

The Artinskian Siderópolis Member macroflora, Rio Bonito Formation and its stratigraphical correlation with other early Permian macrofloras of Paraná Basin, Brazil

A macroflora artinskiana do Membro Siderópolis, Formação Rio Bonito e sua correlação estratigráfica com outras eopermianas da Bacia do Paraná, Brasil

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Abstract

An overview of the composition of the paleoflora preserved in clay-siltstones of the Siderópolis Member, Rio Bonito Formation is presented in order to establish phytostratigraphical comparisons with other Late Pennsylvanian and Cisuralian paleofloras of the Paraná Basin. The Rio Bonito Formation, the most important of the coal bearing lithostratigraphic units of the Paraná Basin belongs to the Gondwana I Supersequence (Pennsylvanian-Early Triassic). The Siderópolis paleoflora occurs in the uppermost layers of coal of Rio Bonito Formation in Santa Catarina coalfield in four distinct localities of the State of Santa Catarina: Lauro Muller, Criciúma, São Marcos and Treviso. In this paleoflora the glossopterid leaves predominate with an evident dominance of the genus *Glossopteris* over *Gangamopteris*, followed by Cordaitalean leaves (*Noeggerathiopsis*) and seeds (*Cordaicarpus*, *Samaropsis*, *Cornucarpus*). Sterile fronds are common and few are fertile (*Sphenopteris*, *Pecopteris*, *Ponsotheca* and *Notoangaridium*). Pteridosperm reproductive structures (*Arberia*, *Arberioopsis*, *Ottokaria*) are not frequent and branches of conifers (*Brasilocladus*, *Buriadia*) are rare. Concerning other paleofloras of the basin, the Siderópolis paleoflora is distinguished by high diversity and many exclusive taxa showing only few similarities with some paleofloras registered in Rio Grande do Sul, occurring in outcrops of the Rio Bonito Formation such as Morro do Papaléo (upper section) and Quitéria. The differences may reflect an upper stratigraphic position, but may also indicate differences in sedimentation and / or in paleoecological conditions.

Keywords: *Glossopteris*; Gondwanan Flora; Artinskian.

Resumo

Apresenta-se aqui uma síntese da composição da paleoflora preservada em siltitos argilosos do Membro Siderópolis, Formação Rio Bonito tendo como objetivo estabelecer comparações fitoestratigráficas com outras paleofloras neopensilvanianas e cisuralianas da Bacia do Paraná. A Formação Rio Bonito, a mais importante das unidades litoestratigráficas portadoras de carvão da Bacia do Paraná, pertence à supersequência Gondwana I (Pensilvaniano-Eotriássico). A paleoflora Siderópolis ocorre nas camadas de carvão mais superiores da Formação Rio Bonito na região carvoeira de Santa Catarina, em quatro áreas distintas do Estado de Santa Catarina: Lauro Muller, Criciúma, São Marcos e Treviso. Na paleoflora, as folhas de glossopterídeas predominam com um evidente domínio do gênero *Glossopteris* sobre *Gangamopteris*, seguido por folhas cordaitaleanas (*Noeggerathiopsis*) e sementes (*Cordaicarpus*, *Samaropsis*, *Cornucarpus*). Frondes estéreis são comuns havendo poucas férteis (*Sphenopteris*, *Pecopteris*, *Ponsotheca*, *Notoangaridium*). Estruturas reprodutivas pteridospérmicas

(*Arberia*, *Arberioopsis*, *Ottokaria*) e ramos de coníferas (*Brasilocladus*, *Buriadia*) são raros. Em relação a outras paleofloras da bacia, a de Siderópolis distingue-se por apresentar diversidade mais alta e muitos táxons exclusivos mostrando apenas umas poucas semelhanças com algumas paleofloras registradas no Rio Grande do Sul, ocorrendo em afloramentos do Rio Bonito tais como Morro do Papaléo (porção superior) e Quitéria. Essas diferenças podem refletir uma posição estratigráfica superior, mas pode também indicar diferenças em condições de sedimentação e / ou paleoecológicas.

Palavras-chave: *Glossopteris*; Flora Gondvânica; Artinskiano.

INTRODUCTION

The geological and biological data obtained for the lower Permian Brazilian coal basins (in Paraná Basin) have led to the conclusion that tectonic and environmental conditions, as well as the peat forming plant communities were important factors that influenced the formation and characterization of coal deposits (Mendonça Filho et al., 2013).

The available paleobotanical literature on the coal roof shale floras in Paraná Basin, although very extensive, has encompassed mainly the coalfields of the State of Rio Grande do Sul (Guerra-Sommer et al., 1984; Cazzulo-Klepzig et al., 2005, 2007; Guerra-Sommer et al., 2008; Iannuzzi, 2010; Simas et al., 2012, 2013). On the contrary, there is relatively few data for the nearby Santa Catarina Coalfield (Machado, 1972; Bortoluzzi et al., 1978; Bernardes de Oliveira, 1980a).

Palynofacies, palynological and paleobotanical analyses on the Bonito coal seam in the region of Lauro Müller developed by Mendonça Filho et al. (2013), indicated changes in palaeoecological conditions that have favored the development of different plant communities during the depositional time span from a forested gymnosperm at the base to a lycophytes (*Brasilodendron* type), subarborescent plant dominated scenario at the top.

The paleoflora of the Siderópolis Member has been described for distinct areas in the State of Santa Catarina by different authors as shown below. This paleoflora has been considered as Artinskian and stand out as the most typical and diversified postglacial example of the *Glossopteris* flora associated with coal deposits found in the Lower Gondwana strata of the basin (Bernardes-de-Oliveira, 1980a; Iannuzzi, 2010). Nevertheless, the absence of correlative studies of this flora with other Gondwana floras has prevented major biostratigraphic, lithostratigraphic and paleogeographic considerations.

GEOLOGIC AND STRATIGRAPHIC SETTINGS

The Rio Bonito Formation, the most important coal bearing lithostratigraphic units of the Paraná Basin, belongs to the Gondwana I Supersequence (Pennsylvanian-Early Triassic) of Milani et al (1998). In the states of Santa Catarina and Paraná, Schneider et al. (1974) subdivided it into three members, designated from the base to the top as Triunfo Member (coastal and fluvial sandstones), Paraguaçu

Member (mudstones and fine grained marine sandstones) and Siderópolis Member (coastal and fluvial sandstones). Coal seams occur mostly in Triunfo Member, in the State of Paraná and in the Siderópolis Member in the State of Santa Catarina.

The “Catarinense coalfield” or the “Sul Catarinense coalfield” (Machado, 1972; Bortoluzzi et al., 1978 respectively), is an elongated polygonal basin of north-south direction, located in the southeastern portion of the State of Santa Catarina in an area of approximately 1.200 km². The basin is comprised by portions of the Tubarão, Araranguá, Urussanga and Mampituba river basins, with 95 km length and an average of 20 km width, within an area delimited by coordinates 28°1’ S to 29°30’ S and 49°10’ W to 49°37’ W.

From the base to the top, five major coal beds can be seen in the sedimentary sequence viz. Bonito, Ponte Alta, Irapuá, Barro Branco and Treviso (Putzer, 1952; Mendes, 1963), which belong to the Siderópolis Member and deposited mainly in coastal wetland environments, associated to coastal and deltaic deposits (Northfleet et al., 1969; Medeiros and Thomaz Filho, 1973) (Figure 1).

These coal seams were designated by Bortoluzzi et al. (1978), from the base to the top, as Pre-Bonito “C” and “D”, Bonito, Ponte Alta, Irapuá “A”, “B”, and Barro Branco. The top Barro Branco coal seam which occurs throughout the basin has been extensively mined, whereas Irapuá, Ponte Alta and Bonito as well as the minor Pre-Bonito seams seem to be irregularly distributed in the basin and have been exploited either as open casts or gallery mines. Based on sequence stratigraphic method, but also taking into account paleontological and former lithostratigraphic criteria, Holz et al. (2010) concluded that the Rio Bonito succession in Paraná Basin included two third order sequences. In the State of Santa Catarina, the Siderópolis Member and almost all its coal seams are linked to the LPTS-4, of Artinskian age (Holz et al., 2010).

In the State of Rio Grande do Sul, the Rio Bonito Formation is not formally subdivided into different lithostratigraphic members and the coal seams are included in the underlying LPTS-3 and were deposited at the Sakmarian-Artinskian interval.

The coal palynofloras are included in the *Protohaploxypinus goraiensis* Subzone within the palynostratigraphic framework for the Brazilian Paraná Basin (Souza and Marques-Toigo, 2003).

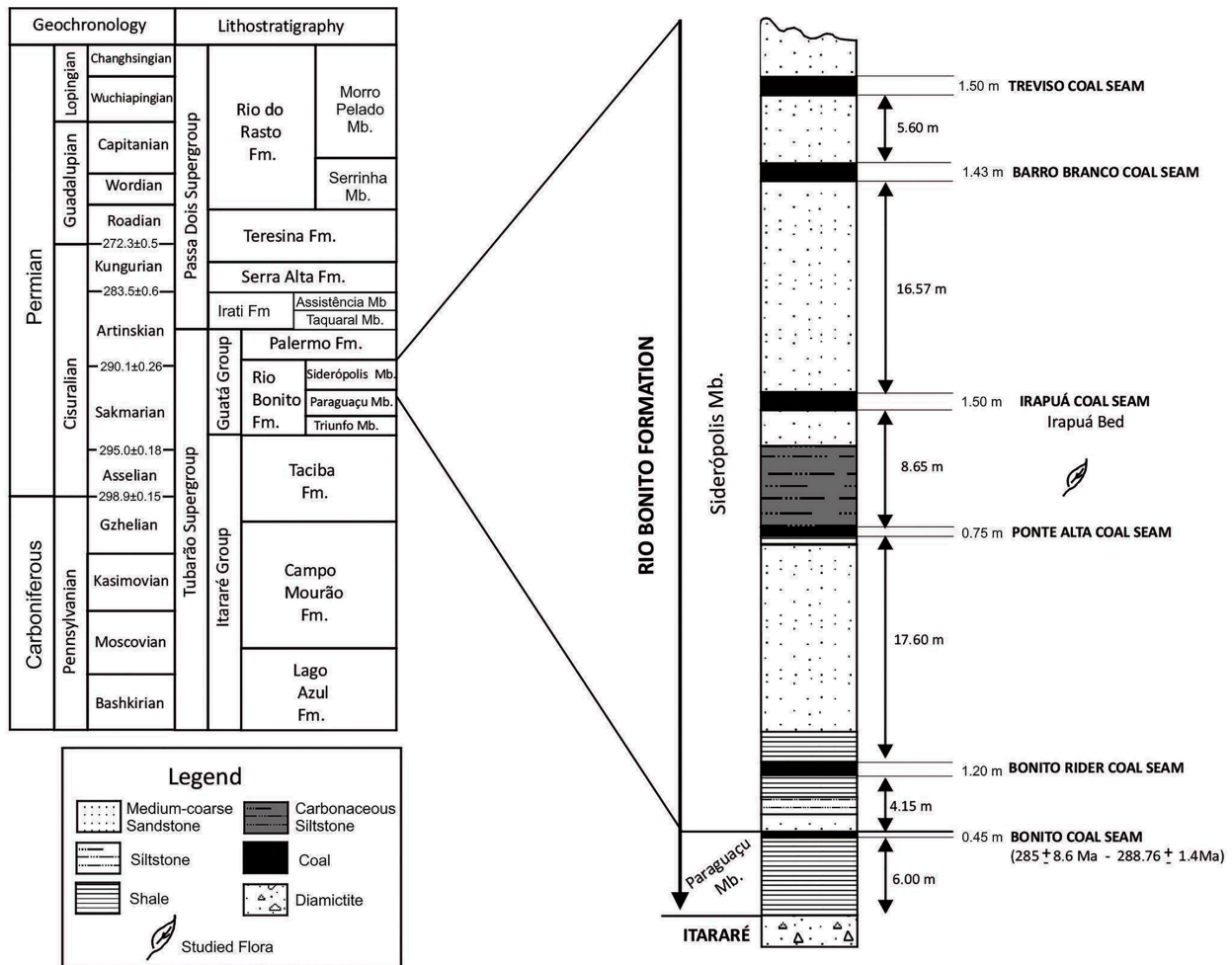


Figure 1. Siderópolis Member coal beds in Santa Catarina. Modified from Iannuzzi (2010), based on data from Machado (1972) and Guerra-Sommer et al. (2008).

Formal relationships are also established with the *Glossopteris-Rhodopteridium* Zone of Guerra-Sommer and Cazzulo-Klepzig (1993) within the phytostratigraphic chart for the lower Permian of southern Brazilian Paraná Basin (Iannuzzi, 2010).

THE SIDERÓPOLIS MEMBER PALEOFLORA

Previous studies

The Siderópolis Member paleoflora has its components registered in several taphofloras occurring in distinct areas of three municipalities of the State of Santa Catarina: Lauro Muller (Bonito and Barro Branco beds), Criciúma (Irapuá Bed) and Treviso (Treviso Bed) (Figure 2).

The first study of the Early Gondwanan Siderópolis Member paleoflora (then not yet so designated) was made by

D. White (1908a) based on material collected by I. C. White (1908b), recovered from fossiliferous horizons throughout all the “Rio Bonito Beds”, in Lauro Muller (formerly known as Minas), in the northern portion of the Santa Catarina Coalfield (Figure 2).

Later, Rigby (1972a) presented a list of phytofossil components based on new collections deposited at the Universidade de São Paulo from three different horizons (I to III), previously studied by D. White (1908a) and probably associated with the Barro Branco and Bonito beds of Putzer (1952) 127 as seen in Table 1. In the same study, Rigby (1972a) also has detailed the phytofossil forms from another horizon which he considered older than the Bonito coal bed, on the Lauro Müller to Barro Branco road (0.5 to 1.0 miles) designated BB whose taphofloristic composition is also given in Table 1.

The Irapuá bed (the third coal bed from the base of the Siderópolis Member) consists of thin interbeds of coal and carbonaceous shale, reaching an overall average thickness of

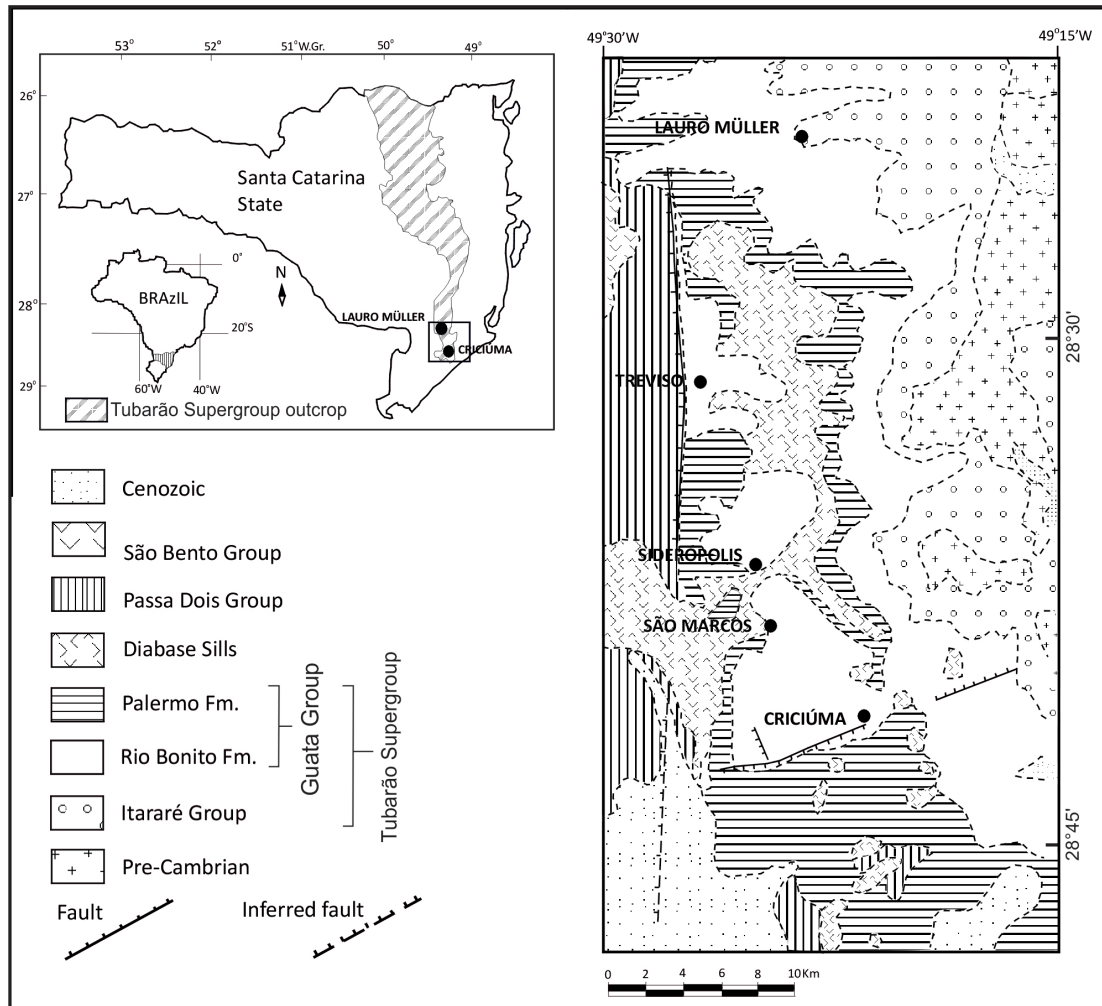


Figure 2. Map of the Santa Catarina coal region showing the geographic locations of the Siderópolis Member taphofloras in the State of Santa Catarina. Modified from Bernardes-de-Oliveira (1977).

2 to 3 m (see Figure 1) with lateral pinch outs over relatively short distances as seen in the outcrop at the Bainha locality (Iannuzzi, 2010). The beds containing plant fossils consist of clayey siltstone and fine to medium-grained sandstones that are interpreted as floodplain deposits formed primarily by deposition from suspension (over bank deposits) and secondarily by low-energy streams after flood events (Facies B and C of Iannuzzi, 2002). All these beds have been generated within a lagoon/barrier and/or fluvial system on a vast coastal plain (Putzer, 1952; Krebs, 2004).

Since the beginning of the second half of the twentieth century several authors have developed studies on plant fossiliferous levels in silty-clayey deposits associated with the Irupá bed in Criciúma Municipality, State of Santa Catarina (Dolianiti, 1946, 1948, 1952, 1953a, 1953b, 1953c, 1954a, 1954b, 1956a, 1956b, 1971; Barbosa, 1958; Mussa, 1958; Millan, 1965, 1967a, 1967b, 1969a, 1969b, 1971; Yoshida, 1966, 1968; Rigby, 1969, 1972a, 1972b,

1972c; Bernardes-de-Oliveira, 1969, 1977, 1978, 1980a, 1980b, 1988; Rösler, 1973, 1975; Bernardes-de-Oliveira and Pontes, 1977; Bernardes-de-Oliveira and Carvalho, 1981; Bernardes-de-Oliveira and Yoshida, 1981).

Outcrops containing the Irupá paleoflora are about 10 m thick, exposed along the south side of a small hill (Morro Cechinel) in the urban area of Criciúma and named as “Bainha”, “Bairro 20” and “Hospital” and along the railway in the area of the coal loading station in the neighboring district of São Marcos, named as “São Marcos” (Bernardes-de-Oliveira, 1977, 1980a). Plant fossils recovered from these outcrops represent a paleoflora informally called the *Irupá Bed flora* (Bernardes-de-Oliveira, 1980a; Iannuzzi, 2010).

The Treviso bed was recognized by Putzer (1952) as the uppermost of the five layers of coal identified in Santa Catarina Coalfield (Figure 2). Read (1941) described a phytossiliferous assemblage from Ferreira River margin outcrop (Treviso municipality) preserved in a silty-clayey

Table 1. Siderópolis Member paleoflora in Lauro Muller, northern portion of the Santa Catarina Coalfield (after Rigby, 1972a).

Bed	Horizon	Components
Barro Branco Coal Bed	I or Joaquim Branco	<i>Lycopodiopsis</i> sp. <i>Phyllothea griesbachi</i> Zeiller <i>Schizoneura gondwanensis</i> Feistm. <i>Paracalamites australis</i> Rigby <i>Sphenopteris lobifolia</i> Morris <i>Gangamopteris obovata</i> (Carr.) White <i>Glossopteris browniana</i> Brongn. <i>G. communis</i> Feistm. <i>G. occidentalis</i> White <i>Vertebraria</i> sp. <i>Arberia minasica</i> (White) emend. Rigby <i>Derbyella aurita</i> White <i>Noeggerathiopsis spathulata</i> (Dana) Feistm. <i>Walikali millani</i> Rigby Gymnosperm branches <i>Samaropsis seixasi</i> (White) Seward <i>S. moreirana</i> (White) Dolianiti <i>S. mendesi</i> Rigby <i>S. yoshidae</i> Rigby <i>Cordaicarpus oliveiranus</i> (White) Millan
	II	Lycophyte leaves <i>Paracalamites australis</i> Rigby <i>Sphenopteris lobifolia</i> Morris <i>Gangamopteris obovata</i> (Carr.) White <i>Glossopteris ampla</i> Dana <i>G. communis</i> Feistm. <i>G. occidentalis</i> White <i>Vertebraria</i> sp. <i>Arberia minasica</i> (White) emend. Rigby <i>Noeggerathiopsis spathulata</i> (Dana) Feistm. <i>Cordaicarpus oliveiranus</i> (White) Millan
	III	<i>Gangamopteris obovata</i> (Carr.) White <i>Glossopteris browniana</i> Brongn. <i>Vertebraria</i> sp. <i>Arberia minasica</i> (White) emend. Rigby <i>Noeggerathiopsis spathulata</i> (Dana) Feistm. <i>Samaropsis moreirana</i> (White) Dolianiti <i>Cordaicarpus oliveiranus</i> (White) Millan
Older than Bonito Coal Bed (?)	BB	<i>Lycopodiopsis</i> sp. <i>Gangamopteris obovata</i> (Carr.) White <i>Glossopteris browniana</i> Brongn. <i>G. angustifolia</i> Brongn. <i>G. communis</i> Feistm. <i>Arberia minasica</i> (White) emend. Rigby <i>Noeggerathiopsis spathulata</i> (Dana) Feistm. <i>Samaropsis moreirana</i> (White) Dolianiti <i>S. thomasi</i> Schopf

level associated to the coal layer containing the following elements: *Glossopteris* cf. *G. ampla* Dana, *G. indica* Schimper, *Lepidodendron pedroanum* (Carruthers) Zeiller and *Lepidostrobus* sp., including this plant association in the Irapuá bed. Among the material collected later from the same outcrop, Lejal-Nicol and Bernardes-de-Oliveira (1979) identified a new lycophyte species, *Cyclodendron brasiliensis*. The richness in lycopsids and field observations lead to agree with Putzer's (1952) point of view and consider this plant horizon as belonging to Treviso bed.

These researches generated an extensive contribution to the knowledge of the floristic composition of the coal measures of Siderópolis Member, as detailed in Table 2-4.

The most abundant paleofloristic components of the Siderópolis Member Paleoflora

The glossopteridophytes, the most abundant elements in the Siderópolis Member Paleoflora, are represented by *Glossopteris* (Figures 4F and 5A-G), *Gangamopteris* (Figure 4A-E) (?), *Rhabdotaenia* (Figure 10A, B), *Vertebraria* and *Ottokaria*

Table 2. Plant species list of the Siderópolis Member Paleoflora, Rio Bonito Formation, Paraná Basin, in the State of Santa Catarina (after Bernardes-de-Oliveira, 1980a, 1980b, 1988; Bernardes-de-Oliveira and Pontes, 1977; Bernardes-de-Oliveira and Carvalho, 1981; Bernardes-de-Oliveira and Yoshida, 1981).

TAXA	GEOGRAPHIC LOCATION	BRAZIL						
		PARANÁ BASIN						
		STATE OF SANTA CATARINA						
STRATIGRAPHIC LOCATION		RIO BONITO FORMATION SIDERÓPOLIS MEMBER						
		1	2	3	4	5	6	7
LYCOPHYTA	LYCOPSIDA	<i>Cyclodendron brasiliense</i>						•
		<i>Lepidodendron</i>						•
		<i>Lepidoistrobus</i>						
MONILOPHYTA	Sphenopsida	<i>Phyllothea australis</i> Brongn.	•					
		<i>Phyllothea griesbachii</i> Zeller	•			•		
		<i>Giridia indica</i> Pant, Naut. & Misra	•					
		Notocalamitaceae	•					
		"Incertae Sedis"	•	•	•	•	•	
INCERTAE SEDIS	Filicopsida Sphenopterida	<i>Ponsothea lobifolia</i> Bern.-de-Ol.	•					
		<i>Pecopteris</i> aff. <i>P. cambuyensis</i> Read	•					
		<i>Pecopteris</i> sp.	•					
		<i>Sphenopteris lobifolia</i> Morris	•	•	•	•	•	
		<i>Sphenopteris</i> sp. Bern.-de-Ol.	•					
		<i>Chiropteris reniformis</i> Kawasaki	•					
		<i>Notoangardium cricumense</i> (Rigby)	•					•

BRAZIL - GEOGRAPHIC LOCATION OUTCROPS

1. Criciúma, SC - Boinha-Irapuá Bed;
2. Criciúma, SC - Bairro 20-Irapuá Bed;
3. Criciúma, SC - Hospital-Irapuá Bed;
4. Criciúma, SC - São Marcos Coal loading station-Irapuá Bed;
5. Lauro Müller, SC - Barro Branco Bed (I, II, III);
6. Lauro Müller, SC - Older than Bonito Bed(?);
7. Treviso, SC - Ferreiro River margin-Treviso Bed.

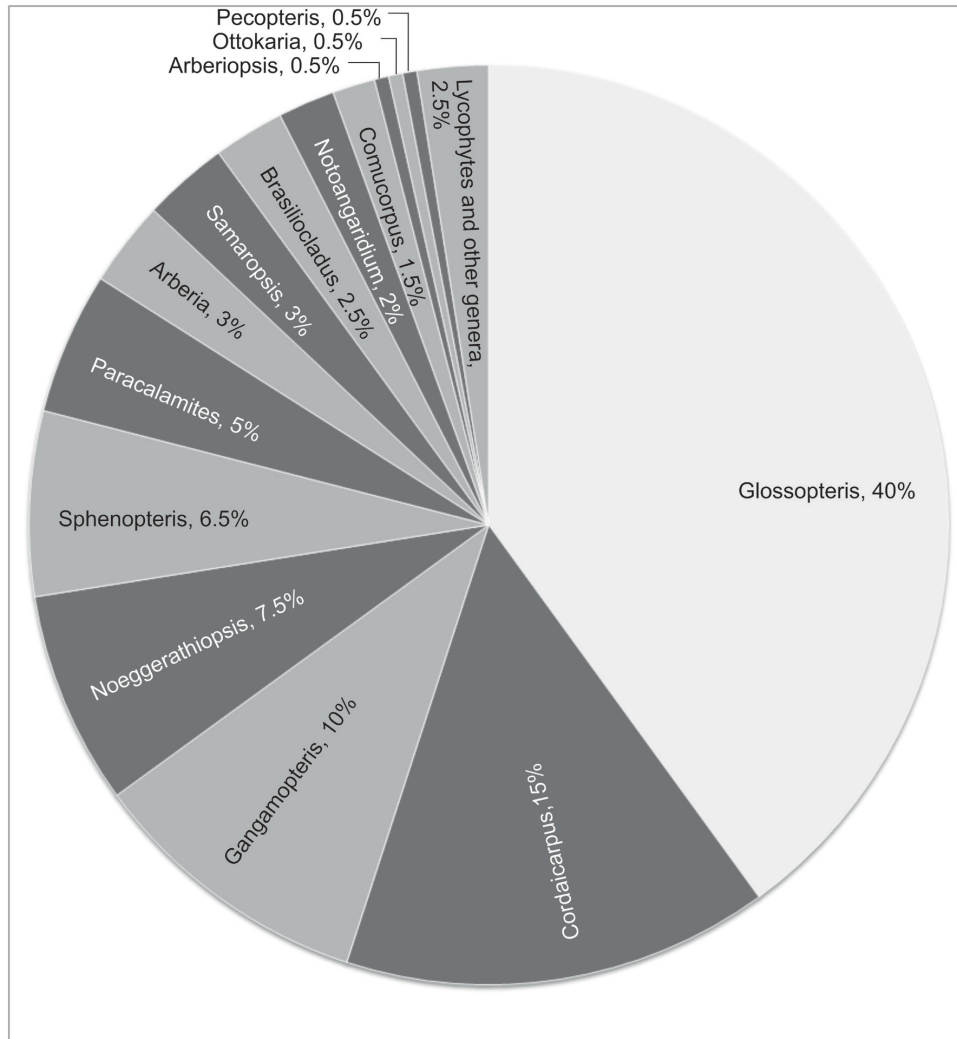


Figure 3. Quantitative representation of Siderópolis Member Paleoflora components. Modified from Bernardes-de-Oliveira, 1977.

(Figure 10G-J) genera and constitute more than 50% of the total plant association (Figure 3). The foliar genus *Glossopteris*, represented by eleven species, is dominant in the assemblage. The genus *Gangamopteris* is less abundant, constituting 10% of the total but yet diversified as represented by six species. The other glossopterid components account for less than 1% of the total.

Fertile fronds of filicophytes identified as *Ponsotheca* Bernardes-de-Oliveira (1980b) are rare (about 0.1% of the total composition), but sterile fronds (pteridophylles) which could correspond to filicophytes or pteridospermophytes like *Sphenopteris*, *Pecopteris* and *Notoangaridium*, constitute 9% of the total floristic composition (Figures 6A-C and 7E).

The cordaitophytes, represented by the genus *Noeggerathiopsis*, constitute 7.5% of the total association thus corresponding to the third group in abundance (Figure 8A-C).

The sphenophytes constitute about 5.5% of the paleoflora and are commonly represented by *Paracalamites* (5%),

while other vegetative forms (*Phyllothea*) and reproductive structures (*Notocalamites*) are rare (Figure 9A-G).

Delicate sterile shoots of coniferophytes such as *Brasiliocladus* Bernardes-de-Oliveira and Yoshida (1981) and few specimens of *Buriadia* associated to *Cornucarpus* seeds constitute about 4% of the paleoflora (Figure 7A-G).

Fructifications like *Arberia* and *Arberioopsis* Bernardes-de-Oliveira (1978) are here considered in the pteridospermophytes, corresponding to 3.5% of the total paleoflora (Figure 10C-F). The dispersed seeds of the genera *Cordaicarpus* (Figure 8D-F) and *Samaropsis* (Figure 8G-J) tentatively included in this plant group constitute 15% and 3% of the total plant association respectively.

The lycophytes are absent in most outcrops of the Siderópolis Member paleoflora but show an almost exclusive assemblage in the Ferreira River outcrop in Treviso Municipality (Figure 11A-C).

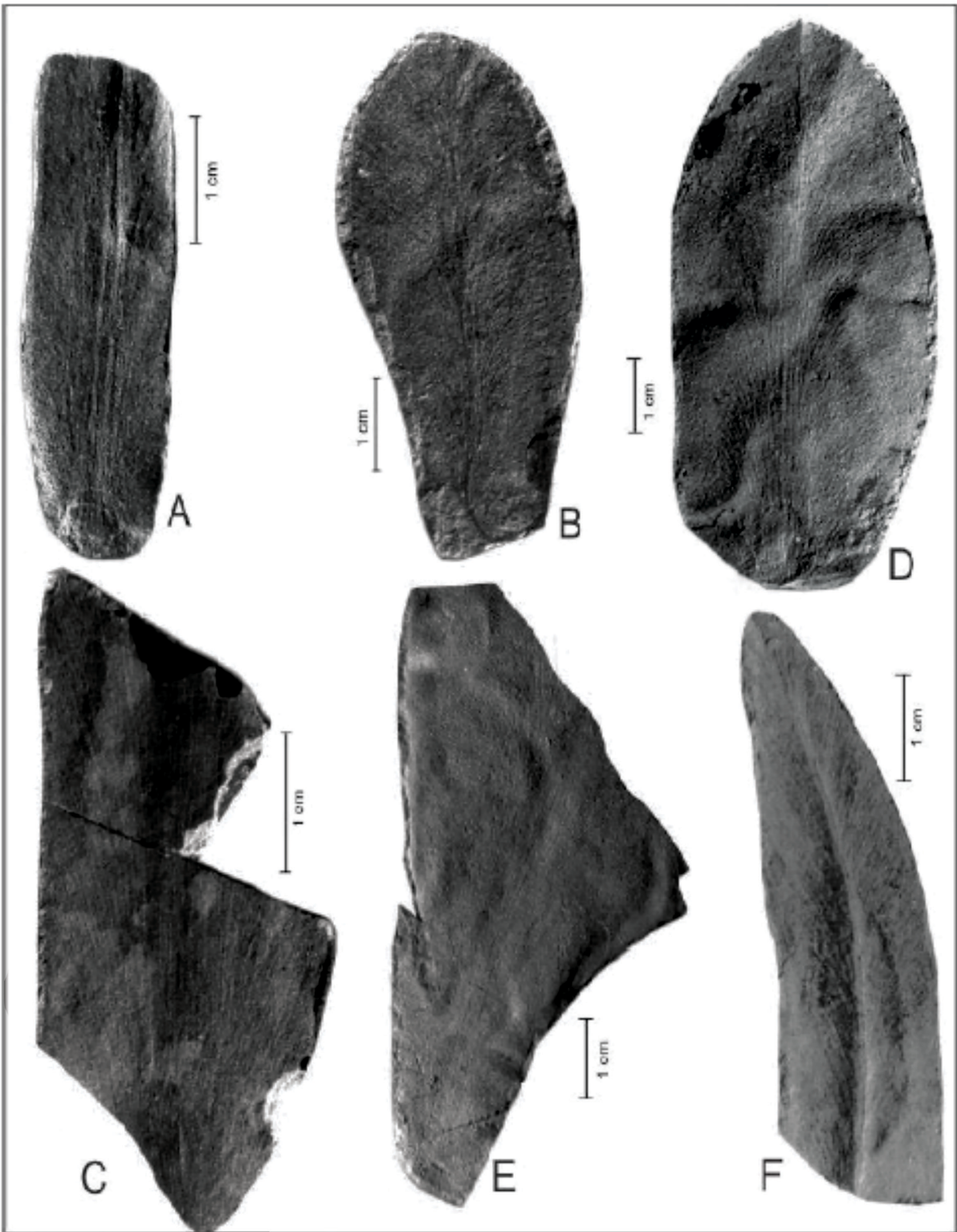


Figure 4. A-F. Irapuá coal seam, Municipality of Criciúma, SC: (A) *Gangamopteris* sp., GP/3T-175 from São Marcos; (B) *Gangamopteris intermedia*, GP/3T-221 from Bainha; (C) *Gangamopteris* cf. *G. buriadica*, GP/3T-215 from Bainha; (D) *Gangamopteris mosesii*, GP/3T-218 from Bainha; (E) *Gangamopteris obovata*, GP/3T-211 from Bainha; (F) *Glossopteris angustifolia*, GP/3T-178 from São Marcos.

Table 3. Plant species list of the Siderópolis Member Paleoflora, Rio Bonito Formation, Paraná Basin, in the State of Santa Catarina. (For legend see Table 2).

TAXA	GEOGRAPHIC LOCATION	BRAZIL							
		PARANÁ BASIN							
		STATE OF SANTA CATARINA							
		RIO BONITO FORMATION SIDERÓPOLIS MEMBER							
STRATIGRAPHIC LOCATION		1	2	3	4	5	6	7	
PTERIDOSPERMOPHYTA	GLOSSOPTERIDALES	<i>Gangamopteris</i> cf. <i>G. buriadica</i> Feistm.	•						
		<i>G. intermedia</i> Maithy	•			•			
		<i>G. mosesi</i> Dolianiti	•			•			
		<i>G. obovata</i> (Carr.) White	•	•	•	•	•	•	
		<i>G. rigbyi</i> Bern.-de-Ol.	•			•			
		<i>Gangamopteris</i> sp.				•			
		<i>Glossopteris ampla</i> Dana	•				•		?
		<i>G. angustifolia</i> Brongn.	•	•		•			•
		<i>G. browniana</i> Brongn.	•	•	•	•	•	•	
		<i>G. communis</i> Feistm.	•	•		•	•	•	
		<i>G. cf. G. formosa</i> Feistm.							
		<i>G. cf. G. longicaulis</i> Feistm.							
		<i>G. cf. G. occidentalis</i> White							
		<i>G. cf. G. sewardi</i> Plumst.							
		<i>G. spathulato-cordata</i> Feistm.emend.	•						
		Ban.& Gosh var. <i>dolianitii</i> Bern.-de-Ol.							
		<i>G. taenioides</i> Feistm.	•						
		(?) <i>Rhabdotaenia cricumensis</i> (Dol.) Bern.-de-Ol.	•	•					
		<i>Arberia</i> aff. <i>A. brasiliensis</i> Lundqvist			•				
		<i>A. minasica</i> (White) emend. Rigby	•			•	•	•	
		<i>Arberia</i> sp.							
		<i>Arberioopsis boureaui</i> Bern.-de-Ol.	•						
		(?) <i>Arberioopsis</i> sp. A Bern.-de-Ol.	•						
		(?) <i>Arberioopsis</i> sp. B Bern.-de-Ol.				•			
		(?) <i>Arberioopsis</i> sp. C Bern.-de-Ol.				•			
		<i>Problematicum</i> sp.A Rigby	•						
		<i>Ottokaria</i> aff. <i>O. bengalensis</i> Zeiller				•			
		<i>O. sancta-catharinae</i> Dolianiti	•						
		<i>O. cf. O. transvalensis</i> Plumst.		•					
		<i>Ottokaria</i> sp. Bern.-de-Ol.	•						
		Fructifications like <i>Ottokaria</i> sp. A Bern.-de-Ol.	•						
		Fructifications like <i>Ottokaria</i> sp. B Bern.-de-Ol.	•						

Some paleoenvironmental aspects of the Siderópolis Member Paleoflora

Considering that taphofloras are almost always formed by autochthonous and allochthonous material and that the vegetation registered by several taphofloras has undergone distinct selection process due to transport from different sources to distinct depositional areas, it is possible to propose distribution models for the species. Thus, the phytofossil assemblages show their paleoecology as much as biostratigraphy.

Botrychiopsis, *Phyllothea* and Lycophyte association is related with meso-hydrophilic environments, whilst ferns and

glossopterids with mesophilic environment. Low diversity of the specimens is considered as a result of inherent abiotic stress areas of flooding at high latitudes that are stable for a long period of time (Guerra-Sommer, 1989).

Although the paleoflora of Siderópolis involves several taphofloras from larger or smaller distances between them, it is possible to infer ecological features present in these phytofossil records.

- 1) The taphofloras of the Bairro 20 and Hospital outcrops (Criciúma, SC) - rich in seeds and some stems, could be related to deposits more distal in aqueous body of the

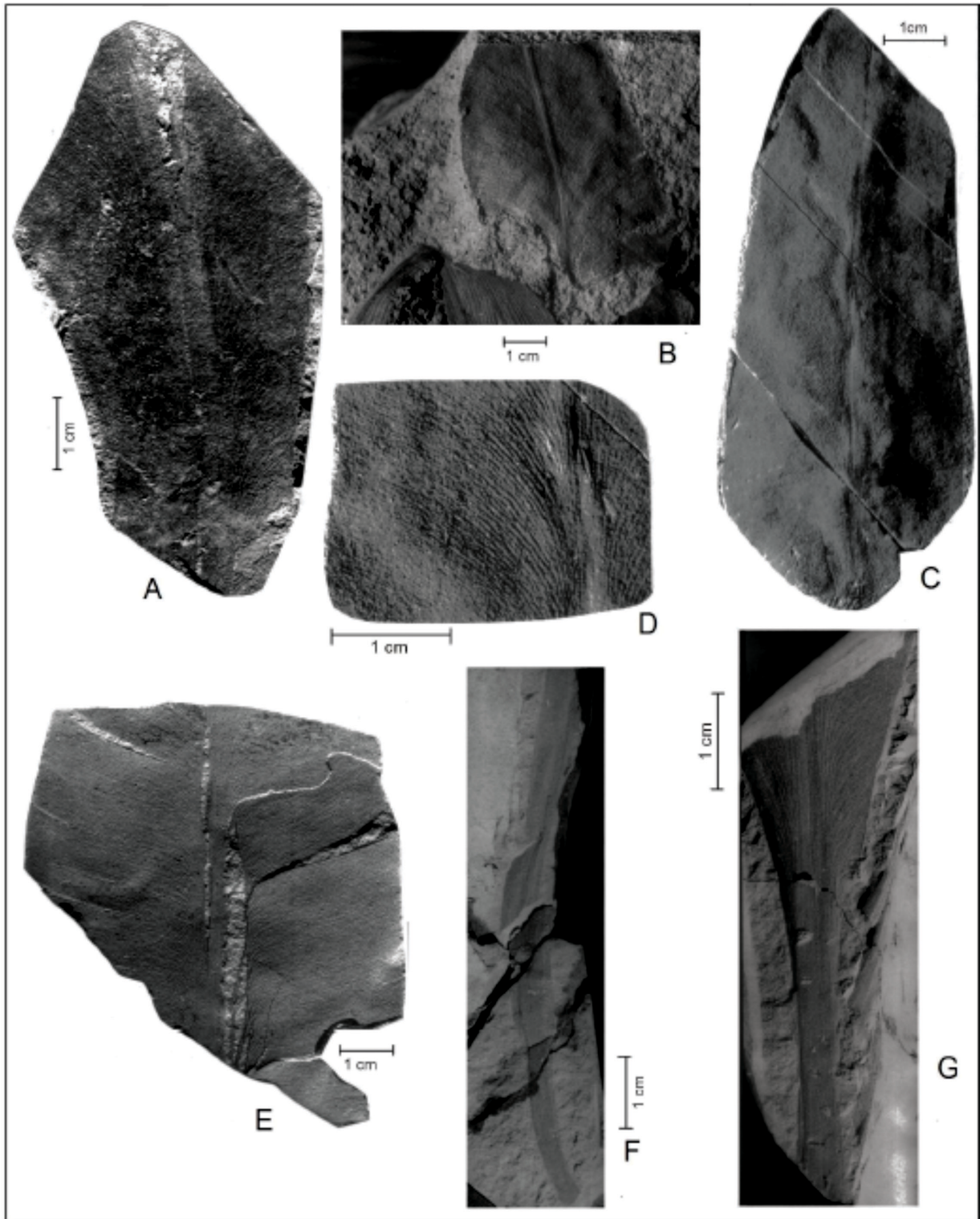


Figure 5. A-G. (A, C, D, E, F, and G from Irapuá coal seam, Criciúma, SC); (B from Barro Branco coal seam, Lauro Müller, SC). (A) *Glossopteris browniana*, Bairro 20, GP/3T-188; (B) *G. communis*, Barro Branco, GP/3T; (C) *G. communis*, Bainha, GP/3T-193; (D) *G. communis* detail of GP/3T-193; (E) *G. cf. G. occidentalis*, Bainha, GP/3T-227; (F) *G. taenioides*, Bainha, GP/3T-203; (G) *G. cf. G. longicaulis*, São Marcos, GP/3T-180.

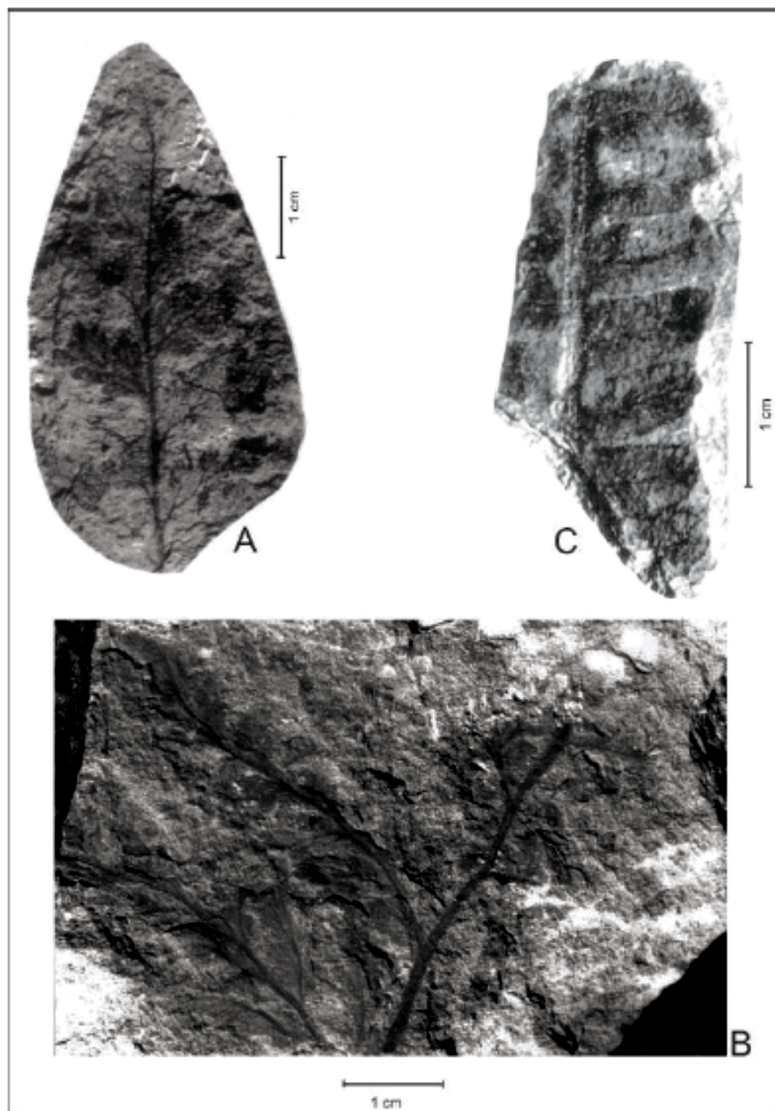


Figure 6. A-C. Irapuá coal seam, Criciúma, Municipality, SC. (A) *Sphenopteris lobifolia* GP/3T-144; (B) *Ponsotheca lobifolia* DNPM-1176 both from Bainha; (C) *Pecopteris* sp. from São Marcos, GP/3T-149.

sedimentation. Bainha and São Marcos outcrops (also in Criciúma, SC), richer in leaf, leafy branches and forms of fruiting bodies, could be related to proximal environments within a deltaic system. The Treviso taphoflora may have been deposited in a more brackish transitional environment - representing a marshy plant community, formed by endemic elements such as *Brasilodendron pedroanum*, *Cyclodendron brasiliense* and rare allochthonous glossopterids.

- 2) Bainha and São Marcos outcrops represent deltaic deposits which would be deposited near flood plain community elements since they are rich in sphenophytes and mesophilic elements such as glossopterid leaves and fructifications, very rare forms of lycophytes (possibly from brackish waters of mangrove type) and rare coniferous remains (related to distant highland forms).

- 3) The dominance of a lycophyte assemblage, almost pure and mutually exclusive in the Treviso bed in relation to the other plant groups, as seen in Lejal-Nicol and Bernardes-de-Oliveira (1979), may be related to some typical conditions evident in brackish (i.e. tidal flats), distal deltaic or mangrove paleoenvironments.

Correlation of Siderópolis Member Paleoflora with other Permian Southern Brazil paleofloras

The typical postglacial *Glossopteris* paleoflora of the Siderópolis Member of Santa Catarina State differs from the pre glossopterid interglacial taphofloras of the lower and middle stages of Itararé Group registered in different sites of the State of São Paulo namely, Bandeirantes Highway 96 km,

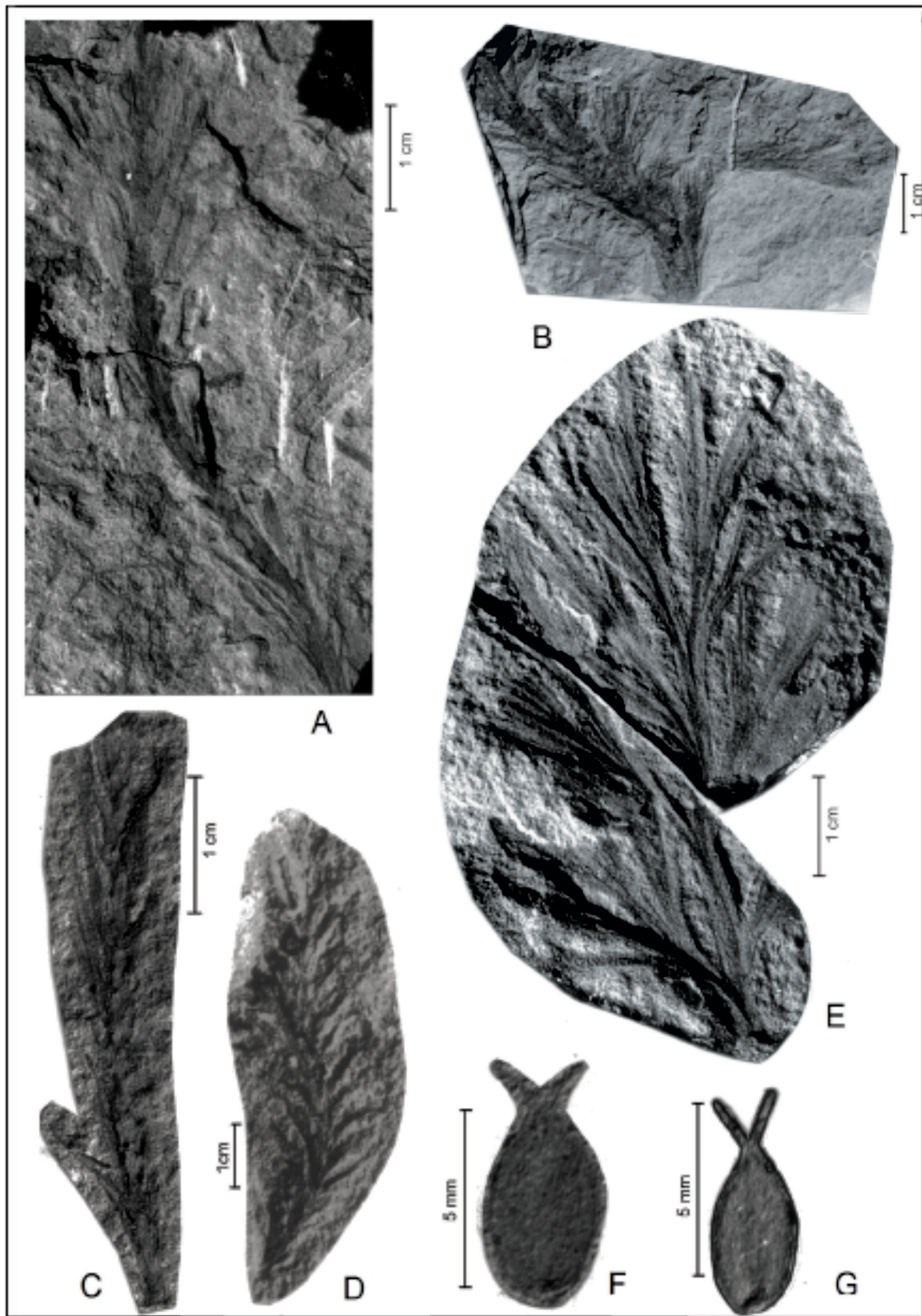
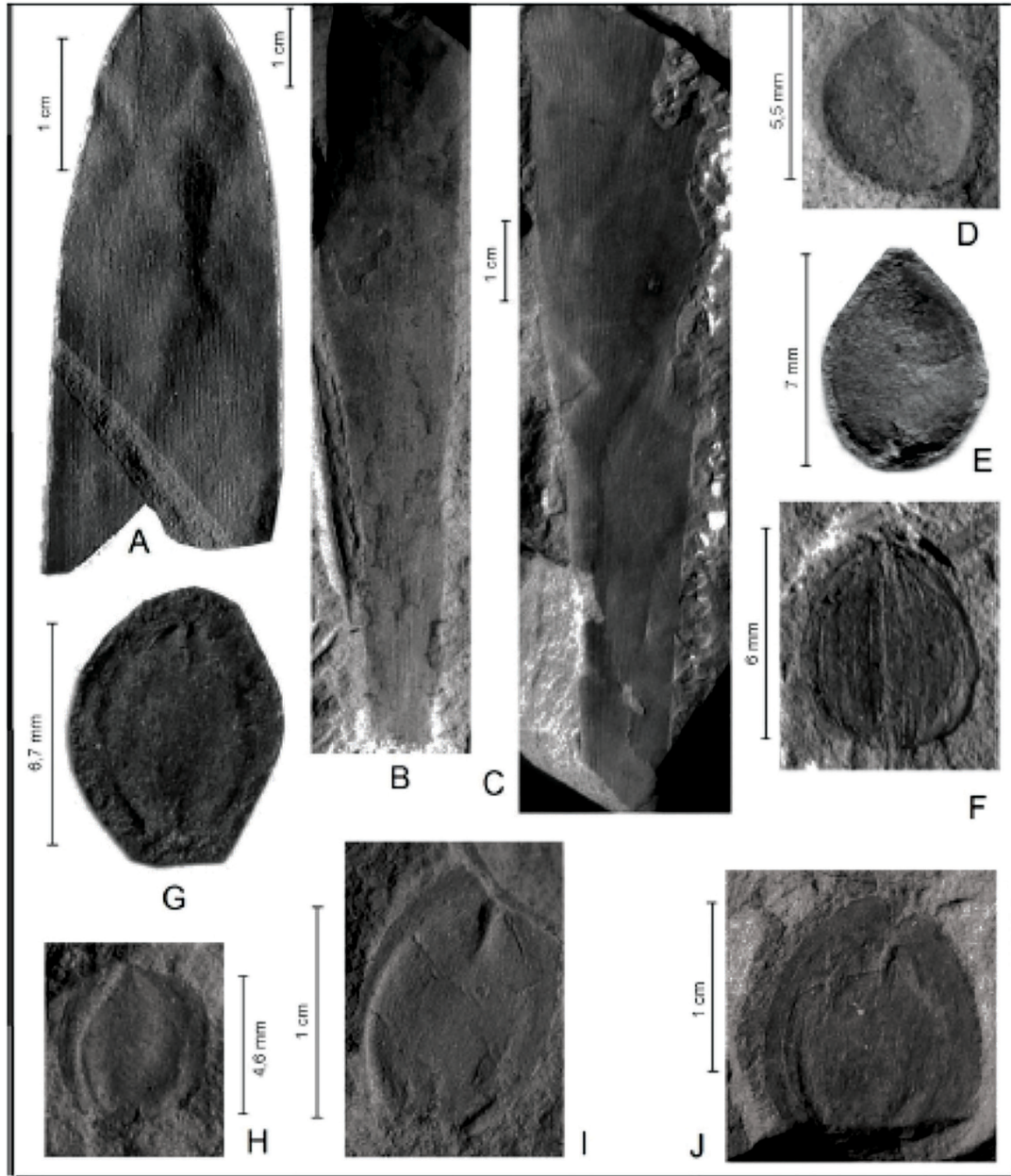


Figure 7. A-G. Irapuá coal seam, Criciúma, SC. (A, B, C) *Brasiliocladus acicularis* from Bainha, (A) DGP-7/1051, (B) GP/3T-250, (C) GP/3T-265; (D) *Buriadia mendesi* from Bainha, DGP-7/1057 (Holotype); (E) *Notoangaridium cricumensis* from São Marcos, GP/3T-166; (F, G) *Cornucarpus furcatus*, (F) From São Marcos, GP/3T-169, (G) From Bainha, GP/3T-171.

Itapeva, Monte Mor, and Salto de Itu by the absence of glossopterids in these late Pennsylvanian associations. It is also distinguished from the glossopterid interglacial Asselian taphoflora of Cerquilha (SP), included in the uppermost part of the Itararé Group, by the absence of the genus *Glossopteris* in that taphoflora (Bernardes-de-Oliveira et al., 2005).

Taphofloras from the immediate postglacial interval of São João do Triunfo and Figueira (State of Paraná, Triunfo

Member, basal portion of the Rio Bonito Formation) evidenced a composition characterized by a less diverse flora with predominance of the genus *Gangamopteris* over *Glossopteris* (Rösler, 1972, 1979; Ricardi-Branco, 1998; Ricardi-Branco and Rösler, 2004) different from the Siderópolis Member paleoflora, where the genus *Glossopteris* is dominant in a proportion of 4:1 over *Gangamopteris* and shows a higher diversity.



Figures 8. A-J. Irupá coal seam, Criciúma, SC. (A, B, C) *Noeggerathiopsis hislopi* (A) GP/3T-255, (B) GP/3T-259 both from Bainha, (C) GP/3T-260 from São Marcos; (D) *Cordaicarpus irapuensis*, GP/3T-168 (Holotype) from Hospital; (E) *Cordaicarpus rocha-camposi* GP/3T-162 from Bainha; (F) *Cordaicarpus zeilleri*, GP/3T-160 from Bainha; (G, H) *Samaropsis milliana*: (G) GP/3T-155 (Holotype), (H) GP/3T-170 both from Bainha; (I, J) *Samaropsis sancti-marci*, (I) GP/3T-186, (J) GP/3T-200 both from São Marcos.

In the State of Rio Grande do Sul, at the Morro do Papaléo Mine section in the Municipality of Mariana Pimentel two depositional sequences have been recognized, the lower one is assigned to a lagoonal / lacustrine facies of the final deposits of the Itararé Group and the upper one to deposits of a fluvial facies of the Rio Bonito Formation (Guatá Group) (Iannuzzi et al.,

2007). The floral assemblages from the Morro do Papaléo Mine occur within distinct stratigraphic levels of both facies. The studies of Corrêa da Silva and Arrondo (1977), Corrêa da Silva (1978), Burjack et al. (1982) and Cazzulo-Klepzig and Guerra-Sommer (1983) are restricted to the floral record found in the lowermost section corresponding to the Itararé Group.

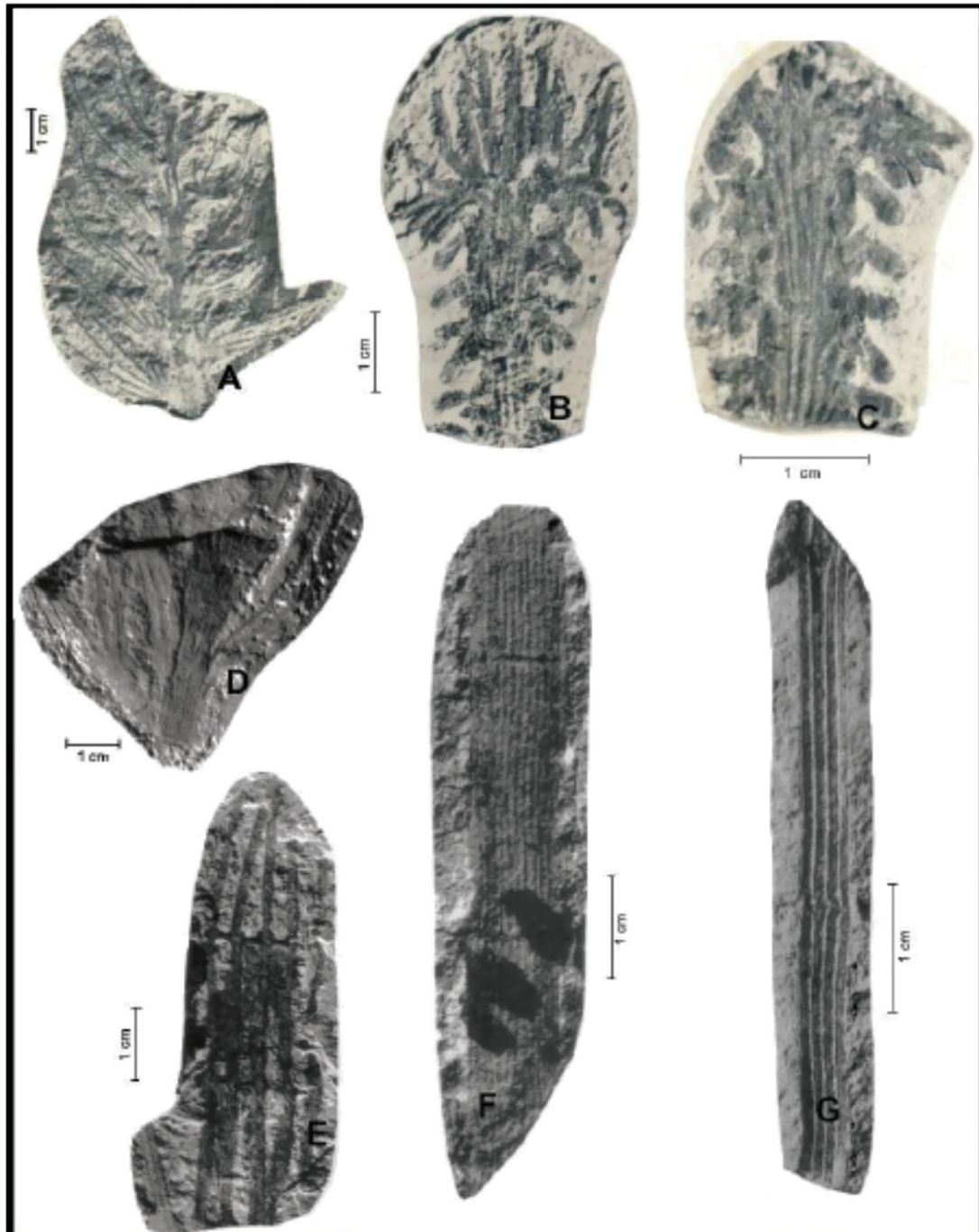


Figure 9. A-G. (A) Joaquim Branco coal seam, Lauro Müller Municipality, SC; (B-G) Irupá coal seam, Criciúma Municipality, SC. (A) *Phyllothea griesbachi*, Joaquim Branco coal seam, DGP7/1161; (B, C) *Notocalamites askosus* from Bainha, DGP7/1054; (D) *Phyllothea australis* from Bainha, GP/3T-139; (E, F, G) *Paracalamites australis* from Bainha, (E) GP/3T-142, (F) GP/3T-140, (G) GP/3T-141.

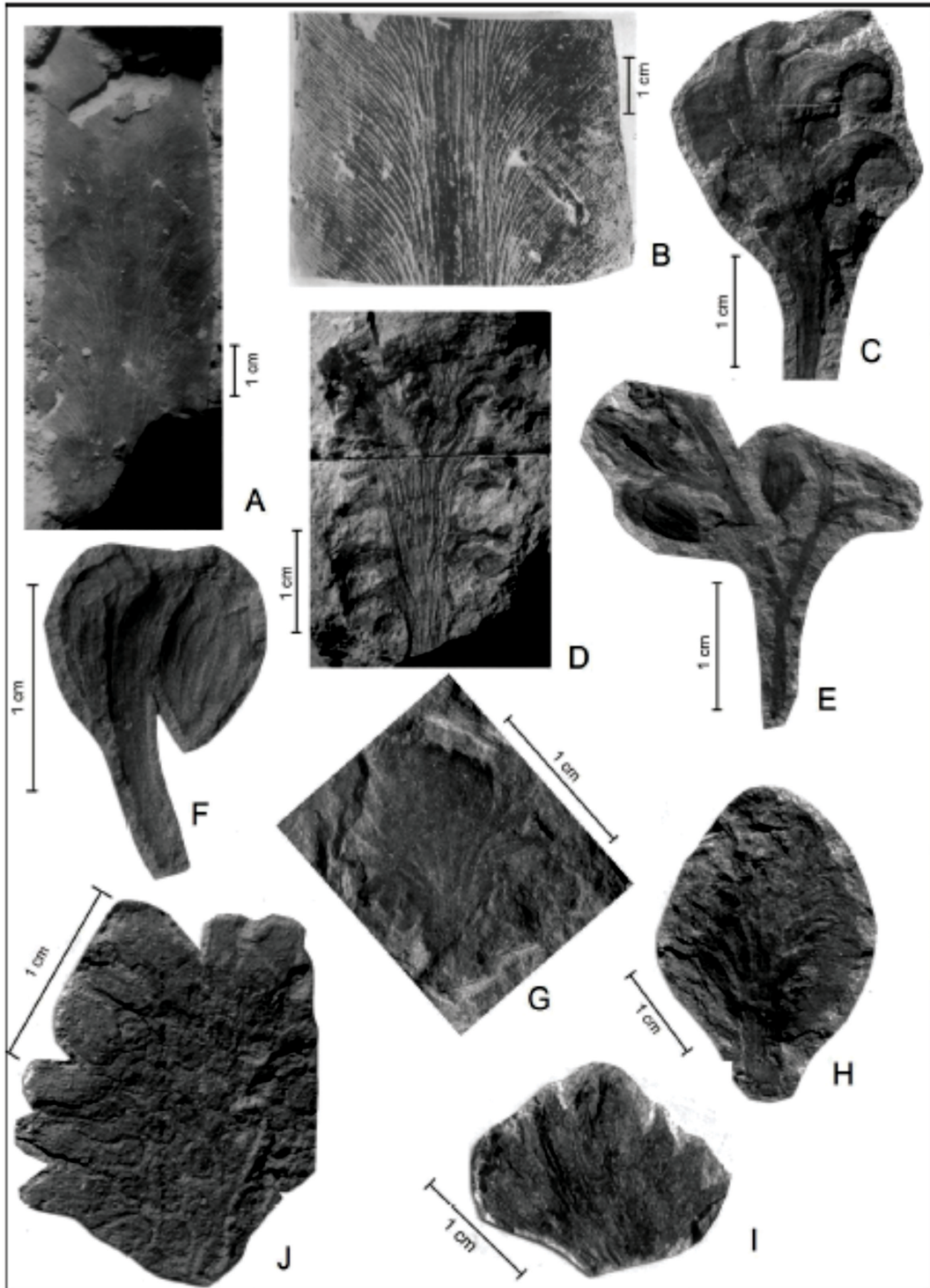


Figure 10. (A, J). Irapuá coal seam, Criciúma, SC. (A, B) ?*Rhabdotaenia criciumensis* from Bairro 20, (A) GP/3T- 209, (B) GP/3T-208; (C, D) *Arberia minasica* from Bainha, (C) GP/3T-235, (D) GP/3T-244; (E) *Arberiaopsis boureaui*, GP/3T-238 (Holotype) from Bainha; (F) *Arberiaopsis* sp.B., GP/3T-239 from São Marcos; (G) *Ottokaria* aff. *O. bengalensis*, GP/3T-192 from São Marcos; (H) *Ottokaria* sp., GP/3T-233 from Bainha; (I) *Ottokaria* cf. *O. transvalensis*, GP/3T-245 from Bairro 20; (J) *Ottokaria sanctae-catharinae*, GP/3T-232 from Bainha.

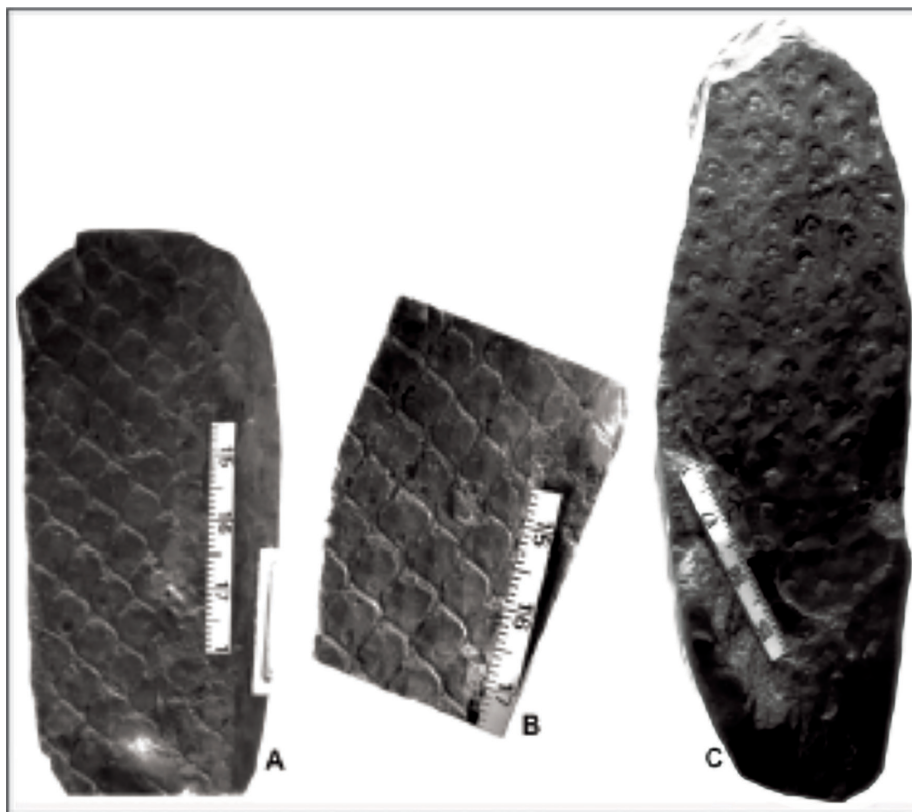


Figure 11. (A-C) *Cyclo dendron brasiliensis*, (A,B)-TR-49, (C)- TR-47 all from Treviso,SC, Ferreira River.

These assemblages bear few species of the genus *Glossopteris* indicating probably a younger floristic level than Cerquilha, in the State of São Paulo, and may be contemporaneous to the Triunfo Member in the State of Paraná.

The upper sequence of the Morro do Papaléo section related to the coal measures of the Rio Bonito Formation contains two phytofossiliferous beds, N7 and N8 as described by Iannuzzi et al. (2003a, 2003b, 2009). The plant-bearing beds of the uppermost section of the Morro do Papaléo were described as two fossiliferous beds containing records of *Gangamopteris* (*G. obovata* var. *major*), *Glossopteris* (*G. indica*, *G. communis*, *G. occidentalis*), ginkgoalean (*Ginkgophytopsis* sp.), cordaitalean leaves (*Cordaites hislopi* = *Noeggerathiopsis hislopi*), as well as ferns (*Asterotheca* sp., *Pecopteris* spp.), abundant lycopsid stems of *Brasilodendron pedroanum*, *Cordaicarpus* and *Samaropsis*-type seeds (Vieira and Iannuzzi, 2000; Iannuzzi et al. (2003a, 2003b). The floristic association was included in the base of the Siderópolis Member by Iannuzzi (2010).

Undoubtedly, these floras have close similarities with the Siderópolis Member paleoflora but they show minor diversification than the latter in relation to the sphenophytes, the glossopterid leaves and fructification species, the seeds of *Cordaicarpus* spp and *Samaropsis* spp. Nevertheless, the absence of *Asterotheca* and *Ginkgophytopsis* in Siderópolis

Member can represent stratigraphic or paleoecological/paleoclimatic factor.

The Quitéria flora was first reported by Piccoli et al. (1991) from the Municipality of Encruzilhada do Sul, around 100 km southwest of Porto Alegre city. The outcrop corresponds to the uppermost strata of Rio Bonito Formation in the State of Rio Grande do Sul. This outcrop was divided into two distinct sedimentary units (Piccoli et al., 1991; Jasper et al., 2006) with two phytofossiliferous levels. The lower level of fossil plants from a dark gray massive mudstones that underlie a succession of thin coal seams, according to Piccoli et al. (1991) and Guerra-Sommer et al. (1995), Boardman and Iannuzzi (2010) and Boardman et al. (2012), is predominantly composed of articulated stems (*Paracalamites* sp.) and *Phyllothea*-like leaf branches. Although less abundant, the glossopterid leaves (*Glossopteris communis*) and pteridophylla fronds (*Rhodopteridium* sp.) still occur and with less common fertile structures (*Arberia minasica*; *Gondwanostachys australis* = *Giridia quiteriensis*) and seeds (*Cordaicarpus* sp.).

The upper level of phytofossils contain abundant stumps and stems of arborescent lycophytes in situ (*Brasilodendron pedroanum*), remains of pteridophylla fronds (*Botrychiopsis valida*, *B. plantiana* and *Rhodopteridium* sp.), fertile and sterile leafy shoots of conifers (*Cori cladus quiteriensis*), rare leafy branches of lycopodiales (*Lycopodites riograndensis*),

Table 4. Plant species list of the Siderópolis Member Paleoflora, Rio Bonito Formation, Paraná Basin, in the State of Santa Catarina. (For legend see Table 2).

TAXA	GEOGRAPHIC LOCATION	BRAZIL						
		PARANÁ BASIN						
		STATE OF SANTA CATARINA						
		RIO BONITO FORMATION SIDERÓPOLIS MEMBER						
STRATIGRAPHIC LOCATION		1	2	3	4	5	6	7
CONIFEROPHYTA	Cordaitales	<i>Noeggerathiopsis hislopi</i> (Bunb) Feistm.	•	•	•	•	•	•
		(?) <i>Noeggerathiopsis</i> sp. A	•					
		(?) <i>Noeggerathiopsis</i> sp. B	•					
		<i>Cordaicarpus irapuensis</i> Bern.-de-Ol.	•		•	•		
		<i>Cordaicarpus rocha-camposi</i> Bern.-de-Ol.	•	•				
		<i>Cordaicarpus zeileri</i> Maithy	•		•	•		
		<i>Cordaicarpus</i> sp. A	•					
		<i>Cordaicarpus</i> sp. B	•					
		<i>Samaropsis bainhensis</i> Millan	•					
		<i>S. cricumensis</i> Millan	•					
		<i>S. mendesi</i> Rigby	•	•			•	
		<i>S. millaniana</i> Bern.-de-Ol.	•		•			
		<i>S. sancti-marci</i> Bern.-de-Ol.	•			•		
		<i>Samaropsis</i> sp. A	•			•		
		<i>Samaropsis</i> sp. B	•					
	Coniferales	<i>Brasiliocladus acicularis</i> Yoshida	•	•	•			
		<i>Buriadia mendesi</i> Bern.-de-Ol.	•					
		(?) <i>Araucarites</i> sp. Bern.-de-Ol.	•	•				
		<i>Cornucarpus furcata</i> (Sur.& Lele) Maithy	•	•	•	•		
	"Incertae sedis" GYMNOSPERMS	<i>Palmatophyllites</i> sp.	•					
<i>Plumstediella apedicellata</i> Millan		•						
<i>Plumstediella</i> sp. Bern.-de-Ol.		•						
Indeterminate branch Bern.-de-Ol.		•			•			
Rhizomorph fragment Bern.-de-Ol.		•						

and glossopterid leaves (*Glossopteris browniana* and *Gangamopteris buriadica*) (Jasper et al., 2005; Jasper et al., 2006; Boardman et al., 2006; Guerra- Sommer et al., 2008; Tybusch and Iannuzzi, 2008; Iannuzzi and Boardman, 2008; Iannuzzi, 2010; Boardman et al., 2012).

Iannuzzi (2010) placed the Quitéria floras in a stratigraphical interval at the transition from the Paraguaçu to Siderópolis members of the State of Santa Catarina, assigning an approximate age of 288-285 Ma (Artinskian, according Cohn et al., 2013, updated).

These Quitéria taphofloras show many forms in common with the paleoflora of the Siderópolis Member, however, are different due to the minor diversity of *Glossopteris* and *Gangamopteris* species, the presence and diversification of the *Botrychiopsis* (*B. plantiana*, *B. valida*) and the presence of *Asterotheca*-type fronds and of fertile and sterile leafy shoots of conifer *Coriocladius*, all three genera absent in Siderópolis paleoflora.

Nevertheless, the absence of these genera in Siderópolis Member paleoflora could be due to stratigraphic or paleoecological/paleoclimatic factor.

FINAL REMARKS

The Siderópolis Member Paleoflora is dominated by glossopterid leaves, with the genus *Glossopteris* predominant over *Gangamopteris*, followed by cordaitalean leaves (*Noeggerathiopsis*) and seeds (*Cordaicarpus*, *Samaropsis*, *Cornucarpus*), fronds are common (*Sphenopteris*, *Pecopteris* and *Notoangaridium*) while reproductive structures of glossopterids or other groups (*Arberia*, *Arberioopsis*, *Ottokaria*, *Plumstediella*) and conifer leaf shoots (*Brasiliocladus*, *Buriadia*) are rare. Concerning to other early Permian floras throughout Paraná Basin, the Siderópolis Paleoflora distinguishes itself by the highest diversity of forms and the presence of several exclusive taxa in both levels, specific (*Buriadia mendesi*, *Cordaicarpus rocha-camposi*, *C. irapuenses*, *Gangamopteris rigbyi*, *Glossopteris spathulato-cordata* var. *dolianitii*, *Samaropsis bainhensis*, *S. cricumensis*, *S. millaniana*, *S. mendesi*) and generic (*Arberioopsis*, *Brasiliocladus*, *Notoangaridium*, *Notocalamites*, *Ponsothea*, *Cyclodendron*).

The only comparable paleofloras were registered in two outcrops namely, Morro do Papaléo (upper section) and Quitéria, of Rio Bonito Formation from the State of Rio Grande do Sul. However, these floras are quite less diversified and do not show several typical taxa of the Siderópolis paleoflora, while other elements are restricted to them (e.g. *Ginkgophytopsis* sp., *Rhodeopteridium* sp., *Kawizophyllum* sp., *Botrychiopsis* spp., *Coricladus quiteriensis*, *Lycopodites riograndensis*, *Giridia quiteriensis*). These differences can be explained by the distinct stratigraphic position, the Siderópolis paleoflora being apparently situated above in relation to the southern paleofloras (Iannuzzi, 2010). However, paleoecological/paleoclimatic factors should not be ruled out in order to justify this dissemblance.

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