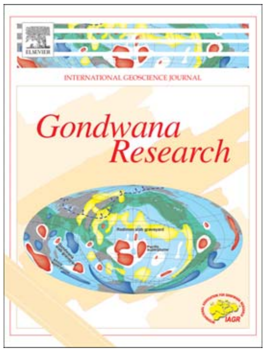

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The burning of Gondwana: Permian fires on the southern continent – a palaeobotanical approach

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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 it has 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.

Keywords: Permian; Gondwana; palaeo-wildfire; climate; peat deposition.

1. Introduction

In modern ecosystems, fire is a significant source of disturbance (Bowman 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 (Preston and Schmidt, 2006; Scott, 2010; Scott and Stea, 2002). 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, *in press*).

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 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 that 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 (Côrrea-da-Silva and Wolf, 1980; Niekerk et al., 2010; Silva and Kalkreuth, 2005; Silva et al., 2008). 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)].

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 Figure 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.

An abrupt change from glacial to post glacial deposits of Early Permian age on the latest glaciation episode of the Late Palaeozoic glaciation of Gondwana (López-Gamundí, 1997; López-Gamundí and Buatois, 2010) records the rapid withdrawal of ice from depositional basins throughout Gondwana (Isbell et al., 2003). Palaeobotanical data (Ziegler, 1990; Cuneo, 1996; Ziegler et al., 2003) have shown that provinciality of Gondwana changed significantly during the course of the Permian, mainly influenced by palaeogeographic and palaeoclimatic parameters (Wagner, 1993; Rees et al., 2002). Waning of Early Cisuralian (Asselian-Sakmarian) glaciation in the Gondwana continent was manifested in floral associations preserved within sandstones and shales deposited in glacio-fluvial and glacio-lacustrine palaeoenvironments. In the South American subcontinent (Eastern and Southern Brazilian Paraná Basin and Western Argentina) palaeobotanical evidence point to a single phytogeographic unit, evidenced by the presence of endemic forms as *Euryphyllum*, *Rubidgea* and *Chiropteris* in hygrophytic setting, mostly dominated by equisetaleans and gymnosperms (glossopterids, conifers, cordaitaleans and ginkgophytes) with a *Botrychiopsis* understory (Cuneo, 1986; Guerra-Sommer and Cazzulo-Klepzig, 1993; Mune et al., 2012). Particularly in Patagonia, the taxonomic diversification and the thermophilic ecological conditions of the palaeofloras, quantitatively dominated by conifers and tree ferns were, considered as consequences of the position of the Patagonia block, which was separated from West Gondwana and situated within lower latitudes during the Permian (Cuneo, 1996). Alternatively, these ecological peculiarities are related to the insular position of the subcontientet (Chumakow and Zharkov, 2002). The diversity of plant associations still continued during the Sakmarian, suggesting that this region remains phytogeographically isolated in Gondwana (Cuneo, 1996).

The sparse occurrence of fossil plant assemblages dominated by *Gangamopteris* and *Cordaites* foliage associated with glacial deposits from India (Talchir Formation) and Africa (Dwyka Formation), indicate extreme conditions for plant growth, which probably took place during interglacial intervals in peri-glacial environments (Chandra and Chandra, 1987; Chandra, 1992; Chandra et al., 1992; Bamford, 2004). The extreme climatic conditions resulting from the glacial cover of the Sydney Basin in Eastern Australia and Tasmania were responsible for the lowest vegetation diversity in Gondwana during the Early Permian, mainly represented by the herbaceous *Botrychiopsis* “tundra”. According to Retallack (1980) this was the only vegetational formation able to grow under these climatic conditions in permafrost areas.

By the Middle Cisuralian (Sakmarian) Gondwana shows ameliorated climatic conditions and a great increase in macrofloral diversity was detected from the dominantly glacial-influenced to the post-glacial strata, probably due to the general retreat of the ice cover. Western Gondwana (South America) had the richest plant assemblages, and Eastern Gondwana (Africa, India, Australia and Antarctica) present less diverse plant associations due to continuing glacial influence (Cuneo, 1996; Bamford, 2004).

South America (South Brazil and Northwest Argentina), was located in middle latitudes, under a seasonal climate, exhibiting market dry seasons (Iannuzzi et al., 2006); palaeofloras were preserved in fluvial-lacustrine settings, characterized by the dominance of glossopterids, cordaitaleans, conifers, early ginkgophytes and fern understory. In the Southern Brazilian Paraná Basin, by the end of the Sakmarian, subarborescent lycopsids (*Brasilodendron*) or glossopterids (*Glossopteris*) are the most representative forms (*Botrichyopsis*, ferns and *Lycopodites* remain as understory) in different roof-shale floras (Jasper et al., 2005; Guerra Sommer et al., 1991, 2008a), associated to the main coal seams originated in paralic, lagoon-barrier settings (Holz, 2003).

The plant assemblages from the eastern African, Australian and Antarctic subcontinents, mainly recorded immediately above glacial deposits, show low generic diversity and *Glossopteris* and *Cordaites* are the most common genera. Peat-forming environments in fluvial and lacustrine settings in the Bowen Basin of Australia (Draper and Beeston, 1985) and Antarctica (Cuneo et al., 1993) indicate improvement of climatic conditions. Retallack (1999) reported from Australia the occurrence of coals formed by accumulating peat in narrow mires within permafrost areas, from plant-associations showing “taiga” affinity, which consisted mainly of probably deciduous *Gangamopteris* plants.

The palaeoflora associated to thin coal seams of the Karharbari Stage (India – Sakmarian), formed in fluvial systems, and indicated dominant woodland vegetation composed by glossopterids and some conifers (*Buriadia*) with accompanying understory herbaceous and shrubby plants (e.g., *Botrychiopsis*), rare ferns (e.g., *Neomariopteris*) and some articulates (Chandra and Chandra, 1987; Bhattacharya, 1991; Srivastava, 1997).

By the end of the Cisuralian, the eastern-western major Gondwana palaeofloristic differentiation persisted. The western South American region (Brazil and Northwest Argentina) was part of a temperate belt with cold winters and warm summers (Scotese, 2002). A diversified plant association can be inferred by the presence of glossopterids, cordaitaleans, conifers, early ginkgophytes, subarborescent lycopsids, ferns, equisetaleans and sphenophylls. This floral composition led to infer forested areas associated to fluvial and paralic settings. The presence of coal seams in Artinskian coal-bearing sequences at eastern and northern Brazilian Paraná Basin (Holz et al., 2010) indicates peat forming areas as consequence of wet conditions prevailing throughout the year in lowlands associated to deltaic systems.

Most of the African taxa at the end of the Cisuralian interval are common to the other Gondwana regions, but the presence of some endemic forms (e.g., *Azaniadendron*) can indicate that this region corresponds to an ecotone (Cuneo, 1996), under moist and cool temperate climatic conditions. Glossopterids were dominant and marattialean ferns were inferred as the understory forms in plant associations developed in delta plains, where peat deposition has commonly occurred; lycopsids and sphenophytes are represented as monospecific stands in inter-distributary ponds (Anderson and Anderson, 1985).

The eastern Indian and Australian taphofloras show lower generic diversity than African and South American regions, but dense forested vegetation, strongly dominated by glossopterids, cordaitaleans and sphenopsids, grew in cool temperate climatic conditions (Rees et al., 2002). Peat deposition areas occurred in fluvio-deltaic systems at the Barakar Formation from India (Chandra and Chandra, 1987; Mitra, 1991; Srivastava, 1992). Otherwise, peat generating palaeofloras dominated by glossopterid and cordaites plants, associated occasionally to small lycopsids (*Cyclodendron*), sphenophytes (*Raniganjia*, *Schizoneura* and *Trizygia*) and shrubby ferns, have been referred for the Sidney and Perth Basins in Western Australia (McLoughlin, 1993).

Palaeofloras from Antarctica, which remain palaeogeographically in a sub-polar to polar location, under a yearly seasonal humid climate, are dominantly composed of woodland glossopterids, rare cordaitaleans and sphenopsids (Cuneo et al., 1993).

From the beginning of the Guadalupian there was a decrease in the number of plant assemblages and also in taxonomic diversity, indicating deterioration in climate resulting from generally drier conditions. Additionally, the absence of coal beds, suggest severe climatic drying, which is probably associated to the Permian icehouse/hothouse transition (Gastaldo et al., 1996). The South American subcontinent occupied mid-latitudes, under a temperate regime with a strong dry season. Brazilian plant assemblages are composed mainly of lycopsids (*Cyclodendron*, *Lycopodiopsis*) and the conifer *Krauselcladus*. The presence of other gymnosperms is evidenced by the presence of different wood morphogenera (Mussa, 1986; Merlotti and Kurzawe, 2011) in lignofloristic associations. Plant growth patterns inferred by growth ring analyses indicate a “Mediterranean-type” of climate (Alves and Guerra-Sommer, 2005).

Indian palaeofloras are also represented by low diversity and sparse woodland associations dominated by glossopterids. The common presence of the lycopsid *Cyclodendron* and also the occurrence of similar fossil wood morphogenera in South American and Indian subcontinents seems to support the hypothesis of Cuneo (1996), which says that both South American and Indian areas would have formed, during the Guadalupian, part of the same phytogeographic unit, experiencing similar climatic conditions.

In Patagonia, palaeofloras remain taxonomically distinct from other subcontinents of Gondwana; *Gangamopteris* and *Cordaites* are absent, whereas, tree ferns are taxonomically diversified. Few taphofloras have been recorded from Antartica, showing fragmented *Glossopteris* leaves (Archangelsky, 1990).

The similarity between Guadalupian palaeofloras from African, Australian and Indian regions in high latitudes and in temperate conditions, is evidenced by the presence of endemics (e.g. the sphenophyte *Raniganjia*) and also by distinct plant assemblages: monospecific stands of sphenophytes (*Schizoneura africana* in Africa), and dense thickets of glossopterids. Both groups are related to different sites, within river channels environment in a deltaic littoral system (Anderson and Anderson, 1985; McLoughlin, 1993).

At the Guadalupian-Lopingian boundary eastern Gondwana seems to return to more humid climatic conditions, allowing the formation of extended peat-swamps in the Lopingian, whereas the western sector is affected by seasonal and strong dryness (Rees, 2002). Consequently, scarce floral associations have been found in South America, whereas diverse plant assemblages are found in Africa, India and Australia, and lower floral diversity associations are found in Antarctica.

In South America, most of the floral associations are concentrated in the Brazilian Paraná Basin, located around mid-latitudes. Low diversity plant associations are characterized by the dominance of ferns (*Pecopteris* and *Astherotheca*), sphenopsids (*Schizoneura*, *Phyllotheca* and *Sphenophyllum*) and glossopterids as less common elements. Floral remains are preserved in siltstone and sandstone sequences interpreted as fluvial settings associated with eolian facies under warm temperate climate (Rohn and Rösler, 1987, 1989).

In the African region, palaeogeographically constrained to high latitudes, glossopterids and sphenophytes (*Phyllotheca*) were dominant and the conifer *Pagiophyllum* (showing affinities with modern conifer taxa) occurred as a rare element in plant assemblages preserved in sediments associated to delta plains and fluvial floodplains, under temperate regime with a strong dry season, as suggested by the common presence or red beds (Bordy et al., 2011). Indian (Raniganj Formation) and Australian (Bowen-Sydney Basin) palaeofloras are very similar and the most taxonomically diverse in Gondwana at the Lopingian. Endemics such as lycopsids (*Cyclodendron*), sphenophytes (*Trizygia*, *Gangamopteris*), ferns (*Dichotomopteris*) and cycads (*Pseudoctenis*) are common elements. Most of the Indo-Australian plant assemblages are associated with thick coal-measures derived from glossopterid swamps forests associated to understory ferns, developed in alluvial plains drained by meandering streams under seasonal cool-temperate regimes (Retallack, 1980; McLoughlin, 1993; Srivastava, 1997).

In Antarctica, different *Glossopteris* morphotypes are strongly dominant elements in plant assemblages found in sedimentary sequences interpreted as alluvial valleys drained by braided or meandering rivers (Cuneo et al., 1993). Peat deposition still continued in backswamp environments, building up expressive coal seams.

Changes in climate and tectonics at the end of the Changhsingian (Lopingian) resulted in dramatic upheavals within wetland ecosystems and peat-forming wetlands disappeared after the end Permian extinction (Greb et al., 2006). The preceding glacial period had ended and the "cool" zonal and markedly seasonal climate was replaced by a "warm equable" virtually non-seasonal and unseasonal climate. The biotic crisis was global and caused to a greater extent by biospheric processes than by momentary external influences. The new climatic organization remained on Earth for more than two hundred million years (Roscher et al., 2011).

4. Permian palaeo-wildfires on Gondwana in space and time

4.1. South America

Macroscopic fossil charcoal remains were recovered from different sites of the coal-bearing strata of the Rio Bonito Formation (Sakmarian/Artinskian) along the Northern and Southern borders of the intracratonic Paraná Basin by Jasper et al. (2006, 2008, 2011a, 2011b). Peat deposition occurred in a cool temperate climate, at 50°S palaeolatitude (Rees, 2002; Scotese, 2002).

Most of this material belongs to different gymnosperm wood types and, only in two localities [Bonito I mine (Santa Catarina coal Basin, Jasper et al., 2011b) and Quitéria outcrop (Rio Grande do Sul state, Jasper et al., 2008)] charred wood attributed to sub-arborescent lycopsids (*Brasilodendron pedroanum*) was found.

The characteristics (size ≥ 1.0 mm and absence of abraded edges) of these macroscopic fossil charcoal pieces allowed Jasper et al. (2011b) to infer that the charred plant fragments had an autochthonous/hypautochthonous origin.

In the coal levels and coal-bearing strata in which the macroscopic charcoal remains described by Jasper et al. (2008, 2011a, 2011b) were discovered, inertinite macerals are also present in high proportions (cf. Tables 1, 2).

4.2. Africa (incl. Arabia and Madagascar)

So far the macroscopic evidence for Permian wildfires in Africa is rather scarce. Glasspool (2003a) described the presence of gymnosperm charcoal within different coals belonging to the Vryheid Formation (Karoo Basin) of the Witbank and the eastern Transvaal Coalfields, and Glasspool (2003b) reported gymnosperm wood and charred peat fragments from the No. 2 coal seam of the Vryheid Formation of the Witbank Basin (Artinskian of South Africa). In both cases, the author correlated the abundance of these charcoal fragments to the inertinite maceral groups and indicated a positive relationship between inertinite-rich lithotypes and charcoal abundance.

Additional macroscopic evidence for fires has recently been discovered in clastic sediments of the Vryheid Formation at the Vereeniging coal field in South Africa. They consist of gymnospermous wood which exhibits all diagnostic characteristics of charcoal (Scott, 2000, 2010): a) black streak, b) silky lustre, c) splintery appearance, d) excellent preservation of anatomical details and e) homogenized cell walls.

Macroscopic fossil charcoal remains from the Vryheid Formation were collected from the Leslie Collection (1892-1904), which is housed in the Bernard Price Institute of Palaeontological Research (Johannesburg, South Africa). The macroscopic fossil charcoal remains come from a plant-bearing horizon overlying the upper most coal seam on the Vaal River, which is included in the coal-bearing Vryheid Formation (informally known as Middle

Ecca) of Veereniging, in the Northern Karoo Basin (Artinskian). The locality was at an approximate palaeolatitude of 55° to 60°, and experienced cool temperate climate conditions (Cairncross and Cadle, 1988; Holland et al., 1989).

The sizes of the collected macroscopic fossil charcoal particles are homogenous, ranging from 10.2 × 3.0 × 1.0 mm to 26.0 × 5.0× 1.2 mm. Observations under SEM show that the woody tissues had been shattered into smaller pieces during diagenetic compression (Figs. 3A, 3B) and the cell walls were homogenized (Fig. 3C). The wood radial section showed abietoid anatomical features and exhibited uniseriate pitting (Figs. 3D-3G), pointing to a conifer affinity. In tangential section clearly defined uniseriate rays are composed of parenchymatous cells (Fig. 3H). Despite the well preserved anatomical features, no specific taxonomic affinities could be established due to the absence of the diagnostic characters like cross-field pits.

Uhl et al. (2007) described macroscopic fossil charcoal, of assumed corystospermalean affinity, from clastic sediments from a single locality belonging to the Late Permian (Changhsingian) Um Irna Formation of Jordan. This area was located at the northern margin of Gondwana in the seasonally dry palaeotropics during time of deposition. During field work in 2011 (by DU and AAH) additional macroscopic charcoals were discovered in three more localities belonging to this formation. These new charcoal localities also include the plant-bearing locality previously described by Mustafa (2003), which represents organic rich wetland sediments deposited in an oxbow lake. The only African (s.l.) evidence for Permian PAHS comes also from the Um Irna Formation of Jordan (Dill et al., 2010).

Inertinite is known from the Sakmarian-Artinskian of Madagascar (Alpern and Rakotoarivelo, 1972), as well as from a number of coal fields of Artinskian and Kungurian age in South Africa, Zambia, Mozambique, Tanzania and Zimbabwe (for details see Table 2). For inertinite, Glasspool (2003a) presented unequivocal evidence that the inertinite from coals of the Artinskian Vryheid Formation of South Africa are of pyrogenic origin. Guadalupian intertinites are only known from a number of boreholes in Mozambique (Falcon et al., 1984).

4.3. Indian subcontinent

So far only a single study provides macroscopic evidence for palaeo-wildfires in the Late Permian (Lopingian) of India (Jasper et al., 2012). These gymnospermous charcoal remains were associated with well-preserved *Glossopteris* leaves, indicating that palaeo-wildfires probably affected vegetation dominated by this plant group. Based on the absence of abraded edges, Jasper et al. (2012) inferred an autochthonous/hypautochthonous origin for this material.

Inertinite is known from a number of Sakmarian to Kungurian (-Rodian) coal deposits from India, Bangladesh and Bhutan (cf. Table 2) and less frequently from the Lopingian of India and Bhutan (cf. Table 2). Coals were interpreted by Navale and Saxena (1989) as being deposited under high humidity and warm temperate climate at approximately the same palaeolatitude as other Gondwana coals during this period (cf. Fig. 1).

Recently Schneebeli-Hermann et al. (2012) reported the occurrence of intertinite as components of the particulate organic matter contents of palynological samples from the latest Permian and Early Triassic of the northern margin of Indian Plate in South Tibet. This is an example where the term inertinite is obviously used as a synonym for micro-charcoals.

4.4. Australia and New Zealand

Inertinite is known from numerous Australian coals deposited between the Artinskian and the Changhsingian (Table 2 and Fig. 1). However, the majority of these records come from the Guadalupian and Lopingian.

Macroscopic fossil charcoal was so far identified by Glasspool (2000) only in the Sydney Basin, eastern Australia, at the Lower Whybrow coal seam (Hunter coalfield) Mount Leonard

Formation (Wuchiapingian). The presence of coal seams at the top interval of the Wuchiapingian at this site, under cool temperate conditions, which is in contrast to the warm climates which occurred in southern Gondwana subcontinents can be explained by the Gondwana rotation about a pole near Australia during the Permian, allowing for the maintenance of cold and cool temperate environmental conditions (Roscher et al., 2011). These environments developed at palaeolatitudes around 55°S (Embleton, 1984; Glasspool, 2000).

The coal and coal-bearing strata are interbedded with volcanic tuff horizons whose center of origin was a volcanic area located in the east of the Sydney Basin (Jones et al., 1987; Brakel et al., 1995; Sniffin and Beckett, 1995; Dutta, 1998). The volcanic activities could have acted as an ignition source for the palaeo-wildfires, confirmed by the presence of the macroscopic fossil charcoal remains (Glasspool, 2000). The fire event as well as the extensive ground fire which probably reached the peat-forming environment and the hinterlands, has been considered by Glasspool (2000) as being the cause of subsequent erosion responsible for the mixing of autochthonous and allochthonous macroscopic fossil charcoal in the coal seam. Foster et al. (1997) also discovered microscopic fossil charcoal remains in palynological samples from a core in Western Australia (Perth Basin). Here micro-charcoal remains occurred in the top-most part of the Permian within this core, but are not registered so far immediately after the Permian-Triassic boundary (Uhl et al., 2010; Abu Hamad et al., 2012). The same pattern can be seen for pyrogenic PAHs in the same core (Grice et al., 2007). This implies that there was probably a major change in fire-regime at the boundary, also evidenced by similar patterns in other regions (e.g., Cathaysia; Shen et al., 2011; Abu Hamad et al., 2012), but so far we do not have enough data from other regions of Gondwana to recognize this as a general or even global pattern.

Another report of microscopic charcoal comes from palynological studies on the Late Permian (Wuchipinigan – Changsinghian?) Kuriwao Group of New Zealand (Crosbie, 1985;

Campbell et al., 2001). Here charcoal and wood fragments dominate most of the palynological residues (Crosbie, 1985), pointing to frequent and/or abundant regional fire activity in high latitudes.

4.5. Antarctica

Inertinite is also known from Lopingian coals of East Antarctica (Holdgate et al., 2005; and references cited therein). These peats where deposited almost direct in juxtaposition to the Late Permian Indian basins with peat formation (cf. Figure 1).

5. Discussion

Most of the evidence for palaeo-wildfires so far reported from the Permian of the Gondwana Realm comes directly from coals or clastic levels directly associated with coal seams. These coals are considered as climate-sensitive sediments, indicating cool temperate biomes for the Permian of Gondwana (Rees, 2002). During this time interval Pangaea was a relatively diverse region in terms of climate and topography. Global geographic patterns of Permian climates were reconstructed by Rees (2002) showing a significant latitudinal climate gradient, similar to the modern, interglacial situation.

These climatic conditions, in connection with other environmental variables (e.g., vegetation, topography, geography) allowed for the development of the *Glossopteris* Flora during the Asselian icehouse stage, which was submitted to different environmental pressures (cold and dry), including fire. The climate also created suitable conditions for the formation of the Gondwana Permian coal seams and the deposition of associated clastic deposits. The diverse fossil charcoal remains which are relatively widespread across the Gondwana supercontinent have been described from many stratigraphic levels whitin these deposits. Deposition of peats started directly after the deglaciation, during the Asselian-Sakmarian, in a cool temperate biome (Rees, 2002), stratigraphically extending up to the Permian-Triassic boundary. The same is true for the occurrence of wildfires within these environments, given the pyrogenic origin of inertinite (cf. Table 2 and Fig. 1). The assumed climate can also be used as an argument against a freeze-drying origin for Gondwana inertinite (Falcon, 1989), as temperatures were probably too high for intensive and wide-spread extreme freezing conditions. In addition, so far no mechanism other than charring has been experimentally shown to be able to produce charcoal.

The lowland-wetland and peat-generating plant associations were components of a *Glossopteris* Flora, dominated by sub-arborescent and herbaceous lycopsids, pteridosperms and ferns, as well as glossopterids, cordaitaleans, rare ginkgoaleans and conifers (Retallack et al., 1977; Anderson and Anderson, 1985; McLoughlin, 1993; Guerra-Sommer et al., 1995; Glasspool, 2000, 2003a). As summarized above, the same plant groups were present in almost all the subcontinents, but with different diversity and dominance patterns in each site.

The accumulation of organic matter in the peat and associated clastic levels was, in a general view, mainly hypautochtonous, but both autochthonous and hypautochthonous/allochthonous conditions were considered by Glasspool (2003b) for South African coals. Coal deposition was related to paralic and fluvial settings, and the peat-formation was placed in back-barrier environments for Brazil (Alves and Ade, 1996; Holz, 1998), in large flat coastal lowlands for South Africa (Falcon et al., 1984; Cairncross, 2001); anoxic floodplains for India (Mukhopadhyay et al., 2010); and deltaic and fluvial systems with a freshwater coastal plain setting supporting also marsh and floodplain communities for Australia (Glasspool, 2000).

The presence of macroscopic fossil charcoal remains in sandy levels of the uppermost Permian on northern Gondwana [Jordan (Uhl et al., 2007)], when warm but seasonally dry climatic conditions prevailed, as well as micro-charcoal from Australia (Foster et al., 1997) and Tibet (Schneebeli-Hermann et al., 2012) provide direct evidence that fires were still an important disturbance factor on Gondwana towards the end of the Permian.

The continuing research and increasing interest about the subject has shown that there are probably many more remains still to be discovered in the Late Palaeozoic, especially the Permian of Gondwana. The abundance of evidence for wildfires in temperate biomes on Gondwana demonstrates that wildfires occurred in several regions and time-slices during the Permian in Gondwana, correspond to the transition from a cold to cool and warm climate interval. The estimated high atmospheric oxygen concentration (e.g., Bergmann et al., 2004; Berner, 2009; Glasspool and Scott, 2010), which peaked during the Early Permian (Fig. 2), made vegetation highly flammable even under wet conditions (Belcher et al., 2010b). The scarcity of charcoal remains after the cessation of peat deposition in the warm Late Permian, despite estimations of elevated O_2 levels until at least the latest Permian (Fig. 2), may be attributed to climatic change that have brought about directional changes in the frequencies and magnitude of these fire events (DiMichele et al., 2004). They could also have been a result of taphonomic bias (cf. Uhl et al., 2004, 2010; Abu Hamad et al., 2012).

As stated above, the presence of coal seams in the Wuchiapingian of Australia can be explained by the rotation of Gondwana around a pole near Australia during the Permian (Roscher et al., 2011). While the Sydney Basin remained transitional between cold and cool climates, this movement allowed the Paraná Basin to move northward into the warm, semi-arid biome (Guerra-Sommer et al., 1995). Furthermore, the intermediate Karoo Basin (South Africa) and Indian Gondwana basins showed some degree of warming during the Sakmarian-Wordian interval (Chandra and Chandra 1987; Falcon, 1989).

The great majority of the macroscopic charcoal remains from the coals or clastic levels directly associated with coal seams (representing wetland/peatland palaeofloras) are of the araucarioid woody gymnosperm type. Most of them show the *Agathoxylon* pattern (Glasspool, 2000; Jasper et al., 2008, 2011a, 2011b, 2012), which represents a wide range of gymnosperm plants and an even broader taxonomic spectrum, including glossopterids and lycopsids. On the other hand, the distinctive wood architecture exhibited by charcoal pieces similar to those of modern Taxaceae (Jasper et al., 2011b) probably represents taxa which are so far not recognized from the contemporary adpression/compression-palaeoflora. These taxa probably lived in areas adjacent to contemporaneously rising uplands.

The presence of conifer derived charcoal supports previous data about a variety of conifers which have been reported from a range of lowland environments within the preservation window. They range from typical wetlands [e.g., *Paranocladus*, *Coricladus* and *Buriadia* (Guerra-Sommer and Bortolluzi, 1982; Anderson and Anderson, 1985; Saxena et al., 1986; Pant and Singh, 1987; Tiwari and Tripathi, 1987; Cuneo, 1996; Singh et al., 2003; Ricardi-Branco and Rösler, 2004; Jasper et al., 2005)] to the margins of the broad basinal lowlands [*Walkomiella* (Mcloughlin, 1993)]. Taking into account the diversity of palynological and floral data from coal-bearing strata in Permian Gondwana (Hart, 1967; Lele and Srivastava, 1980; Anderson and Anderson, 1985; Tiwari and Tripathi, 1987, 1992; McLoughlin, 1993; Millsteed, 1994, 1997; Guerra-Sommer et al., 1995; Jha et al., 1996; Foster et al., 1997; Semkiwa et al., 1998, 2003; Cazzulo-Klepzig, 2001; Jha, 2006), the rarity or even the absence of non-gymnosperm charcoal is somewhat surprising. However, it is possible that this pattern may reflect palaeoecologic peculiarities (e.g., dominance-diversity patterns) in distinct clastic and peat forming environments, as well as different factors like complete burning and/or taphonomic bias (Glasspool, 2003b).

In addition, Jasper et al. (2011a, 2011b) considering, amongst other reasons, the occurrence of macroscopic fossil charcoal remains in localities in which the presence of inertinite has previously been reported, reinforced the connection between palaeo-wildfires and the observed high inertinite contents for these localities. Based on this, Jasper et al. (2012) also stated a possible connection between the events from which the macroscopic fossil charcoal originated and those which produced the inertinite in the Indian Gondwana subcontinent. Following previous statements of Guo and Bustin (1998), Glasspool (2000) also inferred that almost all inertinite in the Australian Permian peat swamps may be attributed to wildfire.

Although some authors (Falcon, 1989; Hunt, 1989; Taylor et al., 1989, 1998) have argued that the high levels of inertinite group macerals in the Gondwana coals and associated rocks cannot have originated exclusively from pyrogenic activities, the co-occurrence of fossil charcoal, inertinite and PAHs at individual localities cannot be ignored (Tables 1, 2, 3). Authors like Scott (2000, 2010), Scott and Stea (2002), Scott and Glasspool (2006, 2007), Glasspool and Scott (2010) and Hudspith et al. (2012) provided a wealth of evidence that almost all inertinite macerals are charcoal, which means they are causally connected to the occurrence of palaeo-wildfires. A probable consequence of these divergences can be exemplified by the comparably large number of researchers who have worked so far on evidence of palaeo-wildfires from the Late Palaeozoic of Eurasia (e.g., Sander, 1987; Sander and Gee, 1990; Scott, 1990, 2000, 2010; 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; Hudspith et al., 2012), in contrast to the low number of researchers working on pyrogenic activities in Gondwana for the same time interval (Glasspool, 2000, 2003a; Uhl et al., 2007; Jasper et al., 2008, 2011a, 2011b, 2012).

Despite this discrepancy, the recently published, detailed descriptions of fossil charcoal remains made from different Permian levels in different localities in Gondwana support the claim that inertinite macerals can indeed be used to indicate palaeo-wildfires (e.g., Scott and Glasspool, 2006; Scott, 2010; Hudspith et al., 2012). These events have obviously been common and widespread over Gondwana during the Permian. If inertinite macerals are accepted as having a pyrogenic origin, then the Gondwana Realm during the Permian was very likely highly prone to fires.

Another argument against the burning hypothesis could be the climate and palaeolatitudes which dominated Gondwana during the Late Palaeozoic: high palaeolatitudes, low temperatures and wet conditions could inhibit fire. However, authors like Bowman et al. (2009) and Flannigan et al. (2009) argued that the occurrence of fire is an important source of disturbance in a variety of terrestrial ecosystems, including areas of high latitudes with low temperatures and wet conditions.

Finally, the anoxic conditions of the peat-forming environments which dominated the Late Palaeozoic Gondwana, could also be used to refute fire as a common element in these systems. Once again, studies carried out in modern peat forming environments, demonstrated that not only fire occurs, but also high inertinite levels are formed under these conditions (Pierce et al., 2004; Rein et al., 2008; Glasspool and Scott, 2010). Considering that the diverse origin (autochthonous, hypautochthonous, allochthonous) of the organic matter which composed the biomass accumulated in the mires of Gondwana, not just local palaeo-wildfire events can be considered, but also those which reached the surrounding areas.

Almost all of the known evidence of Permian wildfires on Gondwana comes from broadly the same latitudes (Fig. 1), as most of this evidence is connected to the occurrence of (climatically controlled) peat deposition. Thus, one could assume that Permian palaeo-wildfires on Gondwana were restricted to such peat-forming environments, whereas other habitats remained free from fires. However, there are some “exceptions”: the charcoal from the Late Permian of Jordan (Uhl et al., 2007), from the North Indian Margin (Schneebeli-Hermann et al., 2012) and from Antarctica (Crosbie, 1985). This shows clearly that fires occurred also in non-peat forming vegetation during this period. Taking this into account, together with the overall numerical discrepancy between the number of published records of Permian (macro- and micro-) charcoal not associated with coal deposits and the published records of contemporaneous inertinite in coals on a global scale (e.g., Abu Hamad et al., 2012), it seems realistic to assume, that many more records of Permian charcoals are waiting for discovery in sediments on Gondwana. Such new findings will probably help to improve the understanding of the history of wildfires during the Permian of Gondwana with its complex interactions and feedbacks between fires and many environmental factors on more refined temporal and spatial scales as it is possible at the moment.

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Figure Captions

Fig. 1. Distribution of inertinite (orange circles) and macroscopic as well as microscopic charcoals (yellow stars) on Gondwana during the (A) Sakmarian, (B) Artinskian and (C) Lopingian (for details concerning localities see Table 1 and 2). Palaeogeographic reconstructions from Ziegler et al. (1997).

Fig. 2. Overview of the number of published reports of fossil evidence for palaeo-wildfires during the Permian on Gondwana [See Tables 1–3 and text for details; intertinite data were taken from Abu Hamad et al. (2012) and additional sources not cited in this work (cf. Table 2)] and modeled atmospheric oxygen concentration: A) Reported occurrences of macroscopic fossil charcoal; B) reported occurrences of inertinites/black carbon; C) reported occurrences of pyrogenic PAHs; D) reconstructed atmospheric oxygen concentrations [Permian highlighted in light grey (redrawn from Berner, 2009)].

Fig. 3. SEM images of macroscopic fossil charcoal samples from Vryheid Formation, Karoo basin, South Africa: A) charred wood with broken tissues; B) charred wood in radial view with tracheids broken into more or less small pieces; C) detail of charred wood with homogenized cell walls (arrow); D) charred wood in radial view with broken tracheids with uniseriate pitting; E) charred wood in radial view with tracheids presenting uniseriate pitting; F) detail of the uniseriate pitting on the tracheids; G) detail of the uniseriate pitting on the tracheids; H) charred wood in tangential view with uniseriate rays (arrow).

Tab. 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

Tab. 2: Overview of published records of Permian inertinites in coals from Gondwana. Data based on Diessel (2010), Glasspool & Scott (2010), and Abu Hamad et al. (2012). For details see text.

locality/area	country	age	references
Mersey, Tasm.	AUS	Sakmarian	Bacon, 1991
Santa Terezinha	BRA	Sakmarian	Kalkreuth et al., 2006
Leão–Butiá	BRA	Sakmarian	Kalkreuth et al., 2006
Candiota	BRA	Sakmarian	Ade et al., 1998; Silva & Kalkreuth, 2005; Kalkreuth et al., 2006
Auranga coalfield	IND	Sakmarian	Jha & Jha, 1996
Son Valley coalfield	IND	Sakmarian	Basu, 1967
West Bakaro coalfield	IND	Sakmarian	Navale & Saxena, 1989
Wankie coalfield	ZWE	Sakmarian	Watson, 1958
Figueira	BRA	Sakmarian– Artinskian	Ricardi-Branco et al., 1998
Sakamena	MDG	Sakmarian– Artinskian	Alpern & Rakotoarivelo, 1972
Irwin River Coal	AUS	Artinskian	Santoso, 1994
Ewington CM.Collie basin	AUS	Artinskian	Santoso, 1994
Sue C. M. Vasse shelf	AUS	Artinskian	Santoso, 1994
Ashford Coal M.	AUS	Artinskian	Flood, 1995
Greta Coal M.	AUS	Artinskian	Edwards, 1975; Diessel & Gammidge, 2003
Barakar Formation	BGD	Artinskian	Bostick et al., 1991; Pareek & Bardhan, 1985
Jamalganji Coalf.	BGD	Artinskian	Imam et al., 2002
Damuda Form.	BTN	Artinskian	Mukherjee et al., 1988
various fields	IND	Artinskian	Pareek, 1990
Karhabari/Son V.	IND	Artinskian	Basu, 1967
L. Gondwana	IND	Artinskian	Ghose & Wolf, 1974
Goodavari Valley	IND	Artinskian	Pareek, 1986; Singh et al., 2012
Barakar F.	IND	Artinskian	Sing & Shukla, 2004
Johilla Coalfield	IND	Artinskian	Singh & Singh, 1987
Sohagpur	IND	Artinskian	Chakrabarti, 1987
Waterberg Fm.	ZAF	Artinskian	Fabiańska & Kruszewska, 2003
Vryheid Form.	ZAF	Artinskian	Glasspool, 2003a
Witbank No.2 coal	ZAF	Artinskian	Glasspool, 2003b
Main S. Gwembe	ZAM	Artinskian	Money & Drysdall, 1973
Collinsville C.M.	AUS	Artinskian - Kungurian	Beeston & Davis, 1976; Mutton, 2003
Maules Creek Fm.	AUS	Artinskian– Kungurian	Gurba & Ward, 2000

Barakar Fm.	IND	Artinskian - Kungurian	Pareek, 1987 ; Jha & Jha, 1996; Gurba & Ward, 2000; Chakrabarti, 1987; Singh & Shukla, 2004
Singrauli coal	IND	Artinskian– Kungurian	Misra & Singh, 1990; Mishra & Cook, 1992
Jharkand	IND	Artinskian– Kungurian	Pophare et al., 2008
Jharia Coalfield	IND	Artinskian– Kungurian	Mishra & Cook, 1992
Moatize	MOZ	Artinskian– Kungurian	Annon, 1983
Mucanha–Vuzi	MOZ	Artinskian– Kungurian	Falcon et al., 1984
Boreholes	MOZ	Artinskian– Kungurian	Falcon et al., 1984
Songwe–Kiwira coalfield	TZA	Artinskian– Kungurian	Semkiwa et al., 2003
Namwele-Mkomolo coalfield	TZA	Artinskian– Kungurian	Semkiwa et al., 1998
Muze coalfield	TZA	Artinskian– Kungurian	Semkiwa et al., 1998
Galula coalfield	TZA	Artinskian– Kungurian	Semkiwa et al., 1998
Highveld coalfield	ZAF	Artinskian– Kungurian	Hagelskamp & Snyman, 1988; Wagner & Hlatshwayo, 2005
Karroo (Ecca age)	ZAF	Artinskian– Kungurian	Fabiańska & Kruszewska, 2003
Queensland	AUS	Kungurian	Follington et al., 1995
Lower Aldebaran Sandstone	AUS	Kungurian	Follington et al., 1995
Jamalganji Coal F.	BGD	Kungurian	Imam et al., 2002
Goodavari Valley	IND	Kungurian	Pareek, 1986
L. Barakar Form.	IND	Kungurian	Pareek & Bardhan, 1985
West Bokaro Basin	IND	Kungurian	Navale, Saxena, 1989
Ruhuhu Form.	TZA	Kungurian	Mpanju et al., 1991
Witbank	ZAF	Kungurian	Mangena et al., 2004
Highveld coal	ZAF	Kungurian	Hagelskamp & Snyman, 1988; Wagner & Hlatshwayo, 2005
Wankie Coalfield	ZWE	Kungurian	Duguid, 1978; Watson, 1958; Carr & Williamson, 1990
Sabi, Lundi–Sabi	ZWE	Kungurian	Duguid, 1978
Mengkarang	IND	Kungurian - Roadian	Suwarna, 2006
German Cr./Moranbah	AUS	Wordian	Mutton, 2003
Foybrook Form.	AUS	Capitanian	Smyth, 1968
Tomago C.M.	AUS	Capitanian	Edwards, 1975; Smyth, 1968
Burnhamwood Fm.	AUS	Guadalupian	Edwards, 1975
Foybrook Fm.	AUS	Guadalupian	Casareo et al., 1996
Coogal Subgroup	AUS	Guadalupian	Edwards, 1975
Tomago Coal measures	AUS	Guadalupian	Edwards, 1975
diff. Boreholes	MOZ	Guadalupian	Falcon et al., 1984
Illawara Coal Measures	AUS	Guadalupian - Changhsingian	Edwards, 1975; Ward et al., 1996; Diessel, 1965, 1985
Lambton SG.	AUS	Wuchiapingian	Diessel, 1965; Edwards, 1975
Wybrow Coal	AUS	Wuchiapingian	Glasspool, 2000 ; Edwards, 1975
Adamstown SG.	AUS	Wuchiapingian	Edwards, 1975

Wongawilli S.	AUS	Wuchiapingian	Diessel, 1965
Boolaroo SG.	AUS	Wuchiapingian	Edwards, 1975
Melville S.	AUS	Wuchiapingian	Gurba & Ward, 1998
Hoskisson S.	AUS	Wuchiapingian	Patterson et al., 1996; Tadros, 1993; Gurba & Ward, 1998
Moranbah Coal Measures	AUS	Wuchiapingian	Retallack et al., 1977, Follington et al., 1995
Galilee Basin	AUS	Wuchiapingian	Mutton, 2003
Rangal Coal Measures	AUS	Wuchiapingian	Mutton, 2003
Bainmedart Coal Measures / Lambert Graben,	Antarctica	Wuchiapingian – Changhsingian	Holdgate et al., 2005
Damodar Valley Basin	IND	Wuchiapingian – Changhsingian	Mishra et al., 1990; Mishra, 1996
Newcastle Coal Measures	AUS	Changhsingian	Edwards, 1975
Torbanite/Joadja	AUS	Changhsingian	Hutton & Cook, 1980
Bulli Seam	AUS	Changhsingian	Diessel, 1965, 1985
Rangal Coal Measures	AUS	Changhsingian	Edwards, 1975; Gray & Bowling, 1995; Walker et al., 2001
Baralaba Coal Measures	AUS	Changhsingian	Edwards, 1975; Follington et al., 1995
Bhangtar	BTN	Changhsingian	Pareek, 1990

Tab. 3: Overview of published records of Permian pyrogenic PAHs on Gondwana. For details see text.

locality/area	country	age	references
Perth Basin	AUS	Changhsingian	Thomas et al., 2004, Grice et al., 2007
Wadi Himara (Jordan)	JOR	Changhsingian	Dill et al., 2010

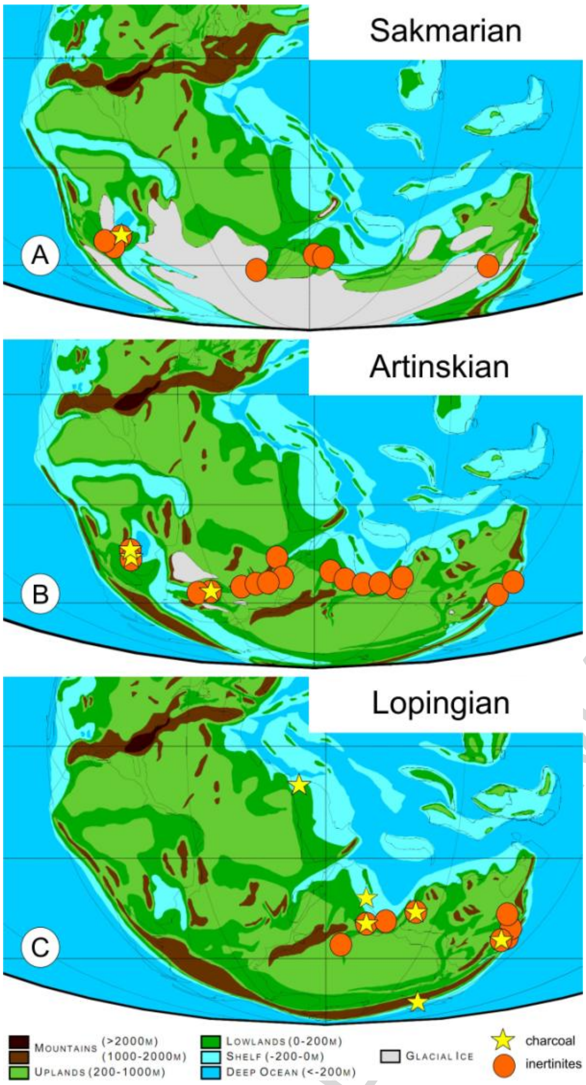

Sakmarian
A
Artinskian
B
Lopingian
C
Mountains (>2000m)
(1000-2000m)
Uplands (200-1000m)
Lowlands (0-200m)
Shelf (-200-0m)
Deep Ocean (<-200m)
Glacial Ice
charcoal
inertinites

Figure 1

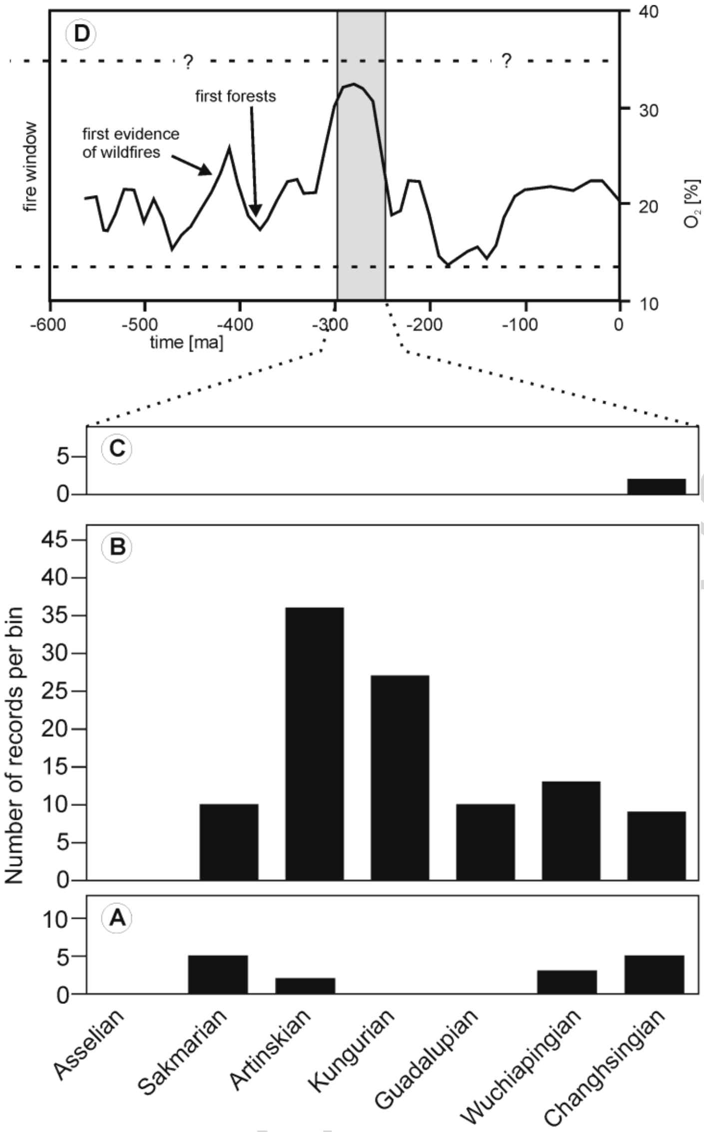

D
fire window
?
?
first forests
first evidence
of wildfires
40
30
20
10
O2 [%]
-600
-500
-400
-300
-200
-100
0
time [ma]
C
5
0
B
45
40
35
30
25
20
15
10
5
0
Number of records per bin
A
10
5
0
Asselian
Sakmarian
Artinskian
Kungurian
Guadalupian
Wuchiapingian
Changhsingian

Figure 2

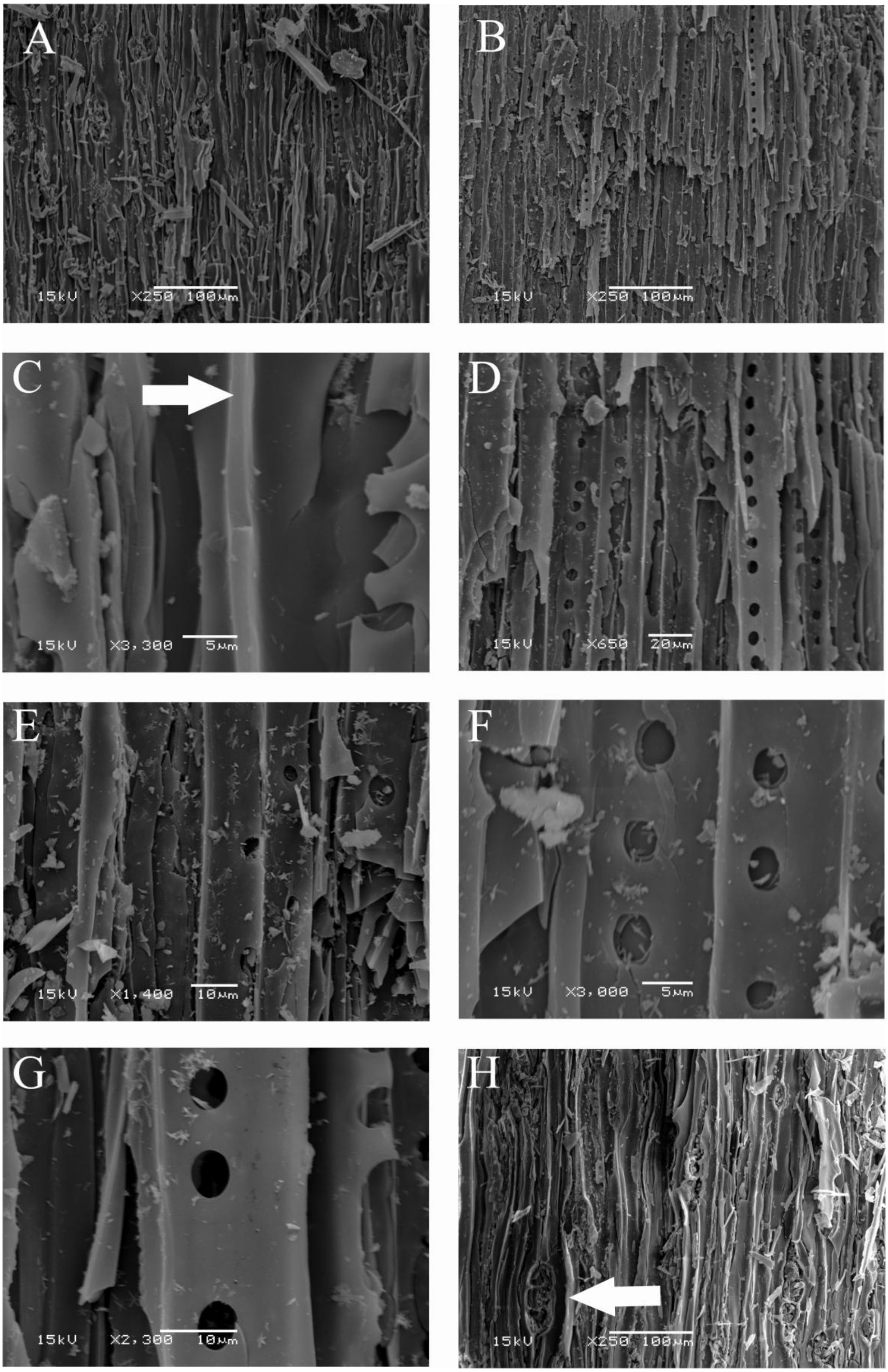
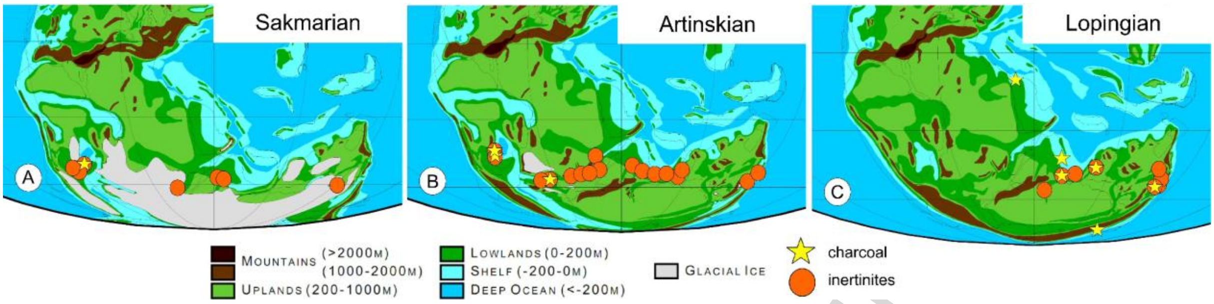

A
15kV X250 100µm
B
15kV X250 100µm
C
15kV X3,300 5µm
D
15kV X650 20µm
E
15kV X1,400 10µm
F
15kV X3,000 5µm
G
15kV X2,300 10µm
H
15kV X250 100µm

Figure 3



Graphical Abstract

Highlights

- An overview on the published evidence of Permian wildfires on Gondwana is presented;
- A new occurrence from Permian macroscopic charcoal is presented for South Africa;
- The data support palaeo-wildfires as common in Gondwana during the Permian.