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ORIGINAL PAPER

Wildfire during deposition of the "Illinger Flözzone" (Heusweiler-Formation, "Stephanian B", Kasimovian–Ghzelian) in the Saar-Nahe Basin (SW-Germany)

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Abstract

Wildfires occurred more or less regularly in many Pennsylvanian ecosystems, not only in seasonally dry regions but also in the ever wet tropics. One of the reasons for this was probably the relatively high atmospheric oxygen conditions prevailing during this period. The present study reports evidence for the occurrence of wildfires during deposition of the Upper Pennsylvanian Heusweiler Formation ("Stephanian B", Kasimovian–Gzhelian) in the intramontane Saar-Nahe (or Saar-Lorraine) Basin in SW-Germany. Based on anatomical features of the charcoal, as well as the co-occurring adpression flora, it seems possible that some of the fires occurred in an ecosystem inhabited by *Cordaites*. Some of the charcoal fragments exhibit traces of pre-charring decay by fungi, indicating either the consumption of litter by ground or surface fires, or of still standing (partly) dead trees by crown fires.

Keywords Pennsylvanian · Wildfire · Flora · Microbial decay · Taphonomy

Introduction

During the last decades, research on Carboniferous wildfires has largely focussed on occurrences of macro-charcoal from former "coal-swamps" of the tropical zone in Canada, Great Britain, Ireland, the U.S.A. and Poland (e.g. Nichols and Jones 1992; Scott and Jones 1994, Falcon-Lang 1998, 1999a, b, 2000; Zodrow et al. 2010), although some earlier studies also mentioned the occurrence of charcoal as direct evidence of Pennsylvanian wildfires in other European coal fields of Pennsylvanian age (e.g. Daubrée 1844, 1846; Grund 1928; Potonié 1929). Additionally, evidence indicates that fires also occurred regularly in the drier hinterland, dominated by Cordaitaleans and conifers (e.g. Falcon-Lang and Bashforth 2005; Scott et al. 2010). The abundance of macro-charcoal in many deposits, together with the abundant occurrence of pyrogenic intertinites in many Pennsylvanian coals (e.g. Glasspool and Scott 2010; Diessel 2010) indicates that fires were regular sources of disturbance in many, even ever-wet, biomes. One of the reasons for this were probably the very high atmospheric oxygen concentrations during this period (e.g. Scott et al. 2014), which would have allowed for the ignition and efficient spread of wildfires even in wet environments containing only wet fuels (e.g. Scott 2000; Belcher et al. 2010).

However, considering the geographically widespread occurrence of continental Pennsylvanian deposits (e.g. Cleal et al. 2009), as well as the abundance of pyrogenic inertinites in many coal deposits from this period (e.g. Glasspool and Scott 2010; Diessel 2010), there are considerable few studies dealing with the biological affinities and palaeoecological implications of the charred plant material. For many regions with Pennsylvanian continental deposits, such studies are almost completely lacking so far. One of these regions is the intramontane Saar-Nahe or Saar-Lorraine Basin, which represents one of the largest intramontane Carboniferous–Permian basins in Europe.

This article is a contribution to the special issue "*Palaeobotanical contributions in honour of Volker Mosbrugger*".

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The sedimentary infill of this basin includes Pennsylvanian-aged deposits which reach up to 6000 m in thickness (Schäfer 1986, 2005). These sediments include more than 500 coal seams from the Bashkirian up to the Gzhelian (Schneider 1991). Especially, the Moscovian coals were targeted by an extensive mining industry in the French and German parts of the basin, although a number of smaller seams from the Kasimovian and Gzhelian have been mined in the northeastern part of the basin (Spuhler 1957; Schneider 1991; Schindler 2007; Cleal et al. 2009).

Hitherto, only the lower Permian sediments from this basin (which roughly correspond to the Rotliegend Group) have been studied in some detail with regard to fossil charcoal as evidence for palaeo-wildfires (e.g. Uhl et al. 2004). Although there is a lack of detailed palaeobotanical and palaeoecological studies of Pennsylvanian charcoals as evidence of wildfires in this basin, charcoal from these deposits has been known for a long time in the form of pyrogenic coal macerals of the inertinite group (i.e. fusinite and semifusinite; e.g. Hoffmann 1928; Semmler 1936; Josten 1956; Schneider 1968), although mostly without referring to the pyrogenic origin of these macerals and its ecological implications. An exception is the work of Daubrée (1844, 1846), who claimed a pyrogenic origin for "mineral-coal" or "Faserkohle" (=fusinite) from the Breitenbach- or Grenzkohlen-seam, mined near Altenkirchen, based on physico-chemical characteristics of this material.

This (as far as the authors are aware) first publication of a fire-hypothesis for the origin of fossil charcoal was, however, immediately and heavily attacked by various people (e.g. Anonymous 1844), including authorities like Goeppert (1850), who vehemently argued against a pyrogenic origin of such material. The discussion regarding a pyrogenic origin for different coal macerals of the inertinite group raged on for several decades (see reviews in Scott 1989, 2000), although in the late 1920s, a number of studies by German coal-petrologists put forward very convincing arguments for a pyrogenic origin of charcoal in Pennsylvanian coals and Cenozoic lignites (e.g. Grund 1928; Potonié 1929). Unfortunately, these results and arguments were largely neglected or overlooked by the international scientific community. Today, it is widely accepted that the macerals fusinite, semifusinite and inertodetrinite are largely of pyrogenic origin and palaeo-wildfires became a common aspect of palaeoenvironmental studies (e.g. Scott 2000, 2010; Glasspool and Scott 2010; Jasper et al. 2017; Benício et al. 2019).

To add more information about the occurrence of palaeo-wildfires in the Saar-Nahe Basin during the Pennsylvanian, we provide a SEM-analysis of macro-charcoal from clastic sediments as well as coals of the somewhat older, so-called "Illinger Flözzone" (Heusweiler Formation), providing evidence for the occurrence of palaeo-wildfires during the "Stephanian B" (Kasimovian–Gzhelian) of this particular basin, together with some ecological interpretations of these findings.

Geological and stratigraphical setting

The Saar-Nahe or Saar-Lorraine Basin can be regarded as the largest and best exposed Late Palaeozoic intramontane basins within the Variscan orogenic belt in Central Europe (Schäfer and Korsch 1998) (Fig. 1). It is interpreted as a half graben structure with a surface extension of 100 km (SW–NE) × 40 km (NW–SE) (Henk 1993; Stapf 1990). The oldest sediments known in this basin are of Bashkirian age (Spiesen Formation) and solely known from drill-core Saar-1 (Birenheide et al. 1976). Sedimentation continued up into the Permian with several hiatuses (e.g. Schindler 2007; Cleal et al. 2009).

The Pennsylvanian deposits of the basin (comprising the Steinkohlen Group) are divided in the Saarbrücken Subgroup (Bashkirian–Moscovian) and the Ottweiler Subgroup (Kasimovian–Gzhelian) (Fig. 2), which are divided by a considerable hiatus at the base of the Holz conglomerate (e.g. Schindler 2007; Cleal et al. 2009). The Ottweiler Subgroup has been divided into four formations: Göttelborn, Dilsburg, Heusweiler and Breitenbach, which contain only a few workable coal seams (e.g. Schindler 2007; Cleal 2008; Cleal et al. 2009).

The Göttelborn Formation attains a thickness of up to 450 m (Müller et al. 1989). The only workable coal-seams are the André-seam and the Grangeleisen-seam (Schindler 2007).

The Dilsburg Formation reaches a thickness of 130 m and also contains two workable seams, the Wahlschied-seam near its base and the Schwalbach-seam near its top (Schindler 2007; Cleal et al. 2009). Biostratigraphically both seams belong to the middle *Alethopteris zeilleri* Zone (Cleal 2008).

The Heusweiler Formation, which starts with coarse clastics above the Schwalbach-seam, is up to 1000 to 1500 m thick (Schneider 1991; Schäfer 2005). There are two noteworthy zones with seams within this formation: (1) the Heusweiler seams, located approximately 200 m above the base of the formation, which occur only in the western part of the basin and (2) the "Illinger Flözzone" (or Reisbach seams), located in the middle of the formation (Schneider 1991; Schindler 2007; Cleal et al. 2009). Biostratigraphically, both seams belong to the upper half of the *Alethopteris zeilleri* Zone (Cleal 2008).

The Breitenbach Formation attains a thickness of 50 to 130 m and contains only a single, workable coal-seam, the Breitenbach or Grenzkohlen seam (Schindler 2007; Cleal 2008; Cleal et al. 2009). Biostratigraphically, this seam belongs to the *Sphenophyllum angustifolium* Zone (Cleal 2008). The occurrence of charcoal as direct evidence of wildfire has first been suggested by Daubrée (1844, 1846), based on the physicochemical properties of this material which are the same as in charcoal, in a pioneering study on the pyrogenic origin of coal macerals of the inertinite group from this seam. In this youngest workable Pennsylvanian (Gzhelian) coal-seam of the Saar-Nahe Basin (Cleal 2008), fusinite and semifusinite occur in distinct bands and lenses, reaching up to 9.5% of the total volume of the coal-seam (Josten 1956).

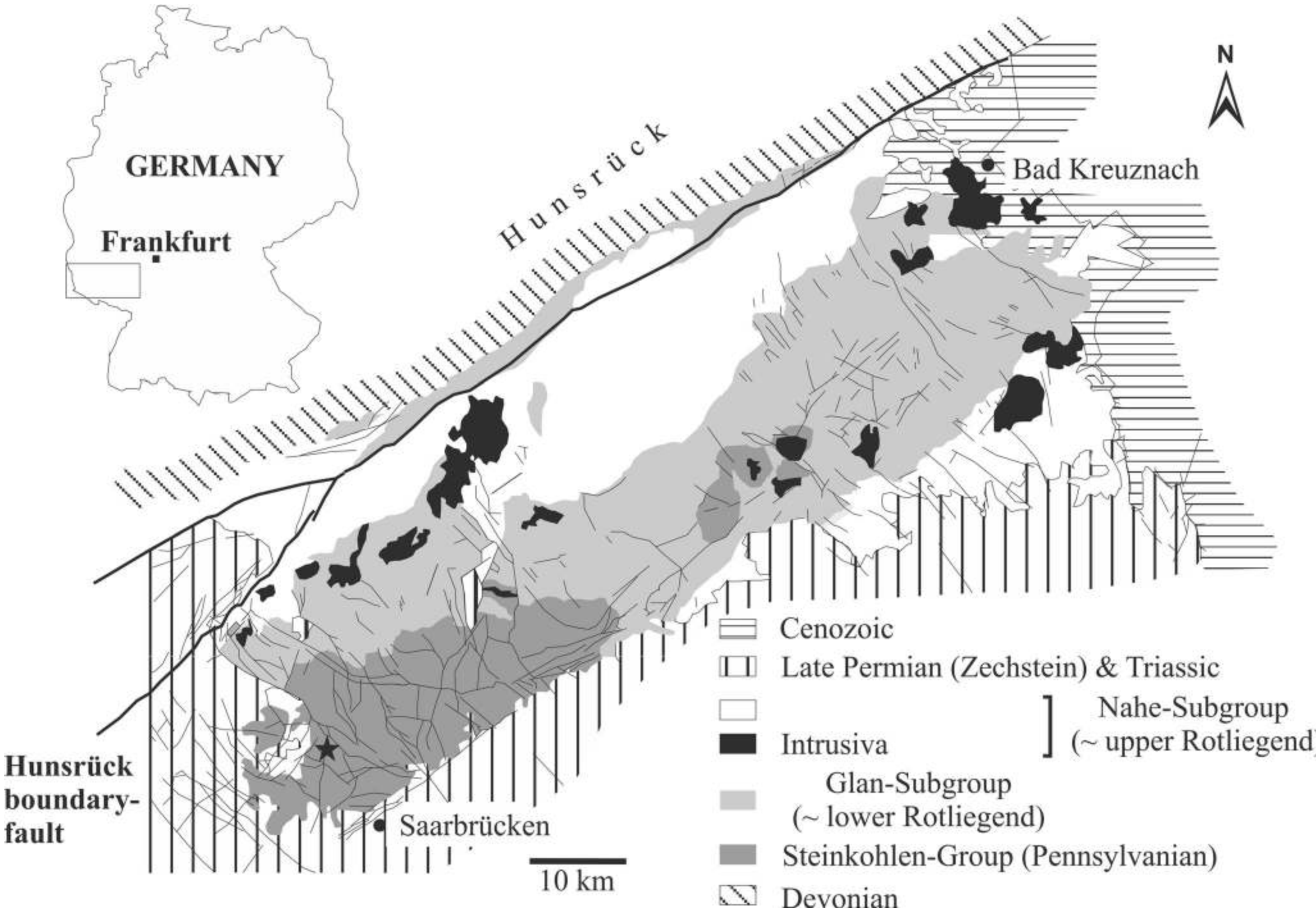

Fig. 1 Geological overview map of the Saar-Nahe Basin (modified from Stapf (1990) and Uhl et al. (2004)). The asterisk (★) marks the position of the locality Reisbach

The Heusweiler Formation consists mainly of fluvial deposits, changing from braided rivers at its base, to meandering rivers in the upper part of the formation (Schäfer 2005). A typical feature of the middle part of the Heusweiler Formation are palaeosoils, which may contain caliche nodules (Möhring and Schäfer 1990; Schäfer 2005). In the upper part, two lake horizons can be observed locally (Boy and Schindler 2012).

The "Illinger Flözzone" (or Reisbach seams) is located in the middle of the formation. The coal seams have been exploited from the 1960s up to the early 2000s in the Reisbach mine located near Reisbach (Fig. 1; Boersma 1978; Schindler 2007; Kerp et al. 2007). Due to intensive sampling, the comparably diverse macroflora (~ 50 taxa) from this zone is well known (Boersma 1978; Kerp et al. 2007; Cleal 2008). In fact, two different floral associations are known from this zone:

1) The flora from clastic intercalations between seams, which is mostly known from reports focussing on biostratigraphy (e.g. Germer et al. 1966; Germer 1971). This flora contains abundant remains of the pteridosperm *Alethopteris bohemica* Franke as well as leaf fragments of *Cordaites* (Germer 1971; Boersma 1978; Kerp et al. 2007). Both taxa are considered to be representatives of vegetation units more adapted to dryer (or less humid) conditions (e.g. Kerp et al. 2007).
2) A roof flora which has been described in detail by Boersma (1978). This flora is dominated by *Sphenophyllum oblongifolium* and *Pecopteris polymorpha*, as well as other members of plant groups adapted to more humid or even wet conditions, like sphenopsids, lycopsids and ferns (Boersma 1978).

Material and methods

The material on which this study is based comes from sediments of the so-called "Illinger Flözzone" (or Reisbach seam) located approximately in the middle of the Heusweiler Formation (Germer et al. 1966). The charcoal presented here comes from two different facies types: (1) a dark, blue-grey claystone, containing numerous fragmentary leaves of *Cordaites*, as well as fragments of *Cordaianthus* and pecopterids (Fig. 5) and (2) coals.

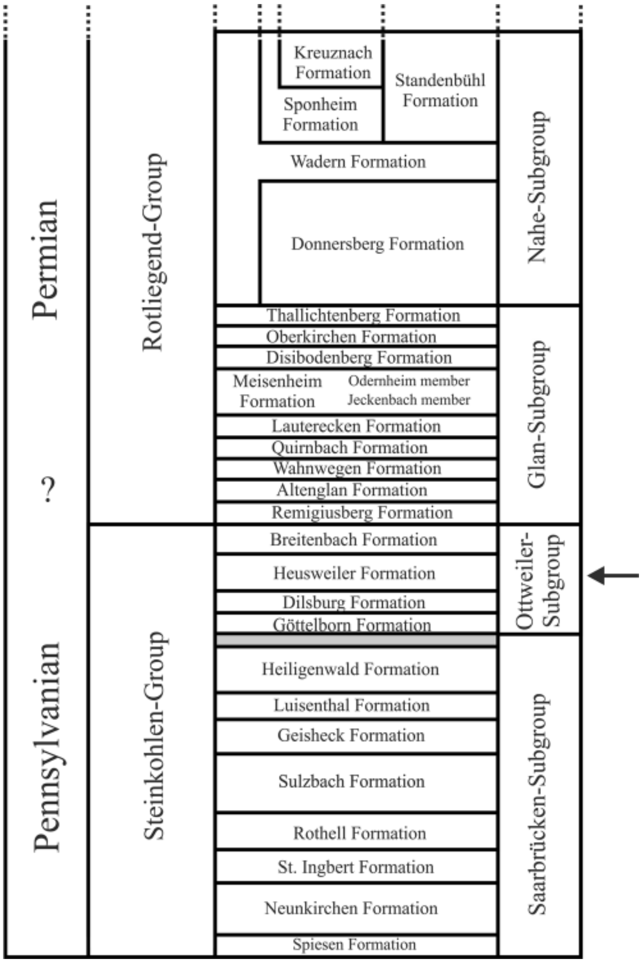

Fig. 2 Overview of the stratigraphy of the Permocarboniferous succession in the Saar-Nahe Basin (based on German Stratigraphic Commission 2002, Menning et al. 2005; Boy et al. 2012). Stratigraphic position of the "Illinger Flözzone" is marked by the arrow

The material was collected in 2003 by the first author during a field trip, led by him and V. Mosbrugger, with students from Tübingen University on the former spoil tip of the Dr. Arnold Schäfer GmbH near Reisbach. At this spoil tip, material mined at the Reisbach II mine, originating from the "Illinger Flözzone" had been dumped. Due to this reason, it is not possible to indicate exactly from which part of this zone the samples originate. Neither the mine nor the spoil tip are accessible today, thus, no additional material could be collected for this study to enlarge the database.

Support for the age of the material is provided by numerous specimens of *Alethopteris bohemica* Franke on other (lithologically similar) slabs of clay from the same finding spot at the spoil tip, as this taxon is only known from the "Illinger Flözzone" (or Reisbach seams) in the Saar-Nahe Basin (Cleal 2008).

The material (5 hand specimens from the clay and 2 from the coal, and 7 SEM stubs from the clay and 2 from the coal) is stored in the collection of the Senckenberg Forschungsinstitut und Naturmuseum Frankfurt under collection numbers SM.B. 22098–SM.B. 22104. SEM stubs have the same collection numbers as their source hand specimens with a supplemental letter (a, b …).

Samples of charcoal were mechanically extracted with needles and forceps from the sediment and subsequently mounted on standard stubs with LeitC (Plano, Münster, Germany). After that, they were sputter-coated and 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 and discussion

Preservation of charcoal

The woody material from the clay analysed in the present study consists of seven pieces of wood with mostly rounded edges, up to 14 × 26 mm large. The material is heavily compressed, resulting in a considerable distortion of the three-dimensional structure of the wood (Fig. 3a–d). The pieces from the coal ($n = 2$) are considerably smaller, up to 6–11 mm large, and completely compressed into a thin shiny layer.

All specimens exhibit a silky lustre and black streak on touch and cell walls are homogenized (Figs. 3c–d and 4b–d). Together with three-dimensional anatomical preservation [which is heavily distorted by compression in the specimens analysed here (Fig. 3a–d)], these features are considered as characteristic for charcoal, as direct evidence for the occurrence of palaeo-wildfires (cf. Scott 2000, 2010).

Anatomy of charcoal

The charred plant material from the clay as well as the coal consists of relatively thin tracheids (Figs. 3–4). No details of pits or rays are visible in this material, which is not uncommon in highly compressed charcoal like this (e.g. Jasper et al. 2008; Uhl et al. 2010). From a taxonomic point of view, it is only possible to state that the charcoal probably originated from pycnoxylic wood, probably of gymnospermous origin.

More conspicuous are traces of pre-charring decay, which can be found in many charcoal specimens from Reisbach. Such traces include shot-like holes in the walls of tracheids (Figs. 3e and 4b–d) which are comparable to traces related to hyphae of modern (mostly brown-rot) fungi penetrating cell walls (cf. Schweingruber et al. 2006; Schwarze 2007; El Atfy et al. 2019). Occasionally, also the course of these shot-like holes through the cell walls can be seen in broken cell walls (Fig. 4d), adding evidence that these holes do not represent remnants of (bordered) pits. These holes, as well as remains of fungal hyphae (Figs. 3f and 4b) and smaller filaments (Fig. 3e

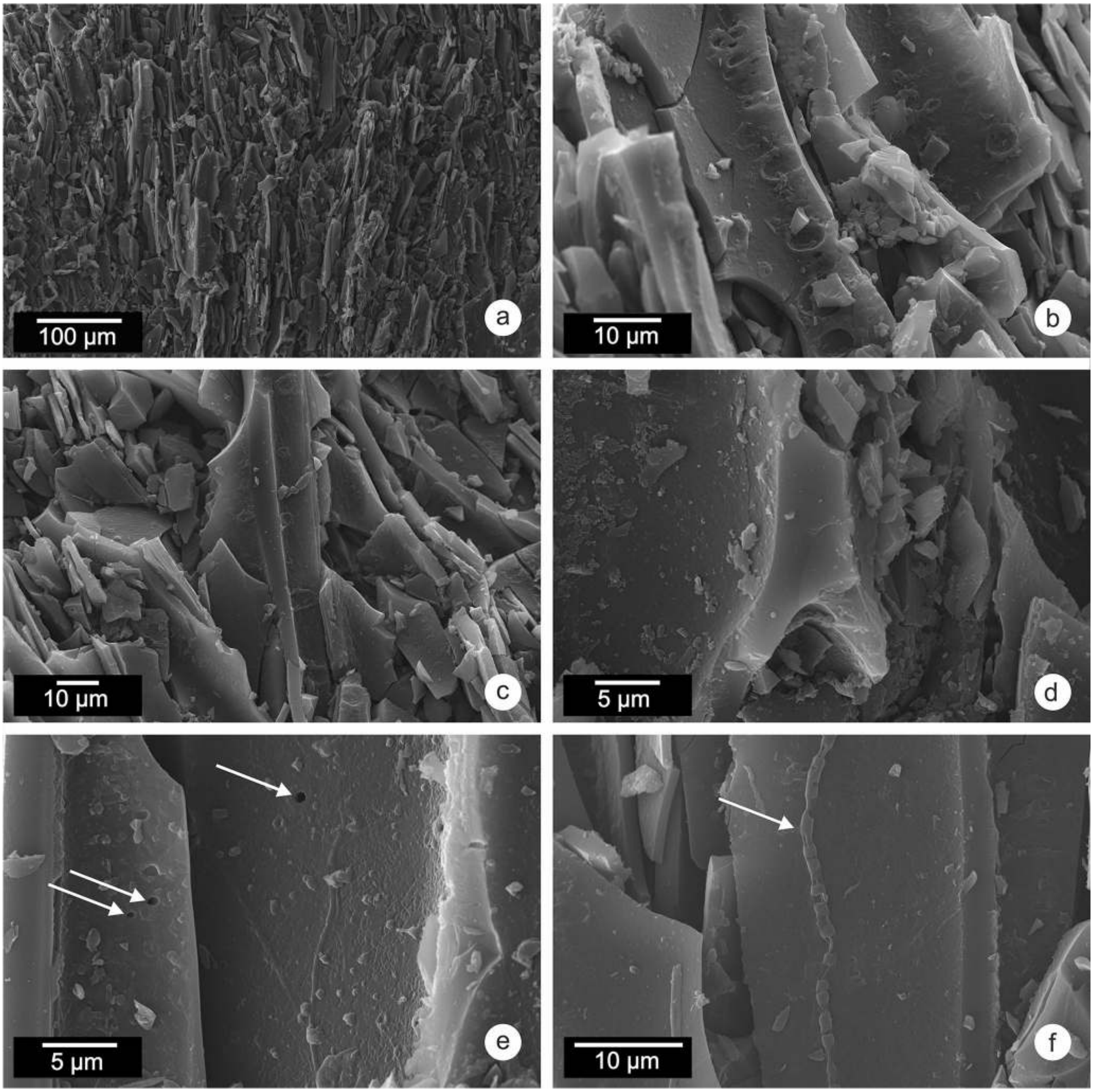

Fig. 3 SEM images of charcoal from clastic sediments from the locality Reisbach. **a** Overview of shattered charcoal exhibiting homogenized cell walls, Coll.-No. SM.B. 22098/a. **b** Details of tracheid walls from shattered charcoal, Coll.-No. SM.B. 22098/a. **c** Details of tracheid walls from shattered charcoal, Coll.-No. SM.B. 22098/a. **d** Detail of homogenized cell wall, Coll.-No. SM.B. 22098/b. **e** Tracheid wall with filamentous structures, may be assignable to ascomycetes or filamentous bacteria and small, shot-like holes (arrows), Coll.-No. SM.B. 22098/b. **f** Tracheid wall with fungal hyphae (arrow), Coll.-No. SM.B. 22098/b

and 4a), probably related to ascomycetes or filamentous bacteria (cf. El Atfy et al. 2019; Uhl et al. 2020 and citations therein), on tracheid walls, can be seen in specimens from both the clay as well as the coal.

It is impossible to determine whether the decay started in dead parts of still living and standing plants as it is often observed in modern, partly dead trees or whether the fungi colonised dead wood on the forest floor. The latter would indicate the occurrence of ground or surface fires, but the evidence from Reisbach is not conclusive for such an interpretation. Only when a larger number of charred plant organs or taxa from one locality/layer, exhibit such traces of decay, and especially when plants without traces of decay are rare in an assemblage, it is possible to argue convincingly for a

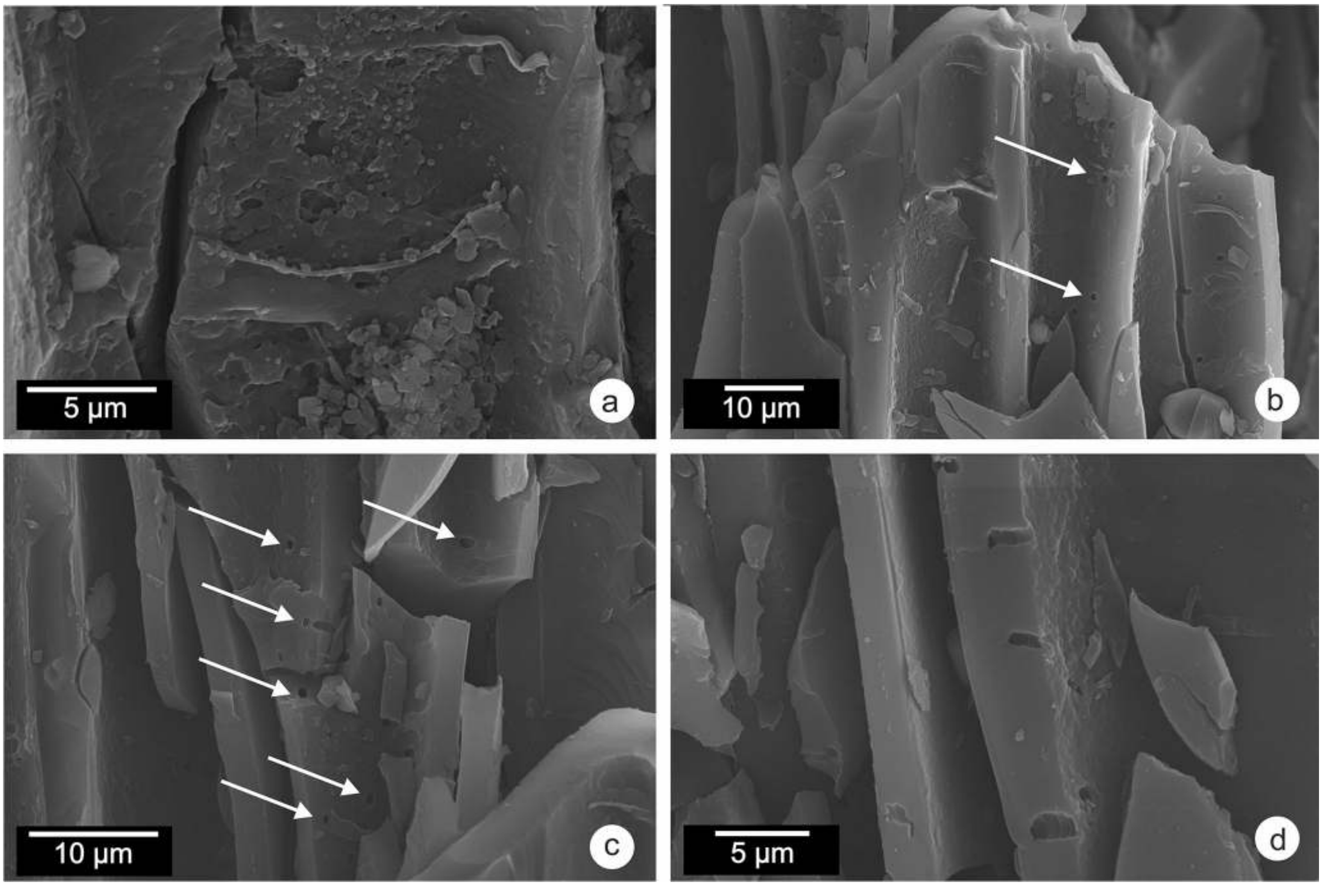

Fig. 4 SEM images of charcoal from coal from the locality Reisbach. **a** Tracheid wall with filamentous structures, may be assignable to ascomycetes or filamentous bacteria, Coll.-No. SM.B. 22100/a. **b** Tracheid with fungal hyphae and small, shot-like holes (arrows), Coll.-No. SM.B. 22100/b. **c** Tracheid wall with numerous small, shot-like holes (arrows), Coll.-No. SM.B. 22100/b. **d** Close-up of homogenized cell wall with shot-like holes passing through, at least part of, the cell wall, Coll.-No. SM.B. 22100/b

ground or surface fire as the most likely source of the charred plant remains (cf. Uhl et al. 2019).

Potonié (1929) mentioned that (partly?) dead, hollow trees which may be struck by lightning can produce large quantities of charcoal due to fires burning or smouldering within the hollow stems. Although the authors are not aware of any study dealing with the in-depth analyses of charcoal from such a source, it seems likely that at least some of the charcoal from such a source should also present traces of pre-charring decay by various microbes.

These observations from the Pennsylvanian charcoal from Reisbach support previous statements, that fossil charcoal from pre-Quaternary depositional systems can be used to acquire additional data about Deep Time interactions between various groups of microbes and plants (cf. El Atfy et al. 2019, and citations therein).

Co-occurring macroflora

On the same clay slab bearing numerous charcoal fragments, several fragments of leaves of *Cordaites* as well as a fragment of a cordaitalean fructification occur (e.g. Fig. 5a). Based on observable morphological details and comparisons with published taxonomical data (based on morphology alone) from the "Illinger Flözzone" (Boersma 1978), these remains can be determined as belonging to *Cordaites* cf. *principalis* (Germar) Geinitz (Fig. 5a–b) as well as *Cordaianthus pitcairniae* (Lindley et Hutton) Renault (Fig. 5c–d). The tentative determination as *Cordaites* cf. *principalis* is based purely on morphological data. Although it is clear that within the genus *Cordaites*, different species can only be distinguished by cuticular analyses (e.g. Šimůnek 2007, 2015), such an analysis has so far not been conducted for *Cordaites* remains from the Reisbach flora. Additionally, small fragments of unidentifiable pecopterid ferns occur (Fig. 5a) on the same slab.

The flora from the clastic intercalations between individual coal seams of the "Illinger Flözzone" is dominated by leaves of the pteridosperm *Alethopteris bohemica* as well as leaves of *Cordaites principalis* (Boersma 1978; Kerp et al. 2007). Fragments of *Cordaites* cf. *principalis* as well as the cordaitalean fructification *Cordaianthus pitcairniae* occur on the same splitting surface as the pieces of charcoal described here. Boersma (1978) interpreted this association as coming from less humid (dryer) habitats. During the Pennsylvanian, potential ladder fuels,

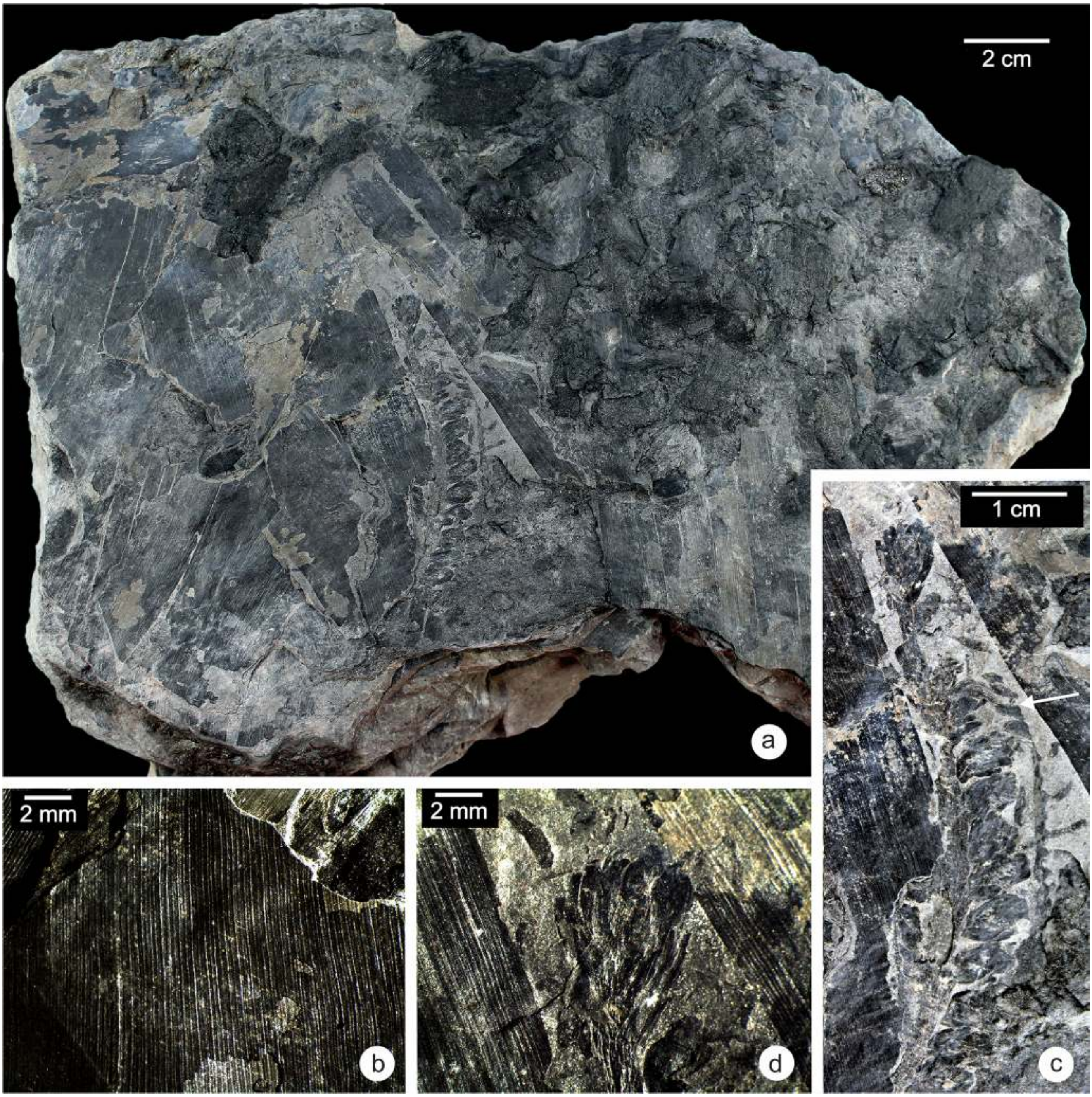

Fig. 5 Macroflora accompanying the fossil charcoal from Reisbach. **a** Overview of slab with numerous charcoal specimens as well as fragmentary *Cordaites* cf. *principalis* leaves, *Cordaianthus pitcairniae*, and a fragment of *Pecopteris* sp., Coll.-No. SM.B. 22098. **b** Close-up of *Cordaites* leaf, showing detail of venation. **c** Close-up of *Cordaianthus pitcairniae* and *Pecopteris* sp. (arrow). **d** Close-up of terminal dwarf shoot of *Cordaianthus pitcairniae*

like vines and lianas, were already important parts of a number of vegetation types (cf. Krings et al. 2003). This implies a considerable probability of surface or ground fires spreading into the crown layer of vegetation types dominated by large tress, like some *Cordaites* species, and also resiniferous medullosaleans (cf. Cleal and Shute 2012).

Although the charcoal from Reisbach cannot directly be linked to *Cordaites*, it seems likely that at least part of the charcoal fragments co-occurring with *Cordaites* remains on individual sediment slabs, are originating from this plant group. It has been demonstrated previously that during the Pennsylvanian (hinterland-)floras dominated by gymnosperms, like Cordaitaleans and the first conifers, were prone to wildfires (e.g. Scott 1978, 1979, 1989; Scott and Jones 1994; Falcon-Lang 2000; Falcon-Lang and Bashforth 2005; Scott et al. 2010). Considering the slightly rounded edges of the charcoal specimens from the clay, it seems possible that the charcoal as well as the other plant remains on the same slabs were transported by water from their original habitat to the place of deposition (Scott 2000; Scott et al. 2014).

Conclusions

The observation of charcoal in clastic sediments, as well as coals from the Upper Pennsylvanian Heusweiler Formation ("Stephanian B", Kasimovian–Gzhelian) in the intramontane Saar-Nahe (or Saar-Lorraine) Basin in SW-Germany, provides evidence for the repeated occurrence of wildfires during deposition of these strata. Together with earlier studies on pyrogenic coal macerals (e.g. Daubrée 1844, 1846; Hoffmann 1928; Semmler 1936; Josten 1956; Schneider 1968), this finding demonstrates that fires were a more or less common source of disturbance in different Pennsylvanian vegetation types in the intramontane Saar Nahe Basin.

Based on anatomical features of the charcoal, as well as the co-occurring adpression flora, it seems possible that some of the fires occurred in vegetation types inhabited by *Cordaites*, but a definite statement about this is not possible. As some of the charcoal fragments exhibit traces of pre-charring decay by fungi, it seems possible that the charcoal represents the remainders of ground or surface fires, although it cannot be excluded that dead branches of standing trees burnt in a crown fire (cf. El Atfy et al. 2019; Uhl et al. 2020).

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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