Acta Palaeobotanica 47(1): 109–125, 2007

The Cobham Lignite Bed: the palaeobotany of two petrographically contrasting lignites from either side of the Paleocene–Eocene carbon isotope excursion

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Received 21 July 2006: accepted for publication 11 November 2006

ABSTRACT. The Cobham Lignite Bed includes two lignites, one preceding and including the onset of the carbon isotope excursion (CIE) associated with the Paleocene-Eocene thermal maximum, the other formed after the onset but during the CIE. The lower laminated lignite is charcoal-rich. The charcoalified plant fossils, formed as a result of wildfire activity, show minimal decay and comprise herbaceous ferns and wood of flowering plants. The upper blocky lignite, in contrast, is rich in decayed leaves, cuticles, and herbaceous tissue, lacks wood and contains almost no charcoal. The lignites record a change in fire regime, from one of episodic fires (during deposition of the lower laminated lignite) to one of no fire (upper blocky lignite). The processes that formed these two lignites were different, the laminated lignite formed as the result of the deposition of locally transported charcoal, while the blocky lignite formed as a result of the *in situ* decay of herbaceous material. The uppermost part of the laminated lignite is distinctive in being very finely laminated and having minimal charcoal. It records an increasing clay content and is overlain by a clay bed at the base of the blocky lignite. This suggests a change in hydrology, with loss of fires, increased run-off and water logging resulting from increased rainfall, linked to the onset of the CIE.

KEY WORDS: coal, charcoal, inertinite, fire, petrography, Paleocene-Eocene thermal maximum

INTRODUCTION

Samples from the Cobham Lignite Bed were collected from Scalers Hill near Cobham in Kent, England (Fig. 1) and span the period preceding and following the onset of the negative stable carbon isotope excursion (CIE) associated with the Paleocene-Eocene boundary (Collinson et al. 2003, 2007). The Paleocene-Eocene boundary marks the onset of a geologically brief period (less than 220 kya) of enhanced greenhouse warming, usually termed the Paleocene-Eocene thermal maximum (PETM; Harrington 2001, Harrington et al. 2005). The Cobham Lignite Bed provides a rare terrestrial record of the PETM's effect on mid-latitude vegetation (Collinson et al. 2003, 2007). The PETM involved a significant mid- to high-latitude temperature increase of between 4–10°C (Bains et al. 1999, Norris & Röhl 1999, Röhl et al. 2000, Harrington 2001, Harrington

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et al. 2005, Wing et al. 2005). The CIE resulted from large amounts of isotopically light carbon (more than 2 × 10^{12} metric tons) being released into the atmosphere (Dickens 1999, Katz et al. 1999, Norris & Röhl 1999, Thomas et al. 1999, Harrington 2001). One of the possible sources of this isotopically light carbon is thought to have been the result of a destabilization of isotopically depleted continental shelf sediments containing methane gas hydrates (Dickens 1999, Katz et al. 2001, Zachos et al. 2005). Svensen et al. (2004) argued that there was as yet no known triggering mechanism for methane hydrate release and suggested that methane might have been released as a result of volcanic intrusion based on evidence of hydrothermal vent complexes. For discussion of conflicting mechanisms see Dickens (2004). Methane hydrate release as a single causal mechanism has recently been questioned, due to a revision (upwards) of the estimated mass of light carbon required to account for the CIE (Pagani et al. 2006a, b).

The 2 m thick Cobham Lignite Bed provides an excellent opportunity to study the floristic and environmental changes occurring immediately prior to, during and after the onset of the CIE, which marks the beginning of the PETM. This paper aims to use coal petrography to document the palaeobotany of the Cobham Lignite Bed prior to, during and after the CIE onset. This technique will document the *in situ* occurrence and distribution of the plant fossils, avoiding the poorly constrained loss of “matrix” and less resistant material that can occur during maceration of lignite. The plant fossils from the lower laminated lignite (formed prior to and during the onset of the CIE) will be compared and contrasted with those from the upper blocky lignite (formed after the CIE onset but during the PETM). These data will contribute to the understanding of the impacts of the PETM upon mid-latitude Paleocene/Eocene palaeoenvironments and vegetation.

MATERIAL AND METHODS

LOCALITY AND STRATIGRAPHY

At Cobham, the Cobham Lignite Bed occurs as a small outlier (Fig. 1) of Paleogene strata in the eastern London Basin (Ellison et al. 1996, Collinson et al. 2003). The bed underlies the early Eocene Woolwich Shell Beds (Woolwich Formation) and overlies the late Paleocene Upnor Formation (Fig. 2). The key biostratigraphic, magnetostratigraphic and sequence stratigraphic markers, including the negative CIE associated with the Paleocene-Eocene boundary, dating this lignite, are described in Collinson et al. (2003). The geological evidence from the site (fine lamination, little or no clastic input and that only of mud grain size) indicates the presence of a shallow still water body such as a coastal plain lake. Minor faulting in the underlying sand and mud unit,

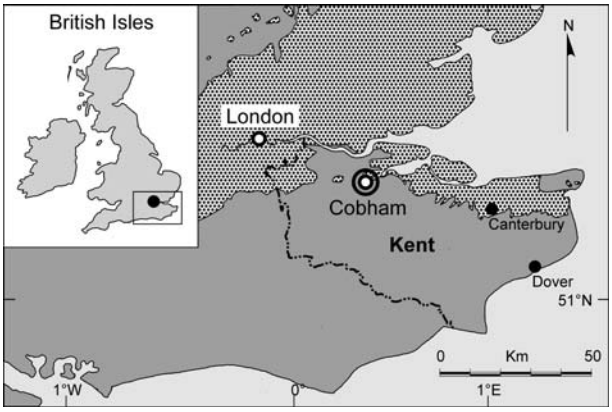

Fig. 1. Map of south-east England showing the position of the Cobham locality. The stippled area indicates the extent of the London Basin (after Ellison et al. 1996)

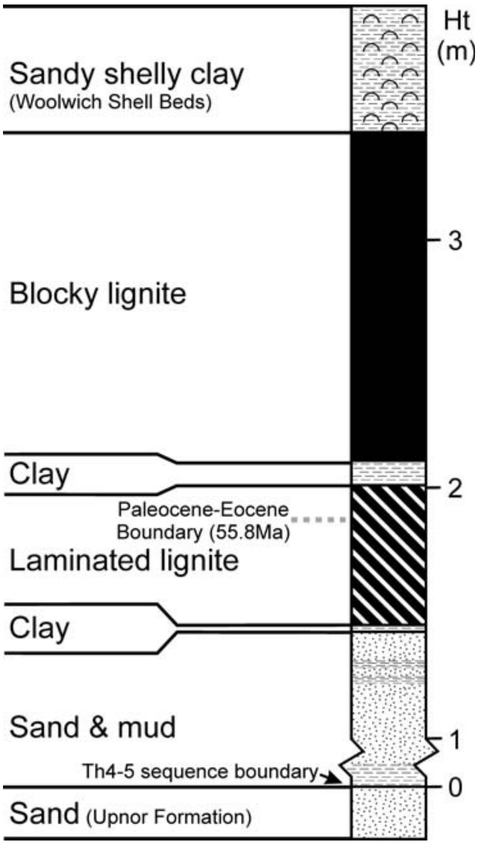

Fig. 2. Lithological column showing the principal geologic units and stratigraphic markers in the Cobham lignite

suggests the area was locally subsiding, while the widespread occurrence of organic deposits underlying the Woolwich Shell Beds, some of which overlie channeling sands, suggests a base level rise over a flood plain low in a transgressive systems tract (Skipper 1999), specifically sequence Th5 (Hardenbol et al. 1998, Collinson et al. 2003). The Cobham Lignite Bed is divided into two principal units (Fig. 2), a lower laminated part up to 55 cm thick, in which the CIE onset occurs (Collinson et al. 2007), and an overlying blocky part (Collinson et al. 2003). Collinson et al. (2003) documented the carbon isotope excursion and briefly examined plant fossils from a few bulk lignite samples after sieving. Collinson et al. (2007) documented the detailed distribution of charcoal in the laminated lignite. In the present paper we compare the distribution and nature of plant fossils in the two lignites using petrographic techniques which allow us to study the plant fossils *in situ* in their original sedimentological and stratigraphic context.

SAMPLE PREPARATION, MICROSCOPY AND PHOTO-MICROSCOPY

Plaster jacketed blocks (columns between 10 × 10 and 20 × 20 cm in cross section) of lignite that had been collected in the field, (see Collinson et al. 2003 for details) were cut in half. One half was retained for future study. The other half was subdivided into manageable coherent overlapping sequences and cleaned in preparation for resin embedding, the method being described in Collinson et al. (2007).

Once prepared, representative resin embedded polished blocks of lignite were examined using a Nikon Optiphot or Microphot reflected light microscope in reflected light under oil (refractive index 1.518 at 23ºC). Work was mostly conducted with a × 20 objective, though a × 40 objective was used where needed. Clast sizes were determined when the × 20 objective was employed, either with a Whipple Grid (35 μm grid spacing), or with a calibrated 100 μm digital scale generated by a Nikon digital sight controller DS-L1 (always used in combination with a DS-5M camera head). All fluorescence microscopy used a Nikon Microphot reflected light microscope, in conjunction with a Nikon HB10101AF Super High Pressure Mercury lamp fitted with a EX450-490 excitation filter, and a BA520 barrier filter. The reflected light and fluorescence photomicrographs were gathered as 24 bit JPEG images with the microscope-mounted Nikon digital camera and controller mentioned above. The digital photomicrographs had either 1280 × 960 or a 2560 × 1920 pixel resolution. The imaging of clasts larger than one field of view usually required photo montage work, using Corel Graphics-Suite™ versions 11 or 12 to assemble in some cases over 90 separate photomicrographs into single digital images.

IDENTIFICATION OF BOTANICAL ENTITIES AND PRESERVATION STATES

All burnt material is herein referred to as charcoal (Scott 2000, 2002, Scott & Glasspool 2007) to avoid the complexities of coal petrographic terminology. Charcoalified plant organs show moderate to high reflectance under oil and are anatomically preserved. Coalified plant tissues show dark grey reflectance and occasionally remnants of cell structure. Cuticles, spores, pollen etc (liptinites) show little reflectance but fluoresce under UV radiation. (Teichmüller 1974, 1982, Crelling 1983).

LAMINATED LIGNITE

PRESERVATION STATES

The plant fossil material found in the lower laminated lignite occurs either as charcoal clasts or micro-charcoal (Fig. 3:1), concentrated in charcoal-rich layers whose thickness varies from around 100 μm to over 500 μm (Collinson et al. 2007). Larger clasts also occur within these layers (Pl. 1, figs 1, 2). Clast sizes vary from micro-charcoal (<35 μm, Fig. 3:1) to the crushed remains of larger clasts in dense layers (Pl. 1, fig. 2), to numerous uncrushed clasts of 200 or 300 μm cross-sectional dimension, grading to increasingly less common clasts up to 8 mm in cross-sectional dimension. Some of these larger charcoal clasts have layers of charcoal-rich material compacted beneath and draped over them (Pl. 1, fig. 2). Clasts have well-preserved three-dimensional macro cellular anatomy, where the cell walls, cell lumens and anatomical relationships between the cells within a clast can be easily seen (Pls 1, 2).

After Collinson et al. (2007) the charcoal-rich layers (47% to 54% charcoal) are separated by charcoal-poor layers (Fig. 3:1; 9% to 21% charcoal). Pyrite framboids are common throughout. The reflectance under oil of the various clasts varies both between clasts and different charcoal layers and, more rarely, within individual clasts and layers. There are no fluorescing cuticles found in the laminated lignite, but *in situ* charcoalified cuticle with high reflectance is rarely observed (Pl. 2, figs 1, 3). Spores and pollen (showing low reflectance) are occasionally observed.

Many of the charcoal clasts are well preserved, exhibiting little or no evidence of decomposition prior to charcoalification (Pl. 1, figs 3–6, Pl. 2, figs 1–5). The charcoalified wood typically occurs as fragments (Pl. 1, fig. 9). Clasts are observed in various planes of section, revealing different tissues (Pl. 1. figs 7, 8, 10, Pl. 2, figs 6, 7). A few specimens, such as those in Plate 1, figure 2 and Plate 2, figure 1 have faecal pellets (Fp) associated with them,

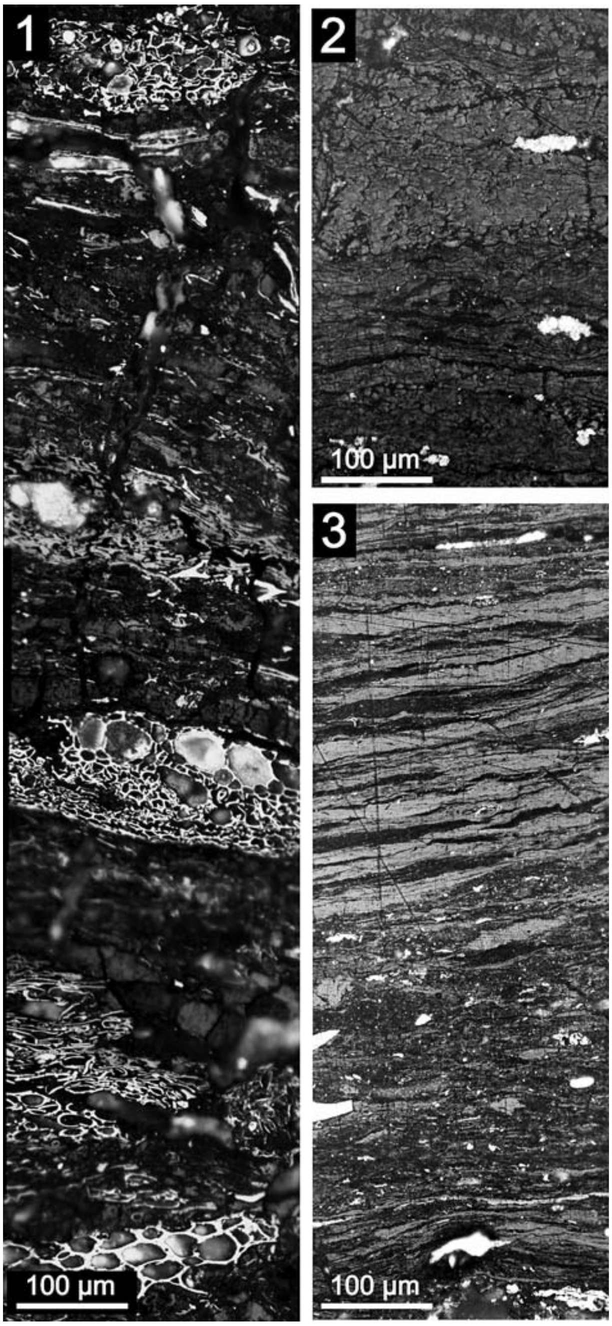

Fig. 3. The Cobham locality has two principal types of lignite: **1** – the lower laminated lignite which is charcoal-rich, with large brightly reflecting charcoal clasts with clear cellular structure occurring in bands separated by charcoal-poor material (with microscopic charcoal <30 µm) and, **2** – the upper blocky lignite which has little or no charcoal present (bright areas are pyrite framboids); **3** – a very finely laminated lignite (upper half of image), with only extremely rare charcoal, which occupies the top 25 mm of the laminated lignite. Reflected light micrographs under oil from polished blocks

indicating arthropod feeding, probably on living or recently senesced tissue. Specimens such as that depicted in Plate 1, figure 1 have some cell lumina in-filled with organic material prior to charcoalifiaction, however, in most cases the lumina are open (Pl. 2, figs 1, 2). In rare cases, some cells are in-filled with mineral inclusions (e.g. Pl. 1, fig. 5). Clasts exhibiting some degree of compaction-related crushing (Pl. 1, fig. 2; Collinson et al. 2007) are common, where thin-walled charcoalified cells have shattered, though thicker-walled cells often survive intact. These crushed clasts sometimes form the bulk of the charcoal fragments that comprise the charcoal-rich bands.

BOTANICAL NATURE AND SYSTEMATIC AFFINITY

The plant parts preserved as charcoal in the laminated lignite are mostly herbaceous axes (Pl. 1, figs 1, 6, Pl. 2, fig. 1), more rarely pieces of woody axes (Pl. 1, fig. 9, Pl. 2, fig. 2). Very rare laminar structures are recorded (probable leaves, Pl. 1, figs 3, 4), as are very rare thick-walled wound reaction tissues (Pl. 1, fig. 2). Spores and pollen are observed very rarely, in section, in reflected light, and do not fluoresce. No fluorescing cuticle has been observed in the laminated lignite either. It is possible that this lack of fluorescence is linked to charring.

The herbaceous axes in transverse section depicted in Plate 1, figures 1 and 6 have the typical U-shaped meristele exhibited by a number of fern species and have vascular tissue with scalariform thickenings (Pl. 1, fig. 7). The specimen in Plate 1, figure 1 is a high reflectance clast, possibly of a terminal section of fern rachis. The level of cellular detail is high, with details of the scalariform thickenings evident in the conducting tissue, though some cell lumina have high reflectance in-fills. The meristele has partly separated away from the parenchymatous ground tissue, as is typical of ferns upon charring (McParland et al., in press). Some of the cells towards the outside of the specimen (except those at the top of the figure) have modified cell walls suggestive of either limited decay or fire related damage. The specimen in Plate 1, figure 6, is in oblique transverse section. The vascular tissue is well-preserved and there is evidence of the leaf lamina continuing to the left and right of the figure. Collectively, these observations, especially the presence of U-shaped meristeles and the presence of scalariform thickenings, indicate a fern affinity.

The specimen in Plate 2, figure 1 is incomplete and lacks any vascular region. It, is comprised mostly of herbaceous parenchyma or collenchyma and has a clear complete epidermis with cuticle (Pl. 2, figs 1, 3). The lack of a radial distribution of vascular strands suggests that it is not an herbaceous angiosperm. It is therefore possibly derived from a fern, but the absence of the vascular region renders any diagnosis inconclusive.

The specimen in longitudinal section depicted in Plate 2, figure 10 has pronounced compaction related crushing of cells upon its upper and lower surfaces. This characteristic is typical of many such clasts found in the laminated lignite. The specimen has patches of vascular tissue with scalariform thickenings (see Pl. 2, fig. 6 for detail) but the stelar organization is unclear due to the crushing.

Clasts of herbaceous thick-walled cells (Pl. 1, fig. 10) lacking serial row organization (see Pl. 1, fig. 9 for comparison) are common. These occur in transverse (Pl. 1, fig. 10) or longitudinal (Pl. 1, fig. 8) section. The various types of herbaceous axes found, occur both in transverse (see Pl. 1, figs 1, 2, Pl. 2, figs 1, 2) and longitudinal section (Pl. 2, fig. 10). There are also numerous, narrow ($\approx$50 to 70 µm), long (over 300 µm) strands of isolated vascular material, often with well-defined scalariform thickenings (Pl. 1, fig. 7). Specimens are also seen in oblique transverse section (Pl. 1, fig. 5) and oblique longitudinal section (Pl. 2, fig. 5). The specimen in Plate 1 figure 5 has two zones, one large and comma shaped and one small and round, with mineralized in-fills. These zones are interpreted as vascular tissues. The specimen also has an associated layer of tissue whose uncompressed cell structure is suggestive of it having been laminar originally. This clast is thus probably a foliar organ sectioned obliquely just before or after the divergence of a subsidiary vascular strand from a larger one. The specimen in Plate 2 figure 5 is probably a leaf stalk near the departure point of a leaf lamina or leaf scale sectioned obliquely. On the basis of their similarity with tissues in specimens with U-shaped meristeles, all of these herbaceous organs are interpreted as being derived from ferns, showing various sections through leaf stalks.

There are many examples of charcoalified woody angiosperm material in the laminated lignite. The specimen in Plate 2, figure 2, is typical of the rare larger woody angiosperm clasts. The xylem tissue occurs in serial rows (Pl. 2, fig. 2), and scattered throughout are vessel elements (Pl. 2, fig 4 and Collinson et al. 2007, fig. 5g, for detail). The diffuse distribution of vessel elements supports the diagnosis of a ring diffuse wood. A smaller but more common example of a woody angiosperm clast is depicted in Plate 1, figure 9. Such clasts have xylem cells in serial rows and, in combination with the occasional larger diameter vessel elements, this allows their classification as angiosperm wood. The limited size of such clasts precludes analysis of vessel distribution. Wood typically shatters upon charring, leaving small clasts like those in the laminated lignite (Scott 1989).

Only two laminar structures were seen in the blocks of laminated lignite examined and these are in vertical section. The specimen depicted (Pl. 1, fig. 3) has clear epidermal cells, (see Pl. 1, fig. 4 for detail) but it lacks stomata, and has no obvious differentiation into palisade and spongy mesophyll, though it does have mesophyll tissue. If cuticle is present, it does not show fluorescence. This structure is interpreted as being a possible leaf, though we have not seen stomatal apertures, so it may represent some other laminar plant organ, such as a scale (e.g. a fern leaf stalk scale, or a flowering plant bud scale). There were no diaspores, flowers, roots, bryophytes or coniferous material found in any part of the laminated lignite. The herbaceous component seems to be exclusively fern, though we cannot entirely rule out an angiosperm derivation for some fragmentary herbaceous tissue.

UPPERMOST LAMINATED LIGNITE

The laminated lignite continues upwards above the maximum negative CIE interval (for details see: Collinson et al. 2003, 2007) for 25 mm and is overlain by the middle clay band. A transitional region, 1 to 2 mm in thickness (Fig. 3:3, lower part of figure) directly above the maximum negative CIE, has occasional charcoal fragments, rare occurrences of low reflectance, poorly structured, charcoal (Pl. 2, fig. 8), some micro-charcoal, and some thin low reflectance strands (Pl. 2, fig. 9). Above this transitional zone, the uppermost laminated lignite has a distinctive micro-structure that is completely different from the underlying laminated lignite, being characterised by having very fine alternating clay-rich and vitrinite (huminite) – rich layers (Fig. 3:3 uppermost part of figure). Charcoal fragments of any kind are rare to absent (maximum 1%). Pyrite framboids continue to occur throughout this region.

BLOCKY LIGNITE

PRESERVATION STATES

In striking contrast to the laminated lignite, charcoal is extremely rare (maximum 0.5%), occurring mostly as isolated fragments of micro-charcoal, or occasionally in very rare thin, broken, ill-defined bands whose cumulative thickness is less than 100 µm out of the ~ 45 mm of sequence studied at a microscopic scale (selected following a coarser scale preliminary microscopic survey to determine its representative nature). Charcoal fragments exceeding 10 µm in maximum dimension are very rare. The fossil plant material in the blocky lignite occurs mostly as decayed, and hence poorly preserved, organic material with a dark grey reflectance (Fig. 3:2, Fig. 4:1, 5). Banding is evident (Fig. 3:2, Fig. 4:3, 5) and pyrite framboids are found throughout. Where remnant identifiable cellular structures are observed, none of the constituent cells have open cell lumina. Numerous laminar structures (e.g. Fig. 4:1, 2) occur horizontal to the bedding plane and these often have a considerable lateral extent. The specimen in Figure 4:2, for example, has a length of over 6 mm. Numerous cuticles with a yellow green fluorescence are found throughout the blocky lignite (Fig. 4: 6, Fig. 5:5–8, Fig. 5:10, 12), though these don't always coincide with the laminar structures horizontal to the bedding plane. Numerous thin rows of cuboidal blocks of material (single block in thickness) with a dark grey reflectance, separated by non-reflecting "squares" are common (Fig. 4:3).

BOTANICAL NATURE

The most obvious features of the blocky lignite are the numerous laminar structures (i.e. Fig. 4:1, 2) occurring horizontal to the bedding plane. None of these structures have open cell lumina. The in-filled cell lumina have huminitic reflectance, separated by non-reflecting rims which are reminiscent of cell walls. The arrangements of cell in-fills found in these laminar structures have a definite pattern reminiscent of leaf material. The elongate to rectangular cell in-fills and masses of irregular shaped cell in-fills are interpreted as being the remains of palisade (PM) and spongy mesophyll (M) respectively. Adjacent to the palisade mesophyll, there is a layer of thin flat cells on the outside of the structure. They are interpreted as an upper epidermis (Ep). The lower epidermis is only preserved in patches, perhaps because it was originally formed from thin-walled cells. Fluorescing cuticle could not be discerned, and is interpreted to have decomposed. Although counter-intuitive, as cuticles are usually considered very resistant, Gupta et al., (2007) have shown that Paleogene leaves with well-preserved cell structure may lack cuticles. Therefore, these elongate laminar structures are interpreted as leaves. There are also irregularly shaped mineral in-fills scattered along the length of this structure and these may be in-fills marking the original location of air spaces in the leaf. The leaf is upside down, as the palisade mesophyll is normally on the upper surface of a bifacial leaf.

The specimen in Figure 4:2 has a reversed orientation to that in Figure 4:1, but is otherwise very similar. If correctly interpreted, the presence of differentiated palisade and spongy mesophyll in a thin laminar leaf suggests that these leaves were most likely derived from angiosperms, though some ferns cannot be precluded as possible progenitors.

The rows of cuboidal blocks are interpreted as in-filled cells (Fig. 4:3). They are often laterally extensive and occur throughout the blocky lignite. The rows examined under fluorescence microscopy usually do not have fluorescent cuticle associated with them. These rows of cell-like structures are interpreted as being the remains of epidermal/hypodermal cells, where cuticles have been lost. The regular rectangular or cuboidal shape of these structures and their common occurrence in rows of single block thickness argues strongly for their origin from a botanical tissue.

The decayed remains of other cellular tissues can also be seen (Fig. 4:4). In Figure 4: 4, there are grey, rectangular (lower half of figure) to irregularly shaped (upper half of figure) vitrinite (huminite) units separated by dark non-reflecting rims. These patterns are interpreted as cell walls and partially or fully in-filled cell lumina all having a grey reflectance, separated by non-reflective (black) matrix between cells in the region of the cell

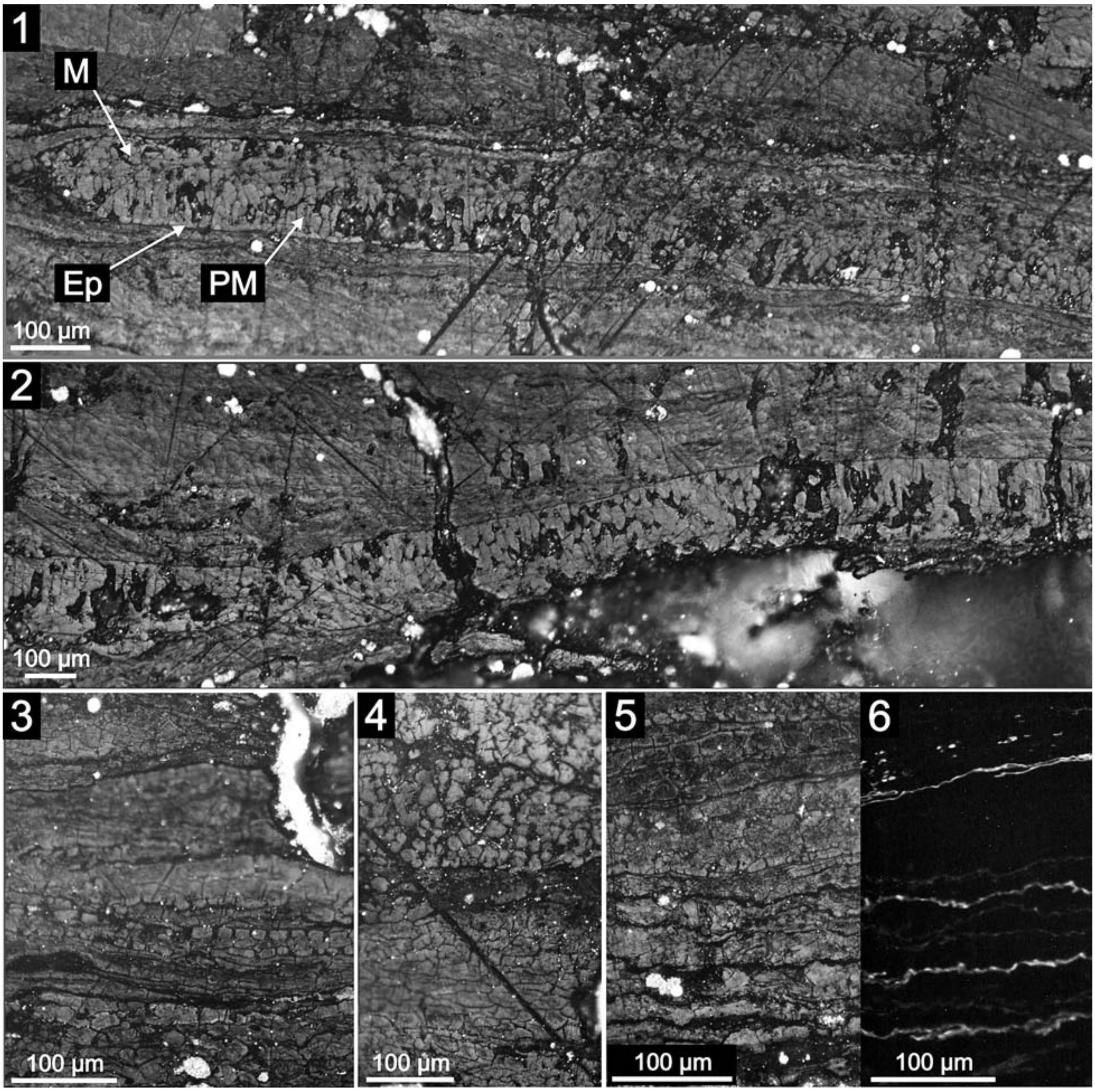

Fig. 4. Examples of the botanical organ and cell preservation types in the blocky lignite: **1 –** probable leaf with cell in-fills and lateral extent, (Ep) epidermis, (PM) palisade mesophyll, (M) spongy mesophyll, **2** – another leaf showing some distortion due to compaction, reversed orientation from 1, **3** – fine layering, with layers of cuboidal blocks interpreted as layers a single-cell thick, **4** – grey, rectangular (lower half of figure) to irregularly shaped (upper half of figure) vitrinite (huminite) units separated by non-reflecting rims. These occur in clusters and are interpreted as being the remnants of decayed in-filled cells of parenchymatous tissue, **5** and **6** – same image of layers of lignite with multiple cuticles preserved (as revealed by fluorescence microscopy). 1–5 reflected light under oil from polished blocks, 6 using fluorescence microscopy

walls following decomposition. The various cell shapes suggest either different stages of decomposition, or different original cell shapes. We interpret these as decomposed herbaceous ground tissue.

Fluorescent cuticles similar to those depicted in Figure 4:6 and Figure 5:5, 7 are common and vary greatly in size. Companion images in reflected light under oil are also shown (Fig. 4:5, Fig. 5:1, 3) for direct comparison. Most cuticles lie horizontal to the bedding plane and are thin elongate structures, with small projections pointing outwards in one direction. This strongly suggests that they are epidermal cuticles. In rare cases (Fig. 5:6, “upper cuticle”), fluorescent cuticle covering both sides of the original organ/cells are found still in association with each other. More rarely, lengthy paired double cuticles exist (Fig. 5:11, 12), where one member of each cuticular pair is thicker, with a brighter fluorescence than its companion. The projections of the brighter

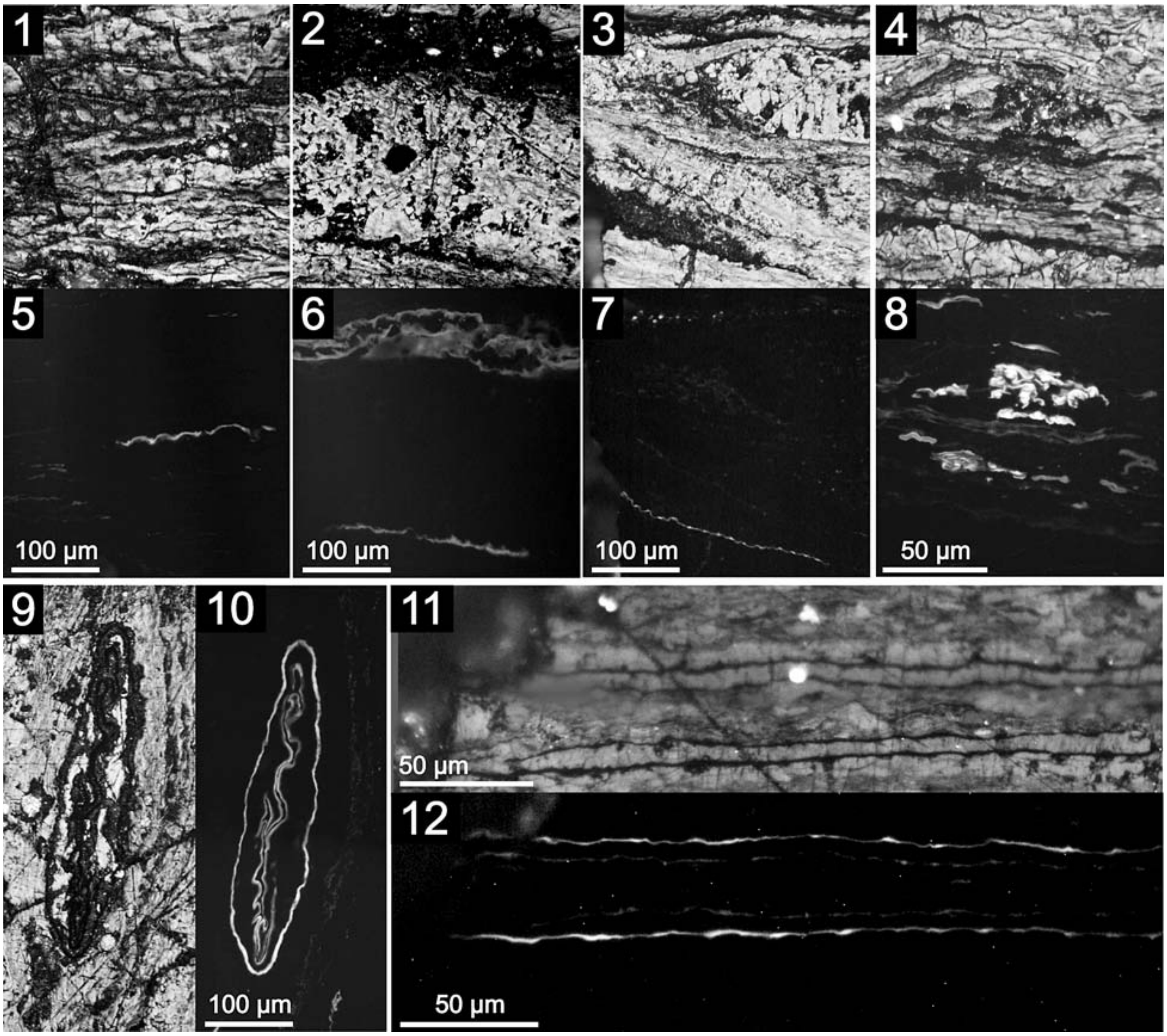

Fig. 5. Examples of reflectance (1–4, 9, and 11) and fluorescence (5–8, 10 and 12) microscopy image pairs of the cuticles and other botanical structures preserved in the blocky lignite: **1**, **5** – isolated cuticle, spores and pollen, **2**, **6** – intact double layered cuticle (above) with single layered cuticle below, **3**, 7 – section of left end of leaf in Fig. 4:2 showing absence of fluorescing cuticle, but with an unrelated thin isolated cuticle (below), **4**, **8** – mass of pollen grains (centre) and spores with open lumens, **9**, **10** – seed cuticles, **11**, **12** – pair of double layered cuticles

cuticles (Fig. 5:12) are pointing outwards, or away from the less bright cuticles. These cuticle pairs are interpreted as belonging to separate foliar organs (i.e. leaves), as the direction of the cuticular projections on the bright fluorescent cuticles suggest they are unrelated to the less bright ones. These distinct fairly thick cuticles may suggest a derivation from flowering plants rather than from ferns. Occasional rare seed cuticles occur (Fig 5:9, 10), with the outer and internal cuticular envelopes being evident. Fluorescing spores and pollen grains are also common. The central brightly fluorescing mass in Figure 5:8 is interpreted as being a number of highly fluorescent pollen grains with nearby less fluorescent spores. None of the material in the blocky lignite showed radial files of cells characteristic of wood. The interlayering of cuticles (fluorescing), with thin layers of grey-reflecting former cell and cell in-fills underscores the non-woody nature of the material making up the blocky lignite (Fig. 4:5, 6). It is possible that a taphonomic bias favoured leaf accumulation/preservation at the expense of wood. However, even in this case, we would have expected to see some woody material preserved.

DISCUSSION

The two types of lignite, which occur on either side of the onset of the CIE, are quite different from each other, as clearly shown by selected examples in Figure 3. The lower laminated lignite is rich in anatomically preserved charcoalified plant fossils (charcoal poor layers 9% to 21%, charcoal rich layers 47% to 54%), mostly comprised of a mix of well-preserved charcoalified material (Pls 1, 2) of both herbaceous fern and woody angiosperm origin, very rare leaf lamina material and no fluorescent cuticle. In contrast, the overlying blocky lignite has almost no charcoal (<0.5% charcoal), but is rich in cuticles (identified by fluorescence). The blocky lignite is mainly composed of poorly-preserved plant material, most of which consists of elongate laminar structures (interpreted as leaves) and herbaceous tissue (Figs 4, 5). The composition is extremely different.

These two lignites were formed by different processes. The laminated lignite resulted from processes involving episodic wild-fire and the charcoalification of plants (Scott 2000) and the deposition of that charcoal, mostly from local sources, via run-off related local transport (Collinson et al. 2007). Conversely, the overlying blocky lignite formed from the sustained deposition of non-woody material and its *in situ* decomposition, as evidenced by it being mostly composed of cuticles, and decayed leaf, epidermal and other herbaceous tissues, with in-filled cell lumina.

The middle clay, laid down after the onset of the CIE, lies between these two lignites (Fig. 2). In the upper 25 mm of the laminated lignite, between the maximum negative interval of the CIE (refer to Collinson et al. 2003, 2007) and the middle clay, the laminated lignite grades (over less than one millimetre) from a charcoal-rich material into a charcoal-poor material, with numerous fine laminations, mostly between 10 and 30 μm thick, that have an increased clay content (Fig 3:3, upper part). This increased clay content is indicative of increased run-off and transport, with fine clay-rich sediments subsequently deposited in the area where the lignite was accumulating. The band of clay forming the middle clay may also indicate that one or more flood events took place, resulting in the deposition of more significant amounts of fine grained sediments in the depositional setting. Collinson et al. (2003) reported the occurrence of *Salvinia*, a free floating water plant in the basal blocky lignite and related this and the occurrence of the increased clay content to a possible change in hydrology. This change in hydrology may be linked to the onset of the CIE, elevated levels of humidity and run-off (Bowen et al. 2004, Kelly et al. 2005) or increased high latitude precipitation (Bice & Marotzke 2002). Using evidence from leaf physiognomy in the Bighorn Basin, Wyoming, USA, Wing et al. (2005) suggested that rainfall declined by ~ 40% near the onset of the PETM then recovered to normal values by late in the event. These apparently contradicting opinions may be reconciled if hydrological changes were linked to seasonal cyclones as suggested by Pujalte and Schmitz (2006).

The blocky lignite, overlying the middle clay, also contains essentially no charcoal but is formed from accumulated, slowly decaying plant material. The remnant cellular structure and ubiquitous presence of in-filled cells suggests peatification in a waterlogged setting. The loss of charcoal in the upper most laminated lignite and the overlying blocky lignite clearly indicates that fires were suppressed during the final phase of laminated lignite deposition. That episodic fire linked with episodic run-off occurred before this is evident from the charcoal banding seen in Figure 3:2. This is described in detail in Collinson et al. (2007). There are a number of likely causes of fire suppression, and these include changes in rainfall, length or occurrence of dry season, and changes in soil moisture budgets and hence vegetation flammability (Viro 1974, Goldammer 1990, Bond & von Wilgen 1996, Nelson 2001, McKenzie et al. 2004). The clays would have provided a low permeability barrier, reducing or preventing drainage and encouraging water-logging. This would favour organic accumulation resulting in peat formation ultimately forming the blocky lignite.

In combination, the increasing clay content in the uppermost laminated lignite, the presence of the middle clay and suppression of fire suggest a change in hydrology and an increased run-off. An increase in rainfall, could simultaneously increase run-off and suppress fire. Pagani et al. 2006b also recognized a change in the hydrological cycle as a key factor in the PETM event.

The charcoalified remains of herbaceous ferns and of woody angiosperms occur throughout the laminated lignite. The absence of conifers is surprising as taxodiaceous conifers in particular are known to be important in Paleocene-Eocene vegetation (Collinson & Hooker 2003) and taxodiaceous conifer forests are documented for sites almost coeval with the PETM (Fairon-Demaret et al., 2003) in Belgium. This absence in the Cobham laminated lignite is confirmed by SEM studies of wood charcoal and by preliminary palynology of 10 samples from both lignites and clays (Collinson et al. 2003). Palms are common at the essentially contemporaneous site of Felpham (Collinson & Cleal 2001) but are absent at Cobham. Ferns with U-shaped meristeles occur at Felpham and in the early Eocene London Clay flora (Collinson 2002, Collinson & Cleal 2001) as well as at Cobham (Pl. 1, fig. 1). Although they are very similar, the leaf stalk anatomy is insufficient evidence to decide if they are the same taxon. The low diversity charcoalified flora combined with the absence of conifers and monocots suggests a specialised fire prone source vegetation consisting of ground ferns and woody angiosperms.

The plant material in the blocky lignite lacks sufficient diagnostic information to categorically identify the plant groups from which it was derived, although the leaf anatomy is suggestive of angiosperms or possibly some ferns (Fahn 1969, Sporne 1975, Esau 1965, 1977). Seeds, pollen and spores are obvious in the blocky lignite, but reproductive structures were not found in the charcoals from the laminated lignite. The absence of woody angiosperm material and the presence of decayed leaf material in the blocky lignite is problematic, as wood, with its inherent much higher levels of lignification, is often considerably more resistant to decay (Martinez et al. 2005). Had woody plants been growing nearby, then it would be expected, given the remnant cell structures preserved, that some evidence would remain in the blocky lignite. The absence of wood suggests that woody plants cannot have been significant in that source vegetation. This may indicate a shift in vegetation or only very localised input from herbs growing in a wetland setting. These hypotheses will be tested in our future research on the comparative palynology of the Cobham Lignite Bed.

CONCLUSIONS

The Cobham Lignite Bed is made up of two different types of lignite, formed by different processes. The lower laminated lignite is rich in well-preserved charcoalified plant fossils, while the overlying blocky lignite is composed mostly of decayed non-woody material. The laminated lignite formed from large amounts of locally produced charcoal resulting from episodic local wildfires (Collinson et al. 2007), while the blocky lignite formed as a result of accumulation and decay of plant material in a waterlogged environment.

The source vegetation which formed the two lignites was subject to different fire regimes. The charcoal-rich laminated lignite, resulted from an episodic and possibly seasonal fire regime, linked with run-off events (Collinson et al. 2007) which transported the resultant charcoal to the depositional setting. The overlying blocky lignite had so little charcoal however, that it can be concluded that fires were absent in the source vegetation.

Between these two lignites lies a band of clay. Underlying this clay is the distinctive upper laminated lignite, which occupies the 25 mm above the maximum negative interval marking the onset of the CIE at the base of the Paleocene-Eocene thermal maximum. The upper laminated lignite contains almost no charcoal, indicating that fire suppression began soon after the onset of the PETM. This fire suppression continued into and throughout the period during which the blocky lignite accumulated. The loss of charcoal combined with increasing clay input leads to the interpretation that fire suppression was the result of increased rainfall. The resultant clay-rich material, including the middle clay, may then have acted as an impermeable barrier, preventing or slowing drainage and increasing water logging, favouring accumulation of the peat which formed the overlying blocky lignite.

The two contrasting lignites, therefore, indicate that the onset of the CIE initiated a change in fire regime, rainfall and local hydrology. There may have been a concomitant change in the local vegetation, from a fire prone vegetation composed of ferns and woody angiosperms to one with few woody plants. This remains to be tested in a palynological study.

ACKNOWLEDGEMENTS

We would like to thank Alfred McAlpine, AMEC and Channel Tunnel Rail Link for access to the Cobham Lignite Bed, Sharon Rose for making arrangements, the Leverhulme Trust for providing the funding (Grant Number F/07/537/0) that made this project possible, and Jackie Skipper and Steve Tracey for help with initial sample collection and field discussions. We would also like to thank personnel from the Geology Department, Royal Holloway University of London, for their support, especially Neil Holloway (assistance with sample polishing and preparation), Sharon Gibbons (Palaeobiology Laboratory) and Kevin D'Souza (photomicrography).

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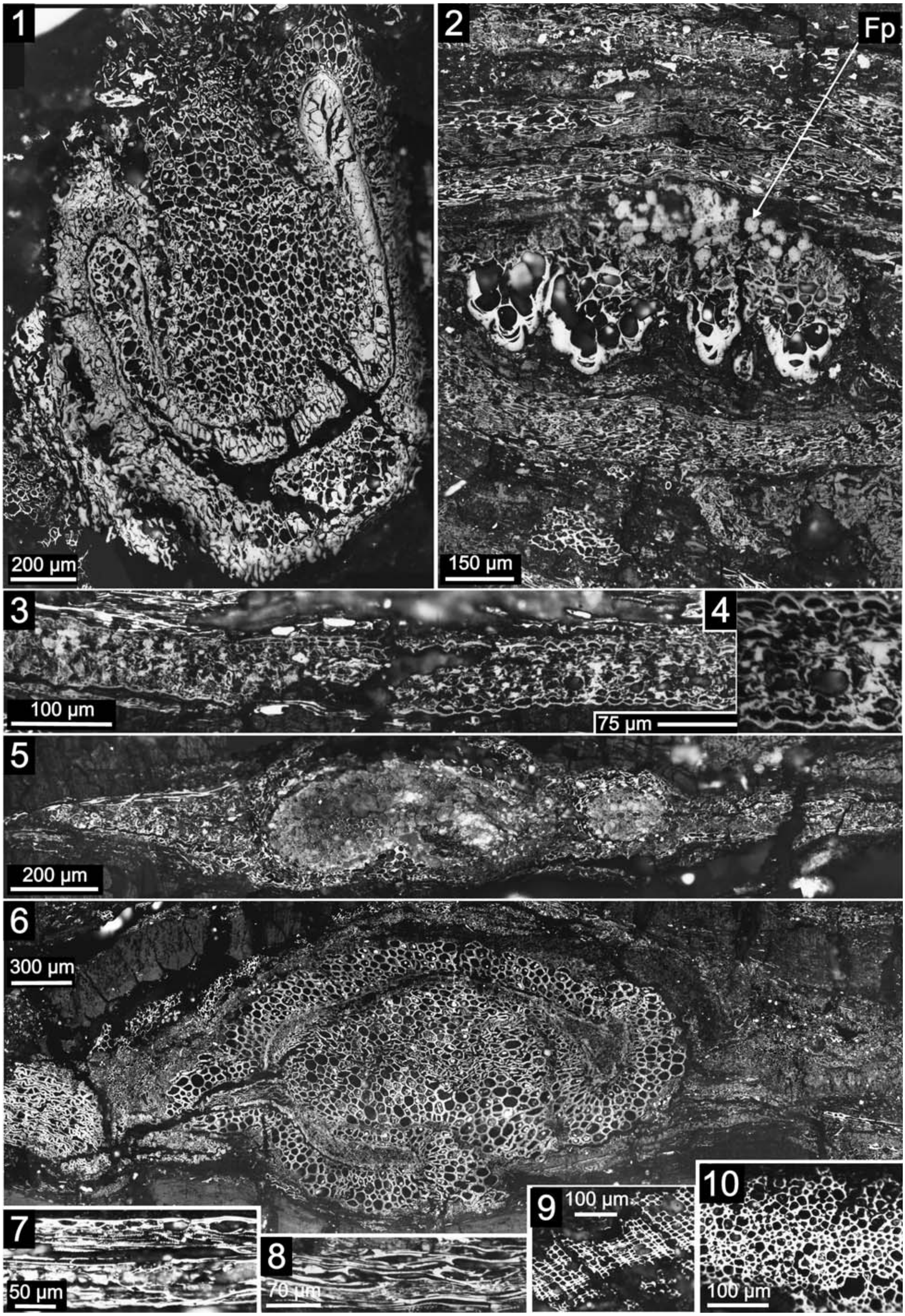
PLATES

Plate 1

Charcoalified plant fossils from the main part of the Cobham laminated lignite. All reflected light under oil

1. Fern leaf stalk in transverse section
2. Wound tissue, with faecal pellets (Fp) and charcoal-rich bands draping around it
3. Elongate laminar structure interpreted as being a leaf or other laminar organ
4. Detail of (3) showing the epidermal cells
5. Laminar organ with two mineralised vascular regions
6. Oblique transverse section of fern stalk
7. Isolated herbaceous vascular strand, and scalariform pitting
8. Isolated shard of thick-walled herbaceous tissue in longitudinal section
9. Fragment of woody tissue with cells in serial rows and some vessel elements
10. Clast of herbaceous parenchymatous tissue


1
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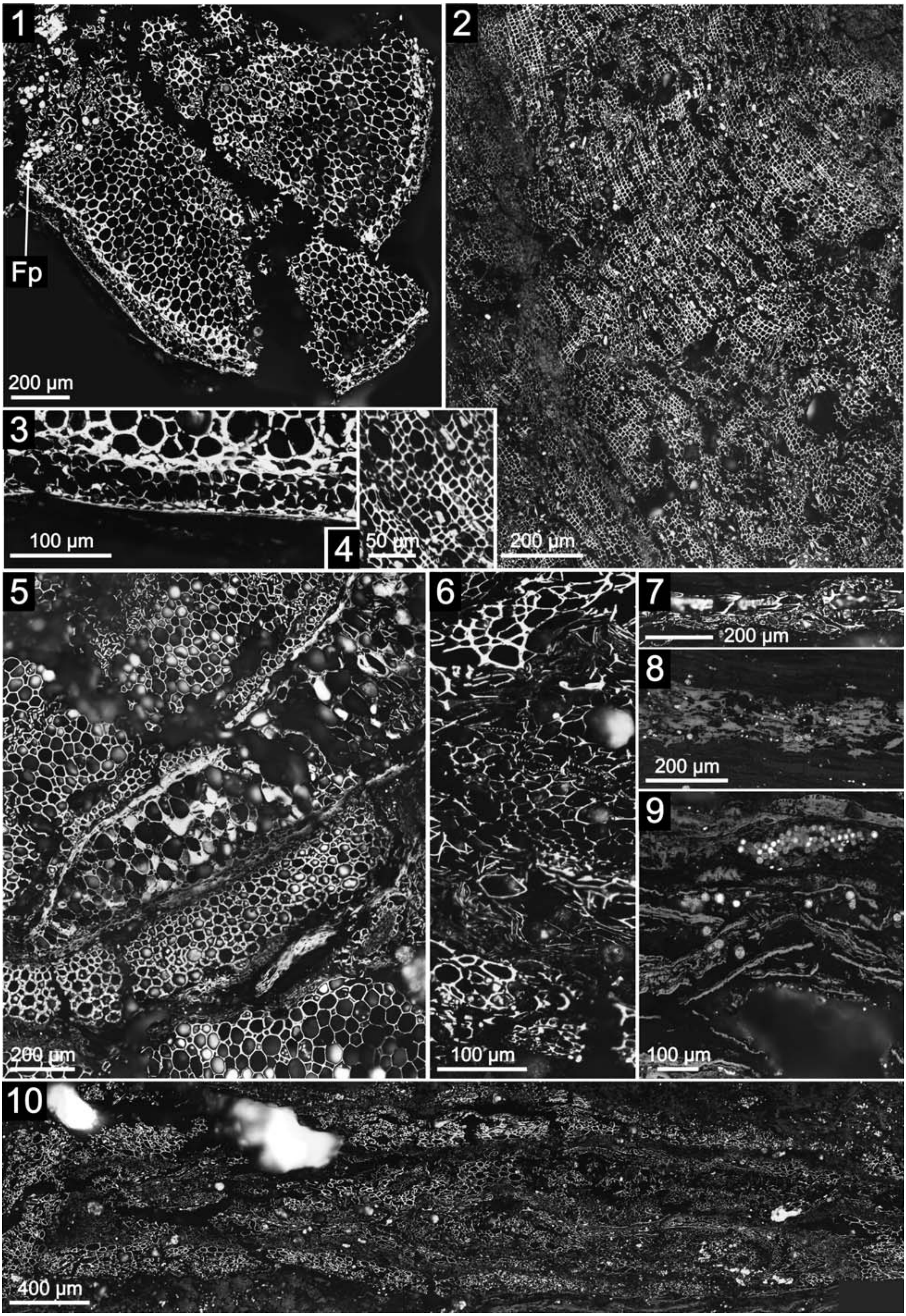
2
Fp
150 µm
3
100 µm
4
75 µm
5
200 µm
6
300 µm
7
50 µm
8
70 µm
9
100 µm
10
100 µm

Plate 2

Charcoalified plant fossils from the Cobham laminated lignite. All reflected light under oil. All from main part of the laminated lignite unless otherwise stated

1. Herbaceous organ with epidermis, faecal pellets (Fp) and cuticle (detail in 3)
2. Large clast of diffuse porous angiosperm wood
3. Detail of Plate 2, fig. 1, showing charcoalified cuticle
4. Detail of angiosperm wood from (Plate 2, fig. 2, showing vessel elements
5. Probable fern sectioned obliquely
6. Detail of Plate 2, fig. 10, herbaceous organ, showing vascular tissue with scalariform pitting
7. Isolated herbaceous vascular tissue
8. Low reflectance clast of poorly structured charcoal from transition zone
9. Thin low reflectance strands from transition zone
10. Herbaceous organ, affected by compaction related crushing, probable fern


1
Fp
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