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Review article

# The record of Triassic charcoal and other evidence for palaeo-wildfires: Signal for atmospheric oxygen levels, taphonomic biases or lack of fuel?

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## ABSTRACT

As wildfires are today important sources of disturbance in many terrestrial ecosystems, it is of great interest to understand how different environmental parameters and fire-activity interacted during past periods of the Earth history. Fossil charcoal, inertinites, and pyrogenic polycyclic aromatic hydrocarbons (PAHs) represent the only direct evidence for the occurrence of such palaeo-wildfires. In the present study, a review of published data, together with new data on the occurrence of fossil charcoal for the Permian and the Triassic is presented. For a long time, it has been speculated, that an assumed lack of evidence for palaeo-wildfires during the Triassic should be explained by a large drop in atmospheric oxygen concentration following or during the end-Permian mass extinction event, preventing the occurrence of wildfires. However, evidence for palaeo-wildfires is relatively common in many middle and late Triassic strata, whereas such evidence is almost totally lacking from early Triassic sediments. The interpretation of this "charcoal gap" or depression is difficult, as many factors (e.g. atmospheric oxygen concentration, taphonomical biases, lack of sediments suitable for the preservation of macroscopic charcoal, lack of fuel, and "ignorance" of scientists) may have influenced not only the production, but also the preservation and recovery of evidence for palaeo-wildfires during this period. Thus, it is not clear whether this Early Triassic "charcoal gap" can also be seen as evidence for an assumed "wildfire gap" or not. Without any doubt further investigations on the early Triassic record of charcoal and other evidence for palaeo-wildfires will be necessary before this problem can be solved. In fact, it can be expected that the number of published records of (early) Triassic evidence for palaeo-wildfires will increase in the future as more and more scientist working on sediments of this age may become aware of the interest in fires from this time. This will certainly make it possible to give a much better picture of the temporal and regional distribution of wildfires during this period in the future.

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## 1. Introduction

Today wildfires are important sources of disturbance in a number of ecosystems, and frequencies and intensities of such fires, as well as their resulting impact on individual ecosystems, are to a great extent controlled by climatic and environmental factors (Bowmann et al., 2009). Due to this climate/environment–fire connection and the role that fires play in different key-nutrient cycles it is of great interest to know, not only how palaeo-fire-activity may have changed through time parallel to global and/or regional climate but also other environmental changes during the Earth history (Belcher et al., 2010a; Scott, 2000, 2010).

The end-Permian mass extinction "event" represents the most severe biological crisis during the entire Phanerozoic, during which several groups of marine as well as terrestrial organisms suffered great losses (Benton, 2003; Benton and Twitchett, 2003; Erwin, 1990, 2006). However, for continental ecosystems, the exact extent and duration of the crisis itself and its effects on Early Triassic ecosystems are still under discussion (e.g. Gastaldo et al., 2005; Grauvogel-Stamm and Ash, 2005; Rees, 2002). Considering the large impact of fires on a number of terrestrial ecosystems (e.g. Bowmann et al., 2009), it is thus of great interest how palaeo-fire-activity reacted to this particular crisis and its aftermath.

The macro-palaeobotanical record is extremely scarce for the entire Early and at least scarce for great parts of the Middle Triassic (e.g. Grauvogel-Stamm and Ash, 2005). Only a few macrofloras are known from the Early Triassic, mostly originating from the almost ubiquitous red beds found during this period in continental regions. These floras consist only of a few opportunistic taxa growing under ephemeral conditions within the relatively dry and/or strongly seasonal areas of sediment deposition (Grauvogel-Stamm and Ash, 2005).

Especially the fossil record of coal-forming vegetation, as seen in the frequency and amount of fossil coals, is scarce for this period and there is a global coal-gap that lasts from the earliest Induan up to the Carnian (Retallack et al., 1996; Veevers et al., 1994). The (published) record of Triassic charcoal and other direct evidence for palaeo-wildfires is also scarce or even non-existing during long periods of the Early and Middle Triassic (Belcher and McElwain, 2008; Scott, 2000; Uhl et al., 2008, 2010).

To get information about palaeo-wildfires, it is necessary to investigate the fossil record of charcoal and inertinite (a group of pyrogenic coal macerals; cf. Hudspith et al., 2012; Scott, 2000, 2010; Scott and Glasspool, 2007) as well as other direct evidence of palaeo-wildfires like pyrogenic polycyclic aromatic hydrocarbons (PAHs). However, either our current knowledge about the Triassic record of charcoal and other evidence for fires, or the record itself is rather scarce. So far a number of different explanations have been evoked to explain the absence of evidence for palaeo-wildfires from so many early and middle Triassic sediments:

I) Atmospheric oxygen concentrations:
It has been suggested that oxygen concentrations were below 12–13% during the Triassic (as reconstructed by early geochemical models; e.g. Berner, 2001, 2005; Berner and Canfield, 1989), and that such low concentrations of atmospheric oxygen may have prevented the ignition and effective spread of wildfires (e.g. Robinson, 1989, 1991; Scott, 2000). A number of early experimental studies on the inflammability of paper and other materials suggested that a rather low threshold of 12–15% oxygen exists for the ignition of fires (e.g. Watson, 1978; Watson et al., 1978; Wildman et al., 2004). However, new data from experiments conducted under fully controlled atmospheric conditions in a large scale controlled atmosphere chamber, Belcher and McElwain (2008) stated recently that the lower limit for atmospheric oxygen concentrations is more likely at 15–17% to allow for the successful ignition of plant material. In addition, more recent experiments coupled to models suggest that atmospheric oxygen concentrations above 18.5% are required to allow for the spread of smouldering fires (Belcher et al., 2010b). An improved version of the geochemical model used in earlier studies (Berner, 2001, 2005; Berner and Canfield, 1989) produced oxygen concentrations for the Early Triassic that are above the ignition threshold but still below the threshold thought to be necessary for the effective spread of fires (Berner, 2009). Other models (e.g. Bergman et al., 2004; Glasspool and Scott, 2010) did not produce such low oxygen concentrations for the Triassic. The model of Bergman et al. (2004) produced oxygen levels comparable to modern concentrations and the model of Glasspool and Scott (2010) reconstructed oxygen concentrations of ~18.5% during this period. The models used by Berner (2001, 2005, 2009) and Bergman et al. (2004) represent geochemical models of rather high complexity, whereas the model of Glasspool and Scott (2010) is primarily based on the distribution and concentration of micro-charcoal and inertinites in selected sediment types (i.e. coals and lignites).

II) Taphonomic reasons:
The semi arid conditions of present-day Australia are a potential analogue of many early to middle Triassic sedimentary deposits (i.e. red beds). As demonstrated by Skjemstad et al. (1996), charcoal mechanically breaks down rapidly in modern sediments deposited under semi arid conditions. However, microscopic charcoal fragments may still be present in comparable modern sediments. Thus many (if not most) early Triassic sediments were probably not suitable for the preservation of macroscopic charcoal (e.g. Belcher and McElwain, 2008; Uhl et al., 2008) and studies on microscopic charcoal or pyrogenic PAHs from this period are largely missing so far. The latter is not surprising as preservation of PAHs depends on the abundance of organic matter present in rocks. PAHs preferentially bind to organic matter (e.g. Cornelissen et al., 2006), therefore rocks with low organic contents (e.g. red beds) will contain generally few or no PAHs at all.
An additional factor that has to be considered here is a kind of "human factor". Some authors (e.g. Jones, 1993; Scott, 2010; Uhl et al., 2010) have speculated that charcoal remains may simply have been overlooked (or neglected) by researchers during field work, as they were not aware of the potential environmental significance of this material or could not identify the black material as fossil charcoal during fieldwork.

III) Lack of potential fuel:
As recently pointed out by Uhl et al. (2010), the scarcity of potential fuel (= vegetation/plant biomass) in the region surrounding areas where sediments have been deposited during this period, may also be a factor that could help to explain the scarcity of Early and Middle Triassic macro-charcoals. As summarized by Grauvogel-Stamm and Ash (2005), there are only a few early Triassic macrofloras worldwide (mostly preserved in red beds not suitable for the preservation of charcoal; see above). The numbers of known plant-bearing localities had increased in the Middle Triassic and from this time on, plants were again more frequently preserved in facies types that were more favourable for the preservation of charcoal (cf. Uhl et al., 2010).

Here a detailed survey on published and hitherto unpublished occurrences of fossil charcoal and other evidence of palaeo-wildfires from the Triassic is presented to get a better idea about variations in the fossil record of charcoal during this period. This data-set can serve as a base for the identification of causal relationships between wildfires, taphonomy, atmospheric oxygen and availability of potential fuel (= plant biomass) during this period.

For comparison and to get an idea about the development of wildfires/fire-activity across the Permian–Triassic boundary and the end-Permian mass-extinction event, data for the entire Permian are also included. About a decade ago, only a small number of occurrences of Permian charcoal had been published (Scott, 2000) and geochemical models reconstructed very low oxygen concentrations during this period (e.g. Berner and Canfield, 1989). Since then, the number of known Permian charcoal occurrences has steadily increased due to increased collecting efforts (cf. Table 1; Scott, 2010; Scott and Glasspool, 2006) and subsequent geochemical models reconstructed relatively high oxygen concentrations (higher than the present value of 21%) during the entire Permian (e.g. Bergman et al., 2004; Berner, 2001, 2002, 2005, 2006, 2009; Glasspool and Scott, 2010).

## 2. Source of data

This work is based on a critical review of the published literature on Permian and Triassic macro- and micro-charcoals and other evidence of wildfires like the occurrence of inertinites in coals and of pyrogenic PAHs. Additionally, field- and laboratory-observations from different regions (i.e., Europe, S-America, NW-China and the Near East Region) have been included. Sources of our data are given in Tables 1–3. For inertinites, the Permian and Triassic data published recently by Diessel (2010; in his Tables 2 and 3) supplemented with data from Glasspool and Scott (2010; online appendix) have been used, as well as a number of additional publications, which have been missed by both compilations or which have been published after both papers.

As stated by Diessel (2010) in his extensive literature survey on the stratigraphic distribution of intertinites in coals, “*it is impossible to access all analysis results that have ever been published, let alone the much larger volume of unpublished material*”, thus one must be fully aware that such an analysis will be incomplete with regard to the existing data. Nevertheless, it can be assumed, that a representative proportion of the published records of Permian and Triassic charcoal (especially considering works published in scientific “mainstream languages” and in internationally

**Table 1**

Overview of published records (and personal observations of the authors) of Permian and Triassic macro-, meso- and micro-remains of fossil charcoals (micro-remains also include records of black carbon originating from fires). For details see text.

| Locality/area | Country | Age | Bin | References |
|---|---|---|---|---|
| Saar-Nahe Basin | DEU | Asselian | 1 | Uhl et al. (2004); Uhl (pers. observation) |
| Thuringian Forest Basin | DEU | Asselian | 1 | Remy (1954); Barthel and Rößler (1997); Barthel (2008) |
| Boskovice Basin | CZE | Asselian | 1 | Simůnek and Martínek (2009) |
| Candiota Coalfield | BRA | Sakmarian | 2 | Jasper et al. (2011b) |
| Leão-Butiá Coalfield | BRA | Sakmarian | 2 | Jasper et al. (2011b) |
| Faxinal Coalfield | BRA | Sakmarian | 2 | Jasper et al. (2011a); Guerra-Sommer et al. (2008b) |
| Morro do Papaléo outcrop | BRA | Sakmarian | 2 | Jasper et al. (2011b) |
| Quitéria outcrop | BRA | Sakmarian | 2 | Jasper et al. (2006, 2008); Cazzulo-Klepzig et al. (1999); Guerra-Sommer et al. (2008a) |
| Saar-Nahe Basin | DEU | Sakmarian | 2 | Noll et al. (2003); Uhl et al. (2004) |
| Chemnitz | DEU | Sakmarian | 2 | Rößler (2001) |
| Geraldine bonebed, Archer County, Texas | USA | Sakmarian ? | 2 | Sander (1987, 1989); Sander and Gee (1990) |
| Rattlesnake Canyon 2, Archer County, Texas | USA | Sakmarian ? | 2 | Sander (1989); Sander and Gee (1990) |
| Santa Catarina Coal Basin | BRA | Artinskian | 3 | Jasper et al. (2011b) |
| Figueira Coalfield | BRA | Artinskian | 3 | Jasper et al. (2011b) |
| South Ash pasture, King County, Texas | USA | Rodian ? | 5 | DiMichele et al. (2004) |
| NW-Shanxi | CHN | Capitanian–Wuchiapingian | 5, 6 | Wang and Chen (2001) |
| Lower Whybrow Coal | AUS | Wuchiapingian | 6 | Glasspool (2000) |
| Mansfeld, Thuringia | DEU | Wuchiapingian | 6 | Brandt (1997) |
| Frankenberg–Geismar, Hesse | DEU | Wuchiapingian | 6 | Uhl and Kerp (2002, 2003) |
| Culmitzsch, Thuringia | DEU | Wuchiapingian | 6 | Uhl et al. (2008) |
| Bletterbach, S-Tyrol | ITA | Wuchiapingian | 6 | Uhl et al. (in press) |
| Perth Basin | AUS | Changhsingian | 7 | Foster et al. (1997) |
| Meishan | CHN | Changhsingian | 7 | Shen et al. (2008, 2011) |
| High Arctic | CAN | Changhsingian | 7 | Grasby et al. (2011) |
| Damodar Valley Basin | IND | Changhsingian | 7 | Jasper et al. (in press) |
| Wadi Himara | JOR | Changhsingian | 7 | Uhl et al. (2007) |
| Svalis Dome (Barents Sea) | RUS | Olenekian–Anisian | 9, 10 | Mangerud and Rømuld (1991) |
| Palatinate | DEU | Anisian | 10 | Schindler et al. (2009); Uhl et al. (2010) |
| Kühwiesenkopf | ITA | Anisian | 10 | E. Kustatscher, Bozen, Italy, and Uhl (unpublished observation) |
| Wadi Mukheiris | JOR | Anisian | 10 | Abu Hamad and Uhl (pers. observation) |
| Rietbergjoch | ITA | Ladinian | 11 | E. Kustatscher, Bozen, Italy, and Uhl (unpublished observation) |
| Cuyana Bassin | ARG | Ladinian | 11 | Mancuso (2009) |
| Franconia | DEU | Ladinian–Rhaetian | 11, 12, 13, 14 | Kelber (1999, 2001, 2003, 2007) |
| Allan Hills (Antarctica) |  | (Ladinian ?) Carnian–Norian ? | 11, 12, 13 | Kumar et al. (2011) |
| Ischigualasto Basin | ARG | Carnian | 12 | Colombi and Parrish (2008) |
| Prince Charles Mountains (Antarctica) |  | Carnian ? | 12 | Cantrill et al. (1995) |
| Petrified Forest National Monument, Arizona | USA | Carnian–Norian | 12, 13 | Jones et al. (2002) |
| Newark basin, New Jersey | USA | Norian | 13 | Axsmith et al. (2004) |
| Chama River Basin, New Mexico | USA | Norian | 13 | Zeigler et al. (2005) |
| Schwäbisch Gmünd, Swabia | DEU | Norian | 13 | Uhl (pers. observation) |
| Pomerania | POL | Norian–Rhaetian | 13, 14 | Marynowski and Simoneit (2009) |
| South Gloucestershire | GBR | Rhaetian | 14 | Whiteside and Marshall (2008) |
| Upper Silesia | POL | Rhaetian | 14 | Marynowski and Simoneit (2009) |
| Tübingen, Swabia | DEU | Rhaetian | 14 | Etzold and Schweizer (2005); Uhl et al. (2008); Uhl and Montenari (2011) |
| Junggar Basin | CHN | Rhaetian | 14 | Uhl (pers. observation) |
| Astartekløft | GRL | Rhaetian | 14 | Belcher and McElwain (2008) (supporting online material); Belcher et al. (2010a) |

accessible sources) have been gathered, forming a solid base for the interpretations presented here. However, it should be clear that the data presented here represent only minimum numbers, as it can be assumed that there are also further, so far undiscovered and/or unpublished, occurrences of charcoal for many of the time slices considered in our analysis. Additionally, many more reports on Permian and Triassic charcoal may exist in the abundant regional literature published by scholarly societies and organizations in a wide range of languages, but this has to be considered as a kind of taphonomical bias, that one must accept but should not forget.

It should also be noted that not all published occurrences of fossil charcoal have been validated according to objective criteria that can be used to identify specimens as charcoal (cf. Scott, 1989, 2000, 2001, 2010). Thus, the reliability of published occurrences of charcoal varies greatly ranging from simple statements that a certain locality/bed/layer etc. yields charcoal (e.g. Barthel, 2008; Etzold and Schweizer, 2005), to more sophisticated analyses including detailed evidence to support the pyrogenic origin of the material under investigation (e.g. Marynowski and Simoneit, 2009; Uhl and Kerp, 2003).

Many published papers deal with the charcoal content of individual localities representing only a very limited outcrop area and time period (e.g. DiMichele et al., 2004; Uhl and Kerp, 2003) whereas others represent larger areas including data from many localities spanning a considerable amount of time (e.g. Uhl et al., 2004). To overcome such discrepancies, data from the same sedimentary unit (i.e. from individual basins or geographical regions) have been combined for the individual time slices (i.e. stages) considered in this analysis. For inertinites, this approach seems to lead to lower numbers of occurrences when compared to the works by Diessel (2010) and Glasspool and Scott (2010) but these authors often gave data for different coal seams/horizons from the same sedimentary unit for the individual time slices.

The data have been pooled into bins which correspond in most cases with stages (cf. Tables 1–3), comparable to the approach used by Diessel (2010). Nonetheless, for the Middle Permian, dating of most samples was too imprecise to follow this approach. Accordingly, the Middle Permian samples have been pooled into a single bin that corresponds to an epoch (i.e. the Guadalupian). Although such an approach leads to bins which are not equally long, bins with equal duration have not been used (as used by Glasspool and Scott, 2010), as dating for most records is not good enough to provide reliable absolute ages.

## 3. Results

Based on our literature review and additional own observations (Tables 1–3; Fig. 1), it becomes evident that a gap (or at least a large depression) exists in the fossil record of fossil evidence for palaeo-wildfires during the Early–Middle Triassic. For all Permian time slices, a number of publications dealing with such evidence with maxima in the Artinskian and (subordinate) in the Wuchiapingian can be cited. However, at the beginning of the Triassic, charcoal and other evidence disappear almost completely from the (published) fossil record.

There seems to be no evidence of Induan macro or micro-charcoal, neither in the literature nor during our own extensive field work. The only record of pyrogenic PAHs in putative Early Triassic sediments comes from the Peace River Basin in West Canada (Nabbefeld et al., 2010). However, as the exact position of the Permian–Triassic boundary is unclear in this basin, it is possible that this particular evidence comes from the Late Permian and not from the Early Triassic (Nabbefeld et al., 2010). Of particular interest for the question of Induan fires are studies on palynology/microscopic charcoal (Foster et al., 1997), black carbon (Grasby et al., 2011; Shen et al., 2008) and pyrogenic PAHs (Grice et al., 2007; Nabbefeld et al., 2010; Shen et al., 2011; Thomas et al., 2004) from profiles that span the Permian–Triassic boundary in different areas worldwide. These studies report evidence of palaeo-wildfires in the Permian strata (i.e. microscopic charcoal and pyrogenic PAHs), but the lack of such evidence in almost all early Triassic strata (exception see above). This could point to a more or less sudden change (as seen in geological timescales) in fire-activity at the boundary, with fires in the Permian and the almost total absence of fires in the earliest Triassic, at least in the source area of the respective sediments. Although several authors speculated about a potential role of wildfires in promoting Late Permian ecosystem collapse (e.g. Grasby et al., 2011; Shen et al., 2011), there is no conclusive evidence which role fires played during the extinction event(s).

However, the "charcoal gap" seems to be largely confined to the Induan. From the Scythian onwards there is a (although very scarce) record of fossil charcoal, starting with microscopic charcoal particles observed in palynological samples from the Late Spathian (latest Scythian) from the Svalis Dome in the Barents Sea (Mangerud and Rømuld, 1991). Macroscopically identifiable charcoal seems to reenter the fossil record not before the early Anisian (Uhl et al., 2010). From this time onward, the number of reports on Triassic charcoal increases slowly but steadily (Fig. 1C; Table 2), reaching comparable numbers as in the Wuchiapingian not before the Carnian.

As stated before, this "charcoal-gap" or depression coincides largely with the coal-gap (Induan–Carnian) reported by previous authors (e.g. Retallack et al., 1996; Veevers et al., 1994). This makes it likely that a causal link may exist between the reduction of the coal-forming vegetation and/or vegetation in general and the occurrence of fossil charcoal as evidence of palaeo-wildfires.

## 4. Discussion

Based on the data presented here, it is now possible to discuss the different explanations which have been proposed for the absence of charcoal from Triassic sediments by various authors:

### *4.1. Atmospheric oxygen concentration*

Previous reconstructions of atmospheric oxygen concentrations during time (e.g. Berner, 2006; Berner and Canfield, 1989) have recently been challenged based on the known fossil record of charcoal during the entire Mesozoic. Based on experiments by Belcher and McElwain (2008), it seems likely that 15–17% atmospheric oxygen are more realistic concentrations to allow for the combustion of plant material as the previously assumed 12–15% (cf. Scott, 2000). Additionally, there is evidence that an oxygen concentration of at least 18.5% is necessary for an effective spread of fires (Belcher et al., 2010b). The relatively good record of charcoal in sediments from the Late Triassic with only a few middle Triassic records and only a single early Triassic record, demonstrates that the atmospheric oxygen concentrations reconstructed by these early model runs were probably too low for the Triassic, as the fossil evidence points to the occurrence of wildfires during large parts of the Triassic.

Additional evidence that can probably be used to support the claim for higher as previously modelled atmospheric oxygen concentrations during (at least parts of) the Triassic can be deduced from the well-known giant Triassic amphibians. These animals thrived during the Triassic, although Berner (2005) erroneously claimed that no giant amphibians have been found during the Triassic. Forms like *Mastodonsaurus* Jaeger 1828 from the Middle to Late Triassic of Germany (Anisian–Carnian; Damiani, 2001) reached skull-length of up to (or even exceeding) 150 cm (Moser and Schoch, 2007; Schoch, 1999) with a total length of probably more than 6 m in some adult specimens (Schoch, 1999). Based on the known fossil record of these amphibians, there is no obvious size-reduction in the Triassic forms as compared to Permian forms, much less than an extinction of giant amphibians per se (although some amphibian lineages got extinct during or around the Late Permian ecosystem collapse). Even early

**Table 2**
Overview of published records of Permian and Triassic inertinites in coals. Data on inertinites based on Diessel (2010), Glasspool and Scott (2010), and additional sources not cited in both summaries. For details see text.

| Locality/area | Country | Age | Bin | References |
|---|---|---|---|---|
| M. Taiyuan Form. | CHN | Asselian | 1 | Li et al. (1997) |
| Rotliegend, Döhlen Basin | DEU | Asselian | 1 | Christoph (1957) |
| Rotliegend, Saar-Nahe Basin | DEU | Asselian | 1 | Josten (1956) |
| Cisco Gr. | USA | Asselian | 1 | Barker et al. (2003) |
| Junger Coalfield, Ordos Basin | CHN | Asselian | 1 | Dai et al. (2006b) |
| Jungar Coalfield, Inner Mongolia | CHN | Asselian | 1 | Dai et al. (2008); Dai et al. (2012a) |
| Daqingshan Coalfield, Inner Mongolia | CHN | Asselian | 1 | Dai et al. (2012b) |
| Mersey, Tasm. | AUS | Sakmarian | 2 | Bacon (1991) |
| Santa Terezinha | BRA | Sakmarian | 2 | Kalkreuth et al. (2006) |
| Leão–Butiá | BRA | Sakmarian | 2 | Kalkreuth et al. (2006) |
| Candiota | BRA | Sakmarian | 2 | Ade et al. (1998); Silva and Kalkreuth (2005); Kalkreuth et al. (2006) |
| Auranga Coalfield | IND | Sakmarian | 2 | Jha and Jha (1996) |
| Son Valley Coalfield | IND | Sakmarian | 2 | Basu (1967) |
| West Bakaro Coalfield | IND | Sakmarian | 2 | Navale and Saxena (1989) |
| Wankie Coalfield | ZWE | Sakmarian | 2 | Watson (1958) |
| Shanxi Form. | CHN | Sakmarian–Artinskian | 2, 3 | Querol et al. (1999); Sun et al. (2002); Xiao et al. (2005); Liu et al. (2004); Belkin et al. (2009); Li et al. (1997) |
| Figueira | BRA | Sakmarian–Artinskian | 2, 3 | Ricardi-Branco et al. (1998) |
| Sakamena | MDG | Sakmarian–Artinskian | 2, 3 | Alpern and Rakotoarivelo (1972) |
| Irwin River Coal | AUS | Artinskian | 3 | Santoso (1994) |
| Ewington CM. Collie basin | AUS | Artinskian | 3 | Santoso (1994) |
| Sue C. M. Vasse shelf | AUS | Artinskian | 3 | Santoso (1994) |
| Greta Coal M. | AUS | Artinskian | 3 | Edwards (1975) |
| Ashford Coal M. | AUS | Artinskian | 3 | Flood (1995) |
| Greta Coal M. | AUS | Artinskian | 3 | Diessel and Gammidge (2003) |
| Barakar Formation | BGD | Artinskian | 3 | Bostick et al. (1991); Pareek and Bardhan (1985) |
| Jamalganji Coalf. | BGD | Artinskian | 3 | Imam et al. (2002) |
| Damuda Form. | BTN | Artinskian | 3 | Mukherjee et al. (1988) |
| L. Shihezi Form. | CHN | Artinskian | 3 | Li et al. (1997) |
| Various fields | IND | Artinskian | 3 | Pareek (1990) |
| Karhabari/Son V. | IND | Artinskian | 3 | Basu (1967) |
| L. Gondwana | IND | Artinskian | 3 | Ghose and Wolf (1974) |
| Goodavari Valley | IND | Artinskian | 3 | Pareek (1986); Singh et al. (2012) |
| Barakar F. | IND | Artinskian | 3 | Singh and Shukla (2004) |
| Johilla Coalfield | IND | Artinskian | 3 | Singh and Sing (1987) |
| Sohagpur | IND | Artinskian | 3 | Chakrabarti (1987) |
| Vorkuta/Petchora | RUS | Artinskian | 3 | Volkova (1986) |
| Waterberg Fm. | ZAF | Artinskian | 3 | Fabiańska and Kruszewska (2003) |
| Vryheid Form. | ZAF | Artinskian | 3 | Glasspool (2003a) |
| Witbank No. 2 Coal | ZAF | Artinskian | 3 | Glasspool (2003b) |
| Main S. Gwembe | ZAM | Artinskian | 3 | Money and Drysdall (1973) |
| Collinsville C.M. | AUS | Artinskian–Kungurian | 3, 4 | Beeston and Davis (1976); Mutton (2003) |
| Maules Creek Fm. | AUS | Artinskian–Kungurian | 3, 4 | Gurba and Ward (2000) |
| Liangshan Fm., Hunan | CHN | Artinskian–Kungurian | 3, 4 | Belkin et al. (2009) |
| Barakar Fm. | IND | Artinskian–Kungurian | 3, 4 | Pareek (1987); Jha and Jha (1996); Gurba and Ward (2000); Chakrabarti (1987); Singh and Shukla (2004) |
| Singrauli Coal | IND | Artinskian–Kungurian | 3, 4 | Misra and Singh (1990); Mishra and Cook (1992) |
| Jharkand | IND | Artinskian–Kungurian | 3, 4 | Pophare et al. (2008) |
| Jharia Coalfield | IND | Artinskian–Kungurian | 3, 4 | Mishra and Cook (1992) |
| Moatize | MOZ | Artinskian–Kungurian | 3, 4 | Annon (1983) |
| Mucanha–Vuzi | MOZ | Artinskian–Kungurian | 3, 4 | Falcon et al. (1984) |
| Boreholes | MOZ | Artinskian–Kungurian | 3, 4 | Falcon et al. (1984) |
| Songwe–Kiwira Coalfield | TZA | Artinskian–Kungurian | 3, 4 | Semkiwa et al. (2003) |
| Namwele–Mkomolo Coalfield | TZA | Artinskian–Kungurian | 3, 4 | Semkiwa et al. (1998) |
| Muze Coalfield | TZA | Artinskian–Kungurian | 3, 4 | Semkiwa et al. (1998) |
| Galula Coalfield | TZA | Artinskian–Kungurian | 3, 4 | Semkiwa et al. (1998) |
| Highveld Coalfield | ZAF | Artinskian–Kungurian | 3, 4 | Hagelskamp and Snyman (1988); Wagner and Hlatshwayo (2005) |
| Karroo (Ecca age) | ZAF | Artinskian–Kungurian | 3, 4 | Fabiańska and Kruszewska (2003) |
| Queensland | AUS | Kungurian | 4 | Follington et al. (1995) |
| Lower Aldebaran Sandstone | AUS | Kungurian | 4 | Follington et al. (1995) |
| Jamalganji Coal F. | BGD | Kungurian | 4 | Imam et al. (2002) |
| Goodavari Valley | IND | Kungurian | 4 | Pareek (1986) |
| L. Barakar Form. | IND | Kungurian | 4 | Pareek and Bardhan (1985) |
| West Bokaro Basin | IND | Kungurian | 4 | Navale and Saxena (1989) |
| Petchora | RUS | Kungurian | 4 | Volkova (1986) |
| Ruhuhu Form. | TZA | Kungurian | 4 | Mpanju et al. (1991) |
| Witbank | ZAF | Kungurian | 4 | Mangena et al. (2004) |
| Highveld Coal | ZAF | Kungurian | 4 | Hagelskamp and Snyman (1988); Wagner and Hlatshwayo (2005) |
| Wankie Coalfield | ZWE | Kungurian | 4 | Duguid (1978); Watson (1958); Carr and Williamson (1990) |
| Sabi, Lundi–Sabi | ZWE | Kungurian | 4 | Duguid (1978) |
| Brazil | BRA | Kungurian–Roadian | 4, 5 | Ybert et al. (1971) |
| Mengkarang | IND | Kungurian–Roadian | 4, 5 | Suwarna (2006) |
| Kuznets Basin | RUS | Kungurian–Guadalupian | 4, 5 | Brownfield et al. (2001); Sallabasheva (1979) |

**Table 2** (*continued*)

| Locality/area | Country | Age | Bin | References |
|---|---|---|---|---|
| Komi Republic, Pechorsky | RUS | Kungurian–Guadalupian | 4, 5 | Brownfield et al. (2001) |
| German Cr./Moranbah | AUS | Wordian | 5 | Mutton (2003) |
| Foybrook Form. | AUS | Capitanian | 5 | Smyth (1968) |
| Tomago C.M. | AUS | Capitanian | 5 | Edwards (1975); Smyth (1968) |
| Burnhamwood Fm. | AUS | Guadalupian | 5 | Edwards (1975) |
| Foybrook Fm. | AUS | Guadalupian | 5 | Casareo et al. (1996) |
| Coogal Subgroup | AUS | Guadalupian | 5 | Edwards (1975) |
| Tomago Coal Measures | AUS | Guadalupian | 5 | Edwards (1975) |
| Xinwen, Kailuan | CHN | Roadian | 5 | Mu-Qiu (1979) |
| SW Fujian | CHN | Guadalupian | 5 | Belkin et al. (2009) |
| SW of China | CHN | Guadalupian | 5 | Belkin et al. (2009) |
| Diff. boreholes | MOZ | Guadalupian | 5 | Falcon et al. (1984) |
| Kuznetsk | RUS | Roadian | 5 | Ammosov (1964); Sallabasheva (1979) |
| Illawara Coal Measures | AUS | Guadalupian–Changhsingian | 5, 6, 7 | Edwards (1975); Ward et al. (1996); Diessel (1965, 1985) |
| Lambton SG. | AUS | Wuchiapingian | 6 | Diessel (1965); Edwards (1975) |
| Wybrow Coal | AUS | Wuchiapingian | 6 | Glasspool (2000); Edwards (1975) |
| Adamstown SG. | AUS | Wuchiapingian | 6 | Edwards (1975) |
| Wongawilli S. | AUS | Wuchiapingian | 6 | Diessel (1965) |
| Boolaroo SG. | AUS | Wuchiapingian | 6 | Edwards (1975) |
| Melville S. | AUS | Wuchiapingian | 6 | Gurba and Ward (1998) |
| Hoskisson S. | AUS | Wuchiapingian | 6 | Patterson et al. (1996); Tadros (1993); Gurba and Ward (1998) |
| Moranbah Coal Measures | AUS | Wuchiapingian | 6 | Retallack et al. (1977); Follington et al. (1995) |
| Galilee Basin | AUS | Wuchiapingian | 6 | Mutton (2003) |
| Rangal Coal Measures | AUS | Wuchiapingian | 6 | Mutton (2003) |
| Dahe Mine | CHN | Wuchiapingian | 6 | Wollenweber et al. (2006) |
| Longtan F. | CHN | Wuchiapingian | 6 | Zhuang et al. (2006); Dai et al. (2005) |
| Heshan Coalfield | CHN | Wuchiapingian | 6 | Shao et al. (2003) |
| Dafang Coalfield | CHN | Wuchiapingian | 6 | Dai et al. (2004); Dai et al. (2005) |
| Leping area | CHN | Wuchiapingian | 6 | Querol et al. (2001) |
| Xingren, Guizhou | CHN | Wuchiapingian | 6 | Dai et al. (2006a) |
| Cu-Schiefer | DEU | Wuchiapingian | 6 | Wolf et al. (1989) (data not from coal seam but from clay!) |
| Zhijin Coalfield | CHN | Wuchiapingian–Changhsingian | 6, 7 | Dai et al. (2003); Dai et al. (2004) |
| Newcastle Coal Measures | AUS | Changhsingian | 7 | Edwards (1975) |
| Torbanite/Joadja | AUS | Changhsingian | 7 | Hutton and Cook (1980) |
| Bulli Seam | AUS | Changhsingian | 7 | Diessel (1965, 1985) |
| Rangal Coal Measures | AUS | Changhsingian | 7 | Edwards (1975); Gray and Bowling (1995); Walker et al. (2001) |
| Baralaba Coal Measures | AUS | Changhsingian | 7 | Edwards (1975); Follington et al. (1995) |
| Bhangtar | BTN | Changhsingian | 7 | Pareek (1990) |
| Leping/SW | CHN | Changhsingian | 7 | Querol et al. (2001) |
| SW of South China | CHN | Changhsingian | 7 | Belkin et al. (2009) |
| Kusnetzk Basin | RUS | Changhsingian (?) | 7 | Hudspith et al. (2012)<br>(near top of Permian and below radiometrically dated earliest Triassic basalt flows, thus Changsinghian age assumed here) |
| Clarence Moreton Basin | AUS | Anisian–Ladinian | 10, 11 | Edwards (1975) |
| Mungaroo Fm | AUS | Ladinian–Norian | 11, 12, 13 | Cook et al. (1985) |
| Ipswich Coal M. | AUS | Carnian | 12 | Cook and Taylor (1963); Chern (2004) |
| Tasmania | AUS | Carnian | 12 | Bacon (1986a, 1986b) |
| Lunzer Coal/Lunzer Decke | AUT | Carnian | 12 | Sachsenhofer (1987) |
| Wayaobao Fm | CHN | Carnian | 12 | Yang et al. (1996) |
| Exmouth Plateau | AUS | L. Triassic | 12, 13, 14 | Cook et al. (1985) |
| Sichuan Basin | CHN | L. Triassic | 12, 13, 14 | Wang (2009) |
| Jiangxi | CHN | L. Triassic | 12, 13, 14 | Querol et al. (2001) |
| Peera Peera Formation | AUS | Norian | 13 | Smyth (1980) |
| Huabachong Fm, Guizhou | CHN | Norian | 13 | Yang et al. (1996) |
| Ganhaizi Fm, Yunnan | CHN | Norian | 13 | Yang et al. (1996) |
| ??? | VNM | Norian | 13 | Krynauw (1983) |
| Xujiahe F. | CHN | Norian–Rhaetian | 13, 14 | Zhuang et al. (2006) |
| Callide Coal Measures | AUS | Rhaetian | 14 | Glikson and Fielding (1991) |
| Junggar Basin | CHN | Rhaetian | 14 | Ligouis (2001) |
| Shemshak F./Alborz | IRN | Rhaetian | 14 | Zamani et al. (2000); Mutton (2003) |
| Mecsek Mountains | HUN | Rhaetian (?) | 14 | Varga and Horváth (1986)<br>(not clear whether Rhaetian coals were included in this study or not) |

Note that the coals in the references of Dai et al. (2006b, 2008, 2012a,b) belong to the Asselian age of the early Permian; however, Dai et al. (2006b, 2008, 2012a,b) classified the coals into Pennsylvanian age only for the aim in accordance with the Chinese traditional stratigraphic classification (personal communication with Shifeng Dai).

Triassic forms like *Parotosuchus helgolandicus* (Schroeder) Chernin 1978 from the Spathian of Germany (i.e. the island of Helgoland in the North Sea) reached a skull-length of more than 80 cm (Schroeder, 1913).

Modern amphibians get the majority of their oxygen supply by diffusion from the surrounding atmosphere or water. Although some modern taxa can tolerate a few days of hypoxic or even anoxic conditions (Bickler and Buck, 2007), it seems unlikely from an amphibian point of view (especially when considering the extraordinary large size of animals like the Early Triassic *P. helgolandicus* and especially the Middle–Late Triassic *Mastodonsaurus*) that the low oxygen concentrations during the entire Triassic, as suggested by earlier models (e.g. Berner, 2005), can be seen as realistic.

More recent models or model runs produced estimations for atmospheric oxygen concentrations well above the suggested ignition threshold of 15% throughout the Triassic (Bergman et al., 2004; Berner, 2009; Glasspool and Scott, 2010) and are thus better in

**Table 3**
Overview of published records of Permian and Triassic pyrogenic PAHs. For details see text.

| Locality/area | Country | Age | Bin | References |
|---|---|---|---|---|
| Perth Basin | AUS | Changhsingian | 7 | Thomas et al. (2004); Grice et al. (2007) |
| Wadi Himara (Jordan) | JOR | Changhsingian | 7 | Dill et al. (2010) |
| Meishan | CHN | Changhsingian | 7 | Shen et al. (2008, 2011); Nabbefeld et al. (2010) |
| Kap Stosch | GRL | Changhsingian | 7 | Nabbefeld et al. (2010) |
| Peace River Basin | CAN | Changhsingian | 7 | Nabbefeld et al. (2010) |
| Peace River Basin | CAN | Induan ?[a] | 8 | Nabbefeld et al. (2010) |
| Northern Carnavon basin | AUS | Carnian–Norian | 12, 13 | Jiang et al. (1998) |
| Pomerania (Poland) | POL | Norian–Rhaetian | 13, 14 | Marynowski and Simoneit (2009) |
| Upper Silesia (Poland) | POL | Rhaetian | 14 | Marynowski and Simoneit (2009) |
| Northern Carnavon basin | AUS | Rhaetian | 14 | Jiang et al. (1998) |

[a] The exact position of the Permian–Triassic boundary is so far unclear in the Peace River Basin and thus it is possible that this evidence comes in fact from the Late Permian (Nabbefeld et al., 2010).

agreement with palaeontological evidence from the Late Triassic. However, according to some of these results (i.e. Berner, 2009), the atmospheric oxygen concentration should be high enough to ignite wildfires during the entire Triassic, but not to sustain the spread of smouldering wildfires (Belcher et al., 2010b). Considering the observed gap in the fossil record of charcoal during the Early Triassic, models and the fossil record are again in disagreement, as soon as atmospheric oxygen concentrations shall be utilized as the most important controlling factor for palaeo-wildfires during this period. Nevertheless, when comparing the trends of the reconstructed oxygen concentrations (e.g. Berner, 2009) and the abundance of published charcoal records, it can be seen that relatively low oxygen concentrations in the Early Triassic seem to correlate with the observed charcoal gap or depression (but see Bergman et al., 2004 for a different model output). Elevated oxygen concentrations in the later part of the Triassic correspond to more abundant records of charcoal. Although the model of Berner (2009) reconstructs a sharp drop of oxygen in the latest Triassic (in contrast to other models; e.g. Bergman et al., 2004), which is not reflected in a reduction of charcoal, it is possible (but not necessary) that the overall correlation between both trends may point to a causal relationship between oxygen and the occurrence of wildfires during this period. Such a potential causal relationship has recently been predicted by Belcher et al. (2010b) based on model-derived, oxygen dependent burning-probabilities. However, despite some parallels of both trends, it is not clear whether atmospheric oxygen was the major or even sole environmental parameter that influenced the occurrence of palaeo-wildfires and charcoal as evidence of these fires or not as discussed in the following sections.

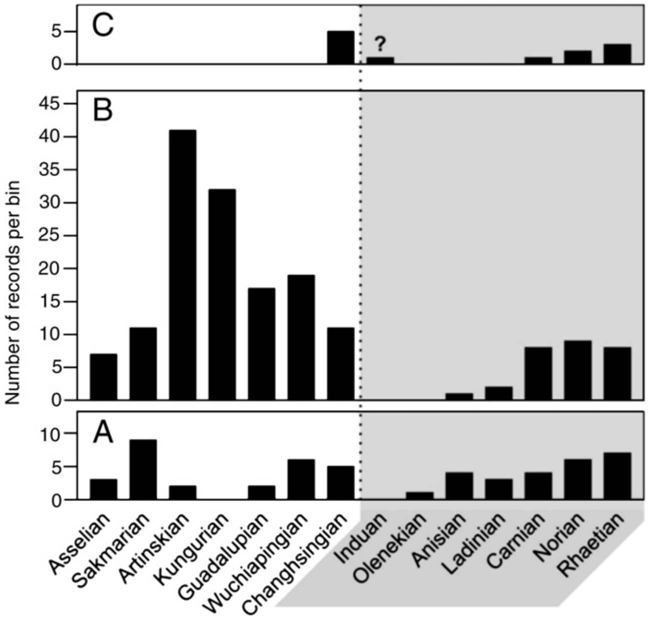

**Fig. 1.** Overview of the number of published reports of fossil evidence for palaeowildfires during the Permian and Triassic [A–C: Triassic highlighted in light-gray. See Tables 1–3 and text for details; intertinite data were mainly taken from Diessel (2010), Glasspool and Scott (2010) and additional sources not cited in both works (cf. Table 2)]. A) Reported occurrences of macroscopic fossil charcoal, B) reported occurrences of inertinites/black carbon and C) reported occurrences of pyrogenic PAHs. The single occurrence in the Induan is questionable (cf. Table 3).

## 4.2. Taphonomy

It is known that in modern sediments deposited under climatic conditions comparable to large parts of the Triassic (i.e. semiarid), like in Australia, macroscopic charcoal breaks down rapidly, leaving only microscopic fragments as evidence of former fires (Skjemstad et al., 1996). Also the red beds, which dominate most of the Triassic (especially the Early Triassic) worldwide, are not suitable for the preservation of charcoal. The same lack of fossil charcoal could be observed in Early Permian red beds from SW Germany, whereas in sediments suitable for the preservation of charcoal like tuff-layers which are interbedded within such red beds charcoal has been preserved (Uhl et al., 2004). Added to this, a general scarcity of early Triassic sediments, as compared to other periods, which provides a smaller volume of sediment in which charcoal could theoretically be discovered, has to be considered (e.g. Belcher and McElwain, 2008; Rees, 2002).

Thus, the scarcity of charcoal remains could also be connected with taphonomic biases, which may lead to erroneous interpretations about frequencies of palaeo-wildfires during the Early Triassic.

## 4.3. Availability of potential fuel

Another factor that has largely been neglected in explanations about the reduction of the presence of charcoal remains during parts of the Triassic is the potential scarcity of fuel (= vegetation/plant biomass). According to Grauvogel-Stamm and Ash (2005), the *Voltzia* sandstone, a fossil Lagerstätte in E France (Alsace) and SW Germany, represents the first moderately diverse macroflora worldwide that has reasonably well been preserved after the Permian–Triassic boundary. Thus, this flora represents the first macroscopic evidence for a recovery of the land vegetation after the crisis at the Permian–Triassic boundary at a global scale. However, there is still an ongoing debate how much land plants suffered during this crisis (e.g. Gastaldo et al., 2005; Grauvogel-Stamm and Ash, 2005; Rees, 2002). The empirical evidence (i.e. the fossil record) tells us that early Triassic macrofloras (which also represent a different type of fuel) are rather scarce. When present, these floras consist only of a few taxa living in highly water-stressed environments, now represented by sediments unfavourable for the preservation of charcoal, i.e. red beds formed under semiarid conditions (cf. Skjemstad et al., 1996; Uhl et al., 2004, 2008). First microscopic evidence of charcoal after the end-Permian extinction event comes from palynofacies studies dealing with early Triassic (i.e. Upper Spathian) sediments from the Svalis Dome in the Barents Sea (Mangerud and Rømuld, 1991).

The recovery phase as seen in palynological studies starts on a global scale in the Late Spathian with the re-appearance of conifer dominated palynofloras (Looy et al., 1999). However, recent studies on early Spathian palynofloras from the Svalis Dome by Hochuli and Vigran (2010) demonstrated that in this region conifer pollen are already present in considerable amounts during this period. This finding may indicate that the sediments deposited at the Svalis Dome derived from an area (or areas), which were more proximal to potential refugia of conifer containing/dominated floras, than other sediments deposited during the Early Triassic. These so far unknown floras may have had a considerable conifer/gymnosperm component, which may in turn represent a more suitable source of fuel than floras dominated by the lycopsid (*Pleuromeia*) and the fern (*Anomopteris*) growing in the main areas of sediment deposition in many regions worldwide. Nevertheless, it seems unlikely that the lack of fuel can be seen as the main or even sole reason for the general scarcity of charcoal during the Early and Middle Triassic, as vegetation types or plant groups which may be better sources of charcoal existed during the Early Triassic, most likely in some kind of refugium somewhere in the hinterland. There are several lines of evidence that such refugia must have existed:

1) there is an increasing evidence from the fossil record that several lineages of assumed “typical” Mesozoic plants already appeared during the Late Palaeozoic, although no macrofossils belonging to these lineages are so far known from the early Triassic (e.g. Voltziales: Looy, 2007; Schweitzer, 1996; Peltaspermales: Poort and Kerp, 1990; Corystospermales: Abu Hamad et al., 2008; Kerp et al., 2006). This clearly indicates that refugia must have existed during this period in which these plants could survive and in which wildfires (at least theoretically) could have occurred. As there is no direct evidence for such refugia, it is only possible to speculate that these must have been located far away from the areas of deposition somewhere in the hinterland.
2) the palynological record demonstrates that in several regions worldwide plants existed during the Early Triassic, although most of these floras are dominated by spores originating from lycopsids and ferns (e.g. Looy et al., 1999). In Europe gymnosperm (i.e. conifer) dominated pollen floras do not reappear prior to the Olenekian (Early Triassic)–Anisian (Middle Triassic) transition (Looy et al., 1999). At the Svalis Dome in the Barents sea, pollen of conifers and pteridosperms already reappear during the Olenekian (Smithian–Spathian boundary), and here, Hochuli and Vigran (2010) observed repeated changes between spore (lycopsids and ferns) dominated floras and pollen (conifers and pteridosperms) dominated floras during the entire Triassic. These authors interpreted these changes as indicative of climate changes resulting in the regional waxing and waning of certain vegetation types (Hochuli and Vigran, 2010). Also in Antarctica early Triassic palynofloras are characterized by the disappearance or at least extreme decline of many pollen types attributable to gymnosperms but also pteridophytes (McLoughlin et al., 1997). At the beginning of the Triassic these palynofloras are dominated by peltasperms and lycopsids but other groups like ferns, corystosperms and conifers become more abundant during the course of the Early Triassic before they constitute the dominant groups in Late Triassic sediments (McLoughlin et al., 1997). These changes are again interpreted as the results of climate changes, with a massive additional disturbance near the Permian–Triassic boundary (McLoughlin et al., 1997). All in all, it can be stated that the Early Triassic record of palynofloras suggests the widespread occurrence of different vegetation types, although the published record of palaeo-wildfires is almost non-existing for this period (with the exception of the single paper by Mangerud and Rømuld, 1991).
3) Plants, as photoautotrophic organisms, are the primary source of food in terrestrial ecosystems. Thus, it is possible to conclude that at least some kind of plant cover must have been accessible wherever the remains of animals (especially more or less large herbivorous tetrapods) can be found in continental deposits. Although there are not many Early Triassic localities yielding vertebrate fossils there is evidence (including the ichnological record) that large tetrapods existed even in areas without a considerable record of plant macrofossils (e.g. Sues and Fraser, 2010). Thus, it can be concluded that within or near these areas enough vegetation must have been present (at least in some patches) to sustain survival of these animals.

It is clear that based only on such indirect evidence nothing can be said about the type of vegetation, the standing biomass or the areal extant (continuous vegetation cover or only patches in small places with favourable conditions [oasis in a wide sense]) covered by plants. It is also possible that vertebrate fossils may have been transported over some distance prior to burial or that the animals may have been migratorial, but even in these cases it is possible to conclude that vegetation must have been present in a part of the habitats of such animals.

Based on the direct palynological evidence, the stratigraphic ranges of certain plant taxa and the indirect evidence based on the occurrence of vertebrates, it is clear that on a global scale plant cover must have been more intensive during the Early (and Middle) Triassic as seen from the scarce record of plant macro remains (cf. Grauvogel-Stamm and Ash, 2005). Thus, the absence of fossil charcoal, which is much more resistant against chemical and biological decay than other plant remains from so many Early and Middle Triassic sediments, is even more puzzling.

Assuming that fires may have occurred in some refugia (located in more or less distance from areas of deposition), there are two possible explanations for the lack of charcoal or other evidence for wildfires during the Early Triassic: a) the distance between these refugia and the areas of deposition were rather long and taphonomic filters prevented the transport of evidence for wildfires into the areas where such sediments are accessible today, or b) these refugia have been located relatively close to the areas of sedimentation but plant fossils (including charcoal) have not been preserved due to unfavourable conditions for the preservation of such fossils in the sediments (i.e. red beds) itself. Again it should be noted that as soon as there is a fossil record of hinterland elements, either in palyno-floras (Mangerud and Rømuld, 1991) or in the macro-record (Uhl et al., 2010), there is also evidence for wildfires. Considering this, it seems highly unlikely that it is possible to use the lack of evidence for early Triassic palaeo-wildfires as conclusive evidence for the lack of fires during the Early Triassic.

## 5. Conclusions

In analogy to the known Early–Middle Triassic coal gap (Retallack et al., 1996; Veevers et al., 1994), it seems possible to talk about a comparable “charcoal gap” or at least “charcoal depression” (Uhl et al., 2010). This gap, however, seems to span a shorter time than the reported coal gap (i.e. the Early and parts of the Middle Triassic). Thus it took about 18 myr for peat forming vegetation to recover after the Permian–Triassic boundary event but only about 5 myr before the first macroscopic evidence of wildfires appears (following the summarized Triassic timescale presented by Preto et al., 2010). However, it took also the same 18 myr before the frequency of fossil charcoal (as seen in the numbers of published papers mentioning evidence for wildfires) reached pre-Triassic values.

At the moment it seems likely that a combination of the reasons stated above (taphonomy, atmospheric oxygen levels, lack of sediments suitable for the preservation of macroscopic charcoal, lack of fuel, and "ignorance" of scientists) can be used to explain the (apparent?) lack of charcoal in the Early Triassic. However, none of these reasons can be identified at the moment as the most important or sole culprit, based on the hard geological evidence (i.e. the fossil record). Although modelling results (i.e. Belcher et al., 2010b; Berner, 2009) are still in favour of low oxygen concentrations as the most important reason, there is some evidence against low oxygen concentrations (i.e. large amphibians) and other explanations may be necessary to explain the absence of evidence for palaeo-wildfires during the Early Triassic. Thus, it is absolutely not clear at the moment whether the observed "charcoal gap" must necessarily be interpreted as a "wildfire gap" (i.e. no production of charcoal due to low oxygen levels) or whether this gap can also be explained by other factors (i.e. no preservation of charcoal, due to lack of fuel and/or taphonomic biases).

Without any doubt, further investigations on the early Triassic record of evidence for wildfires will be necessary before this problem can be solved. In fact, it has to be expected that the number of published records of Triassic charcoal and other fire-evidence will increase in the future as more and more scientist working on Triassic sediments may become aware of the interest in wildfires during this time. This will hopefully provide a much sharper picture of the temporal and regional distribution of wildfires during this period in the future.

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