *Punctatisporites gretensis* Balme and Hennelly 1956; Bonito coal seam, Sample CR5, slide 4b, MC 1225–175; 5. *Granulatisporites austroamericanus* Archangelsky and Gamerro, 1979; Bonito coal seam, Sample CR7, slide 1, MC 1032–1437; 6. *Granulatisporites austroamericanus* Archangelsky and Gamerro, 1979; Bonito coal seam, Sample CR5, slide 2, MC 1106–310; 7. *Horriditriletes filiformis* (Balme and Hennelly) Backhouse 1991; Bonito coal seam, Sample CR5, slide 2–34, MC 996–487; 8. *Horriditriletes uruguaiensis* (Marques-Toigo) Archangelsky and Gamerro 1979; Bonito Coal Seam, Sample CR5, slide 4b, MC 1310–135; 9. *Horriditriletes uruguaiensis* Archangelsky and Gamerro, 1979; Bonito coal seam, Sample CR5, slide 4b, MC 1250–140; 10. *Brevitriletes cornutus* (Balme and Hennelly) Backhouse 1991; Barro Branco coal seam, Sample CR3, slide 1–28, MC 1009–455; 11. *Diatomonozonotriletes subbaculiferus* (Nahuys, Alpern and Ybert) Césari et al., 1995; Barro Branco coal seam, Sample CR1, slide 1b, MC 1160–55; 12. *Diatomonozonotriletes subbaculiferus* (Nahuys, Alpern and Ybert) Césari et al., 1995; Barro Branco coal seam, Sample CR6, slide 1–34, MC 1068–430; 13.*Diatomonozonotriletes* sp.; Barro Branco coal seam, Sample CR3, slide 1–38, 1075–422.

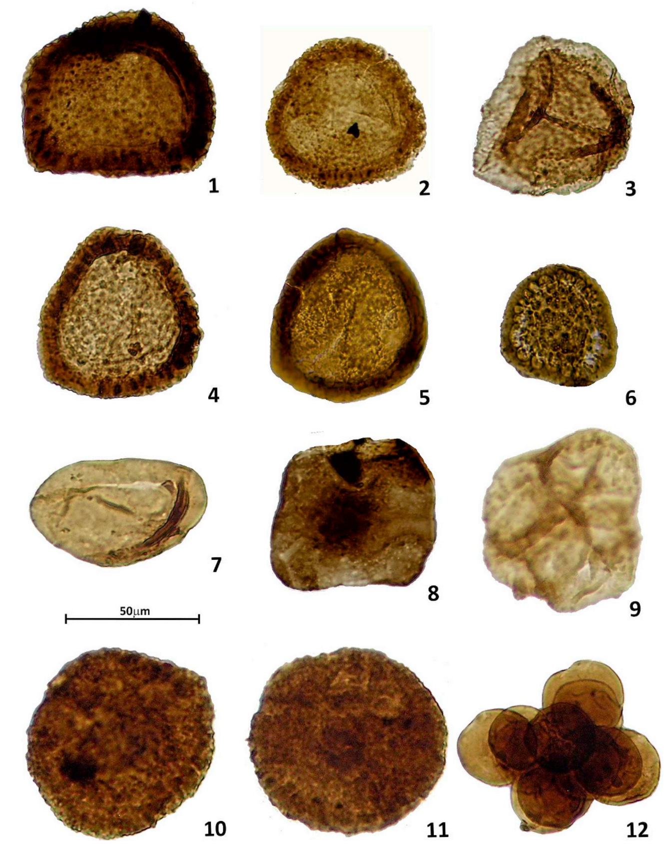

Plate 2. 1. *Lundbladispora braziliensis* (Pant and Srivastava) Marques-Toigo and Pons emend. Marques-Toigo and Picarelli (1984); Barro Branco coal seam, Sample CR1, slide 1b, MC 1125–171; 2. *Lundbladispora braziliensis* (Pant and Srivastava) Marques-Toigo and Pons emend. Marques-Toigo and Picarelli (1984); Bonito coal seam, Sample CR5, slide 4a, MC 1450–135; 3. *Spelaeotriletes triangulus* Neves and Owens 1966; Bonito coal seam, Sample CR5, slide 2a, MC 1360–105; 4. *Lundbladispora braziliensis* (Pant and Srivastava) Marques-Toigo and Pons emend. Marques-Toigo and Picarelli (1984); Barro Branco coal seam, Sample CR1, slide 1a, MC 1330–210; 5. *Lundbladispora riobonitensis* Marques-Toigo and Picarelli (1984); Sample CR6, slide 1, MC 1003–435; 6. *Vallatisporites* sp.; Barro Branco coal seam, Sample CR1, slide 2, MC 1068–398; 7. *Laevigatosporites vulgaris* Ibrahim 1933; Barro Branco coal seam, Sample CR1, slide 1b, MC 1155–70; 8. *Tetraporina* sp.; Barro Branco coal seam, Sample CR1, slide 1b, MC 1215–90; 9. *Quadrisporites* sp.; Bonito coal seam, Sample CR5, slide 1a, MC 1400–190; 10.*Portalites gondwanensis* Nahuys, Alpern and Ybert 1968; Bonito coal seam, Sample CR5, slide 4b, MC 1391–105; 11. *Portalites gondwanensis* Nahuys, Alpern and Ybert 1968; Bonito coal seam, Sample CR5, slide 4a, MC 1475–90; 12. Fungi spores cluster; Bonito coal seam, Sample CR5, slide 1–177; MC 983–280.

(22–62%), which has a slightly higher frequency than Bonito coal seam. *Lundbladispora* it is the dominant genus but, since the Filicopsida relative frequencies increased, Lycopsida group decreased.

Sphenopsida are common to abundant and include *Calamospora plicata, C. liquida, C. sinuosa*, *Calamospora* spp., *Retusotriletes nigritellus* and *Retusotriletes* spp.

Gymnosperms pollen are represented in very low frequencies in the assemblage (4–10%) and include monosaccate pollen (0–2.7%), such as *Cannanoropollis janakii*, *C.* cf. *triangulatus*, *Cannanoropollis* spp., *Potonieisporites novicus*, *Florinites* spp. and by bisaccate pollen (2.7–9.3%) such as *Alisporites* spp., *Limitisporites rectus, Limitisporites* sp., *Scheuringipollenites maximus* and *Scheuringipollenites* spp. Striate and polyplicate pollen grains from Glossopteridales (1.3–4.0%) include *Protohaploxypinus amplus, P. goraiensis, P. limpidus*, *Protohaploxypinus* spp., *Vittatina* cf. *subsaccata*, *V. vittifera* and *Vittatina* spp. Samples CR3 and CR6 do not contain any monosaccate pollen, and bisaccate pollen are not well preserved. A relative frequency of bisaccaate pollen of Barro Branco coal seams is also higher than Bonito coal seam.

Microplanktonic and chlorophyceae algae like elements are rare to relatively common (0–5.3%) and include *Leiosphaeridia* sp. and *Tetraporina punctata, Tetraporina* spp.; fungi are rerpresented by *Portalites gondwanensis* and spores clusters. Their frequency is higher than in the Bonito coal seam.

Based on occurrence of several index species such as *Vittatina* cf. *subsaccata*, *V. vittifera,* the Barro Branco seam coal was dated from *Vittatina costabilis* Zone. The presence of *Protohaploxypinus goraiensis, Protohaploxypinus limpidus* and abundance of *Granulatisporites austroamericanus* allowed us to indicate the *Protohaploxypinus goraiensis* Subzone (lower subzone of *Vittatina costabilis* Zone). No *Hamiapollenites karrooensis* Subzone species were documented.

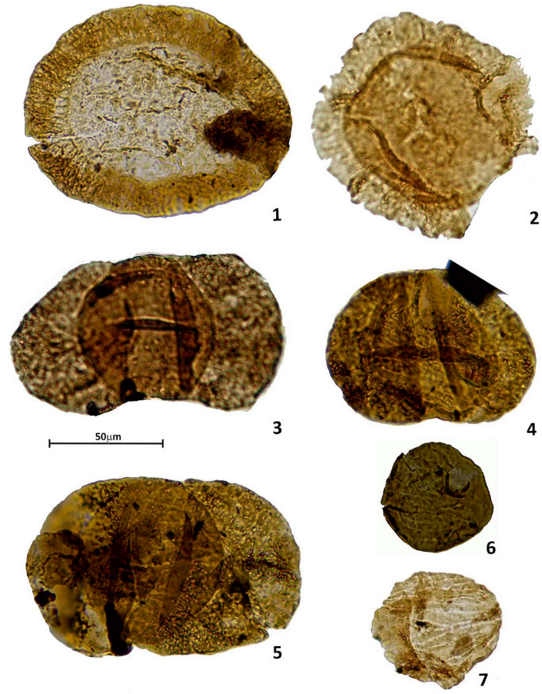

Plate 3. 1. *Cannanoropollis janakii* Potonié and Sah 1960; Bonito coal seam, Sample CR5, slide 2, MC 993–482; 2. *Plicatipollenites malabarensis* (Potonie and Sah) Foster 1975; Bonito coal seam, Sample CR5, slide 4b, MC 1260–155; 3. *Limitisporites* cf. *rectus* Leschik 1956; Bonito coal seam, Sample CR5, slide 4b, MC 1255–65; 4. *Protohaploxypinus goraiensis* (Potonié and Lele) Hart 1964; Barro Branco coal seam, Sample CR1, slide 2, MC 1055–223; 5. *Protohaploxypinus amplus* (Balme and Hennelly) Hart 1964; Bonito coal seam, Sample CR5, slide 2, MC 1062–446; 6. *Vittatina costabilis* Wilson 1962; Bonito coal seam, Sample CR5, slide 2, MC 1063–260; 7. *Vittatina* sp.; Bonito coal seam, Sample CR5, slide 2a, MC 1155–135.

5. Previous palynostratigraphic studies in the Rio Bonito Formation, Paraná Basin

Previous palynostratigraphic studies in the in the Rio Bonito Formation are extensive and well known. Palynoassemblages are reported from São Paulo Paraná, Santa Catarina and Rio Grande do Sul states (Ybert, 1975; Pons, 1976; Marques-Toigo and Piccarelli, 1985; Marques-Toigo, 1988, 1991; Dias, 1993; Souza et al., 1999, 2001; Souza and Callegari, 2004; Mori and Souza, 2012; Mori et al., 2011).

The first palynostratigraphic zonation scheme for late Paleozoic succession in the PB was presented by Daemon (1966) and Daemon and Quadros (1970), with subsequent contributions from Marques-Toigo (1988, 1991), Souza (2000), Souza and Marques-Toigo (2003, 2005) and Souza (2006). Most of the palynological studies are associated with macroflora research in the coalfields of the Rio Grande do Sul State (Guerra-Sommer et al., 1984, 2008b; Cazzulo-Klepzig et al., 2005, 2007; Iannuzzi, 2010; Simas et al., 2012, 2013), likewise on the Santa Catarina State coalfield (Machado, 1972; Bortoluzzi et al., 1978; Bernardes-de-Oliveira et al., 2016). Other palynological works were performed in coal levels and/or adjacent outcrop strata in the coal seams of Rio Bonito Formation (Dias-Fabrício, 1981; Marques-Toigo and Corrêa da Silva, 1984; Guerra-Sommer et al., 1991; Cazzulo-Klepzig et al., 2007; Boardman et al., 2012a).

One of the reference sections of the Rio Bonito Formation, the Quitéria outcrop (located SW of Porto Alegre town, Rio Grande do Sul State), due to their paleontological and palynological contents of the coal seam (Jasper et al., 2006; Boardman et al., 2012a), was assigned to the Irapuá Coal Bed (a coal seam that are deposited below Barro Banco Coal Bed). Palynofloras are typical of *Vittatina costabilis* Zone based on the presence of *Vittatina costabilis*, *V. subsaccata* and *V. vittifera,* all together with *Protohaploxypinus limpidus* and *Stellapollenites talchirensis* and common presence of *Granulatisporites austroamericanus* and *Converrucosisporites confluens* that suggest a correlation with the *Protohaploxypinus goraiensis* Subzone (basal part of *Vittatina costabilis* Zone). No diagnostic species of the *Hamiapollenites karrooensis* Subzone was recovered.

For better understanding the changes in palaeoecological scenario, Mendonça Filho et al. (2013) conducted a palynological and paleobotanical research on the Bonito coal seam in the region of Lauro Müller region (Santa Catarina State), with a forested gymnosperm at the base, to a lycophytes subarborescent plant dominated scenario at the top. More recently, Bernardes-de-Oliveira et al. (2016) studied the macroflora presented in the Siderópolis Member of Rio Bonito Formation (Lauro Muller, Criciúma, São Marcos, and Treviso), but no palynostratigraphy data is presented.

Outside Brazil, a few studies on palynostratigraphy of the Cisuralian were developed in the Chaco-Paraná Basin (Vergel, 1993; Archangelsky and Vergel, 1996; Playford and Dino, 2002), in central-western basins (*e.g.,* Césari and Gutiérrez (2001); di Pasquo et al., 2010; Césari et al. (2013); Gutiérrez et al. (2010a), 2010b, Balarino and Gutiérrez (2006); Balarino et al. (2015) Colorado Basin (Balarino, 2012, 2014), and Paganzo Basin (Césari and Chiesa, 2017) in Argentina. In Uruguay, palynostratigraphic studies were developed in the PB (Gutiérrez et al., 2010a; Beri et al., 2011), and in Paraguay in the PB (Pérez Loinaze et al., 2010).

The Bonito and Barro Branco coal seams palynomorph assemblages identified in the present research are assigned to the lower Permian age. The first palynostratigraphic zonation scheme established for late Paleozoic succession in the PB was presented by Daemon and Quadros (1970), later modified by Marques-Toigo (1991), Souza (2000), that proposed an integrated palynostratigraphic scheme for the southern and northeastern region of the PB, improving the original proposal, and including new data, as presented in Souza and Marques-Toigo (2003, 2005) and Souza (2006).

The biostratigraphic zonation scheme comprehends four interval zones, from base to top: *Ahrensisporites cristatus, Crucisaccites monoletus* (assigned to the late Carboniferous), *Vittatina costabilis* and *Lueckisporites virkkiae* (of Lower Permian age).

The *Vittatina costabilis* zone is defined by the first appearance of the genus *Vittatina* (namely *V. saccata*, *V. subsaccata*, *V. costabilis* and *V. vittifera*), *Protohaploxypinus goraiensis*, *P. limpidus* and *Illinites unicus*. The upper limit of this zone is characterized by the first appearance of the key species of the overlying *Lueckisporites virkkiae*. The *Vittatina costabilis* interval zone is divided into two subzones, the *Protohaploxypinus goraiensis* Subzone (based on the first occurrence of *Protohaploxypinus goraiensis*, *P. limpidus* and *Illinites unicus*) and the *Hamiapollenites karrooensis* Subzone (defined by the first ocorrence of *Hamiapollenites karrooensis*, *Striatopodocarpites fusus* and *Staurosaccites cordubensis* (Souza and Marques-Toigo, 2003, 2005; Souza, 2006).

The *Lueckisporites virkkiae* zone is defined by the first occurrence of the genus *Lueckisporites* (*L. virkkiae*, *L. stenotaeniatus* and *L. agoulaensis*), *Marsupipollenites striatus*, *Protohaploxypinus hartii*, *P. microcorpus*, *Lunatisporites variesectus*, *Alisporites nuthallensis*, *Striatopodocarpites pantii*, *Weylandites lucifer*, *Staurosaccites cordubensis* and by the last occurrence of *Hamiapollenites karrooensis*, *Lundbladispora riobonitensis* and *Potonieisporites novicus*. The top of the zone is marked by the disappearance of the *Lueckisporites* genus (Souza and Marques-Toigo, 2003, 2005; Souza, 2006).

6. Discussion

6.1. Biostratigraphic results

Based on palynostratigraphy stablished for Souza and Marques-Toigo (2003, 2005) and Souza (2006), samples collected in Bonito and

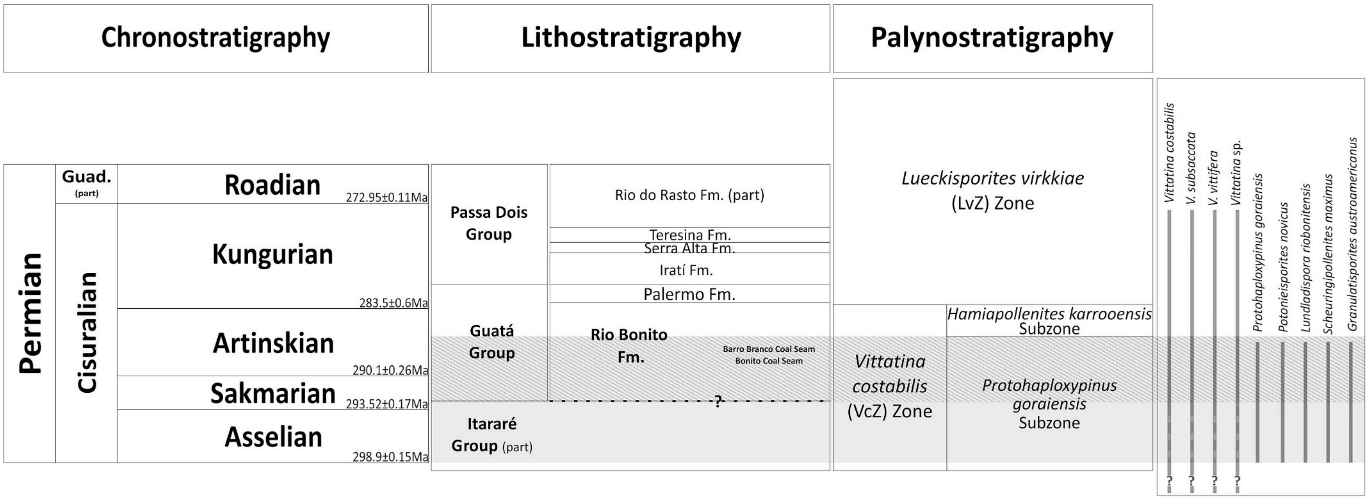

Fig. 4. Stratigraphic distribution of the selected species obtained in the studied Bonito and Barro Branco Coal Seams, Rio Bonito Formation in the Criciúma coal region, Brazil. Lithostratigraphy follows Schneider et al. (1974). Palynostratigraphy according Souza and Marques-Toigo (2003, 2005) and Souza (2006).

Barro Branco coal seams are correlated with *Vittatina costabilis* Zone, and *Protohaploxypinus goraiensis* Subzone, of Asselian? to Artinskian age (lower Cisuralian, Lower Permian) (see Fig. 4). In according to Souza and Marques-Toigo (2003, 2005) and Souza (2006), some key-species are restricted from this age, such as *Protohaploxypinus goraiensis* and *Vittatina* spp., likewise some other diagnostic species of spores, such as *Granulatisporites austroamericanus.* No *Hamiapollenites karrooensis*, key-species from upper biozone, was achieved.

Consequently, the studied assemblages obtained from the Bonito and Barro Branco coal seam, in the Rio Bonito Formation, confirm previous palynostratigraphic age determinations established for the coals of southern PB (Souza and Marques-Toigo, 2003, 2005; Souza, 2006; Mori and Souza, 2010; Mori et al., 2011; Boardman et al., 2012a, 2012b), assigned to the *Vittatina costabilis* Interval Zone, *Protohaploxypinus goraiensis* Subzone dated as Cisuralian age (Lower Permian), based on the occurrence of taxa typical of this unit, some of them stratigraphically restricted to this Interval Zone.

The available radiometric ages in Rio Bonito Fm. (*e.g.,* Rocha-Campos et al., 2008; Santos et al., 2006; Mori and Souza, 2012; Guerra-Sommer et al., 2008a, 2008b, Simas et al., 2012, Cagliari et al., 2014, 2015; Griffis et al., 2018) and palynomorph data suggests a depositional age of lower Cisuralian age, ranging from Asselian? to Artinskian age. Nevertheless, radiometric dating presents some disparities and more studies are needed.

The *Vittatina costabilis* interval Zone is recognized in the lower Itararé Group and the key specie *V. costabilis* is recognized as being a lower Permian marker.

6.2. Palaeoenvironmental results

The palynological assemblages identified in the Bonito and Barro Branco coal seams present a very similar microflora composition, showing a clear dominance of arborescent and herbaceous lycophytes in the peat-forming plant community.

The Barro Branco coal seam shows a relatively higher frequency of algae like composition than in the Bonito coal seam, suggesting a possible fluvial or lagoonal facies influence.

The paleoenvironments of the Bonito and Barro Branco coal seams that generated the palynological assemblages studied can be correlated with those described by Cazzulo-Klepzig et al. (2005, 2007) and Beri et al. (2013), for the most important coal seams in the southernmost PB.

7. Conclusions

The main results from this study are summarized below:

- All studied samples from the Criciúma coal region, southern area of Santa Catarina State, southern PB, were positive for palynology. Twenty-seven (27) species of spores, fourteen (14) species of pollen and four (4) species of microplanktonic, chlorophyceae algae like and fungi were identified;
- The spore-pollen assemblages recovered from Bonito and Barro Branco coal seams are assigned to the *Vittatina costabilis* Interval Zone, *Protohaploxypinus goraiensis* Subzone of the PB, of Asselian?-Artinskian age (Lower Permian);
- The palynological assemblages identified in the Bonito and Barro Branco coal seams present a very similar microflora composition, showing a clear dominance of arborescent and herbaceous lycophytes in the peat-forming plant community;
- The Barro Branco coal seam shows a relatively higher frequency of algae like composition than in the Bonito coal seam, suggesting a possible fluvial or lagoonal facies influence;
- The paleoenvironments of the Bonito and Barro Branco coal seams that generated the palynological assemblages studied can be correlated with those described by Cazzulo-Klepzig et al. (2005, 2007) for the most important coal seams in the southernmost PB.

Acknowledgements

The authors would like to thank the staff of Lauro Muller, 101, Carbonífera Siderópolis, Bonito I, Fontanela Mines for the support in the field work, for mining sample access and complementary information; LNEG's technicians Irene Sousa, for laboratory support and sample preparation; PAS thanks to CNPq (310127/2014-6 and 461628/2014-7 Projects). Special thanks are also due the reviewers for the final revision of the manuscript. The authors would like to thank the anonymous reviewers for all constructive comments about the manuscript.

Palynomorph taxa listed in alphabetic order:

Spore

Apiculatisporites spp.
Brevitriletes cornutus (Balme and Hennelly) Backhouse 1991
Calamospora plicata (Luber and Walts) Hart 1965
Calamospora liquida Kosanke 1950

Calamospora sinuosa Leschik 1955
Calamospora spp.
Converrucosisporites confluens (Archangelsky and Gamerro) Playford and Dino (2002).
Cristatisporites lestai Archangelsky and Gamerro, 1979
Cristatisporites inconstans Archangelsky and Gamerro, 1979
Cristatisporites spp.
Cyclogranisporites parvigranulosus (Leschik) Ybert (1975).
Cyclogranisporites spp.
Diatomonozonotriletes subbaculiferous (Nahuys, Alpern and Ybert) Césari et al., 1995*Diatomozonotriletes* sp.
Granulatisporites austroamericanus Archangelsky and Gamerro, 1979
Horriditriletes filiformis (Balme and Hennelly) Backhouse 1991
Horriditriletes gondwanensis (Tiwari and Moiz) Foster 1975
Horriditriletes ramosus (Balme and Hennelly) Bharadwaj and Saluha 1964
Horriditriletes spinobaculosus (Marques-Toigo) Souza and Callegari, 2004.
Horriditriletes uruguaiensis (Marques-Toigo) Archangelsky and Gamerro, 1979
Horriditriletes spp.
Kraeuselisporites spp.
Laevigatosporites vulgaris (Ibrahim) Ibrahim 1933
Leiotriletes directus Balme and Hennelly 1956
Leiotriletes virkii Tiwari 1965
Leiotriletes spp.
Lophotriletes spp.
Lundbladispora braziliensis (Pant and Srivastava) Marques-Toigo and Pons emend. Marques-Toigo and Picarelli (1984).
Lundbladispora riobonitensis Marques-Toigo and Picarelli (1984).
Lundbladispora spp.
Microbaculatispora trisina (Balme and Hennelly) Anderson 1977
Punctatisporites gretensis Balme and Hennelly 1956
Raistrickia spp.
Retusotriletes nigritellus (Lüber) Foster 1979
Retusotriletes spp.
Spelaeotriletes triangulus Neves and Owens 1966
Vallatisporites arcuatus (Marques-Toigo) Archangelsky and Gamerro, 1979
Vallatisporites splendens Staplin and Jansonius 1964
Vallatisporites sp.

Pollen

Alisporites spp.
Cannanoropollis janakii Potonié and Sah 1960
Cannanoropollis cf. *triangulatus* (Metha) Bose and Maheshwari 1968
Cannanoropollis spp.
Florinites spp.
Limitisporites rectus Leschik 1956
Limitisporites spp.
Plicatipollenites malabarensis (Potonié and Sah) Foster 1975
Potonieisporites novicus Bhardwaj emend. Poort and Veld 1997
Protohaploxypinus amplus (Balme and Hennelly) Hart 1964
Protohaploxypinus goraiensis (Potonié and Lele) Hart 1964
Protohaploxypinus limpidus (Balme and Hennelly) Balme and Playford 1967
Protohaploxypinus spp.
Pteruchipollenites indarraensis (Segroves) Foster 1979
Pteruchipollenites spp.
Scheuringipollenites maximus (Hart) Tewari 1973
Scheuringipollenites spp.
Staurosaccites cordubensis Archangelsky and Gamerro, 1979
Vesicaspora spp.
Vittatina costabilis Wilson 1962
Vittatina cf. *subsaccata* Samoilovich 1953
Vittatina vittifera (Luber and Valts) Samoilovich 1953
Vittatina spp.

Chlorophycean algae

Leiosphaeridia spp.
Quadrisporites spp.
Tasmanites spp.
Tetraporina punctata (Tiwari and Navale) Kar and Bose 1976
Tetraporina spp.

Fungi

Portalites gondwanensis Nahuys et al. emend Souza et al., 2016

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