Permian and Triassic wildfires and atmospheric oxygen levels

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Abstract: - Our present knowledge of Permian and Triassic occurrences of fossil charcoal, as direct evidence of palaeo-wildfire, is summarized. These data show that contrary to previous assumptions at least for the Permian a more or les continuous fossil record of charcoal exists. Permian gaps in the fossil record of charcoal are very likely to be explained by taphonomic biases and can not be linked to changes in atmospheric oxygen concentrations. In contrast the record of Triassic charcoal seems to be extremely scarce and this scarcity may be linked, at least to some extent, to rather low oxygen levels. However, parallel to the delayed recovery of terrestrial vegetation after the mass extinction at the Permian-Triassic boundary the fossil record of charcoal improves from the Ladinian up to the Rhaetian, contrary to a drop in atmospheric oxygen concentrations reconstructed by geochemical modeling. Probably a simple correlation between atmospheric oxygen concentrations and the frequency and intensity of naturally occurring wildfires may not be as easily linked to the abundance of fossil charcoal as proposed earlier. Additional factors like taphonomical filters should be taken into account whenever it is attempted to use the frequency and abundance of fossil charcoal as evidence for changes in atmospheric oxygen concentrations.

Key-Words: - Permian; Triassic; charcoal; atmospheric oxygen; taphonomy; vegetation recovery

1 Introduction

It has been predicted for several regions of the world that an increased frequency of wildfires together with their negative impacts on human civilization, will come along with a future climate change [29]. Such a climate change from icehouse conditions to a greenhouse world occurred also during the Permian and the Triassic [7, 23, 25]. Knowledge regarding the development of fire-frequencies as well as the intensities of fire induced devastation during this period is therefore essential for any evaluation of potential effects of a future or contemporary climate change - not only from an ecological, but also from an economical and political point of view.

The occurrence of fossil charcoal in sediments is widely accepted as the direct evidence of palaeowildfires [32, 33, 34]. So far, the oldest undisputed charcoal has been described from the Late Silurian of West-England [13], and from this time on there is a more or less continuous fossil record of charcoal [28, 33]. During the last decades special attention has been paid to the Late Carboniferous. For this time very high atmospheric O_2-concentrations have been reconstructed using geochemical modeling methods [1, 4]. Furthermore, widespread evidence exists for very intense fires within various terrestrial ecosystems [9, 10, 33].

Several authors have speculated that fire frequencies, as represented by the abundance and frequency of fossil charcoal, have decreased during the Latest Carboniferous and Permian, because of a drop in atmospheric O_2-concentrations [26, 27, 33]. This assumption is based on experimental data, which indicate a required atmospheric oxygen concentration of at least 13% for sustained biomass combustion [5, 6]. According to the reconstruction by Berner and Canfield [4] the atmospheric oxygen concentration would have dropped below this level during the Late Permian. More recent results from geochemical modeling, however, moved the high O_2-peak forward into the Permian and the acclaimed threshold of 13% atmospheric oxygen has probably not been reached before the Triassic (cf. Fig. 1; [2, 3]). Following this new reconstruction it has to be questioned whether changes in the atmospheric oxygen concentration are indeed the main reasons for the observed decrease of evidence for wildfires during the Latest Carboniferous and the Permian, as well as the Triassic or whether additional reasons have to be taken into account for the low charcoal abundances and frequencies during this period.

Here we present a tentative overview of previously published, as well as hitherto unpublished records of Permian and Triassic charcoals during this periods, to establish a first temporal framework for the causal interpretation of the fossil record of wildfires during this time.

2 Records of Permian charcoal

Most detailed reports on Late Palaeozoic charcoal from the northern hemisphere prior to the extensive review on Pre-Quaternary fires by Scott [33] came from Westphalian and pre-Westphalian deposits. For the Stephanian and the entire Permian, only few investigations had been made on this subject up to this date [30, 31, 35]. Although the occurrence of charcoal has anecdotally been reported from a number of localities from the latest Carboniferous (‘‘post’’-Stephanian C = lowermost Rotliegend of Central Europe) and Permian of Central Europe (cf. [39] and citations therein), no detailed descriptions of the material had been given and no anatomical or petrologic evidence supporting such an interpretation of the respective material had been presented.

Only recently it has been demonstrated that in the rather humid Lower Rotliegend (upper Gzhelian – Asselian) of the Saar-Nahe basin in SW Germany all sedimentary lithologies investigated so far yielded charcoal remains in varying abundance (cf. Fig. 2A) [39]. In contrast most sedimentary facies (i.e. red beds, deposited under strong climatic seasonality) from the more arid Upper Rotliegend (Asselian – Sakmarian) of this area yielded no macroscopically identifiable charcoal remains (cf. Fig. 2B) [39]. Only in volcanically influenced sediments charcoal has been found here. However, in these cases most charcoals were silicified and the few non-silicified charcoals were found in tuffs or tuffites that have been deposited subaquatically [39]. As demonstrated by Skjemstad et al. [36] charcoal breaks down rapidly under semi-arid conditions and it has been assumed by Uhl et al. [39] that this, together with a generally sparse vegetation cover, is also very likely the main reason for the low abundance of charcoal in sediments from the Upper Rotliegend of the Saar-Nahe basin. Additional reports of Early Permian charcoals come from Northern America, where fossil charcoal has been discovered at several localities in lacustrine and marine sediments [30, 31, 33]. Charcoal found in coals [17, 19, 37] and in lacustrine Kungurian sandstones of the Rio Bonito Formation, in the Paraná Basin, South Brazil (Fig. 2C), is proof that during the Early Per-

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mian wildfires also occurred in the mid latitudes of Gondwana.

The up to now the published record of Middle Permian charcoal is rather scarce. So far only a few reports of fossil charcoal from this period have been substantiated by anatomical [8] or petrographic evidence [12]. However, records of Middle Permian wildfires are geographically widespread, including the Euramerican floral province [8], Cathaysia [42] and the high latitudes of Southern Gondwana [12].

Plant bearing localities from the Late Permian of the Northern hemisphere, especially from Euramerica, are very rare. An analysis of marine marls from the lower Zechstein (Wuchiapingian) of NW-Hesse (Germany) provided abundant charcoal fragments, not only consisting of charred woods, but also of charred conifer needles (cf. Fig. 2D–E) [38]. Remains of Wuchiapingian charcoal have also been discovered in Zechstein sediments near the abandoned village of Culmitzsch in E-Thuringia (Germany) (cf. Fig. 2F). Further reports of Wuchiapingian charcoals come from Cathaysia, were a lycopsid dominated vegetation experienced more or less regular wildfires during this time [41, 42, 43].

Additional to charcoals from the Late Permian of Central Europe and China also charcoals from the uppermost Permian (Changhsingian) deposits of Jordan have recently been discovered (Fig. 2G), which testify for the first time to the occurrence of palaeo-wildfires in the low latitudes of Northern Gondwana during this period [40]. These charcoals are abundant in facies types, like clays deposited in abandoned channels, which are favourable for the preservation of charcoal, whereas other facies types deposited under more dry conditions yielded no macroscopically identifiable charcoal at all.

3 Records of Triassic charcoal

Charcoal is extremely rare in clastic sediments from the Triassic [33] and only a few reports deal with Triassic charcoal in detail. Substantiated reports on macroscopically identifiable charcoal from the Early Triassic (Indusian – Olenekian) and the Anisian are completely missing so far. Only occasionally shattered remains of charcoal have been reported from studies on the palynofacies of early to middle Triassic sediments [24]. So far the oldest substantiated Triassic record of macroscopically identifiable charcoal comes from the Ladinian of S-Germany [20, 21, 22]. The record of Carnian and Norian charcoal is also extremely scarce, but the occurrence of charcoal has repeatedly been testified for N-America [18, 45], as well as S-Germany [20, 21, 22].

Harris [15, 16] described charcoal from Rhaetian – Liassic fissure fills in Carboniferous limestones of South Wales. Although Harris [15] could give no definitive age assignments for his material he stated that it would be most likely of lower Liassic age, based on taxonomic similarities with Liassic floras from S-Germany. Harris [16] also reported the occurrence of charcoal in Rhaetian – Lower Liassic deltaic deposits of Eastern Greenland. In this case the charcoal has not been identified, but it is abundant and has a widespread occurrence in this area. Later on Scott [33] considered the charcoal described by Harris [15, 16] to be of Early Jurassic age. In S-Germany (Franconia, Bavaria) charcoal has also been recorded from Rhaetian sediments [20, 21, 22]. In SW-Germany charcoal is frequent in Rhaetian sandstones (Fig. 2H–I). This material shows characteristics which are considered to be typical for charcoal by several authors [33], like black streak, silky lustre and homogenized cell-walls when investigated under the SEM, giving proof to the occurrence of wildfires during the uppermost Triassic in Central Europe.

4 Discussion

Our brief overview has shown that the fossil record of Permian charcoals is obviously not as scarce as previously believed by various authors [18, 33], although the fossil record of Permian charcoal is in fact less abundant than that of Carboniferous charcoal [33]. However, according to recent model results the highest atmospheric oxygen concentrations were not reached during the Carboniferous, thus promoting widespread and intense wildfires, but during the Permian and probably did not fall below the assumed crucial threshold of 13% during the entire Permian (cf. Fig. 1), but remained above this level until the Lower Triassic [2]. Instead of low oxygen levels it is therefore necessary to evaluate other potential reasons for the lower abundance of charcoal during the Permian.

One of the potential reasons is a generally scarcer vegetation cover during the Permian in many areas worldwide, than during the Carboniferous. Climatic deterioration as well as tectonic reorganization of landscapes led to the disappearance of coal forming forests in most regions worldwide [23] and probably the potential amount of available fuel for wildfires decreased on a large scale. Regionally such a reason has also been discussed for the scarceness of charcoal in Upper Rotliegend (Asselian – Sakmarian) sediments from SW-Germany [39]. Another potential reason are taphonomic filters and it has already been proposed that charcoal produced during wildfires has not been preserved due to degradation under the semi-arid and arid conditions prevailing during parts of the Permian [39], like it has been observed in present-day Australia where buried charcoal breaks down rapidly under semi-arid conditions [36]. Both reasons, maybe together with other, so far unidentified reasons, can probably explain the lower abundance of Permian charcoal as compared to the Carboniferous.

In contrast to the Permian the record of Triassic charcoal actually seems to be extremely scarce and this scarcity of charcoal may in fact be linked, at least to some extent, to rather low oxygen levels, which probably dropped below 13% during parts of the Triassic [2, 3]. However, these geochemical model results also suggest that oxygen levels were lowest during the Triassic – Jurassic transition interval. This low-oxygen phase corresponds at least partly to the Rhaetian, a phase with widespread and abundant evidence of palaeo-wildfires. After a global "charcoal gap" from the Indusian up to the Anisian, the fossil record of charcoal seems to increase slowly from the Ladinian up to the Rhaetian, contrary to a modeled drop in atmospheric oxygen concentrations. This seems to contradict a direct relationship between oxygen concentrations and fire-frequencies. However, based on physico-chemical considerations and experimental evidence it has to be assumed that oxygen concentrations [5, 6], together with chemical and physical properties of the fuel [44], have actually an influence on the intensity and frequency of naturally occurring fires. But, why is the fossil record of charcoal increasing from the Ladinian onwards, despite low oxygen levels? A potential explanation may be linked to the recovery patterns of terrestrial vegetation seen after the devastating mass-extinction at the Permian-Triassic boundary.

As Grauvogel-Stamm and Ash [14] have shown, the worldwide fossil record of land plants is extremely scarce during an Early Triassic survival phase and only from the Anisian onward do fossil plant remains become more frequent, pointing to a recovery of terrestrial ecosystems during this period. Considering the fact that most of the potential refugia for many Early Triassic plants, which may have experienced wildfires during this period, were probably far away from the areas were sediments from this period have been deposited [11, 14] it seems likely that no charcoal as direct evidence of wildfires within such potential refugia, has been deposited within sediments from this period. However, the scarce records of charcoal remains in palynofacies samples from the Early Triassic [24] demonstrate that actually wildfires occurred somewhere in the hinterland.

It seems, that we have to consider that the scarceness of charcoal during the Triassic is not only related to the low atmospheric oxygen concentrations prevailing during this period, but also reflects the rather slow recovery of the terrestrial vegetation after the mass-extinction at the Permian-Triassic boundary. Additionally, as considered above for the Permian, taphonomic filters have to be taken into account which may have further decreased the quantity of fossil charcoal within most sediments (i.e. the widespread red beds) deposited during the Triassic.

Our results and interpretations indicate that a simple correlation between atmospheric oxygen concentrations and the frequency and intensity of naturally occurring wildfires may not be as easily linked to the abundance of fossil charcoal as proposed by previous authors [18, 26, 27, 33]. Additional factors like the global or regional density of the vegetation, as well as taphonomic filters, which are independent from oxygen concentrations, should be taken into account whenever it is attempted to use the frequency and abundance of fossil charcoal as evidence for changes in atmospheric oxygen concentrations.

References:

[1] Berner, R.A., Modelling atmospheric O_2 over Phanerozoic time, *Geochimica et Cosmochimica Acta*, Vol. 65, 2001, pp. 685-694.

[2] Berner, R.A., Examination of hypotheses for the Permo-Triassic boundary extinction by carbon cycle modeling, *Proceedings of the National Academy of Sciences*, Vol. 99, 2002, pp. 4172-4177.

[3] Berner, R.A., The carbon and sulfur cycles and atmospheric oxygen from middle Permian to middle Triassic, *Geochimica et Cosmochimica Acta*, Vol. 69, 2005, pp. 3211-3217.

[4] Berner, R.A., and Canfield, D.E., A new model for atmospheric oxygen over Phanerozoic time, *American Journal of Science*, Vol. 289, 1989, pp. 333–361.

[5] Clark, F.R.S., and Russell, D.A., Fossil charcoal and the palaeoatmosphere, *Nature*, Vol. 290, 1981, pp. 428.
[6] Cope, M.J., and Chaloner, W.G., Fossil charcoal and the palaeoatmosphere. Reply, *Nature*, Vol. 290, 1981, pp. 428.
[7] DiMichele, W.A., Pfefferkorn, H.W., and Gastaldo, R.A., Response of Late Carboniferous and Early Permian plant communities to climate change, *Annual Review of Earth and Planetary Science*, Vol. 29, 2001, pp. 461-487.
[8] DiMichele, W.A., Hook, R.W., Nelson, W.J., and Chaney, D.S., An unusual Middle Permian flora from the Blaine Formation (Pease River group: Leonardian-Guadalupian series) of King County, West Texas, *Journal of Paleontology*, Vol. 78, 2004, pp. 765-782.
[9] Falcon-Lang, H.J., The impact of wildfire on an Early Carboniferous coastal environment, North Mayo, Ireland, *Palaeogeography, Palaeoclimatology, Palaeoecology*, Vol. 139, 1998, pp. 121-138.
[10] Falcon-Lang, H.J., and Scott, A.C., Upland ecology of some Late Carboniferous cordaitalean trees from Nova Scotia and England, *Palaeogeography, Palaeoclimatology, Palaeoecology*, Vol. 156, 2000, pp. 225-242.
[11] Gall, J.-C., and Grauvogel-Stamm, L., The early Middle Triassic 'Grès à Voltzia' Formation of eastern France: a model of environmental refugium, *Compte Rendu Palevol*, Vol. 4, 2005, pp. 569-584.
[12] Glasspool, I., A major fire event recorded in the mesofossils and petrology of the Late Permian, Lower Whybrow coal seam, Sydney Basin, Australia, *Palaeogeography, Palaeoclimatology, Palaeoecology*, Vol. 164, 2000, pp. 373-396.
[13] Glasspool, I.J., Edwards, D., and Axe, L., Charcoal in the Silurian as evidence for the earliest wildfire, *Geology*, Vol. 32, 2004, pp. 381-383.
[14] Grauvogel-Stamm, L., and Ash, S.R., Recovery of the Triassic land flora from the end-Permian life crisis, *Compte Rendu Palevol*, Vol. 4, 2005, pp. 525-540.
[15] Harris, T.M., A Liasso-Rhaetic flora in South Wales, *Proceedings of the Royal Society of London, ser. B*, Vol. 147, 1957, pp. 289-308.
[16] Harris, T.M., Forest fire in the Mesozoic, *Journal of Ecology*, Vol. 46, 1958, pp. 447-453.
[17] Holz, M., Vieira, P.E., and Kalkreuth, W., The Early Permian coal-bearing succession of the Paraná Basin in Southernmost Brazil: depositional model and sequence stratigraphy, *Revista Brasileira de Geociências*, Vol. 30, 2000, pp. 420-422.
[18] Jones, T.P., Ash, S., and Figueiral, I., Late Triassic charcoal from Petrified Forest national Park, Arizona, USA, *Palaeogeography, Palaeoclimatology, Palaeoecology*, Vol. 188, 2002, pp. 127-139.
[19] Kalkreuth, W., Holz, K.M., Machado, G., Mexias, A., Silva, M.B., Willett, J., Finkelman, R., and Burger, H., Petrology and chemistry of Permian coals from the Paraná Basin: 1. Santa Terezinha, Leão-Butiá and Candiota Coalfields, Rio Grande do Sul, Brazil, *International Journal of Coal Geology*, Vol. 68, 2006, pp. 79-116.
[20] Kelber, K.-P., Der Nachweis von Paläo-Wildfeuer durch fossile Holzkohlen aus dem süddeutschen Keuper, *Terra Nostra*, Vol. 99/8, 1999, pp. 41.
[21] Kelber, K.-P., Preservation and taphonomy of charcoal from the Upper Triassic of southern Germany, Abstract, *12th Plant Taphonomy Meeting*, 26th of October 2001, Altlengbach, Austria, 2001.
[22] Kelber K-P. Die Erhaltung und paläobiologische Bedeutung der fossilen Hölzer aus dem süddeutschen Keuper (Trias, Ladinium bis Rhätium), In: Schüssler H, Simon T. (eds.): *Aus Holz wird Stein - Kieselhölzer aus dem Keuper Frankens* (Offsetdruck Eppe GmbH), Bergatreute-Aulendorf, 2007, pp. 37-100.
[23] Kerp, H., The modernization of landscapes during the Late Paleozoic-Early Mesozoic, *Paleontological Society Papers*, Vol. 6, 2000, pp. 79-113.
[24] Mangerud, G., and Rømuld, A., Spathian–Anisian (Triassic) palynology at the Svalis Dome, southwestern Barents Sea, *Review of Palaeobotany and Palynology*, Vol. 70, 1991, pp. 199-216.
[25] Retallack, GJ., Permian-Triassic life crisis on land, *Science*, Vol. 267, 1995, pp. 77–80
[26] Robinson, J.M., Phanerozoic O_2 variation, fire, and terrestrial ecology, *Palaeogeography, Palaeoclimatology, Palaeoecology*, Vol. 75, 1989, pp. 223-240.
[27] Robinson, J.M., Phanerozoic atmospheric reconstructions: a terrestrial perspective, *Palaeogeography, Palaeoclimatology, Palaeoecology*, Vol. 97, 1991, pp. 51-62.
[28] Rowe, N.P., and Jones, T.P., Devonian charcoal, *Palaeogeography, Palaeoclimatology, Palaeoecology*, Vol. 164, 2000, pp. 347-354.

[29] Ryan, K.C., Global Change and Wildland Fire. In: *Wildland fire in ecosystems: effects of fire on flora*, USDA Forest Service General Technical Report, RMRS-GTR-42 (2), 2000, pp. 175-184.

[30] Sander, P.M., Taphonomy of the Lower Permian Geraldine bonebed in Archer County, Texas, *Palaeogeography, Palaeoclimatology, Palaeoecology*, Vol. 61, 1987, pp. 221-236.

[31] Sander, P.M., and Gee, C.T., Fossil charcoal: techniques and applications, *Review of Palaeobotany and Palynology*, Vol. 63, 1990, pp. 269-279.

[32] Scott, A.C., Observations on the nature and origin of fusain, *International Journal of Coal Geology*, Vol. 12, 1989, pp. 443-475.

[33] Scott, A.C., The Pre-Quaternary history of fire, *Palaeogeography, Palaeoclimatology, Palaeoecology*, Vol. 164, 2000, pp. 297–345.

[34] Scott, A.C., Preservation by fire, In: Briggs D.E.G. and Crowther P.R. (eds.), *Palaeobiology a synthesis II*. Blackwell Scientific Publ., 2001, pp. 277-280.

[35] Scott, A.C., and Glasspool, I.J., The diversification of Paleozoic fire systems and fluctuations in atmospheric oxygen concentration, *Proceedings of the National Academy of Science U.S.A.*, Vol. 103, 2006, pp. 10861–10865.

[36] Skjemstad, J.O., Clarke, P., Taylor, J.A., Oades, J.M., and McClure, S.G., The chemistry and nature of protected carbon in soil, *Australian Journal of Soil Research*, Vol. 34, 1996, pp. 251-271.

[37] Silva, M.B., and Kalkreuth W., Petrological and geochemical characterization of Candiota coal seams, Brazil – Implication for coal facies interpretations and coal rank, *International Journal of Coal Geology*, Vol. 64, 2005, pp. 217-238.

[38] Uhl, D., and Kerp, H., Wildfires in the late Palaeozoic of Central Europe - The Zechstein (Upper Permian) of NW-Hesse (Germany), *Palaeogeography, Palaeoclimatology, Palaeoecology*, Vol. 199, 2003, pp. 1-15.

[39] Uhl, D., Lausberg, S., Noll, R., and Stapf, K.R.G., Wildfires in the Late Palaeozoic of Central Europe - an overview of the Rotliegend (Upper Carboniferous - Lower Permian) of the Saar-Nahe Basin (SW-Germany), *Palaeogeography, Palaeoclimatology, Palaeoecology*, Vol. 207, 2004, pp. 23-35.

[40] Uhl, D., Abu Hamad, A.M.B., Kerp, H., and Bandel, K., Evidence for palaeo-wildfire in the Late Permian palaeotropics – charcoalified wood from the Um Irna Formation of Jordan, *Review of Palaeobotany and Palynology*, Vol. 144, 2007, pp. 221-230.

[41] Wang Zi-Qiang, Vegetation declination on the eve of the P-T Event in North China and plant survival strategies: an example of Upper Permian refugium in Nortwestern Shanxi, China, *Acta Palaeontologica Sinica*, Vol. 39 (Suppl.), 2000, pp. 127-153.

[42] Wang Zi-Qiang, and Chen An-Shu, Traces of arborescent lycopsids and dieback of the forest vegetation in relation to the terminal Permian mass extinction in North China, *Review of Palaeobotany and Palynology*, Vol. 117, 2001, pp. 217-243.

[43] Wang Zi-Qiang, and Zhang Zhiping, Gymnosperms on the eve of the terminal Permian mass extinction in North China and their survival strategies, *Chinese Science Bulletin*, Vol. 43, 1998, pp. 889-897.

[44] Wildman, R.A., Hickey, L.J., Dickinson, M.B., Berner, R.A., Robinson, J.M., Dietrich, M., Essenhigh, R.H., and Wildman, C.B., Burning of forest materials under late Paleozoic high atmospheric oxygen levels, *Geology*, Vol. 32, 2004, pp. 457-460.

[45] Zeigler, K.E., Heckert, A.B., and Lucas, S.G., Taphonomic analysis of a fire-related Upper Triassic vertebrate fossil assemblage from North-Central New Mexico, *New Mexico Geological Society, 56th Field Conference Guidebook, Geology of the Chama basin*, 2005, pp. 341-354.

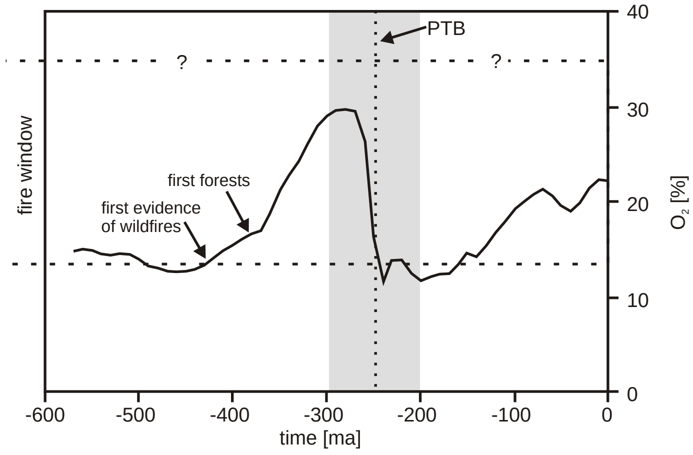
Figure captions:

Fig. 1.

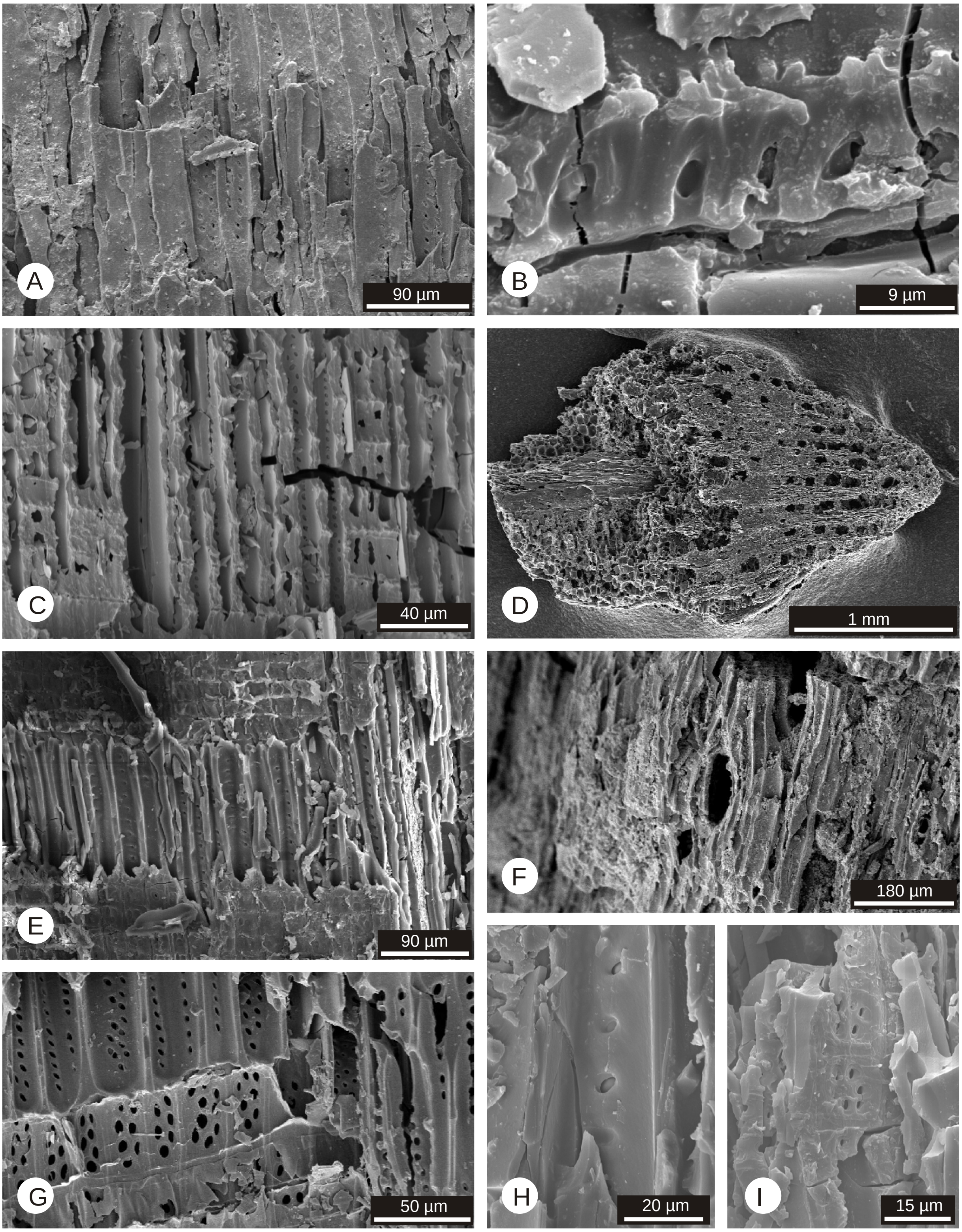
Reconstructed atmospheric oxygen concentrations over the last 600 million years (redrawn from Berner, 2002). Permian and Triassic highlighted in grey; PTB = Permian – Triassic boundary

Fig. 2.

SEM-images of charcoal remains from the Permian and Triassic. A) Gzhelian/Asselian, Saar-Nahe basin SW-Germany (from Uhl et al., 2004); B) Asselian/Sakmarian, Saar-Nahe basin SW-Germany (from Uhl et al., 2004); C) Kungurian, Paraná Basin, Rio Grande do Sul, S-Brazil (from Jasper et al., submitted); D – E) Wuchiapingian, Frankenberg, NW-Hesse, Germany (from Uhl and Kerp, 2003), F) Wuchiapingian, Culmitzsch, E-Thuringia, Germany; G) Changhsingian, Wadi Himara, Jordan (from Uhl et al., 2007); H – I) Rhaetian, Tubingen, SW-Germany.



Uhl et al., Fig. 1



Uhl et al., Fig. 2