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The *Botrychiopsis* genus and its biostratigraphic implications in Southern Paraná Basin

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ABSTRACT

Botrychiopsis has been considered an important floristic element of Westphalian/Artinskian associations of the Paraná Basin. The occurrence of *Botrychiopsis* in roof-shales of the Rio Bonito Formation in Southern Paraná Basin (Quitéria area), supported by the identification of *Botrychiopsis valida*, enlarges the genus biochron. Consequently, the stratigraphic hierarchy for *Botrychiopsis plantiana* and *Botrychiopsis valida* was defined for the Paraná Basin. Although it is climatically controlled and related to a deglaciation icehouse stage, stratigraphic distribution of the genus presents a substantial climate tolerance, from cold/cool to warm/temperate conditions. A new phytostratigraphic zonation is proposed for the southern portion of the basin that includes the *Botrychiopsis* Zone (Asselian/Kungurian), which is subdivided into the *Botrychiopsis plantiana* (Asselian/Artinskian) and *Botrychiopsis valida* (Late Artinskian/Kungurian) subzones.

Key words: *Botrychiopsis*, biostratigraphy, Paraná Basin, Permian, palaeoclimatology, Gondwana.

INTRODUCTION

The intracratonic Paraná Basin covers 1.700.000 square kilometers of East and Central South America (1.100.000 square kilometers in Brazil) and encloses Paleozoic, Mesozoic and, locally, Cenozoic sedimentary and volcanic rocks. According to Milani et al. (1998), the Paraná Basin comprises six stratigraphic megasequences bounded by interregional unconformities (*sensu* Vail et al. 1977). The three lower megasequences (Ordovician – Silurian, Devonian and Carboniferous – Early Triassic) consist of transgressive – regressive cycles whereas the three upper megasequences (Late Triassic, Jurassic – Early Cretaceous and Late Cretaceous) encompass continental strata and volcanic rocks. Each megasequence corresponds to previously proposed lithostratigraphic units.

The Carboniferous – Early Triassic (CET) megasequence represents a second-order transgressive – regressive cycle. It contains a basal transgressive unit overlain by a regressive succession. The basal succession includes the Itararé Group and Rio Bonito and Palermo formations.

Botrychiopsis plantiana, recoverd from thick sandstone and siltstone strata, was recorded in the megafloras of the lower part of the Brazilian Gondwana succession, which comprises lowland glaciocontinental deposits of the Itararé Group (Millan

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1975, 1979, Cazzulo-Klepzig and Guerra-Sommer 1983, Zampirolli 2001).

The synonymization of distinct *taxa* to this morphogenus, which is characterized by heteromorphy, took place for more than a century (1844-1971) during which several Earth Science paradigms were established and abandoned, from the Fixist models to Plate Tectonics. The main studies that produced the current genus conception are presented in Fig. 1.

Studies of Archangelsky and Arrondo (1971) demonstrated the biogeographic and biostratigraphic importance of the genus in Gondwana successions. These sequences occur in Argentina (Sessarego and Césari 1986, Archangelsky et al. 1987, Archangelsky and Cúneo 1987, Andreis and Archangelsky 1996); Brazil (Millan 1975, 1979, 1987a,b, Rösler 1978, Guerra-Sommer and Cazzulo-Klepzig 1981, Guerra-Sommer and Cazzulo-Klepzig 1993); South Africa (Rayner 1985, 1986, Rayner and Coventry 1985, Anderson and Anderson 1985, Kovács-Endrödy 1991), India (Srivastava 1997) and Australia (Rigby 1973, 1993, Retallack 1980).

The paleofloristic assemblages show a homogeneous composition dominated by foliar organs of plants with arborescent habit as well as remnant shrub-like plants, such as *Botrychiopsis plantiana*.

Shrub-like plants identified as *Botrychiopsis plantiana* have also been recorded in the southernmost portion of the Paraná Basin, within the *Glossopteris* Flora and are associated with fluvial, delta and estuarine sedimentary rocks at the base of the Rio Bonito Formation (Pasqualini et al. 1986).

The presence of *Botrychiopsis* in Paleozoic Gondwana floras of the Paraná Basin has usually been associated with tundra and taiga environments (Archangelsky 1971, 1978, 1984, Rocha-Campos and Archangelsky 1985, Retallack 1980, 1999).

In their description of the *Glossopteris* Flora Early Permian evolution in Southern Brazil, Guerra-Sommer et al. (1991, 2001) regarded *Botrychiopsis plantiana* as a remnant plant from a rigorous periglacial cold climate.

The first records of *Botrychiopsis* within roof-shales in Southern Paraná Basin (Quitéria area), as discussed herein, allow to infer the relationship between the biostratigraphic distribution of this genus and its tolerance to climate changes. In this case, climate change has been associated with a deglaciation phase of an icehouse period and is represented by an evolution from cool-temperate to warm-temperate climate. The validation of this hypothesis would then broaden the current parameters used to interpret the climatic conditions favorable for the development of these plants.

This paper comprises the first step of a larger project that aims to evaluate the chronostratigraphic significance of the *Botrychiopsis* within Gondwana. It was carried out to verify earlier taxonomic and biostratigraphic descriptions of *Botrychiopsis* forms of the Southern Paraná Basin. This revision was required due to the reduced nature of previous descriptions, which did not define the diagnostic differences between previously identified and original material.

REVIEW OF THE *Botrychiopsis* OCCURENCE IN SOUTHERN PARANÁ BASIN

Forms related to *Botrychiopsis* have been identified in Rio Grande do Sul State in Faxinal, Base of Morro Papaléo and Quitéria outcrops (Fig. 2).

The Faxinal outcrop, described by Morgenthal et al. (1970) and later by Andreis et al. (1979), is located in the northeastern portion of the Barão do Triunfo topographic Sheet, close to the confluence of the Grande and Faxinal creeks, about 10 km west-northwestward from the Mariana Pimentel District.

The exposure includes variable amounts of sandstone and mudstone related to the uppermost part of the Itararé Group in the Rio Grande do Sul State. It represents the westernmost exposure of a paleovalley that extends from Potreiro Grande, 4 kM eastwards from the Mariana Pimentel District.

Andreis et al. (1979) recognized two informal siltstone facies (white and grayish brown siltstone facies). Isolated *Rubidgea*-type leaves, *Botrychiopsis* fronds and small platispermic seeds represent most of the quantitatively poor megafloristic association. Minor amounts of the *Cordaites*, *Glos-*

Taxa	**Quotation**	**Author**	**Year**
Botrychiopsis weissiana	*Botrychiopsis weissiana*	Kurtz	1895
	Botrychiopsis weissiana	Kurtz	1921
	Adiantites (?) *robustus*	Wallkom	1934
	Cardiopteris cf. *frondosa*	Wallkom	1934 (?)
	? *Noeggerathia* sp.	Wallkom	1934 (?)
	Botrychiopsis weissiana	Kurtz & Frengüelli	1944
	Gondwanidium plantianum	Gerth & Frengüelli	1944
	? *Adiantites* sp.	Frengüelli	1946
	Gondwanidium plantianum	Gerth & Frengüelli	1946
	Botrychiopsis weissiana	Archangelsky & Arrondo	1971
Botrychiopsis plantiana	*Odontopteris plantiana*	Carruthers	1869
	Neuropteridium validum	Feistmantel & Kurtz	1895
	Neuropteridium validum	Feistmantel & Seward	1903
	Neuropteridium validum	Feistmantel & Arber	1905
	Neuropteridium plantianum	White	1908
	Neuropteridium plantianum	Lundqvist	1919
	Neuropteridium validum	Feistmantel & Kurtz	1921
	Neuropteridium validum	Kurtz	1921
	Neuropteridium plantianum	Dolianiti	1953
	Botrychiopsis plantiana	Archangelsky & Arrondo	1971
	Gondwanidium plantianum	Rigby	1973
Botrychiopsis valida	*Otopteris ovata*	Mc'Coy	1847
	Neuropteris valida	Feistmantel	1876
	Neuropteris valida	Feistmantel	1879
	Neuropteridium validum	Feistmantel	1880
	Godwanidium validum	Gothan	1927
	Gondwanidium validum	Gothan	1941
	Gondwanidium validum	Gothan	1966
	Botrychiopsis valida	Archangelsky & Arrondo	1971
	Botrychiopsis ovata	Gould	1976
	Botrychiopsis ovata	Rettalack	1980

Fig. 1 – Current *Botrychiopsis* genus conception.

sopteris, *Gangamopteris* and *Ginkgoites* genera as well as articulate stems and conifer branches are also present.

According to Andreis et al. (1979) both white and grayish brown facies represent the final filling stage of large lakes, and considered then as related to the end of the Itararé Group sedimentary cycle (Corrêa da Silva 1970 and Bossi and Piccoli 1979).

According to Milani et al. (1998), these sediments correspond to lowland glaciocontinental sediments, deposited during the deglaciation produced by warming of a glacial climate.

The specimens hereby presented were previously studied by Guerra-Sommer et al. (1980) and Cazzulo-Klepzig and Guerra-Sommer (1983) and are stored (samples PB 3097 e PB 3098) in the Paleobotanic Sector of the Earth Sciences Institute of the Federal University of the Rio Grande do Sul State (UFRGS).

Samples from Faxinal include basal fragments

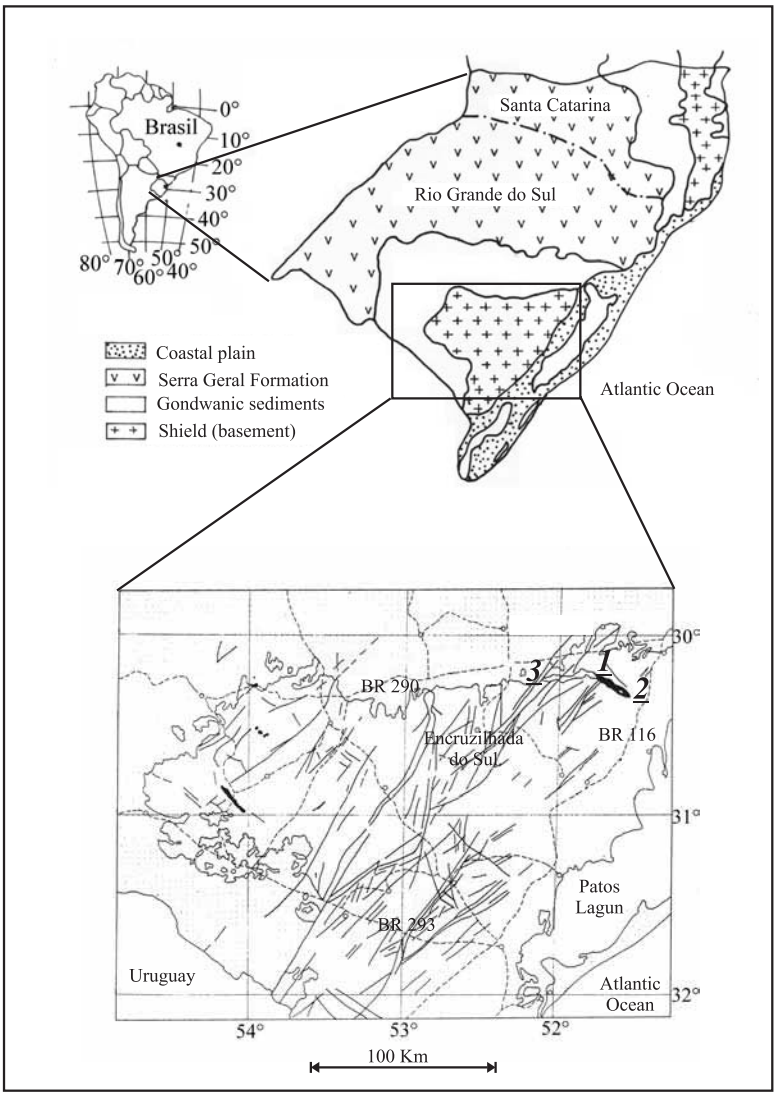

Fig. 2 – Localization of the Faxinal (1), Base of Morro Papaléo (2) and Quitéria (3) outcrops.

of long bipinnate fronds (3,9 to 8,2 cm long and 0,6 to 2,9 cm wide). They present a main robust rachis, between 0,6 cm (proximal part) and 0,2 cm (distal portion) wide, which features a solid longitudinal nervure (Fig. 3b). From the widely decurrent (Fig. 3e), separated (Fig. 3f) to slightly imbricated (Fig. 3b) rachis, minor sessile pines displaying complete limbus emanate with a somewhat acute angle of insertion (50˚ a 70˚). The pines outline is subcircular and either smooth (Fig. 3f) or showing small insertions (Fig. 3a,b, and d). These insertions originate their bipinnate aspect, with pines ranging from oblong and rhomboidal at their base (Fig. 3e and f) to oblong-elliptical or elliptical at their apex (Fig. 3a), being 0,4 to 3,2 cm long and 1,1 to 1,4 cm wide. These pines present an open venation, derived from the rachis nervures, which is denser at its base and that disperses along the pinnules (Fig. 3a,b,c and d). As the nervures go along the pinnules they suffer dichotomy, which can occur twice or four times (Fig. 3a). Pinnules are strongly decurrent and the more developed ones are free down to their base and

may present an asymmetrical, subcircular to slightly oblong outline.

The associated microflora, composed of trilete spores (75%) and monosaccate pollen (15%), rare bisaccate and striate pollens, was related by Andreis et al. (1979) to the H1/H2 biostratigraphic interval of Daemon and Quadros (1970). It corresponds to the upper part of the *Potonieisporites-Lundbladispora* Zone proposed by Archangelsky and Marques-Toigo (1978) for the Chaco-Paraná Basin (Argentina). According to Andreis et al. (1979), this interval is equivalent to either the Stephanian C – Sakmarian boundary or, according to Faddeieva (1976), to the base of the Asselian in Russia.

The outcrop Base Morro Papaléo is situated in the Barão do Triunfo topographic sheet (SH-22-0-1-2), 8 Km northwestward of Mariana Pimentel. It is located in a ravine on the lower part of the southwestern border of the Morro Papaléo (UTM 0438317 E and 6647584 N).

This outcrop, described by Pasqualini et al. (1986), comprises an alternation of carbonaceous, fossiliferous siltstone, mica-rich, fine-grained sandstone, lenticular, coarse-grained sandstone and conglomerate, and sandstone exhibiting iron-rich concretions. Plane bedded siltstone and sandstone and cross-bedded sandstone are common sedimentary features.

Pasqualini et al. (1986) related the fossiliferous beds to the bottom of efemerous water bodies associated with the margins of interdistributary lakes.

The taphoflora is mostly composed of glossopterids with pinnate venation (*Glossopteris communis*, *Glossopteris indica*) and *Botrychiopsis plantiana* associated with articulates (*Phylloteca indica*) and conifers (*Buriadia isophylla*). *Gangamopteris* sp., *Glossopteris angustifolia*, *Cordaites* and protoglossopterids (*Rubidgea obovata*) occur as minor elements.

Some specimens formerly described by Pasqualini et al. (1986) were analyzed herein, as well as others stored in the Paleobotanic Sector of the Earth Science Institute at UFRGS.

The samples comprise basal and medial-basal fragments of elongated and bipinnate fronds (3,8 to 9,0 cm long and 0,6 to 7,9 cm wide). They present a robust main rachis, with strong longitudinal nervures, which can be 0,9 cm wide at its proximal portion and disperse at the more distal pines (Fig. 3b). In a subordinate way, and showing somewhat acute insertion angles (50° to 70°), sessile, widely decurrent to pseudopetiolate pines emanate from the rachis. They change from isolated to slightly imbricated, show complete limbus, and can either present or lack insertions on their borders, therefore producing their bipinnate aspect.

The pines from the basal portions of the fronds are decurrent and separated (Fig. 3e) to fairly imbricated (Fig. 3b). They can present rhomboidal (Fig. 3e), rhomboidal-ovoid (Fig. 3f) or rhomboidal-elongated (Fig. 3b) outlines with no insertions. They are 0,8–1,8 cm long and 1,3–1,8 cm wide. These pines present an open venation, derived from the rachis nervures, which is denser at its base, disperses at the apex and can dichotomize twice to three times.

The pines from the medial-basal portions of the fronds are rather imbricated and change from extensively decurrent to pseudopetiolate. They present either an elliptical-elongated or oblong-elliptical outline that can display slight to strong insertions on their borders. In this latter case a bipinnate morphology is produced and the lobes correspond to the pinnules. The pine length spans from 0,7 to 5,4 cm and their width between 0,9 and 2,8 cm. They present an open venation, derived from the rachis nervures, which is denser at its base and more disperse along the pinnules. As the nervures go along the pinnules they suffer dichotomy, from twice to four times. The pinnules are strongly decurrent and the more developed ones are free down to their base. They always present an asymmetrical outline that can be subcircular to slightly oblong (Fig. 3).

One of the samples (PB 2575), previously described by Guerra-Sommer et al. (1986), presents the central axis of the plant perpendicularly positioned relative to the bedding planes and from which four fronds radiate (3,3 cm long and 1,8 cm wide)

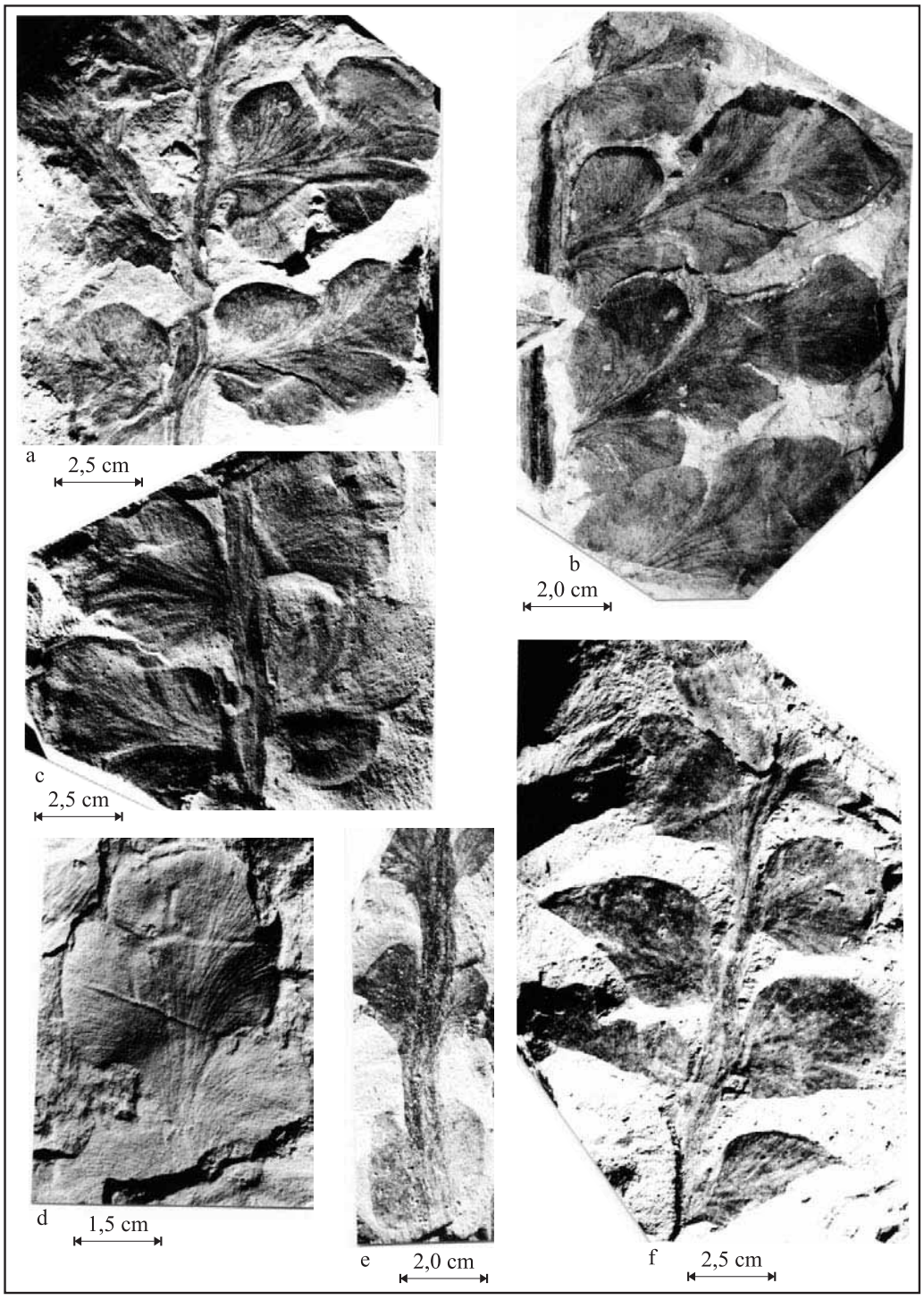

Fig. 3 – *Botrychiopsis plantiana* fronds from Faxinal and Base of Morro Papaléo: (a) apical portion of the frond with pines whit complete limbus, presenting small insertions and venation - PB 2677; (b) detail from the average portion of a frond – PB 2935; (c) detail from pines and it insertion in the rachis – PB 3009; (d) detail of a pine with venation – PB 3097; (e) basal portion of the frond – PB 2679; (f) basal portion of the frond, representing the morphological differentiation – PB 2499.

and a rachis (0,6 cm wide) with strong longitudinal nervures. From the rachis subaltern, separated, sessile, extensively decurrent pines emanate, exhibiting entire limbus, slightly acute insertion angles (50° a 70°) and a reniform morphology. These pines are 0.6 cm long and 1.3 cm wide and show venation derived for the rachis nervures. Venation is open, denser at its base (dispersing towards the apex) and can dichotomize twice to three times.

Samples from Base of Morro do Papaléo lack spores and pollen probably due to non-preservation.

The Quitéria outcrop is located in the Pantano Grande County (Rio Grande do Sul State), in the southeastern border of the Paraná Basin (UTM 0387516 E and 6643183 N). It is about 130 km from Porto Alegre, along the BR 290 freeway, and can be localized in the Quitéria topographic sheet (SH22-NH). It comprises a sedimentary package about 8 meters thick, characterized by the intercalation of carbonaceous shale, argillite, fine- to coarse-grained sandstone, matrix-supported (silty to sandy) conglomerate and thin, up to 25 cm thick coal beds.

The fronds are preserved in a light-yellow, fine-grained sandstone bed (45 cm thick) that exhibits plane bedding and is situated immediately above a carbonaceous argillite bed. Both horizontal and in-situ lycophyte stems (*Brasilodendron*) occur in association with this level, as well as Coniferophyta, *Cordaites*, Filicophyta and scattered fragments of glossopterids (*Rubidgea* sp. and *Glossopteris* sp.).

Piccoli et al. (1991) related the sedimentary succession to a delta system dominated by low-energy fluvial processes, with well-developed alluvial plain facies and peat-forming swamps in the interdistributary lowlands.

Based on specific features, mostly those related to lycophyte specimens of the *Brasilodendron* genus, and previous regional stratigraphic studies (Menezes 1994, Chaves et al. 1994, Della Fávera et al. 1994, Holz 1995, Lopes and Lavina 1995, Holz 1997) Jasper and Guerra-Sommer (1999) suggested a barrier-lagoon system (and associated washover fans), similar to the model formulated by Reison (1992).

The samples are stored in the Botany and Paleobotany Sector of the UNIVATES Natural Sciences Museum and in the Paleobotany Sector of the DPE/UFRGS.

The samples from Quitéria include basal and medial-basal fragments of elliptical, elongated and bipinnate fronds (3,5 to 11,6 cm long and 0,4 to 5,1 cm wide). They present a robust main rachis (0,1 to 0,9 cm thick) that encompasses strong longitudinal nervures (Fig. 4 and Fig. 5a) from which sessile pines in a sub-opposite trend emanate with slightly acute insertion angles (60° to 80°). These pines are decurrent to extensively decurrent, separated to slightly imbricated, and present complete limbus, with (bipinnate morphology) or without insertions on their borders.

The pines of the frond basal portions are widely decurrent and either separated (Fig. 4b and d and Fig. 5c) or slightly imbricated (Fig. 4a and c and Fig. 5a). They present a rhomboidal (Fig. 4d and Fig. 5c), rhomboidal-elongated (Fig. 4c and Fig. 5a), rhomboidal-widened (Fig. 4a) or reniform outline (Fig. 4b and Fig. 5b) on which insertions are sometimes observable (Fig. 4 and Fig. 5). Pines are 0,4 to 1,1 cm long and 0,8 to 2,5 cm wide. Pine venation, derived from the rachis nervures, is open, denser towards its base and disperse at its apex, and dichotomize twice to four times (Fig. 4 and Fig. 6).

The pines of the medial-basal portions of the fronds are slightly imbricated and vary from decurrent (Fig. 6b) to extensively decurrent (Fig. 6a). They present an elliptical or elliptical-elongated outline and can present insertions (bipinnate morphology) on their borders (Fig. 6d). Their lengths vary from 0,5 to 5,0 cm and their width from 0,7 to 2,8 cm. These pines display an open venation, derived from the rachis nervures, which is denser at its basal and central portions and disperses along the pinnules. As the nervures go along the pinnules they dichotomize twice to four times (Fig. 4 and Fig. 6). Pinnules are strongly decurrent and the more developed ones are free down to their base, presenting a subcircular to elliptical-elongated outline.

A palynological study on samples collected in

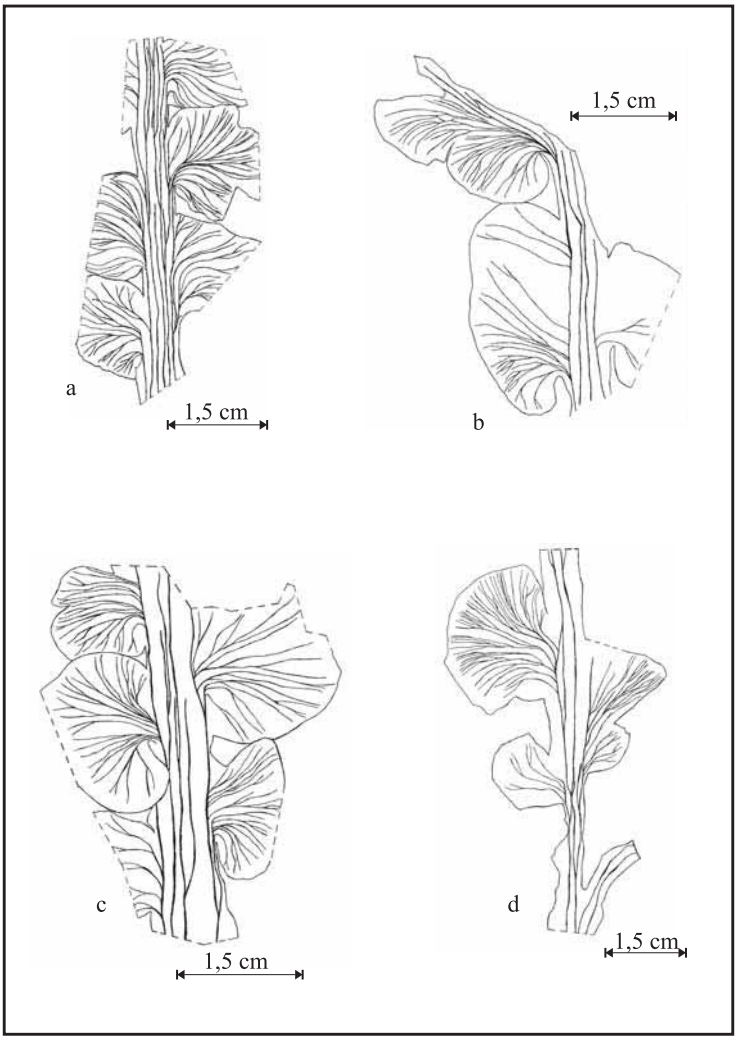

Fig. 4 – *Botrychiopsis valida* fronds from Quitéria. (a) middle portion of a frond with pines, showing the venation of the rachis, the insertion of the pines in the rachis and is venation – PbU 0281; (b) middle portion of the frond with complete limbus presenting small insertions and the venation of the rachis and pines – PbU 0233; (c) basal portion of the frond with the insertion of the pines and venation – PbU 0252; (d) basal portion of the frond with the insertion of the pines and venation – PbU 0062.

coalbeds of Quitéria outcrop has shown the presence of well preserved, abundant and diverse microflora. It is mainly composed of trilete spores, 70% produced by pteridophytes, less frequent to rare Gymnospermae pollens, alga, acritarchs and *incertae sedis*. Zonati and Cingulicavati spores, related to herbaceous and shrub-like Lycophyta, mainly represented by the genera *Lundbladispora*, *Vallatisporites*, *Cristatisporites* and *Kraeuselisporites*, are the dominant elements. Apiculati and Murornati spores were less common and point to the presence of Filicophyta and Sphenophyta and are represented by forms linked to the *Punctatisporites*, *Calamospora*, *Leiotriletes*, *Deltoidospora*, *Murospora*,

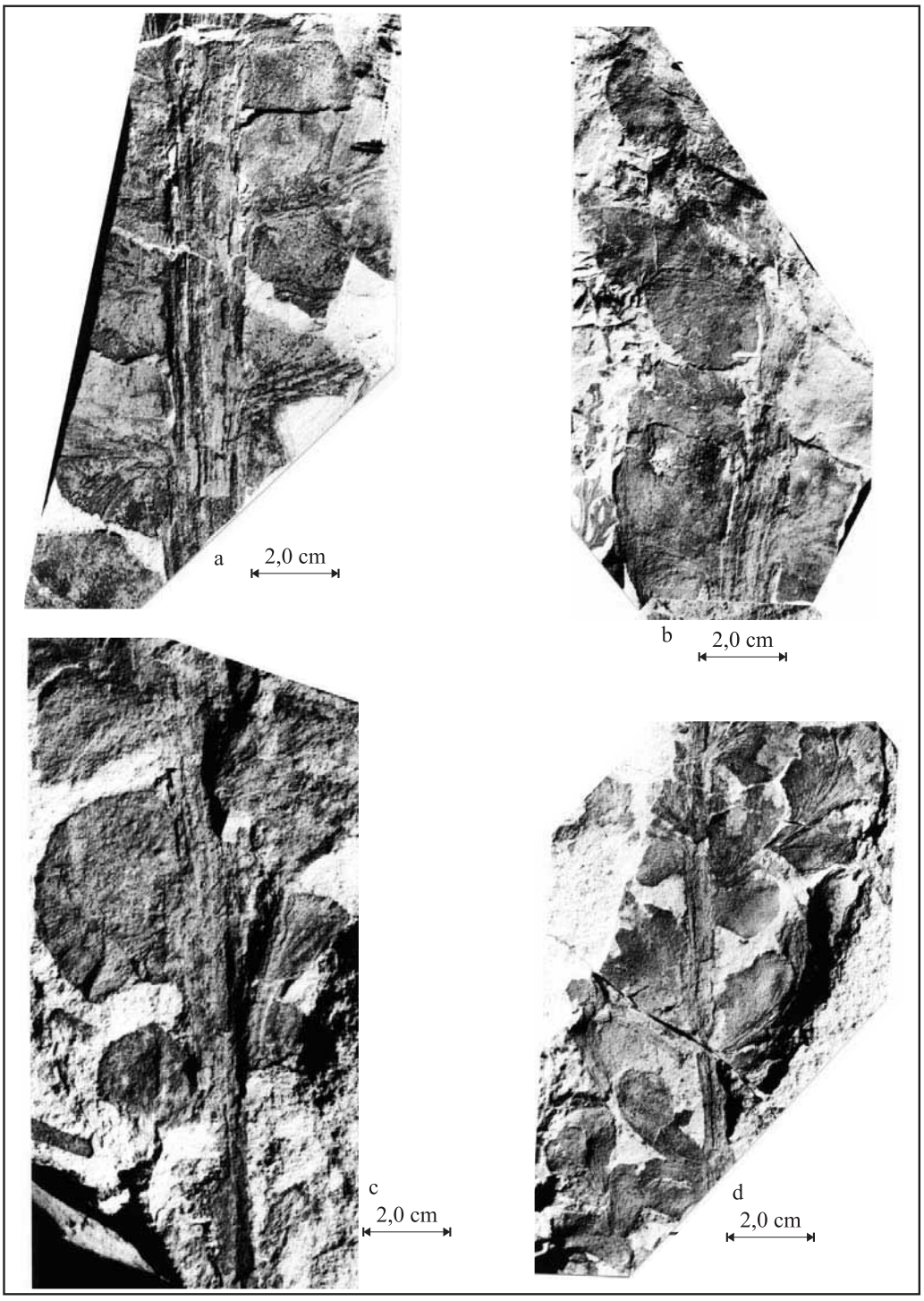

Fig. 5 – *Botrychiopsis valida*.fronds from Quitéria (a) detail of the middle portion of a frond with pines and it insertion in the rachis – PbU 0281; (b) middle portion of the frond with complete limbus presenting small insertions and venation – PbU 0233; (c) basal portion of the frond with the insertion of the pines – PbU 0062; (d) apical portion of the frond with pines presenting a complete limbus with insertions and venation – PbU 0061.

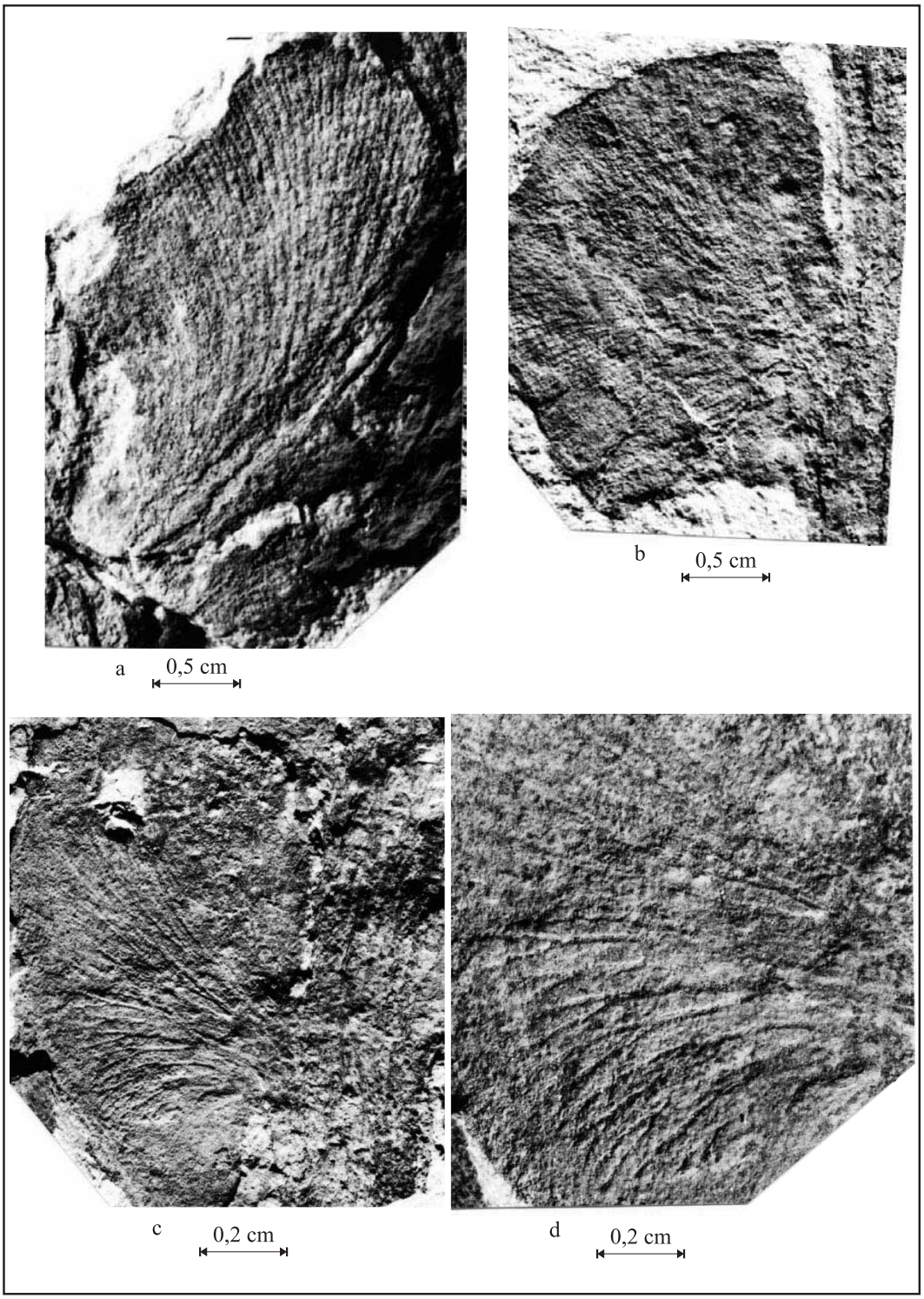

Fig. 6 – Details of pines of *Botrychiopsis valida* from Quitéria (a) detail of an apical pine with venation – PbU 0061; (b) detail of a basal pine – PbU 0062; (c) detail of a pine with venation – PbU 0233; (d) detail of venation of a basal pine, showing venation dichotomy – PbU 0062.

Apiculatisporis, *Granulatisporites*, *Cyclogranisporites* and *Convolutispora* genera.

Monosaccate pollen (*Plicatipollenites*, *Caheniasaccites*, *Potonieisporites* and *Cannanoropollis* genera) is less common and indicates the occurrence of Cordaitophyta. On the other hand, bisaccate pollen, such as *Scheuringipollenites*, *Vesicaspora* and *Limitisporites*, is related to Glossopteridophyta.

The identified striated pollen specimens have a botanical affinity with Coniferophyta, such as *Protohaploxypinus*, *Vittatina* and *Lunatisporites*. Monolete spores are rare and essentially represented by forms of *Cycadopites*.

Due to the predominance of species related to Zonati and Cingulicavati spores the palynoflora is comparable, in the Paraná Basin, to the microfloristic association identified in the Candiota Superior and Banco Louco beds in the Candiota Coalfield by Meyer (1999).

Among the spore-pollinnic associations proposed by Marques-Toigo and Corrêa da Silva (1984) for the coal measures of the Rio Grande do Sul State, this type of palynoflora is comparable to the *Puntatisporites*, *Lundbladispora* and *Portalites* Association, which is related to plants of hydrophylous to hygrophilous environments.

In terms of biostratigraphy, the microflora identified in the Candiota Upper Coal Seams was included in the *Caheniasaccites ovatus* Zone of Marques-Toigo (1988) – Artinskian/Kungurian. Based on isotopic dating of tonstein beds interbedded in the coal seams, Cazzulo-Klepzig (2001) linked this zone to Late Kungurian/Early Roadian age.

Palynological analyses on samples from Quitéria confirm its correspondance with the *Caheniasaccites ovatus* biozone (Kungurian/Early Roadian).

TAXONOMIC AFFINITIES

In this chapter, the taxonomic affinities of the previously described material (Faxinal, base of the Morro Papaléo and Quitéria) are re-evaluated.

The morphological features of the studied specimens indicate affinities with the *Eusphenopteris* Novik (1947) and *Botrychiopsis* (Kurtz) Archangelsky and Arrondo (1971).

The *Eusphenopteris* Novik (1947) genus is characterized by a bipinnate frond, with alate rachis and alternated pines. These pines show a poorly defined rachis as the pinnule limbus presents decurrent spreading. Pinnules are trilobate and deeply incised, with an open, dichotomized venation that arises from a central nervure starting from the rachis. Within Carboniferous Gondwana successions these forms have been considered intermediate between *Botrychiopsis* and *Dactylophylum* (Zampirolli 2001). In Western Gondwana this genus was recorded by Cúneo (1990), in the Mojón de Hierro Formation (Upper Paleozoic Tepuel Group), Arroyo Garrido area (Chubut Province of Argentina). It was also found by Zampirolli (2001), in the Santa Marta Farm (Itapeva region in the São Paulo State), within Neo-Carboniferous interglacial rocks (Itararé Subgroup of the Paraná Basin).

Based on previous studies (Archangelsky et al. 1987, Archangelsky and Cúneo 1991, Iannuzzi 1994, Ricardi 1994, Iannuzzi et al. 1998), Iannuzzi and Rösler (2000) have stated that the *Eusphenopteris* genus was a rare component of the *Archeosigillaria/ Lepidondrops/ Frenguellia*, Euroamerican and Northern *Rhacopteris Nothorhacopteris* floras, although common in the Southern *Nothorhachopteris* Flora, during the Carboniferous.

Among the main features of the *Eusphenopteris* genus are its tripinnate frond with trilobate pinnules, deeply incised margins and subtriangular outline, showing an open and dichotomized venation that arises from a single and thick nervure going into the pinnules from the rachis. Although presenting an open and dichotomized venation in the pinnules, the studied material does not show all other features of the *Eusphenopteris* genus.

The morphology of the analyzed material points towards the *Botrychiopsis* (Kurtz) Archangelsky and Arrondo (1971).

A review of Paleozoic fronds related to *Botrychiopsis*, taking into account not only morpho-

logical and taxonomic data, but also stratigraphic implications, was presented by Archangelsky and Arrondo (1971). The authors, based on Argentinean material and relating it to Gondwana and extra-Gondwana data, confirmed Kurtz's (1895a, b) original interpretations. A new diagnosis was defined and the concepts of frond, pines and pinnules were reviewed. Furthermore, descriptive features diagnostic of the following three species were presented: *Botrychiopsis weissiana* (Kurtz) Archangelsky and Arrondo (1971), *Botrychiopsis plantiana* (Carruthers) Archangelsky and Arrondo (1971) and *Botrychiopsis valida* (Feistmantel) Archangelsky and Arrondo (1971), the latter only compared with the Upper Paleozoic of India. According to Archangelsky and Arrondo (1971) the different species present a wide geographic distribution and clear chronostratigraphic boundaries that allow some phylogenetic assumptions in terms of an ascendancy of *Botrychiopsis weissiana* in relation to *Botrychiopsis plantiana*, and of this one to *Botrychiopsis valida*.

Cúneo (1990) confirms the genus features pointing out that the pines are arranged in a slightly subopposite way, with a rachis that goes to the base of the apical pinnule. Furthermore, pines are lobate with deccurent insertions, its venation is open and can be dichotomized up to three times.

In this study, both generic and specific propositions of Archangelsky and Arrondo (1971) are accepted. A pteridophytic or pteridospermic affinity has been proposed for this genus.

Considering the original diagnosis of Kurtz (1895a,b), emended by Archangelsky and Arrondo (1971), *Botrychiopsis weissiana* presents some features that were not seen in the studied samples of the Faxinal and Base of Morro Papaléo outcrops. The morphological characters of *Botrychiopsis weissiana* include an alate basal portion of the frond, a twisted insertion of the pines with a pronounced imbrication, and an ovoid-spatulated morphology of the frond apical pinnule.

Similarly, it is not possible to correlate the studied samples with *Botrychiopsis valida*. In Feistmantel's (1879) previous description, also emended by Archangelsky and Arrondo (1971), this species presents divided basal frond pinnules, confluent along the entire frond and presenting subrhombic morphology with sinuous margins. These characteristics are not present in the studied samples.

The main morphological features of this material are apical, medial and medial-basal fragments of the pines. The pines have long and bipinnate fronds presenting a robust main rachis that can disperse in the distal pines. The rachis presents strong longitudinal nervures from which minor sessile pinnules radiate displaying slightly acute insertion angles (50° to 70°). The pinnules are generally decurrent to pseudopetiolate, separated to slightly imbricated, presenting entire limbus with or without insertions on their borders. They may assume a sublobate morphology, from rhomboidal, rhomboidal-ovaled or rhomboidal-elongated to elliptical, elliptical-elongated or oblong-elliptical morphology. They present an open venation derived from the rachis nervures, which is denser at their base and disperse along their limbus, which can dichotomize twice to four times. These elements link this material to *Botrychiopsis plantiana* (Archangelsky and Arrondo 1971).

This conclusion is reinforced by comparative analysis of the samples discussed herein and the specimens shown by Archangelsky and Arrondo (1971, Slide V, Fig. 1 and 2, Slide VI, Fig. 1, 2 and 3) and their diagnoses.

This review also confirms the designations of Guerra-Sommer et al. (1980), Cazzulo-Klepzig and Guerra-Sommer (1983) and Pasqualini et al. (1986).

Botrychiopsis valida

The Quitéria frond samples were not correlated to *Botrychiopsis weissiana* due to the lack of some critical morphological features, such as the basal portion of the alate frond, the twisted insertion of the pines displaying heavily delineated imbrication and the ovoid-spatulated morphology of the frond apical pinnules.

On the other hand, the Quitéria forms can not be associated with *Botrychiopsis plantiana* due to

the absence of characteristics such as the connected to slightly imbricate pinnules of the frond base and the spatulate shape with the rounded distal margin of the apical pinnules.

However, these specimens can be correlated to another species, *Botrychiopsis valida*, taking into account the material described by Feistmantel (1880), Archangelsky and Arrondo (1971), Rigby (1973), Anderson and Anderson (1985) Gould (1975), Retallack (1980), Rayner (1995), Rigby (1985) and Archangelsky and Cúneo (1981).

The pines and pinnules morphology along the fronds supports the identification of the Quitéria material with *Botrychiopsis valida*. Among the main features used for its identification the presence of a robust and well-defined main rachis can be considered, with solid longitudinal nervures, from which subopposite sessile pinnules emanate with slightly acute insertion angles (60˚ to 80˚). These pinnules are extensively decurrent to decurrent, separated to slightly imbricated, and have entire limbus presenting, or not, insertions on their borders.

Furthermore, the decurrent aspect of the separated basal pines, with rhomboidal, elongate-rhomboidal or reniform outline, are very similar to the material previously related to *Botrychiopsis plantiana* by Gould (1975, Fig. 3C and D) and later on to *Botrychiopsis valida* by Retallack (1980).

Some other aspects also evidence the association of the specimen hereby analyzed to *Botrychiopsis valida*, largely by comparison with the material described and synonymized by Archangelsky and Arrondo (1971) as well as that identified by Rigby (1973), Anderson and Anderson (1985), Gould (1975), Retallack (1980) and Rayner (1995). Among these evidences, the presence of slightly imbricate, highly decurrent to decurrent pinnules with elliptical or elongated-elliptical outline and sub-lobate border insertions was observed. The pinnules present an open venation, derived from the rachis nervures, denser at their basal and central portions and dispersing along the upper portions of the pinnules, which dichotomize twice to four times (similar to the basal pinnules).

Botrychiopsis valida was previously described as *Neuropteris valida* by Feistmantel (1876) within Eopermian sedimentary successions of India. Later, Feistmantel (1879, 1880) again mentioned the same species, also within Indian sedimentary rocks. Gothan (1927) registered the presence of *Gondwanidium validum* in the Serra de los Llanos (Argentina). Archangelsky and Arrondo (1971) synonymized all these specimens to *Botrychiopsis valida*, stressing that this species was restricted to India. In their specific description, Archangelsky and Arrondo (1971) highlight that the frond base presents well-defined, subcircular to slightly elongated and clearly separated pinnules with a large insertion base. The pines present normal insertions and vary from slightly imbricate to united. The highest number of pinnules per pine (up to 5 cm long) is five. The usual insertion angles range from 70˚ to 80˚. All pinnules are convergent, the apical ones presenting a subrhombic morphology with sinuous margins. According to Archangelsky and Arrondo (1971), another important aspect of this species is the presence in the medial portions of the frond of just produced pines. These pines present fused pinnules at their base and free ones at their apical portions. Similar features are reported by Anderson and Anderson (1985, pl. 167, Fig. 2) and can be seen in the material presented herein. However, Retallack (1980) considered the designation of *Botrychiopsis valida*, defended by Archangelsky and Arrondo (1971), as *nomen vanum* and sinonymized to *Botrychiopsis ovata* (Mc'Coy). Retallack (1980) also states that the specimen classified as *Botrychiopsis plantiana* by Gould (1975, Fig. 3C, D) should also correspond to the *Botrychiopsis ovata* species. Later, Rigby (1985) suggests, keeping the *Botrychiopsis ovata* species, including in this species other taxa such as *Otopteris ovata* Mc'Coy (1847, p. 148; pl. IX, Fig. 2), *Aneimites austrina* Etheridge (1888, p. 1304; pl. 37), *Cardiopteris polymorpha* in White (1969a,b; p. 98; plates A and B, Fig. 1), *Gondwanidium plantianum* in Rigby (1973, p. 4-5; plate 1, Fig. 2 and plate 2 Fig. 3), *Triphyllopteris austrina* in Morris (1975, p. 104; pl. 8.1c, Fig. 8.1 and 8.4

k, u), *Botrychiopsis* in Retallack (1980, p. 394-395; Fig. 21.3 E-G) and *Otopteris ovata* in Archangelsky (1983, p. 161-163; pl. 1-3).

Even so, in this paper the designation *Botrychiopsis valida* is maintained in accordance with Archangelsky and Arrondo (1971) criteria.

THE BIOSTRATIGRAPHIC IMPLICATIONS OF THE *Botrychiopsis* GENUS IN SOUTHERN PARANÁ BASIN

The *Botrychiopsis* genus was proposed by Kurtz (1895a,b), based on Carboniferous material of the Rio Jejenes Formation (San Juan Province, Argentina). Similar forms, previously recorded by Frengüelli (1944, 1946, 1954) under other denominations, were identified by Archangelsky and Arrondo (1971) as *Botrychiopsis weissiana*.

According to Archangelsky and Arrondo (1971), the description of distinct biocrons for the species of the *Botrychiopsis* genus highlights not just its phylogenetic relationship but also its chronostratigraphic importance. The phylogenetic associations come from the *Botrychiopsis weissiana* and *Botrychiopsis plantiana* sequential record within Argentinean Gondwana associations. Forms related to *Botrychiopsis valida* would also be descended from *Botrychiopsis weissiana* developed in distant areas, hence differentiating from the Western Gondwana coeval forms. Based on these evidences and the inferences of Gothan and Sahni (1937), it seems that the group development occurred from an ancestral stock identified in Peninsular India and Australia Namurian successions.

However, some aspects of this evidence, such as the presence of *Botrychiopsis weissiana* and *Botrychiopsis plantiana* as coeval elements within Argentinean Paleozoic floras (Archangelsky and Azcuy 1985), suggest the need of re-evaluating presupposed phylogenetic relations. Although these data support the idea that the specific relations should be reviewed, studies on distinct basins have confirmed the stratigraphic importance of the different morpho-species.

In a first inference to the *Botrychiopsis* chronostratigraphic impact Archangelsky and Arrondo (1971) indicated a time span from Upper Carboniferous (Westphalian) to Lower Permian (Artinskian) for the genus. The *Botrychiopsis weissiana* biochron was restricted to the Carboniferous System (Tupense local age – Westphalian/Stephanian of Western Europe). This geochronological position was corroborated by marine invertebrates (Antelo 1972) and palynology (Menéndez 1965).

Botrychiopsis plantiana is linked to the earliest Conifers and Ginkgoales occurrences in the Trampeadero and Libertad formations (Paganzo Basin), in Upper Carboniferous sequences of Trampeaderense local age.

The record of *Botrychiopsis plantiana* in the Nueva Lubecka Formation, referred to the Lubekense A/B (Sakmarian/Artinskian), according to palynological and marine invertebrates (Antelo 1972), is considered as a Carboniferous relict.

Archangelsky and Arrondo (1971) considered *Botrychiopsis valida* as exclusive to Indian successions (Kaharbari Formation). The age interval was attributed to the Artinskian through the analysis of marine invertebrates (Robison 1967), hence comprising the youngest species of the genus (Archangelsky and Arrondo 1971).

In the Paraná Basin, Carruthers (1869) registered *Botrychiopsis plantiana* in coal-bearing strata, later named *Odontopteris plantiana*. White (1908) and Lundqvist (1919) designated the same form with the epithet *Neuropteridium plantianun*. Dolianiti (1948) named similar species found in the Itararé Group of the Rio Grande do Sul State (Acampamento Velho outcrop) as *Gondwanidium plantianum*.

In an attempt to characterize a Pre-*Glossopteris* Flora for Upper Paleozoic successions of the Northern Paraná Basin (Monte Mor outcrop – Itararé Group, São Paulo State), Millan (1975, 1979) pointed out *Botrychiopsis plantiana* as the diagnostic element. A Westphalian/Stephanian age was proposed for the succession based on palynological data (Trindade 1970). According to Iannuzzi (pess. comm. 2002), however, from the analysis of the

available type-material studied by Millan (1975, 1979), which is now kept in the Museu Nacional (UFRJ), it is impossible to establish the specific affinity of the material. Therefore, the specimens described by Millan (1975, 1979) remain here termed *Botrychiopsis* sp.

On the informal phytostratigraphic zonation of the Late Paleozoic Paraná Basin, Rösler (1978) recorded the presence of *Botrychiopsis plantiana* in Taphoflora A, relating it to the early stages of deglaciation in the Paraná Basin (Sakmarian/ Artinskian). Andreis and Archangelsky (1996), in a review of the Neopaleozoic basins of South America, related the Taphoflora A to a probable Stephanian age, taking into account the lack of the *Glossopteris* genus. According to Guerra-Sommer and Cazzulo-Klepzig (1981) the Itararé Group taphoflora in the Rio Grande do Sul State, including *Botrychiopsis plantiana*, can be related to the Cerquilho (Taphoflora A and B of Rösler 1978) and Argentinean Bajo de Veliz (Lubekense A) taphoflora.

Studies of Millan (1987a) on the megafloristic association of coal-bearing strata from Itapeva (São Paulo State) – the Santa Marta Flora of the Itararé Group – record a large amount of *Botrychiopsis plantiana* fronds and subordinate Sphenopsida (*Paracalamites*, *Sphenophyllum*), Cordaitales (*Cordaites*) and platispermics seeds (*Cordaicarpus*). An Itapevense local age was indicated for this association.

In an attempt to define floristic stages for coalbeds of the Itararé Group, Millan (1987b) correlated the Monte Mor Taphoflora (Montemorense Stage) to the Trampeaderense Megafloristic Zone of the Argentinean Paganzo Basin (Azcuy and Jelin 1980). This taphoflora is regarded as Westphalian/ Stephanian and correlated to the *Potonieisporites-Lundbladispora* Zone (Archangelsky and Césari 1986). According to Millan (1987b), *Botrychiopsis plantiana* is the leading element of the Itapevense Sub-Stage (Itapeva Flora). A Stephanian age for the Itapevense Sub-Stage was estimated by correlation with palynological data (Lima et al. 1976).

Zampirolli (2001) carried out a detailed review of the formerly described Santa Marta Taphoflora (Millan 1987a), using the same material that is now stored in the National Museum (Universidade Federal do Rio de Janeiro). In this review, in addition to *Botrychiopsis*, other important diagnostic elements have been included, such as *Sphenopteris* sp. and *Nothorhacopteris* cf. *argentinica*. Palynological data from the same strata are comparable with the *Ahrensisporites cristatus* Interval Zone of the Itararé Group lower portion (Zampirolli et al. 2000, Souza 2000). Taking in account mega- and microfloristic data, Zampirolli (2001) estimated a Westphalian age for the Santa Marta Flora. According to Zampirolli (2001) this association is comparable to the NBG Zone of Argentina (Middle to Late Carboniferous – Tupense – according to Archangelsky and Cúneo 1991).

In a study on the biostratigraphic importance of the upper Paleozoic taphofloras in Southern Paraná Basin, Guerra-Sommer and Cazzulo-Klepzig (1993) characterized some morphogenera as very important in terms of dating and correlation. In their attempt to establish paleofloristic associations based on observable boundaries of lithostratigraphic units, *Botrychiopsis plantiana* (recorded in the Faxinal and Francisquinho outcrops by Andreis et al. 1979) was regarded as one of the main elements related to the interval of deposition of the Itararé sequences in the Rio Grande do Sul State (Sakmarian).

Botrychiopsis plantiana remains a significant component of the Eopermian *Glossopteris* flora, then associated with *Glossopteris*, *Gangamopteris*, *Phyllotheca*, *Buriadia* (Pasqualini et al. 1986), which was related by Guerra-Sommer et al. (1986) to the basal sequences of the Rio Bonito Formation.

In a preliminary biozoning of the Southern Paraná Basin (Guerra-Sommer and Cazzulo-Klepzig 1993) the *Botrychiopsis plantiana* Zone was identified (Itararé Group and base of the Rio Bonito Formation) and related to the Sakmarian-Artinskian.

The main feature of the lower subzone (*Gangamopteris angustifolia*) is the predominance of *Botrychiopsis plantiana* associated with protoglossopterids (*Rubidgea obovata* and *Rubidgea lancio-*

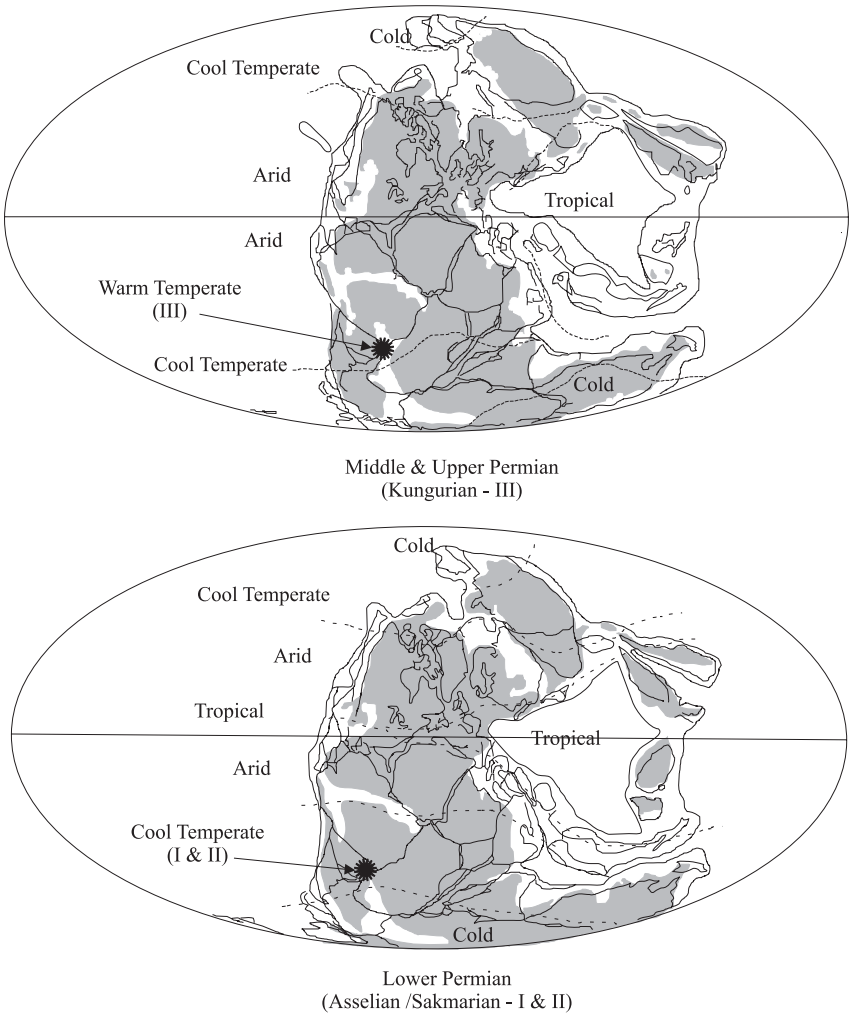

Fig. 7 – Palaeomaps of megafloristic associations in biomes at cold-cool, cool (I-II) and warm temperate (III) climates in the Lower and Midle/Upper Permian (Adapted from Scotese 2002).

latus) and the first glossopterids, mostly represented by *Gangamopteris* (*Gangamopteris obovata*, *Gangamopteris buriadica* and *Gangamopteris angustifolia*). *Glossopteris* (*Glossopteris communis* and *Glossopteris indica*) occur as complementary elements. The *Phyllotheca indica* Subzone comprises elements related to articulate (*Phyllotheca indica*) associated with *Glossopteris* (*Glossopteris communis*) and Conifers (*Buriadia isophylla*).

Recent data have shown that paleofloristic evolution in the Southern Paraná Basin during deposition of the Carboniferous – Early Triassic Megasequence was closely related to palaeoclimate, in addition to biostratigraphic and paleoecological controls (Guerra-Sommer et al. 2001). This assumption was confirmed by the evaluation of taphofloristic parameters from different biostratigraphic units.

The homogeneous composition of Early Permian (Sakmarian) wet lowland biomes, characterized by the *Glossopteris* flora and herbaceous to shrub-like plants considered to be relicts from a rigorous cold climate (*e.g. Botrychiopsis plantiana*), suggests the persistence of an ice age. The progressive colonization of the lowland clastic habitats by

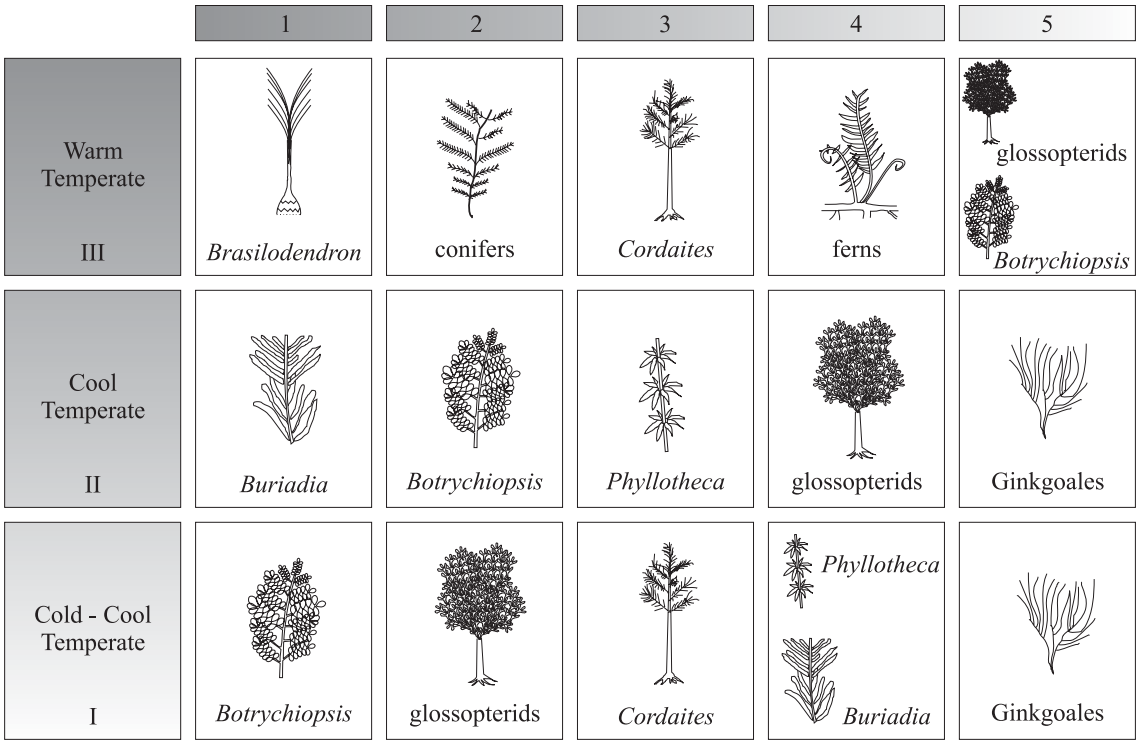

Fig. 8 – Megafloristic associations in biomes at cold-cool, cool and warm temperate climates in the Lower and Midle/Upper Permian in Southernmost Paraná Basin, Brazil. (1) Predominant; (2) Abundant; (3) Commom; (4) Less commom; (5) Rare. (I) Asselian wet biome; (II) Sakmarian/Artinskian wet biome; (III) Kungurian wet biome.

Cordaitales, Ginkgoales, Coniferales, in addition to the herbaceous articulates, indicates an Early Artinskian climate warming.

Glossopterids with pinnate venation and related to *Glossopteris* are common in Early Permian coal-bearing strata (Artinskian/Kungurian) whereas *Gangamopteris* (palmate form) is poorly represented. The sudden enrichment of filicoid fronds is characteristic of the landscape units in this stage. Arborescent lycophyte communities become important, associated with glossopterid-dominated communities. This event coincides with the waning of the Permian icehouse stage, which reached its peak around the Asselian/Sakmarian boundary.

The record of *Botrychiopsis valida* within coal-bearing megafloras in the Southern Paraná Basin, associated with Glossopterids (*Glossopteris*, *Gangamopteris* and *Rubidgea*), Filicophyta (*Rhodeopteridium*?), Conifers (*Buriadia* and *Ferruglio-cladus*?) and arborescent Lycophyta (*Brasilodendron pedroanum*), as presented herein, indicates a larger biogeographic distribution range of this genus in the Gondwana.

CONCLUSIONS

Botrychiopsis has been considered an important floristic element of Westphalian/Artinskian associations of the Paraná Basin. In the Southern Paraná Basin, several authors have related its occurrence to glacial-influenced environments. This genus has been recorded within associations related to a Permian glacier retreat (icehouse stage – Asselian/Kungurian). During the early deglaciation phases (cold/cool temperate climate), the *Glossopteris* Flora, linked to wet biomes, changed gradually. However, during the latest deglaciation stages, when a fast transition took place in the wet biomes

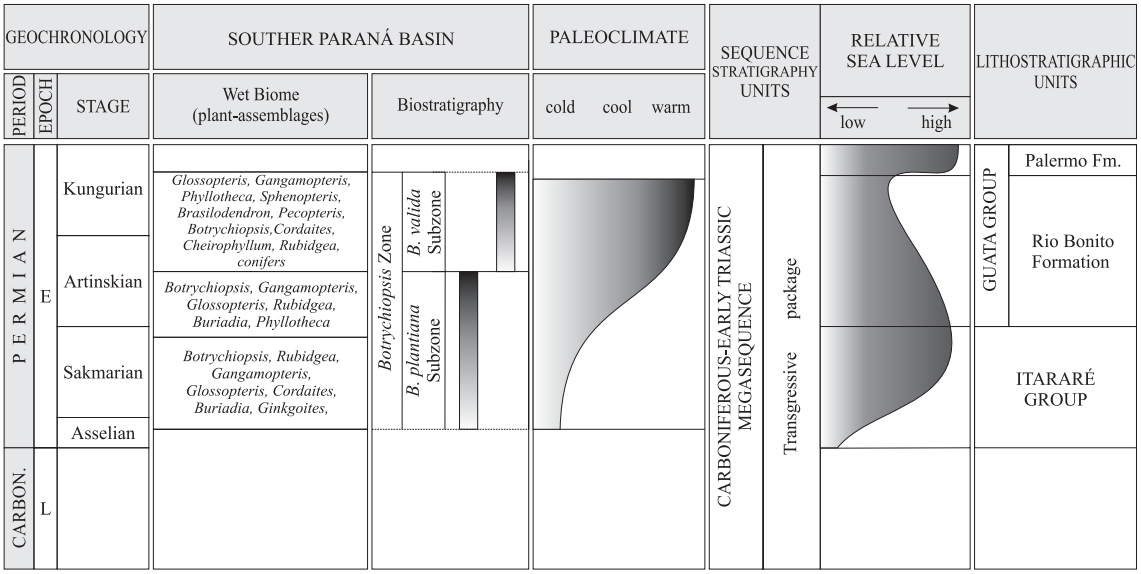

Fig. 9 – *Botrychiopsis* Zone and related plant-assemblages, palaeoclimate, sequence stratigraphy units, relative sea level and litostratigraphic units of Early Permian in Southern Paraná Basin, Brazil.

due to warming (warm temperate climate), in association with peat formation, the *Botrychiopsis* genus persisted, then represented by *Botrychiopsis valida*.

In the phytostratigraphie scheme presented by Guerra-Sommer and Cazzulo-Klepzig (1993), the *Botrychiopsis plantiana* Zone ranges from Sakmarian to Artinskian.

The new data here presented enlarge the *Botrychiopsis* genus biochron and define a stratigraphic hierarchy between *Botrychiopsis plantiana* and *Botrychiopsis valida*. In the Southern Paraná Basin, *Botrychiopsis plantiana* is restricted to Asselian/Artinskian and *Botrychiopsis valida* to Kungurian. It is also reported that the stratigraphic range of the *Botrychiopsis* genus in Southern Paraná Basin is related to a deglaciation stage (icehouse) and, therefore, to a wide climate range, from cold/cool temperate to warm temperate. Megafloristic association in biomes cold-cool, cool and warm-temperate climates were identified, in the Lower and Midle/Upper Permian in Southernwest Paraná Basin (Fig. 7 and 8).

A new phytostratigraphic scheme is proposed. It includes an Asselian/Artinskian *Botrychiopsis* Zone encompassing the Asselian/Artinskian *Botrychiopsis plantiana* and the upper Artinskian/Kungurian *Botrychiopsis valida* subzones (Fig. 9).

The Faxinal microflora associated with the *Botrychiopsis plantiana* Subzone suggests a Stephanian C/Sakmarian or lower Asselian age. The Quitéria microflora on the other hand, is related to the *Caheniasaccites ovatus* Zone (Kungurian to lower Roadian).

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RESUMO

O gênero *Botrychiopsis* tem sido considerado um elemento florístico importante das associações do intervalo Westphaliano/Artinskiano da Bacia do Paraná. O registro de formas relacionadas ao gênero *Botrychiopsis*, especificamente *Botrychiopsis valida*, em *roof-shales* na área de Quitéria, Formação Rio Bonito, no sul da Bacia do Paraná amplia o biocron do gênero, definindo uma hierarquia

estratigráfica para as espécies *Botrychiopsis plantiana* e *Botrychiopsis valida* para esta bacia. A distribuição estratigráfica do gênero está condicionada a controle climático relacionado a um ciclo de deglaciação em estágio *icehouse*, com espectro de tolerância climática abrangente, desde condições climáticas do tipo frio até temperado/quente. É proposto um novo zoneamento fitoestratigráfico para essa porção da bacia, incluindo uma Zona *Botrychiopsis* (Asseliano/Kunguriano) com duas sub-zonas *Botrychiopsis plantiana* (Asseliano/Artinskiano) e *Botrychiopsis valida* (topo do Artinskiano/Kunguriano).

Palavras-chave: *Botrychiopsis*, biostratigrafia, Bacia do Paraná, Permiano, paleoclimatologia, Gondwana.

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