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The burning of Gondwana: Permian fires on the southern continent—A palaeobotanical approach

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ABSTRACT

Fossil charcoal has widely been accepted as a direct indicator for the occurrence of palaeo-wildfires. In Upper Palaeozoic sediments of Euramerica and Cathaysia, records of these remains are relatively common and (regionally and stratigraphically) more or less homogeneously distributed in terrestrial sequences. On the other hand, just a few records have been published for the Permian of Gondwana and only recently has it been demonstrated that macroscopic charcoals are also common here. Most Permian macroscopic charcoal from Gondwana is gymnospermous and has been reported from coal-bearing strata. Macroscopic charcoal occurrences are spread out in different sequences and also in distinct stratigraphic intervals in the Permian [e.g., Paraná Basin (Sakmarian/Artinskian of Brazil), Karoo Basin (Artinskian of South Africa), Damodar Basin (Lopingian of India) and Dead Sea area (Changhsingian of Jordan)]. They range from peri-glacial/post-glacial to warm temperate climatic systems throughout the Permian. Macro- and micro-charcoal occurrences are compared to inertinite incidences to support the pyrogenic origin for these coal macerals and to provide an up to date overview on the known evidences of Permian wildfires on Gondwana in space and time.

1. Introduction

In modern ecosystems, fire is a significant source of disturbance (Bowmann et al., 2009; Flannigan et al., 2009) and can be compared to *herbivory* as an important factor of modification in different biomes (Bond and Keeley, 2005). In addition, wildfires have occurred more or less regularly in different ecosystems since the appearance of the first embryophytic land plants (Glasspool et al., 2004) and it can be assumed that, during past periods of the Earth's history, these events would have played a role in the shaping/evolution of different biomes (Scott and Stea, 2002; Preston and Schmidt, 2006; Scott, 2010).

Despite geochemical [pyrogenic polycyclic aromatic hydrocarbons (PAHs)] and petrological evidence (interinites), the most reliable method to reconstruct the occurrence of palaeo-wildfires in different palaeoenvironments and time periods is the occurrence of macroscopic and microscopic fossil charcoal in clastic sediments (*sensu* Jones and Chaloner, 1991; Scott, 2010). Such remains, occurring in different geological levels around the world, confirm the occurrence of (palaeo) wildfires since the Silurian (Glasspool et al., 2004) up to the Quaternary (Scott, 1989, 2000, 2010; MacDonald et al., 1991; Scott and Glasspool, 2006; Flannigan et al., 2009).

Direct evidence of Late Palaeozoic palaeo-wildfires has largely been studied in the Northern Hemisphere for the last two decades and macroscopic fossil charcoal remains are well described from Europe (e.g., Scott, 1990; Scott and Jones, 1994; Falcon-Lang, 2000; Uhl and Kerp, 2003; Uhl et al., 2004, 2008), North America (e.g., Sander, 1987; Sander and Gee, 1990; Falcon-Lang, 2000; DiMichele et al., 2004) and China (e.g., Wang and Chen, 2001; Shen et al., 2011) and used to support the pyrogenic origin of inertinite in coals (Scott, 2000, 2010; Scott and Glasspool, 2007). Additionally, fossil charcoal and other evidence of palaeo-wildfires from the Northern Hemisphere is also widely used to reconstruct fire related aspects of a number of palaeoenvironmental and palaeoclimatic issues (e.g., Belcher et al., 2010a; Bond and Scott, 2010; Uhl et al., 2010; 2012).

In an attempt to contribute to a palaeo-wildfire scenario concerning Gondwana during the Permian, this paper has the primary goal of summarizing information about fossil evidence for palaeo-wildfires coming

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from different regions all over Gondwana. The occurrences of fossil macro- and micro-charcoals are compared to inertinite occurrences to support the observation that, contrary to earlier assumptions (e.g., Falcon, 1989; Hunt, 1989; Taylor et al., 1989) which still persist in the literature (Hower et al., 2011; Richardson et al., 2012), the majority of macerals belonging to this group are of pyrogenic origin (Scott, 2000, 2010 and references cited therein; Scott and Glasspool, 2007).

2. A case for the pyrogenic origin of Permian Gondwana inertinite

The occurrence of palaeo-wildfires in the Permian of Gondwana was not accepted for a long time. This denial is probably based on different opinions concerning the definition/identification of fossil charcoal. Scott (2000) dedicated a chapter of his review paper on the pre-Quaternary history of fire to the so called "Problem of the Gondwana inertinites". The controversy was based on the statements of authors like Falcon (1989), Hunt (1989) and Taylor et al. (1989) who considered it to be improbable that fire was responsible for the high inertinite levels (in some cases more than 50%) observed in many (but not all!) Permian coals from Gondwana.

Falcon (1989) argued that the subarctic to cold temperatures which dominated in Gondwana during the Permian, when the coals were deposited, contributed to a low plant growth and thus slow accumulation of biomass. Consequently, the degradation of the plant biomass should have also been gradual or somewhat inhibited, allowing for the formation of inertinite by processes other than fire (e.g., freeze-drying).

Hunt (1989) and Taylor et al. (1989) also proposed that the cold-climate conditions have to be seen as responsible for high inertinite levels of Gondwana Permian coals. They stated that the low temperatures in the mires must have been responsible for the reduction of the plant matter decomposition by microorganisms and, in such a cold and dry environment, partially or totally humified plant tissues would, if exposed to air, be "freeze-dried" with minimal oxidation.

For a long time fire was not considered as a possible origin for the abundant inertinite present in many Gondwana Permian coals (Falcon, 1989; Hunt, 1989; Taylor et al., 1989, 1998) in contrast to opinions concerning northern hemisphere inertinite. So, while fires were considered to have been common events in the Late Palaeozoic Eurasian peat forming environments, and the co-occurrence of inertinite and macroscopic as well as microscopic fossil charcoal in the same levels was largely accepted/expected because of their common pyrogenic origin, in the Gondwana Realm it was neither considered the only nor a significant factor at all (Corrêa-da-Silva and Wolf, 1980; Silva and Kalkreuth, 2005; Silva et al., 2008; Niekerk et al., 2010). In this way, despite high inertinite levels, the occurrence of fossil charcoal was not accepted as evidence of palaeo-wildfires for the Late Palaeozoic Gondwana until the last decade (Jasper et al., 2008). Thus, it seems possible that previous researchers simply may have overlooked macroscopic fossil charcoal remains from this age and area, as other authors (Jones, 1993; Scott, 2010; Uhl et al., 2010) assumed before for other examples.

The present study, although mainly focusing on macroscopic as well as microscopic fossil charcoal (*sensu* Jones and Chaloner, 1991; Scott, 2010) from the Gondwana Permian as primary (and undisputed) evidence for the occurrence of palaeo-wildfires; also discusses the "Problem of the Gondwana inertinites" (Scott, 2000). Therefore, a review of the Permian occurrences published to date of the three palaeo-wildfire indicators [inertinite, PAHs and (macroscopic/microscopic) fossil charcoal] was carried out in order to understand large scale regional and temporal trends (see Tables 1–3 and Fig. 1). The database is based on data compiled by Abu Hamad et al. (2012) supplemented by recently published works and additional references that have been discovered by continuing literature surveys [for comments why such a database will probably be incomplete with regard to the existing data see Diessel (2010) and Abu Hamad et al. (2012)].

Table 1
Overview of published records of Permian macro- and micro-charcoals from Gondwana. For details see text.

Locality/area	Country	Age	Type of evidence	References
Candiota coalfield	BRA	Sakmarian	Macro	Jasper et al. (2011b)
Leão-Butiá coalfield	BRA	Sakmarian	Macro	Jasper et al. (2011b)
Faxinal coalfield	BRA	Sakmarian	Macro	Jasper et al. (2011a); Guerra-Sommer et al. (2008b).
Morro do Papaléo outcrop	BRA	Sakmarian	Macro	Jasper et al. (2011b)
Quitéria outcrop	BRA	Sakmarian	Macro	Jasper et al. (2006, 2008); Cazzulo-Klepzig et al. (1999); Guerra-Sommer et al. (2008a)
Santa Catarina coal basin	BRA	Artinskian	Macro	Jasper et al. (2011b)
Figueira coalfield	BRA	Artinskian	Macro	Jasper et al. (2011b)
Lower Whybrow coal	AUS	Wuchiapingian	Macro	Glasspool (2000)
Damodar Basin	IND	Wuchiapingian–Changhsingian	Macro	Jasper et al. (2012)
South Island, Kuriwao Group	NZL	Wuchiapingian–Changhsingian	Micro	Crosbie (1985); Campbell et al. (2001)
Perth Basin	AUS	Changhsingian	Micro	Foster et al. (1997)
Tibet/North Indian Margin	CHN	Changhsingian	Micro	Schneebeli-Hermann et al. (2012)
Wadi Himara	JOR	Changhsingian	Macro	Uhl et al. (2007)

The data on charcoal occurrence are collated by stages (cf. Tables 1–3), following the approach used by Abu Hamad et al. (2012). However, for the Middle Permian, the dating of most samples was too imprecise to follow this approach consistently. The Middle Permian samples have therefore been pooled into a single bin that corresponds to an epoch (i.e., the Guadalupian) in Fig. 2. Although such an approach leads to bins which are not equally long, bins with equal duration (as used by Glasspool and Scott, 2010) have not been used, as dating for most records is not good enough to provide reliable absolute ages.

Different proportions of inertinite in individual coal seams show that there are short scale regional and temporal trends in adjacent coal deposits (see compilations in Diessel, 2010; Glasspool and Scott, 2010). However, the reconstruction of such small scale trends is beyond the scope of the present study, as these trends could only be reconstructed for a few regions and time-slices and not for the entirety of the area covered by this study.

3. The general Gondwana palaeobotanical scenario during the Permian

It is worth highlighting that palaeo-wildfire events only occurred when suitable fuel (= biomass) was present, and that during the Permian vegetation was one of the most important ecological factors for the occurrence of wildfires. Fire dynamics depends on and reflects the vegetation (as well as climate and atmospheric oxygen; cf. Scott, 2000 for discussion of the so-called fire-triangle) which occupied the burning area, creating a strong connection between both. So, a general view about the composition and development of the vegetation which could potentially be burned is also necessary if palaeo-wildfire is in discussion. To give the non-palaeobotanist an idea about the development of vegetation on Gondwana during the Permian we provide a short summary.