CLIMATE & BIOTA of the EARLY PALEOGENE
Austrian Journal of Earth Sciences | Volume 105/1 | 88 - 109 | Vienna | 2012

The Early Eocene of Schöningen (N-Germany) – an interim report

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KEYWORDS

Apectodinium acme
fire regime
palynology
mangrove
Eocene
climate

Abstract

The open cast mine Schöningen Südfeld (Lower Saxony, northern Germany), exposed a continuous section of about 170 m which ranges in age from the latest Paleocene to the earliest Middle Eocene, thus encompassing the entire Early Eocene. The section includes 10 coal seams with clastic interbeds, all of which show marine influence to various degrees. A standard section for the Early Eocene Schöningen Formation has been compiled from numerous overlapping partial sections. The section is unique worldwide in its position at the marine and terrestrial interface allowing insights into the interaction between land and sea during the greenhouse climate. Selected aspects of field observations and results of a representative palynological survey are discussed with respect to their significance for the interpretation of environment and climate. Dinocyst associations show a distinct *Apectodinium* acme in the lower part of the section near the expected position of the Paleocene-Eocene boundary, but concomitant changes in the terrestrial vegetation have not been observed. Vegetation changed mainly in response to shoreline conditions as indicated by a unique succession with *Thomsonipollis magnificus* and *Pistillipollenites macgregorii* substituting for the true tropical mangrove of the Middle Eocene. Type and distribution of charcoal allows the distinction of a low frequency from a high frequency fire regime and an essentially fire free regime following each other from base to top. Palynological and charcoal evidence from the Schöningen section suggests a change from a more temperate alternating wet/dry climate at the beginning to a tropical perhumid climate towards the end of the Early Eocene and into the Middle Eocene.

1. Introduction

Research on the Early Paleogene gained a major impetus by the discovery of several hyperthermal events mainly concentrated around the Early Eocene. They were initially recognized on the basis of marked carbon isotope excursions and contemporary changes in foraminifera faunas from deep sea cores, most prominent among them the Paleocene-Eocene Thermal Maximum (PETM) at the Paleocene-Eocene boundary (Bralower et al., 1995; Kenneth and Stott, 1991). Controversial discussions concerning their causes ensued and gradually settled on the massive release of methane gas hydrates from destabilized continental shelf sediments into the atmosphere (e. g. Dickens et al., 1997; MacLennan and Jones, 2006; Bowen and Zachos, 2010). It logically follows, therefore, that ocean warming is the consequence of a corresponding or even greater temperature increase in the atmosphere which should have had notable impact on terrestrial biota. The search for evidence of this impact, however, has produced considerable ambiguity, thus far. For instance, an increase in precipitation and terrestrial runoff has been invoked to explain the *Apectodinium* acme, raised clay contents in shelf carbonates and discrepancies between isotope records from marine and terrestrial sources during the PETM (Crouch et al., 2003; Bowen et al., 2004). On the other hand, reduced precipitation and periods of drought have been recognized for the onset of the PETM in Europe as well as the Rocky Mountains region of the USA (Collinson et al., 2007; Schmitz and Pujalte, 2003; Wing et al., 2005; Kraus and Riggins, 2006). Similarly, significant Holocene scale migrations of vegetation in response to the PETM have been reported along potential pathways in the American Rocky Mountains region (Wing et al., 2005), although contemporaneous changes in vegetation in other Rocky Mountains sites, along the Gulf Coast, U.S.A. and in tropical South America appear to be minor in comparison or can not be directly related to the hyperthermal event (Harrington, 2001, 2008; Wing and Harrington, 2001; Wing et al., 2003; Jaramillo, 2002, 2011). Little to no response to the PETM except local changes in fire regime were noted in Europe (Collinson et al., 2009; Hofmann et al. 2011). By nature, mammals were better adapted to follow latitudinal climate shifts along open north-south routes in the Great Plains and their turnover at the PETM indeed appears more convincing as a stepped response (Gingerich, 2003; Woodburne et al., 2009). But while considerable uncertainties still remain regarding the response of terrestrial biota to the PETM they are even greater for hyperthermal events occurring later in the Early Eocene.

Here we describe a nearly 170 m thick section of largely continuous and conformable strata which has been exposed in the open cast mine Schöningen Südfeld near the town of Schöningen (Helmstedt Mining District, Lower Saxony, northern Germany; Fig. 1) and which we measured and sampled at high resolution during the past fifteen years. The section consists of an alternation of marginal marine to fluvial clastic sediments with 10 major lignite seams and ranges in age from probable latest Paleocene to the early Middle Eocene. Thus, it is expected to include all hyperthermal events so far proposed for this time interval and should throw new light on their possible effect on vegetation. In addition to sedimentological analysis in the field emphasis has been placed on the collection of palynological data as a potential high-resolution proxy of vegetation responses to climate variability. Environment reconstructions are based almost exclusively on sedimentology and palynology since calcareous shells and vertebrate bones have been dissolved during early diagenesis in the massive presence of humic acids. Thus, age constraints are restricted to pollen and spores (Pflug, 1952, 1986; Lenz, 2005), dinoflagellate cysts (Köthe, 2003) and scattered glauconite-based radiometric dates (Ahrendt et al., 1995). Attempts to secure palaeomagnetic information by the LIAG (Leibniz Institute for Applied Geophysics, Hannover) have failed thus far due to unsuitable lithologies. A high-resolution framework of isotope data for critical intervals is envisaged but is still awaiting funding.

The amount of data accumulated now allows us to present a state-of-the-art report after completion of field work and a representative palynological survey.

2. Geological setting and stratigraphy

The Helmstedt-Stassfurt salt wall with its rim synclines is a prominent structure extending NW-SE for more than 70 km within the Subhercynian Basin between the Harz and Flechtingen basement highs in northern Germany (Brandes et al., in press). Lignite deposits within these rim synclines are economically important and have been mined in the areas of Stassfurt-Egeln in the southeast and Helmstedt-Schöningen in the northwest. The Paleogene succession of both rim synclines in the mining district of Helmstedt-Schöningen unconformably overlies the Mesozoic basement. The lithostratigraphy shown in Figure 2 is a modification of the standard subdivision from the northern part of the eastern syncline adopting the local situation in the western syncline near Schöningen.

The Waseberg Formation (Gürs et al., 2002; Gürs, 2005; Standke, 2008) represents the basal part of the Paleogene succession and is largely synonymous with the Süpplingen Formation of Lietzow and Ritzkowski (1996) and Blumenstengel and Krutzsch (2008). Lietzow and Ritzkowski (1996) included the Main Seam in the Süpplingen Formation. We regard the lignite bearing succession as a lithologic unit and therefore use the base of the Main Seam as the base of the Schöningen Formation, which has been introduced as such by Lietzow and Ritzkowski (1996) and subsequently applied by Stottmeister (2007) and Blumenstengel and Krutzsch (2008). Later the term Elz Formation has been applied to the same succession by Gürs et al. (2002), Gürs (2005), and Standke (2008).

Here we propose the Schöningen Formation to comprise the coal bearing succession as exposed in the mine Schöningen Südfeld, previously called "Unterflözgruppe" or "Liegende Flözgruppe" (lower seam group) from the base of the Main Seam to the base of Seam 9. Seam 9 of the Schöningen Südfeld mine is the lateral equivalent of the lower seam ("Unterflöz") of

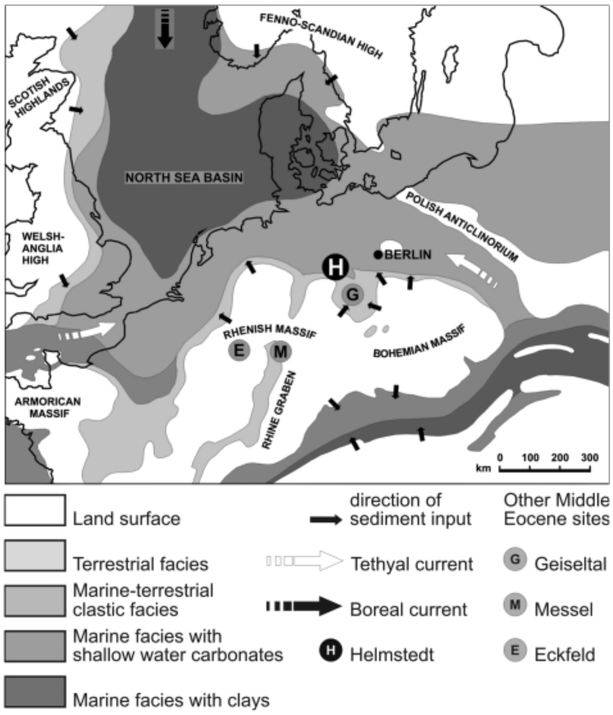

Figure 1: Palaeogeographic map of northwestern Europe during the Early Eocene (adapted from Ziegler, 1990) showing the position of the Schöningen section in relation to well-known Middle Eocene fossil sites such as the Geiseltal, Messel and Eckfeld.

the former open cast mine Alversdorf (Wintgen, 1991; Schiemann, 1994) and therefore part of the coal bearing sequence of the Helmstedt Formation ("Oberflözgruppe", upper seam group). The marine "Emmerstedter Grünsand" (e.g. Ritzkowski, 1990; Ahrendt et al, 1995) respectively Emmerstedt Formation (Gürs et al., 2002; Lietzow and Ritzkowski, 2005; Stottmeister, 2007) which has been recognised further to the north on the basis of glauconite bearing sediments between the Schöningen and the Helmstedt Formations can not be distinguished in the outcrops at Schöningen as already noted by Quitzow (1948).

The coal bearing succession is terminated by a distinct erosional disconformity, locally even by an angular unconformity (e.g. Dienemann, 1926; Manger, 1952; Lietzow and Ritzkowski, 1996), and followed by the fully marine glauconitic Annenberg Formation (Gramann et al.,1975). The Gehlberg and Silberberg formations continuing the marine Paleogene succession to the base of the Oligocene have been described from outcrops further to the north but not identified at Schöningen.

On the basis of invertebrate fossils from the overlying marine succession the coal bearing succession of the Helmstedt district was originally regarded as Oligocene (Barth, 1892; Dorstewitz, 1902; Schmierer, 1913), but an Eocene age was also suggested by Linstow (1907) and Harbort (1909). The latter was confirmed by remains of Middle Eocene vertebrates at the base of the overlying marine succession (Schröder, 1913, 1918). Later, Quitzow (1948) was able to assign an Early Eocene age to the lower group of seams, now Schöningen Formation, based on lithologic arguments and scarce diatoms from glauconitic sediments of what is now called Emmerstedt Formation. Pflug (1952) distinguished different associations of spores and pollen ("Pollenbilder") from the lower and the upper group of seams ("HU-Bild" respectively "HO-Bild"). Since the "HO-Bild" was closely comparable with microfloras from the Middle Eocene of the Geiseltal he regarded the upper group of seams (Helmstedt Formation) as Middle Eocene and the lower group of seams as Lower Eocene. This has generally been confirmed by later studies (Pflug, 1986; Lenz, 2005).

Recent correlations of dinocyst and nannoplankton zones to the global timescale (Köthe, 2003, 2009) place the Paleocene/Eocene boundary (55.8 Ma) in the lower part of dinocyst zone D 5nb which was recognized just above the Main Seam (Ahrendt et al., 1995; Köthe, 2003).

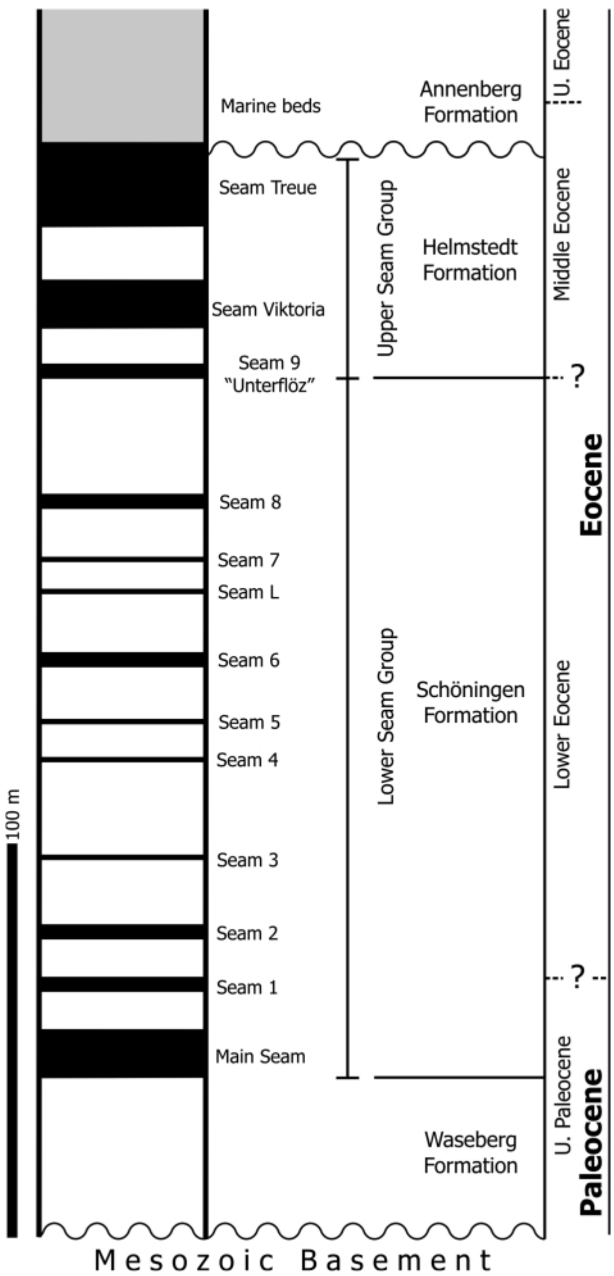

Figure 2: General lithostratigraphy of the Paleogene succession of the western rim syncline of the Helmstedt-Stassfurt salt wall at Schöningen (modified from Brandes et al., in press).

The Ypresian-Lutetian (Lower-Middle Eocene; 48.6 Ma) boundary is placed in the upper part of dinocyst zone D 9na (Köthe, 2003, 2009) and is therefore assumed to be located within or even above the Emmerstedt Formation or its equivalents. A position below the Helmstedt Formation is supported by Pflug (1986) who compared a microflora from the Emmerstedt Formation ("Palyno-Zone Hu4") with the microflora from the lower Middle Eocene oilshale of Messel. The base of the transgressive Annenberg Formation is located still within the Lutetian (Middle Eocene; Gramann et al., 1975; Anderson, 1990). Thus, given that the Main Seam and the upper group of seams are equivalent in age in both rim synclines most of the Schöningen Formation at Schöningen is Early Eocene in age and the Helmstedt Formation entirely Middle Eocene. The age model is supported by the few glauconite-based K/Ar dates of Ahrendt et al. (1995).

Palaeogeographically the Helmstedt-Schöningen area was located at the southern shore of the Eocene North Sea (Fig. 1) between the Harz Mountains and the Flechtingen Rise at about 42° palaeolatitude. Situated near the mouth of a broad estuary draining much of the Bohemian Massif (Standke, 2008; Blumenstengel and Krutzsch, 2008) the area was exposed to changing sea levels, to subsidence due to subsurface salt migration into the Helmstedt-Stassfurt salt wall and to varying intensities of terrestrial runoff. Besides, warm tethyal and cool boreal longshore currents alternated in influencing the regional climate.

3. Material and methods

From more than 50 partial sections, measured and sampled at mostly high-resolution during various mining stages, about 20 sections from the central part of the Schöningen Südfeld mine have been selected to construct a simplified section (Figs. 3, 4). Sedimentological analysis is largely restricted, thus far, to field observations of bedding features, grain size and organic content. In the absence of shelly fossils and bones megafossils are limited to plant remains such as conifer twigs, leaves (mostly fragmentary), fruits/seeds (rare), wood and rooting structures including in-situ tree stumps and seagrasses.

From a set of more than one thousand samples about 300 have been selected and prepared for palynological analysis. Fully quantitative (300 specimens) respectively semiquantitative (at least 150 specimens) counts of the more common and ecologically important species or groups of species have been carried out in order to detect possible major changes in vegetation. Phytoplankton, mainly dinocysts and *Botryococcus*, and selected palynofacies elements which are most resistant to chemical treatment such as resin particles, cuticles, fungal remains and, in particular, fragments of charcoal have been counted as additional percentages above the percentage of total pollen and spores.

Preparation of samples followed standard techniques, but varied slightly over the years depending on experience and preference of different workers. In general, a few grams of lignite were briefly boiled with 15% H_2O_2 and 2% KOH. Repetition of this process with lower concentrations has given excellent results with improved palynomorph concentration.

Samples from the unconsolidated clastic interbeds have also been briefly boiled with H_2O_2 and exposed to ultrasonic vibration for less than one minute in order to disaggregate the sediment and separate organic from mineral matter. KOH was applied for organic rich sediments only. Cold hydrofluoric acid was applied for several days to remove silica and silicates. In samples with a high proportion of quartz sand the coarser sand fraction was carefully decanted to reduce the amount of HF needed for silicate removal; loss of pollen has proved to be negligible. All samples were sieved through a 10 µm mesh screen.

SEM-work has been done on a JEOL JSM-6060LV at the Senckenberg Forschungsinstitut und Naturmuseum in Frankfurt am Main.

Identification of pollen and spore taxa is mainly based on the detailed systematic study of Hammer-Schiemann (1998). Preparation residues and slides from her thesis and material used for the present study by W.R. are currently lodged at the collections of the Geoscience Center Göttingen. Most of the remaining material including several thousand samples is stored at the Senckenberg Forschungsinstitut und Naturmuseum in Frankfurt am Main.

4. The Schöningen-Südfeld section

4.1 Waseberg Formation

Since we define the base of the Main Seam as the base of the Schöningen Formation outcrops of the underlying Waseberg Formation are restricted to a few ditches at the base of the mine. But, the thickness of the Waseberg Formation exceeds 40 m at Schöningen Südfeld (Figs. 2, 3) since mottled clays with carbonaceous patches indicating terrestrial sediments have been drilled at that depth (personal observation W.R.). Most of the Waseberg Formation seems to consist of medium to light gray clayey silt to sands.

4.2 Schöningen Formation

The lower seams and interbeds: The lower three seams, Main Seam, Seam 1 and Seam 2, are the main target of coal mining with a total coal thickness of 15 to 18 m (Fig. 4). They are not only closely associated, being separated by clastic interbeds of somewhat restricted thickness varying between 3 and 15 m, they are also very similar in their macropetrographic constitution and palynological fingerprint. All three seams are composed of an alternation at the scale of several decimetres of dark and medium brown layers (Pl. 1a) which often have tree stumps at their base and show tissue preservation in the coal matrix to varying degree. Quite frequent and conspicuous are layers and lenses of charcoal mainly made up of chunks of charred wood often more than 1 cm in diameter (Pl. 1c, d). Most striking, however, is the occurrence of sizeable carbonate concretions which formed preferentially around tree stumps at a stage of tissue degradation that only allows recognition of a general coniferous wood anatomy (Pl. 1b).

Palynologically the seam structure is more complex and commonly overprinted by successive stages in the peat-forming vegetation particularly at the base and top of the seams (see discussion under “mangroves” below). There seems to be a tendency towards progressive stabilization of a Myricaceae/Betulaceae dominated mire forest during seam formation (Hammer-Schiemann, 1998; Riegel et al., 2008). The Main Seam is petrographically and palynologically divided into a more massive lower part with a dominance of taxodiaceous pollen and an upper more layered part in which Myricaceae/ Betulaceae pollen predominates. This twofold division may reflect an amalgamation of two or more seam splits closer to the depocenter near the salt wall. A striking palynological feature, especially in Seam 1 and Seam 2, is the frequent and close association of Sphagnum and fern spores (*Stereisporites*, *Laevigatosporites*) with charcoal horizons proably representing secondary vegetation succeeding forest fires (Hammer-Schiemann, 1998; Riegel et al., 2007).

The two clastic interbeds separating the three lower seams differ markedly from one another in facies and environment. In Interbed 1, about 5 to 8 m thick, light coloured silts to medium grained sands, locally including massive root traces and large logs of drift wood make up the lower part. They are superseded by dark clayey silts and silty clays grading into Seam 1 at the top. In contrast, in Interbed 2 dark clayey silts dominate in the lower part while the upper part is characterized by irregularly alternating dark silts and light coloured sand layers with bimodal cross-bedding indicating tidal action.

Except for rare local occurrences of dinocysts and foraminifera (Lietzow, 1991) there is no indication of marine influence in Interbed 1. Instead the presence of *Botryococcus* (Hammer-Schiemann, 1998), drift wood and rooting suggests strong freshwater input and local emergence at least for the lower part. Interbed 2, on the other hand, includes diverse dinocyst assemblages with peak abundances of *Apectodinium homomorphum* (Pl. 2f).

The clastic interval: The mainly clastic interval between Seam 2 and Seam 4 is about 34 m thick and consists of Interbeds 3 and 4 separated by the thin Seam 3. A thin veneer of white sand covering Seam 2 ushers in an extended interim of increased clastic input leading to a facies of uncertain degree of marine influence. Interbed 3 begins with a fivefold succession of fining upward cycles of light grey clayey fine sands to dark silts at about 1 m scale. The following 3 meters of dark argillaceous sediments are mostly thin-bedded to laminated, bioturbated to various degrees and succeeded by massive dark brown carbonaceous sand, the accommodation of which provided the first emergent surface as indicated by intensive rooting at its top.

The small Seam 3 (about 1 m thick) and a locally restricted thin rider seam is a notable interruption within an extended sequence of marginal marine facies. Thickness variation in Seam 3 is mainly due to widespread erosion at its top cutting

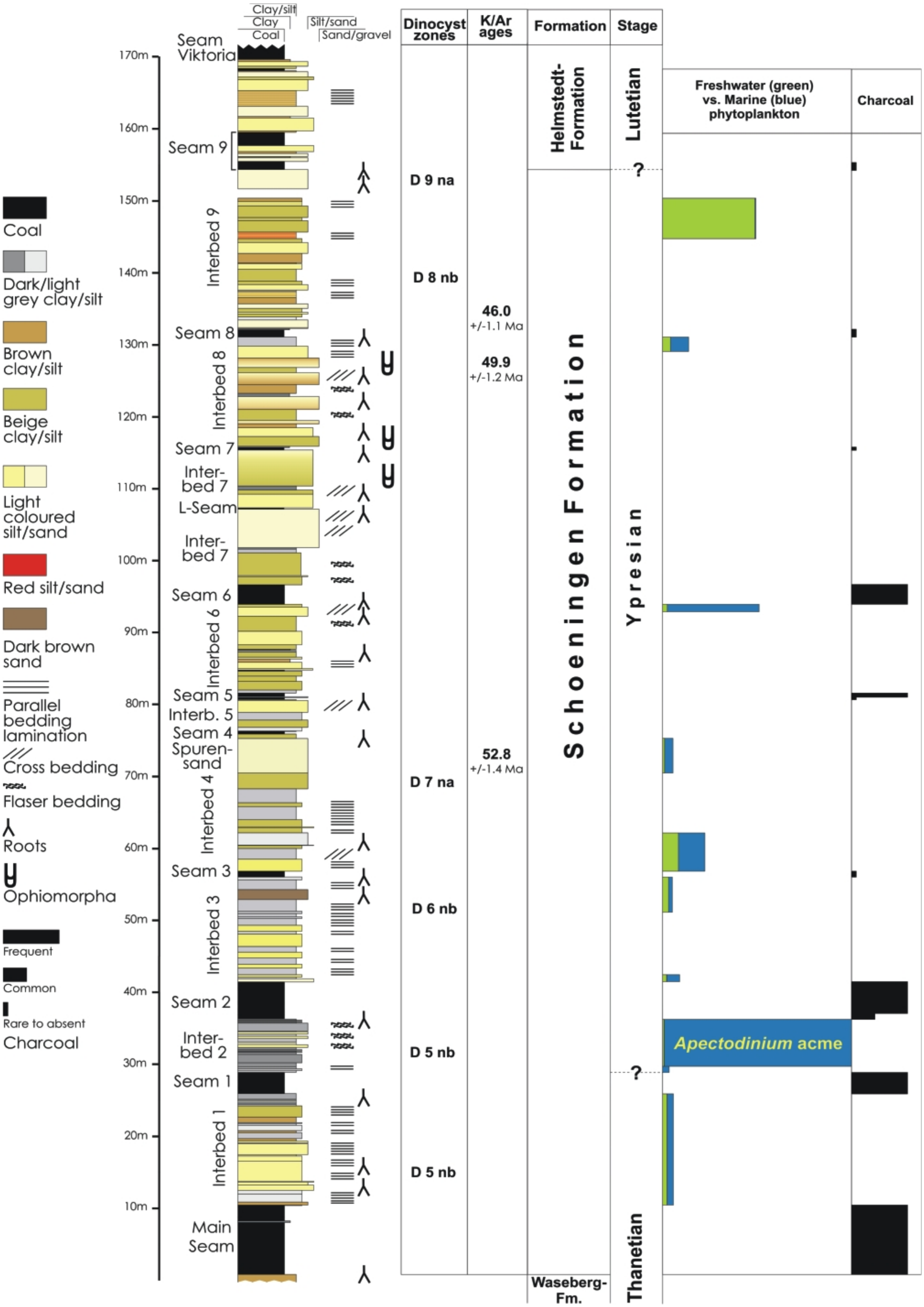

Figure 3: Composite section from the central part of the opencast mine Schöningen Südfeld. Position of scattered data on dinocyst zones and radiometric ages have been transferred from Ahrendt et al. (1995) as shown in Lietzow and Ritzkowski (2005).

well into the seam and including deep channelling and avulsion in the overlying sediment as well as within-seam injection of sand lenses. This is one of the few events of a catastrophic nature within an otherwise rather conformable sequence.

The lower part (~11m) of Interbed 4 consists of a repeated change between predominantly dark clays and light coloured sands, often in close alternation showing tidal influence and bioturbation. But a thin lignite seam (10-15 cm) with remains of *Sphagnum* and numerous small charcoal fragments is locally developed within this sequence indicating intermittent subaerial exposure.

Above that a perfect mix of grain sizes from clay to medium grained quartz sand and mica forms a 7 m thick massive bed in which all bedding features are completely removed by intensive bioturbation (Pl. 2b). The slight greenish colour is due to a small fraction of glauconite. The bed is easily traceable through much of the Helmstedt/Schöningen district and referred to in the literature as "Spurensand" with respect to the intensity of bioturbation. Rooting begins at the top of the "Spurensand" and intensifies throughout the 0.5 to 1 m of argillaceous sediments on which Seam 4 is seated.

The upper seams (Seam 4 to Seam 8) and interbeds: Another phase of coal formation is initiated with Seam 4. Although the clastic interbeds continue to bear their marginal marine and mostly intertidal fingerprint, the organic facies of the five lignite seams differs markedly from that of the lower three seams.

Seam 4 consists of four coal layers which form a single 1.5 m thick seam in places but are separated by interbeds in the center of the mine. Significantly, Seam 4 lacks a notable charcoal fraction, but individual lignite layers may be intensely bioturbated at their top.

Relatively deep water anoxic environments are indicated by dark pyritic mudstones at the base of Interbed 5. A shallowing-upward trend eventually leads to homogeneous light coloured sand locally including in-situ growth of seagrass (Pl. 2e). Further shallowing is indicated by rooted mudstones forming the substrate of Seam 5.

Seam 5 is only about 1 m thick and mostly bipartite. The lower part consists of blocky lignite with tree stumps at its top. The upper part is thin-bedded and rich in finely dispersed charcoal. This petrographic change is accompanied by a change in pollen assemblages from mire forest elements to herbaceous or small woody elements such as *Sphagnum* (*Stereisporites*), fern spores and pollen of Restionaceae (*Milfordia*) and Ericaceae and marks a change from forest mire to fen.

The lower half of Interbed 6 consists of alternating greyish-brown clayey silts and silty clays in two cycles each with a fining-upward trend and ending in a small coal seam (about 10 cm) respectively carbonaceous clay with rooting below which may be interpreted as stunted seam formation. The upper half of the interbed is characterized by a coarsening-upward trend from mainly silt to medium grained sand. In the silts and mudstones above intensive bioturbation and abundant and diverse phytoplankton indicate an increase of marine influence almost to the base of Seam 6. Thick, flat-lying root branches immediately underlying Seam 6 show that its formation was initiated by tall mire forest growth on a marine substrate.

The facies change observed in Seam 5 is repeated in Seam 6 but more pronounced. Blocky lignite makes up the lower 1 m, but the remaining 3 m of the seam consist mostly of thin-bedded to laminated lignite. There, bedding planes are commonly covered with small particles of charcoal (Pl. 1e, f) suggesting high frequency of wild fires sustained by a largely herbaceous vegetation as indicated by the abundance of *Sphagnum* and fern spores and pollen of Restionaceae and Ericaceae.

Above Seam 6 interbeds are more sand dominated, thicker and lighter in colour along with an intermittent increase of fluvial influence. At first, tidal sedimentation resumes immediately following Seam 6 as indicated by flaser and ripple bedding and thin vertical bioturbation tubes. Higher up about 5 m of light coloured to white sands with grain sizes from medium grain to fine gravel and large scale cross-bedding appear to fill a broad depression and mark a general change to shoreline sedimentation and proximity to fluvial input.

A thin seam (up to 17 cm) with eroded top has proved to be traceable over much of the mine and was added later as a regular coal seam horizon (L-Seam) to the numbered seams. Palynologically it is fingerprinted by the exceptional frequency of *Milfordia* (Restionaceae) which has been identified as a brackish marsh element at Helmstedt (Lenz, 2005).

Medium to coarse grained sands alternating with clay/silt flasers, clay drapes and laminae continue up to Seam 7 over a thickness of almost 9 m in a more or less cyclic succession. Throughout, these sands are bioturbated with varying intensity by thin mostly vertical tubes. Typical *Ophiomorpha* type tubes appear in the upper part of Interbed 7 for the first time (Pl. 2c). Another characteristic of these sands is what is tentatively termed here as "clastic hardgrounds", i.e. very intensely bioturbated surfaces marked by changes in colour and grain size (Pl. 2d).

Seam 7 is only about 0,5 m thick, rather impure, and bioturbated at its top. In sharp contrast to Seam 6 palynological residues are devoid of charcoal particles. The seam is sandwiched between medium to coarse grained sands which are intensely rooted below and bear *Ophiomorpha* tubes above.

Most of the Interbed 8 is made up of five coarsening-upward cycles each of which is 1 to 3 m thick and ranges from bedded dark silty clays to massive coarse grained sands which are in part *Ophiomorpha* bearing. The tops of sands often show rooting below layers of dark silty clays suggesting terrestrialization at the end of each cycle of sediment aggradation.

Seam 8 reaches more than 1m in thickness. It gradually develops from dark silty clays with only fine rooting at its base suggesting that it originated from gradual terrestrialization of an open water body rather than by paludification of an exposed surface as most seams at Schöningen. Palynological residues proved to be devoid of charcoal although charcoal has been recorded megascopically in a few layers.

Light coloured silts and fine sands at the base of Interbed 9

Figure 4: Overview of the highwall at the centre of mine Schöningen Südfeld showing the entire Paleogene section as exposed in fall 2007 (MS – Main Seam, S1 to S9 – Seam 1 to Seam 9 according to Fig. 2).

may be interpreted as overbank, splay or levee deposist of meandering fluvial channels which have been observed to cut deep into Seam 8 and Interbed 8 locally. Most of the interbed above is made up of grey to brown mudstones closely interbedded with thin layers, lenses and laminae of light coloured silts and fine sands. There, bioturbation is rather reduced and phytoplankton represented by *Botryococcus* and freshwater dinoflagellates. Thus, Interbed 9, the stratigraphic position in which the marine Emmerstedt Formation should be expected (Lietzow and Ritzkowski, 2005), is indeed the least marine interbed of the entire section. The Emmerstedt Formation is, therefore, considered to be either missing or replaced by Interbed 9 of the Schöningen Formation.

Towards the top Interbed 9 grades into well sorted and fine grained light coloured to white sands which are densely bioturbated by thin vertical tubes in the lower part and include several horizons with conspicuous palm stumps higher up (Pl. 2g, h).

4.3 Helmstedt Formation

Seam 9 consists of several splits at Schöningen Südfeld which are equivalent to the lower seam at former mine Alversdorf (Wintgen, 1991; Natge-Efoghe, 1997) and sandwiched between light coloured large scale cross-bedded sands. The lignite consists mainly of dark organic matrix containing sizeable trunks of wood in some layers (Wintgen, 1991). Seam 9 includes the last regular occurrence of *Thomsonipollis magnificus* (Pl. 1i), which is even abundant at the base of the seam (Schiemann, 1994) in analogy to several seams of the Schöningen Formation. Stratigraphically it is separated from Seam Viktoria only by an interbed of 3 to 8 m and therefore added to the Helmstedt Formation. Although it is considered to be older than the Wulfersdorf Seams at Helmstedt mainly on basis of *T. magnificus* (Lenz, 2005), it is tentatively placed into the Middle Eocene because of a general increase in thermophilic elements.

4.4 Summarizing remarks

In summary, considering the number of factors acting on sedimentation and biota the succession exposed in Schöningen Südfeld (Figs. 3, 4) appears remarkably conformable and homogeneous reflecting rather stable conditions over a period of more than 6 million years. Long term changes only range from marginal marine to more shoreline and terrestrial sedimentation. Tidal sediment features, intensive bioturbation, changing marine and freshwater conditions and the regional palaeogeography are highly compatible with an estuarine environment. No major extinctions nor innovations can be observed in the flora except for a slight increase of thermophilic and a corresponding decrease of temperate elements.

5. Selected aspects

Several aspects which came up during field observations and palynological investigations deserve further discussion since they have considerable bearing on climatic and environmental interpretations concerning the Early Eocene.

5.1 *Apectodinium* acme

There are two major changes in phytoplankton development within the Schöningen section: a replacement of the mostly marine phytoplankton assemblages by freshwater phytoplankton, mainly *Botryococcus* and freshwater dinocysts (cf. *Geiselodinium*), towards the top of the Schöningen Formation (Interbed 9) and a dramatic increase of *Apectodinium* in Interbed 2. About 30 to 40 cm above Seam 1 *Apectodinium* suddenly rises from near zero to about one third of the total palynomorph assemblage and essentially maintains this level to the very base of Seam 2. *Apectodinium* makes up 68.3 to 100% of all dinocysts in this interval and forms a rather homogeneous population which is tentatively assigned to *A. homomorphum* (Pl. 2f). Rare specimens of *Glaphyrocysta* have been observed and juvenile stages of *Thalassiphora* (Gocht, 1968) are a regular component near the top of Interbed 2. Although *Apectodinium augustum*, considered to be a key species, has not been identified yet, the peak abundance of *Apectodinium* in this interval fulfils most of the criteria commonly used to identify an *Apectodinium*-acme in many sections at the Paleocene-Eocene boundary around the world (Crouch et al., 2001, 2003; Sluijs et al., 2005). We, therefore, consider the peak abundance of Apectodinium in Interbed 2 as the *Apectodinium* acme following the Paleocene-Eocene Thermal Maximum. Thus, the Paleocene-Eocene (Thanetian-Ypresian) boundary is expected to be somewhere near the top of Seam 1 which is only slightly higher than the earliest Eocene age determined for Interbed 1 just above the Main Seam on the basis of the dinocyst zonation (Köthe, 2003; Ahrendt et al., 1995).

It is important to note that *Apectodinium* is rare above Seam 2 which represents a time interval of about 20 kyr according to conservative estimates of peat accumulation and compaction. *Apectodinium* remains at low frequency levels until a new brief increase just below Seam 6 where it reaches about 37% of the total palynomorph assemblage and is associated with a greater diversity of other dinocysts, such as *Wetzeliella* spp., *Homotryblium* sp., *Spiniferites* sp. and various as yet unidentified gonyaulacoid forms.

Significantly, a major change in terrestrial vegetation as reflected by pollen and spores has not been recorded in connection with the *Apectodinium*-acme at Schöningen except for a general increase in inaperturate pollen which is consistent with observations from southern England (Cobham; Collinson et al., 2009) and the North Sea (Kender et al., 2011). Other taxa such as *Plicapollis pseudoexcelsus* used to identify floral changes forced by the PETM have proved to be strictly ecotonal elements in marine/terrestrial successions at Schöningen.

5.2 Marine-terrestrial interaction

Since shelly faunas are totally missing the degree of marine influence in the interbeds has to be inferred mainly from the type and degree of bioturbation (Pl. 2a-d) and the proportion of marine versus freshwater phytoplankton. Marine phytoplankton is represented by a variety of dinocysts including the somewhat restricted marine *Apectodinium* group and prasinophycean phycomata. Freshwater phytoplankton consists mainly of *Botryococcus*. Freshwater dinocysts appear to be restricted to some horizons in interbed 9 and zygospores of Zygnemataceae (*Tetraporina*) are very rare, but occur in different levels of our section. Unequivocal evidence of terrestrial conditions are root horizons and coal seams. Transitional environments are indicated by specific pollen/spore assemblages restricted to interbed/lignite seam interfaces in part associated with marine phytoplankton and sporadic elements of true mangrove.

5.3. Mangroves

The history of individual extant mangrove taxa may be traced back into the Upper Cretaceous. But complex zoned mangrove associations which are comparable to those known today have not been recognized before the Eocene (Greb et al., 2006; Plaziat et al., 2001). Their probably northernmost advance followed in the wake of the Eocene greenhouse phase and was reconstructed on the basis of pollen assemblages from

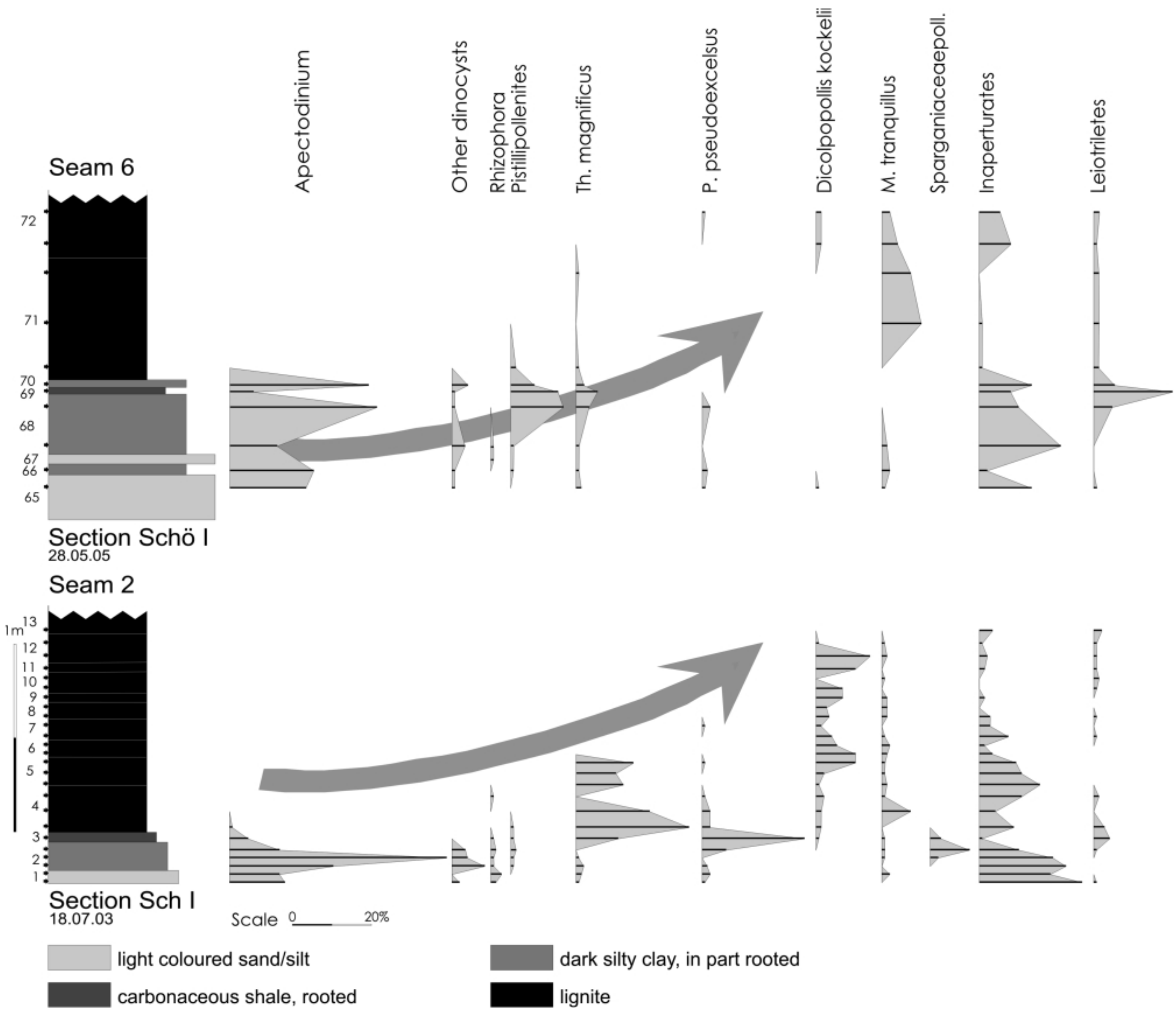

Figure 5: Palynomorph spectrum of the basal parts of Seams 2 and 6 showing successions (arrows) at marine terrestrial interfaces typical for the early Eocene Schöningen Formation.

the Wulfersdorf seams in the former Helmstedt open cast mine (Helmstedt Formation, early Middle Eocene, Lutetian; Lenz and Riegel, 2001; Lenz, 2005; Riegel et al., 2011). There, above marine beds, pollen of *Rhizophora*, *Avicennia* and *Nypa* occur at the base of several seams in this order of succession together with *Psilodiporites iszkaszentgyoergyi*, then a close associate (Frederiksen et al., 1985; Lenz, 2005) of mangrove elements. This compares closely with mangroves of the Indo-Malayan region, in particular the Gulf of Bengal (Blasco, 1977). Since *Nypa* is considered as the only fully tropical element (Mai, 1995), its presence at Helmstedt gives a clear signal of a humid tropical climate for the early Middle Eocene along the southern shore of the North Sea in Central Europe.

In contrast to the Helmstedt Formation pollen of true mangrove elements are exceedingly rare or entirely missing in the Schöningen Formation of Schöningen Südfeld. There, interbed/lignite transitions have been studied at high resolution from two major seams, Seam 6 and Seam 2 (fig. 5), which clearly rest on marine sediments with diverse dinocyst assemblages and intensely bioturbated tidal sediments. In either case, pollen of true mangrove elements is missing except for rare occurrences of *Rhizophora* (*Zonocostides ramonae*). Instead, *Pistillipollenites mcgregorii* (Pl. 1g), *Thomsonipollis magnificus* (Pl. 1i) and palm pollen of the *Monocolpopollenites tranquillus* type have been recognized in successive peaks at the base of Seam 6 along with the total decline of marine phytoplankton. According to *in situ* pollen which has been found in some Paleogene flowers, Gentianaceae or Euphorbiaceae have been suggested as potential source plants for *Pistillipollenites mcgregorii* (Crepet and Daghlian, 1981; Stockey and Manchester, 1988), The source of *Thomsonipollis magnificus* is still unknown, while *Monocolpopollenites tranquillus* has been assigned to phoenicoid palms (Thomson and Pflug, 1953; Thiele-Pfeiffer, 1988) which may occur in association with back mangrove environments (Tomlinson, 1986). But, affinities of *M. tranquillus* should be treated with caution (Nichols et al., 1973; Harley and Morley, 1995; Harley, 2006).

A variant of this occurs at the base of Seam 2. There, following peak abundances of dinocysts, especially *Apectodinium*, at the top of Interbed 2, peaks of *Sparganiaceaepollenites*, *Plicapollis pseudoexcelsus*, *Thomsonipollis magnificus* and *Dicolpopollis kockeli* occur in this order and in close succession within the basal 50 cm of Seam 2. Again, true mangrove pollen is restricted to rare appearances of *Zonocostides ramonae*. Very unexpected is the early appearance of *Sparganiaceaepollenites* (Pl. 10h), since modern sources of this pollen type, Sparganiaceae and Typhaceae, are regarded as typical freshwater plants (e.g. Cook et al., 1974), but *Typha* may also occur in brackish marshes (e.g. Godfrey and Wooten, 1979). *P. pseudoexcelsus*, second in this order, has been recorded as a back mangrove element in the Middle Eocene Helmstedt Formation (Lenz and Riegel, 2001; Lenz, 2005; Wilde et al., 2008). *Pistillipollenites mcgregorii* is rather reduced, but, as in Seam 6, precedes the occurrence of *Thomsonipollis magnificus*.

Since the sedimentary facies of the Middle Eocene at Helmstedt is nearly identical to that of Seams 2 and 6 of the Early Eocene at Schöningen Südfeld the absence of true mangrove at Schöningen has significant bearing on climatic interpretations. In particular, the total absence of *Nypa* as the most tropical mangrove element together with its close associate *P. iszkaszentgyoergyi* and the only sporadic occurrences of *Rhizophora* and, questionably, of *Avicennia* pollen as the more temperature tolerant representatives indicate extratropical conditions for the Early Eocene of Schöningen with temperatures which were definitely cooler than in the Middle Eocene of the region. This is substantiated by the near absence of other tropical elements such as Sapotaceae and the greater frequency of temperate elements such as *Alnipollenites* at Schöningen.

5.4 Seagrass meadows

In the light coloured fine to medium grained sands of Interbed 5 remains of herbaceous plants with extensive radiating rooting systems have been found buried in-situ at some depth below the seam (pl. 2e). Based on the habit and mode of growth these plants have been tentatively identified as seagrasses. Among modern seagrasses intense rooting systems such as those observed at Schöningen are especially known from *Posidonia* (e.g. Kuo and den Hartog, 2006; Hogarth, 2007). Today, seagrasses are known to be important in trapping sediment and stabilizing sediment surfaces against erosion thus affecting sea floor topography (e.g. Hertweck, 1978, Clairefond and Jeudy de Grissac, 1979, Wanless, 1981; Garcia and Duarte, 2001; Kendrick et al., 2005). Accordingly, the mound-like structures around tufts of shoots are the result of enhanced sediment accumulation. Erosional surfaces around the plants (Pl. 2e) indicate that scouring by currents was controlled by the growth of the seagrasses. Apparently, the emergent shoots of individual plants were eroded repeatedly and began to regrow afterwards. The fossil seagrasses observed in Interbed 5 are limited to a certain package of sand with a thickness of about 2 m which is part of a shallowing-upward sequence. The sands below do not show rooting, but the clays and clayey silts above are intensely rooted toward the top by thick root branches and served as the soil for the woody vegetation of the overlying Seam 5. The limitation of the seagrasses in Interbed 5 indicates that their growth was restricted to a certain water depth of a few meters similar to that of their modern counterpart such as *Posidonia* which may reach considerable depth (e.g. Duarte, 1991; Gobert et al., 2006), but forms climax communities between 30 m and 1 m (den Hartog, 1977); in turbid waters such as those to be expected at Schöningen from the sedimentary context, the lower limit of *Posidonia* is less than 10 m (Gobert et al., 2006).

Modern seagrass meadows act as important “carbonate factories” serving as substrates and habitat for a wealth of carbonate producing organisms (e.g. Brasier, 1975; Hertweck, 1978; Ivany et al., 1990). However, due to the highly acidic early diagenetic environment all carbonate has been completely removed at Schöningen in contrast to other examples (e.g. the Pliocene of Rhodes; Moissette et al., 2007). Thus, although no remains of carbonate producing organisms have been found between the seagrasses they may be considered as indirect evidence of former carbonate production. Palynological residues have abundant *Tricolpopollenites liblarensis* and peridermal cells both of which are introduced from external sources. But the presence of *Apectodinium* confirms at least marginal marine conditions.

5.5 Palm beach

Well sorted fine grained white sands below Seam 9 are characterized by conspicuous monocotyledonous stumps preserved in-situ and arranged in several succeeding horizons (Pl. 2g, h). Although no anatomical details are preserved, it is clear from the kind of anchoring roots and from the general pattern of internal structures in cross section that they represent stumps of palms. Since the palm stump horizons are found in a transitional position between barren sands densely bioturbated by a distinct type of vertical burrows and a lower split of Seam 9 they may be envisaged as having colonized the sand beach of the estuary strongly reminiscent of modern palm studded sandy beaches of the tropics. As may be expected from well sorted sands pollen is relatively rare, but the few spectra known thus far indicate the common pollen influx from hardwood mire forests with a dominance of *Tricolporopollenites cingulum* or *Triporopollenites robustus*, respectively, and only slightly raised values of palm pollen.

5.6 Fire regime

Type and distribution of charcoal allow us to distinguish at least three different fire regimes with significant climatic implications succeeding respectively alternating within the Early Eocene at Schöningen. In the lower three seams charcoal occurs in discrete layers or lenses up to 1 cm or even more in thickness (Pl. 1c). They are mainly made up of chunks of charcoal several millimetre to a few centimetre in size and showing a distinctly coniferous wood structure (Pl. 1d). Only rare examples of angiosperm wood have been observed in coal petrographic sections. Charcoal layers are intimately associated with an abundance of *Sphagnum* and/or fern spores which we interpret as originating from a pioneering vegetation in forest clearings following wild fires.

Major portions of Seam 5 and particularly Seam 6 are thin bedded to laminated and bedding planes are mostly covered with minute particles of charcoal (Pl. 1e). Associated palynomorph assemblages show a notable increase in herbaceous elements, i.e. *Sphagnum* (*Stereisporites*), fern spores, and pollen of Ericaceae and Restionaceae indicating a herb dominated peat forming vegetation which is supported by tiny fragments of charred non-woody tissues (Pl. 1f). The laminated lithotypes of Seam 6 bear a striking similarity with the laminated lignite of the Cobham Lignite Bed near the Paleocene-Eocene boundary in southern England (Collinson et al., 2007, 2009). But the two clearly differ in age and species composition since the dominant fern spore species (*Cicatricosisporites*) at Cobham is entirely missing in Seam 6.

Thus far, no or very little charcoal has been observed in Seam 4 and in Seams 7 to 9. This corresponds with the complete lack of charcoal registered in all seams of the Middle Eocene Helmstedt Formation (Bode, 1994; Riegel et al., 1999) and sharply contrasts with the abundance of charcoal in the other seams of the Schöningen Formation. The striking lack of charcoal has been interpreted by Riegel et al. (1999) as indicating highly perhumid conditions preventing the flammability of forest litter (Goldammer, 1993). Besides, the charcoal free lignites of the Middle Eocene and parts of the Lower Eocene consist almost entirely of finely detrital organic matrix with little or no tissue preservation probably due to the particularly intensive biodegradation of plant litter under a perhumid climate.

Our charcoal record suggests that an alternating wet/dry climate predominated during most of the Ypresian in Central Europe with a low frequency fire regime in the beginning (Main Seam, Seam 1 and 2) and a high frequency fire regime later (Seam 5 and 6). The corresponding change in type of charcoal from woody to herbaceous is in accordance with obser-

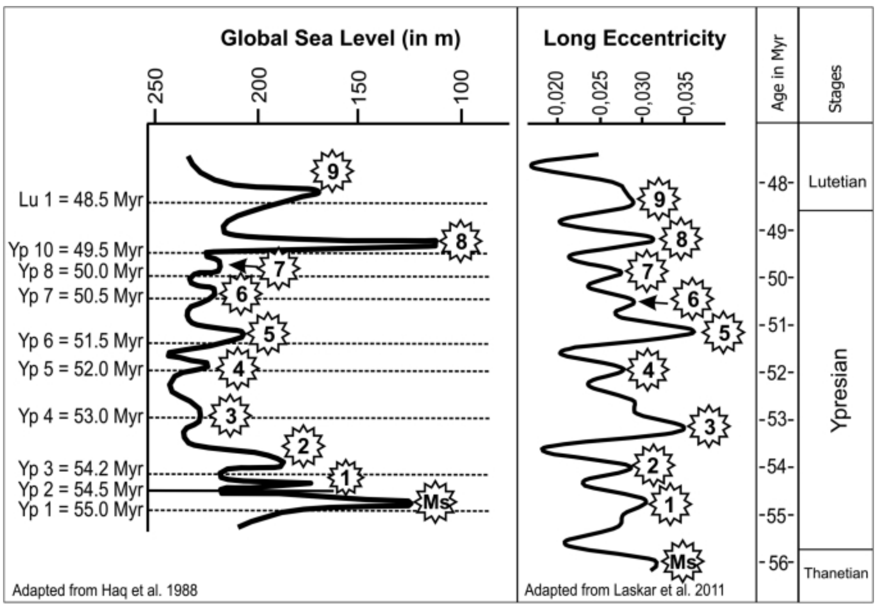

Figure 6: Comparison of the global sea level curve (Haq et al., 1988) and the filtered long eccentricity of Laskar et al. (2011; La2010a solution) with putative correlation to seams in the Schöningen Südfeld section. Age discrepancies between calculated eccentricity maxima and sea level peaks may be due to the underlying database.

vations from modern environments that woody vegetation favours lower to rare fire frequencies whereas frequent fires tend to promote herbaceous vegetation (Mueller-Dombois and Goldammer, 1990; Heisler et al., 2004).

This fire regime pattern is interrupted, however, by the largely charcoal-free intervals around Seam 4 and Seams 7 and 8, the latter leading to the persistent perhumid conditions of the Middle Eocene. These charcoal-free intervals within the Schöningen Formation are also associated with a remarkable increase of paratropical to tropical elements such as palm pollen, particularly around Seam 4, and the regular occurrence of pollen of Sapotaceae, thus, supporting a general warming trend in connection with perhumid conditions towards the Middle Eocene and a possible intermittent warm spell at the level of Seam 4.

The fire regime pattern of the lower part of the Schöningen Formation lends some support for the seasonally wet/dry climate assumed for the PETM at the Wilson Lake section, New Jersey, USA (Zachos et al., 2006), but a SST of 33° C for a nearshore marine site at a similar midlatitude is hardly compatible with our palynological data. A strongly seasonal climate is implied by extremely well expressed growth rings in gymnosperm charcoal from the Main Seam at Schöningen (Pl. 1d).

5.7 Sphagnum

Spores generally assigned to the peat moss *Sphagnum* (*Stereisporites*) are ubiquitous throughout the Schöningen Formation and even dominate palynological assemblages in certain layers, particularly in those associated with charcoal. Among the various form species assignable to *Sphagnum*, *Stereisporites triancorae* seems to be the most common, but differs markedly from all known modern *Sphagnum* spores. It is important, therefore, that in a thin seam within Interbed 4 with abundant *S. triancorae* slightly charred remnants of *Sphagnum* leaves showing the typical water storage cells were found. Furthermore, the association of *Sphagnum* spores with pollen of Ericaceae, Restionaceae and various fern spores is more reminiscent of modern ombrogenous mires of temperate rather than tropical climates. In addition, the occurrence of the *Sphagnum* bearing seam amidst the mainly marine clastic Interbed 3 demonstrates phases of at least local emergence within the estuary.

The frequent occurrence of *Sphagnum* spores in association with pollen of Ericaceae has repeatedly been noted in Paleocene to lower Eocene coals of Texas and Wyoming (Nichols and Traverse, 1971; Nichols and Pocknall, 1994; Nichols, 1995) suggesting that temperate type ombrogenous mires were already widespread in the early Paleogene.

5.8 Thermophilic versus temperate floral elements

Additional information on the regional climate development during the Early Eocene is available from the distribution of certain thermophilic and more commonly temperate elements in pollen assemblages. *Monocolpopollenites tranquillus*, the major representative of palms, is rare mostly with less than 1% in the lower part of the section up to Interbed 6. Seam 4, however, is a striking exception with peak abundances of more than 20%. From Seam 6 upward *M. tranquillus* maintains a constant level between 2% and 4%.

Sapotaceae, a family of tropical trees, is represented by *Tetracolporopollenites* spp. and exceedingly rare in the lower part of the section. From the Main Seam to Seam 2 it has been recorded in only 20% of all samples with 1 or 2 specimens. In Interbed 9 and Seam 9 it occurs regularly with a few percent of total pollen, thus indicating a transition to the Middle Eocene Helmstedt Formation where *Tetracolporopollenites* spp. is a regular and important element of mire forest associations (Lenz, 2005).

On the other hand pollen of the temperate *Alnus* (*Trivestibulopollenites verus*) occurs rather regularly in the lower part of the section and occasionally reaches even up to 3 to 5% in Interbed 1 and Seam 1 (Hammer-Schiemann, 1998; own observations W.R.). It is very rare further up and has not been recorded above Seam 8 nor in the Middle Eocene Helmstedt Formation (Lenz, 2005).

6. Discussion and conclusions

With few exceptions (Collinson et al., 2007, 2009) most studies of the climate and biota of the Early Paleogene are based on fully marine or entirely continental sections. Despite some uncertainties in detailed correlation the 170 m thick section of the Schöningen Südfeld opencast mine spans the entire Early Eocene from the latest Paleocene to the earliest Middle Eocene and bridges the gap between the marine and terrestrial realm by numerous alternations of coal seams and more or less marine clastic interbeds. It seemed appropriate and timely, therefore, to present and describe a generalized section which may serve as a standard for this type of facies and palaeogeographic context and to give an update on our current knowledge of biotic proxies relevant to environment and climate of the Early Eocene.

During the 6 to 8 myr represented by the section long term facies changes are limited to minor shifts from predominantly tidal sedimentation to shoreline deposits and intermittent fluvial influence. Except for some tidal and fluvial channels there are no obvious unconformities in the section, but since coal formation required only a minute fraction (about 1/40) of the time represented by the section, numerous condensations, hiatuses and minor discontinuities are expected to be included in the interbeds. Some of these are indicated by clastic hardgrounds and bioturbated seam tops.

To remove previous uncertainties about the nomenclature and formation boundaries a formal definition of the Schöningen Formation is given on the basis of our lithologic description using the base of the Main Seam and the base of Seam 9 as the base respectively top of the Schöningen Formation which succeeds the Waseberg Formation and is overlain by the Helmstedt Formation.

The Thanetian-Ypresian stage boundary (Paleocene/Eocene boundary) is tentatively placed at the top of Seam 1 being constrained by the approximate position of dinocyst zone D5b and the apparent *Apectodinium*-acme in Interbed 2. The Ypresian-Lutetian boundary (Lower/Middle Eocene boundary) is projected from somewhat northern localities into our section at approximately the base of the Helmstedt Formation.

Pollen and spore assemblages are remarkably uniform throughout the section. There are no striking innovations nor extinctions despite the numerous hyperthermal events proposed on the basis of marine isotope records. The only exception is the sudden increase of palm pollen (*Monocolpollenites tranquillus*) in Seam 4 at about the middle of the Schöningen Formation, possibly linked to the Early Eocene Climatic Optimum (EECO). However, no recognizable response of the terrestrial vegetation can be associated with the *Apectodinium*-acme in Interbed 2. Long term vegetation changes involve a decrease in inaperturate (mostly taxodiaceous) pollen and temperate elements and a gradual increase of thermophilic elements in the upper part of the Schöningen Formation. Significant quantitative changes commonly occur at the base of coal seams and are strictly successional in response to hydrologic conditions at the transition from open estuary to peat mire.

In contrast to the tropical mangrove of the Middle Eocene these initial successions are characterized by a unique association of *Pistillipollenites* and *Thomsonipollis* together with certain ferns, palms and woody dicots (e.g. *Plicapollis pseudoexcelsus*) but essentially lacking elements of the typical mangrove.

Type and distribution of charcoal give a clear signal for changes in fire regime throughout the Schöningen Formation from a low frequency fire regime associated with woody vegetation to a high frequency fire regime under a herbaceous cover reflecting a wet/dry climate on a decadal respectively seasonal scale. An essentially fire free regime indicating perhumid conditions occurs intermittently (Seam 4) and toward the top of the Schöningen Formation.

In summary, evidence from palynology and charcoal suggest a wet/dry and warm temperate climate for most of the Lower Eocene in the area of Schöningen. This is in sharp contrast with more tropical perhumid conditions indicated for the Middle Eocene of Helmstedt (Lenz, 2005; Riegel et al., 1999). Only one thermal event can be recognized near the middle of the Schöningen Formation (Seam 4) and possibly related to the EECO. Other thermal events could not be detected in the palynological record, thus far.

Our results clearly suggest that in Central Europe the peak of the Paleogene greenhouse climate was in the Middle Eocene as previously expressed by palynologists working in central Germany (Pflug, 1986; Krutzsch, 1967, 2011) and not in the Early Eocene as inferred from marine isotope records. This is strongly supported by the absence of charcoal in other Middle Eocene localities of the region, such as the Geiseltal, Messel and Eckfeld (personal observations) and by palynological data from the Gulf Coast Region of North America. There, the occurrence of *Sphagnum* spores and Ericaceae pollen in parts of the coal bearing Paleocene/Eocene Wilcox Group (Nichols and Traverse, 1971; Nichols and Pocknall, 1994) contrasts with the mangrove biota with the tropical *Nypa* from the marginal marine Laredo Formation of the Middle Eocene (Westgate and Gee, 1990). Diversity of the tropical vegetation in South America also suggests a more humid climate towards the Middle Eocene (Jaramillo, 2002).

The discrepancy between marine isotope data and evidence from terrestrial vegetation may be explained either by a significant decoupling of the terrestrial climate from ocean temperatures or by misleading proxy records. In any case, we consider it quite conceivable that an equable perhumid climate has a more pervasive greenhouse effect on terrestrial vegetation than an alternating wet/dry climate with considerable temperature fluctuations.

The section of the Schöningen Formation consists of a more or less regular tenfold alternation of coal seams and interbeds. The filtered version of the most recent calculation of Laskar et al. (2011) for eccentricity clearly shows a significant peak in the latest Paleogene (about 56 Ma), 8 distinct peaks for the Ypresian and another peak at the base of the Lutetian (Fig. 6). Position and number of these peaks suggest a correlation with the succession of ten seams at Schöningen Südfeld. Furthermore, the sea level curve of Haq et al. (1988) also shows eight peaks for the Ypresian (Fig. 6). Considerable uncertainties still exist, however, in ranking minor coal seams and root horizons, especially in the upper part of the section, within a sequence stratigraphic scheme to confirm any potential relationship between our succession, eccentricity and the sea level curve. Besides, underlying processes and controls and their various effects on facies and environment are not well understood yet and require further study.

Acknowledgements

The authors are particularly grateful to the mine management of E-on, formerly Braunschweigische Kohlebergwerke, Helmstedt and Schöningen, for liberally giving permission to enter the mine over many years and allowing access to the outcrops under study. Technical support has also been granted whenever needed and readily carried out by helpful miners. Karin Schmidt (Forschungsinstitut und Naturmuseum Senckenberg, Frankfurt am Main) has been a thoughtful and reliable assistant in the field and a great help in securing samples and plant material. Alan Lord (London/Frankfurt am Main) kindly checked the manuscript for language and consistency. Two anonymous reviewers finally helped improving the manuscript.

References

Ahrendt, H., Köthe, A., Lietzow, A., Marheine, D. and Ritzkowski, S., 1995. Lithostratigraphie, Biostratigraphie und radiometrische Datierungen des Unter-Eozän von Helmstedt (SE-Niedersachsen). Zeitschrift der deutschen geologischen Gesellschaft, 146, 450-457.

Anderson, H.-J., 1990. A molluscan fauna of the Annenberg beds (Middle Eocene) from the openminecast "Treue" near Helmstedt (Lower Saxony, FRG). Veröffentlichungen aus dem Übersee-Museum Bremen Reihe A, 10, 1-2.

Barth, 1892. Beiträge zur Geologie von Helmstedt. Zeitschrift für Naturwissenschaften, 65, 107-131.

Blasco, F., 1977. Outlines of ecology, botany and forestry of the mangals of the Indian subcontinent. In: V.J. Chapman (ed.). Ecosystems of the world. Vol.1. Wet coastal ecosystems. Elsevier, Amsterdam, pp. 241-260.

Blumenstengel, H. and Krutzsch, W., 2008. Tertiär. In: G.H Bachmann, B.-C. Ehling, R. Eichner and M. Schwab (eds.). Geologie von Sachsen-Anhalt. E. Schweizerbart´sche Verlagsbuchhandlung, Stuttgart, pp. 267-292.

Bode, T., 1994. Untersuchungen zur Fazies und Genese der eozänen Helmstedter Braunkohlen im unteren Teil der Oberflözgruppe im Tagebau Helmstedt (Bezirk Braunschweig). Diploma Thesis (unpublished), University of Göttingen, 95 pp.

Bowen, G.J., Beerling, D.J., Koch, P.L., Zachos, J.C. and Quattlebaum, T., 2004. A humid climate state during the Palaeocene/Eocene thermal maximum. Nature, 432, 495-499.

Bowen, G.J. and Zachos, J.C., 2010. Rapid carbon sequestration at the termination of the Paleocene-Eocene Thermal Maximum. Nature Geoscience, 3, 866-869.

Bralower, T.J., Zachos, J.C., Thomas, E., Parrow, M., Paull, C.K., Kelly, D.C., Premoli Silva, I., Sliter, W.V. and Lohmann, K.C., 1995. Late Paleocene to Eocene paleooceanography of the equatorial Pacific Ocean: stable isotopes recorded at Ocean Drilling Program Site 865, Allison Guyot. Paleooceanography, 10, 841-865.

Brandes, C., Pollok, L., Schmidt, C., Wilde, V. and Winsemann, J., 2012. Basin modelling of a lignite-bearing salt rim syncline: insights into rim syncline evolution and salt diapirism in NW Germany. Basin Research, 24. doi: 10.1111/j.1365-2117.2012.00544x

Brasier, M.D., 1975. An outline history of seagrass communities. Palaeontology, 18, 681-702.

Clairefond, P. and Jeudy de Grissac, A., 1979. Description et analyse de structures sédimentaire en milieu marin: recensement de quelques exemples dans l'herbier de Posidonies autour de l'ile de Port Cros (Parc National). Travaux Scientifiques du Parc National de Port-Cros, 5, 79-104.

Collinson, M.E., Steart, D.C., Scott, A.C., Glasspool, I.J. and Hooker, J.J., 2007. Episodic fire, runoff and deposition at the Palaeocene-Eocene boundary. Journal of the Geological Society London, 164, 87-97.

Collinson, M.E., Steart, D.C., Harrington, G.J., Hooker, J.J., Scott, A.C., Allen, L.O., Glasspool, I.J. and Gibbons, S.J., 2009. Palynological evidence of vegetation dynamics in response to paleoenvironmental change across the onset of the Paleocene-Eocene Thermal Maximum at Cobham, Southern England. Grana, 48, 38-66.

Cook, C.D.K., Gut, B.J., Rix, E.M., Schneller, J. and Seitz, M., 1974. Water plants of the world. A manual for the identification of the genera of freshwater plants. W. Junk, The Hague, 561 pp.

Crepet, W.L. and Daghlian, C.P., 1981. Lower Eocene and Paleocene Gentianaceae: floral and palynological evidence. Science, 214, 75-77.

Crouch, E.M., Heilmann-Clausen, C., Brinkhuis, H., Morgans, H.E.G., Rogers, K.M., Egger, H. and Schmitz, B., 2001. Global dinoflagellate event associated with the late Paleocene thermal maximum. Geology, 29, 315-318.

Crouch, .M., Dickens, G.R., Brinkhuis, H., Aubry, M.-P., Hollis, C.J., Rogers, K.M. and Visscher, H., 2003. The Apectodinium acme and terrestrial discharge during the Paleocene-Eocene thermal maximum: new palynological, geochemical and calcareous nannoplankton observations at Taiwanui, New Zealand. Palaeogeography, Palaeoclimatology, Palaeoecology, 194, 387-403.

den Hartog, C., 1977. Structure, function, and classification in seagrass communities. In: C.P. McRoy and C. Helfferich (eds.). Seagrass ecosystems, a scientific perspective. Marine Science, 4, 89-121.

Dickens, G.R., Castillo, M.M. and Walker, J.C.G., 1997. A blast of gas in the latest Paleocene; simulating first-order effects of massive dissociation of oceanic methane hyrates. Geology, 25, 259-262.

Dienemann, W., 1926. Beiträge zur Stratigraphie und Tektonik der Helmstedter Braunkohlenmulde. Jahrbuch der Preußischen Geologischen Landesanstalt zu Berlin 44 (1925), 108-123.

Dorstewitz, R., 1902. Geologische Beschreibung der Helmstedter Braunkohlenmulde. Braunkohle, 1, 195-200, 208-212, 224-227.

Duarte, C.M., 1991. Seagrass depth limits. Aquatic Botany, 40, 363-377.

Frederiksen, N.O., Wiggins, V.D., Ferguson, I.D., Dransfield, J. and Ager, C.M., 1985. Distribution, paleoecology, paleoclimatology, and botanical affinity of the Eocene pollen genus *Diporoconia* n. gen. Palynology, 9, 37-60.

Garcia, E. and Duarte, C.M., 2001. Sediment retention by a Mediterranean *Posidonia oceanica* meadow: the balance between deposition and resuspension. Estuarine, Coastal and Shelf Science, 52, 505-514.

Gingerich, P.D., 2003. Mammalian responses to climate changeat the Paleocene-Eocene boundary: Polecat Bench record in the northern Bighorn Basin, Wyoming. In: S.L. Wing, P.D. Gingerich, B. Schmitz and E. Thomas (eds.). Causes and consequences of globally warm climates in the early Paleogene. Geological Society of America, Special Paper, 369, 463-478.

Gobert, S., Cambridge, M.L., Velimirov, B., Pergent, G., Lepoint, G., Bouquegneau, J.-M., Dauby, P., Pergent-Martini, C. and Walker, D.I., 2006. Biology of *Posidonia*. In: A.W.D., Larkum, R.J., Orth and C.M., Duarte (eds). Seagrasses: biology, ecology and conservation. Springer, Dordrecht, pp. 387-407.

Gocht, H. 1968. Zur Morphologie und Ontogenie von *Thalassiphora* (Dinoflagellata). Palaeontographica A, 129, 149-156.

Godfrey, R.K. and Wooten, J.W., 1979. Aquatic and wetland plants of the southeastern United States, Monocotyledons. The University of Georgia Press, Athens, 712 pp.

Goldammer, J.G., 1993. Feuer in Waldökosystemen der Tropen und Subtropen. Birkhäuser Verlag, Basel, Boston, Berlin, 251 pp.

Gramann, F., Harre, W., Kreuzer, H., Look, E.-R. and Mattiat, B., 1975. K-Ar ages of Eocene to Oligocene glauconitic sands from Helmstedt and Lehrte (Northwestern Germany). Newsletter on Stratigraphy, 4, 71-86.

Greb, S.F., DiMichele, W.A. and Gastaldo, R.A., 2006. Evolution and importance of wetlands in earth history. Geological Society of America Special Paper, 399, 1-40.

Gürs, K., 2005. Das Tertiär Nordwestdeutschlands in der Stratigraphischen Tabelle von Deutschland 2002. Newsletter of Stratigraphy, 41, 313-322.

Gürs, K., Lietzow, A. and Ritzkowski, S., 2002. Tertiär, Nordwestdeutschland. In: Stratigraphische Kommission von Deutschland (ed.). Stratigraphische Tabelle von Deutschland 2002, Potsdam.

Hammer-Schiemann, G., 1998. Palynologische Untersuchungen zur Fazies und Ökologie der Unterflözgruppe im Tagebau Schöningen (Untereozän, Helmstedt, Bez. Braunschweig). PhD Thesis, University of Göttingen, 107 pp.

Haq, B.U., Hardenbol, J. and Vail, P.R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In: C.K., Wilgus, B.S., Hastings, C.G.S.G., Kendall, H.W., Posamentier, C.A., Ross and Van Wagoner, J.C. (eds): Sea-level changes: an integrated approach. SEPM Special Publication, 42, 71-108.

Harbort, E., 1909. Beitrag zur Kenntnis präoligozäner und cretacischer Gebirgsstörungen in Braunschweig und Hannover. Monatsberichte der deutschen geologischen Gesellschaft, 1909, 381-391.

Harley, M.M., 2006. A summary of fossil records of Arecaceae. Botanical Journal of the Linnean Society, 151, 39-67.

Harley, M.M. and Morley, R.J., 1995. Ultrastructural studies of some fossil and extant palm pollen and the reconstruction of the biogeographical history of subtribes Iguarinae and Calaminae. Review of Palaeobotany and Palynology, 85, 153-182.

Harrington, G.J., 2001. Impact of Paleocene/Eocene greenhouse warming on North American paratropical forests. Palaios, 16, 266-278.

Harrington, G.J., 2008. Comparisons between Paleocene-Eocene paratropical swamp and marginal marine pollen floras from Alabama and Mississippi, USA. Palaeontology, 51, 611-622.

Heisler,J.L., Briggs, J.M., Knapp, A.K., Blair, J.M. and Seery, A., 2004. Direct and indirect effects of fire on shrub density and aboveground productivity in a mesic grassland. Ecology, 84, 2245-2257.

Hertweck, G., 1978. Lebensgemeinschaften und Sedimente der Secche della Meloria vor der Küste von Livorno (Italien). Beiträge zur Meerestechnik, 5, 191-214.

Hofmann, Ch.-Ch., Mohamed, O. and Egger, H., 2011. A new terrestrial palynoflora from Paleocene/Eocene boundary in the northwestern Tethyan realm (St. Pankraz, Austria). Review of Palaeobotany and Palynology, 166, 295-310.

Hogarth, P.J., 2007. The biology of mangroves and seagrasses. Oxford University Press, Oxford, 273 pp.

Ivany, L.C., Portell, R.W. and Jones, D.S., 1990. Animal-plant relationships and paleobiogeography of an Eocene seagrass community from Florida. Palaios, 5, 244-258.

Jaramillo, C., 2002. Responses of tropical vegetation to Paleogene warming. Paleobiology, 28, 222-243.

Jaramillo, C., 2011. PETM effects on Neotropical vegetation. Berichte der Geologischen Bundesanstalt, 85, 97.

Kender, S., Stephensen, M.H., Riding, J.B., Leng, M.J., Knox, R.W.O´B, Vane, C.H., Peck, V.L., Kendrick, C.P., Ellis, M.A. and Jamieson, R., 2011. Oceanographic, vegetation and climatic change at the Palaeocene-Eocene boundary in the North Sea region. Berichte der Geologischen Bundesanstalt, 85, 99.

Kendrick, G.A., Marbá, N. and Duarte, C.M., 2005. Modelling formation of complex topography by the seagrass Posidonia oceanica. Estuarine, Coastal and Shelf Science, 65, 717-725.

Kenneth, J.P. and Stott, L.D., 1991. Abrupt deep-sea warming, palaeoceanographic changes and benthic extinctions at the end of the Palaeocene. Nature, 353, 225-229.

Köthe, A., 2003. Dinozysten-Zonierung im Tertiär Norddeutschlands. Revue de Paléobiologie, 24, 895-923.

Köthe, A., 2009. Calcareous nannoplankton and dinoflagellate cysts Paleogene biostratigraphy of the Loburg I/90 cored borehole (Saxony-Anhalt, central Germany). Zeitschrift für geologische Wissenschaften, 37, 381-425.

Kraus, M.J. and Riggins, S., 2006. Transient drying during the Paleocene-Eocene Thermal Maximum (PETM): Analysis of paleosols in the Bighorn basin, Wyoming. Palaeogeography Palaeoclimatology Palaeoecology, 245, 444-461.

Krutzsch, W., 1967. Der Florenwechsel im Alttertiär Mitteleuropas aufgrund von sporenpaläontologischen Untersuchungen. Abhandlungen des zentralen geologischen Instituts Berlin, 10, 17-37.

Krutzsch, W., 2011. Stratigrafie und Klima des Paläogens im mitteldeutschen Ästuar im Vergleich zur marinen nördlichen Umrahmung mit einer stratigraphischen Tabelle. Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 162, 19-47.

Kuo, J. and den Hartog, C., 2006. Seagrass morphology, anatomy, and ultrasstructure. In: A.W.D., Larkum, R.J., Orth and C.M., Duarte (eds), Seagrasses: biology, ecology and conservation. Springer, Dordrecht, pp. 51-87.

Laskar, J., Fienga, A., Gastineau, M., and H. Manche, H., 2011. La2010. A new orbital solution for the long term motion of the Earth. Astronomy & Astrophysics manuscript no. La2010_v4 (arXiv:1103.1084v1 [astro-ph.EP] 5 Mar 2011).

Lenz, O.K., 2005. Palynologie und Paläoökologie eines Küstenmoores aus dem Mittleren Eozän Mitteleuropas – Die Wulfersdorf Flözgruppe aus dem Tagebau Helmstedt, Niedersachsen. Palaeontographica B, 271, 1-157.

Lenz, O.K. and Riegel, W., 2001. Isopollen maps as a tool for the reconstruction of a coastal swamp from the Middle Eocene at Helmstedt (Northern Germany). Facies, 45, 177-194.

Lietzow, A., 1991. Das Paläogen des Tagebaus Schöningen, Baufeld Esbeck bei Helmstedt (östliches Niedersachsen). Diploma Thesis (unpublished), University of Göttingen, 104 pp.

Lietzow, A. and Ritzkowski, S., 1993. RCNPS-RCNNS 4th biannual meeting Hannover 11.-15.10.1993, Teil 1, Exkursion Helmstedt area (unpublished fieldguide), pp. 1-16.

Lietzow, A. and Ritzkowski, S., 1996. Bergbau und die tertiäre Schichtenfolge. In: K. Cornelius, H. Elsner, A. Lietzow, S. Ritzkowski, H. Schütte and H. Thieme (eds.). Exkursion A 1. Braunschweigische Kohlenbergwerke AG, Tagebau Schöningen. 63. Tagung der Arbeitsgemeinschaft Nordwestdeutscher Geologen vom 28.-31.5. 1996 in Helmstedt (unpublished field guide), pp. 30-35.

Lietzow, A. and Ritzkowski, S., 2005. Das kontinentale Paläogen bei Helmstedt, südöstliches Niedersachsen. In: C.-H. Friedel and P. Balaske (eds.). Das Tertiär im mitteldeutschen Ästuar. Stand und aktuelle Probleme. Workshop, 25. November 2005, Halle/Saale. Exkursionsführer und Veröffentlichungen, Deutsche Gesellschaft für Geowissenschaften, 230, 20-22.

Linstow, O. von, 1907. Beiträge zur Geologie von Anhalt. Festschrift zum siebzigsten Geburtstag von Adolf v. Koenen. E. Schweizerbartsche Verlagsbuchhandlung, Stuttgart, pp. 19-24.

MacLennan, J. and Jones, S.M., 2006. Regional uplift, gas hydrate dissociation and the origins of the Paleocene-Eocene thermal maximum. Earth and Planetary Science Letters, 245, 65-80.

Mai, D.H., 1995. Tertiäre Vegetationsgeshichte Europas. Gustav Fischer Verlag, Jena, Stuttgart, New York, 691 pp.

Manger, G., 1952. Der Zusammenhang von Salztektonik und Braunkohlenbildung bei der Entstehung der Helmstedter Braunkohlenlagerstätten. Mitteilungen aus dem Geologischen Staatsinstitut in Hamburg, 21, 7-45.

Moisette, P., Koskeridou, E., Cornée, J.-J., Guillocheau, F. and Lécuyer, C., 2007. Spectacular preservation of seagrasses and seagrass-associated communities from the Pliocene of Rhodes, Greece. Palaios, 22, 200-211.

Mueller-Dombois,D. and Goldammer, J.G., 1990. Fire in tropical ecosystems and global environmental change: an introduction. In: J.G. Goldammer (ed.). Fire in the tropical biota: Ecosystem processes and global challenges. Ecological Studies, 84, 1-10.

Muller, J., 1959. Palynology of Recent Orinoco delta and shelf sediments: Reports of the Orinoco Shelf Expedition Micropaleontology, 5, 1-32.

Natge-Efoghe, C., 1997. Palynologische Untersuchungen am unteren Zwischenmittel im Tagebau Alversdorf, Mitteleozän, Helmstedter Oberflözgruppe. Diploma Thesis (unpublished), University of Göttingen, 182 pp.

Nichols, D.J., 1995. The role of palynology in paleoecological analyses of Tertiary coals. International Journal of Coal Geology, 28, 139-159.

Nichols, D.J., Amesh, T. and Traverse, A., 1973. On Arecipites Wodehouse, *Monocolpopollenites* Thomson and Pflug, and the species *Monocolpopollenites tranquillus*. Taxon, 22, 241-256.

Nichols, .J. and Pocknall, D.T., 1994. Relationships of palynofacies to coal-depositional environments in the upper Paleocene of the Gulf Coast Basin, Texas, and the Powder River Basin, Montana and Wyoming. In: A. Traverse (ed.), Sedimentation of organic particles, Cambridge University Press, Cambridge, New York, Melbourne, 217-237.

Nichols, D.J. and Traverse, A., 1971. Palynology, petrology, and depositional environments of some early Tertiary lignites in Texas. Geoscience and Man, 3, 37-48.

Pflug, H.D., 1952. Palynologie und Stratigraphie der eozänen Braunkohlen von Helmstedt. Paläontologische Zeitschrift, 26, 112-137.

Pflug, H.D., 1986. Palyno-Stratigraphie des Eozän/Oligozän im Raum von Helmstedt, in Nordhessen und im südlichen Anschlussbereich. In: H. Tobien (ed.), Nordwestdeutschland im Tertiär. Beiträge zur Regionalen Geologie der Erde, 18, Gebrüder Borntraeger, Berlin, Stuttgart, pp. 567-582.

Plaziat, J.-C., Cavagnetto, C., Koeniguer, J.-C. and Baltzer, F., 2001. History and biogeography of the mangrove ecosystem, based on a critical account of the paleontological record. Wetlands Ecology and Management, 9, 161-179.

Quitzow, H.W., 1948. Über die Altersbeziehungen zwischen der älteren Braunkohlenformation Mitteldeutschlands und dem marinen Eozän Norddeutschlands. Abhandlungen der geologischen Landesanstalt Berlin Neue Folge, 214, 21-27.

Riegel, W., Bode, T., Hammer, J., Hammer-Schiemann, G., Lenz, O. and Wilde, V., 1999. The paleoecology of the Lower and Middle Eocene at Helmstedt, northern Germany – A study in contrasts. Acta Palaeobotanica, Supplementum, 2, 349-358.

Riegel, W., Wilde, V. and Lenz, O.K., 2007. *Sphagnum* und Fusit als Proxies für Klima und Umwelt im Untereozän von Schöningen, Niedersachsen. In: O. Elicki and J.W. Schneider (eds.). Fossile Ökosysteme. 77. Jahrestagung der Paläontologischen Gesellschaft, Kurzfassungen der Vorträge und Poster. Technische Universität Bergakademie Freiberg, Institut für Geologie, Wissenschaftliche Mitteilungen, 111-112.

Riegel, W., Wilde, V. and Lenz, O.K., 2008. From PETM to MECO – a palynological perspective of floral changes along a coastal plain in Central Europe during the early and middle Eocene. Terra Nostra, 2008/2, 234.

Riegel, W., Wilde, V. and Lenz, O., 2011. The edge of the sea at the time of Messel – mangroves and related coastal wetlands in the Eocene of the Helmstedt mining district. In: T., Lehmann, and S., Schaal (eds.). The world at the time of Messel: Puzzles in palaeobiology, palaeoenvironment, and the history of early primates. 22nd International Senckenberg Conference, Conference Volume, 141-142.

Ritzkowski, S., 1990. Marine Ingressionen in den terrestrischen Sedimentfolgen des Eozän von Helmstedt, SE-Niedersachsen. Veröffentlichungen aus dem Übersee-Museum Bremen A, 10, 113-118.

Schiemann, G., 1994. Palynologische Untersuchungen am Unterflöz der Helmstedter Oberflözgruppe (Mittleres Eozän) im Tagebau Alversdorf. Diploma Thesis (unpublished), University of Göttingen, 74 pp.

Schmierer, T., 1913. Aufnahme des Blattes Helmstedt (G.-A. 42, 47) im Sommer 1910. Jahrbuch der Königlich Preußischen Geologischen Landesanstalt, 31 (2) (1910), 508-550.

Schmitz, B. and Pujalte, V., 2003. Sea-level, humidity, and land-erosion records across the initial Eocene thermal maximum from a continental-marine transect in northern Spain. Geology, 31, 689-692.

Schröder, H., 1913. Das Vorkommen der Gattung Lophiodon in der Braunkohle Sachsens. Centralblatt für Mineralogie, Geologie und Paläontologie, 1913, 351.

Schröder, H., 1918. Eocaene Säugetierreste aus Nord- und Mitteldeutschland. Jahrbuch der Preußischen Geologischen Landesanstalt zu Berlin, 37 (1) (1916), 164-195.

Sluijs, A., Pross, J. and Brinkhuis, H., 2005. From greenhouse to icehouse; organic-walled dinoflagellate cysts as paleoenvironmental indicators in the Paleogene. Earth-Science Reviews, 68, 281-315.

Standke, G., 2008. Paläogeografie des älteren Tertiärs (Paläozän bis Untermiozän) im mitteldeutschen Raum. Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 159, 81-103.

Stockey, R.A. and Manchester, S.R., 1988. A fossil flower with in situ Pistillipollenites from the Eocene of British Columbia. Canadian Journal of Botany, 66, 313-318.

Stottmeister, L., 2007. Tertiär. In: L. Stottmeister, H. Jordan and H.-G. Röhling (eds.), Erläuterungen zur Geologischen Karte 1:25000 von Sachsen-Anhalt (GK 25) Blatt Helmstedt 3732. 2. neubearbeitete Auflage. Landesamt für Geologie und Bergwesen Sachsen-Anhalt, Halle, 260 pp.

Thiele-Pfeiffer, H., 1988. Die Mikroflora aus dem mitteleozänen Ölschiefer von Messel bei Darmstadt. Palaeontographica B, 211, 1-86.

Thomson, P.W., and Pflug, H., 1953. Pollen und Sporen des mitteleuropäischen Tertiärs. Palaeontographica B, 94, 1-138.

Tomlinson, P.B., 1986. The botany of mangroves. Cambridge University Press, Cambridge, New York, Melbourne, 419 pp.

Wanless, H.R., 1981. Fining-upwards sedimentary sequences generated in seagras beds. Journal of Sedimentary Petrology, 51, 445-454.

Westgate, J.W. and Gee, C.T., 1990. Paleoecology of a middle Eocene mangrove biota (vertebrates, plants, and invertebrates) from southwest Texas. Palaeogeography, Palaeoclimatology, Palaeoecology, 78, 163-177.

Wilde, V., Lenz, O.K. and Riegel, W., 2008. Mangrove structure and development in the Lower and Middle Eocene of Helmstedt, northern Germany. Terra Nostra, 2008/2, 306-307.

Wing, S.L., Harrington, G.J., Bowen, G.J. and Koch. P.L., 2003. Floral change during the initial Eocene thermal maximum in the Powder River Basin, Wyoming. Geological Society of America Special Paper, 369, 425-440.

Wing, S.L. and Harrington, G.J., 2001. Floral response to rapid warming in the earliest Eocene and implications for concurrent faunal change. Paleobiology, 27, 539-563.

Wing, S.L., Harrington, G.J., Smith, F.A., Bloch, J.I., Boyer, D.M. and Freeman, K.H., 2005. Transient floral change and rapid global warming at the Paleocene-Eocene boundary. Science, 310, 993-996.

Wintgen, C., 1991. Sedimentologische Untersuchungen am unteren Zwischenmittel der Helmstedter Oberflözgruppe im Tagebau Alversdorf. Diploma Thesis (unpublished), University of Göttingen, 101 pp.

Woodburne, M.O., Gunnell, G.F. and Stucky, R.K., 2009. Climate directly influences Eocene mammal faunal dynamics in North America. Proceedings of the National Academy of Sciences, 106, 13399-13403.

Zachos, J.C., Schouten, S., Bohaty, S., Quattlebaum, T., Sluijs, A., Brinkhuis, H., Gibbs, S.J. and Bralower, 2006. Extreme warming of mid-latitude coastal ocean during the Paleocene-Eocene Thermal Maximum: Inferences from TEX86 and isotope data. Geology, 34, 737-740.

Ziegler, P.A., 1990. Geological atlas of western and central Europe. Shell Internationale Petroleum Maatschappij B.V., The Hague, 239 pp.

Received: 13 October 2011
Accepted: 19 March 2012

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PLATE 1:

FIGURE A: Seam 2 with distinct colour-banding in the lower half.

FIGURE B: Large carbonate concretion in Seam 1 (length about 1,5 m).

FIGURE C: Coal block from Seam 2 showing large fragments of charcoal (light streaks).

FIGURE D: Charred conifer wood with well expressed growth rings from Main Seam.

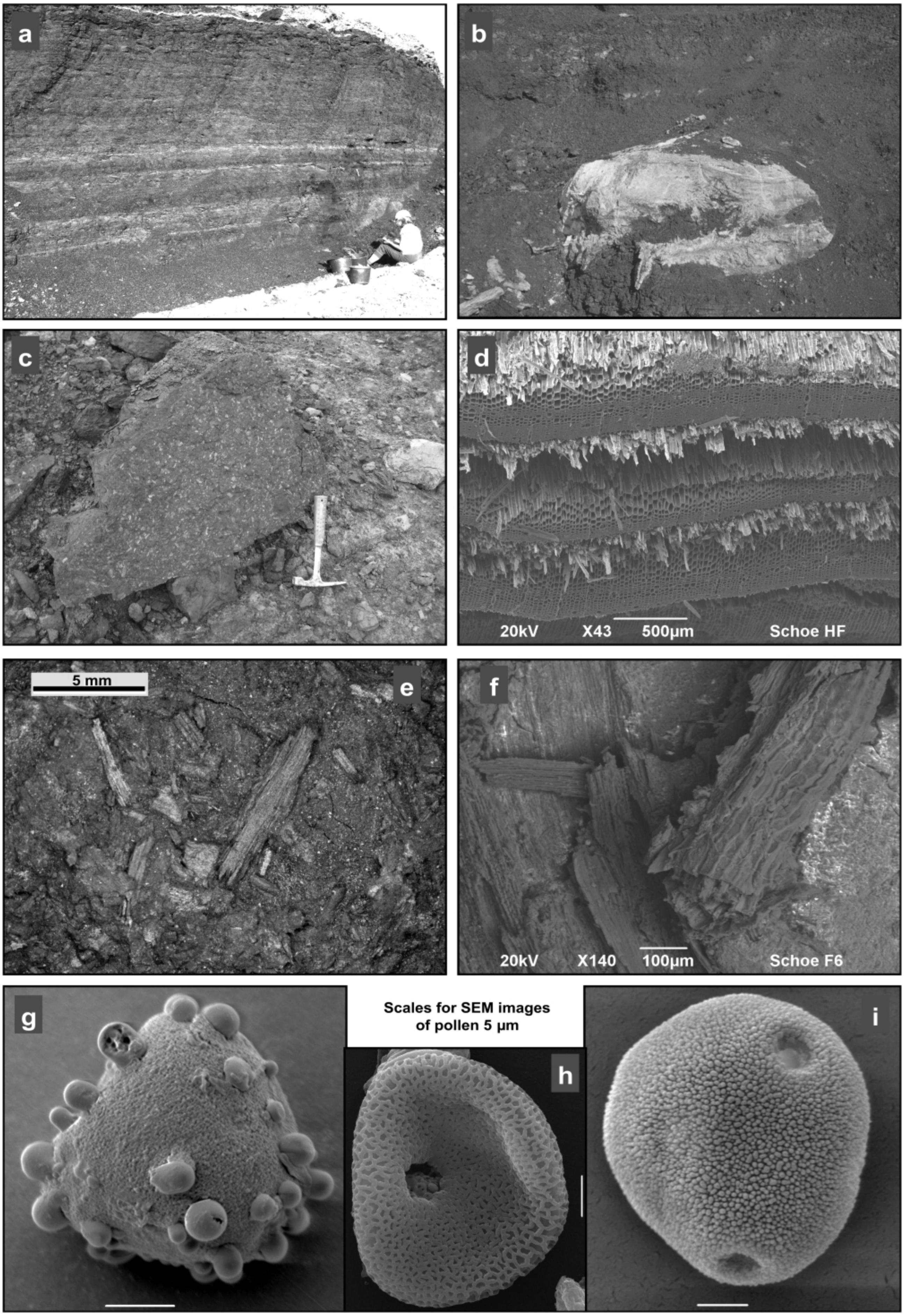
FIGURE E: Minute pieces of charcoal on a bedding plane in the upper part of Seam 6 (LM).

FIGURE F: Charred fragments of woody (right) and non-woody (left) tissues on a bedding plane in the upper part of Seam 6 (LV-SEM, uncoated sample).

FIGURE G: Pistillipollenites macgregorii.

FIGURE H: Pollen grain of Sparganiaceae.

FIGURE I: Thomsonipollis magnificus.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of pollen 5 µm
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Plate 2:

Figure a: Small-scale cross-bedding and bioturbation just below Seam 6 (10 –Eurocent coin for scale).

Figure b: Spurensand of Interbed 4 with intense bioturbation (hammer for scale).

Figure c: Ophiomorpha and some vertical traces in sands below Seam 7 (tip of hammer for scale).

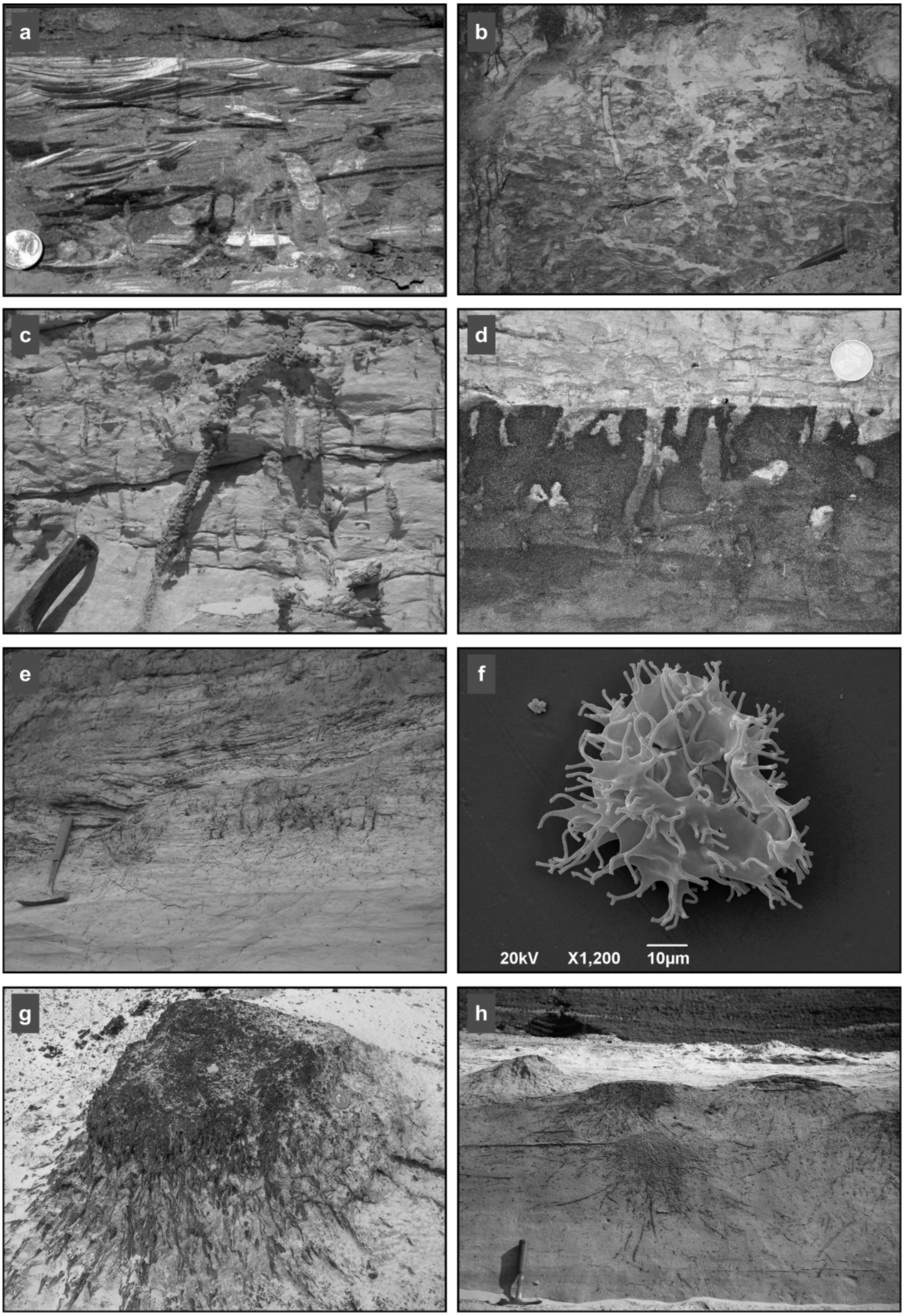
Figure d: “Clastic hardground” with intense bioturbation from the top between Seams 6 and 7 (2 –Eurocent coin for scale).

Figure e: Seagrass-plants in-situ (right of hammer) below Seam 5 with erosional surface above.

Figure f: *Apectodinium* cf. *homomorphum* (SEM) from the *Apectodinium*-acme at the base of Interbed 2.

Figure g: Individual palm stump in-situ (1-Euro-coin for scale).

Figure h: Two succeeding horizons with palm stumps in-situ (cross section, hammer for scale).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Zeitschrift/Journal: Austrian Journal of Earth Sciences

Jahr/Year: 2012

Band/Volume: 105_1

Autor(en)/Author(s): Riegel Walter, Wilde Volker, Lenz Olaf K.

Artikel/Article: The Early Eocene of Schöningen (N-Germany) - an interim report. 88-109