Journal of South American Earth Sciences 26 (2008) 435–444

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

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

Palaeobotanical evidence of wildfires in the Late Palaeozoic of South America – Early Permian, Rio Bonito Formation, Paraná Basin, Rio Grande do Sul, Brazil

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ARTICLE INFO

Article history:
Received 2 July 2007
Accepted 13 August 2008

Keywords:
Charcoal
Wildfire
Gondwana
Early Permian
South America

ABSTRACT

Fossil charcoal, as direct evidence of palaeowildfires, has repeatedly been reported from several plant-bearing deposits from the Late Palaeozoic of the Northern Hemisphere. In contrast charcoal reports from the Late Palaeozoic deposits of the Southern Hemisphere are relatively rare in comparison to the Northern Hemisphere. Although the presence of pyrogenic coal macerals has repeatedly been reported from Late Palaeozoic coals from South America, no detailed anatomical investigations of such material have been published so far. Here is presented an anatomical analysis of charcoal originating from Early Permian sediments of the Quitéria Outcrop, Rio Bonito Formation, Paraná Basin, located in the central-eastern portion of Rio Grande do Sul, Brazil. This charcoal comes from two different coaly facies, and it was possible to scrutinize between three types, based on anatomical characters of the charcoal. Two of these charcoal types can be correlated to gymnosperm woods, and the other type corresponds to strongly permineralized bark with characteristic features of lycopsids. The presence of charcoal in different facies, ranging from parautochtonous to allochtonous origin, indicates that different vegetation types, i.e. plants which grew under wet conditions in the lowland as well as in the more dry hinterland, have experienced wildfires. Taking into account previous petrographic and lithological analyses from the facies in which the charcoal occurs and from the conditions of the wood and bark fragments, it was possible to speculate that the intensity of such wildfires most probably corresponds to forest-crown fires. Moreover, it is possible to state that wildfires have been a more or less common element in distinct Late Palaeozoic terrestrial ecosystems in the South American part of Gondwana. The data support previous assumptions on the occurrence of wildfires in the Early Permian of the Paraná Basin which were based solely on coal-petrographic data.
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ARTICLE INFO

Article history:
Received 2 July 2007
Accepted 13 August 2008

Palavras-chave:
Charcoal
Incêndios vegetacionais
Gondwana
Permiano inferior
América do Sul

RESUMO

Fósseis de material orgânico carbonizado (charcoal) têm sido utilizados de forma recorrente como evidência direta da ocorrência de paleo-incêndios vegetacionais em associações florísticas do Paleozóico Superior do Hemisfério Norte. Todavia, registros de charcoal de depósitos contemporâneos do Hemisfério Sul são relativamente raros. Apesar da presença de elementos pirogênicos macerados ter sido repetidamente citada para os depósitos de carvão do Paleozóico Superior da América do Sul, estudos anatômicos detalhados desse tipo de material não foram realizados até o momento. No presente trabalho é apresentada análise anatômica de fragmentos de charcoal provenientes do afloramento Quitéria, Formação Rio Bonito, Permiano Inferior (Sakmariano), Bacia do Paraná, localizado na porção central do Rio Grande do Sul (Brasil). Os fragmentos carbonizados provêm de folhelhos carbonosos associados a finas lentes de carvão e de conglomerados com matriz carbonosa e podem ser classificados em três morfotipos, com base em suas características anatômicas. Em sua grande maioria, os fragmentos foram incluídos em dois morfotipos de lenhos gimnospérmicos sendo, também, identificáveis fragmentos de córtex com características típicas de licófitas arborescentes, incluídos em um terceiro morfotipo. Os diferentes morfotipos representam amplo espectro vegetacional, incluindo formas com origem parautóctone, procedentes de áreas baixas,

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doi:10.1016/j.jsames.2008.08.002

marginais à turfeira, até formas representativas de condições de solo mais bem drenado, com origem alóctone. Com base nas características litológicas e petrográficas das facies em que ocorrem os charcoal e também pelas características desses fragmentos preservados, foi possível definir que os incêndios que ocorreram na área de estudo restringiram-se ao dossel, sendo bastante intensos. Além disso, fica confirmado que incêndios vegetacionais ocorriam de modo bem mais freqüente do que se supunha até recentemente durante o Paleozóico Superior no continente Gondwana Ocidental, sendo que os dados aqui apresentados corroboram estudos anteriores os quais relatam a ocorrência de paleo-incêndios nesta porção de Gondwana durante este período, com base em estudos petrográficos de camadas de carvão.

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1. Introduction

Fire is a major driver of a large number of modern ecosystem processes (Scott and Stea, 2002; Preston and Schmidt, 2006) and it can be assumed that it also played a comparable role during past periods of the Earth's history. In effect, Bond and Keeley (2005) compare wildfires to *herbivory* as a factor of modification of various biomes during periods of hundreds of millions of years.

Evidence of palaeowildfires, in the form of fossil charcoal (or fusinite and semifusinite *sensu* Scott and Glasspool, 2007), can be found from the Silurian onwards (Edwards and Axe, 2004; Glasspool et al., 2004) in many pre-Quaternary (Scott, 1989, 2000; Scott and Glasspool, 2006) and Quaternary (MacDonald et al., 1991) deposits in varying abundance.

According to Scott (2000), the factors affecting the frequency and intensity of wildfires in modern ecosystems include: climatic seasonality (a marked dry season strongly favors the occurrence

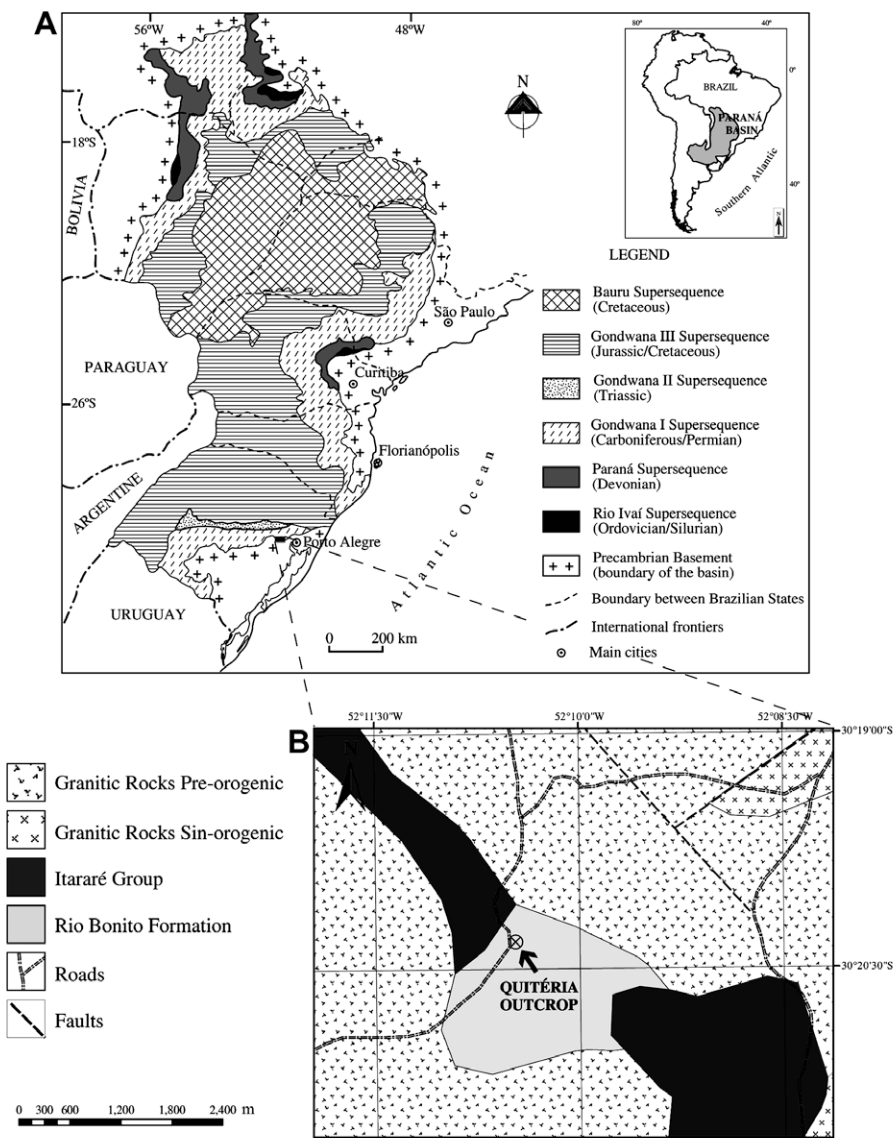

Fig. 1. (A) simplified geological map of the Paraná Basin in Brazil with major tectonic elements and geographic references; (B) location map from the Quitéria area (based on Guerra-Sommer et al., 2008).

of wildfires), the availability of fuel plant material, the humidity in the plant material and sources of ignition.

For palaeowildfires one additional factor has probably to be taken into account: the atmospheric oxygen-level (Scott, 2000; Scott and Glasspool, 2006). An important fact to note is that, in the case of the Late Palaeozoic, and more specifically in Permian times, the atmospheric oxygen concentration was significantly higher than today, as indicated by geochemical models (Berner, 2001, 2002, 2005, 2006; Scott and Glasspool, 2006). So far, charcoal as direct evidence of wildfires during the Permian has been reported from Europe (Uhl and Kerp, 2003; Uhl et al., 2004), North America (Sander, 1987; Sander and Gee, 1990; DiMichele et al., 2004) and China (Wang and Chen, 2001), as well as several localities from former Gondwana (Scott, 2000; Glasspool, 2000, 2003; Scott and Glasspool, 2006). The majority of reports of Gondwana charcoals come from coal-petrographic investigations (Scott, 2000; Scott and Glasspool, 2006), and only a few occurrences from Gondwana have been studied in detail, including examples from South Africa (Glasspool, 2003), New South Wales, Australia (Glasspool, 2000) and Jordan (Uhl et al., 2007).

Although the pyrogenic origin of the abundant inertinite occurring in many Permian Gondwana coals has been a matter of debate for several decades (cf. discussion in Scott, 2000), it has been repeatedly demonstrated that inertinites from several Australian and South-African coals are in fact of pyrogenic origin (e.g. Glasspool, 2000, 2003). Consequently the pyrogenic origin of such inertinites has also been assumed for other Gondwana coals from this period (Scott and Glasspool, 2006). After the complete revision of the classification and definition of the inertinite group macerals, Scott and Glasspool (2007) demonstrate that fusinite and semifusinite are indicative of wildfires.

Up to now only a few petrographic studies have reported the occurrence of putative charcoal from the Permian of South America, and most of these were focused on the coal bearing sequences of the Paraná Basin in Rio Grande do Sul, southernmost Brazil (Holz et al., 2002; Silva and Kalkreuth, 2005; Kalkreuth et al., 2006). They

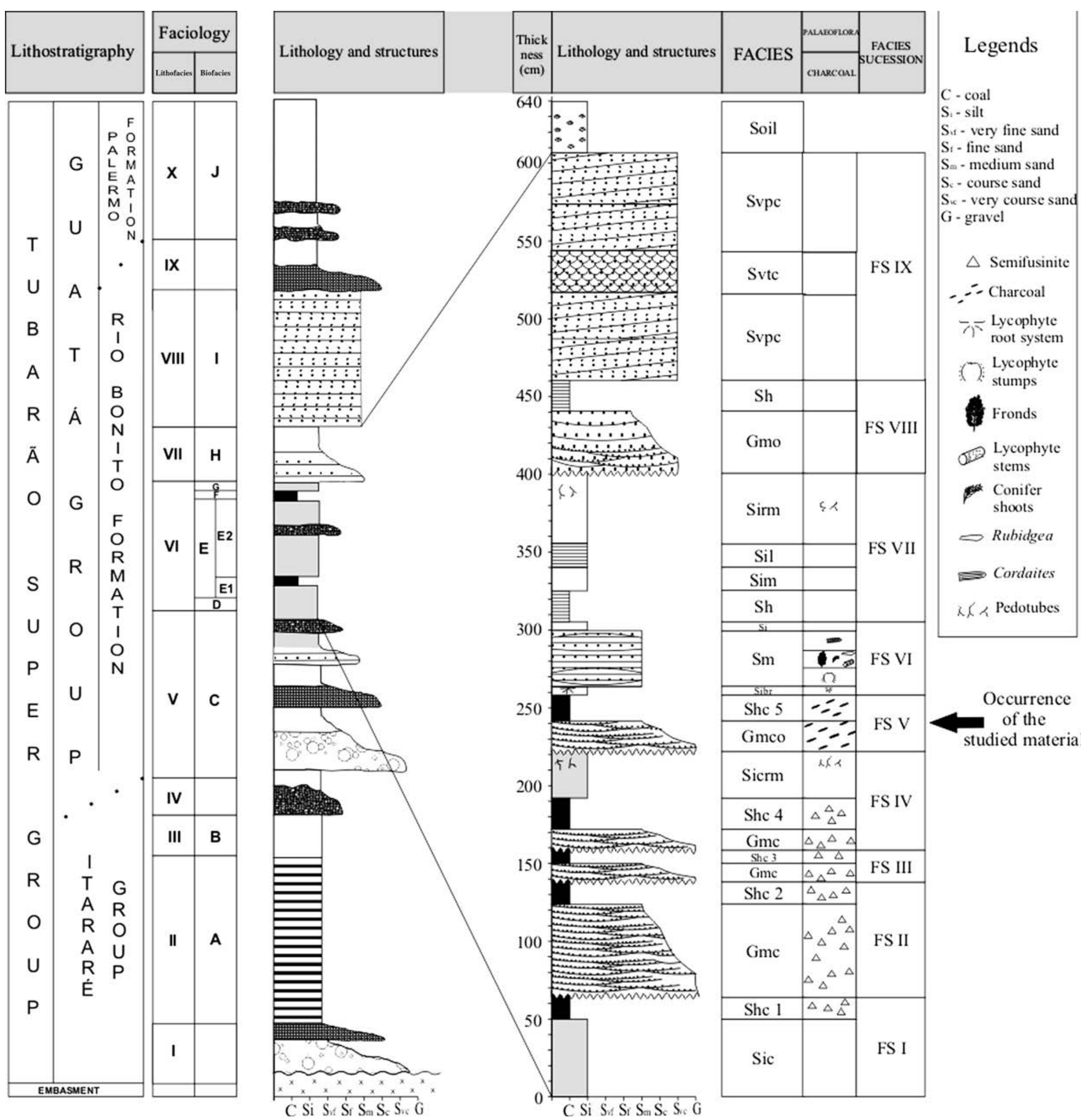

Fig. 2. Columnar section of the Quitéria outcrop, from Jasper et al. (2006), and its position in the regional columnar section from Piccoli et al. (1991).

deal with the petrology, chemistry and stratigraphic sequence of these strata and report the abundant presence of fusinite in different facies. Silva and Kalkreuth (2005) indicated that the observed fusinite can probably be seen as evidence of wildfires occurring at the margins of the coal-forming mire systems. However, they did not present any anatomical analysis of the studied material and did not insert it in a formal classification of coal macerals. A systematic identification of the plants involved in the formation of this material has also been neglected, and thus palaeoecological interpretations are not possible so far.

Additional to these coal-petrological studies there is only one indirect report of charcoal occurrence from Early Permian sediments in organic rich clastic layers from the Quitéria outcrop in the Paraná Basin, in the central-eastern portion of Rio Grande do Sul (Jasper et al., 2006). However, a detailed anatomical analysis, together with evidence for the alleged charcoal nature of this material is lacking so far. This study presents the results of a detailed anatomical analysis of the mentioned material to fill a gap in the current knowledge on Permian palaeowildfires in the Paraná Basin.

2. Materials and methods

For the present study, 50 samples from Early Permian beds of the Quitéria outcrop (Fig. 1), Rio Grande do Sul, Brazil (Rio Bonito Formation, Paraná Basin) have been examined for their charcoal contents. The samples were collected in three distinct facies, previously described by Jasper et al. (2006): (1) coaly matrix-supported conglomerate with dispersed organic matter (Gmc); (2) coaly matrix-supported conglomerate (Gmco) and; (3) coaly shale and coal (Shc – in this paper subdivided in Shc 1–5) (Fig. 2). The choice of the facies for this study was based on field observations on the preferential occurrence of putative charcoal fragments.

Fossil charcoal fragments, varying between 0.9 cm and 4.2 cm and with irregular diameters between 0.3 cm and 0.7 cm, were found dispersed in the sediment. In the laboratory, they were mechanically extracted from the rocks. No chemical treatment was necessary for removing impurities, given the good conservational conditions of the organic matter and their easy isolation from the sediment. Selected charcoalified material was subsequently investigated with a Jeol JSM-840 scanning electron microscope after gold-coating at Tübingen University.

3. Geologic and stratigraphical setting

The Paraná Basin is a large (1,400,000 km^2) intracratonic subsidence basin covering parts of southern Brazil, Paraguay, Uruguay and Argentina. Basin floor subsidence, in addition to Palaeozoic and Mesozoic sea level changes, created six second-order sequences deposited from the Ordovician to Late Cretaceous, separated by regional unconformities (Milani et al., 1998). The coal-bearing Rio Bonito Formation, which is the object of this study, integrates part of two third-order depositional sequences of the Carboniferous-Early Triassic second-order sequence, named S2 and S3 (Holz et al., 2002).

Coal deposits of the Rio Bonito Formation occur adjacent to paralic, i.e. estuarine, deltaic, backshore, foreshore and shoreface siliciclastic deposits, deposited in back-barrier environments (Holz, 1998). Tissue preservation and gelification index of coals corroborate deposition in a coastal swamp environment (Alves and Ade, 1996). Deposition occurred within the cool temperate climatic belt (Scotese, 2000) or, according to the criteria of Rees et al. (1999), in the cool temperate biome, at palaeolatitudes of approximately 50°S.

The studied area comprises the Quitéria outcrop, which is located in the vicinity of the southeastern outcrop belt of the Rio Bonito Formation of the Paraná Basin, southern Brazil (Fig. 1). The nine vertical facies successions (FS) identified in the Quitéria outcrop (Jasper et al., 2006) represent cycles of relative variations of the water level in a lagoon, ranging from markedly falling water level, to relative rising water level. The basal section corresponds to coaly shales and thin coal layers (Shc facies) with a parautochtonous origin, representing, according to Jasper and Guerra-Sommer (1999), a coastal depositional system associated with a restricted lagoon protected by barrier/island in micro-tidal conditions as described for other areas by Leeder (1999) and Reinson, (1992). These facies are interbedded with matrix-supported conglomerates (Gmc and Gmco facies) of allochtonous origin interpreted as distal alluvial fans. Petrographic analyses demonstrated the presence of low weathering glass fragments, represented by vitreous vesicular and laminar shaped fragments in reddish silt-sandy matrix (Fig. 3). Guerra-Sommer et al. (2008) report the occurrence of vitrinite associated with inertinite for these facies. This composition indicates the proximity to the source, probably related to close hinterlands originated by reworking of volcanic debris.

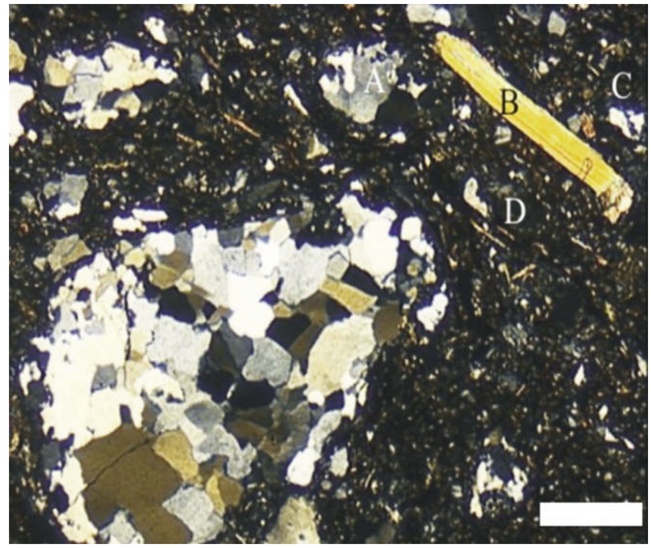

Fig. 3. Optic microphotography of material collected from the Gmco facies at the Quitéria outcrop, representing different angular and prismatic shapes. (A) lithic fragment – granite; (B) crystal fragment – muscovite; (C) crystal fragment – quartz; (D) original glass fragment (scale corresponds to 0.5 mm).

The deposition interval of the outcropping sedimentary package was correlated by Jasper et al. (2006) to the final parasequences of the Rio Bonito Formation transgressive tract (PS E 5 – Fig. 1 of Jasper et al., 2006), where coal levels are thin. This correlation is confirmed by *Striatopodocarpites fusus* in the palynological association found in the shale underlying the roof-shale, indicative of the *Hamiapollenites karrooensis* palynostratigraphic sub-zone of Souza and Marques-Toigo (2003), corresponding to the Sakmarian according to the criteria of Guerra-Sommer et al. (2007).

4. Palynology and palaeobiology

The input of sandy material in the flooded lowlands changed the ecology of the former environment, with the generation of a clastic sandy soil. The transition from a peat-forming to a clastic environment in the Quitéria outcrop is represented by a peculiar peat-clastic interface. The coaly shale and coal interval (Sch facies) records the regional vegetation of coal-forming plant communities, transported from nearby areas to the mire which developed in a restricted lagoon protected by a barrier island; some elements of marine microplankton commonly found in south Brazilian coal palynofloras (Cazzulo-Klepzig, 2001) point to an enlarged tolerance to salinity (from fresh to brackish water). These fossils have been carried to the mire and were deposited together with the planktonic algae *Botryococcus* that flourished in fresh to brackish water. Based on the model of Remy (1975) spores derived from terrestrial plants flourishing at the mire margins (herbaceous and arborescent lycopsids, small ferns) as well as spores and pollen grains from hygrophilous/mesophilous arborescent vegetation inhabiting nearby areas (cordaites and glossopterids) were transported into the mires. The presence of conifers is reflected by rare and striate pollen grains (Guerra-Sommer et al., 2008).

In contrast, the palynogical content of the Gmco facies is characterized by a significant increase in gymnosperm pollen grains, indicative of mesophilous environments, against sporomorphs, showing changes in the vegetation dynamics and supporting an allochtonous origin for the palynological assemblage. The lowland clastic substrate, developing after the cessation of peat formation, was colonized by a pioneer community, preserved in a thin roof-shale level (40 centimeters thick), composed mainly of *Brasilodendron pedroanum in situ* basal casts, arborescent conifers (*Coricladus quiteriensis* from Jasper et al., (2005)) and understory *taxa* such as *Botrichyopsis plantiana, Lycopodites riograndensis*, *Rubidgea* sp. and *Cordaites* sp. (Jasper and Guerra-Sommer, 1998, 1999; Jasper et al., 2006, 2007; Guerra-Sommer et al., 2008; Salvi et al., 2008).

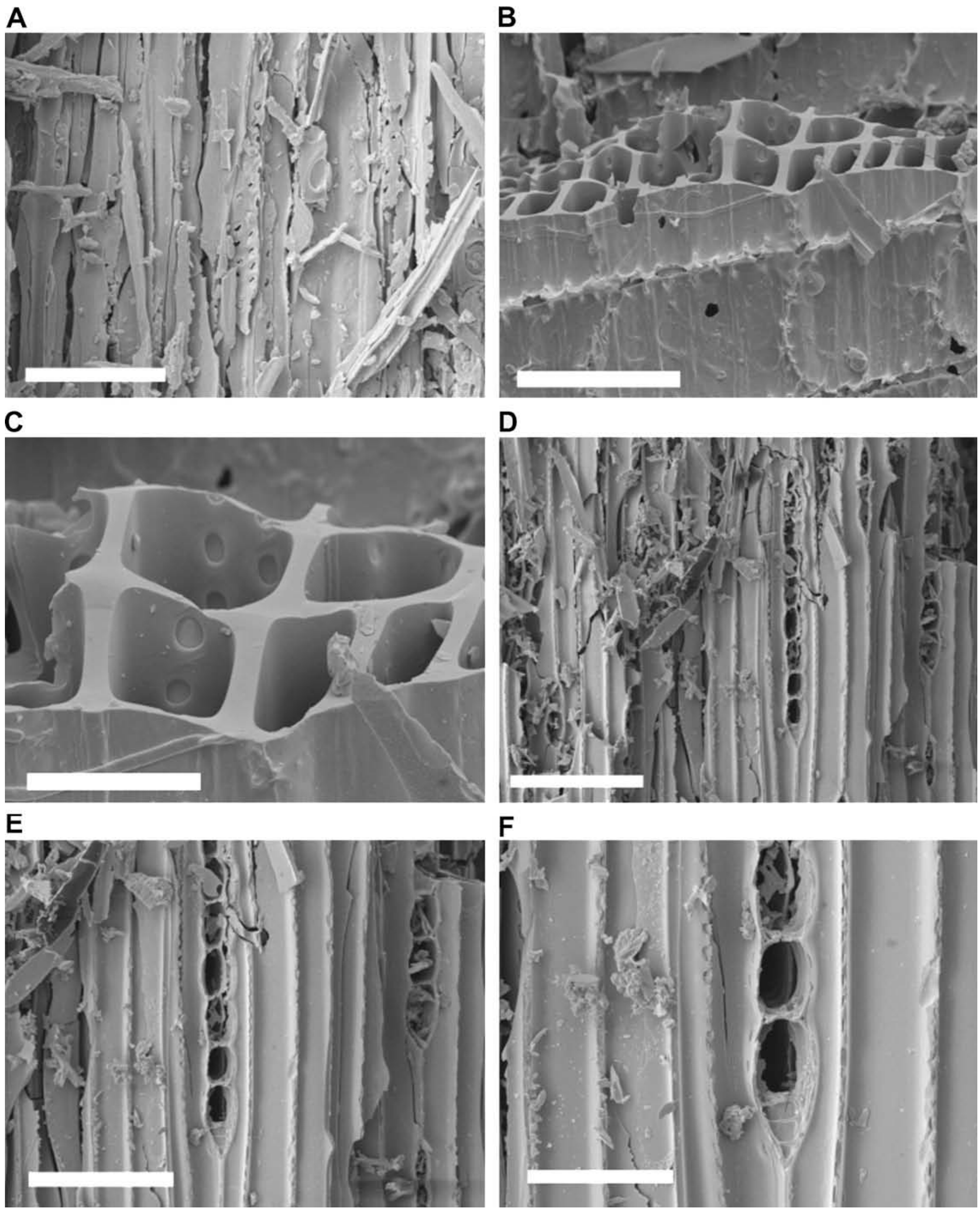

Fig. 4. Electronic microphotographs of the *Quitéria outcrop charcoal type 1*. (A) general view (scale corresponds to 40 μm); (B) detail of the uniseriate and biseriate bordered pitting with inconspicuous cross-field pits (scale corresponds to 50 μm); (C) detail of the circular and oval pits and the condition of homogenization of the cell walls (scale corresponds to 20 μm); (D) general view of the rays (scale corresponds to 50 μm); (E) detail of a uniseriate ray (scale corresponds to 25 μm) and (F) detail of a uniseriate ray (scale corresponds to 10 μm).

Boardman et al., (2006) registered the presence of leaves of *Glossopteris browniana* in the top levels of the Quitéria outcrop. However, the stratigraphic profile presented by them does not match the vertical section established by Jasper et al. (2006), so it is difficult to judge from which facies their specimens originated.

5. Results

5.1. Identification and preservation of the fossil charcoal

The following characters have been used for the identification of the charcoal nature of the material investigated, as proposed by (Scott, 1989, 2000): (a) black color and visible streaks, (b) silky luster, (c) homogenized cell walls, and (d) excellent preservation of cellular details.

Based on these criteria only the samples collected from the Gmco and Shc 5 facies (Fig. 2), can be identified as charcoal. However, based on the classification of Scott and Glasspool (2007), semifusinite is abundant in almost all of the 50 samples collected in the three facies (Gmc, Gmco and Shc [1–5]).

5.2. Anatomy of charcoal remains

Different types of plant remains could be distinguished based on their anatomy. However, their small size makes it mostly

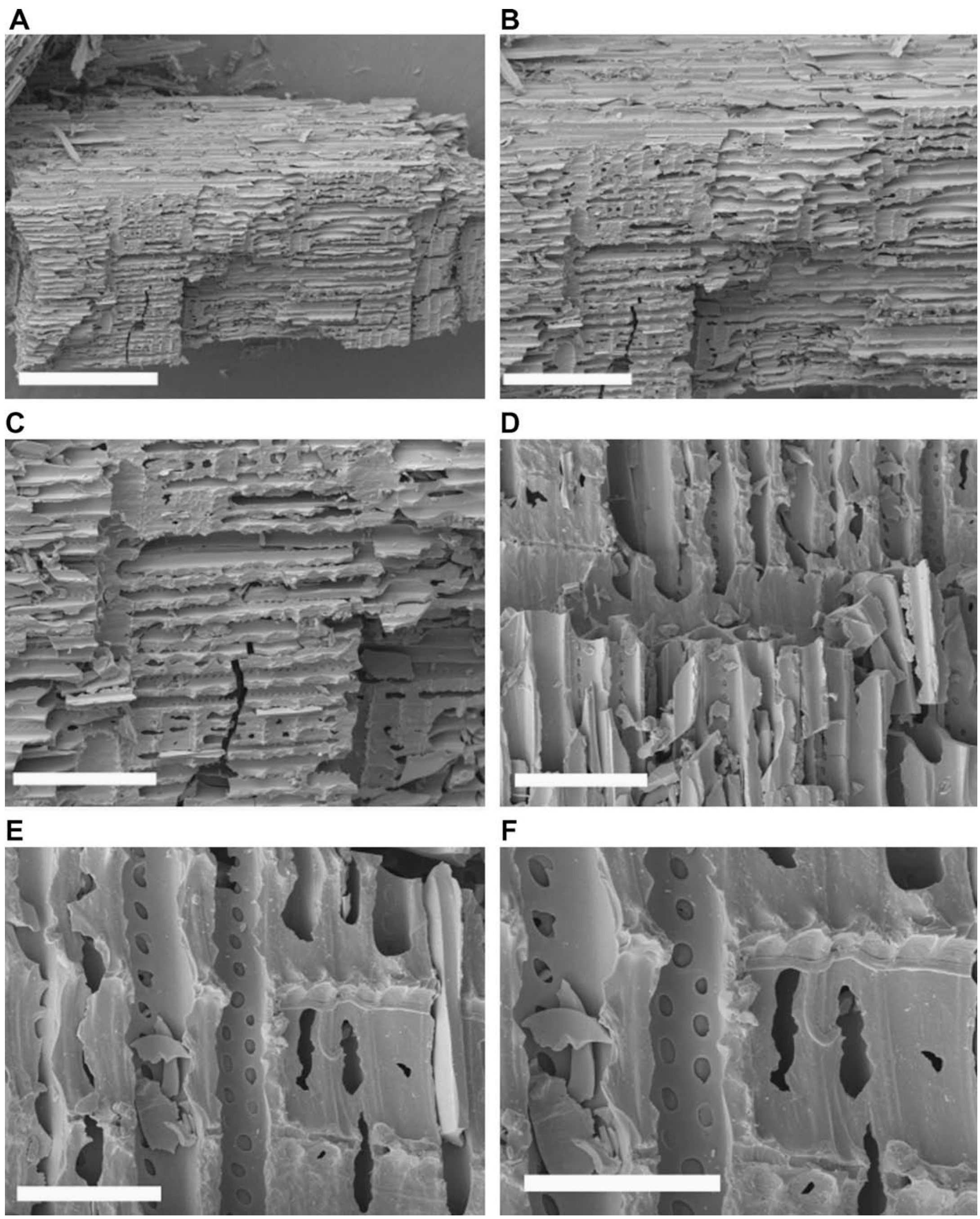

Fig. 5. Electronic microphotographs of the *Quitéria outcrop charcoal type 2*. (A) general view (scale corresponds to 100 μm); (B) general view (scale corresponds to 80 μm); (C) general view (scale corresponds to 60 μm); (D) detail of the tracheids with uniseriate and biseriate bordered pits (scale corresponds to 40 μm); (E) detail of the circular and oval form of the pits (scale corresponds to 30 μm) and (F) detail of the biseriate alternately arranged pits (scale corresponds to 20 μm).

impossible to establish specific taxonomic/systematic affinities, and also to decide whether they represent distinct ontogenetic stages of individual *taxa* or the natural variations of few *taxa*. All in all it was just possible to determine that two of these types correspond to gymnosperms and one to lycopsids. To demonstrate the anatomical diversity and organize a basic data-set for future work on charcoal in the source area, these types are described here briefly.

5.2.1. Charcoal type 1 (Fig. 4A–F)

Description: Pycnoxylic secondary woods, in radial view tracheids are 14–28 μm wide. They exhibit uniseriate and biseriate bordered pitting (Fig. 4A–C). Pits are circular to oval (2–6 μm in diameter) with circular to oval apertures and touching (Fig. 4A–C). When biseriate they are arranged oppositely or sub-oppositely (Fig. 4C). Rays are very abundant and composed of parenchymatous cells, 12–32 μm long and 18–24 μm high (Fig. 4D–F). Rays are uniseriate and 2–9 cells high (Fig. 4D and E). Cross-field pits are rarely visible and inconspicous (Fig. 4B). Leaf traces or growth rings are not visible. The cell walls are homogenized (Fig. 4B and C).

Remarks: This type of charcoal is the most common at the outcrop, occurring in the Gmco facies. Other remarks will be discussed together with the remarks of charcoal type 2.

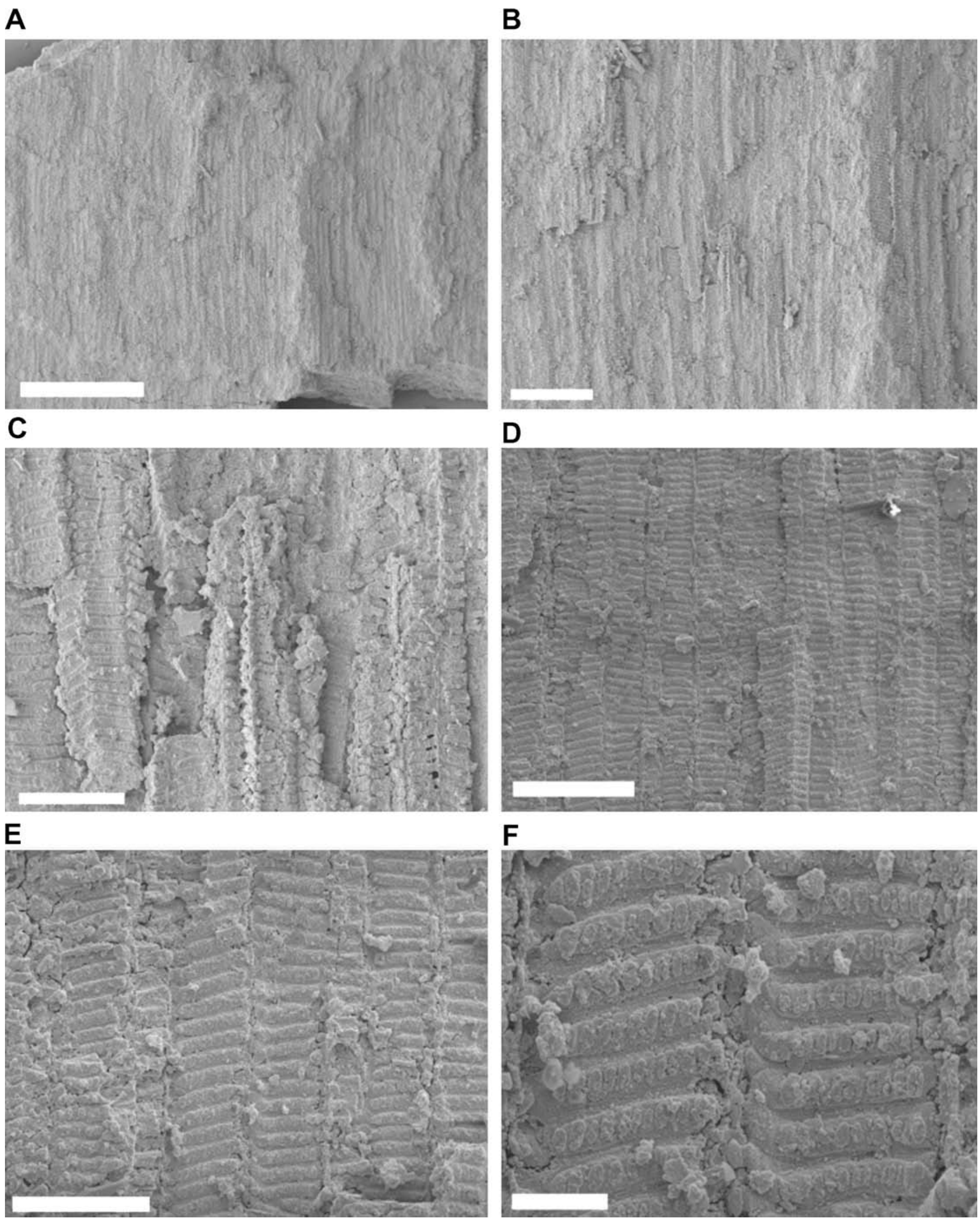

Fig. 6. Electronic microphotographs of the *Quitéria outcrop charcoal type 3*. (A) general view (scale corresponds to 50 μm); (B) general view (scale corresponds to 10 μm); (C) detail of the tracheids (scale corresponds to 8 μm); (D) detail of the scalariform pitting (scale corresponds to 20 μm); (E) detail of the anastomoses and vertical fimbrils connecting the horizontal bars (scale corresponds to 10 μm) and (F) detail of the anastomoses and vertical fimbrils connecting the horizontal bars (scale corresponds to 5 μm).

5.2.2. Charcoal type 2 (Fig. 5A–F)

Description: Pycnoxylic secondary wood, in radial view the tracheids are 8–16 μm wide. They exhibit uniseriate and rarely biseriate bordered pitting (Fig. 5D and E). Pits are circular to oval (1–3 μm in diameter) with circular or oval apertures and touching (Fig. 5E and F). Where the pits are biseriate they are arranged alternately (Fig. 5E and F). Rays are short and homogeneous, uniseriate (2–8 cells high) (Fig. 5A–D). No details of cross-fields visible, due to excessive damage (probably by sediment-load induced compression). Leaf traces or growth rings are not visible.

Remarks: This type of charcoal also occurs in the Gmco facies. The most prominent differences between the gymnosperm charcoal types 1 and 2 are dimensions of the tracheids (8–16 μm wide, as compared to 14–28 μm in charcoal type 1) and the arrangement of bisseriate pits, which are alternating in charcoal type 2 and opposite to sub-opposite in charcoal type 1. Different dimensions of tracheids can represent different growing stages of an individual *taxon*. The alternating position of bordered pits in the charcoal type 2 correspond to features included in the *Dadoxylon* Endlicher (1847) type of wood which has been broadly attributed to Palaeozoic woods from the northern hemisphere. Nevertheless, for taxonomic affiliations of woods from the southern hemisphere, especially from the Gondwana Realm, it will be necessary to consider that Marguerier (1973) as created the morphogenus *Australoxylon*, with mixed araucarioid/abietoid radial piting. However, considering the small size of the charcoal fragments, a taxonomic affiliation of both wood types to any known *taxon* established previously is impossible at the moment. All that can be stated is that both pycnoxylic wood types probably belong to gymnosperms.

5.2.3. Charcoal type 3 (Fig. 6A–F)

Description: Strongly permineralized bark with charred fragments of tracheids adhering to the permineralized matrix. In radial view the tracheids are 19–30 μm wide (Fig. 6A–C) and scalariform with minute anastomoses or vertical fimbrils connect the horizontal bars (Fig. 6A–F).

Remarks: This charcoal type is common, but has only been found in the coaly shale and coal facies immediately overlying the Gmco facies (Shc 5 – Fig. 2). It can be distinguished by its scalariform pitting with minute anastomoses or vertical fimbrils connecting the horizontal bars from all other charcoal types. Scalariform pitting with minute anastomoses or vertical fimbrils connecting the horizontal bars is a distinctive character of the arborescent lycopsids (Taylor and Taylor, 1993). Such lycopsids were in fact the dominant forms in the clastic swamp palaeoenvironment of the Quitéria outcrop, as evidenced by their massive representation in the roof-shale level (Sm facies). Otherwise, the high percentage of *Lundbadispora* spores, frequently grouped into tetrads together with lycopsid megaspores demonstrates that arborescent lycopsids were also the most important group of the coal generating flora (Jasper et al., 2006; Guerra-Sommer et al., 2008). Nevertheless, the absence of preserved anatomical features in the external compressed cast fragments identified as *Brasilodendron pedroanum* (Jasper and Guerra-Sommer, 1998) prevents secure taxonomic affiliation with the charcoal fragments presented here.

5.3. Palaeoenvironmental significance and taphonomy

In the framework proposed by Jasper et al. (2006) for the palaeoecological changes occurring during the time of deposition of the different phases of a cyclic deposition associated with a restricted lagoon at Quitéria outcrop, the Gmco facies is interpreted as containing fossil material of mostly allochtonous origin. In contrast, the Shc facies is interpreted as preserving parautochtonous fossil material; its palynological contents show great similarities with the macrofloristic association preserved in the overlying clastic roof-shale level.

The exclusive presence of charcoal type 3, representing bark of arborescent lycopsids in Shc 5 facies is in accordance with the palynological spectrum detected in the coaly shales and coals. It is important to observe that lycopsid bark, which constitutes the majority of a lycopsid stem, is much denser than the secondary wood, with few spaces that could be filled with a permineralization agent (in this case probably pyrite or one of its oxidation products, which are common in coals from the Paraná Basin [Kalkreuth et al., 2006]). As charred plant material is very susceptible to mechanical stresses (e.g. Scott, 2000), it can be assumed that the macroscopically identifiable charcoal remains, in the present case, might only have been preserved when they were in direct connection with the permineralized tracheids. Taking into account that arborescent lycopsids were dominant also in the swamps, it can be inferred that almost all the local vegetation was exposed to periodical burning events. The presence of thick bands of inertinite, composed almost entirely of inertodetrinite (Guerra-Sommer et al., 2008) in Shc facies, suggests a mechanical breakdown of the precursor material (fusinite) before the final deposition within the mire.

In contrast, the massive occurrence of charcoal representing charred fragments of gymnosperms woods in the Gmco facies evidences the occurrence (or even dominance) of gymnosperms (cordaites, conifers and/or glossopterids) in the nearby areas. Considering the high probability of volcanic activities in these areas, supported by the low weathering glass fragments identified in petrographic analyses, it can be assumed that these activities, together with lightning as the most common source of ignition (Scott, 2000), were a potential source of ignition for the wildfires.

The charcoal fragments are not abraded. Such delicate material would have been smashed into rounded pieces in the high energy depositional setting required to produce the conglomerates, although it is known that charcoal fragments can stay largely intact when transported as bedload of finer clastic sediments (i.e. sands), even over wide distances (Blong and Gillespie, 1978). Additionally, the fragments are not degraded, a fact that would also reinforce the hypothesis of parautochtonous origin for the material.

The homogenization conditions of the cell walls, if compared with the experimental results of Jones and Chaloner (1991), and the presence of vitrinite described by Guerra-Sommer et al. (2008) in the studied facies, indicates a maximum temperature of charring between 340 °C and 600 °C. These temperatures may be correlated with the characteristic of the wildfire which produced the charcoalified remains from the Quitéria outcrop, associated, probably, to forest-crown fires.

The occurrence of wildfires in the studied area during the Early Permian also corroborates modeling results that the atmospheric conditions during this time in this portion of the Gondwana Realm were in the fire window established by Jones and Chaloner (1991).

6. Conclusions

From the evidence discussed herein it is possible to draw the following conclusions:

(1) The charcoalified plant remains from the Quitéria outcrop (Rio Bonito Formation, Paraná Basin) testifies to the occurrence of wildfires in this area during the Early Permian (Sakmarian) and verifies earlier interpretations based on coal petrography analyses based on this and other outcrops nearby.
(2) The charred plant fragments are mostly well preserved. This evidence reinforces the hypothesis of parautochtonous origin for at least some of the material.

(3) The majority of the wood remains from Coaly matrix-supported Conglomerate (Gmco) facies corresponds to the basic type of gymnosperm wood (cordaites, conifers and/or glossopterids).
(4) In Coaly Shale (Shc 5) charcoal fragments from arborescent lycopsids were identified, pointing to the occurrence of wildfires within mire systems.
(5) The charcoalified remains of the Coaly Shale (Shc 5) facies represent wildfires that occurred very close to the coal-mires.
(6) The charcoalified remains of the Coaly Matrix Supported Conglomerates (Gmc and Gmco) are the result of forest-crown fires.
(7) Potential sources of ignition for the wildfires, besides the lightning strikes, are volcanic activities in nearby areas. Thus pyroclastic activities might be considered as directly correlated with the occurrence of wildfires.

Acknowledgements

The authors thank Dr. H. Schultze, Universität Tübingen, Germany, for support with SEM facilities. A. Jasper gratefully acknowledges financial support by Baden-Württembergisches Brasilien-Zentrum, Germany, CAPES, FAPERGS and UNIVATES, Brazil. D. Uhl gratefully acknowledges financial support from a Feodor Lynen Research Fellowship from Alexander von Humboldt-Foundation (Bonn/Bad Godesberg, Germany). M. Guerra-Sommer gratefully acknowledges financial support from CNPq, Brazil. The authors are grateful for the helpful comments from two anonymous referees.

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