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Acta Palaeobotanica 58(2): 175–184, 2018
DOI: 10.2478/acpa-2018-0012

e-ISSN 2082-0259
ISSN 0001-6594

Charred conifer remains from the Late Oligocene – Early Miocene of Northern Hesse (Germany)

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Received 3 August 2018; accepted for publication 2 October 2018

ABSTRACT. Fire is an important constituent of many modern and fossil ecosystems. During the last decades a large number of studies have dealt with fires in pre-Cenozoic ecosystems. Evidence for the occurrence of Palaeogene and Neogene wildfires (e.g. in the form of pyrogenic inertinites in lignite deposits) is geographically and stratigraphically widespread. However, as compared to earlier periods (i.e. the Permian and Cretaceous), fewer studies have focussed so far on plants burnt (or charred) in wildfires from these periods, even though these periods are of considerable interest for our understanding of the evolution of modern ecosystems. Here we report the occurrence of charred wood remains belonging to different conifer taxa from the base seam of the former Frielendorf opencast lignite mine in Northern Hesse (Germany). These findings are evidence that these conifers, and the types of vegetation they were growing in, were affected by wildfires occurring during the Late Oligocene – Early Miocene in this region.

KEYWORDS: Cupressaceae, lignite, conifers, Palaeo-wildfire, Frielendorf Formation, Geoarchive Marburg

INTRODUCTION

Fire is an important source of disturbance in many modern ecosystems and also were important in fossil ecosystems (e.g. Potonié 1929, Scott 2000, 2010, Scott et al. 2014). Charcoal, direct evidence of wildfires, is known since the Silurian (Glasspool et al. 2004). Various authors have recognized 'high' fire phases like the Late Palaeozoic (e.g. Glasspool et al. 2015) and Cretaceous (e.g. Scott et al. 2014), as well as 'low' fire phases such as the early Triassic (e.g. Scott 2000, Abu Hamad et al. 2012, Scott et al. 2014) and parts of the Cenozoic (e.g. Scott 2000, Diessel 2010, Bond 2015). In recent decades there has been increased interest in Quaternary and pre-Cenozoic palaeowildfires (e.g. Scott 2000, 2010, Abu Hamad et al. 2012, Brown et al. 2012, Scott et al. 2014; and citations therein). Additionally, a number of studies have dealt with evidence for Palaeogene and Neogene (Miocene – Pliocene) wildfires (e.g. Martin 1996, Figueiral et al. 2002, Bond 2015, Robson et al. 2015, Sluiter et al. 2016, Wedmann et al. 2018; and citations therein), periods important for our understanding of the evolution of modern ecosystems and their fire ecology (e.g. Bond 2015).

The present study describes woody charcoal assignable to taxodioid Cupressaceae and other, unidentifiable, conifers from a Late Oligocene – Early Miocene lignite deposit in Northern Hesse (Germany), adding new evidence for the occurrence of wildfires during this period in Central Europe. Together with numerous records from earlier studies of Central European lignites from this time period (e.g. Schuckmann 1925, Bode 1928, Grund 1928, Potonié 1929, Grebe 1953, Figueiral et al. 2002, Gee 2005; and citations therein),

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these new records indicate that palaeo-wildfires were much more frequent than previously assumed (e.g. Scott 2000, Bond 2015).

GEOLOGY AND STRATIGRAPHY

The charcoal described here comes from the base of a lignite seam at the former Frielendorf open pit mine in Northern Hesse, Germany (Fig. 1), collected in 1893 (Menzel 1920). Although Menzel (1920) provided no profile of the mine, the seam he mentioned can be correlated with the Flöz III of Steckhan (1952), who assigned a latest Oligocene age to this seam based on palynological data. Menzel (1920) had assigned a Miocene age to the lignite, based on its very sparse macroflora consisting of the following taxa: *Castanopsis schmidtiana* (Geinitz) Kräusel, *Sequoia langsdorfii* (Brongniart) Heer, cf. *Pinus saturnii* Unger and *Quercus apocynophyllum* Ettingshausen. According to a letter from Blanckenhorn to Menzel (cited in Menzel 1920), the lignite contained abundant additional leaf remains but they dried out and peeled off very quickly, or were too fragmented to be identified to specific or even generic level.

Later, Kirchheimer (1937) argued for a Late Oligocene age for Menzel's material, based on the abundant occurrence of *Castanopsis schmidtiana*. However, there are a few verified earliest Miocene occurrences of this taxon (cf. Mai 1989). Recent work assigns this seam, under the name Basis-Flöz (base-seam), to the base of the Schorn Member of the Frielendorf Formation (Fig. 2), for which a Late Oligocene to Early Miocene age is assumed based on palynological data (Ritzkowski et al. 2011).

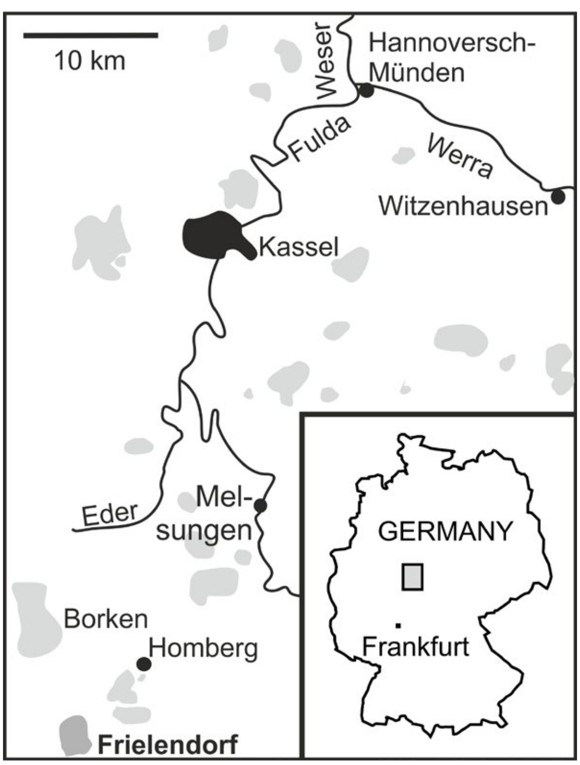

Fig. 1. Overview map of Palaeogene and Neogene lignite deposits (grey shading) in Northern Hesse. Redrawn and modified from Bergbaulicher Verein Kassel (1928)

Formation	Member	Bed	
Frielendorf Formation	Stellberg Member	—	Carlstollen-seam
		—	
	Schorn Member	Tannwald-clay/ Habichtswaldsand	
		Base-seam	

Fig. 2. Overview of the regional lithostratigraphical subdivision of Late Oligocene to Early Miocene deposits in Northern Hesse. Modified from Ritzkowski et al. (2011)

MATERIAL AND METHODS

The piece of lignite from which the charcoal described here was extracted contains several seeds of *Castanopsis schmidtiana* described by Menzel (1920), as well as some undescribed charcoal fragments (Fig. 3). Samples (including small pieces of *Castanopsis* seed-coats) were extracted mechanically from the sediment with the aid of preparation needles and tweezers under a binocular microscope in the laboratory. Due to the very fragile nature of the specimens, these could not be cleaned further with acids to remove adhering mineral remains, as even very careful treatment led to their total fragmentation. All charcoal specimens analysed for the present study are stored in the Geoarchive Marburg, the former geological-palaeontological collection of Marburg University, Germany, now curated at the Senckenberg Research Institute and Natural History Museum Frankfurt (Schindler et al. 2014), under accession numbers SMB-Mbg 3738A to SMB-Mbg 3738G.

Selected charcoal samples were mounted on standard stubs with LeitC (Plano, Münster, Germany) and subsequently examined with the aid of a JEOL JSM 6490 LV scanning electron microscope (SEM; accelerator current 20 kV) at the Senckenberg Forschungsinstitut und Naturmuseum Frankfurt (Germany).

RESULTS

PRESERVATION

The wood specimens analysed for the present study can be identified as charcoal due to the following characteristics (following Scott 2000, 2010): black colour and streak, homogenized cell walls (e.g. Fig. 4F, 5B) and excellent three-dimensional preservation of anatomical details (Figs 4, 5). In contrast, the *Castanopsis*

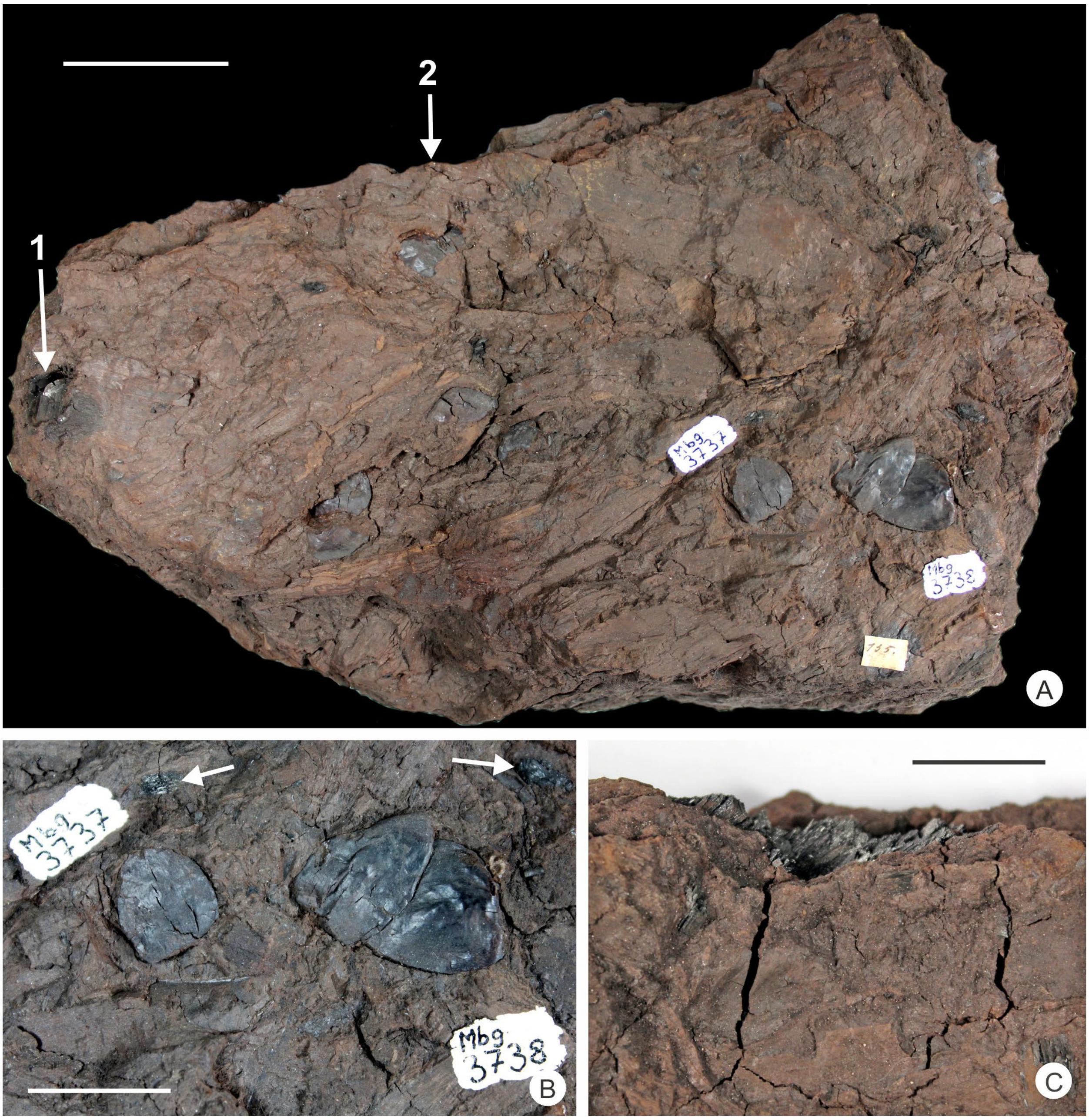

Fig. 3. Piece of lignite from Frielendorf. (**A**) Overview of lignite slab with two specimens of *Castanopsis schmidtiana* (Geinitz) Kräusel (originally figured by Menzel 1920; Pl. 15, Fig. 5, 6) as well as the charcoal specimens analysed for the present study (arrows point to the two largest pieces of charcoal); **1** – Charcoal type-1 (indet. conifer), **2** – Charcoal type-2 (Cupressaceae?-type), scale bar = 5 cm; (**B**) close-up of seeds of *Castanopsis schmidtiana* (Geinitz) Kräusel, together with small pieces of charcoal (arrows), scale bar = 2 cm; (**C**), close-up of Cupressaceae?-type charcoal specimen exposed at the side of the lignite specimen, scale bar = 2 cm

seed coats showed no evidence of charring (e.g. homogenized cell walls or black streak), despite exhibiting a slightly silky lustre. The size of the woody charcoal pieces ranges from ca 2 × 1 × ‘1’ mm to ca 50 × 50 × ‘5’ mm, and all specimens are compressed due to compaction of the lignite. In some larger specimens, however, small fragments still show excellent three-dimensional preservation of anatomical features, especially of the thicker-walled latewood (Figs 4, 5), allowing observation of some taxonomically useful details. Numerous studies of the coal petrology of lignites, as well as higher-rank coals (cf. Potonié 1929, Scott 2000; and citations therein) have noted that parts of otherwise crushed charcoal specimens may show excellent three-dimensional preservation of anatomical features. A noteworthy detail, at least from a taphonomical point of view, is the preservation of pits in one of the examined specimens. Here the pits have been split in radial sections, exhibiting the torus and

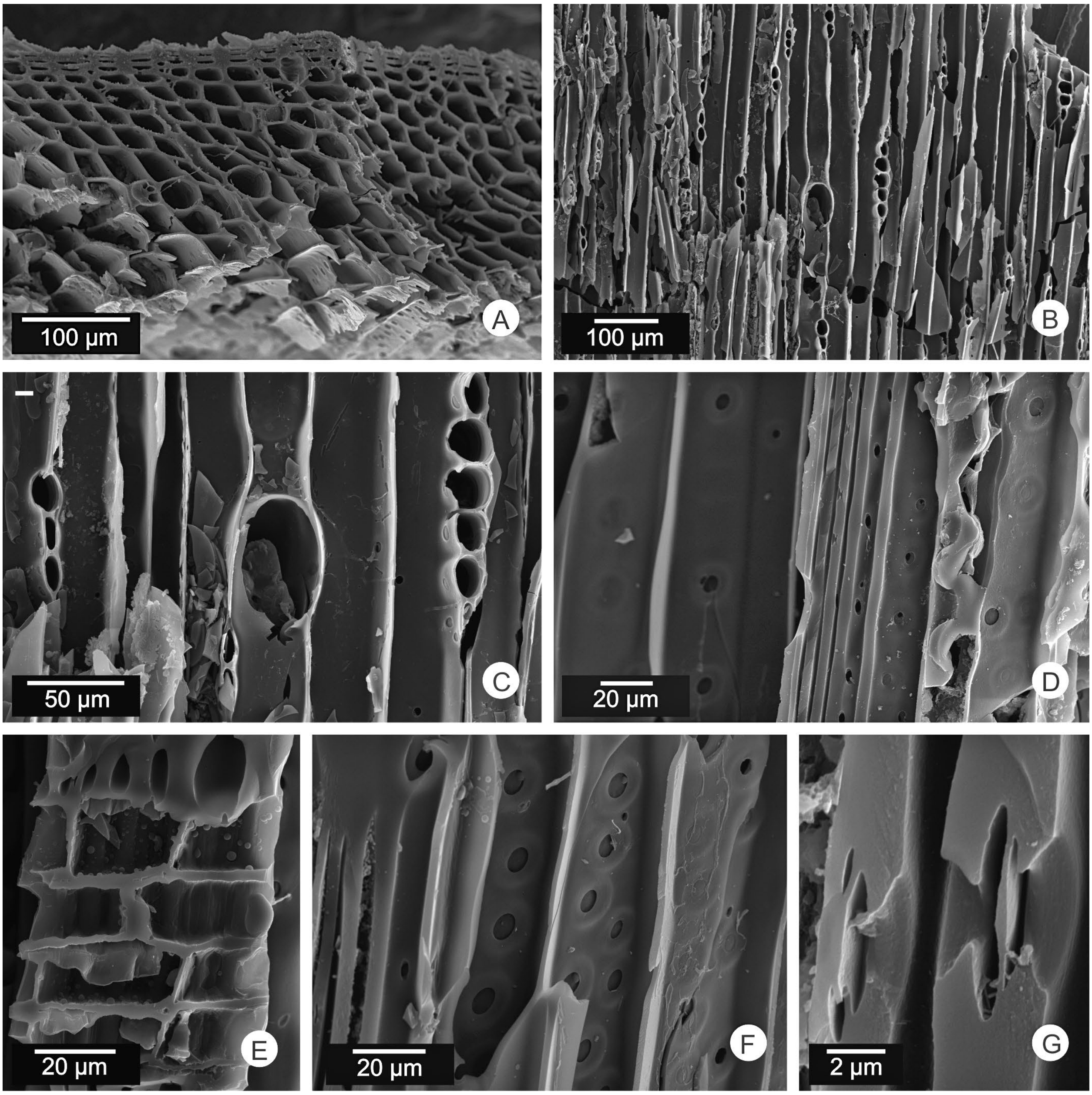

Fig. 4. SEM images of Charcoal type-1 (indet. conifer) charcoal from the Frielendorf Formation in Northern Hesse. (**A**) Slightly oblique cross section, showing transition from earlywood to latewood; (**B**) tangential view exhibiting rays; (**C**) close-up of B; (**D**) radial view of latewood and growth-ring boundary; (**E**) radial view of cross-field; (**F**) radial view of uni- and biseriate pitting on radial walls of tracheids; (**G**) split of radial walls showing aspirated pits; Inv.-Nr. SMB-Mbg 3738A

the margo of the corresponding pits, and in one of these pits the torus is obviously fused to the porus (Fig. 4G). Possibly this happened during charring, comparable to the homogenization of different cell-wall layers. It is also possible that pit aspiration occurred prior to charring. This observation may explain why some pits appear closed under SEM in radial view (Fig. 4D, F).

ANATOMY AND TAXONOMY

Two anatomically different 'types' of charcoal were distinguished. Both are conifers (see description below). A specific or even generic assignment cannot be made, due to the relatively small size of the three-dimensionally preserved woody fragments and the limited number of diagnostic features they show.

Charcoal type-1 (indet. conifer; Fig. 4)

Description. The growth rings are incompletely preserved. The thin-walled earlywood was compacted during diagenesis of the surrounding lignite (Fig. 4A). Distinct growth ring boundaries can be observed, marked by a few rows of radially narrow latewood (Fig. 4A, D, F). The lumina of tracheids are rectangular to polygonal in cross section (Fig. 4A). Bordered pits on the radial tracheid walls occur in one, occasionally two, vertical rows (Fig. 4D, F). When in two rows, the pits are alternating or oppositely arranged (Fig. 4D, F). The pits usually are not touching (Fig. 4D, F). No axial parenchyma could be observed. The rays are uniseriate and 2–6 cells high (Fig. 4B, C). The cell walls of ray cells are relatively thick; no pits were observed (Fig. 4E). The ray cells are round in tangential view (Fig. 4B, C). Cross-field pitting was not observed in radial view (Fig. 4E). In slightly oblique tangential view a few large pits can be observed (Fig. 4C) but their characteristics (which are frequently modified during charring; Gerards et al. 2007) remain unclear. Occasionally, large idioblasts of unknown function can be observed in tangential view (Fig. 4B, C).

R e m a r k s. The observable characters are in agreement with wood of a number of conifer groups (e.g. Philips 1948, Heinz 2004, IAWA committee 2004). However, due to the very fragmentary preservation of the charcoal from Frielendorf, and the likelihood that some aspects and especially dimensions of the cells changed during charring (e.g. Cutter et al. 1980, Osterkamp et al. 2018), this type of charcoal (observed in 2 specimens from Frielendorf) can only be identified as indet. conifer.

Charcoal type-2 (Cupressaceae?-type; Fig. 5)

D e s c r i p t i o n. The growth rings are narrow, with earlywood usually only 2–4 cells wide (Fig. 5A) and latewood usually only 1 cell wide, occasionally 2 cells wide (Fig. 5A, B). The transition from earlywood to latewood is distinct (Fig. 5A, B). The lumina of tracheids are rectangular to polygonal in cross section (Fig. 5A). Intertracheary pits on radial walls occur in one vertical row, with the pits usually not touching (Fig. 5G, H). No axial parenchyma were observed. The rays are uniseriate and usually 1–2 or up to 6 cells high (Fig. 5C, D). The cell walls of the ray cells are relatively thick (Fig. 5C, D), often with pronounced triangular intercellular spaces between the cells and tracheids (Fig. 5D). The ray cells in tangential view are round to ovate (Fig. 5C, D). Cross-field pitting consists of (3–) 4 pits arranged in two vertical(?) or horizontal(?) rows (Fig. 5E, F), but the cross-field pit type could not be determined with certainty.

R e m a r k s. The characteristics detailed above were observed in four charcoal specimens from Frielendorf. The appearance of the growth ring boundaries and intertracheary pits suggests affinities with the Cupressaceae, and what appear to be relatively large cross-field pits suggest the Taxodioideae (e.g. Philips 1948, Heinz 2004, IAWA committee 2004).

Van der Burgh (1973) suggested that pronounced triangular intercellular spaces in the rays, as observed in Charcoal type-2, would be characteristic for *Glyptostroboxylon tenerum* (Kraus) Conwentz (the type of wood produced by modern *Cunninghamia*; Dolezych & van der Burgh 2004). However, other authors have reported such triangular intercellular spaces in rays of other taxa belonging to taxodioid Cupressaceae, such as *Metasequoia* (Visscher & Jagels 2003). Larson (1994) noted that such triangular intercellular spaces are a more general feature that is typical for a number of (unspecified) species growing in very wet habitats. This supports an interpretation that this type of wood may have originated from a conifer growing in wet habitats of the peat-forming source vegetation of the lignite.

Menzel (1920) described and figured a few fragmentary conifer twig remains from Frielendorf, which he assigned to *Sequoia langsdorfii* (Brongniart) Heer. *Glyptostrobus* is another cupressaceous taxon that is a frequent constituent of Late Oligocene to Early Miocene peat-forming vegetation of Central Europe but which has not been reported from Frielendorf so far. This genus occurs in different Late Oligocene localities in the nearby Westerwald region, where it probably formed an important constituent of riparian or even swamp vegetation (e.g. Uhl et al. 2011, Krüger et al. 2017).

DISCUSSION

The evidence for wildfires presented here, together with the abundant literature on Palaeogene and Neogene wildfires (see below), somewhat contradicts the conclusions of Bond (2015) that the Cenozoic was a time of rather low fire activity as compared to older periods. However, this author's conclusion apparently was based on a rather selective and incomplete review of studies of charcoal as evidence for Palaeogene and Neogene wildfires, completely neglecting studies dealing with

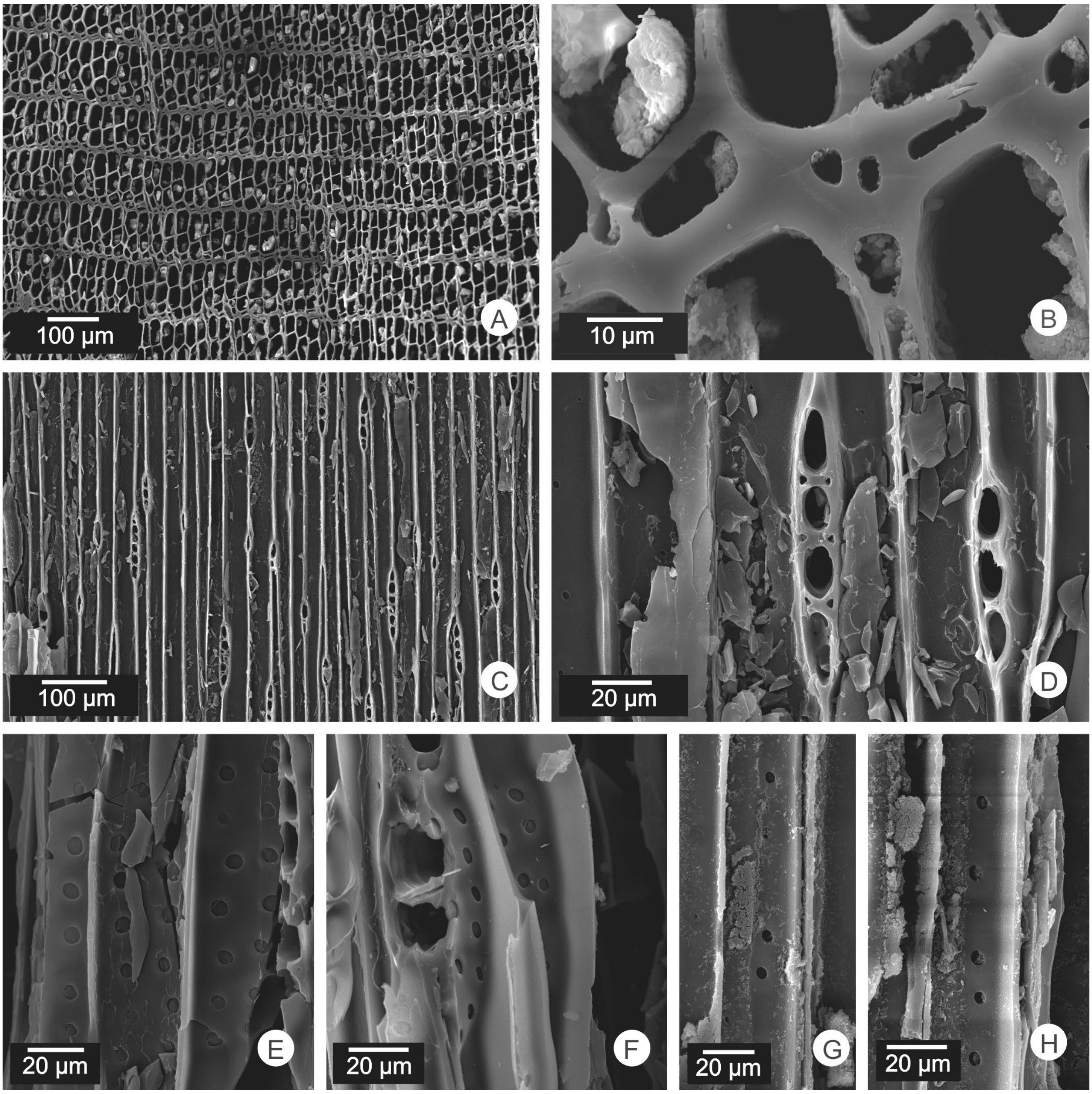

Fig. 5. SEM images of Charcoal type-2 (Cupressaceae?-type) from the Frielendorf Formation in Northern Hesse. (**A**) Cross section, exhibiting seven growth rings; (**B**) detail of A, showing homogenized cell walls; (**C**) tangential view with numerous rays; (**D**) details of rays with intercellular spaces; (**E**) radial view of cross-field; (**F**) slightly oblique tangential to radial view of cross-field and ray; (**G**) radial view of uniseriate pitting on radial walls of tracheids; (**H**) radial view of uniseriate pitting on radial walls of tracheids; Inv.-Nr. SMB-Mbg 3738B

charred mesofossils (e.g. Martin 1996, Figueiral et al. 2002).

The presence of relatively large pieces of charcoal provides evidence for the occurrence of wildfire(s) during the deposition of the base seam of the Schorn Member of the Frielendorf Formation. These findings supplement earlier reports of charcoal (fusinite and semi-fusinite) in numerous Central European lignite deposits (e.g. Schuckmann 1925, Bode 1928, Grund 1928, Potonié 1929, Grebe 1953, Figueiral et al. 2002, Gee 2005, Uhl et al. 2011; and citations therein). Despite the frequent occurrence of charcoal in lignites from several Oligocene and Miocene time slices, only a few of these occurrences have been studied from a palaeobotanical point of view. Examples are occurrences of charcoal in Oligocene lignites of the Westerwald region (Uhl et al. 2011), as well as Miocene lignites from the Lower Rhine Embayment in north-western Germany (e.g. Figueiral et al. 2002) and the Staniantsi Basin in Bulgaria (e.g. Uhl et al. 2014). In some cases the charred wood belongs to taxodioid Cupressaceae (Uhl et al. 2011, 2014); others have reported a wide variety of taxa, including not only conifers but also numerous angiosperm taxa (e.g. Figueiral et al. 2002).

More numerous are studies mentioning charcoal in the form of (pyrogenic) inertinites. The published total inertinite levels (used by some authors as a proxy for the occurrence of pyrogenic inertinites like fusinite, semifusinite and inertodetrinite; e.g. Diessel 2010, Glasspool & Scott 2010, Abu Hamad et al. 2012) are generally low in most coals and lignites from the Eocene up to the Pliocene (e.g. Diessel 2010). Although Diessel (2010) listed a large number of coals/lignites containing inertinites from the Oligocene and Miocene, all of these coals contained only very low volume-percentages of inertinites (between 0.4 and 6.8%), in contrast to Palaeocene and Eocene deposits (between 0.2 and 57.3%). Potonié (1929), in his pioneering study of the pyrogenic origin of fossil charcoal ("Fusit") in coals and lignites, pointed out that these low volume-percentages come mostly from lignites as compared to higher-rank coals from older periods, and that during compaction and coalification the chemically inert fusinite and semifusinite lost less of their initial three-dimensional structure as compared to other coal macerals. These macerals lost less volume and are thus volumetrically overrepresented in higher-rank coals.

Besides the intertinites from Oligocene coals/lignites, the occurrence of charcoal in Oligocene deposits has sometimes been mentioned anecdotally in papers on sedimentology and general geology (e.g. Winkelmolen 1972, Bestland 1987). An Oligocene – Miocene seam from the Latrobe valley in the Gippsland Basin in Australia contains abundant charcoal in certain lithotypes, and it has been argued that the source peatlands were subject to repeated fires during the Late Oligocene up to the Early Miocene (e.g. Holdgate et al. 2014, 2016, Korasidis et al. 2016, 2017, Sluiter et al. 2016).

The published fossil record of wildfire is more extensive for the Miocene than for the Oligocene. Evidence for Miocene wildfires is known from a number of European regions (e.g. NW Germany: Grebe 1953, Figueiral et al. 2002, Gee 2005, Holdgate et al. 2016; Bulgaria: Uhl et al. 2014; central Poland: Kowalski 2017, Kowalski & Fagúndez 2017; Austria: Masselter & Hofmann 2005; Spain: Peñalver & Gaudant 2010), North America (e.g. Oregon: Retallack 2004; Idaho: Davis & Ellis 2010; Banks Island, Canada: Williams et al. 2008) and South America (e.g. Chile: Schöning & Bandel 2004, Abarzuá et al. 2016), Asia (e.g. Yunnan, China: Li et al. 2017; S-Korea: Sohn et al. 2013; Indonesia: Smyth et al. 2011; Turkey: Gürdal & Bozcu 2011), India (e.g. Goswami & Deopa 2018), Africa (e.g. South Africa: Roberts et al. 2013, Sciscio et al. 2016; Namibia: Hoetzel et al. 2013), New Zealand (e.g. Mildenhall 1989, Pole 2003, Mildenhall et al. 2014), Australia (e.g. Martin 1996, Holdgate et al. 2007, 2016) and marine sediments in the Pacific Ocean (e.g. Herring 1985, Bond & Scott 2010).

In the last decades some studies have dealt in more detail with charcoal from Palaeogene and Neogene lignite deposits (e.g. Martin 1996, Figueiral et al. 2002, Uhl et al. 2011, 2014). Many older studies merely mentioned the occurrence of fossil charcoal in lignites, without providing detailed information (e.g. Schuckmann 1925, Potonié 1929). Our new data from the Frielendorf Formation, together with abundant data from the literature, suggest that there is great potential for further in-depth studies (using modern techniques like SEM) of the fire ecology of such deposits.

ACKNOWLEDGEMENTS

The authors are grateful to Claudia Franz (Senckenberg Forschungsinstitut und Naturmuseum Frankfurt) for technical assistance with SEM. Financial support was provided by CAPES (A072/2013, 8107-14-9) and CNPq (444330/2014-3, 305436/2015-5), Brazil; and by the Alexander von Humboldt Foundation (BRA 1137359 STPCAPES), Germany. The comments of two anonymous reviewers helped to improve this contribution.

REFERENCES

ABARZÚA A.M., VARGAS C., JARPA L., GUTIÉRREZ N.M., HINOJOSA L.F. & PAULA S. 2016. Evidence of Neogene wildfires in Central Chile: Charcoal records from the Navidad formation. Palaeogeogr., Palaeoclimatol., Palaeoecol., 459: 76–85.

ABU HAMAD A.M.B., JASPER A. & UHL D. 2012. The record of Triassic charcoal and other evidence for palaeo-wildfires: Signal for atmospheric oxygen levels, taphonomic biases or lack of fuel? Int. J. Coal Geol., 96–97: 60–71.

BERGBAULICHER VEREIN KASSEL (Ed.) 1928. Der Kasseler Braunkohlenbergbau (Festschrift zum 350jährigen Bestehen), Kassel 1928.

BESTLAND E.A. 1987. Volcanic stratigraphy of the Oligocene Colestin Formation in the Siskiyou Pass area of southern Oregon. Oregon Geol., 49(7): 79–86.

BODE H. 1928. Neue Beobachtungen zur Entstehung des Fusits. Mitt. Abt. Gesteins-, Erz, Kohle. u. Salzunters., Preuss. Geol. Landesanst. Berlin, 3: 12–22.

BOND W.J. 2015. Fires in the Cenozoic: a late flowering of flammable ecosystems. Front. Plant Sci., 5: 749.

BOND W.J. & SCOTT A.C. 2010. Fire and the spread of flowering plants in the Cretaceous. New Phytol., 188: 1137–1150.

BROWN S.A.E., SCOTT A.C., GLASSPOOL I.J. & COLLINSON M.E. 2012. Cretaceous wildfires and their impact on the Earth system. Cretaceous Research, 36: 162–190.

CUTTER B.E., CUMBIE B.G. & MCGINNES E.A. 1980. SEM and shrinkage analyses of Southern Pine wood following pyrolysis. Wood Sci. Tech., 14: 115–130.

DAVIS O.K. & ELLIS B. 2010. Early occurrence of sagebrush steppe, Miocene (12 Ma) on the Snake River Plain. Rev. Palaeobot. Palynol., 160: 172–180.

DIESSEL C.F.K. 2010. The stratigraphic distribution of inertinite. Int. J. Coal Geol., 81: 251–268.

DOLEZYCH M. & VAN DER BURGH J. 2004. Xylotomische Untersuchungen an inkohlten Hölzern aus dem Braunkohlentagebau Berzdorf (Oberlausitz/ Deutschland). Feddes Repert., 115: 397–437.

FIGUEIRAL I., MOSBRUGGER V., ROWE N.P., UTESCHER T., JONES T.P. & VON DER HOCHT F. 2002. Role of Charcoal Analysis for Interpreting Vegetation Change and Paleoclimate in the Miocene Rhine Embayment (Germany). Palaios, 17: 347–365.

GEE C.T. 2005. The genesis of mass carpological deposits (bedload carpodeposits) in the Tertiary of the Lower Rhine Basin, Germany. Palaios, 20: 463–478.

GERARDS T., DAMBLON F., WAUTHOZ B. & GERRIENNE P. 2007. Comparison of cross-field pitting in fresh, dried and charcoalified softwoods. Iawa J., 28: 49–60.

GLASSPOOL I.J., EDWARDS D. & AXE L. 2004. Charcoal in the Silurian as evidence for the earliest wildfire. Geology, 32: 381–383.

GLASSPOOL I.J. & SCOTT A.C. 2010. Phanerozoic concentrations of atmospheric oxygen reconstructed from sedimentary charcoal. Nat. Geosci., 3: 627–630.

GLASSPOOL I.J., SCOTT A.C., WALTHAM D., PRONINA N. & SHAO L. 2015. The impact of fire on the Late Paleozoic Earth system. Front. Plant Sci., 6: 756.

GOSWAMI P.K. & DEOPA T. 2018. Lithofacies characters and depositional processes of a Middle Miocene. Lower Siwalikfluvial system of the Himalayan foreland basin, India. J. Asian Earth Sci., 162: 41–53.

GREBE H. 1953. Beziehungen zwischen Fusitlagen und Pollenführung in der Rheinischen Braunkohle. Pal. Z., 27: 12–15.

GRUND H. 1928. Beiträge zum Studium fossiler Holzkohlenbildungen besonders in Braunkohlenlagerstätten. Jahrb. Preuss. Geol. Landesanst., 49: 1–32.

GÜRDAL G. & BOZCU M. 2011. Petrographic characteristics and depositional environment of Miocene Çan coals, Çanakkale-Turkmey. Int. J. Coal Geol., 85: 143–160.

HEINZ I. 2004. Systematische Erfassung und Dokumentation der mikroanatomischen Merkmale der Nadelhölzer aus der Klasse der Pinatae. Unpublished PhD Thesis Technical University München, 209 p.; https://mediatum.ub.tum.de/doc/603463/603463.pdf

HERRING J.R. 1985. Charcoal fluxes into sediments of the North Pacific Ocean: the Cenozoic record of burning. In: The carbon cycle and atmospheric CO_2: natural variations Archean to Present. Geophys. Monogr., 32: 419–442.

HOETZEL S., DUPONT L., SCHEFUSS E., ROMMERSKIRCHEN F. & WEFER G. 2013. The role of fire in Miocene to Pliocene C4 grassland and ecosystem evolution. Nat. Geosci., 6: 1027–1030.

HOLDGATE G.R., WALLACE M.W., O'CONNOR M., KORASIDIS V. & LIEVEN U. 2016. The origin of lithotype cycles from Oligo–Miocene brown coals from Australia and Germany. Int. J. Coal Geol., 166: 47–61.

HOLDGATE G.R., WALLACE M.W., SLUITER I.R.K., MARCUCCIO D., FROMHOLD T.A., WAGSTAFF B.E. 2014. Was the Oligocene-Miocene a time of fire and rain? Insights from brown coals of the southeastern Australian Gippsland Basin. Palaeogeogr., Palaeoclim., Palaeoecol., 41: 65–78.

HOLDGATE G.R., CARTWRIGHT I., BLACKBURN D.T., WALLACE M.W., GALLAGHER S.J., WAGSTAFF B.E., CHUNG L.I. 2007. The Middle Miocene Yallourn coal seam – the last coal in Australia. Int. J. Coal Geol., 70. 95–115.

IAWA Committee. 2004. IAWA list of microscopic features for softwood identification. IAWA Journal, 25: 1–70.

KIRCHHEIMER F. 1937. Grundzüge einer Pflanzenkunde der deutschen Braunkohle. 153 pp., Halle/ Saale (Knapp).

KORASIDIS V.A., WALLACE M.W., WAGSTAFF B.E., HOLDGATE G.R., TOSOLINI A.-M.P. & JANSEN B. 2016. Cyclicfloral succession and fire in a Cenozoic wetland/peatland system. Palaeogeogr., Palaeoclimatol., Palaeoecol., 461: 237–252.

KORASIDIS V.A., WALLACE M.W., WAGSTAFF B.E. & HOLDGATE G.R. 2017. Oligo-Miocene peatland ecosystems of the Gippsland Basin and modern analogues. Glob. Planet. Change, 149: 91–104.

KOWALSKI R. 2017. Miocene carpological floras of the Konin region (Central Poland). Acta Palaeobot., 57: 39–100.

KOWALSKI R. & FAGÚNDEZ J. 2017. *Maiella miocaenica* gen. et sp. nov., a New Heather Genus (Ericeae, Ericaceae) from the Central European Miocene. Int. J. Plant Sci., 178: 411–420.

KRÜGER P., PAUDAYAL K., WUTTKE M. & UHL D. 2017. Ein Beitrag zur oberoligozänen Makroflora von

Norken (Westerwald, Rheinland-Pfalz, W-Deutschland). Mainzer Naturw. Archiv, 54: 65–81.

LARSON P.R. 1994. The vascular cambium: development and structure. Springer-Verlag, New York.

LI S., HUGHES A.C., SU T., ANBERÉE J.L., OSKOLSKI A.A., SUN M., FERGUSON D.K. & ZHOU Z. 2017. Fire dynamics under monsoonal climate in Yunnan, SW China: past, present and future. Palaeogeogr., Palaeoclim., Palaeoecol., 465: 168–176.

MAI D.H. 1989. Fossile Funde von *Castanopsis* (D. Don) Spach (Fagaceae) und ihre Bedeutung für die europäischen Lorbeerwalder. Flora, 182: 269–286.

MARTIN H.A. 1996. Wildfires in past ages. Proc. Linn. Soc. N.S.W., 116: 3–18.

MASSELTER T. & HOFMANN C.-C. 2005. Palynology and palynofacies of Miocene coal-bearing (clastic) sediments of the Hausruck area (Austria). Geobios, 38: 127–138.

MENZEL P. 1920. Über hessische fossile Pflanzenreste. Jahrb. Preuss. Geol. Landesanst., 41: 340–391.

MILDENHALL D.C. 1989. Summary of the age and paleoecology of the Miocene Manuherikia Group, Central Otago, New Zealand. J.R. Soc. New Zeal., 19: 19–29.

MILDENHALL D.C., KENNEDY E.M., LEE D.E., KAULFUSS U., BANNISTER J.M., FOX B. & CONRAN J.G. 2014. Palynology of the early Miocene Foulden Maar, Otago, New Zealand: Diversity following destruction. Rev. Palaeobot. Palynol., 204: 27–42.

OSTERKAMP I.C., DE LARA D.M., GONÇALVES T.A.P., KAUFFMANN M., PÉRICO E., STÜLP S., UHL D. & JASPER A. 2018. Changes of wood anatomical characters of selected species of *Araucaria* during artificial charring – implications for palaeontology. Acta Bot. Bras., 32: 198–211.

PEÑALVER E. & GAUDANT J. 2010. Limnic food web and salinity of the Upper Miocene Bicorb palaeolake (eastern Spain). Palaeogeogr., Palaeoclim., Palaeoecol., 297: 683–696.

PHILLIPS E.W.J. 1948. Identification of softwoods by their microscopic structure. Forest Prod. Res. Bull., 22: 1–56.

POLE M. 2003. New Zealand climate in the Neogene and implications for global atmospheric circulation. Palaeogeogr., Palaeoclim., Palaeoecol., 193: 269–284.

POTONIÉ R. 1929. Spuren von Wald- und Moorbränden in Vergangenheit und Gegenwart. Jahrb. Preuss. Geol. Landesanst., 49: 1184–1203.

RETALLACK G.J. 2004. Late Miocene climate and life on land in Oregon within a context of Neogene global change. Palaeogeogr., Palaeoclim., Palaeoecol., 214: 97–123.

RITZKOWSKI S., GRIMM M.C. & HOTTENROTT M. 2011. Niederhessische Tertiärsenke. In: Deutsche Stratigraphische Kommission (Eds), Stratigraphie von Deutschland IX. Tertiär, Teil 1. – Schriftenr. Deut. Ges. Geowiss., 75: 303–343.

ROBERTS D.L., SCISIO L., HERRIES A.I.R., SCOTT L., BAMFORD M.K., MUSEKIWA C. & TSIKOS H. 2013. Miocenefluvial systems and palynofloras at the southwestern tip of Africa: Implications for regional and globalfluctuations in climate and ecosystems. Earth Sci. Rev., 124: 184–201.

ROBSON B., COLLINSON M., RIEGEL W., WILDE V., SCOTT A. & PANCOST R. 2015. Early Paleogene wildfires in peat-forming environments at Schöningen, Germany. Palaeogeogr., Palaeoclim., Palaeoecol., 437: 53–62.

SCHINDLER E., UHL D. & AMLER M.R.W. 2014. GeoArchive Marburg moved to Senckenberg Research Institute and Natural History Museum Frankfurt. Boll. Soc. Paleont. Ital., 53: 135–136.

SCHÖNING M. & BANDEL K. 2004. A diverse assemblage of fossil hardwood from the Upper Tertiary (Miocene?) of the Arauco Peninsula, Chile. J. South Am. Earth Sci., 17: 59–71.

SCHUCKMANN W. 1925. Zur Entstehung fossiler Holzkohle. Senckenbergiana, 7: 195–196.

SCISCIO L., TSIKOS H., ROBERTS D.L., SCOTT L., VAN BREUGEL Y., SINNINGHE DAMSTE J.S., SCHOUTEN S. & GROCKE D.R. 2016. Miocene climate and vegetation changes in the Cape Peninsula, South Africa: Evidence from biogeochemistry and palynology. Palaeogeogr., Palaeoclim., Palaeoecol., 445: 124–137.

SCOTT A.C. 2000. The pre-Quaternary history of fire. Palaeogeogr., Palaeoclim., Palaeoecol., 164: 297–345.

SCOTT A.C. 2010. Charcoal recognition, taphonomy and uses in palaeoenvironmental analysis. Palaeogeogr., Palaeoclim., Palaeoecol., 291: 11–39.

SCOTT A.C., BOWMAN D.M.J.S., BOND W.J., PYNE S.J. & ALEXANDER M.E. 2014. Fire on Earth: and introduction. Wiley Blackwell, 413 pp.

SLUITER I.R.K., BLACKBURN D.T. & HOLDGATE G.R. 2016. Fire and Late Oligocene to Mid-Miocene peat mega-swamps of south-eastern Australia: a floristic and palaeoclimatic interpretation. Austr. J. Bot., 64: 609–625.

SMYTH H.R., CROWLEY Q.G., HALL R., KINNY P.D., HAMILTON P.J. & SCHMIDT D.N. 2011. A Toba-scale eruption in the Early Miocene: The Semilir eruption, East Java, Indonesia. Lithos, 126: 198–211.

SOHN Y.K., KI J.S., JUNG S., KIM M.-C., CHO H. & SON M. 2013. Synvolcanic and syntectonic sedimentation of the mixed volcaniclastic–epiclastic succession in the Miocene Janggi Basin, SE Korea. Sed. Geol., 288: 40–59.

STECKHAN W. 1952. Der Braunkohlenbergbau in Nordhessen. Hess. Lagerstättenarchiv, 1: 212 pp. Hess. Landesanstalt für Bodenforschung, Wiesbaden.

UHL D., DOLEZYCH M. & BÖHME M. 2014. *Taxodioxylon*-like charcoal from the Late Miocene of Western Bulgaria. Acta Palaeobot., 54: 101–111.

UHL D., SCHINDLER T. & WUTTKE M. 2011. Paläoökologische Untersuchungen im Oberoligozän von Norken (Westerwald, Rheinland-Pfalz, W-Deutschland) – Erste Ergebnisse. Mainzer naturwiss. Archiv, 48: 115–127.

VAN DER BURGH J. 1973. Hölzer der niederrheinischen Braunkohlenformation. 2. Hölzer der Braunkohlengruben „Maria Theresia“ zu Herzogenrath, „Zukunft West“ zu Eschweiler und „Victor“ (Zülpich Mitte) zu Zülpich. Nebst einer systematisch-anatomischen Bearbeitung der Gattung *Pinus* L. Rev. Palaeobot. Palynol., 15: 73–275.

VISSCHER G.E. & JAGELS R. 2003. Separation of *Metasequoia* and *Glyptostrobus* (Cupressaceae) based on wood anatomy. IAWA J., 24: 439–450.

WEDMANN S., UHL D., LEHMANN T., GARROUSTE R., NEL A., GOMEZ B., SMITH K.T.K. & SCHAAL S.F.K. 2018. The Konservat-Lagerstätte Menat (Paleocene; France) – an overview and new insights. Geol. Acta, 16: 189–213.

WILLIAMS C.J., MENDELL E.K., MURPHY J., COURT W.M., JOHNSON A.H. & RICHTER S.L. 2008. Paleoenvironmental reconstruction of a Middle Miocene forest from the western Canadian Arctic. Palaeogeogr., Palaeoclim., Palaeoecol., 261: 160–176.

WINKELMOLEN A.M. 1972. Shape sorting in Lower Oligocene, Northern Belgium, Sed. Geol., 7: 183–227.