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Indo-Brazilian Late Palaeozoic wildfires: an overview on macroscopic charcoal

Incêndios vegetacionais Indo-Brasileiros no Neopaleozoico: uma revisão dos registros de carvão vegetal macroscópico

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Abstract

Sedimentary charcoal is widely accepted as a direct indicator for the occurrence of paleo-wildfires and, in Upper Paleozoic sediments of Euramerica and Cathaysia, reports on such remains are relatively common and (regionally and stratigraphically) more or less homogeneously distributed. On the contrary, just a few reliable records have been published for the Late Paleozoic of Gondwana and only recently it has been demonstrated that macroscopic charcoals (and thus fires) were also common in the southern continent during this period. The most important Gondwanan records are predominantly charred gymnosperm woods mainly related to coal bearing strata. Late Paleozoic macro-charcoal occurs in both, the Damodar Basin (India) and the Paraná Basin (Brazil), demonstrating that paleo-wildfires were spread out in different sequences and distinct stratigraphic intervals during this period in Gondwana. Based on the so far published records as well as new samples from the Seam-VI coalfield, Raniganj Formation (Damodar Basin – Lopingian of India), an overview of the Late Paleozoic Indo-Brazilian macro-charcoal remains is presented. The hitherto unpublished samples were anatomically analyzed under Scanning Electron Microscope and a gymnosperm affinity could be established. The data presented here reinforce the relevance of paleo-wildfire as a source of environmental disturbance over large areas of Gondwana during the Late Paleozoic.

Keywords: Macro-charcoal; Gymnosperms; Paraná Basin; Damodar Basin; Permian.

Resumo

Carvão vegetal macroscópico é amplamente aceito como um indicador direto da ocorrência de paleo-incêndios vegetacionais, sendo relativamente bem estudado e distribuído de forma homogênea em depósitos do Paleozoico Superior da Euramérica e Cataísia. Por outro lado, apenas alguns registros deste tipo de material foram publicados para o Paleozoico Superior do Gondwana e, somente recentemente foi demonstrado que carvão vegetal macroscópico (e, portanto, incêndios) também é comum no continente meridional. Os mais importantes registros do Gondwana se constituem em fragmentos carbonizados de lenhos gimnospérmicos e estão associados, principalmente, a depósitos de carvão mineral. Registros de *macro-charcoal* (carvão vegetal macroscópico) foram descritos para níveis do Paleozoico Superior da Bacia Damodar (Índia) e da Bacia do Paraná (Brasil), demonstrando que paleo-incêndios vegetacionais ocorriam em sequências e intervalos estratigráficos variados no Gondwana durante esse período. Com base nos registros publicados até o momento e em novos exemplares provenientes do nível de carvão *Seam-IV*, Formação Raniganj, Bacia Damodar (Lopingiano da Índia), uma revisão acerca dos registros indo-brasileiros de carvão vegetal macroscópico em níveis do Paleozoico Superior são apresentados. O material inédito foi analisado sob Microscópio Eletrônico de Varredura para a definição de características anatômicas, sendo estabelecida uma afinidade gimnospérmica para os fragmentos. Os dados apresentados reforçam a importância dos paleo-incêndios vegetacionais como elemento perturbador dos diferentes paleoambientes gondvânicos durante o Paleozoico Superior.

Palavras-chave: Macro-charcoal; Gimnospermas; Bacia do Paraná; Bacia Damodar; Permiano.

INTRODUCTION

Although widely studied and regionally and stratigraphically more or less homogeneously distributed in Euromerican and Cathaysian Late Paleozoic sequences (Sander, 1987; Sander and Gee, 1990; Scott, 1990; Scott and Jones, 1994; Falcon-Lang, 2000; Wang and Chen, 2001; Uhl and Kerp, 2003; DiMichele et al., 2004; Uhl et al., 2004, 2008; Shen et al., 2011), macroscopic charcoal of this time interval was only recently described in detail for the Gondwanan area (Jasper et al., 2008, 2011a, 2013). Considering that many scientists accept these remains as a direct indicator for the occurrence of paleo-wildfires (Jones and Chaloner, 1991; Scott, 2010), and that they are common in the southern continent, a scenario in which fire was a more or less common event in many Late Paleozoic ecosystems of Gondwana has also to be considered.

Such a paleobotanical approach partially contradicts earlier assumptions (e.g., Falcon, 1989; Hunt, 1989; Taylor et al., 1989) which considered that occurrences of paleo-wildfires were not common in the Gondwanan Late Paleozoic mires and surroundings. A debate about this topic persists in recent literature (e.g. Hower et al., 2011; Richardson et al., 2012) where arguments against the pyrogenic origin of the Gondwanan inertinites (group of macerals) in coal layers are presented.

In a comparative review of the then known occurrences of fossil macro- and micro-charcoals as well as inertinite occurrences all over the Late Paleozoic of Gondwana, Jasper et al. (2013) demonstrated that the paleobotanical evidences are mostly spatially and temporally coincident with the occurrence of inertinites, supporting that a pyrogenic origin for them has to be considered. In addition, several localities showed positive result for macroscopic charcoal in diverse Permian sequences in the Gondwanan area (Jasper et al., 2011b, 2011c, 2012) reinforcing that, despite abundant occurrences, this kind of remains were obviously partially neglected in previous Late Paleozoic paleobotanical studies (Abu Hamad et al., 2012).

With the aim to improve the concept of a Gondwanan paleo-wildfire scenario during the Permian and to show the lack of information about macroscopic charcoal of that age, this paper reviews the so far described macroscopic charcoal occurrences for India and Brazil, two significant parts of this ancient continent. Moreover, complementary data of the Damodar Basin (Raniganj Formation – India) are presented, enabling a more detailed evaluation of the paleo-wildfire dynamics on the area than previously suggested by Jasper et al. (2012).

THE LATE PALEOZOIC INDO-BRAZILIAN MACROSCOPIC CHARCOAL RECORD

Macroscopic charcoal (*sensu* Jones and Chaloner, 1991; Scott, 2010) in sediments is widely accepted as a direct indicator for the occurrence of paleo-wildfires (Scott, 1989, 2000, 2010; MacDonald et al., 1991; Scott and Glasspool, 2006; Glasspool et al., 2004; Flannigan et al., 2009) and was considered as absent or rare in Gondwanan late Paleozoic sediments until the last decade (Jasper et al., 2013). Besides some short reports (e.g. Cazzulo-Klepzig et al., 1999; Jasper et al., 2006; Guerra-Sommer et al., 2008a), the first detailed description of this kind of material was made for a Permian exposure at the southern border of the Paraná Basin, Rio Bonito Formation, Rio Grande do Sul State, Brazil, by Jasper et al. (2008). These authors described charred woods related to gymnosperms and charred barks with lycopsid characteristics for two different coal facies of the Quitéria Outcrop. Those first results highlighted that macroscopic charcoal (hence paleo-wildfires) could in fact be formed in the Late Paleozoic ecosystems from Gondwana.

Additional findings from the Permian of the Paraná Basin were described by Jasper et al. (2008). In total, seven localities distributed on Paraná Basin's southern and eastern borders were studied and several macroscopic charcoal presenting anatomical features supporting a taxonomic affiliation to the morphogenus *Agathoxylon* (Philippe and Bamford, 2008) could be identified. The authors reinforced that this type of wood is very common for Late Paleozoic gymnosperms in Gondwana, deriving from different phylogenetic affinities and diverse taxa, including the widely distributed Glossopteridales (Prevec et al., 2009). However, the presence of tracheids with spiral thickening of the tertiary wall associated with uniseriate isolated pits in one of the samples (see Figures 6F-H and 7A-C of Jasper et al., 2011a), allowed a relation of that material in particular to conifers.

Although not the main aim of the paper, Manfroi et al. (2012) confirmed with Scanning Electron Microscope (SEM) images the presence of charred parenchyma cells associated to leaf cushions of *Brasilodendron pedroanum* (Chaloner et al., 1979). The studied samples came from the coal-bearing strata from the Artinskian of the Santa Catarina Coalfield, Rio Bonito Formation, Paraná Basin, Santa Catarina State, Brazil. These results reinforced the statement made by Jasper et al. (2008), according to which, sub-arborescent Lycophytes could also be preserved as macroscopic charcoal in Gondwana.

In case of India, macroscopic charcoal has been described for carbonaceous shale associated with Seam-VI of the Raniganj Formation, Upper Permian, Damodar Basin by Jasper et al. (2012, 2016, In press) and Mahesh et al. (2015). The anatomical features demonstrated that plants with a pycnoxylic gymnospermous wood were submitted to paleo-wildfire events in that area during the late Permian, demonstrating that not only the western part of Gondwana, but also the eastern, was subject to burning.

Jasper et al. (2013), provided a review of the Gondwanan macroscopic charcoal occurrences and showed that, despite a few exceptions (e.g. Jasper et al., 2008; Manfroi et al., 2012) the most important Gondwanan records are predominantly charred gymnosperm woods, mainly related to coal-bearing strata (Table 1). The remains are spread out in different sequences and also in distinct stratigraphic Permian intervals

Table 1. Published records of Permian charcoal. Data based on Abu Hamad et al. (2012), Jasper et al. (2013, In press).

Localities	Country	Age	Evidence type	References
Candiota coalfield	Brazil	Sakmarian	Macroscopic	Jasper et al. (2011a)
Leão-Butiá coal-field	Brazil	Sakmarian	Macroscopic	Jasper et al. (2011a)
Faxinal coalfield	Brazil	Sakmarian	Macroscopic	Degani-Schmidt et al. (2015), Jasper et al. (2011b), Guerra-Sommer et al. (2008b)
Morro Papaléo outcrop	Brazil	Sakmarian	Macroscopic	Jasper et al. (2011b), Jasper et al. (2011c)
Quitéria outcrop	Brazil	Sakmarian	Macroscopic	Costa et al. (2016), Jasper et al. (2006, 2008), Cazzulo-Klepzig et al. (1999), Guerra- Sommer et al. (2008a)
Santa Catarina Coal Basin	Brazil	Artinskian	Macroscopic	Jasper et al. (2011a)
Figueira coalfield	Brazil	Artinskian	Macroscopic	Jasper et al. (2011a)
Bonito coal seam, Santa Catarina state		Artinskian	Macroscopic	Manfroi et al. (2012)
Barro Alto Outcrop	Brazil	Guadalupian	Macroscopic	Manfroi et al. (2015)
Prince Charles Mountains	Antarctica	Rodian – Wordian	Macroscopic	Slater et al. (2015)
Andradina outcrop, Parnaíba	Brazil	Lopingian	Macroscopic	Kauffmann et al. (2016)
Sohagpur Coalfield, Barakar Formation	India	Early Permian (Cisuralian)	Macroscopic	Jasper et al. (In press)
Seam-VI, Raniganj Formation	India	Late Permian	Macroscopic	Present study
Weller Formation, Allan Hills, South Victoria Land	Antarctica	Late Permian	Macroscopic	Tewari et al. (2015)
Bore core SKB-1, Karanpura Coalfield, Raniganj Formation	India	Late Permian	Macroscopic	Mahesh et al. (2015)
Bore core SKB-1, Karanpura Coalfield, Barren Measure Formation	India	Late Permian	Macroscopic	Mahesh et al. (2015)
Lower Whybrow coal	Australia	Wuchiapingian	Macroscopic	Glasspool (2000)
South Island, Kuriwao group	New Zealand	Wuchiapingian – Changhsingian	Microscopic	Crosbie (1985), Campbell et al. (2001)
Perth Basin	Australia	Changhsingian	Microscopic	Foster et al. (1997),
Tibet, North Indian margin	China	Changhsingian	Microscopic	Schneebeli-Hermann et al. (2012)
Wadi Himara	Jordan	Changhsingian	Macroscopic	Uhl et al. (2007)
Damodar Valley Basin	India	Changhsingian	Macroscopic	Jasper et al. (2012)
Zewan Formation, Kashmir	India	Changhsingian	Macroscopic	Jasper et al. (2016)

[e.g. Paraná Basin (Sakmarian/Artinskian of Brazil), Karoo Basin (Artinskian of South Africa), Damodar Basin (Lopingian of India) and Wadi Himara (Lopingian of Jordan)]. According to the authors, they range from periglacial/postglacial to warm temperate climatic conditions and, if compared to known occurrences of inertinites, the macro-charcoal support the pyrogenic origin for these coal macerals also for the Gondwana.

Considering the so far restricted data about Late Paleozoic Gondwanan macroscopic charcoal which, as shown before, also occurs in India and Brazil, the constant mapping of new occurrences will provide an up to date overview on the distribution dynamics of paleo-wildfires in space and time. As stated by Abu Hamad et al. (2012), the interpretation of the so far established "Gondwanan late Paleozoic macroscopic charcoal gap" could be difficult, considering that many factors (including non-compliance by Gondwanan scientists) may have influenced the recovery of evidence for paleo-wildfires for this area and time interval.

GENERAL GEOLOGICAL CONTEXT OF THE INDO-BRAZILIAN STUDIED SEQUENCES

The comparative overview presented here is restricted to the Late Paleozoic macroscopic charcoal remains so far described from India and Brazil and to the new occurrence presented here for the first time. Considering that those remains are yet restricted to the Damodar Basin, in India, and to the Paraná Basin, in Brazil, the geological context of both areas is described in a general approach.

The Damodar Basin (Figure 1) includes the Permian deposits of the Talchir, Karharbari, Barakar, Barren Measures and Raniganj formations (Murthy et al., 2010). Specifically the Raniganj Formation, from where the macroscopic charcoal has so far been studied and the new remains presented here originate, is lithologically characterized by the association of coals, organic rich carbonaceous shales, siltstones and sandstones (Mukhopadhyay et al., 2010). However, the coal seams are usually thinner and less frequent and sandstones vary from fine to coarse grained.

The Raniganj Formation, which overlies the sandstones of the Barren Measures Formation and underlies the claystones of the Panchet Formation, was deposited under a warm, temperate, humid paleoenvironment (Lele, 1976; Chandra, 1992; Tiwari and Tripathi, 1992; Ghosh, 2002). Its coaly sediments were deposited during a regressive phase, representing an anoxic floodplain enabling the deposition of significant peat (Mukhopadhyay et al., 2010).

The Paraná Basin (Figure 2) occupies approximately 1,700,000 km^2 in southeastern South America covering parts of southern Brazil, Paraguay, Uruguay and Argentina. Six depositional super-sequences that resulted from second-

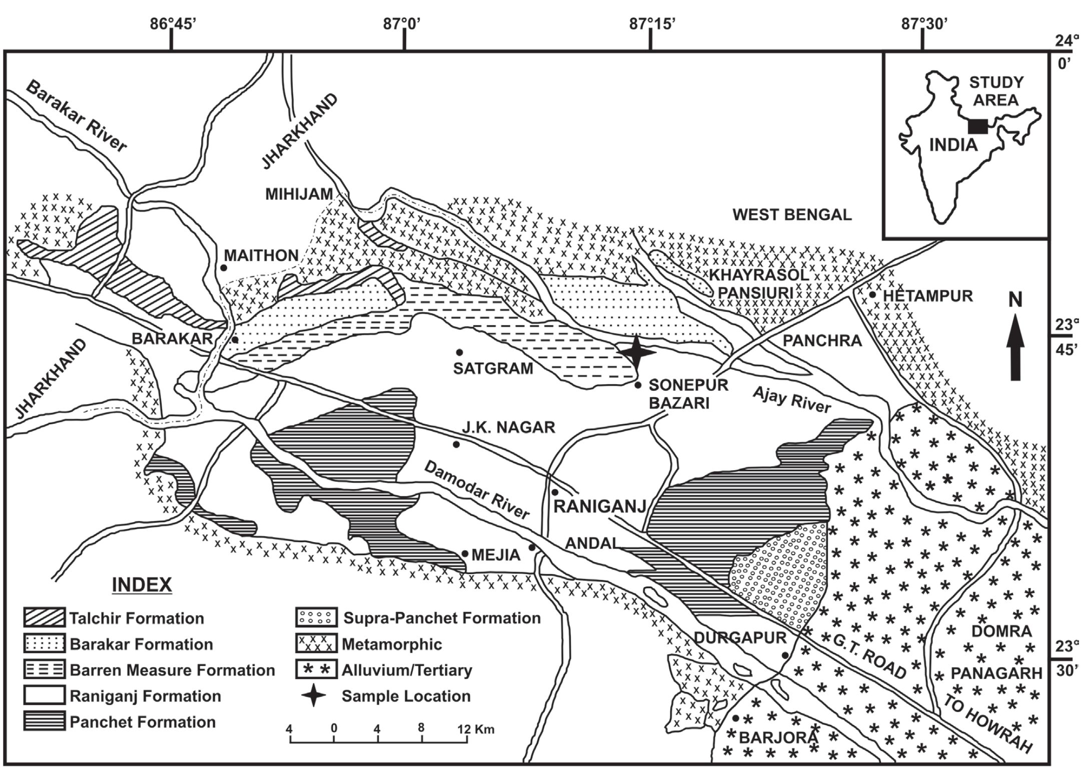

Figure 1. Simplified map of the Damodar Basin with the position of the sampling location of the new macroscopic charcoal remains described here (modified from Jasper et al., 2012, Figure 2).

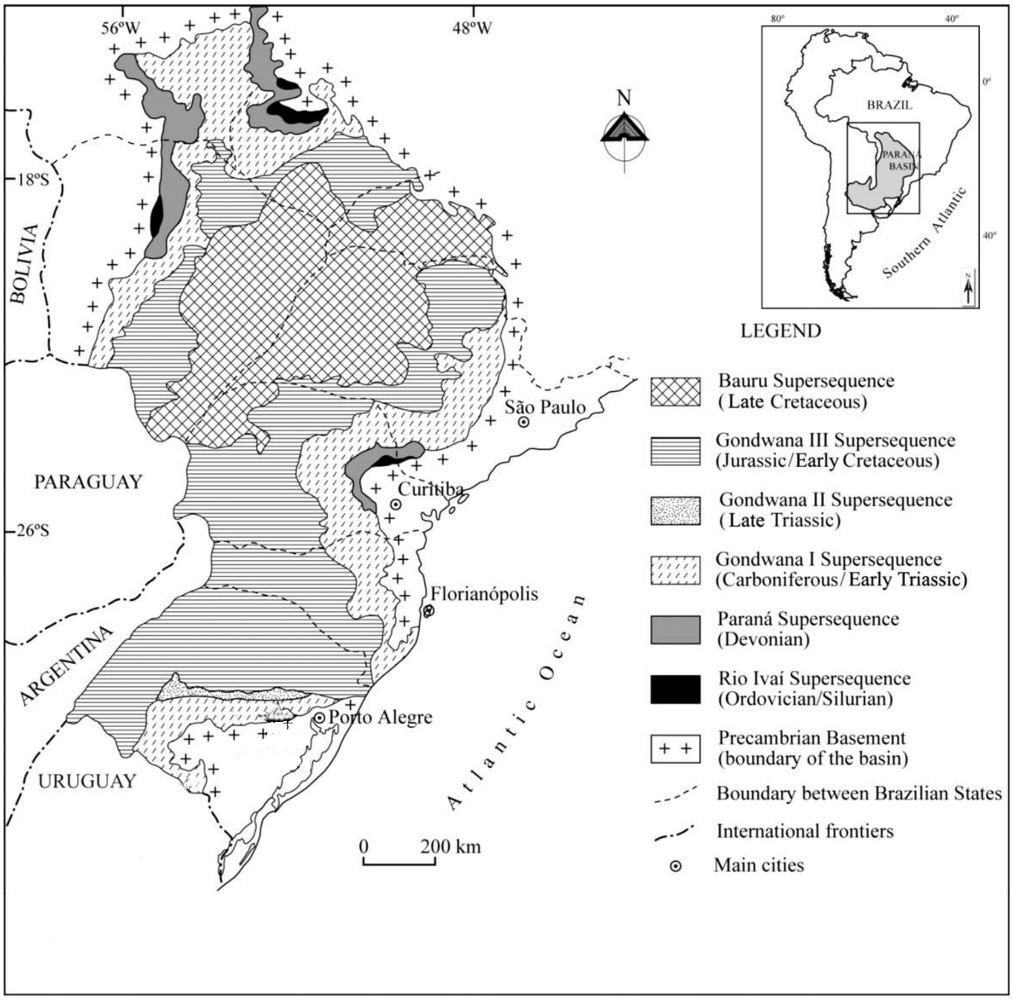

Figure 2. Simplified map of the Paraná Basin with the sedimentary units and the distribution of the Gondwana I Supersequence outcropping area where the macro-charcoal remains occur (modified from Milani et al., 1998).

order eustatic and tectonic events can be observed from the base to the top, comprising Ordovician to Cretaceous sediments (Milani et al., 2007).

So far, macroscopic charcoal was described only for the Permian coal-bearing strata of the Rio Bonito Formation, which constitutes a second-order transgressive-regressive cycle (Milani et al., 2007; Holz et al., 2010). The Rio Bonito paleoenvironmental context is related to fluvio-paralic and lagoon back-barrier systems, which were deposited under a fluctuation between relatively dry and humid conditions, reflecting climatic seasonality (Guerra-Sommer et al., 2008b; Holz et al., 2010).

MATERIAL AND METHODS

Considering that the present paper aims to show the current status of the aleo-wildfire studies for the Indian and Brazilian Late Paleozoic strata, the data mostly summarize the results published so far about the issue. On the other hand, a new occurrence of macroscopic charcoal is also presented, demonstrating the continuing need for research on such remains.

The material studied here in more detail was collected from the shale associated with the Seam-VI of the Raniganj Formation. The samples are complementary to those analyzed by Jasper et al. (2012) and were provided by subsequent sampling made in the area by the Birbal Sahni Institute of Paleosciences staff in different layers from the same area. They are permanently stored in the Paleobotany Collection of the Botany and Paleobotany Sector – Natural Science Museum, at UNIVATES, Brazil (specimens PbU 918 to 922).

The material was identified as macroscopic charcoal based on the characteristics established by Jones and Chaloner (1991) and Scott (2010): black color and streak; silky luster; homogenized cell walls; well-preserved anatomical details. The material was extracted mechanically from sediment samples with the aid of preparation needles and tweezers, under a binocular microscope. Due to the very fragile nature of all of the specimens, they could not be cleaned with water or any acids to remove adhering mineral remains. The fragments were mounted on standard stubs with LeitC (Plano GmbH, www.plano-em.de).

Subsequently, the samples were examined with the aid of a Zeiss EVO LS15 Scanning Electron Microscope (SEM) at the TECNOVATES (*Parque Científico e Tecnológico do Vale do Taquari*) in UNIVATES, for morpho-anatomical descriptions. Considering the absence of conclusive anatomical features, the taxonomical inferences were maintained in a general view, which did not affect the final remarks presented here given that they are of a paleoenvironmental nature.

RESULTS

Eight macroscopic charcoal fragments, measuring between 0.1 × 0.2 × 0.2 and 0.2 × 0.4 × 0.6 cm were recovered from the sediment samples. They have no abraded edges and, under SEM analysis, they present well-preserved anatomical details (Figure 3A, B) and homogenized cell-walls (Figure 3C, D).

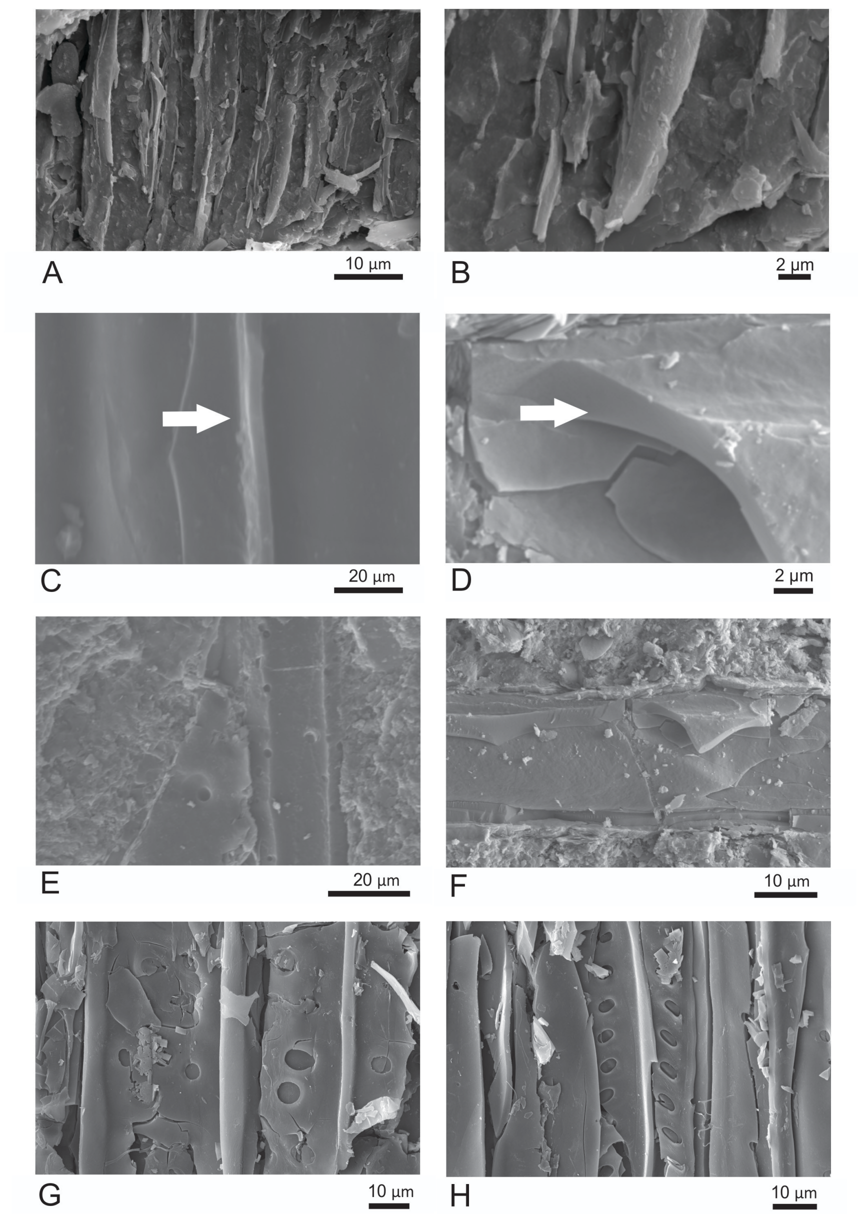

Figure 3. SEM images of additional macro-charcoal remains from the Seam-IV coalfield (Raniganj Formation, Damodar Basin, India). (A, B) general view of tracheids with preserved cell features; (C, D) detail of the cell-walls homogenization (arrow) observed in the samples; (E, F) detail of the woody tissues shattering observed in some of the samples; (G) tracheids exhibiting uniseriate and tri-seriate circular pitting; (H) tracheids exhibiting uniseriate circular pitting.

The woody tissues are shattered into more or less small pieces, preventing the visualization of complete tissue characteristics (Figure 3E, F). Tracheids are 15-25 μm in width, exhibiting uniseriate and tri-seriate circular pitting [with 1-4 μm in diameter (Figure 3G, H)]. Rays, cross-field pits, leaf traces or growth rings are not visible.

DISCUSSION

The presence of homogenized cell-walls in the studied material confirms that the samples are macroscopic charcoal, a direct indicator for the occurrence of paleo-wildfires (Jones and Chaloner, 1991; Scott, 2010). The tracheids have typical gymnosperm affinities, with clear uniseriate and tri-seriate circular pitting (Philippe and Bamford, 2008).

Despite the restricted taxonomical inferences, prevented by the absence of more characteristic features, the macroscopic charcoal samples described here demonstrate the occurrence of paleo-wildfires in more than one layer of the Seam-VI of the Raniganj Formation. That reinforces the suggested "Late Paleozoic burning Gondwana" (Jasper et al., 2013) in contradiction with previous assumptions which considered paleo-wildfires as an unusual event in that time and area (Falcon, 1989; Hunt, 1989; Taylor et al., 1989).

The repetitive association of macroscopic charcoal samples to Permian coal and coal-bearing strata all around Gondwana demonstrates that areas around the mire systems could burn. Modern mires and swamps can burn if they are submitted to a severe dry season (Cypert, 1961; Richardson, 2010; Wu et al., 1996), such fire events during Permian times may have been intensified by the high atmospheric oxygen levels (Berner, 2006). In that context, the increasing recovery of macroscopic charcoal in late Paleozoic Gondwanan deposits fits with the increase in paleoatmospheric oxygen concentration (pO_2) reconstructed during the Permian on Earth (Glasspool and Scott, 2010).

In addition, the pyrogenic origin for the Gondwanan coals high inertinite concentrations have to be considered. If the pO_2 levels reached 30% during the Permian (Berner, 2006; Glasspool and Scott, 2010), it is fully plausible that mires in the area burned regularly, allowing the deposition of the macerals over longer periods of time. Thus "frequent fire in the Gondwanan mires" during the Late Paleozoic (Uhl and Jasper, 2011; Jasper et al., 2013) has to be considered as an important source of disturbance in the paleoecological reconstructions for that ancient continent.

In view of recent findings as in the present study, further studies on late Paleozoic wildfires is needed, focusing on the macroscopic charcoal remains, concentrating the efforts on the macroscopic charcoal remains from peat-forming as well as non-peat-forming environments. If compared with the sampling/descriptions so far carried out for this period in Euramerica and Cathaysia, it becomes evident that the Gondwana database for Permian paleo-wildfires needs enlargement. Only such an effort will enable a global comparative evaluation about those paleo-wildfires in space (Northern and Southern Hemisphere) and time (during the entire Phanerozoic).

CONCLUSIONS

From the evidence presented here, it is possible to draw the following conclusions:

1. New macroscopic charcoal with gymnosperm affinity from the Raniganj Formation (Damodar Basin) coal-bearing strata could be identified;
2. Paleo-wildfires occurred more than once during the Permian in the Raniganj Formation Seam-VI area;
3. Both Damodar and Paraná basins demonstrate repetitive paleo-wildfire events during the Permian;
4. Constant and repetitive paleo-wildfire events in Gondwanan Permian mire systems can be related to high pO_2 levels registered for that period;
5. Pyrogenic origin for the high inertinite macerals concentration in some Gondwanan Permian coals has to be seriously considered;
6. More macroscopic charcoal sampling from Gondwanan Late Paleozoic deposits is necessary to furnish the construction of a global paleo-wildfires scenario for the Phanerozoic.

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