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Lagoonal sediments with a singular phytofossiliferous association of Rio Bonito formation

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The Quiteria Outcrop (Encluzilhada do Sul, Rio Grande do Sul, Brazil) is an important paleontological site of the Upper Paleozoic from the South portion of the Paraná Basin, presenting singular fitofossiliferous registers with a great importance to understand the palaeoecological processes occurred in the mire systems of the Gondwana. The outcrop is divided in two levels, one inferior with a lot of organic mater and the other superior, clastic and rich in fossil plants. It can be observed the occurrence of a roof-shale level with the preservation of in situ arborescent lycophits, which dominated the association, bound with canopy forms, allowing infer stratification for the preserved system. Also, the area had preserved the first registers of charcoal for the Upper Paleozoic of the Parana Basin and it will confirm, if compared with other studied areas, a frequency in the occurrence of palaeo-wildfires during this period in landscapes associated to the coal formation in the basin.

Keywords: Upper Paleozoic; Parana Basin; lagunar system; roof-shale flora; in situ mega-flora; charcoal.

INTRODUCTION

The paleoflora preserved in the upper clastic level located above the fine layer of coal in the Quiteria outcrop provides a unique record of the conditions of the upper Paleozoic in the Paraná Basin. The outcrop is located in the rural area of the municipality of Encruzilhada do Sul in the Rio Grande do Sul state, in private property utilized at preset for the raising of extensive herds of cattle. Until the decade of the 1990s, the area was used for the open pit mining of kaolin, but this practice was abandoned after extraction became economically unfeasible. The preservation of the site depends solely on the actions of the owner. The amateur nature of the mining operation, including the use of inadequate machinery and non-specialized workers, led to the exposure of the layers of phytofossils located below the layers of commercially relevant kaolin.

Interdisciplinary studies involving taxonomy, sedimentology, stratigraphy, paleoecology and taphonomy have made reconstruction of the depositional sequence possible. The outcrop, oriented basically from northwest to south east, exposes a unique register of the sediments of the Rio Bonito Formation overlying the southern Rio-Grandense shield. The depositional interval of the sedimentary package has been correlated to the final sequences of the transgressive interval of the Rio Bonito Formation, and thin layers of charcoal are found (Jasper *et al.* 2006). Paleobotanical studies conducted by Jasper and Guerra-Sommer (1998; 1999), Jasper *et al.* (2003), Jasper et al. (2005), Jasper *et al.* (2007a; 2007b) Jasper *et al.* (*in press*) and Salvi *et al.* (2008) have shown that the paleoflora preserved in the outcrop provide a unique record of great scientific importance (Fig. 1).

LOCALIZATION

The outcrop is located in the municipality of Encruzilhada do Sul, in the western central part of the state of Rio Grande do Sul, on the southeastern border of the Paraná Basin (geographical coordenates of 30º17'S – 52º11'W Fig. 2). The site is some 100 km west of Porto Alegre along highway BR 290, and is accessed by a secondary road leading off to main highway to the left. The Quiteria Outcrop is in a pasture on the left-hand side, some 20 km along this secondary road, and the entrance of the fazenda can be seen from this point.

The outcrop is unique, and nothing similar has been found in the vicinity. This is important, since the designation "Quiteria Outcrop" has often been confused with references to other sites with fossil occurrences described by Piccoli *et al.* (1991) in their regional study, since the various sites were all located on a map designated as the "Quiteria geological map". This confusion in names has led to erroneous interpretations about the stratigraphy and phytofossiliferous composition of the outcrop. In a detailed analysis of the area, Jasper *et al.* (2006) explain that the Quiteria Outcrop corresponds to Lithofacies VII, described by Silva and Menegat (1988), and Piccoli *et al.* (1991), from the Quiteria geological map.

Figure 1: Holotype of Coricladus quiteriensis Jasper et al. 2005 (PbY 074 – stored in the collection of the SBP/MCN/UNIVATES), showing the richness and conservation level of the fitofossils preserved principally in the roof-shale level of the Quiteria Outcrop.

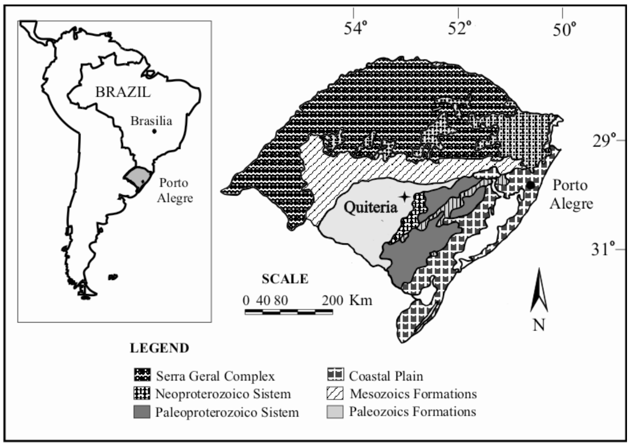


Figure 2: Localization map of the Quiteria Outcrop, Rio Grande do Sul, Brazil (adapted from Salvi et al., 2008)

DESCRIPTION OF SITE

The Quiteria Outcrop is a 6.4-meter-thick layer which shows discontinuous contact with both the underlying, non-exposed layer and that which overlies it. Two depositional intervals can be identified in the outcrop (Fig. 3).

The lower, light to dark grey interval (approximately 3.5 m thick) has a rich content of organic material. It is composed of a succession of carboniferous siltite layers, conglomerates rich in organic material, and fine layers of coal. This lower layer has an abrupt contact with the upper interval, which consists basically of dark to light yellow sandstone and siltite, approximately 2.9 m thick. This upper layer provides a dense association of in situ caulinar bases attributed to arborescent lycophytes.

The facies analysis of the outcrop made by Jasper et al. (2006) identified 16 facies, with diagnostic parameters including textural, structural, and paleofloristic data (Fig. 4).

Figure 3: Photocomposition of the Quiteria Outcrop, showing the occurrence of two depositional intervals, one basal with darkness color and the other at the top with clearest color (adapted from Jasper et al., 2006).

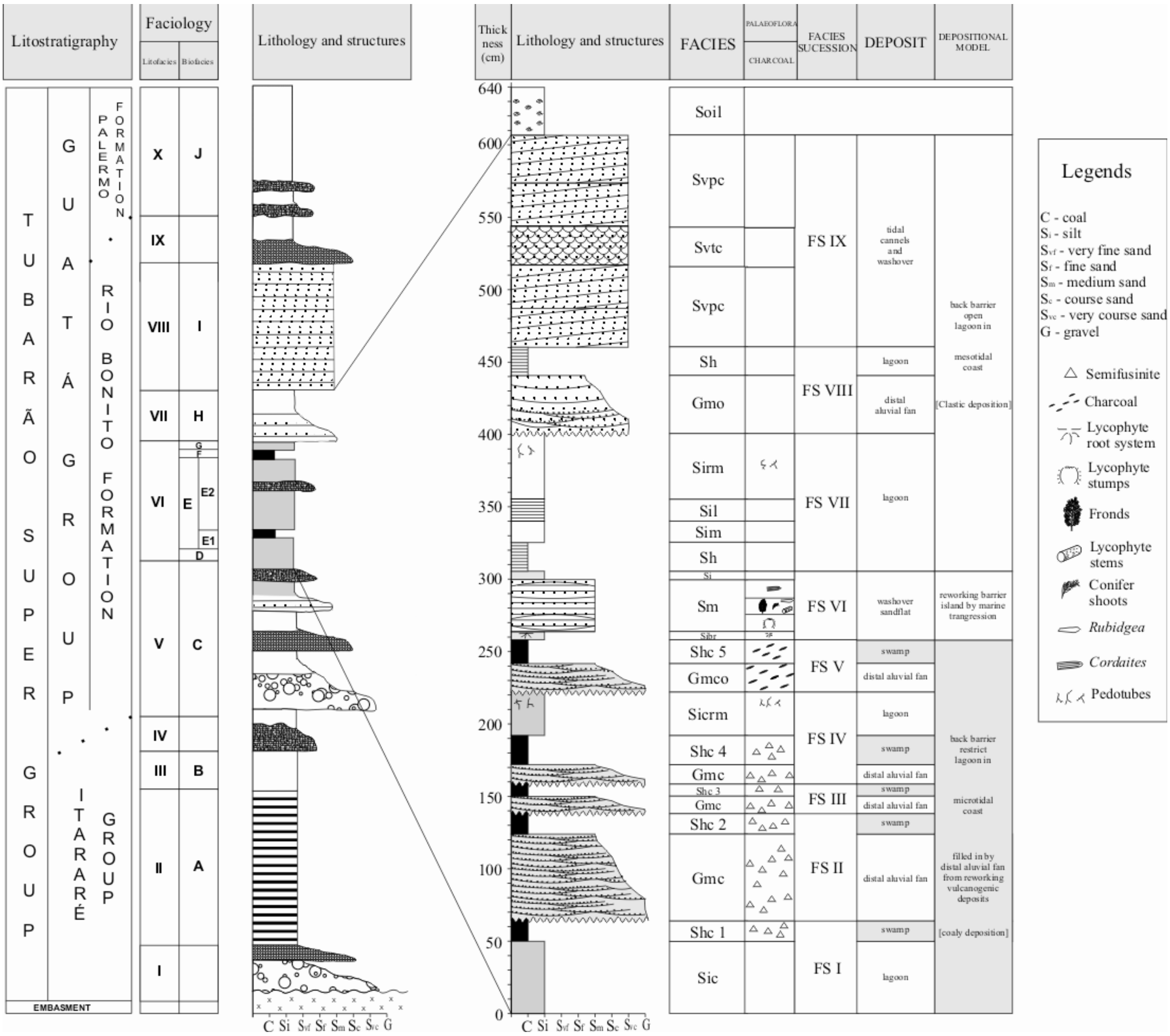


Figure 4: Columnar section of the Quitéria outcrop, with emphasis to the levels with fossil contains, Facies Succession (SF) and interpretation of the depositional landscape. Used symbols for the identification of the facies: coaly siltstone (Sic); coaly shale and coal (Shc); matrix-supported conglomerate (Gmc); coaly matrix-supported conglomerate (Gmco); coaly siltstone with root marks (Sicrm); siltstone with Brasilodendron pedroanum roots (Sibr); medium sand (Sm); siltstone (Si); shale to coaly shale (Sh); massive siltstone (Sim); siltstone with lamination (Sil); siltstone with root marks (Sirm); very coarse sandstone with planar cross bedding (Svpc); very coarse sandstone with through cross bedding (Svtc) (after Jasper et al., 2006; Guerra-Sommer et al., 2008; Jasper et al. in press).

The lower interval, represented by the succession of the first five facies (SF I to V), provides a depositional model of a swamp, such as would be associated with a restricted lagoon protected by a barrier off a micro-tidal coast, with periodic deposits from alluvial fans. The sixth facies results from washover fans, representing the reworking of the barrier due to marine transgression and more open lagoon deposits, without organic deposits, whereas the upper part of the succession (Facies VII to IX) represents a later lagoon, also associated with barrier islands along the coast, but subject to meso-tides, and revealing a greater incidence of washover deposits. The succession pattern of facies shows that the deposition involved large volumes of sediments from distant alluvial fans, with the amount of sediment increasing during periods of accommodation to regressive conditions. This succession represents seven cycles of variation in relation to the water level of the lagoon, with the lowest layer corresponds to a very low water level, and the succeeding layers indicating increasing water levels.

History of previous studies

The first reference to the Quiteria Outrop was made by Silva and Menegat (1988) and Piccoli *et al.* (1991) during the geological mapping of the region. These authors pointed out the unique nature of the outcrop in the area of Quiteria, an outcrop with litho and biofacies different from the others found in the area. The type section of the outcrop was identified as lithofacies VII by Piccoli *et al.* (1991) and denominated the Quiteria Outcrop, name confirmed in the study of Jasper and Guerra-Sommer (1998).

Jasper and Guerra-Sommer (1998; 1999) describe the occurrence of caulinar bases from cormophytic arboreal lycophytes in a layer of roof shale at the top of the outcrop. Considering the paleoenvironmental conditions in which this group of plants developed, as well as the models proposed for the formation of the peat in the Paraná Basin during the Permian Alves and Ade, 1996; Holz, 1998) it is likely that a lagoon/barrier depositional system prevailed during the deposition of the outcrop, although periodic events of washover are also revealed.

Guerra-Sommer et al. (2001) related the paleoecologic characteristics of the different taphoflora of the Lower Permian of the Parana Basin to the climatic evolution during this time interval, linking the paleoflora prior to the deposition of the Quiteria Outcrop to the second stage in the evolution of the flora reigning during the interval which gave rise to the coal. During this stage, the paleofloristic composition was characterized by the introduction of new taxons, not just the reorganization of existent species, as had been characteristic of the first stage, involving flora developed in a periglacial climatic regime (Itarare Group).

The characterization of the different taxa preserved in the megafloristic association of the Quiteria Outcrop (Jasper et al. 2003; 2005; 2006; 2007a; Salvi et al. 2008) has been important for the correlation of this paleoflora with similar associations found elsewhere in Gondwana.

The identification of Botrychiopsis valida (Fig. 5) as a parauthochtone element in this flora (Jasper *et al.* 2003; 2007a) made it possible to define a stratigraphic hierarchy between the different species of this genus in Gondwana. Based on this distribution, a phytostratigraphic system was outlined for the southern part of the Parana Basin. These studies also made it possible to confirm that the temporal, geographic and paleoenvironmental distributions of the different species attributed to the genus were closely related to different phases of the icehouse stage of the Paleozoic. *Botrychiopsis weissiana*, for example, developed in cold climates associated with periglacial sedimentation (Westphalian), whereas *Botrychiopsis plantiana* constituted part of the interglacial flora of cool yet temperate climates (Stephanian/Asselian); *Botrychiopsis valida* (found in the Quiteria Outcrop) was found in communities arising from sequences associated with charcoal under conditions of a mild temperate climate during the final phase of deglaciation (Sakmarian).

Figure 5: Impression from Botrychiopsis valida frond found at the roof-shale level of the Quiteria Outcrop (Sm Facies), presenting a robust rachis and reniform pinules well defined.

The presence of branches of conifers, with frequent organically attached fertile structures, made it possible to describe a new taxon, denominated *Coricladus quiteriensis* by Jasper *et al.* (2005) (Fig.6). The abundance and spatial distribution of these elements in the taphoflora, and the excellence of their preservation, have made it possible to confirm that these plants were common in low coastal environments in the Parana Basin during the lower Permian.

Figure 6: Impression from stem of Coricladus quiteriensis found at the roof-shale level of the Quiteria Outcrop (Sm Facies), presenting a principal stem with ramifications of second and third order, also with reproductive structures organically connected.

The integration of paleontological data and those obtained from the stratigraphic sequences established by Jasper *et al.* (2006) in the Quiteria outcrop led to the conclusion that the two depositional intervals represent distinct dynamic conditions along the coast (Fig. 4). The lower interval represents the depositional system of a coastal lagoon protected by barriers with prevailing micro-tide conditions; the lagoon then silted up with sediments from the distant alluvial fans composed of reworked debris of volcanic origin (Fig. 7) previously deposited on higher land. The palinological assemblies preserved in the charcoal and carbonaceous shale (Fig. 8), the presence of acritarcs (*Tetraporina*, *Brazilea*, *Portalites* and *Quadrisporites*) and algae (*Botryococcus*) corroborates the presence of this coastal system whereas the predominantly arborescent lycophyte spores complement the filicophyte, sphenophyte, and herbaceous lycophyte spores, as well as gymnosperm pollen from *Cordaites*, *Glossopteris* and conifers. The palinoflora of the conglomeratic level reveals a marked increase in monosacadic pollen derived from *Cordaites*, reflecting transport from better-drained areas of vegetation in the upland part of the system.

The overlying clastic interval represents the same system, but under more open conditions, probably generated by the break up of the barriers, the result of washover fans, and the generation of a washover plain. These periodic depositions along the coast led to the reconfiguration of the morphology of the depositional system, generating sandy soils, poor in nutrients, which then constituted the substrate for the beginning of a new process of plant succession. This pioneer plant flora, consisting of arboreal lycophytes, is represented in the roof-shale layer. The abundance of cormophytic lycophyte bases (of *Brasilodendron pedroanum*) with *in situ* fasciculated roots (Fig. 9) found in the roof-shale layer, as well as the association with forms related to *Botrychiopsis valida*, fronds of rodeopterideas, herbaceous lycophytes with attached reproductive structures (*Lycopodites riograndesis*), and sterile branches of conifers organically associated with fertile branches (*Coricladus quiterensis*) made it possible to infer the presence of a stratified forest with canopy forms as authochtonous undergrowth vegetation.

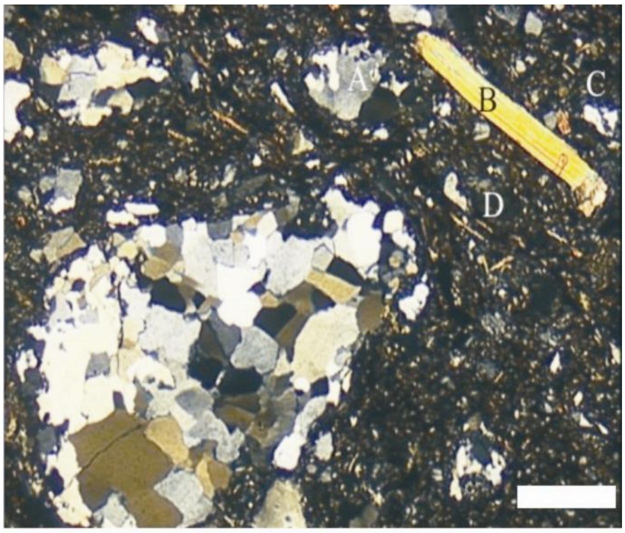


Figure 7: Optical microphotography of petrographic blade from the basal level of the Quiteria Outcrop (Gmco Facies) presenting: Litic fragments – granite (A); Cristal fragments – muscovite (B) and quartz (C); Original Volcanic Glass fragments (D) (after Jasper et al. in press).

Figure 8: Detail of the contact of the basal level, rich in organic mater, and the upper level, clastic, of the Quiteria Outcrop. Featured the Gmco Facies (arrow), whose microphotography was represented in Fig. 7.

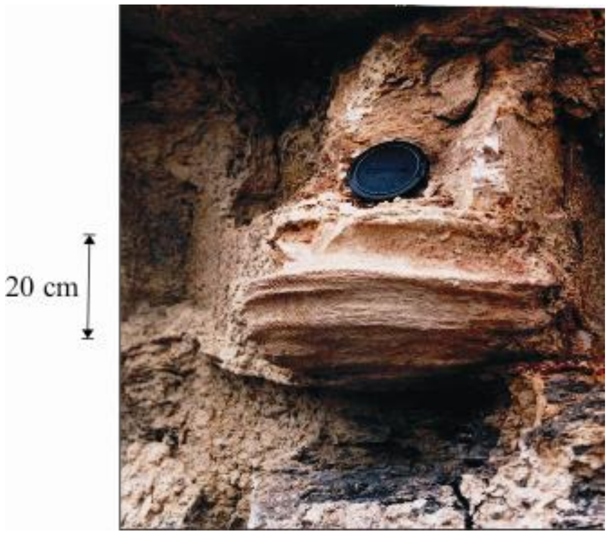


Figure 9: Compressed and in situ caulinar base of Brasilodendron pedroanum from the roof-shale level of the Quiteria Outcrop (Sm Facies).

The presence of rare parauthochtonous leaves (?*Rubidgea* sp. – Fig. 10) indicates that these plants also developed in more restricted areas of the overall coastal environment; on the other hand, the presence of leaves of *Cordaites* (Fig. 11) concentrated exclusively in the sandstone layer at the top of the roof shale, suggests that distant washover fans transported fragments of plant associations from well-drained inland areas of the flood plain for deposit along the coast.

Figure 10: Impression from a fragment of ?Rubidgea sp. frond found at the roof-shale level of the Quiteria Outcrop (Sm Facies). Observe the preservation, in the same sample, of microphiles and portion from a stem of Brasilodendron pedroanum (basal portion of the sample).

The integration of these data suggests that the roof-shale flora constitutes an autochthone/ parauthochtone succession of lowland flora in clastic soil along the coast under conditions of low nutrient availability, a situation known to be stressful for most land plants. Such plant communities, dominated by arboreal cormophytic lycophytes, are typical of the paleoecology and palaeoclima of Gondwana.

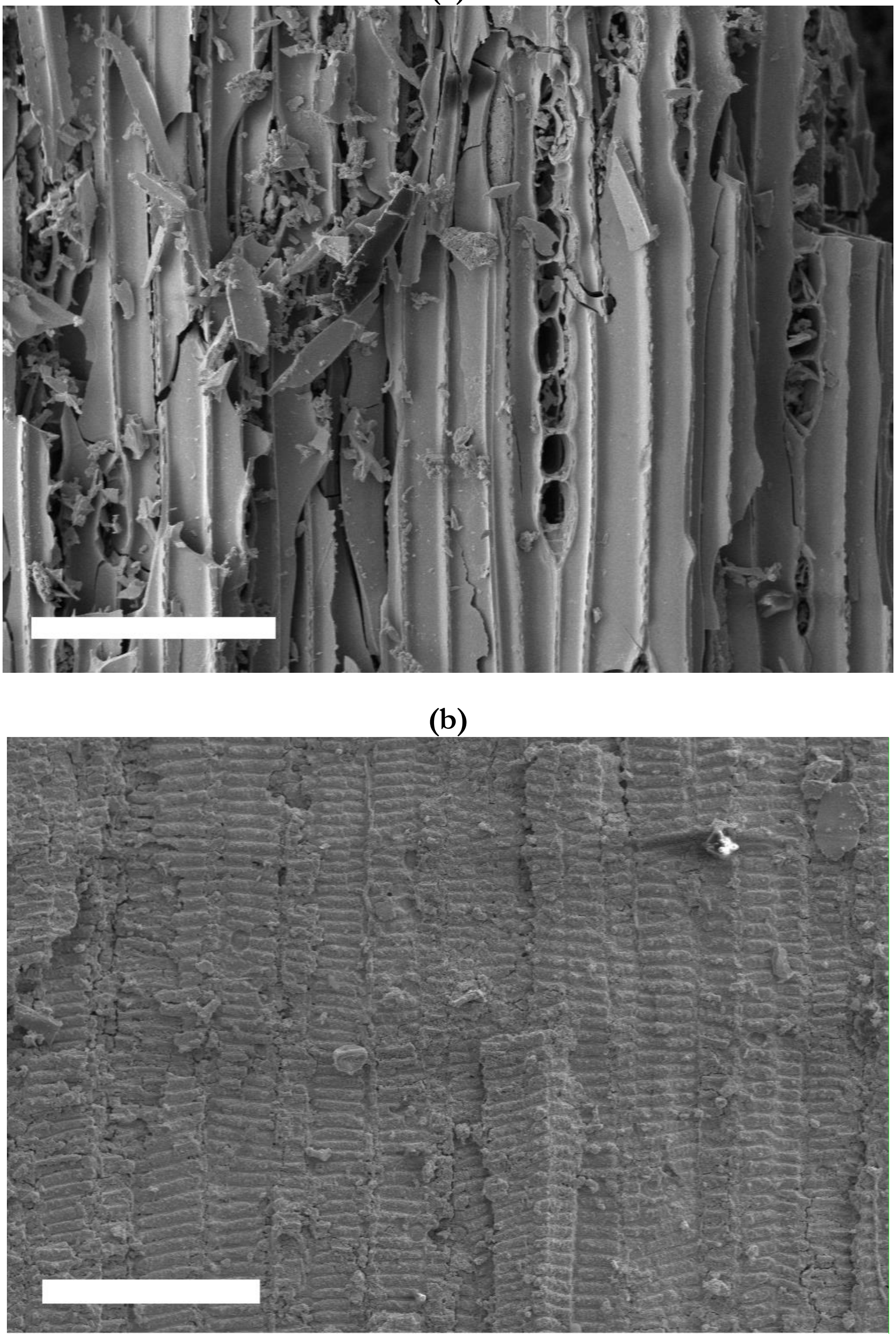
The analyses of Jasper *et al.* (2006) also revealed the similarity in composition of the megafloristic association of the paleo plant community deposited authochtonously in the roof shale layer and the nearby para-authochtonous community which gave rise to peats, as detected by palinological assemblies.

The charcoal (*sensu* Jones and Chaloner, 1991) first identified for the upper Paleozoic interval in the Parana Basin by Jaster *et al.* (2006) is confirmed by Jasper *et al.* (2007b) and Jasper *et al.* (*in press*) for the Quiteria Outcrop. The fragments of charcoal found in the conglomerates layer of the lower interval of the sequence studied varied from 0.9 to 4.2 cm in length and from 0.3 to 0.7 cm in thickness. The anatomical characteristics of the carbonized wood fragments (Fig. 12) made it possible to establish taxonomic affinities confirming the correlation between conifers and lycophytes, prevalent in the roof-shale layer.

Figure 11: Impression from a fragment of ?Cordaites sp. frond found at the roof-shale level of the Quiteria Outcrop (Sm Facies). Observe that the sediment of preservation from the samples is thick sandy, representing the lenses described by Jasper (2006).

Other authors (Holz *et al.*, 2002; Silva and Kalkreuth, 2005; Kalkreuth *et al.*, 2006) have already considered the possibility of the occurrence of forest fires in the systems which would have given rise to the peat and the deposits of charcoal in the Parana Basin. This hypothesis was based on the occurrence of fusinites in the layers of charcoal. However, as the authors themselves admit, the confirmation of the occurrence of such large-scale plant fires in this environments would only be possible if accumulations of charcoal were found, since the origin of the fusinite could also be related events other than fires.

(a)



(b)

Figure 12: Electronic microphotographs from charcoal fragments providing from the basal level of the Quiteria Outcrop (Gmco Facies): a) fragment with gymnospermic affinity with feature to the tracheids in longitudinal position and the occurrence of simple transversal rays (scale corresponds to 20 µm); b) fragment with licofitic affinity, with tracheids presenting the typical scalariform pitting of the vascular criptogames (scale corresponds to 20 µm).

Since the studies of Scott and Glasspool (2007) associate fusinite diretly with the occurrence of plant fires, the suggestion of Holz *et al.* (2002), Silva & Kalkreuth (2005) and Kalkreuth *et al.* (2006) deserves a careful evaluation, especially considering the presence of charcoal in the Quiteria Outcrop reported by Jasper *et al.* (2007b).

The uniqueness of the fossil assemblies found in the Quiteria Outcrop shows that this paleoflora continues to be a relevant source for research. One example is the herbaceous lycophyte forms found by Salvi *et al.* (2008) in the roof shale layer. These were identified as a new species of herbaceous lycophyte (*Lycopodites riograndensis*) by Jasper *et al.* (2006) and Salvi *et al.* (2008) pointed out that this species has phylogenetic correlations with representatives of the *Lycopodites* genus found in the upper part of the Itarare Subgroup of the Tiete Formation near Cerquilho in the state of São Paulo, on the Itapema Fazenda (of Asselian/Sakmarian age).

SYNOPSIS OF THE ORIGIN, GEOLOGICAL EVOLUTION AND IMPORTANCE OF THE SITE

During the lower Permian (Kungurian), some 275 M.a. ago, the place that is today known as the Quiteria Outcrop was a coastal lagoon which was part of the greater southeastern coastal system of the megacontinent of Gondwana (Fig. 13). The vegetation in the region was dominated by a canopy of lycophytes, with an undergrown of conifers, pteridosperms, herbaceous lycophytes, and filicophytes (Fig. 14).

Due to the relatively calm conditions in the central part of the lagoon, the organic material produced by the plants growing along the shore ended up accumulating on its floor, giving rise to the lower layer of the present-day outcrop, dark and rich in organic material (Fig. 2). During the same interval of time in which this organic material was accumulating in the lagoon, charcoal from plant fires in the surrounding area, caused by volcanic processes, was also transported into the lagoon. This is clear from the fragments of plant charcoal preserved along with grains of pollen and bits of volcanic glass.

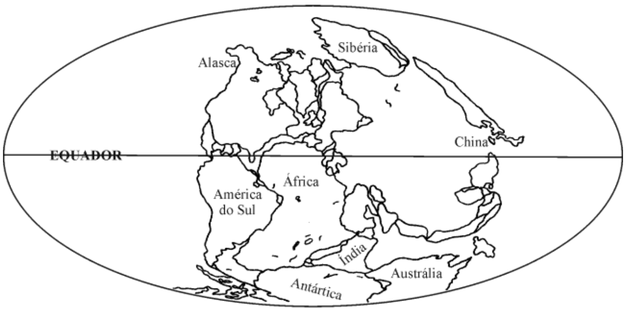


Figure 13: Continental mass distribution in the Permian, featured to the position of the Gondwana megacontinent, formed by South America, Africa, Antarctic, India and Australia.

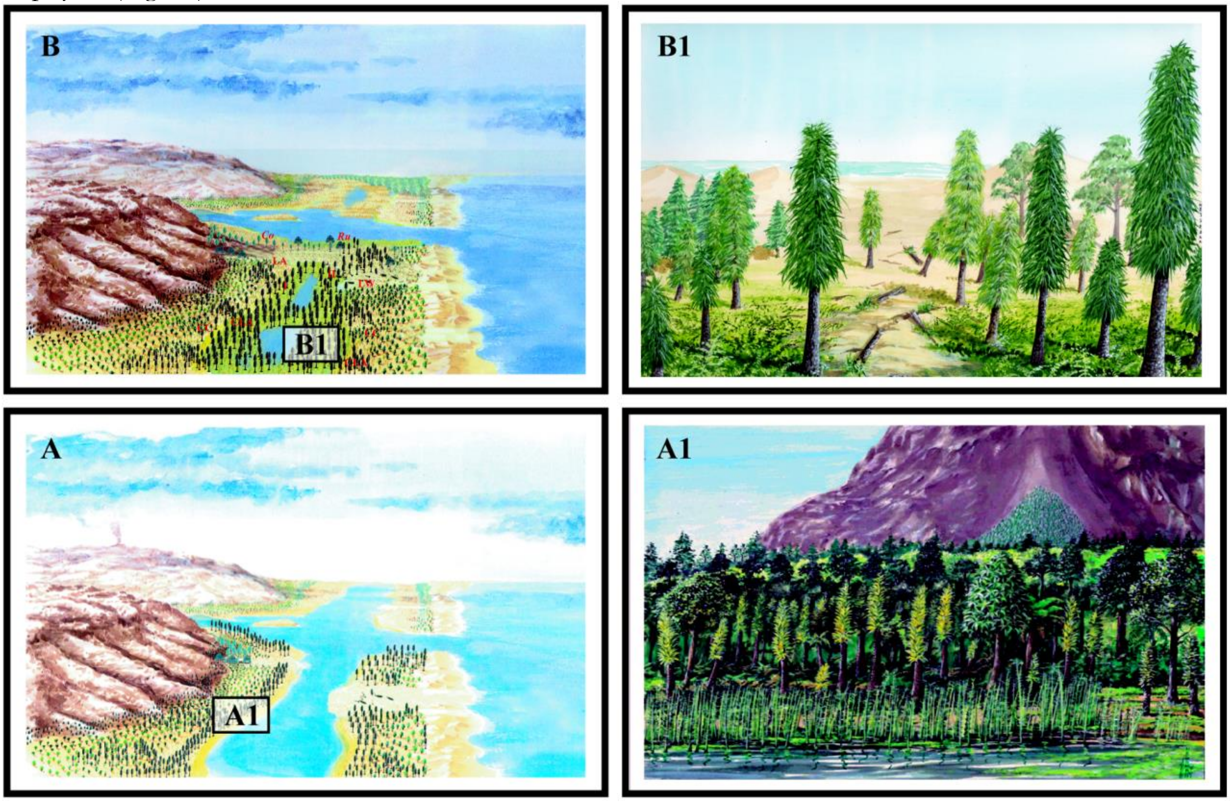


Figure 14: Reconstruction the coastal ecosystem dominated by washover fans preserved on the Quiteria Outcrop. Palaeoecological reconstruction for the coal deposition interval (A); detail of the peat-forming plant community (A1); palaeoecological reconstruction for the overlying clastic deposition interval (B); detail of the clastic plant community (B1) (after Guerra-Sommer et al., 2008).

But this was a coastal region, and dramatic events such as storms upset the equilibrium of the lagoon, eventually filling it with sand from the barriers. This sand then promoted the growth of vegetation throughout the whole area, although such growth had previously been restricted to the margins of the lagoon (Fig. 14).This new vegetation may have been relatively resistant to environmental changes, but it could not withstand the onslaught of one final storm, which covered the whole coastal portion of the area today exposed in the Quiteria Outcrop. Thanks to the processes of fossilization, this vegetation remains preserved in the roof shale layer, which is the light yellow portion immediately overlying the larker layer of the outcrop (Fig. 2).

Once the equilibrium of the local environment had been lost, the vegetation which had been so abundant was unable to establish itself again in the area. Its demise led to the final level of deposition, consisting of the kaolin which can be found in the outcrop.

After these depositional events, many other rocks were formed over the system, thus favoring the termination of the process of fossilization of the remains of living creatures which had lived in the area. A final geological event caused the covering of the entire southern part of Brazil and the formation of the Serra Geral mountain range: the separation of South America from Africa, which continues up to today, although on a much-reduced scale.

Once the remains of the lagoon were thickly buried, the reverse process started, i.e., the removal of these rocks and sediments by erosional processes, which continued for millions of years, and the eventual/gradual exposure of the present-day Quiteria Outcrop. The exposed layer containing the original surface deposits of kaolin had again returned to the surface.

The economic value of kaolin during the 1980s led to its extraction from this site. However, the miners had no idea of the true extension of the reserves, and mechanized equipment was used to open an extensive front. With this procedure, the fossil-containing layer below the kaolin was also exposed. However, it was only at the end of the decade of the 1980s, during the geological mapping of the area by geology students from the Federal University of Rio Grade do Sul, that the outcrop came to the attention of science. It has since been extensively studied and has revealed much of importance for paleobotany, biostratigraphy, and biogeography, not only on a local level, but also regionally and internationally.

PROTECTIVE MEASURES

Existent measures

At present, the Quiteria Outcrop is the sole responsibility of the owner of the where it is located; no special protective measures have been undertaken, nor is there any official restriction on collection from the site. The physical appearance of the front has also deteriorated due to weathering, and unsupervised and occasionally destructive collection continues. Moreover, due to the lack of centralization of the material collected from the outcrop, the total number of specimens found there is uncertain.

Proposed measures

Measures which seem appropriate and which should be relatively easily implanted include making the outcrop a legally protected heritage site (an option suggested to the owner which was well received) and provision of physical protection of the exposed face of the outcrop by fencing it off, monitoring collection of future samples should helps preservation the site.

Problems to implement the measures

Since the outcrop is isolated and located on private property, protective measures will be difficult to implement. However, since the owner is willing to cooperate, it seems that such implementation should be feasible. However, the limited public resources available for the conservation of the Brazilian fossil heritage makes effective actions for the control and conservation of this important register of the history of the Parana Basin impossible.

Authors sugestions

The opening of new fronts for scientific and educational studies would help increase our knowledge of this paleoflora. Moreover, the data from all collections having specimens from the Quiteria Outcrop should be integrated, thus providing a single register of all this material which should facilitate future studies.

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