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Charcoal in the Late Jurassic (Kimmeridgian) of Western and Central Europe—palaeoclimatic and palaeoenvironmental significance

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Abstract Although fossil charcoal, as direct evidence of palaeo-wildfires, occurs in the fossil record at least since the Late Silurian, it is not equally distributed in sedimentary rocks from different ages. As the occurrence of wildfires is indeed not only controlled by climatic and environmental parameters, but also by the concentration of atmospheric oxygen, it has been argued by various authors that the fossil record of charcoal must also be influenced by (long-term) variations in atmospheric oxygen concentrations. Geochemical models have reconstructed low oxygen concentrations during almost the entire Jurassic, resulting, at least theoretically, in very low fire frequencies during this period. Here we describe new discoveries of fossil charcoal fragments from two Late Jurassic (Kimmeridgian) localities in Western (Boulonnais area in northern France) and Central Europe (Nusplingen Lithographic Limestone Fossillagerstätte in southwestern Germany). Combining our new data with currently available—but rather scarce—data on the occurrences of charcoal fragments during this particular interval of time demonstrates that all of these occurrences lie either within a Late Jurassic winter-wet climate belt, characterised by a marked seasonality, or within the assumedly drier part of a temperate climate belt, near the boundaries of the winter-wet climate belt. This is somewhat surprising as the preservation potential of charcoal is generally considered to be rather low under comparable climatic conditions, although charcoal production is usually high under seasonally dry climatic conditions. As almost all Kimmeridgian charcoals discovered to date come from marine deposits, it seems likely that taphonomic factors may have favoured the preservation of charcoal in such environments. Considering all data and interpretations, it seems possible that on a global scale fire frequencies were low during the Kimmeridgian due to relatively low atmospheric oxygen conditions during this period. Only in areas with a pronounced seasonality (i.e. under a winter-wet climate) could fires have occurred frequently enough to produce a certain amount of charcoal, and this charcoal has only been preserved under favourable conditions in marine sediments or in peat bogs with relatively high fire frequencies.

Keywords Charcoal · Wildfire · Atmospheric oxygen · Taphonomy · Kimmeridgian · Jurassic

Introduction

Fossil charcoal (including the coal macerals fusinite [fusain] and semi-fusinite) isolated from sedimentary rocks and pyrogenic polyaromatic hydrocarbons represent direct evidence of palaeo-wildfires (Scott 1989, 2000, 2010),

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occurring in the fossil record at least since the Late Sílurian (Glasspool et al. 2004). However, despite a high preservation potential, fossil charcoal, the most easily observable evidence for fires, is not equally distributed in sedimentary rocks from different ages (Scott 2000, 2010).

Today the occurrence of wildfires is controlled by a number of climatic and environmental parameters, and fires are important sources of disturbance in many ecosystems (Bowman et al. 2009). Thus, it is not surprising that charcoal production is also controlled by climatic and other environmental changes, even on longer time-scales (Flannigan et al. 2009). An additional factor that has to be taken into account when investigating fossil wildfires are changes in the atmospheric oxygen concentration, as the ignition of fuel and subsequent spread of fires depends on the availability of atmospheric oxygen (Belcher and McElwain 2008; Belcher et al. 2010). In the past it has been argued by various authors that the fossil record of charcoal must also have been influenced by (long-term) variations in atmospheric oxygen concentrations (e.g. Scott 2000) and that such changes have been amongst the primary causes for long-term variations in the occurrence of palaeo-wildfires (e.g. Glasspool and Scott 2010).

Some geochemical models have assumed low oxygen concentrations during almost the entire Jurassic (Berner 2009), resulting in, at least theoretically, very low fire frequencies during this period. This interpretation is not in accordance with the fossil record of charcoal (Belcher and McElwain 2008; Marynowski et al. 2011) and the fossil record in general for many Jurassic time slices. In our study we focus on the occurrence of fossil charcoal from two localities in the Kimmeridgian of Central and Western Europe, in context with previously known evidence for palaeo-wildfires during this period, to evaluate potential relationships between the occurrence of such evidence and environmental as well as taphonomic factors.

To date only a few studies have dealt with evidence for palaeo-wildfires in the Kimmeridgian. One potential source of information on the occurrence of palaeo-wildfires is the abundance and frequency of inertinites within coal, as most, or even all, inertinites are of pyrogenic origin (Scott and Glasspool 2007) and the overall inertinite contents of coals is frequently used as an indicator for the occurrence of palaeo-wildfires (e.g. Diessel 2010; Glasspool and Scott 2010). Diessel (2010) in his overview on the stratigraphic distribution of inertinites (which he used as a proxy for the general occurrence of palaeo-wildfires within mire-systems) listed only a single Kimmeridgian locality from Australia with only very low inertinite contents (approx. 1%; Salehi 1986). Additionally, Glasspool and Scott (2010), in an attempt to use inertinite concentrations as a proxy for atmospheric oxygen concentrations (assuming that fires, as the source of intertinites, are more frequent and intense in high oxygen concentrations), listed inertinites from Kimmeridgian coals from a drill-core originating from offshore New Jersey (Hower and Wild 1994) and inertinite-free coals from the Kimmeridgian of Spain (Diaz-Somoano et al. 2007). It can generally be assumed that both the scarcity of records and the rather low inertinite concentrations in some coals in fact reflect a scarcity of palaeo-wildfires within the relatively few mire-systems during this period.

Additional evidence of Kimmeridgian palaeo-wildfires comes from macroscopic charcoal remains. In their recent overview on Mesozoic fire records, Belcher and McElwain (2008) listed only a single occurrence of charcoal deriving from the Kimmeridgian of Sutherland, Scotland (Harris and Rest 1966 [wrongly cited as 1963]). The occurrence of fossil charcoal from this area is considerably well documented because several studies have dealt with the taxonomy and ecology of the charred plant remains from the Kimmeridgian of Sutherland, Scotland (e.g. van der Burgh and van Konijnenburg-van Cittert 1984; van Konijnenburg-van Cittert 2008). Another record of Kimmeridgian charcoal fragments (erroneously cited as being of Middle Jurassic age by Belcher and McElwain 2008) has been published by Jones (1997). This author reported numerous charcoal-containing layers within Oxfordian and Kimmeridgian sediments of a drill core from the Witch Ground Graben in the central North Sea. Further occurrences of Kimmeridgian charcoal fragments, which were overlooked by Belcher and McElwain (2008), have been reported in the Kimmeridgian of Tanzania (Süss and Schultka 2001, 2006) and southwestern Germany (Schweigert and Dietl 2006). From Tanzania Süss and Schultka (2001, 2006) reported diverse assemblages of charred wood remains from the world-famous dinosaur locality Tendaguru. At this locality woody charcoal, belonging to various gymnosperm taxa, occurs in different horizons spanning a considerable amount of time, from the Oxfordian–Kimmeridgian boundary interval, through almost the entire Kimmeridgian, up to the Tithonian or even the Early Cretaceous (Aberhan et al. 2002; Bussert et al. 2009). Additionally, Schweigert and Dietl (2006) reported the occurrence of a single specimen of poorly preserved macroscopic charcoal of gymnospermous affinity from the Kimmerigian of Nusplingen in southwestern Germany as well as microscopic charcoal occurring on certain bedding planes of the Nusplingen Lithographic Limestone.

Here we report the occurrence of additional (and much better preserved) charcoal specimens from the Nusplingen Lithographic Limestone in southwestern Germany as well as the occurrence of as-yet unpublished charcoal fragments from Kimmeridgian deposits of the Boulonnais area in northern France. We also present data on the taphonomy of both charcoal occurrences as well as on the palaeoenvironmental implications of the occurrence of Kimmeridgian charcoals on a global scale.

Material and methods

Material

The studied material comes from two localities: Nusplingen in southwestern Germany and the Boulonnais in northern France. All specimens are stored in the palaeobotanical collection of the Staatliches Museum für Naturkunde in Stuttgart, Germany under catalogue numbers SMNS P2206/1, SMNS P2206/2, SMNS P2206/3 (all Nusplingen) and SMNS P2207 (Boulonnais).

The material from both localities was identified as charcoal based on the following characteristics, which can be considered to be diagnostic for this type of preservation (Scott 1989, 2000, 2010):

1) black colour and streak,
2) splintery fracture,
3) silky lustre,
4) internal anatomy preserved,
5) homogenised cell walls under the scanning electron microscope (SEM).

Nusplingen, southwestern Germany

The Nusplingen Lithographic Limestone (= Nusplingen Plattenkalk) is a Fossillagerstätte, largely comparable to the lower Tithonian Solnhofen Lithographic Limestones in Bavaria. However, the Nusplingen Lithographic Limestone is of Late Kimmeridgian age (Fig. 1) (Schweigert 1998, 2007) and thus approximately 500 ka older than the lithographic limestones of Solnhofen and Eichstätt.

The locality Nusplingen is located about 12 km north of the Upper Danube valley, in the western part of the Swabian Alb (Fig. 1). To date, no other localities yielding fossiliferous laminated limestones are known from this region. According to Bantel et al. (1999), the laminated limestones were deposited in a more or less anoxic lagoonal environment. This lagoon was surrounded by sponge/microbial mounds, and these mounds formed small islands during the deposition of the lithographic limestone due to tectonic uplift (Dietl and Schweigert 2004). The thickness of the Nusplingen Lithographic Limestone is between 10.5 and 17 m. For detailed sections see Dietl et al. (1998) and Bantel et al. (1999). General overviews on this locality have been published by Dietl and Schweigert (1999, 2001, 2004).

Fossils from the Nusplingen Lithographic Limestone have been known since the middle of the 19th century (Dietl et al. 2000), and in 1983 the whole occurrence of the laminated limestone was designated a Protected Excavations Area because of its extraordinary fossils (Bloos 2004). At the present time the fossiliferous sediments are being excavated by the Staatliches Museum für Naturkunde in Stuttgart in two small quarries (Nusplingen and Egesheim quarries; Fig. 1a). Since 1993 approximately 8,000 fossils have been recovered, belonging to more than 350, mostly marine, taxa (Dietl and Schweigert 2011). Fossils from the upper part of the succession, which consists of more bituminous layers, are in particular excellently preserved, often with organic matter (e.g. Briggs et al. 2005; Klug et al. 2010; Schweigert et al. 1996). Many remains of land plants also occur in this part of the succession, probably derived from the nearby islands surrounding the lagoon (Dietl and Schweigert 2001, 2011). Most of the plants are preserved as compressions, with cuticles, exhibiting even fine details of epidermal structures and stomatal complexes, still preserved. In some specimens, interpreted as araucarian cone scales, Schweigert and Dietl (2003) were able to identify amber still in situ within resin vessels. Some years ago, Schweigert and Dietl (2006) reported—also for the first time—the occurrence of a single, although very badly preserved specimen of charcoal.

Since this time some additional and much better preserved macroscopic charcoal fragments, between 3 × 5 mm and 32 × 24 mm large, have been discovered in the Nusplingen quarry. These fragments come from different horizons, but it seems that they are most abundant in horizon D while the specimens from horizon C are generally better preserved (cf. Fig. 1b). Microscopic charcoal is also present at this locality (Schweigert and Dietl 2006).

Boulonnais, northern France

The studied material comes from the base of the Argiles de Châtillon Formation, which belongs to the upper part of the *Alacostephanus eudoxus* ammonite zone (overlying parts of the Argiles de Châtillon Formation belong to the *A. autissiodorensis* zone and the lower part of the *Gravesia gigas* zone), exposed at a cliff a few kilometres north of Audresselles in the Boulonnais area (Figs. 2, 3). The Argiles de Châtillon Formation is overlain by sediments of the Grès de la Crèche Formation (upper part of *Gravesia gigas* zone) and underlain by the Grès de Chatillon Formation (Herbin et al. 1995; Wignall et al. 1996).

The sediments of the Argiles de Châtillon Formation have been interpreted as a low-energy shelf facies deposited below the wave base, although storm-influenced layers have been recognised (Fürsich and Oschmann 1986). According to Proust et al. (1993, 1995), the base of the Formation, from where the charcoal originates, represents a transgressive system tract.

The material studied here was collected in 1990 by A. and B. Ziegler, Staatliches Museum für Naturkunde Stuttgart. The sampling locality is located between Audresselles and Cran-aux-Oeufs (cf. Fig. 2), and charcoal seems to be restricted to a single bedding plane about 40 cm above the

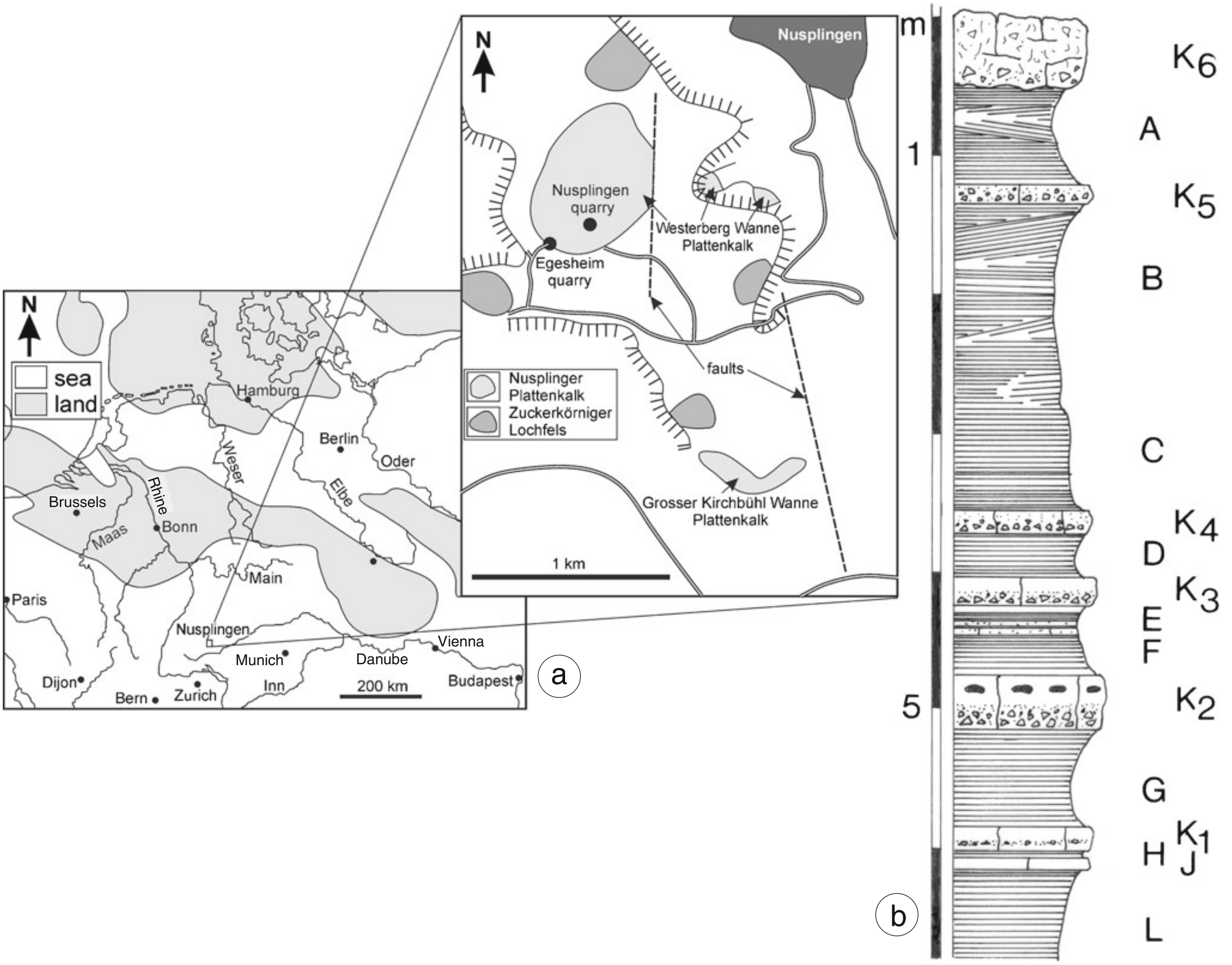

Fig. 1 Map showing the geographic position (**a**) and a standard profile (**b**) of the locality Nusplingen (Nusplingen quarry) in southern Germany (from Dietl et al. 1998; Klug et al. 2005)

base of the Argiles de Châtillon Formation. On this particular bedding plane charcoal fragments of between approximately 1 × 2 and 8 × 11 mm, together with uncharred plant debris, are common (Fig. 6a)

Methods

Charcoal samples 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 all specimens, these could not be cleaned with water or any acids to remove adhering mineral remains. The charcoal samples were mounted on standard stubs with LeitC (Plano GmbH, Wetzlar Germany), and subsequently examined with the aid of a JEOL JSM 6490 LV SEM (JEOL, Tokyo, Japan; at 15 and 20 kV, respectively) at the Senckenberg Forschungsinstitut und Naturmuseum Frankfurt.

Results

Nusplingen lithographic limestone, southwestern Germany

Preservation and taphonomy

Macroscopic charcoal is generally very rare within the Nusplingen Lithographic Limestone and so far it seems that most fragments have been preserved in more bituminous layers in which other kinds of organic matter (e.g. cuticles) also occur. The size of the hitherto discovered fragments

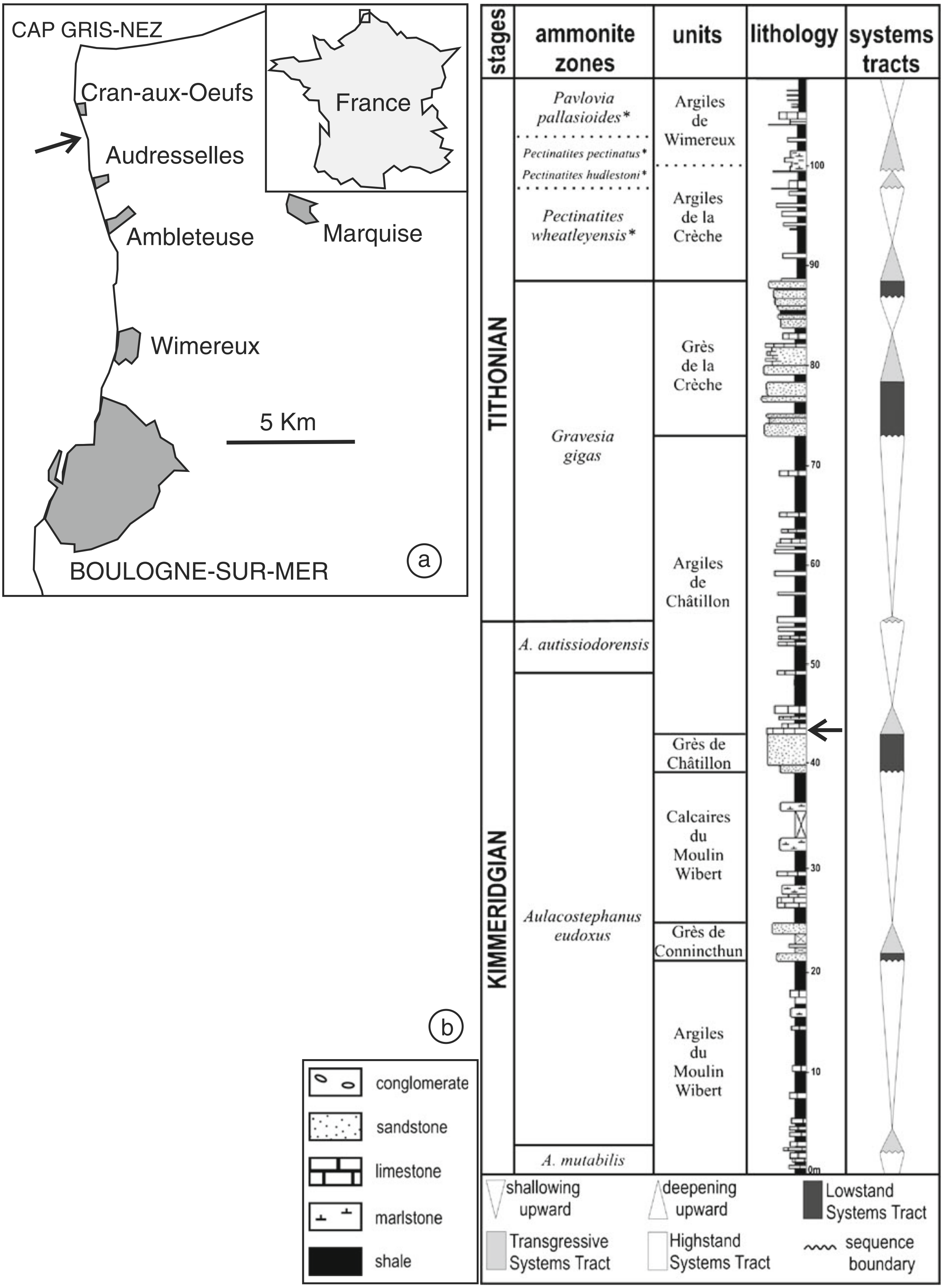

Fig. 2 Map showing the geographic position (**a**, *arrow*) and the profile (**b**) of the Jurassic strata near Audresselles in the Boulonnais area in northern France (from Schlirf 2003, based on Proust et al. 1995). *Arrow* in **b** points to the charcoal-bearing layer

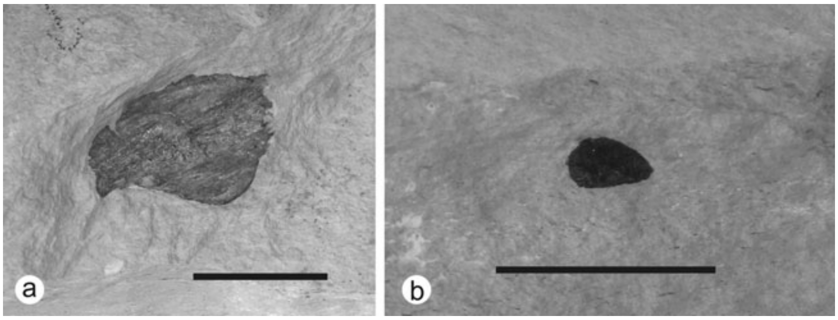

Fig. 3 Overview of charcoal in massive limestones from Nusplingen. **a** Specimen SMNS P2206/3 with excellent three-dimensional preservation and cell lumina partly filled with calcite, **b** specimen SMNS P2206/2 with fragmented cell walls due to the growth of calcite crystals within cell lumina. *Scale bar*:2 cm

ranges from 3 × 5 mm to 32 × 24 mm. The edges of all specimens are rounded.

The preservation of macroscopic charcoal fragments differs between specimens, and generally three modes of preservation can (so far) be differentiated at this locality:

1) Charcoal shattered through compaction of sediments, resulting in poorly preserved tissues (Fig. 4a, b). This is seen in a specimen (SMNS P2206/1) preserved on the surface of an individual limestone slab from horizon D.
2) Lumina of cells filled with calcite, forming casts of the cells. Original cell walls are shattered, probably due

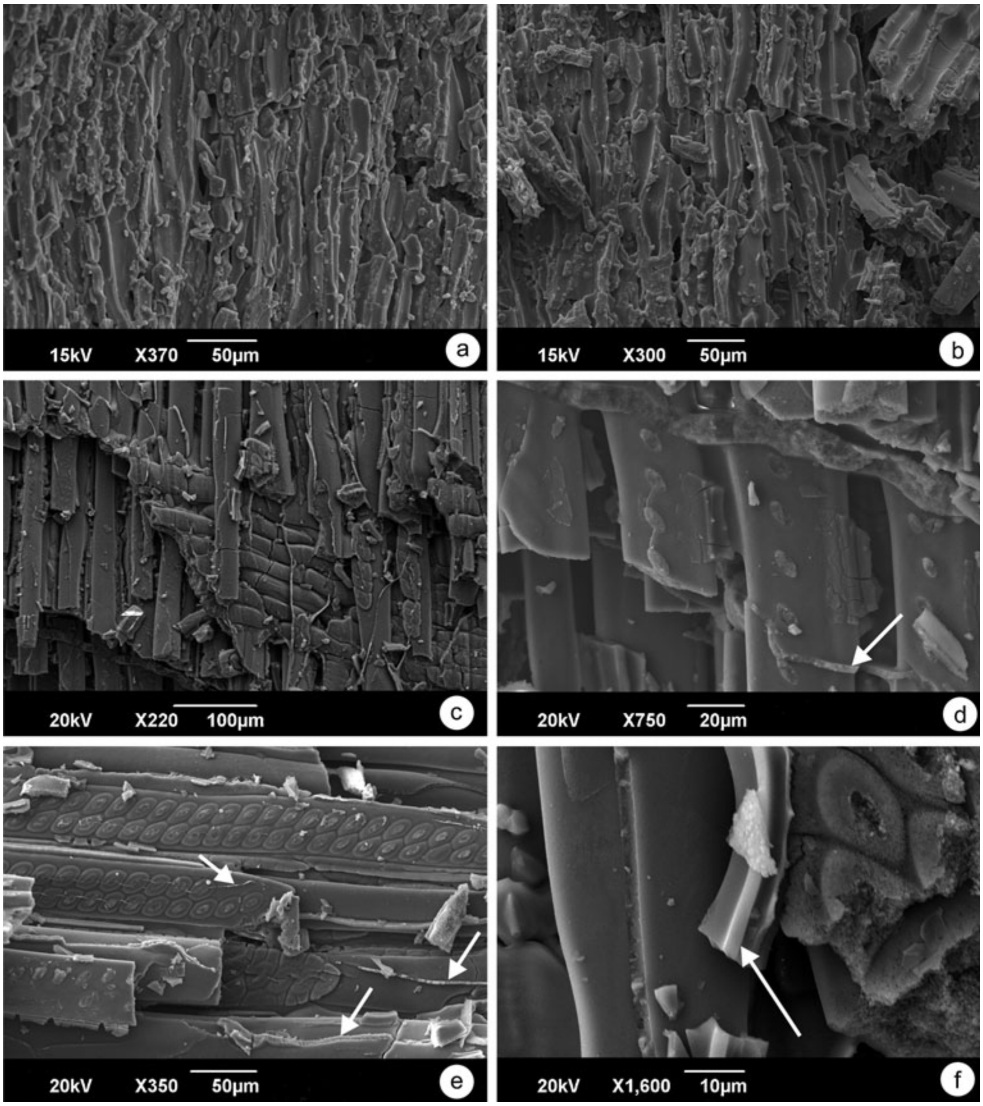

Fig. 4 Scanning electron microscopic (SEM) images of fossil charcoal from Nusplingen. **a**, **b** Inv.-Nr. SMNS P2206/1 from horizon D, **c**–**f** Inv.-Nr. SMNS P2206/2 from horizon D. **a**, **b** Poorly preserved and fragmented secondary wood, **c** calcite casts of tracheids and ray cells, with only a few remnants of charred cell walls in radial view, **d** calcite casts of uniserialy pitted tracheids with “ridges” of calcite (*arrow*) that filled the gaps between individual fragments of the shattered walls, **e** calcite casts of biserial, alternating pitting on tracheids with “ridges” of calcite (*arrows*) that filled the gaps between individual fragments of the shattered walls, **f** calcite casts of tracheids with remnant of charred cell wall; *arrow* points to homogenised cell wall as evidence of charring

to expanding calcite within cell lumina (Fig. 4c–f). Thus, charred cell walls are only occasionally preserved as larger fragments, but they are recognisable as fossil charcoal due to homogenised cell walls (Fig 4f). On several of the calcite casts "ridges" of calcite can be observed that filled the gaps between individual fragments of the shattered wall (Fig. 4d, e). This is seen in a specimen (SMNS P2206/2) preserved within a more massively appearing limestone from horizon D.

3) Woody tissue (almost) completely three-dimensionally (3D) preserved with only occasional calcite infillings in cell lumina (Fig. 5). Parenchymatic cells of wood rays are destroyed due to calcite filling (Fig. 5d). This type of preservation is seen in a specimen (SMNS P2206/3) preserved within a massive limestone of horizon C.

The relatively small size of the fragments, their abraded edges and their general scarceness indicates considerable transport by water prior to sedimentation.

Description and potential taxonomic affinity

All specimens investigated to date have pycnoxylic wood, with uni- or biserial pitting on tracheid walls and occasional rays, pointing to a gymnospermous affinity of all specimens. The best preserved charcoal specimens from horizon C (e.g. Fig. 5) exhibit anatomical characteristics that allow a tentative assignment to the morphogenus *Agathoxylon* HARTIG. Although this morphogenus of fossil wood exhibits similarities to modern Araucariaceae, it is impossible to infer any taxonomic relationship to this particular group because this type of wood occurs in a number of rather different plant groups from the Carboniferous (or even Devonian) up to the

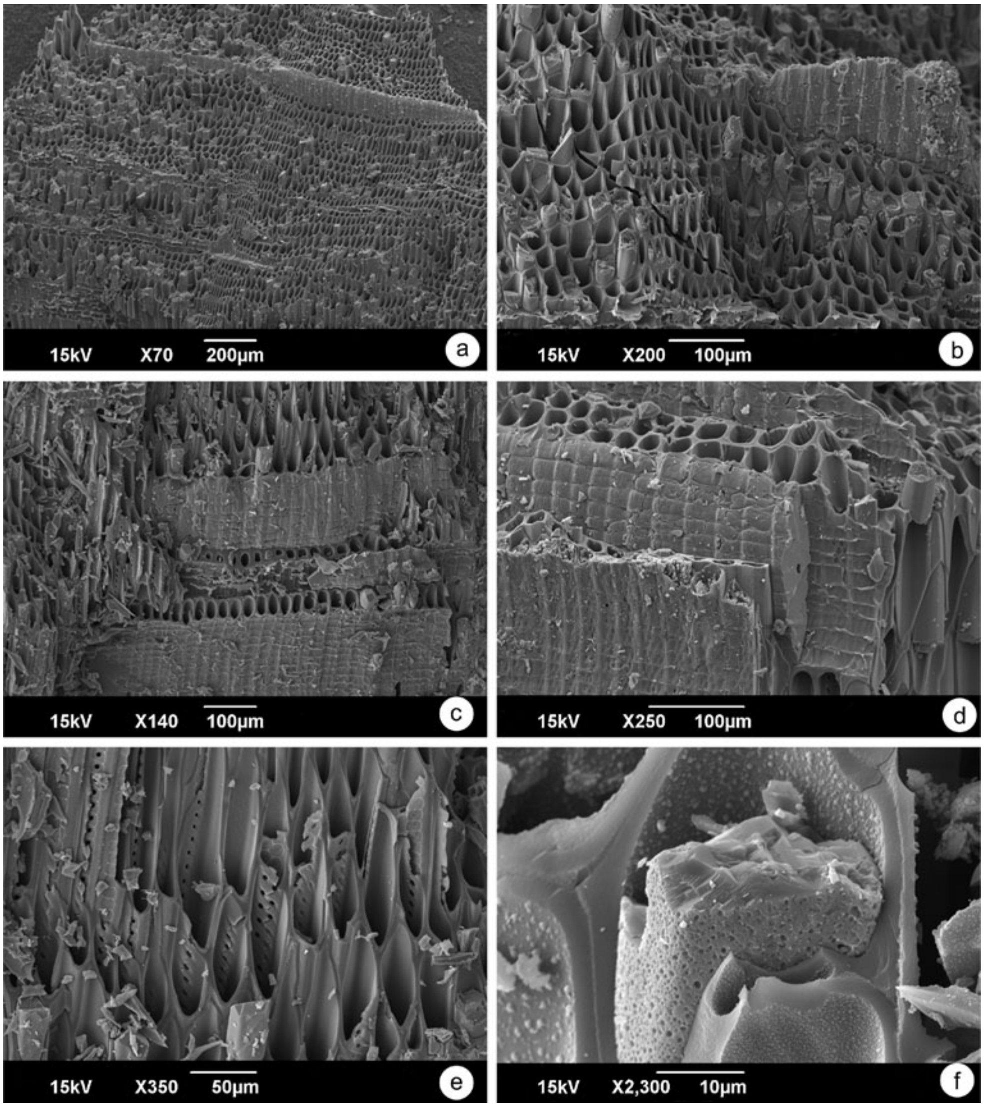

Fig. 5 SEM images of fossil charcoal from Nusplingen (all Inv.-Nr. SMNS P2206/3 from horizon C). **a** Charred wood in cross-section with a zone of smaller tracheids ("growth ring") in the centre part of the image, **b** detailed view of "growth ring" in **a**, **c** wood in radial view with two rays, **d** detailed view of a ray filled with calcite in radial view, **e** detailed view of uniserial and biserial (alternating) pitted tracheids, **f** detail of calcite cast in a tracheid; the "granulation" on the tracheid wall, which is also seen on the surface of the cast, seems to be a feature of the original plant and not a preservational artefact

Present (Philippe 2011). In one larger specimen, a zone of smaller tracheids (probably a faint growth ring) is visible in cross-section (Fig. 5a, b).

The macroflora from Nusplingen is dominated by different groups of gymnosperms, including conifers, ginkgoales, bennettitaleans and seed ferns (Dietl and Schweigert 2011; Mutschler 1927), all of which may be a potential source of the charcoal deposited in the lagoon.

Boulonnais, northern France

Preservation and taphonomy

The size of the fragments ranges from approximately1 × 2 to 8 × 11 mm. Edges of individual specimens are mostly rounded. Fragments with sharp edges occur, but these are mostly small and may represent parts of larger fragments which broke off shortly before deposition.

The overall small size of the fragments and their abraded edges indicate considerable transport by water prior to sedimentation. The deposition in a distinct layer together with other small plant detritus points to deposition during a distinct "event" (see below).

Description and potential taxonomic affinity

Due to the overall poor preservation of this material only some basic anatomical characteristics can be observed. All studied specimens represent pycnoxylic woods, with rare evidence of rays (Fig. 6b–d). The overall characteristics of the charcoal from the Boulonnais are in agreement with a general gymnosperm affinity of the wood, but a more detailed description or even a more specific affiliation is impossible due to the overall bad preservation of this material.

Discussion

Seen on a global scale the number of previously published records of fossil charcoal (macro-remains as well as inertinites) discovered in sediments from the Kimmerdigian is rather low. The same is true for most other Jurassic stages (Belcher and McElwain 2008; Fig. 2), but there is no obvious (long-lasting) gap in the Jurassic record of charcoal and other evidence of wildfires. Based on the latter, Belcher and McElwain (2008) concluded that atmospheric oxygen concentrations clearly did not drop below a certain threshold (approx. 15%) during the entire Jurassic. However, considering the general scarceness of Kimmeridgian evidence for wildfires, it seems likely that oxygen concentrations were comparatively low during this stage, possibly around 15% or slightly higher, as suggested by more recent reconstructions based on geochemical modelling (e.g. Berner 2009). These relatively low oxygen concentrations possibly influenced the ignition and spread of wildfires, leading not only to a relatively low number of wildfires but also to less intense and smaller wildfires during the entire Kimmeridgian. From a climatic point of view, evidence of palaeo-wildfires in the

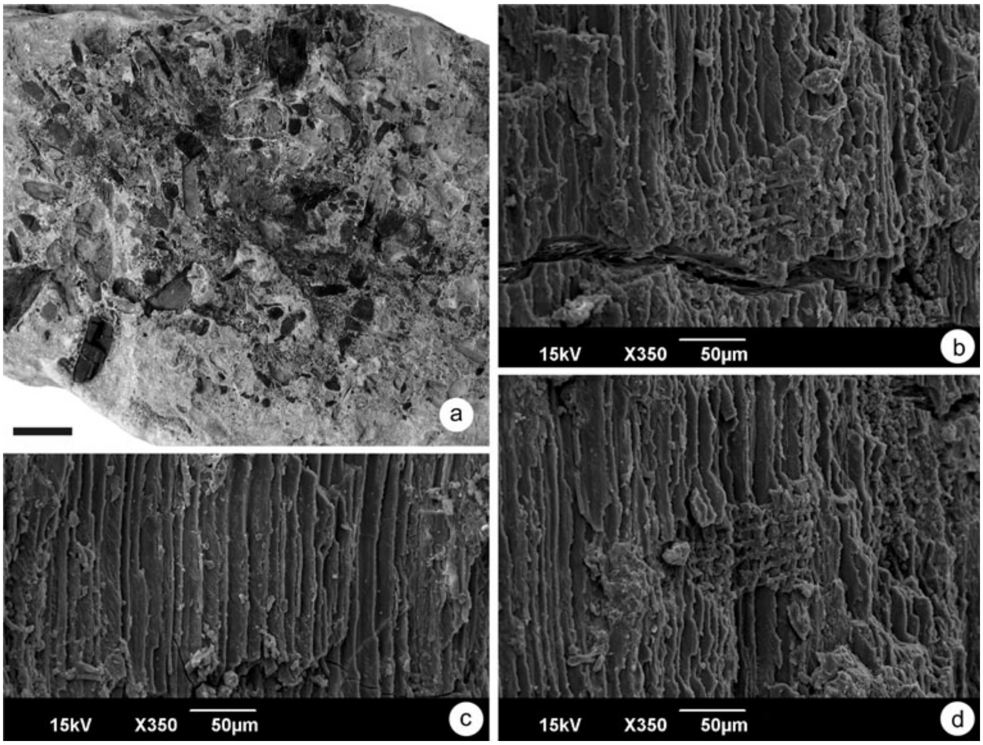

Fig. 6 Charcoal from Boulonnais area (all Inv.-Nr. SMNS P2207). **a** Overview of charcoal bearing layer; *scale bar*: 2 cm, **b** SEM image of secondary wood in radial view with remains of ray, **c** SEM image of secondary wood in tangential (?) view, **d** SEM image of secondary wood in radial view with remains of ray

Kimmeridgian seems to be restricted to the assumed winter-wet climate belt with seasonally dry conditions and to adjacent areas in the warm temperate climate belt (Fig. 7), according to the reconstruction of Late Jurassic climate belts (approx. 150 myr ago) by Rees et al. (2000). Winter-wet climates during the Jurassic were partly comparable to modern Mediterranean climates and areas with charcoal in adjacent warm temperate climate belt probably at the drier end within this climate belt (van Konijnenburg-van Cittert 2008). As the map provided by Rees et al. (2000) integrates over some period of time, it can also be taken as a certainty that the boundaries between different climate belts given in this map do not necessarily represent the exact situation during deposition of the Kimmeridgian charcoals discussed here. Indeed, other climate reconstructions for the Late Jurassic (Scotese 2002) reconstruct relatively dry conditions going further to the north than on the reconstruction used here, bringing at least the North American records within drier conditions.

Today's winter-wet climates (=Mediterranean climates s.l.) are prone to regular wildfires, as they are dry during summer,

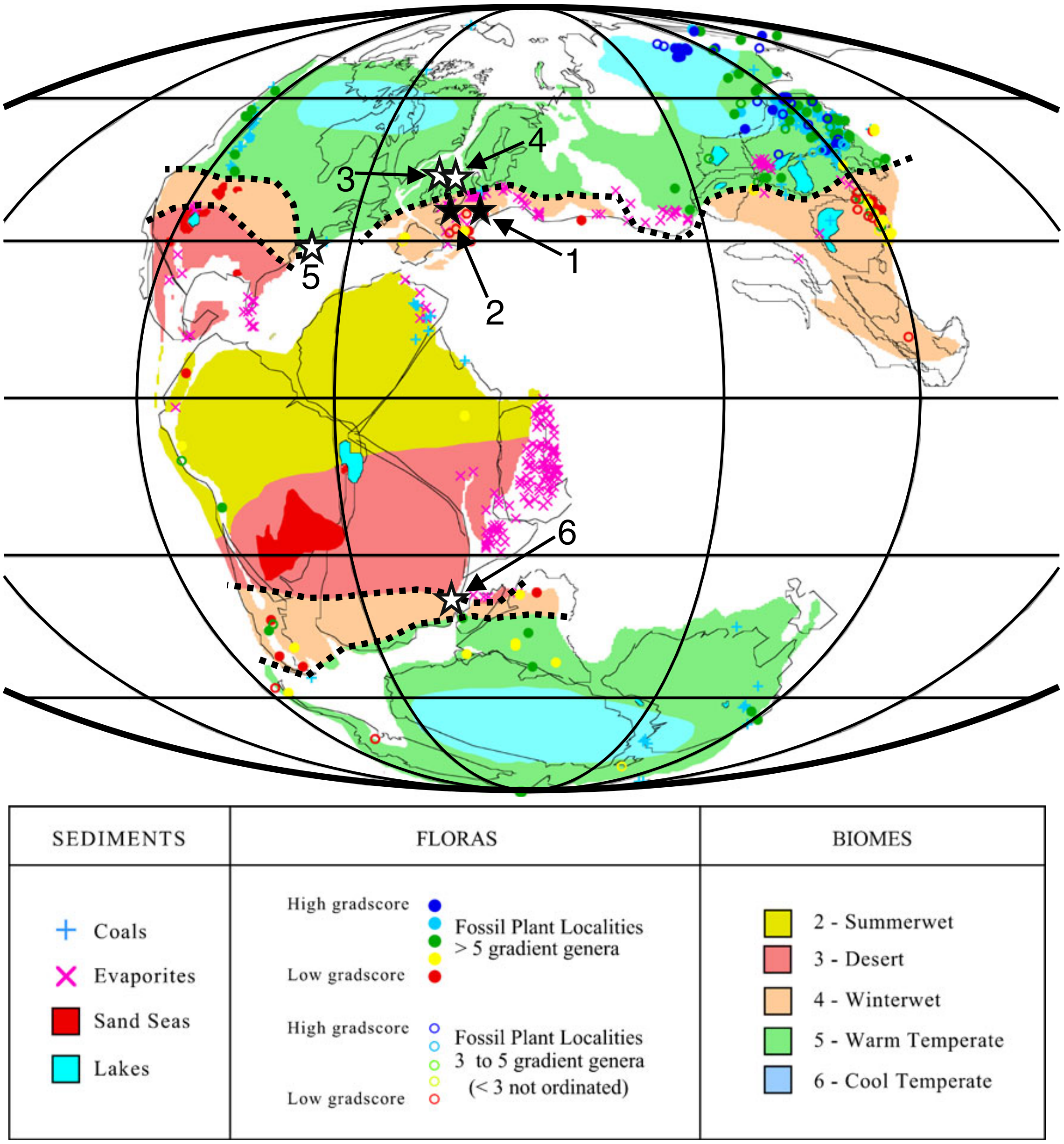

Fig. 7 Reconstruction of global climate belts during the Late Jurassic (150 myr BP), modified from Rees et al. (2000), with occurrences of fossil charcoal discovered in Kimmeridgian sediments. *Filled stars* this study, *open stars* previous studies. *1* Nusplingen Lithographic Limestone, southwestern Germany, *2* Boulonnais area, northern France, *3* different localities, Scotland (van Konijnenburg-van Cittert and van der Burgh 1984; van Konijnenburg-van Cittert 2008), *4* Witch Ground Graben, central North Sea (Jones 1997), *5* coal seams off-shore New Jersey (Hower and Wild 1994), *6* Tendaguru, Tanzania (Aberhan et al. 2002; Süss and Schultka 2001, 2006)

resulting in low moisture contents of potential fuels (e.g. Naveh 1975; Scott 2000). In these climate zones plants are often adapted to regular fires (pyrophytes), but no evidence has yet been recorded for such adaptations by Kimmeridgian plants.

It is also likely that the distribution of fossil charcoal during the Kimmeridgian depends on the available fuel (=plant biomass). According to modelling studies by Beerling and Woodward (2001), net primary production (=plant growth) during the Late Jurassic was rather high in the areas that can be more or less correlated with the winter-wet and warm temperate climate belts sensu Rees et al. (2000). Consequently, it can be assumed that potential fuel for wildfires was probably available in greater abundance in these regions than in other regions.

Based on the (so far) scarce record of Kimmeridgian charcoal and the geographically restricted occurrence of this evidence it seems possible that a generally low occurrence of palaeo-wildfires, probably caused by relatively low atmospheric oxygen concentrations, was modified by climatic factors (dryness during summer) regionally, supporting the ignition and spread of wildfires due to low moisture content of potential fuels (cf. Belcher and McElwain 2008; Wildman et al. 2004). Such regionally more frequent fires may have resulted in higher charcoal production within the winter-wet climate zone and the drier parts of the temperate climate zone. It is possible that fires also occurred in more arid regions, but in such areas fossil charcoal has a generally low preservation potential, as macroscopic charcoal easily breaks down mechanically under such climatic conditions (Skjemstad et al. 1996; Uhl et al. 2004, 2010; Uhl and Montenari 2011).

When we have a closer look on the known occurrences of Kimmeridgian charcoals we find that most of them have been preserved in marine deposits, whereas others come from coal deposits (which are known to be excellently suited for the preservation of charcoal; Scott 1989, 2000; Scott and Glasspool 2006).

The occurrence of macroscopic charcoal in marine sediments is also known from other periods (e.g. Carboniferous: Scott et al. 1997; Late Permian: Uhl and Kerp 2003). Theoretically, charcoal can enter the oceans by different means (via wind transport, fluvial transport, etc.) and stay afloat for a more or less considerable amount of time depending, amongst other factors, on palaeohydraulic conditions, burning temperature and taxon-specific internal anatomy (and probably biochemical composition) (e.g. Nichols et al. 2000), most likely resulting in a very scattered occurrence of charcoal in marine sediments. Taking these factors into account, it seems likely that the relative abundance of charcoal in our Kimmeridgian localities points to some proximity to the source of the charcoal. In the case of Nusplingen, these were probably the islands surrounding the lagoon, which were also the source area for the diverse and well-preserved compression-flora known from this locality (Dietl and Schweigert 2001; Mutschler 1927).

More than 20 taxa of terrestrial plants have been identified to date based on macro-remains from both limestone quarries at Nusplingen, with most of these belonging to gymnosperms (Dietl and Schweigert 2001, 2011; Mutschler 1927). These remains probably originated from the islands surrounding the lagoon (Fig. 8), and it seems likely that these plant remains may have been transported into the

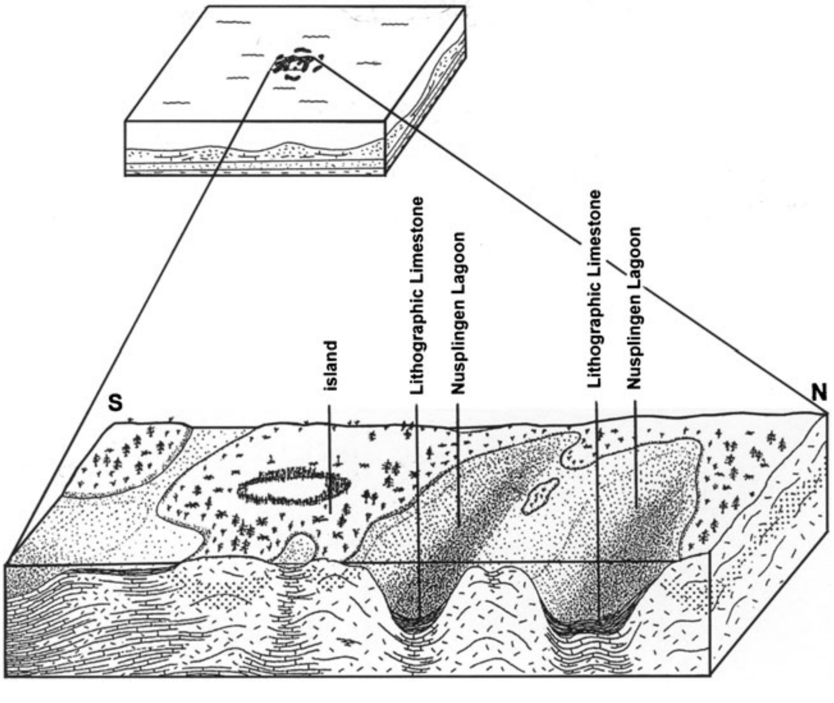

Fig. 8 Reconstruction of the Nusplingen lagoon (from Dietl and Schweigert 2004), demonstrating the direct vicinity of the vegetated source area for the charcoal on the islands and the area of deposition within the lagoon

lagoon during storm events, either directly by wind transport or by floods caused by heavy rainfall. Given the large size of the charcoal fragments, wind transport seems unlikely for these fragments, and thus we have to assume that they were either washed into the sea by creeks or small rivers, occasional floods caused by heavy rainfall or by wave-activity that flooded the beaches of the islands (perhaps during storm events) where charcoal and other plant parts may have accumulated in drift lines. The latter possibility appears to be the most likely one, because sand-sized limestone particles have been observed glued onto the surface of some plant material with remains of resin, and these would be expected to occur on a beach (G. Schweigert, personal observation)

In the case of the material from the Boulonnais, it is likely that the charcoal originated from the nearby continent, which was laid a few kilometres to the east and north of our locality during the Kimmeridgian (Proust et al. 1995). Although no macrofloras are known from this area, it can be assumed that in the source region, which was situated in the north and/or east (e.g. Proust et al. 1995), gymnosperms (certainly belonging to different systematic groups) were an important component of the vegetation, as in several other contemporaneous European floras (e.g. Barale 1981; Vakhrameev 1991; van Konijnenburg-van Cittert 2008). As the charcoal comes from a horizon that has been deposited during the initial phase of a transgressive system tract (Proust et al. 1995), it seems possible that these charcoals were "washed" into the sea from a previously exposed surface (perhaps a forest floor or even a drift line at the nearby coast) during the transgression. A reworking of considerably older (>50 ka) material cannot be totally excluded but seems unlikely due to the mechanical instability of charcoal.

The charcoal-bearing sediments from the Kimmeridgian of the Tendaguru area in Tanzania (Aberhan et al. 2002) and the Lothbeg Siltstone in Scotland (van Konijnenburg-van Cittert 2008) have also been interpreted as (marginal) marine sediments deposited near the land, and in both cases it is likely that the charcoal originated from nearby terrestrial ecosystems. Jones (1997) interpreted the Kimmeridgian charcoals from the Witch Ground Graben in the central North Sea as being derived from a nearby coast, where the source vegetation (probably dominated by conifers) experienced more or less regular fires under seasonal climate conditions throughout large parts of the Kimmeridgian. This interpretation is supported by climatic reconstructions based on terrestrial palynomorphs from the southern North Sea pointing to an increase in aridity during the Kimmeridgian (Abbink et al. 2001).

It seems possible that this pattern can also be explained by taphonomic factors favouring the preservation of charcoal in peat bogs and under certain marine conditions (i.e. absence of large mechanical stress during transport and/or sedimentation). However, it is also possible that additional occurrences of fossil charcoal have simply been overlooked by palaeontologists working on Kimmeridgian deposits because they did not regard them as scientifically interesting (e.g. in palynological analyses) (Scott 2010) or considered them as unimportant whilst focussing on other groups of organisms (Uhl et al. 2010).

Conclusions

Based on the data that is currently available on the distribution of fossil charcoal during the Kimmeridgian and our interpretations we can draw the following conclusions:

- On a global scale, fire frequencies were probably low during the Kimmeridgian due to relatively low atmospheric oxygen conditions during this period.
- Only in areas with a pronounced seasonality (i.e. under a winter-wet climate) did fires occur frequently enough to produce a considerable amount of charcoal.
- This charcoal seems to have only been preserved under favourable conditions in marine sediments or in peat bogs with relatively high fire frequencies.

Further studies aimed at locating additional charcoal occurrences from the Kimmeridgian are necessary to test this hypothesis.

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