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The age, palaeoclimate and palaeoecology of the Brassington Formation (Miocene) of Derbyshire, UK

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Abstract

The Brassington Formation of Derbyshire and Staffordshire is the most extensive Miocene sedimentary succession in the UK. Due to its unique position at the margin of northwest Europe, the pollen from this lithostratigraphical unit provides evidence on the development of vegetation affected by North Atlantic currents and hypothesised atmospheric circulation changes while the climate cooled. Palynostratigraphy demonstrates that the uppermost Kenslow Member of the Brassington Formation is not coeval. The oldest pollen assemblage is from the more southernly Bees Nest Pit, which represents a subtropical conifer-dominated forest of late Serravallian age (c. 12 Ma). A younger assemblage was observed from the more northerly Kenslow Top Pit; this indicates that a subtropical mixed forest was present during the early Tortonian (11.6–9 Ma). The shift from a conifer-dominated to a mixed forest was related to precipitation. Whilst the total precipitation did not change between the two assemblages, the younger assemblage had more uniform rainfall throughout the year. The diachronous nature of the Kenslow Member means that the depositional model of the Brassington Formation needs revising, and this will have implications for Neogene to recent uplift of the southern Pennines.

Introduction (not headed)

Miocene sediments are poorly represented in the onshore UK rock record, especially when compared to extensive deposits of this age in continental Europe (Donders et al. 2009). The sparse onshore UK deposits include the aeolian/colluvial deposits of the St Agnes Outlier in Cornwall, pipe fills at Trwyn y Parc in Anglesey and weathering horizons in northeast Scotland (Walsh et al. 1987; 1996; Hall et al. 2015). However, the most geographically extensive and volumetrically abundant Miocene unit in the UK is the Brassington Formation of Derbyshire and Staffordshire (Boulter et al.

1971; Pound & Riding 2015). The Brassington Formation is predominantly a succession of sands, gravels and clays found in c. 60 karstic cavities distributed in three distinct clusters in the southern part of the Lower Carboniferous Peak Limestone Group outcrop of the Peak District (Fig. 1). The larger cavities were extensively quarried for silica sand brickmaking (Yorke 1954; 1961). The formation is considered to have formed from a continuous, extensive sheet of alluvial/fluvial/lacustrine sediment which blanketed much of the East Midlands during the Neogene (Walsh et al. 1980, fig. 15). Boulter & Chaloner (1970), Boulter (1971a;b) and Walsh et al. (1996) assigned the Brassington Formation to the Late Miocene to Early Pliocene based on palaeobotany. This age assessment was recently refined to Late Miocene (late Tortonian) based on palynostratigraphy (Pound et al. 2012a). The formation is located close to the anticlinal crest of the Pennine Hills, and hence the age of the Brassington Formation has been used to estimate uplift rates (Westaway 2009; 2012; Banks et al. 2012). This paper provides new palynological data from the two principal outcrops in both main Brassington Formation clusters which helps elucidate both the age, lithostratigraphy and palaeoenvironment of this important unit, and the geomorphology of the English Midlands.

Geological background and setting

The Brassington Formation is, by a considerable margin, the most important Miocene lithostratigraphical unit throughout onshore UK. It is up to 70 m in thickness, and found in steep-sided karst solution cavities in Derbyshire and Staffordshire (Fig. 1). It outcrops in a narrow, c. 20 km long NW-SW zone of the Peak Limestone Group massif (Ford & King 1969). This zone can be divided into three clusters of cavities. These are the Friden cluster in the north, the central Brassington cluster and the sourthernmost Weaver Hills cluster. The latter is in undolomitised limestone, whereas the former two clusters are largely in highly porous, intensely dolomitised limestone (Fig. 1). These infills of collapsed heterolithic siliciclastic material exhibit different architectures, but are largely synclinal (Ijtaba 1973). The formation was formalised by Boulter et al. (1971), who erected three members; these are the Kirkham, Bees Nest and Kenslow members in ascending stratigraphical order. The lowermost Kirkham Member is a thick (c. 55 m) succession of white and red unconsolidated sand, which is largely massive and sporadically pebbly and clay-rich. White sand overwhelmingly predominates over red, and this may represent bleaching. The overlying Bees Nest Member is 5–10 m of unfossiliferous variecoloured, predominantly red, sandy clays. The uppermost unit is the Kenslow Member, which is up to c. 5 m of fossiliferous grey clay. The fossil content entirely comprises plant remains, largely poorly-sorted wood fragments with some cones, fruits, leaves, pollen, seeds, spores and stems (Boulter & Chaloner 1970). The three members constitute a fining-upwards succession which appears to be stratigraphically coherent (Walsh et al. 1980; Pound et al. 2012a).

The genesis of the Brassington Formation has proved controversial. The current consensus postulates that it largely represents weathering products from Triassic strata, and was first deposited by alluvial, fluvial and lacustrine processes over the majority of the southern part of the White Peak of Derbyshire and Staffordshire. These sand-rich sediments overlaid the Lower Carboniferous (Tournasian to Visean) Peak Limestone Group and the lowermost Bowland Shale Formation (Serpukovian) (Walsh et al. 1980; Pound et al. 2012a). Small portions of the Brassington Formation serendipitously slumped post-depositionally into the karst cavities, hence protecting them from glacial erosion during the Quaternary (Walsh et al. 1972).

The Kirkham Member is composed of siliciclastic sheets of sands with clay and pebbles; these represent erosion products from the retreating sandstone escarpments of the Triassic Sherwood Sandstone Group. It was deposited northwards onto Carboniferous strata (Walsh et al. 1980). The overlying Bees Nest and Kenslow members represent low energy aquatic or lacustrine and shallow lacustrine/swampy settings respectively. The Triassic escarpments have now retreated but, because the Kirkham Member karst-fills are relatively uniform, the Sherwood Sandstone Group clearly formed an essentially continuous sheet over most of the southern part of the Peak District. In some of the cavities, the lowermost sediments (particularly those close to the cavity walls) are coarse chert gravels derived from the Peak Limestone Group and/or blocks of Bowland Shale Formation. The chert gravel clearly is an insoluble residue derived from weathering of the Peak Limestone Group. By contrast, the shale blocks are from the former cover of the Bowland Shale Formation, some of which exhibit evidence of intensive weathering.

The Brassington Formation today is c. 300–360 m above sea level (asl). During Miocene times, the region was 150–250 m lower in order for Triassic erosion products to be deposited. Analysis of palaeocurrents in the Brassington cluster indicate a southerly provenance (Walsh et al. 1980). It follows therefore that the southern Pennines have been subjected to significant uplift since the deposition of the Kenslow Member (Walsh et al. 1980). Based on the Tortonian age model of Pound et al. (2012a), and assuming that deposition was at or near sea level, a continuous uplift rate for this region is 0.03–0.06 mm a^{-1}. This is significantly lower than 0.1–0.13 mm a^{-1} suggested by Westaway (2009).

Materials and Methods

Bees Nest Pit is located immediately south of Manystones Lane between Brassington and Wirksworth; Kenslow Top Pit is to the east of Rake Lane, near Friden (Fig. 1; 2; Table 1). Two samples were taken from the grey lignitic clay from the top of the type section of the Brassington Formation at Bees Nest Pit (Fig. 2) (Boulter et al. 1971; Walsh et al. 1972). The grey lignitic clay is from the top of the Kenslow Member; this overlies 5 m of the varicoloured clays of the Bees Nest Member and c.35 m of the white silica sands of the Kirkham Member (Walsh et al., 1980). A further sample of grey clay was taken from a crack located in a large piece of fossil wood donated to the British Geological Survey (Fig. 3; BGS fossil specimen number GSM 76976). The wood fragment came from the Kenslow Member at the west end of Kenslow Top Pit (Fig. 2) (Walsh et al., 1980) and was illustrated by Yorke (1961, fig. 62). The two samples from Bees Nest Pit (Table 1: KM-1a; b) and the grey clay from the Kenslow Top Pit wood fragment (Table 1: KM-2) were processed for palynomorphs. One sample from Bees Nest Pit (KM-1a) and KM-2 were processed through the standard acid digestion method (e.g. Wood et al. 1996). The other sample from Bees Nest Pit (KM-1b) was processed using the sodium hexametaphosphate technique of Riding and Kyffin-Hughes (2004; 2006). Pollen residues were mounted in elvacite and examined under a transmitted light microscope. Pollen and spore identification principally used Boulter (1971a), Stuchlik et al. (2001; 2002; 2009; 2014), Beug (2004) and the pollen reference collection at Northumbria University. To reconstruct palaeoclimate parameters, the Co-existence Approach (CA) was used with the NECLIME Palaeoflora database (Mosbrugger & Utescher, 1997; Utescher & Mosbrugger, 2010; Utescher et al., 2014). Modern relic taxa such as *Cathaya* and *Sciadopitys* had a much wider geographical distribution during the Cenozoic (Liu & Bassinger, 2000). This has the potential to bias the CA results; therefore the proposals of Utescher et al. (2014) for these relic taxa were followed. Using the overlapping envelopes of a pollen assemblages Nearest Living Relatives it has been possible to reconstruct seven parameters. These are: Mean Annual Temperature (MAT); Coldest Month Mean Temperature (CMMT); Warmest Month Mean Temperature (WMMT); Mean Annual Precipitation (MAP); Wettest Month Mean Precipitation (MPwet); Driest Month Mean Precipitation (MPdry); and Warmest Month Mean Precipitation (MPwarm).

Results

Palynology

The palynological results are presented herein in Table 2 and Figs. 4 and 5. The palynoflora from the grey lignitic Kenslow Member clay at Bees Nest Pit (KM-1) is dominated by gymnosperm taxa (86.2%), with angiosperms and spores being minor components of the assemblage (6.6% and 0.8% respectively); 6.4% of pollen grains proved indeterminate (Fig. 4). Both the acid (KM-1a) and non-acid processing technique (KM-1b) yielded the same palynoflora from Bees Nest Pit, and as such the pollen assemblage will be described here as a single assemblage (KM-1) (Fig. 4). *Pinus* dominates the flora (38.6%) with *Picea* (13.2%), *Sciadopitys* (10.4%) and *Tsuga* (9.9%) all being major components of the palynomorph assemblage (Fig. 4). Other gymnosperm pollen recorded includes Cupressaceae (4.7%), *Cathaya* (4.1%), *Cedrus* (4.3%) and *Keteleeria* (0.9%) (Fig. 4). The most abundant angiosperm pollen in the grey lignitic clay is of *Ilex* type (*Ilexpollenites iliacus*) (2.1%), *Carya* (1.6%) and *Quercus* type (*Quercoidites microhenrici*) (Fig. 4). Other angiosperm pollen present include *Alnus*, cf. *Asperula* (Rubiaceae), *Betula*, Ericaceae (both *Ericipites baculatus* and *E. callidus* are present), Poaceae and cf. *Rhamnus* in low percentages (<1%) (Fig. 4). Spores are rare in the grey lignitic clay with the most abundant (0.5%) being those of the Lygodiaceae (*Leiotriletes wolffii*). Single specimens of *Lycopodium* and Polypodiaceae spores were also recorded (Fig. 4).

The Kenslow Top Pit wood fragment (KM-2) also derives from the lignitic clay of the Kenslow Member. The palynoflora from clay adhering to this wood fragment is dominated by gymnosperm taxa (50.1%). However, in KM-2, the angiosperms (33.8%) and spores (7.8%) are more numerous than in KM-1, whilst 8.3% of pollen grains were indeterminate (Table 2; Fig. 4). The dominant taxa are Ericaceae (25.2%), *Pinus* (20.4%), *Tsuga* (9.3%) and *Picea* (7.1%) (Fig. 4). The Ericaceae are represented by *Ericipites ericius*, *E. costatus,* Ericaceae indeterminate (3.3%) and *E. baculatus* (3.0%) (Fig. 4). The gymnosperms are also represented by pollen of Cupressaceae (4.5%), *Cedrus* (3.8%), *Cathaya* (2.8%), *Keteleeria* (1.3%) and *Sciadopitys* (1.0%) (Fig. 4). Angiosperm pollen, other than Ericaceae, are more diverse in KM-2 than in KM-1, but do not occur in high proportions (Fig. 4). Most abundant, after Ericaceae, are pollen of Poaceae (2.0%), *Corylopsis* (1.3%) and *Corylus* (1.0%). *Alnus*, *Compositoipollenites rizophorous*, *Ilexpollenites iliacus*, *I. margaritatus*, *Juglans*, *Liquidambar*, *Quercoidites microhenrici*, *Symplocoipollenites vestibulum*, *Symplocospollenites rotundus* and *Ulmus* all occur as less than 1% of the assemblage (Fig. 4). Spores of Bryophytes, Lycopodiophytes and Pteridophytes are also more diverse KM-2 than in KM-1 (Fig. 4). *Triplanosporites sinuous* (4.3%) is the most common, followed by spores of *Sphagnum* (1.5%), *Leiotriletes wolffi* (1.3%) and *Lycopodium* (<1%) (Fig. 4).

Palaeoclimate

The flora from KM-1 represents a subtropical, seasonally wet climate with a MAT of 17–18.4 °C (Fig. 6).The WMMT was reconstructed as 26.5–28.3°C, and the CMMT as 6.2–12.5 °C (Fig. 6). Using the co-existence approach, the MAP of the flora from KM-1 was reconstructed as 1146–1322 mm yr^{-1} (Fig. 6). Precipitation was not evenly distributed throughout the year; MPwet was 225–293 mm, MPdry was 8–32 mm and MPwarm was reconstructed as being close to the MPwet 175–217 mm (Fig. 6). The palynoflora from KM-2 also represents a subtropical, seasonally wet climate with a MAT of 17–18.4°C (Fig. 6). The reconstructed WMMT was 26.5–28.3°C and the CMMT was 6.2–6.7 °C (Fig. 6). MAP was 1096–1562 mm yr^{-1} with a pronounced seasonality; the MPwet was 216–293 mm and MPdry was 7–41 mm. The warmest month was neither the driest nor the wettest month because MPwarm was 173–175 mm (Fig. 6).

Palynostratigraphy

The age of the uppermost Kenslow Member of the Brassington Formation was originally defined as Late Miocene–Early Pliocene, based on the pollen floras from the plant-bearing grey clay at Bees Nest and Kenslow Top pits (Fig. 7) (Boulter, 1971a; 1971b; Boulter et al., 1971). This was subsequently revised to Late Miocene, most likely late Tortonian (9–7 Ma), by Pound et al. (2012a) using a previously undescribed flora from a mottled grey-brown clay from the east end of Kenslow Top Pit (Table 1; 2: KM-3). This age assignment came from the presence of *Quercoidites microhenrici* and Symplocaceae pollen, together with sparse *Carya* and the absence of Arecaceae pollen (Pound et al., 2012a). However, the pollen floras of KM-1 from the Bees Nest Pit Kenslow Member and KM-2 from the Kenslow Member of the west end of Kenslow Top Pit are significantly different to the KM-3 flora reported by Pound et al. (2012a).

The higher occurrence of *Carya* in the KM-1 suggests that this occurrence of the Kenslow Member is older than both KM-2 and KM-3 (Fig. 4; 7). *Carya* is a typical component of Middle Miocene floras of northwest Europe (Donders et al., 2009; Larsson et al., 2011). However, many Middle Miocene samples have higher pollen diversities than either of the samples reported here; often with abundant thermophilic elements, corresponding to the Mid-Miocene Climatic Optimum (MMCO) (Nagy, 1990; Jiménez-Moreno et al., 2005; Larsson et al., 2011). Whilst KM-1 contains one taxon considered to be a thermophilic Rubiaceae (Jiménez-Moreno, 2006), it does not contain members of the Arecaceae or other megathermic or thermophilic taxa typical of MMCO European pollen assemblages (Jiménez-Moreno, 2006; Uhl et al., 2006; Jiménez-Moreno & Suc, 2007). It is therefore considered to be younger than the MMCO (17–14.5Ma), but older than the late Tortonian (9–7.25

Ma) KM-3 flora reported in Pound et al. (2012a). The KM-1 flora from the Bees Nest Pit Kenslow Member is low-diversity, which makes it difficult to directly compare to samples from continental Europe (which typically have higher diversities). However, a high proportion of Pinaceae pollen (71.13%) and *Carya* (the second most abundant angiosperm pollen) makes it comparable to the Serravallian (13.65–11.61 Ma of Austria (Jiménez-Moreno et al., 2008), Denmark (Larsson et al., 2011) and France (Gardère & Pais, 2007). The relatively high-proportion of *Sciadopitys* (Fig. 4) may correspond to the second *Sciadopitys* maximum in the successions of the Lower Rhine District which is in the upper Serravallian Garzweiller Seam (Zagwijn & Hager, 1987; Utescher et al., 2012).

The key pollen taxa used to date the KM-3 flora of Pound et al. (2012a) are present in the KM-2 sample from the Kenslow Top Pit wood fragment (Fig. 3; Table 1; 2), and therefore this sample can also be attributed to the Late Miocene (Fig. 7). Proportional comparison with continental European sites is difficult because, although many show increasing-amounts or peaks in Ericaceae pollen, it was not a dominant element (Gardère & Pais, 2007; Worobiec, 2009; Larsson et al., 2011) until the Taxodiaceae-Ericaceae coastal Atlantic forests of the Early Pliocene (Fauquette et al., 2007). However, an Early Pliocene age is precluded due to the presence of pollen types indicative of the Late Miocene (Donders et al., 2009; Ivanov et al., 2010; Pound et al., 2012a). *Triplanosporites sinuosus* is the most common spore in the assemblage, and is not known after the Middle Miocene in Poland (Stuchlik et al., 2001). The differences with the KM-3 assemblage reported in Pound et al. (2012a) are difficult to attribute to geographical differences, because the two samples come from the same karstic depression, and are only c. 200 m from each other (Fig. 2). Therefore the proportional differences (Fig. 4; Table 2) are likely to stem from some temporal difference. As KM-2 contains *Cathaya* sp. and shares lithological characteristics with the Kenslow Member at Bees Nest Pit (Boulter et al., 1971; Walsh et al., 1980), it is likely to be temporally intermediate between the palynologically younger and (?)stratigraphically higher KM-3 sample of Pound et al. (2012a) and the older, stratigraphically comparable Bees Nest Pit Kenslow Member. It is therefore proposed to be early Tortonian in age (11.61–9 Ma), possibly late Serravallian if *Triplanosporites sinuosus* can be proven to be stratigraphically important (Fig. 7). The pollen and spore assemblages of the Kenslow Member therefore suggest variable deposition times between the lithologically comparable fossil wood-bearing grey clays (Kenslow Member of Bees Nest Pit (KM-1) and the Kenslow Member of Kenslow Top Pit (KM-2)) and the stratigraphically higher mottled clay (KM-3) described by Pound et al. (2012a) (Fig. 7;8).

Palaeoecology

The Kenslow Member has preserved a diverse palynomorph assemblage that indicates the presence of different vegetation types during the Middle to Late Miocene from the western margin of northwest Europe. All three assemblages are dominated by pollen from trees and shrubs, demonstrating the presence of a forest type biome during Kenslow Member times (Pound et al., 2012a; b). However, there is a decrease in the proportion of trees and shrubs from the oldest assemblage (KM-1) to KM-3, the youngest association (Fig. 5); this trend was previously reported in Pound et al. (2012b). This decrease in trees and shrubs is matched by an increase in the proportion of herbaceous and understory taxa (Fig. 5), which was a common trend across Europe during the late Neogene (e.g. Larsson et al., 2011). Fern spores are most dominant in KM-2 (considered to be stratigraphically and temporally in the middle of the Kenslow Member), whilst the youngest KM-3 sample contains the highest proportion of *Sphagnum,* and represents a warm-temperate mixed forest (Pound et al., 2012a).

The oldest KM-1 palynomorph assemblage, from the Kenslow Member at Bees Nest Pit is dominated by conifers, with a low proportions of angiosperms and ferns (Fig. 4). *Pinus* dominates the assemblage, but this genus is commonly over-represented in palynomorph assemblages, whereas other gymnosperm taxa may be under-represented (Webb & McAndrews, 1976; Pound et al., 2015). *Sciadopitys* comprises 10.4% of the assemblage and today is represented by a single species. This is *Sciadopitys verticillata* which inhabits temperate regions of Japan between the altitudes of 300 and 1500 m, although its natural range has been greatly modified by anthropogenic activity (Tsukada, 1963). During the Neogene it was a common component of the peat-forming swamp community (Figueiral et al., 1999; Ivanov et al., 2007) and is found abundantly in the post-glacial bogs of Japan (Tsukada, 1963). It is also considered to be a component of the Miocene well-drained lowland conifer forests in association with *Cathaya*, *Cedrus*, *Pinus*, *Sequoia* and *Tsuga* (Larsson et al., 2011). The Kenslow Member sediment which yielded the Bees Nest Pit pollen assemblage also contains large fragments of wood up to 1 m long (Fig. 3). This wood has previously been identified as *Sequoia* by Yorke (1954), and reassessed as *Cryptomeria anglica* by Boulter (1969), Boulter & Chaloner (1970) and Boulter (1971). Pollen identified and counted as Cupressaceae in this study includes pollen that is attributable to *Cryptomeria* type (Boulter, 1971). Today this genus is monotypic and inhabits humid warm-temperate to cool-temperate areas of China and Japan (Tsukada, 1982). At the southern limit of its distribution on Yakushima Island, Japan (30.5°N, 130.5°E), *Cryptomeria japonica* co-dominates forests with *Tsuga sieboldii* and *Abies firma* from altitudes of 800 to 1800 m, in a subtropical humid climate (Suzuki and Tsukahara, 1987). A subtropical humid climate is also reconstructed from the Co-existence Approach results (Fig. 6). A MAT of 17–18.4°C, with mild winters of >6.2°C and hot summers of 26.5–28.3°C (Fig. 6) is envisaged. Precipitation was high, but seasonally distributed with the wettest month receiving 225–293 mm, and the driest month as little as 8 mm (Fig. 6). As the reconstructed range for the warmest month is 175–217 mm, it may be that the wettest period was late spring to early summer, which is comparable to the modern forests of *Cryptomeria japonica* on Yakushima Island (Suzuki & Tsukahara, 1987). A subtropical forest environment is supported by the dominant angiosperms in the assemblage such as *Carya*, Ericaceae, *Ilex* and evergreen *Quercus* (Fig. 4; Table 2). These are typical indicators of the Miocene mesothermic forests. The dominance of conifer pollen and wood in the Kenslow Member of Bees Nest Pit indicates that a warm-temperate, predominantly needleleaf, forest was growing in Britain during the late Serravallian.

The KM-2 palynomorph assemblage contains a high proportion of Ericaceae grains (Fig. 4). Boulter (1971) originally interpreted this as reflecting a heathland that would have inhabited surrounding uplands. However, the Neogene warm-temperate forests of Europe would have had an extensive shrub layer, and the Ericaceae have been frequently assigned to this ecological group (Ivanov et al., 2007; Larsson et al., 2011). Several of the Ericaceae grains in the Kenslow Top Pit wood fragment (*Ericipites callidus*, *E. costatus* and *E. ericius*) have affinities with the genus *Vaccinium* (Table 2). Modern species of this genus can achieve prodigious sizes, for example *Vaccinium arboreum* forms a medium to large shrub (up to 10 m high) in the mesophytic forests of Florida and Louisiana (Wenslaff & Lyrene, 2003). In the southern mixed hardwood forests of North America, *Vaccinium arboreum* is structurally important to the understory of both the transitional forests between the early pine-dominated stands and the near-climax pine-hardwood forests (Quarterman & Keever, 1962). Aside from the dominance of Ericaceae pollen, KM-2 also contains a greater number of angiosperm taxa than KM-1 (Fig. 4; Table 2). The presence of *Juglans* sp., *Liquidambar* sp. and *Symplocos* spp. shows a strong affinity with continental European warm-temperate mixed forests during the Serravallian and Tortonian (Ivanov et al., 2007; Larsson et al., 2011; Szulc & Worobiec, 2012). The wood fragment that the pollen assemblage was extracted from is *Cryptomeria anglica*, thereby demonstrating that these trees were members of the forest community that surrounded the depositional setting. This similarity with the Bees Nest Pit is also seen in the diversity of gymnosperm taxa, and the high proportion of *Pinus* sp. and *Tsuga* sp. (Fig. 4; Table 2). Climatically, the Co-existence Approach reconstruction shows that only the warmest month precipitation was likely to have been different from that reconstructed by the Bees Nest Pit pollen assemblage (Fig. 6). However, the high angiosperm proportions and the spore content (Fig. 5) shows that the flora is distinctly different. The spore assemblage is dominated by *Triplanosporites sinuosus* that has no confirmed modern relative. However, Chateauneuf (1980) compared the genus to members of the family Lygodiaceae, whilst Stuchlik et al. (2001) demonstrated morphological similarities with some members of the genus

Cyathea. Today, species of Cyatheaceae and Lygodiaceae are found in tropical, sub-tropical and temperate zones, and have been assigned to the understory component of swampy or riparian forests during the Miocene (Kayseri-Özer et al., 2014). The entire flora from KM-2 reconstructs a warm-temperate mixed forest with an extensive understory component (Fig. 4).

Discussion

Multiple Miocene ages for the Kenslow Member

Based on the palynostratigraphy of the Kenslow Member samples from Bees Nest Pit (KM-1) and the wood fragment from Kenslow Top Pit (KM-2), the Kenslow Member was deposited diachronouosly (Fig. 7; 8). Furthermore, the KM-3 assemblage from the east side of Kenslow Top Pit reported by Pound et al. (2012a) is younger than both the Kenslow Member at Bees Nest Pit and the Kenslow Member at the west end of Kenslow Top Pit. This implies that this youngest pollen and spore assemblage was deposited in an unidentified lithological unit of the Brassington Formation at Kenslow Top Pit that may be equivalent to the uppermost clays of the Kenslow Member reported from Kirkhams Pit by Walsh et al. (1980). These diachronous ages for the Kenslow Member may be explained in several ways. Palaeocurrent indicators from the sands of the Kirkham Member at Bees Nest Pit indicate that sediment was supplied from the south (Walsh et al., 1980). Similarly, palaeocurrent proxies for the more northern Friden cluster of pits mainly show sediment being transported from the south, but some material is of western and northern provenance (Walsh et al., 1980). As most palaeocurrent proxies indicate a sediment source from the south, the Miocene depocentre of the southern Pennines may have slowly shifted north, thus accounting for the younger age of the Kenslow Member at the more northerly Kenslow Top Pit. An alternative hypothesis posits uniform deposition ages for the Kirkham Member, and possibly the Bees Nest Member, followed by asynchronous subsidence of the various pockets, and deposition of the Kenslow Member into these hollows (Pound et al., 2012a). This diachronous subsidence and deposition of the Kenslow Member would be comparable to the procesess that formed the karstic fill of the Gray Fossil Sites of Tennessee, USA (Zobaa et al., 2011).

The new palynostratigraphical age assessments for the Kenslow Member of the Brassington Formation provide evidence for a poorly-known part of the onshore UK geological record and have implications for the uplift of the Pennines (Walsh et al., 1972; Westaway, 2009; Pound et al., 2012a). Pennine uplift has been estimated on the assumption that the Brassington Formation was deposited at or near sea-level and subsequently foundered into the karstic hollows (Walsh et al., 1972; Westaway, 2009). Calculating a time-averaged uplift rate has been a relatively simple matter of dividing the degree of uplift by the age of the Kenslow Member (Westaway, 2009; Pound et al., 2012a). In Westaway (2009), the age of the Kenslow Member was taken as Early Pliocene, giving an uplift rate of 0.10–0.13 mm yr^{-1}, based on an uplift of 300 m from the Brassington Formation at sea-level to the present day topography. Subsequently Pound et al. (2012a) demonstrated that the Kenslow Member is late Tortonian in age, and therefore a time-averaged uplift rate of 0.03–0.06 mm yr^{-1} was determined. The multiple ages for the Kenslow Member (Fig. 7; 8) mean that the estimate of Pound et al. (2012a) is the most rapid time-averaged estimate possible. Moreover, the time-averaged uplift rates depend on the Brassington Formation being entirely deposited before karstification took place (Westaway, 2009). If, the karstic hollows formed asynchronously during Brassington Formation deposition, with each Kenslow Member then forming in the hollow, then the use of this unit to determine Pennine uplift requires further research.

Miocene climates and vegetation

The palynological data and interpretations on the Brassington Formation material studied herein provides evidence for an important interval in geological time. The Miocene was an interval that was both warmer and wetter than the present day (Utescher et al., 2011; Pound et al., 2012b; Denk et al., 2013; Quaijtaal et al., 2014). These warmer than present day climates peaked during the Middle Miocene Climatic Optimum (MMCO) between 17 and 14.5 Ma. Then, the global climate cooled steadily with six Miocene isotope events (Mi-events) indicating that there was a step-like pattern to the cooling (Quaijtaal et al., 2014). The regions immediately adjacent to the North Atlantic do, however, show a more muted response to the Miocene cooling than more continental regions due to the influence of the North Atlantic Thermohaline Circulation (NATC) (Pound et al., 2012b; Denk et al., 2013; Utescher et al., 2015). During the Miocene, the British Isles formed a peninsula separating the Atlantic Ocean from the North Sea (Harzhauser & Piller, 2007). This unique location on the northwest edge of the Eurasian continent, separating the Atlantic Ocean from the North Sea, makes the albeit sparse Miocene sediments of the UK ideal for understanding the development of Neogene oceanic climates.

The Brassington Formation has now revealed three windows into this interval of global climatic cooling (Figs. 4; 6; 7). The oldest sample (KM-1) from the Kenslow Member at Bees Nest Pit shows that a subtropical, seasonally wet, conifer-dominated forest inhabited the outer margin of northwest

Europe at around 12 Ma (Figs. 4; 6). Periods of proportionally higher conifer concentrations have been identified in the Serravallian of the Porcupine Basin, offshore southwest Ireland (Quaijtaal et al., 2014; 2015). The middle to late Serravallian has also been identified as a warm and dry interval in the Roer Valley Graben in the southeast of the Netherlands (Donders et al., 2009). The latest Serravallian in Portugal and central Europe has also been identified as an interval of relatively low precipitation (Antunes & Pais, 1984; Böhme et al., 2008). Following this, there were then two "washhouse" intervals at c. 10 Ma and 9–8 Ma in Europe associated with tectonic changes in Central America (Böhme et al., 2008). However, the MAP reconstructed from the three Brassington Formation floras is significantly higher than estimates for the Iberian Peninsula and central Europe based on herpetological data (Böhme et al., 2008). This supports the small-mammal based reconstructions of van Dam (2006), that the modern west–east precipitation gradient was already well-established during the late Middle Miocene. Changes in the MPwarm of the flora preserved in the Kenslow Member may reflect the hypothesised shifting of atmospheric circulation between the Serravallian and the Tortonian (Quan et al., 2014).

Comparing the new temperature reconstructions for the Kenslow Member flora herein with those of continental Europe shows comparable MATs to the records from the Netherlands (Donders et al., 2009). However warmer MATs and CMMTs have been reconstructed for leaf floras from the Weisselster and Molasse basins (northeast and southern Germany, respectively), which may have had a colder climate that was less influenced by the NATC (Mosbrugger et al., 2005). The WMMT of both the Tortonian Kenslow Top Pit floras are higher than other northern European localities that bordered the then isolated North Sea (Quan et al., 2014). This shows that, despite a globally warmer climate, the NATC had a warming effect on the terrestrial realms bordering the North Atlantic (Denk et al., 2013). The warmer than present MATs reconstructed for the Tortonian Kenslow Top Pit floras (Fig. 6) are inconsistent with climate model results for this region, which either show cooler than modern temperatures or no change (Knorr et al., 2011; Micheels et al., 2011). Some of this data–model disparity may stem from the manner that vegetation and land-surfaces are treated in each model (Knorr et al., 2011; Micheels et al., 2011; Pound et al., 2011). However, neither of the two floras reported for the Tortonian of the Brassington Formation are inconsistent with the current global vegetation reconstruction (Pound et al., 2011). The way vegetation is represented in climate models may be causing at least some of this mismatch. The Miocene forests of northwest Europe would have had considerable stature; modern old-stand *Cryptomeria japonica* attain heights of up to 65 m and *Scidopitys verticillata* can reach 45 m. Both these species can live for thousands of years (Tsukada, 1963; 1982; Suzuki & Tsukahara, 1987). This situation has implications for the accurate simulation of carbon cycling, evapotranspiration and surface roughness (Cox, 2001; Essery et al.,

2001) in Miocene climate modelling studies. Most vegetation and land surface scheme models use parameters defined from common modern trees, rather than those that were typical of the Neogene. For example within the widely used Meteorological Office Surface Exchange Scheme (MOSES), evergreen needleleaf trees are assigned a fixed height of only 10 m (Hough & Jones, 1997; Cox et al., 1999; Pound et al., 2011). Correct boundary conditions, however small, can have important regional impacts (Krinner et al., 2012; Pound et al., 2014). Therefore it is important for palaeoclimate modelling studies to work closely with the palaeontological data community to develop realistic simulations of past climates.

Conclusions

From two new palynomorph assemblages, the age of the Kenslow Member of the Brassington Formation is refined, and deposition is shown to be diachronous. This new evidence changes our understanding of the Brassington Formation, and makes a sedimentological restudy essential. The oldest flora is from the late Serravallian, and was produced by a subtropical, seasonally wet conifer-dominated forest. Sediments of the Serravallian were previously unknown from onshore UK. The second new flora is slightly younger (early Tortonian), and represents a subtropical mixed forest with a high proportion of representatives of the Ericaceae. When combined with the palynoflora of Pound et al. (2012a), the late-Middle–Late Miocene record of the UK demonstrates a general cooling trend comparable to the more complete continental records. However, the floras from the Brassington Formation provide a unique view on the development of European precipitation records, and may support the hypothesised regional shift in wind directions from the Serravallian into the Tortonian by Quan et al. (2014).

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Sample number	Grid reference	Locality	Latitude	Longitude	Lithotype	Description
KM-1a; b	SK 24100 54580	Bees Nest Pit	53.08	-1.64	Grey clay	Grey fossiliferous clay of the Kenslow Member, north side of pond to the east of the pit entrance
KM-2	SK 18185 61586	Kenslow Top Pit*	53.15	-1.73	Grey clay	Grey clay extracted from a cavity in a fossil wood fragment, which originally came from the Kenslow Member at Kenslow Top Pit
KM-3	SK 18289 61420	Kenslow Top Pit	53.15	-1.73	Mottled grey-brown clay	Pollen sample reported in Pound et al. (2012a)

Table 1. Sample details of the three pollen assemblages extracted from the Kenslow Member of the Brassington Formation. The grid reference for KM-2 is based on the locality map of Walsh et al. (1972).

Division	Family	Pollen/spore	Nearest Living Relative	KM-1 Bees Nest Pit, Kenslow Member	KM-2 Kenslow Top Pit, Kenslow Member (clay from wood fragment)	KM-3 Kenslow Top Pit (Pound et al., 2012a)
Bryophyta	Sphagnaceae	*Stereisporites* spp.	*Sphagnum* spp.	0.00%	1.51%	11.58%
Lycopodiophyta	Lycopodiaceae	*Lycopodium* sp.	*Lycopodium* spp.	0.13%	0.76%	0.00%
Pteridophyta	Lygodiaceae	*Leiotriletes wolffi*	*Lygodium* spp.	0.53%	1.26%	0.00%
	Osmundaceae	*Osmunda* sp.	*Osmunda* spp.	0.00%	0.00%	1.76%
	Polypodiaceae	*Verrucatosporites favus*	Polypodiaceae	0.13%	0.00%	0.28%
	Unknown	*Triplanosporites sinuous*	Unknown	0.00%	4.28%	0.00%
Gymnosperm	Cupressaceae	Cupressaceae	Cupressaceae	4.68%	4.53%	1.11%
	Pinaceae	*Abies* sp.	*Abies* spp.	0.00%	0.00%	1.76%
		Cathaya sp.	*Cathaya* spp.	4.14%	2.77%	0.00%
		Cedrus sp.	*Cedrus* spp.	4.28%	3.78%	2.69%
		Keteleeria sp.	*Keteleeria* spp.	0.94%	1.26%	0.00%
		Picea sp.	*Picea* spp.	13.24%	7.05%	3.06%
		Pinus sp.	*Pinus* spp.	38.64%	20.40%	10.38%
		Tsuga sp.	*Tsuga* spp.	9.89%	9.32%	0.74%
	Sciadopityaceae	*Sciadopitys* sp.	*Sciadopitys verticillata*	10.43%	1.01%	0.00%
Angiosperm	Araliaceae	*Hedera* sp.	*Hedera* spp.	0.00%	0.00%	0.74%
	Asteraceae	Asteraceae	Asteraceae	0.00%	0.00%	0.37%
	Aquifoliaceae	*Ilexpollenites iliacus*	*Ilex* spp.	2.14%	0.50%	0.00%
		Ilexpollenites magaritatus	*Ilex* spp.	0.00%	0.76%	0.00%
	Betulaceae	*Alnus* sp.	*Alnus* spp.	0.27%	0.76%	1.39%
		Carpinus sp.	*Carpinus* spp.	0.00%	0.00%	2.59%
		Corylus sp.	*Corylus* spp.	0.00%	1.01%	0.09%
		Trivestibulopollenites betuloides	*Betula* spp.	0.27%	0.00%	4.26%
	Caryophyllaceae	Caryophyllaceae	Caryophyllaceae	0.00%	0.00%	3.61%
	Ericaceae	Ericaceae	Ericaceae	0.00%	3.27%	7.88%
		Ericipites baculatus	Ericaceae	0.13%	3.02%	0.00%
		Ericipites callidus	*Calluna* spp., *Vaccinium* spp.	0.27%	0.00%	0.00%
		Ericipites costatus	*Vaccinium vitis-idae*, *Andromeda* spp., *Pieris* spp.	0.00%	3.78%	0.00%
		Ericipites ericius	*Calluna* spp., *Daboecia* spp., *Vaccinium* spp.	0.00%	15.11%	0.00%
	Fabaceae?	*Tricolpopollenites ipilensis*	Fabaceae	0.00%	0.00%	0.09%
		Tricolpopollenites liblarensis	Fabaceae	0.00%	0.00%	1.20%
	Fagaceae?	*Tricolpopollenites microhenrici*	*Quercus* spp.	1.07%	0.25%	0.93%

	Hamamelidaceae	*Corylopsis sp.*	*Corylopsis* spp.	0.00%	1.26%	0.00%
		Liquidambar sp.	*Liquidambar* spp.	0.00%	0.50%	1.02%
	Icacinaceae	*Compositoipollenites rizophorus*	Icacinaceae	0.00%	0.25%	20.11%
	Juglandaceae	*Carya* sp.	*Carya* spp.	1.60%	0.00%	0.09%
		Juglans sp.	*Juglans* spp.	0.00%	0.25%	0.56%
	Myricaceae	*Myrica* sp.	*Myrica* spp.	0.00%	0.00%	0.56%
	Plumbaginaceae	*Armeria* sp.	*Armeria* spp.	0.00%	0.00%	1.30%
		Limonium sp.	*Limonium* spp.	0.00%	0.00%	2.87%
	Poaceae	Poaceae	Poaceae	0.40%	2.02%	3.61%
	Polemoniaceae	*Polemonium* sp.	*Polemonium* spp.	0.00%	0.00%	0.93%
	Polygonaceae	*Polygonum* sp.	*Polygonum* spp.	0.00%	0.00%	1.20%
	Rhamnaceae	cf. *Rhamnus* sp.	*Rhamnus* spp.	0.13%	0.00%	0.00%
	Rubiaceae	cf. *Asperula* sp.	*Asperula* spp.	0.13%	0.00%	0.00%
	Sapindaceae	*Aesculus* sp.	*Aesculus* spp.	0.00%	0.00%	0.09%
	Saxifragaceae	*Saxifraga* sp.	*Saxifraga* spp.	0.00%	0.00%	0.09%
	Smilacaceae	*Periporopollenites echinatus*	*Smilax* spp.	0.00%	0.00%	1.30%
	Symplocaceae	*Symplocoipollenites vestibulum*	*Symplocos* spp.	0.00%	0.25%	0.83%
		Symplocospollenites rotundus	*Symplocos* spp.	0.00%	0.50%	0.00%
	Ulmaceae	*Ulmus* sp.	*Ulmus* spp.	0.13%	0.25%	2.78%
		Indeterminate		6.42%	8.31%	6.12%

Table 2: Percentages of pollen and spores from the Kenslow Member of the Brasssington Formation at Bees Nest and Kenslow Top pits.

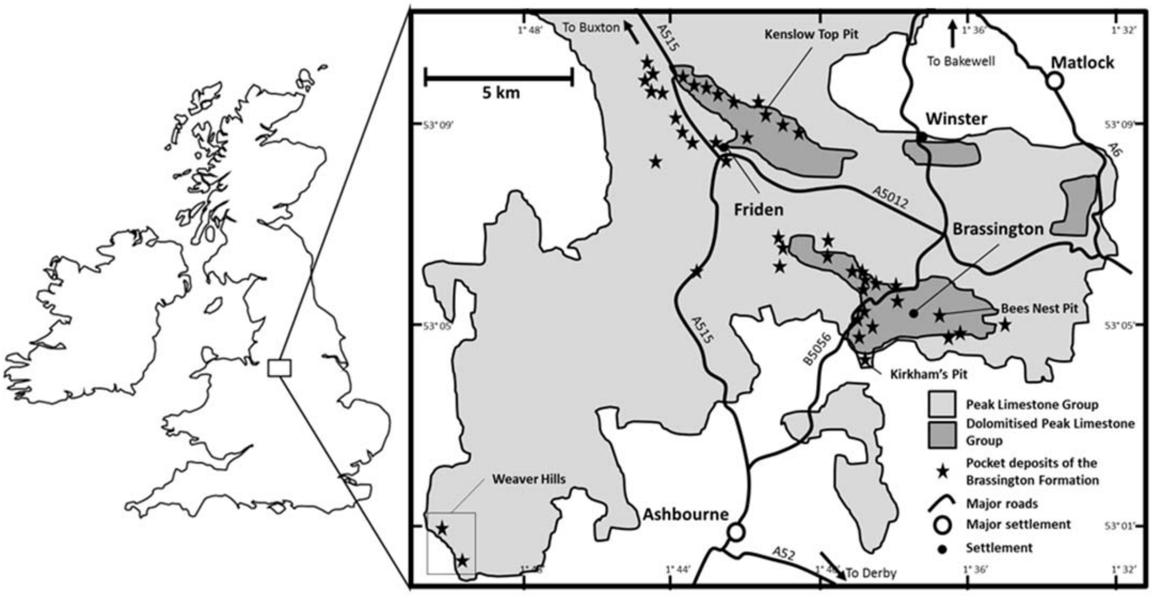


Figure 1. The location of Bees Nest and Kenslow Top pits on a sketch geological map of parts of Derbyshire and Staffordshire, UK illustrating the distribution of dolomitised limestone in the southern Pennines. Adapted from Pound et al. (2012a)

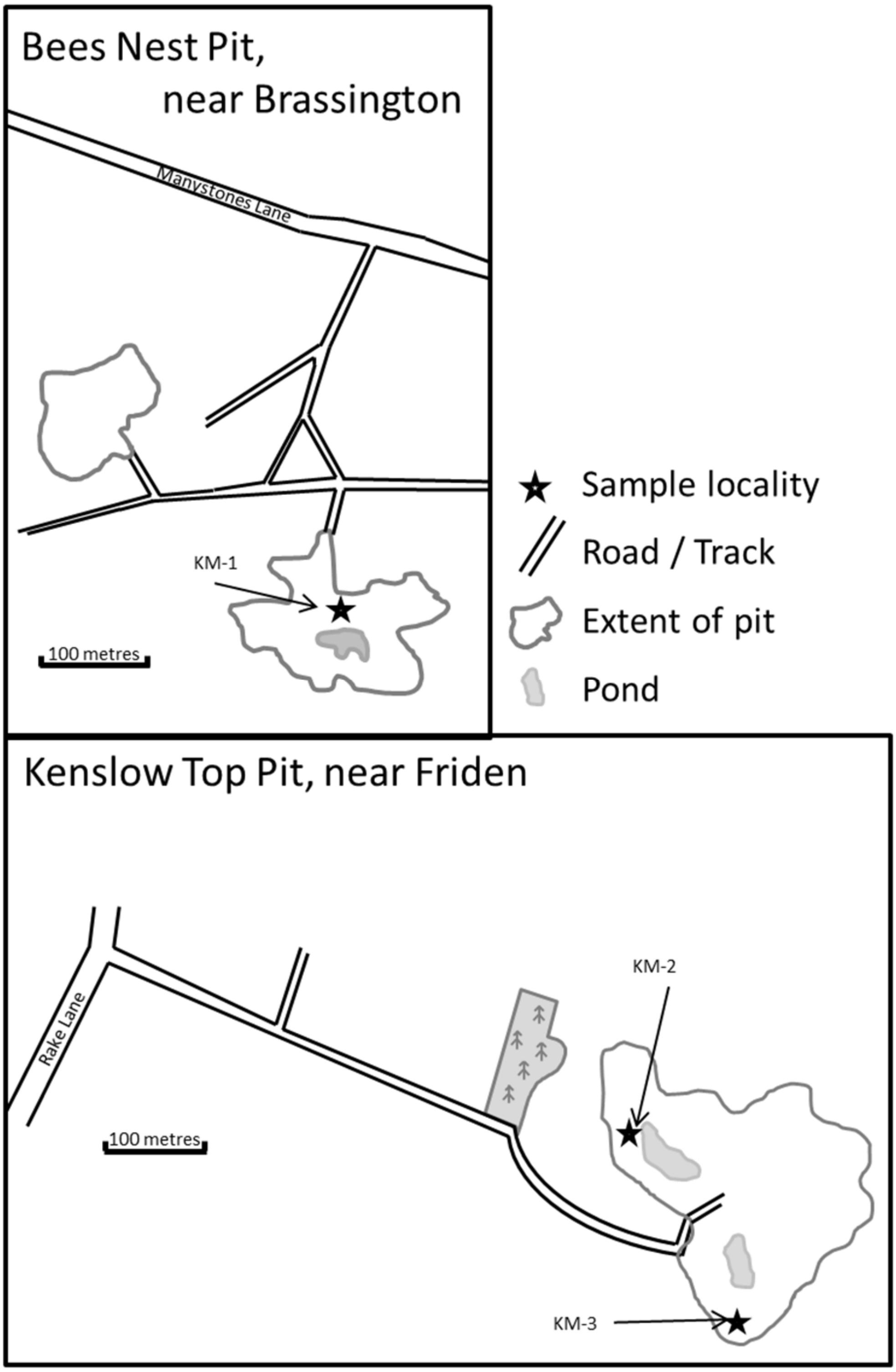
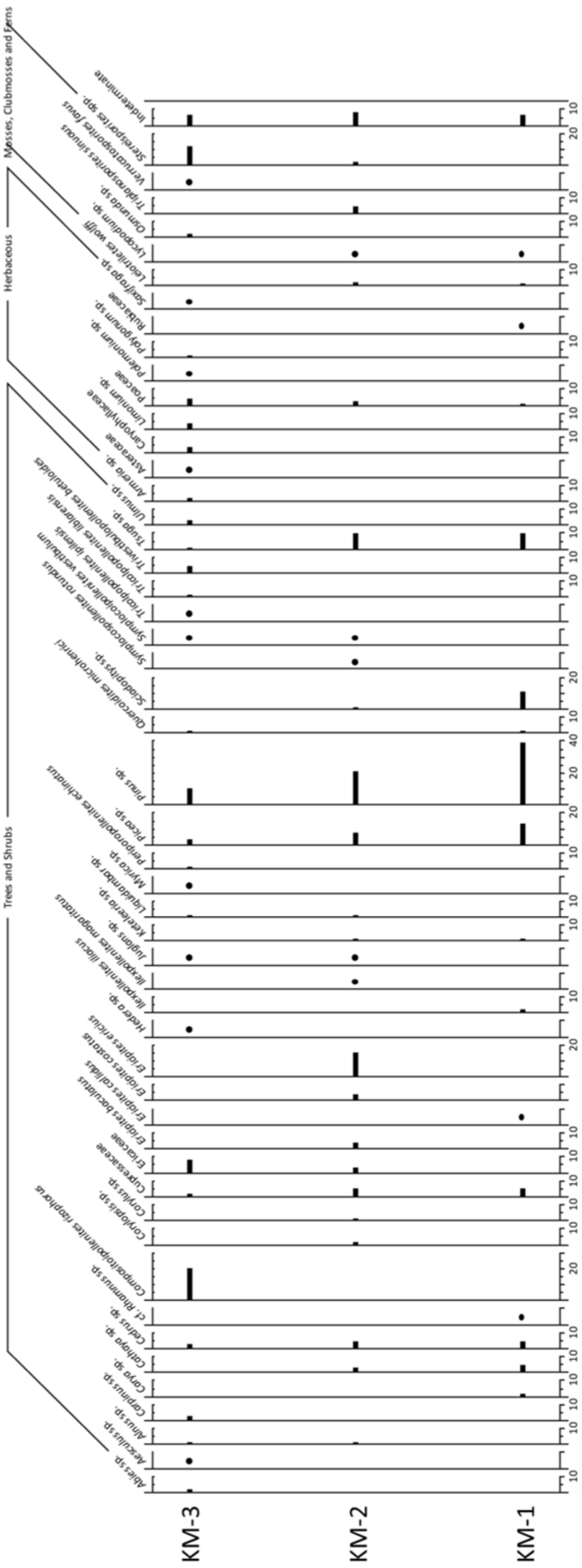


Figure 2. Sketch maps of Bees Nest Pit, near Brassington (SK 24117 54585) and Kenslow Top Pit, near Friden (SK 18180 61585). Based on the maps of Walsh et al. (1972).

Figure 3. Photograph of the wood fragment (BGS fossil specimen number GSM 76976) from the now unexposed Kenslow Member of Kenslow Top Pit that sample KM-2 was extracted from (Fig. 2).



653

654 Figure 4. The percentages of pollen and spores in the three samples. A circle indicates a taxon which represents <1% of the assemblage. The pollen/spore assemblage from the wood fragment from the west end of Kenslow Top Pit is asterisked.

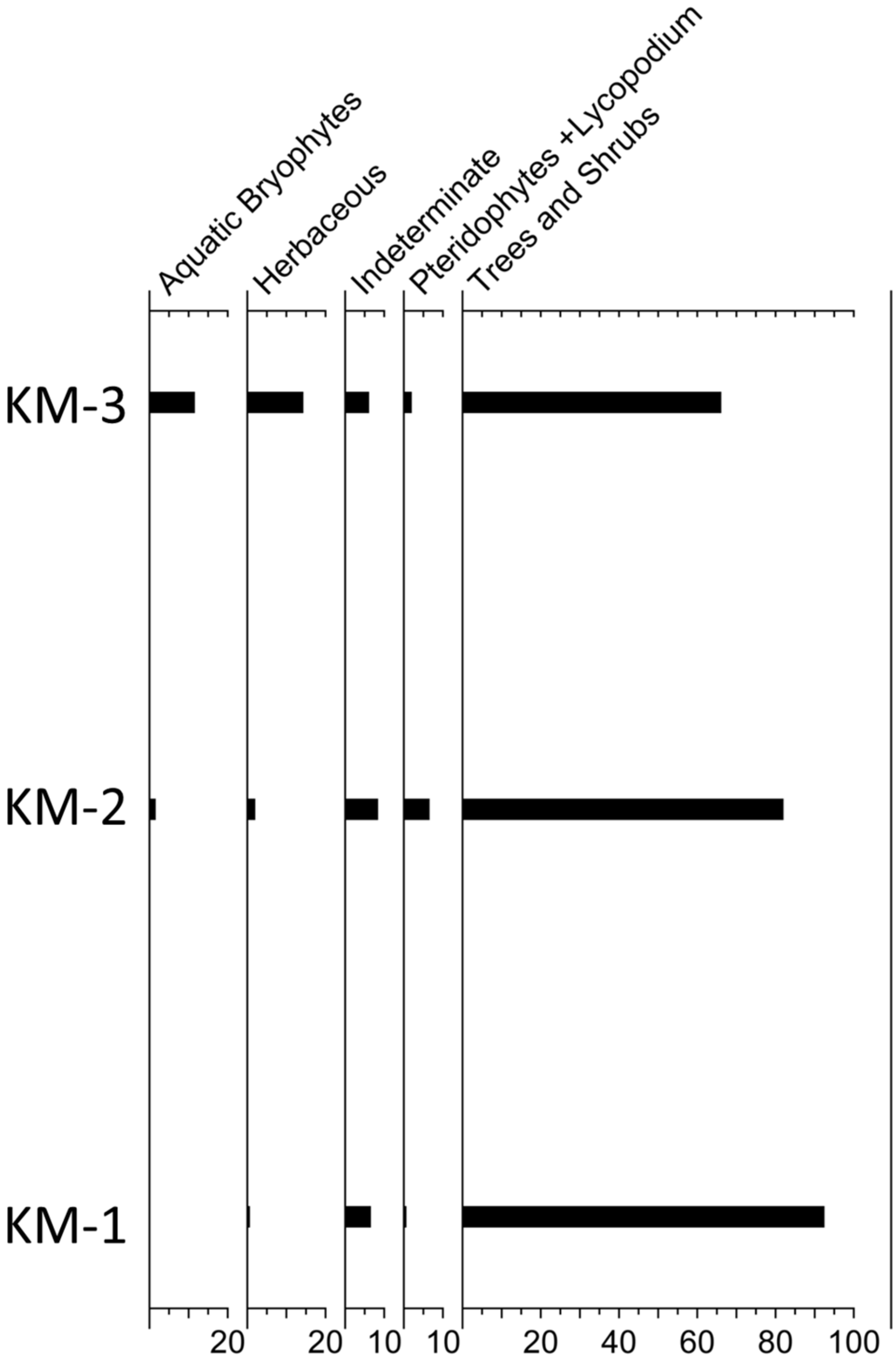


Figure 5. Changes in the pollen/spore assemblages presented as percentages in five ecological groups. The pollen/spore assemblage from the wood fragment from the west end of Kenslow Top Pit is asterisked.

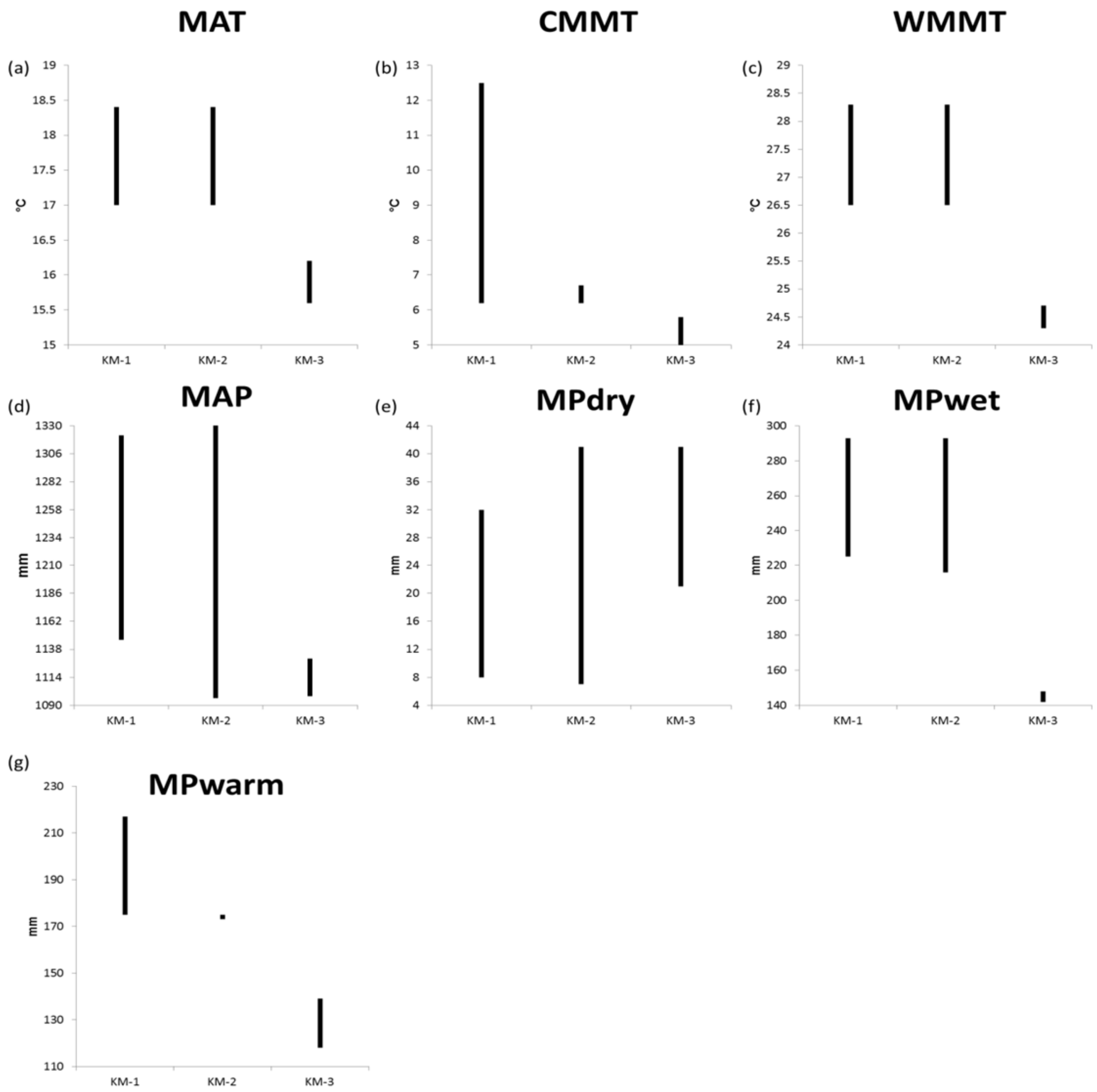
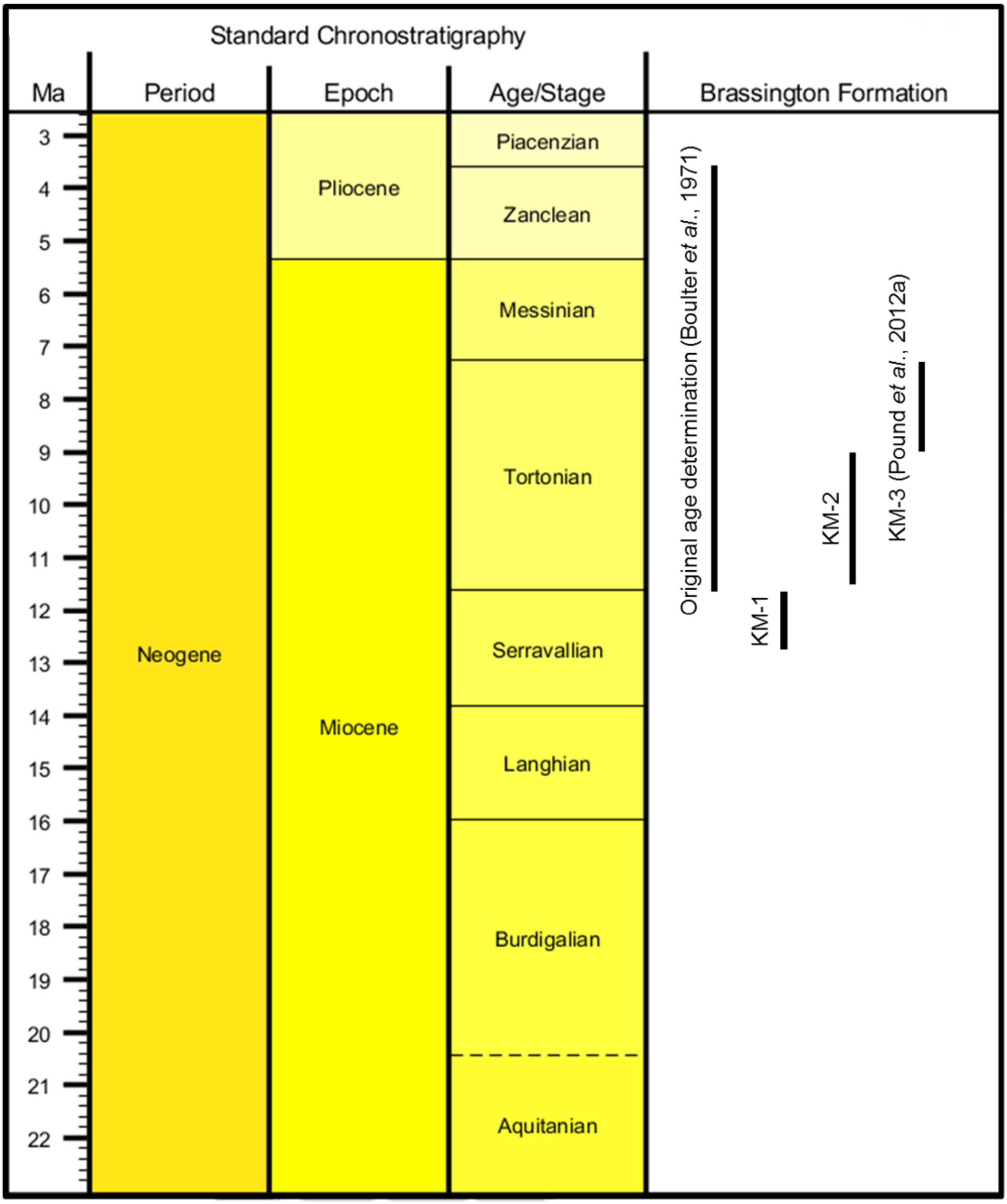


Figure 6. The palaeoclimatology of the three pollen/spore assemblages from the Kenslow Member of the Brassington Formation reconstructed using the Co-existence Approach (CA).



665

666 Figure 7. Standard chronostratigraphical position of the three KM samples from the Brassington Formation compared to the original age determination of Boulter et al. (1971). Global chronostratigraphy follows Gradstein et al. (2012).

669

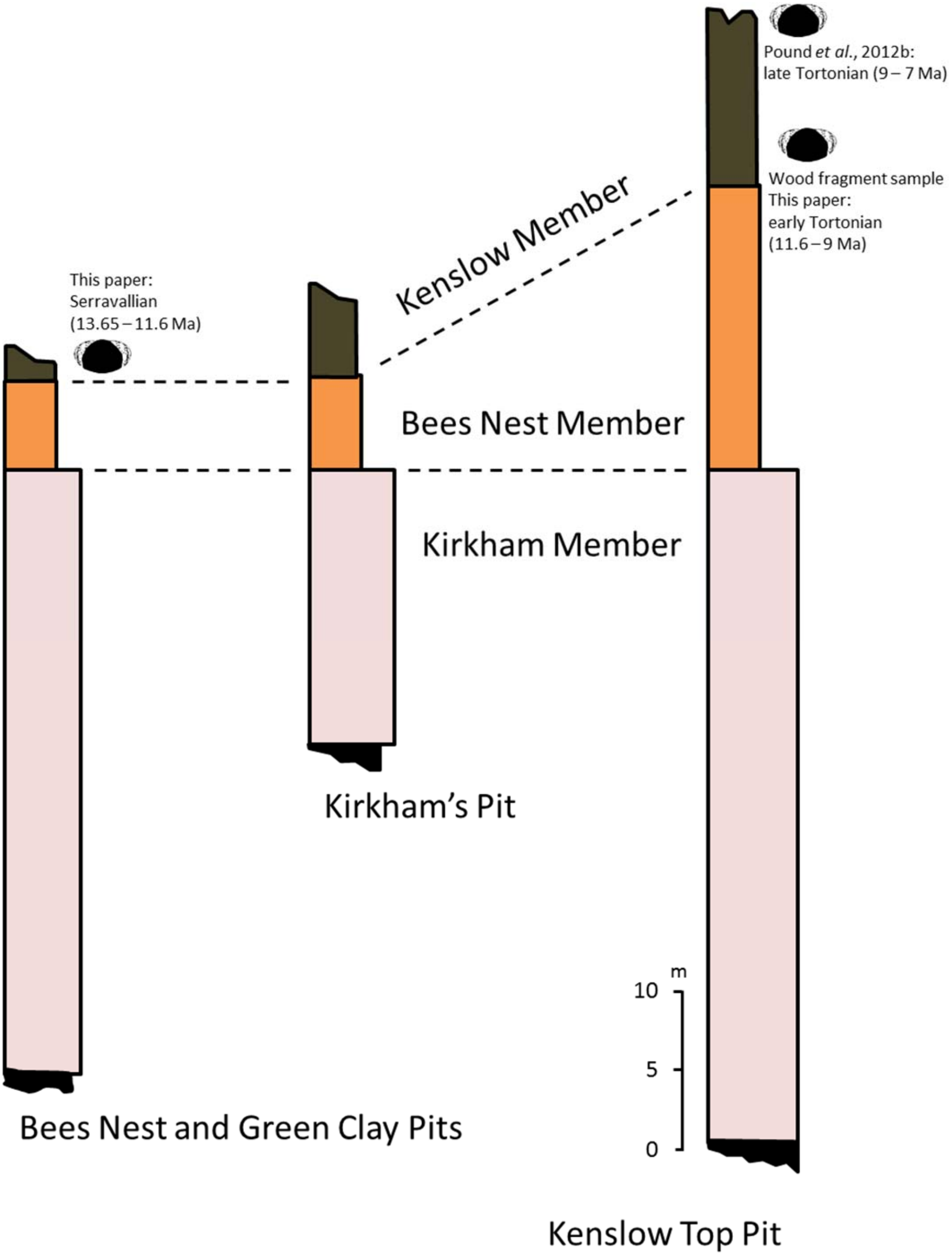


Figure 8. Sketch lithostratigraphical logs of the Brassington Formation at the three main exposures showing the approximate stratigraphical locations of the three pollen/spore assemblages, and their inferred ages. The simplified logs are based on more detailed ones in Walsh et al. (1980). Green Clay Pit is immediately north of Bees Nest Pit (Walsh et al. 1972, fig. 1).

Appendix 1

This appendix lists, in alphabetical order, all valid formally defined palynomorph taxa below the generic level which are mentioned in this contribution with full author citations. Taxonomic names and citations are based upon Stuchlik et al. (2001; 2002; 2009; 2014).

Compositoipollenites rizophorous (Potonié 1934) Potonié 1960

Ericipites baculatus Nagy 1969

E. callidus (Potonié 1931) Krutzsch 1970

E. costatus Grabowska 2014

E. ericius (Potonié 1931) Potonié 1960

Ilexpollenites iliacus (Potonié 1931) Thiergart 1938 ex. Potonié 1960

I. margaritatus (Potonié 1931) Thiergart 1938

Leiotriletes wolffii Krutzsch 1962

Quercoidites microhenrici (Potonié 1931) Potonié et al. 1950 ex. Potonié 1960

Symplocoipollenites vestibulum (Potonié 1931) Potonié 1960

Symplocospollenites rotundus (Potonié 1931) Potonié et al. 1950 ex Potonié 1960

Triplanosporites sinuous Pflug 1952 ex Thomson & Pflug 1953