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

2 UK

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7

8 Abstract

9 The Brassington Formation of Derbyshire and Staffordshire is the most extensive Miocene

10 sedimentary succession in the UK. Due to its unique position at the margin of northwest Europe, the

11 pollen from this lithostratigraphical unit provides evidence on the development of vegetation

12 affected by North Atlantic currents and hypothesised atmospheric circulation changes while the

13 climate cooled. Palynostratigraphy demonstrates that the uppermost Kenslow Member of the

14 Brassington Formation is not coeval. The oldest pollen assemblage is from the more southerly Bees

15 Nest Pit, which represents a subtropical conifer-dominated forest of late Serravallian age (c. 12 Ma).

16 A younger assemblage was observed from the more northerly Kenslow Top Pit; this indicates that a

17 subtropical mixed forest was present during the early Tortonian (11.6–9 Ma). The shift from a

18 conifer-dominated to a mixed forest was related to precipitation. Whilst the total precipitation did

19 not change between the two assemblages, the younger assemblage had more uniform rainfall

20 throughout the year. The diachronous nature of the Kenslow Member means that the depositional

21 model of the Brassington Formation needs revising, and this will have implications for Neogene to

22 recent uplift of the southern Pennines.

23

24 Introduction (not headed)

25 Miocene sediments are poorly represented in the onshore UK rock record, especially when

26 compared to extensive deposits of this age in continental Europe (Donders et al. 2009). The sparse

27 onshore UK deposits include the aeolian/colluvial deposits of the St Agnes Outlier in Cornwall, pipe

28 fills at Trwyn y Parc in Anglesey and weathering horizons in northeast Scotland (Walsh et al. 1987;

29 1996; Hall et al. 2015). However, the most geographically extensive and volumetrically abundant

30 Miocene unit in the UK is the Brassington Formation of Derbyshire and Staffordshire (Boulter et al.

31 1971; Pound & Riding 2015). The Brassington Formation is predominantly a succession of sands,

32 gravels and clays found in c. 60 karstic cavities distributed in three distinct clusters in the southern

33 part of the Lower Carboniferous Peak Limestone Group outcrop of the Peak District (Fig. 1). The

34 larger cavities were extensively quarried for silica sand brickmaking (Yorke 1954; 1961). The

35 formation is considered to have formed from a continuous, extensive sheet of

36 alluvial/fluvial/lacustrine sediment which blanketed much of the East Midlands during the Neogene

37 (Walsh et al. 1980, fig. 15). Boulter & Chaloner (1970), Boulter (1971a;b) and Walsh et al. (1996)

38 assigned the Brassington Formation to the Late Miocene to Early Pliocene based on palaeobotany.

39 This age assessment was recently refined to Late Miocene (late Tortonian) based on

40 palynostratigraphy (Pound et al. 2012a). The formation is located close to the anticlinal crest of the

41 Pennine Hills, and hence the age of the Brassington Formation has been used to estimate uplift rates

42 (Westaway 2009; 2012; Banks et al. 2012). This paper provides new palynological data from the two

43 principal outcrops in both main Brassington Formation clusters which helps elucidate both the age,

44 lithostratigraphy and palaeoenvironment of this important unit, and the geomorphology of the

45 English Midlands.

46

47 **Geological background and setting**

48 The Brassington Formation is, by a considerable margin, the most important Miocene

49 lithostratigraphical unit throughout onshore UK. It is up to 70 m in thickness, and found in steep-

50 sided karst solution cavities in Derbyshire and Staffordshire (Fig. 1). It outcrops in a narrow, c. 20 km

51 long NW-SW zone of the Peak Limestone Group massif (Ford & King 1969). This zone can be divided

52 into three clusters of cavities. These are the Friden cluster in the north, the central Brassington

53 cluster and the sourthernmost Weaver Hills cluster. The latter is in undolomitised limestone,

54 whereas the former two clusters are largely in highly porous, intensely dolomitised limestone (Fig.

55 1). These infills of collapsed heterolithic siliciclastic material exhibit different architectures, but are

56 largely synclinal (Ijtaba 1973). The formation was formalised by Boulter et al. (1971), who erected

57 three members; these are the Kirkham, Bees Nest and Kenslow members in ascending

58 stratigraphical order. The lowermost Kirkham Member is a thick (c. 55 m) succession of white and

59 red unconsolidated sand, which is largely massive and sporadically pebbly and clay-rich. White sand

60 overwhelmingly predominates over red, and this may represent bleaching. The overlying Bees Nest

61 Member is 5–10 m of unfossiliferous variecoloured, predominantly red, sandy clays. The uppermost

62 unit is the Kenslow Member, which is up to c. 5 m of fossiliferous grey clay. The fossil content

63 entirely comprises plant remains, largely poorly-sorted wood fragments with some cones, fruits,

64 leaves, pollen, seeds, spores and stems (Boulter & Chaloner 1970). The three members constitute a

65 fining-upwards succession which appears to be stratigraphically coherent (Walsh et al. 1980; Pound

66 et al. 2012a).

67   The genesis of the Brassington Formation has proved controversial. The current consensus

68 postulates that it largely represents weathering products from Triassic strata, and was first

69 deposited by alluvial, fluvial and lacustrine processes over the majority of the southern part of the

70 White Peak of Derbyshire and Staffordshire. These sand-rich sediments overlaid the Lower

71 Carboniferous (Tournasian to Visean) Peak Limestone Group and the lowermost Bowland Shale

72 Formation (Serpukovian) (Walsh et al. 1980; Pound et al. 2012a). Small portions of the Brassington

73 Formation serendipitously slumped post-depositionally into the karst cavities, hence protecting

74 them from glacial erosion during the Quaternary (Walsh et al. 1972).

75   The Kirkham Member is composed of siliciclastic sheets of sands with clay and pebbles;

76 these represent erosion products from the retreating sandstone escarpments of the Triassic

77 Sherwood Sandstone Group. It was deposited northwards onto Carboniferous strata (Walsh et al.

78 1980). The overlying Bees Nest and Kenslow members represent low energy aquatic or lacustrine

79 and shallow lacustrine/swampy settings respectively. The Triassic escarpments have now retreated

80 but, because the Kirkham Member karst-fills are relatively uniform, the Sherwood Sandstone Group

81 clearly formed an essentially continuous sheet over most of the southern part of the Peak District. In

82 some of the cavities, the lowermost sediments (particularly those close to the cavity walls) are

83 coarse chert gravels derived from the Peak Limestone Group and/or blocks of Bowland Shale

84 Formation. The chert gravel clearly is an insoluble residue derived from weathering of the Peak

85 Limestone Group. By contrast, the shale blocks are from the former cover of the Bowland Shale

86 Formation, some of which exhibit evidence of intensive weathering.

87   The Brassington Formation today is c. 300–360 m above sea level (asl). During Miocene

88 times, the region was 150–250 m lower in order for Triassic erosion products to be deposited.

89 Analysis of palaeocurrents in the Brassington cluster indicate a southerly provenance (Walsh et al.

90 1980). It follows therefore that the southern Pennines have been subjected to significant uplift since

91 the deposition of the Kenslow Member (Walsh et al. 1980). Based on the Tortonian age model of

92 Pound et al. (2012a), and assuming that deposition was at or near sea level, a continuous uplift rate

93 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

94 Westaway (2009).

95

96 **Materials and Methods**

97 Bees Nest Pit is located immediately south of Manystones Lane between Brassington and

98 Wirksworth; Kenslow Top Pit is to the east of Rake Lane, near Friden (Fig. 1; 2; Table 1). Two samples

99 were taken from the grey lignitic clay from the top of the type section of the Brassington Formation

100 at Bees Nest Pit (Fig. 2) (Boulter et al. 1971; Walsh et al. 1972). The grey lignitic clay is from the top

101 of the Kenslow Member; this overlies 5 m of the varicoloured clays of the Bees Nest Member and

102 c.35 m of the white silica sands of the Kirkham Member (Walsh et al., 1980). A further sample of

103 grey clay was taken from a crack located in a large piece of fossil wood donated to the British

104 Geological Survey (Fig. 3; BGS fossil specimen number GSM 76976). The wood fragment came from

105 the Kenslow Member at the west end of Kenslow Top Pit (Fig. 2) (Walsh et al., 1980) and was

106 illustrated by Yorke (1961, fig. 62). The two samples from Bees Nest Pit (Table 1: KM-1a; b) and the

107 grey clay from the Kenslow Top Pit wood fragment (Table 1: KM-2) were processed for

108 palynomorphs. One sample from Bees Nest Pit (KM-1a) and KM-2 were processed through the

109 standard acid digestion method (e.g. Wood et al. 1996). The other sample from Bees Nest Pit (KM-

110 1b) was processed using the sodium hexametaphosphate technique of Riding and Kyffin-Hughes

111 (2004; 2006). Pollen residues were mounted in elvacite and examined under a transmitted light

112 microscope. Pollen and spore identification principally used Boulter (1971a), Stuchlik et al. (2001;

113 2002; 2009; 2014), Beug (2004) and the pollen reference collection at Northumbria University. To

114 reconstruct palaeoclimate parameters, the Co-existence Approach (CA) was used with the NECLIME

115 Palaeoflora database (Mosbrugger & Utescher, 1997; Utescher & Mosbrugger, 2010; Utescher et al.,

116 2014). Modern relic taxa such as *Cathaya* and *Sciadopitys* had a much wider geographical

117 distribution during the Cenozoic (Liu & Bassinger, 2000). This has the potential to bias the CA results;

118 therefore the proposals of Utescher et al. (2014) for these relic taxa were followed. Using the

119 overlapping envelopes of a pollen assemblages Nearest Living Relatives it has been possible to

120 reconstruct seven parameters. These are: Mean Annual Temperature (MAT); Coldest Month Mean

121 Temperature (CMMT); Warmest Month Mean Temperature (WMMT); Mean Annual Precipitation

122 (MAP); Wettest Month Mean Precipitation (MPwet); Driest Month Mean Precipitation (MPdry); and

123 Warmest Month Mean Precipitation (MPwarm).

124

125 **Results**

126 **Palynology**

127   The palynological results are presented herein in Table 2 and Figs. 4 and 5. The palynoflora from the

128   grey lignitic Kenslow Member clay at Bees Nest Pit (KM-1) is dominated by gymnosperm taxa

129   (86.2%), with angiosperms and spores being minor components of the assemblage (6.6% and 0.8%

130   respectively); 6.4% of pollen grains proved indeterminate (Fig. 4). Both the acid (KM-1a) and non-

131   acid processing technique (KM-1b) yielded the same palynoflora from Bees Nest Pit, and as such the

132   pollen assemblage will be described here as a single assemblage (KM-1) (Fig. 4). *Pinus* dominates the

133   flora (38.6%) with *Picea* (13.2%), *Sciadopitys* (10.4%) and *Tsuga* (9.9%) all being major components

134   of the palynomorph assemblage (Fig. 4). Other gymnosperm pollen recorded includes Cupressaceae

135   (4.7%), *Cathaya* (4.1%), *Cedrus* (4.3%) and *Keteleeria* (0.9%) (Fig. 4). The most abundant angiosperm

136   pollen in the grey lignitic clay is of *Ilex* type (*Ilexpollenites iliacus*) (2.1%), *Carya* (1.6%) and *Quercus*

137   type (*Quercoidites microhenrici*) (Fig. 4). Other angiosperm pollen present include *Alnus*, cf. *Asperula*

138   (Rubiaceae), *Betula*, Ericaceae (both *Ericipites baculatus* and *E. callidus* are present), Poaceae and cf.

139   *Rhamnus* in low percentages (<1%) (Fig. 4). Spores are rare in the grey lignitic clay with the most

140   abundant (0.5%) being those of the Lygodiaceae (*Leiotriletes wolffii*). Single specimens of

141   *Lycopodium* and Polypodiaceae spores were also recorded (Fig. 4).

142   The Kenslow Top Pit wood fragment (KM-2) also derives from the lignitic clay of the Kenslow

143   Member. The palynoflora from clay adhering to this wood fragment is dominated by gymnosperm

144   taxa (50.1%). However, in KM-2, the angiosperms (33.8%) and spores (7.8%) are more numerous

145   than in KM-1, whilst 8.3% of pollen grains were indeterminate (Table 2; Fig. 4). The dominant taxa

146   are Ericaceae (25.2%), *Pinus* (20.4%), *Tsuga* (9.3%) and *Picea* (7.1%) (Fig. 4). The Ericaceae are

147   represented by *Ericipites ericius*, *E. costatus,* Ericaceae indeterminate (3.3%) and *E. baculatus* (3.0%)

148   (Fig. 4). The gymnosperms are also represented by pollen of Cupressaceae (4.5%), *Cedrus* (3.8%),

149   *Cathaya* (2.8%), *Keteleeria* (1.3%) and *Sciadopitys* (1.0%) (Fig. 4). Angiosperm pollen, other than

150   Ericaceae, are more diverse in KM-2 than in KM-1, but do not occur in high proportions (Fig. 4). Most

151   abundant, after Ericaceae, are pollen of Poaceae (2.0%), *Corylopsis* (1.3%) and *Corylus* (1.0%). *Alnus*,

152   *Compositoipollenites rizophorous*, *Ilexpollenites iliacus*, *I. margaritatus*, *Juglans*, *Liquidambar*,

153   *Quercoidites microhenrici*, *Symplocoipollenites vestibulum*, *Symplocospollenites rotundus* and *Ulmus*

154   all occur as less than 1% of the assemblage (Fig. 4). Spores of Bryophytes, Lycopodiophytes and

155   Pteridophytes are also more diverse KM-2 than in KM-1 (Fig. 4). *Triplanosporites sinuous* (4.3%) is

156   the most common, followed by spores of *Sphagnum* (1.5%), *Leiotriletes wolffi* (1.3%) and

157   *Lycopodium* (<1%) (Fig. 4).

158

159   **Palaeoclimate**

160   The flora from KM-1 represents a subtropical, seasonally wet climate with a MAT of 17–18.4 °C (Fig.

161   6).The WMMT was reconstructed as 26.5–28.3°C, and the CMMT as 6.2–12.5 °C (Fig. 6). Using the

162   co-existence approach, the MAP of the flora from KM-1 was reconstructed as 1146–1322 mm yr^{-1}

163   (Fig. 6). Precipitation was not evenly distributed throughout the year; MPwet was 225–293 mm,

164   MPdry was 8–32 mm and MPwarm was reconstructed as being close to the MPwet 175–217 mm

165   (Fig. 6). The palynoflora from KM-2 also represents a subtropical, seasonally wet climate with a MAT

166   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.

167   6). MAP was 1096–1562 mm yr^{-1} with a pronounced seasonality; the MPwet was 216–293 mm and

168   MPdry was 7–41 mm. The warmest month was neither the driest nor the wettest month because

169   MPwarm was 173–175 mm (Fig. 6).

170

171   **Palynostratigraphy**

172   The age of the uppermost Kenslow Member of the Brassington Formation was originally defined as

173   Late Miocene–Early Pliocene, based on the pollen floras from the plant-bearing grey clay at Bees

174   Nest and Kenslow Top pits (Fig. 7) (Boulter, 1971a; 1971b; Boulter et al., 1971). This was

175   subsequently revised to Late Miocene, most likely late Tortonian (9–7 Ma), by Pound et al. (2012a)

176   using a previously undescribed flora from a mottled grey-brown clay from the east end of Kenslow

177   Top Pit (Table 1; 2: KM-3). This age assignment came from the presence of *Quercoidites microhenrici*

178   and Symplocaceae pollen, together with sparse *Carya* and the absence of Arecaceae pollen (Pound

179   et al., 2012a). However, the pollen floras of KM-1 from the Bees Nest Pit Kenslow Member and KM-2

180   from the Kenslow Member of the west end of Kenslow Top Pit are significantly different to the KM-3

181   flora reported by Pound et al. (2012a).

182   The higher occurrence of *Carya* in the KM-1 suggests that this occurrence of the Kenslow Member is

183   older than both KM-2 and KM-3 (Fig. 4; 7). *Carya* is a typical component of Middle Miocene floras of

184   northwest Europe (Donders et al., 2009; Larsson et al., 2011). However, many Middle Miocene

185   samples have higher pollen diversities than either of the samples reported here; often with

186   abundant thermophilic elements, corresponding to the Mid-Miocene Climatic Optimum (MMCO)

187   (Nagy, 1990; Jiménez-Moreno et al., 2005; Larsson et al., 2011). Whilst KM-1 contains one taxon

188   considered to be a thermophilic Rubiaceae (Jiménez-Moreno, 2006), it does not contain members of

189   the Arecaceae or other megathermic or thermophilic taxa typical of MMCO European pollen

190   assemblages (Jiménez-Moreno, 2006; Uhl et al., 2006; Jiménez-Moreno & Suc, 2007). It is therefore

191   considered to be younger than the MMCO (17–14.5Ma), but older than the late Tortonian (9–7.25

192   Ma) KM-3 flora reported in Pound et al. (2012a). The KM-1 flora from the Bees Nest Pit Kenslow

193   Member is low-diversity, which makes it difficult to directly compare to samples from continental

194   Europe (which typically have higher diversities). However, a high proportion of Pinaceae pollen

195   (71.13%) and *Carya* (the second most abundant angiosperm pollen) makes it comparable to the

196   Serravallian (13.65–11.61 Ma of Austria (Jiménez-Moreno et al., 2008), Denmark (Larsson et al.,

197   2011) and France (Gardère & Pais, 2007). The relatively high-proportion of *Sciadopitys* (Fig. 4) may

198   correspond to the second *Sciadopitys* maximum in the successions of the Lower Rhine District which

199   is in the upper Serravallian Garzweiler Seam (Zagwijn & Hager, 1987; Utescher et al., 2012).

200   The key pollen taxa used to date the KM-3 flora of Pound et al. (2012a) are present in the KM-2

201   sample from the Kenslow Top Pit wood fragment (Fig. 3; Table 1; 2), and therefore this sample can

202   also be attributed to the Late Miocene (Fig. 7). Proportional comparison with continental European

203   sites is difficult because, although many show increasing-amounts or peaks in Ericaceae pollen, it

204   was not a dominant element (Gardère & Pais, 2007; Worobiec, 2009; Larsson et al., 2011) until the

205   Taxodiaceae-Ericaceae coastal Atlantic forests of the Early Pliocene (Fauquette et al., 2007).

206   However, an Early Pliocene age is precluded due to the presence of pollen types indicative of the

207   Late Miocene (Donders et al., 2009; Ivanov et al., 2010; Pound et al., 2012a). *Triplanosporites*

208   *sinuosus* is the most common spore in the assemblage, and is not known after the Middle Miocene

209   in Poland (Stuchlik et al., 2001). The differences with the KM-3 assemblage reported in Pound et al.

210   (2012a) are difficult to attribute to geographical differences, because the two samples come from

211   the same karstic depression, and are only c. 200 m from each other (Fig. 2). Therefore the

212   proportional differences (Fig. 4; Table 2) are likely to stem from some temporal difference. As KM-2

213   contains *Cathaya* sp. and shares lithological characteristics with the Kenslow Member at Bees Nest

214   Pit (Boulter et al., 1971; Walsh et al., 1980), it is likely to be temporally intermediate between the

215   palynologically younger and (?)stratigraphically higher KM-3 sample of Pound et al. (2012a) and the

216   older, stratigraphically comparable Bees Nest Pit Kenslow Member. It is therefore proposed to be

217   early Tortonian in age (11.61–9 Ma), possibly late Serravallian if *Triplanosporites sinuosus* can be

218   proven to be stratigraphically important (Fig. 7). The pollen and spore assemblages of the Kenslow

219   Member therefore suggest variable deposition times between the lithologically comparable fossil

220   wood-bearing grey clays (Kenslow Member of Bees Nest Pit (KM-1) and the Kenslow Member of

221   Kenslow Top Pit (KM-2)) and the stratigraphically higher mottled clay (KM-3) described by Pound et

222   al. (2012a) (Fig. 7;8).

223

224   **Palaeoecology**

225   The Kenslow Member has preserved a diverse palynomorph assemblage that indicates the presence

226   of different vegetation types during the Middle to Late Miocene from the western margin of

227   northwest Europe. All three assemblages are dominated by pollen from trees and shrubs,

228   demonstrating the presence of a forest type biome during Kenslow Member times (Pound et al.,

229   2012a; b). However, there is a decrease in the proportion of trees and shrubs from the oldest

230   assemblage (KM-1) to KM-3, the youngest association (Fig. 5); this trend was previously reported in

231   Pound et al. (2012b). This decrease in trees and shrubs is matched by an increase in the proportion

232   of herbaceous and understory taxa (Fig. 5), which was a common trend across Europe during the late

233   Neogene (e.g. Larsson et al., 2011). Fern spores are most dominant in KM-2 (considered to be

234   stratigraphically and temporally in the middle of the Kenslow Member), whilst the youngest KM-3

235   sample contains the highest proportion of *Sphagnum,* and represents a warm-temperate mixed

236   forest (Pound et al., 2012a).

237   The oldest KM-1 palynomorph assemblage, from the Kenslow Member at Bees Nest Pit is dominated

238   by conifers, with a low proportions of angiosperms and ferns (Fig. 4). *Pinus* dominates the

239   assemblage, but this genus is commonly over-represented in palynomorph assemblages, whereas

240   other gymnosperm taxa may be under-represented (Webb & McAndrews, 1976; Pound et al., 2015).

241   *Sciadopitys* comprises 10.4% of the assemblage and today is represented by a single species. This is

242   *Sciadopitys verticillata* which inhabits temperate regions of Japan between the altitudes of 300 and

243   1500 m, although its natural range has been greatly modified by anthropogenic activity (Tsukada,

244   1963). During the Neogene it was a common component of the peat-forming swamp community

245   (Figueiral et al., 1999; Ivanov et al., 2007) and is found abundantly in the post-glacial bogs of Japan

246   (Tsukada, 1963). It is also considered to be a component of the Miocene well-drained lowland

247   conifer forests in association with *Cathaya*, *Cedrus*, *Pinus*, *Sequoia* and *Tsuga* (Larsson et al., 2011).

248   The Kenslow Member sediment which yielded the Bees Nest Pit pollen assemblage also contains

249   large fragments of wood up to 1 m long (Fig. 3). This wood has previously been identified as *Sequoia*

250   by Yorke (1954), and reassessed as *Cryptomeria anglica* by Boulter (1969), Boulter & Chaloner (1970)

251   and Boulter (1971). Pollen identified and counted as Cupressaceae in this study includes pollen that

252   is attributable to *Cryptomeria* type (Boulter, 1971). Today this genus is monotypic and inhabits

253   humid warm-temperate to cool-temperate areas of China and Japan (Tsukada, 1982). At the

254   southern limit of its distribution on Yakushima Island, Japan (30.5°N, 130.5°E), *Cryptomeria japonica*

255   co-dominates forests with *Tsuga sieboldii* and *Abies firma* from altitudes of 800 to 1800 m, in a

256   subtropical humid climate (Suzuki and Tsukahara, 1987). A subtropical humid climate is also

257   reconstructed from the Co-existence Approach results (Fig. 6). A MAT of 17–18.4°C, with mild

258   winters of >6.2°C and hot summers of 26.5–28.3°C (Fig. 6) is envisaged. Precipitation was high, but

259   seasonally distributed with the wettest month receiving 225–293 mm, and the driest month as little

260   as 8 mm (Fig. 6). As the reconstructed range for the warmest month is 175–217 mm, it may be that

261   the wettest period was late spring to early summer, which is comparable to the modern forests of

262   *Cryptomeria japonica* on Yakushima Island (Suzuki & Tsukahara, 1987). A subtropical forest

263   environment is supported by the dominant angiosperms in the assemblage such as *Carya*, Ericaceae,

264   *Ilex* and evergreen *Quercus* (Fig. 4; Table 2). These are typical indicators of the Miocene

265   mesothermic forests. The dominance of conifer pollen and wood in the Kenslow Member of Bees

266   Nest Pit indicates that a warm-temperate, predominantly needleleaf, forest was growing in Britain

267   during the late Serravallian.

268   The KM-2 palynomorph assemblage contains a high proportion of Ericaceae grains (Fig. 4). Boulter

269   (1971) originally interpreted this as reflecting a heathland that would have inhabited surrounding

270   uplands. However, the Neogene warm-temperate forests of Europe would have had an extensive

271   shrub layer, and the Ericaceae have been frequently assigned to this ecological group (Ivanov et al.,

272   2007; Larsson et al., 2011). Several of the Ericaceae grains in the Kenslow Top Pit wood fragment

273   (*Ericipites callidus*, *E. costatus* and *E. ericius*) have affinities with the genus *Vaccinium* (Table 2).

274   Modern species of this genus can achieve prodigious sizes, for example *Vaccinium arboreum* forms a

275   medium to large shrub (up to 10 m high) in the mesophytic forests of Florida and Louisiana (Wenslaff

276   & Lyrene, 2003). In the southern mixed hardwood forests of North America, *Vaccinium arboreum* is

277   structurally important to the understory of both the transitional forests between the early pine-

278   dominated stands and the near-climax pine-hardwood forests (Quarterman & Keever, 1962). Aside

279   from the dominance of Ericaceae pollen, KM-2 also contains a greater number of angiosperm taxa

280   than KM-1 (Fig. 4; Table 2). The presence of *Juglans* sp., *Liquidambar* sp. and *Symplocos* spp. shows a

281   strong affinity with continental European warm-temperate mixed forests during the Serravallian and

282   Tortonian (Ivanov et al., 2007; Larsson et al., 2011; Szulc & Worobiec, 2012). The wood fragment

283   that the pollen assemblage was extracted from is *Cryptomeria anglica*, thereby demonstrating that

284   these trees were members of the forest community that surrounded the depositional setting. This

285   similarity with the Bees Nest Pit is also seen in the diversity of gymnosperm taxa, and the high

286   proportion of *Pinus* sp. and *Tsuga* sp. (Fig. 4; Table 2). Climatically, the Co-existence Approach

287   reconstruction shows that only the warmest month precipitation was likely to have been different

288   from that reconstructed by the Bees Nest Pit pollen assemblage (Fig. 6). However, the high

289   angiosperm proportions and the spore content (Fig. 5) shows that the flora is distinctly different. The

290   spore assemblage is dominated by *Triplanosporites sinuosus* that has no confirmed modern relative.

291   However, Chateauneuf (1980) compared the genus to members of the family Lygodiaceae, whilst

292   Stuchlik et al. (2001) demonstrated morphological similarities with some members of the genus

293   Cyathea. Today, species of Cyatheaceae and Lygodiaceae are found in tropical, sub-tropical and

294   temperate zones, and have been assigned to the understory component of swampy or riparian

295   forests during the Miocene (Kayseri-Özer et al., 2014). The entire flora from KM-2 reconstructs a

296   warm-temperate mixed forest with an extensive understory component (Fig. 4).

297

298   **Discussion**

299

300   **Multiple Miocene ages for the Kenslow Member**

301   Based on the palynostratigraphy of the Kenslow Member samples from Bees Nest Pit (KM-1) and the

302   wood fragment from Kenslow Top Pit (KM-2), the Kenslow Member was deposited diachronuously

303   (Fig. 7; 8). Furthermore, the KM-3 assemblage from the east side of Kenslow Top Pit reported by

304   Pound et al. (2012a) is younger than both the Kenslow Member at Bees Nest Pit and the Kenslow

305   Member at the west end of Kenslow Top Pit. This implies that this youngest pollen and spore

306   assemblage was deposited in an unidentified lithological unit of the Brassington Formation at

307   Kenslow Top Pit that may be equivalent to the uppermost clays of the Kenslow Member reported

308   from Kirkhams Pit by Walsh et al. (1980). These diachronous ages for the Kenslow Member may be

309   explained in several ways. Palaeocurrent indicators from the sands of the Kirkham Member at Bees

310   Nest Pit indicate that sediment was supplied from the south (Walsh et al., 1980). Similarly,

311   palaeocurrent proxies for the more northern Friden cluster of pits mainly show sediment being

312   transported from the south, but some material is of western and northern provenance (Walsh et al.,

313   1980). As most palaeocurrent proxies indicate a sediment source from the south, the Miocene

314   depocentre of the southern Pennines may have slowly shifted north, thus accounting for the

315   younger age of the Kenslow Member at the more northerly Kenslow Top Pit. An alternative

316   hypothesis posits uniform deposition ages for the Kirkham Member, and possibly the Bees Nest

317   Member, followed by asynchronous subsidence of the various pockets, and deposition of the

318   Kenslow Member into these hollows (Pound et al., 2012a). This diachronous subsidence and

319   deposition of the Kenslow Member would be comparable to the procesess that formed the karstic

320   fill of the Gray Fossil Sites of Tennessee, USA (Zobaa et al., 2011).

321   The new palynostratigraphical age assessments for the Kenslow Member of the Brassington

322   Formation provide evidence for a poorly-known part of the onshore UK geological record and have

323   implications for the uplift of the Pennines (Walsh et al., 1972; Westaway, 2009; Pound et al., 2012a).

324   Pennine uplift has been estimated on the assumption that the Brassington Formation was deposited

325   at or near sea-level and subsequently foundered into the karstic hollows (Walsh et al., 1972;

326   Westaway, 2009). Calculating a time-averaged uplift rate has been a relatively simple matter of

327   dividing the degree of uplift by the age of the Kenslow Member (Westaway, 2009; Pound et al.,

328   2012a). In Westaway (2009), the age of the Kenslow Member was taken as Early Pliocene, giving an

329   uplift rate of 0.10–0.13 mm yr^{-1}, based on an uplift of 300 m from the Brassington Formation at sea-

330   level to the present day topography. Subsequently Pound et al. (2012a) demonstrated that the

331   Kenslow Member is late Tortonian in age, and therefore a time-averaged uplift rate of 0.03–0.06 mm

332   yr^{-1} was determined. The multiple ages for the Kenslow Member (Fig. 7; 8) mean that the estimate of

333   Pound et al. (2012a) is the most rapid time-averaged estimate possible. Moreover, the time-

334   averaged uplift rates depend on the Brassington Formation being entirely deposited before

335   karstification took place (Westaway, 2009). If, the karstic hollows formed asynchronously during

336   Brassington Formation deposition, with each Kenslow Member then forming in the hollow, then the

337   use of this unit to determine Pennine uplift requires further research.

338

Miocene climates and vegetation

340   The palynological data and interpretations on the Brassington Formation material studied herein

341   provides evidence for an important interval in geological time. The Miocene was an interval that was

342   both warmer and wetter than the present day (Utescher et al., 2011; Pound et al., 2012b; Denk et

343   al., 2013; Quaijtaal et al., 2014). These warmer than present day climates peaked during the Middle

344   Miocene Climatic Optimum (MMCO) between 17 and 14.5 Ma. Then, the global climate cooled

345   steadily with six Miocene isotope events (Mi-events) indicating that there was a step-like pattern to

346   the cooling (Quaijtaal et al., 2014). The regions immediately adjacent to the North Atlantic do,

347   however, show a more muted response to the Miocene cooling than more continental regions due

348   to the influence of the North Atlantic Thermohaline Circulation (NATC) (Pound et al., 2012b; Denk et

349   al., 2013; Utescher et al., 2015). During the Miocene, the British Isles formed a peninsula separating

350   the Atlantic Ocean from the North Sea (Harzhauser & Piller, 2007). This unique location on the

351   northwest edge of the Eurasian continent, separating the Atlantic Ocean from the North Sea, makes

352   the albeit sparse Miocene sediments of the UK ideal for understanding the development of Neogene

353   oceanic climates.

354   The Brassington Formation has now revealed three windows into this interval of global climatic

355   cooling (Figs. 4; 6; 7). The oldest sample (KM-1) from the Kenslow Member at Bees Nest Pit shows

356   that a subtropical, seasonally wet, conifer-dominated forest inhabited the outer margin of northwest

357 Europe at around 12 Ma (Figs. 4; 6). Periods of proportionally higher conifer concentrations have

358 been identified in the Serravallian of the Porcupine Basin, offshore southwest Ireland (Quaijtaal et

359 al., 2014; 2015). The middle to late Serravallian has also been identified as a warm and dry interval in

360 the Roer Valley Graben in the southeast of the Netherlands (Donders et al., 2009). The latest

361 Serravallian in Portugal and central Europe has also been identified as an interval of relatively low

362 precipitation (Antunes & Pais, 1984; Böhme et al., 2008). Following this, there were then two

363 "washhouse" intervals at c. 10 Ma and 9–8 Ma in Europe associated with tectonic changes in Central

364 America (Böhme et al., 2008). However, the MAP reconstructed from the three Brassington

365 Formation floras is significantly higher than estimates for the Iberian Peninsula and central Europe

366 based on herpetological data (Böhme et al., 2008). This supports the small-mammal based

367 reconstructions of van Dam (2006), that the modern west–east precipitation gradient was already

368 well-established during the late Middle Miocene. Changes in the MPwarm of the flora preserved in

369 the Kenslow Member may reflect the hypothesised shifting of atmospheric circulation between the

370 Serravallian and the Tortonian (Quan et al., 2014).

371 Comparing the new temperature reconstructions for the Kenslow Member flora herein with those of

372 continental Europe shows comparable MATs to the records from the Netherlands (Donders et al.,

373 2009). However warmer MATs and CMMTs have been reconstructed for leaf floras from the

374 Weisselster and Molasse basins (northeast and southern Germany, respectively), which may have

375 had a colder climate that was less influenced by the NATC (Mosbrugger et al., 2005). The WMMT of

376 both the Tortonian Kenslow Top Pit floras are higher than other northern European localities that

377 bordered the then isolated North Sea (Quan et al., 2014). This shows that, despite a globally warmer

378 climate, the NATC had a warming effect on the terrestrial realms bordering the North Atlantic (Denk

379 et al., 2013). The warmer than present MATs reconstructed for the Tortonian Kenslow Top Pit floras

380 (Fig. 6) are inconsistent with climate model results for this region, which either show cooler than

381 modern temperatures or no change (Knorr et al., 2011; Micheels et al., 2011). Some of this data–

382 model disparity may stem from the manner that vegetation and land-surfaces are treated in each

383 model (Knorr et al., 2011; Micheels et al., 2011; Pound et al., 2011). However, neither of the two

384 floras reported for the Tortonian of the Brassington Formation are inconsistent with the current

385 global vegetation reconstruction (Pound et al., 2011). The way vegetation is represented in climate

386 models may be causing at least some of this mismatch. The Miocene forests of northwest Europe

387 would have had considerable stature; modern old-stand *Cryptomeria japonica* attain heights of up to

388 65 m and *Scidopitys verticillata* can reach 45 m. Both these species can live for thousands of years

389 (Tsukada, 1963; 1982; Suzuki & Tsukahara, 1987). This situation has implications for the accurate

390 simulation of carbon cycling, evapotranspiration and surface roughness (Cox, 2001; Essery et al.,

391   2001) in Miocene climate modelling studies. Most vegetation and land surface scheme models use

392   parameters defined from common modern trees, rather than those that were typical of the

393   Neogene. For example within the widely used Meteorological Office Surface Exchange Scheme

394   (MOSES), evergreen needleleaf trees are assigned a fixed height of only 10 m (Hough & Jones, 1997;

395   Cox et al., 1999; Pound et al., 2011). Correct boundary conditions, however small, can have

396   important regional impacts (Krinner et al., 2012; Pound et al., 2014). Therefore it is important for

397   palaeoclimate modelling studies to work closely with the palaeontological data community to

398   develop realistic simulations of past climates.

399

400   Conclusions

401   From two new palynomorph assemblages, the age of the Kenslow Member of the Brassington

402   Formation is refined, and deposition is shown to be diachronous. This new evidence changes our

403   understanding of the Brassington Formation, and makes a sedimentological restudy essential. The

404   oldest flora is from the late Serravallian, and was produced by a subtropical, seasonally wet conifer-

405   dominated forest. Sediments of the Serravallian were previously unknown from onshore UK. The

406   second new flora is slightly younger (early Tortonian), and represents a subtropical mixed forest with

407   a high proportion of representatives of the Ericaceae. When combined with the palynoflora of

408   Pound et al. (2012a), the late-Middle–Late Miocene record of the UK demonstrates a general cooling

409   trend comparable to the more complete continental records. However, the floras from the

410   Brassington Formation provide a unique view on the development of European precipitation

411   records, and may support the hypothesised regional shift in wind directions from the Serravallian

412   into the Tortonian by Quan et al. (2014).

413

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420

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632

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)

633   Table 1. Sample details of the three pollen assemblages extracted from the Kenslow Member of the

634   Brassington Formation. The grid reference for KM-2 is based on the locality map of Walsh et al.

635   (1972).

636

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.
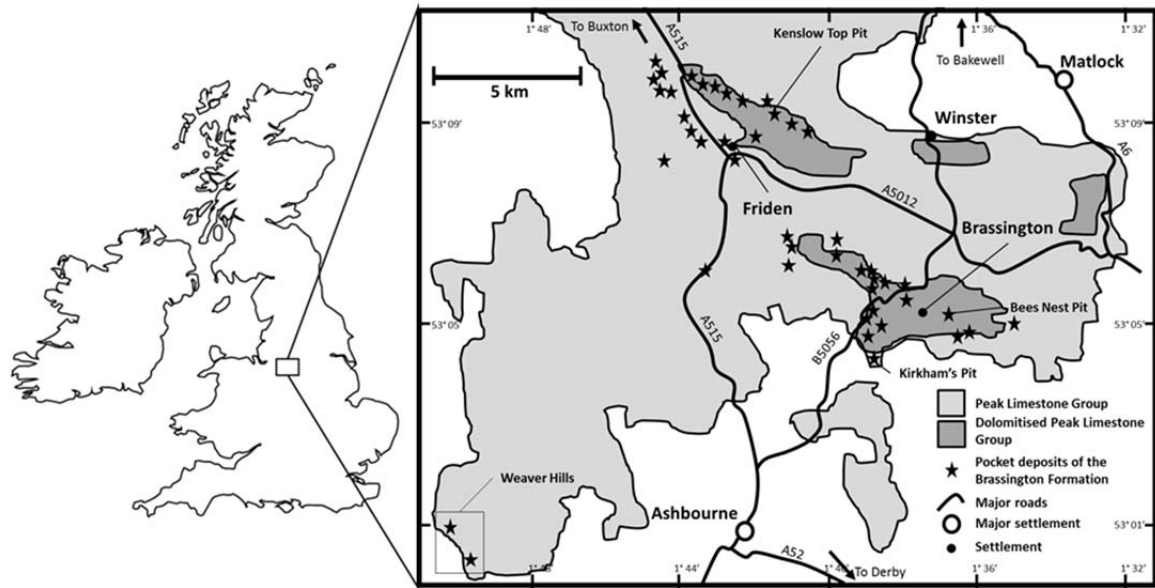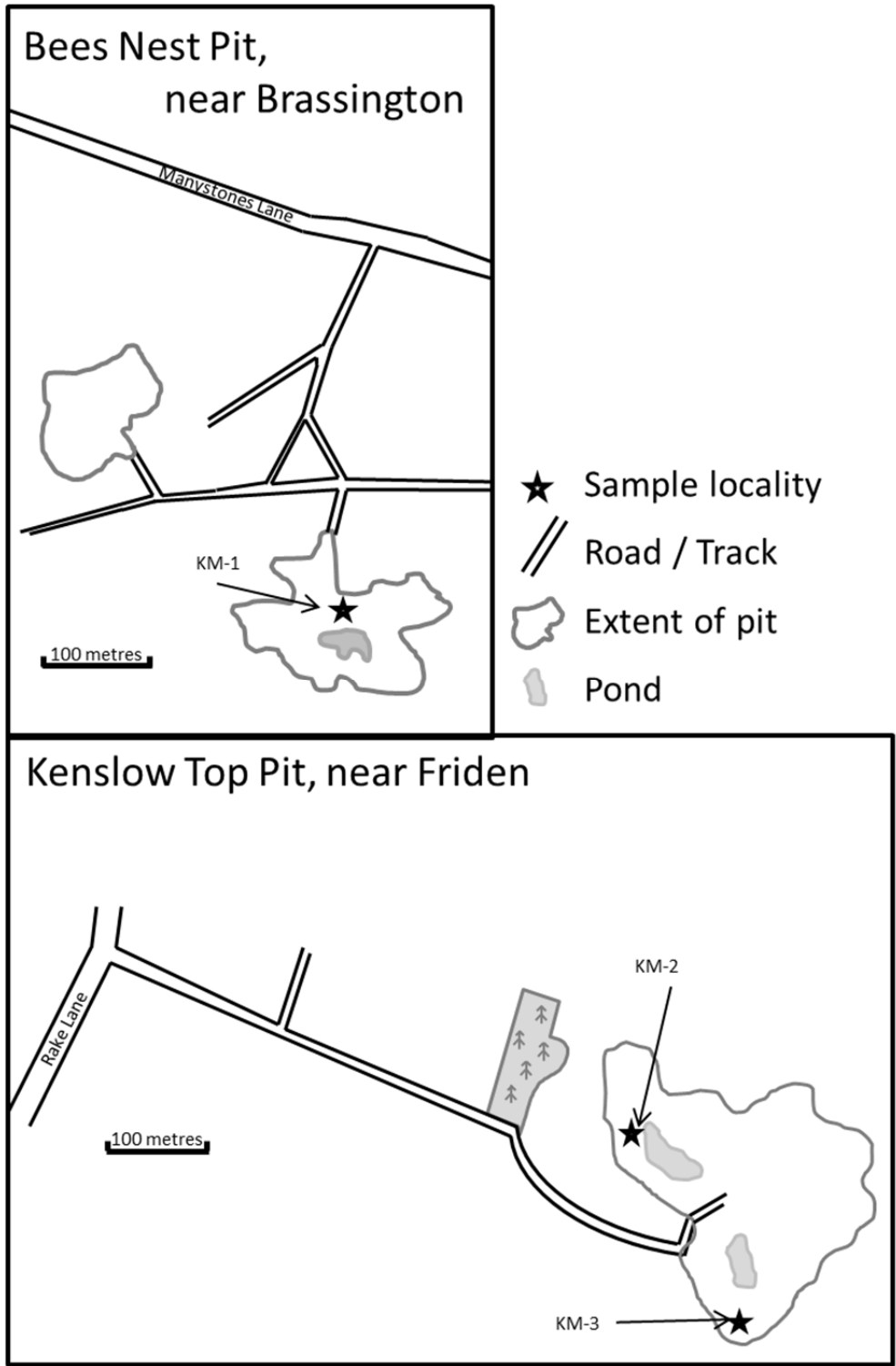
640

641   Figure 1. The location of Bees Nest and Kenslow Top pits on a sketch geological map of parts of

642   Derbyshire and Staffordshire, UK illustrating the distribution of dolomitised limestone in the

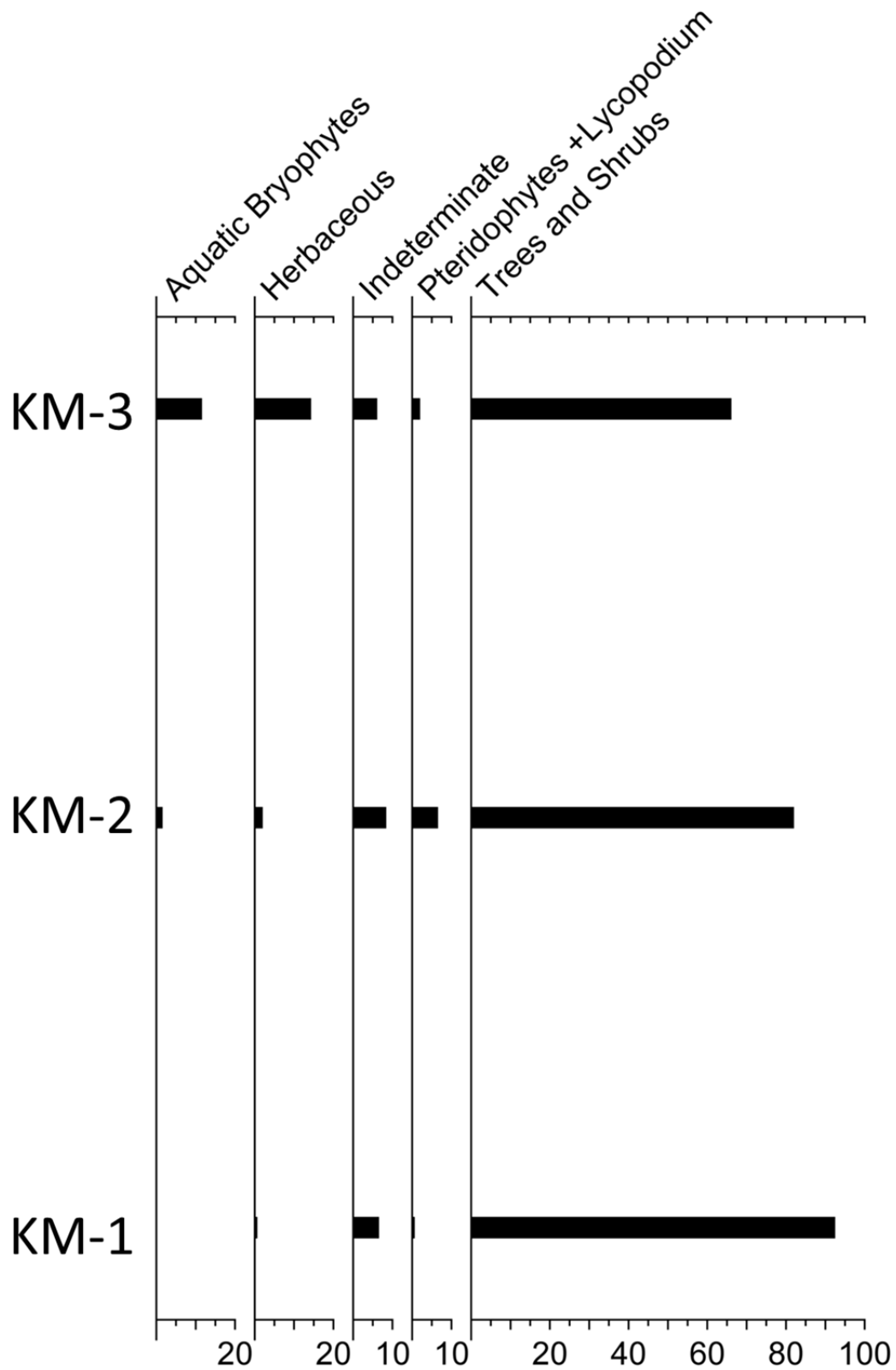643   southern Pennines. Adapted from Pound et al. (2012a)

644

645

646   Figure 2. Sketch maps of Bees Nest Pit, near Brassington (SK 24117 54585) and Kenslow Top Pit, near

647   Friden (SK 18180 61585). Based on the maps of Walsh et al. (1972).

648

649

650   Figure 3. Photograph of the wood fragment (BGS fossil specimen number GSM 76976) from the now

651   unexposed Kenslow Member of Kenslow Top Pit that sample KM-2 was extracted from (Fig. 2).

652

653

654 Figure 4. The percentages of pollen and spores in the three samples. A circle indicates a taxon which

655 represents <1% of the assemblage. The pollen/spore assemblage from the wood fragment from the

656 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.
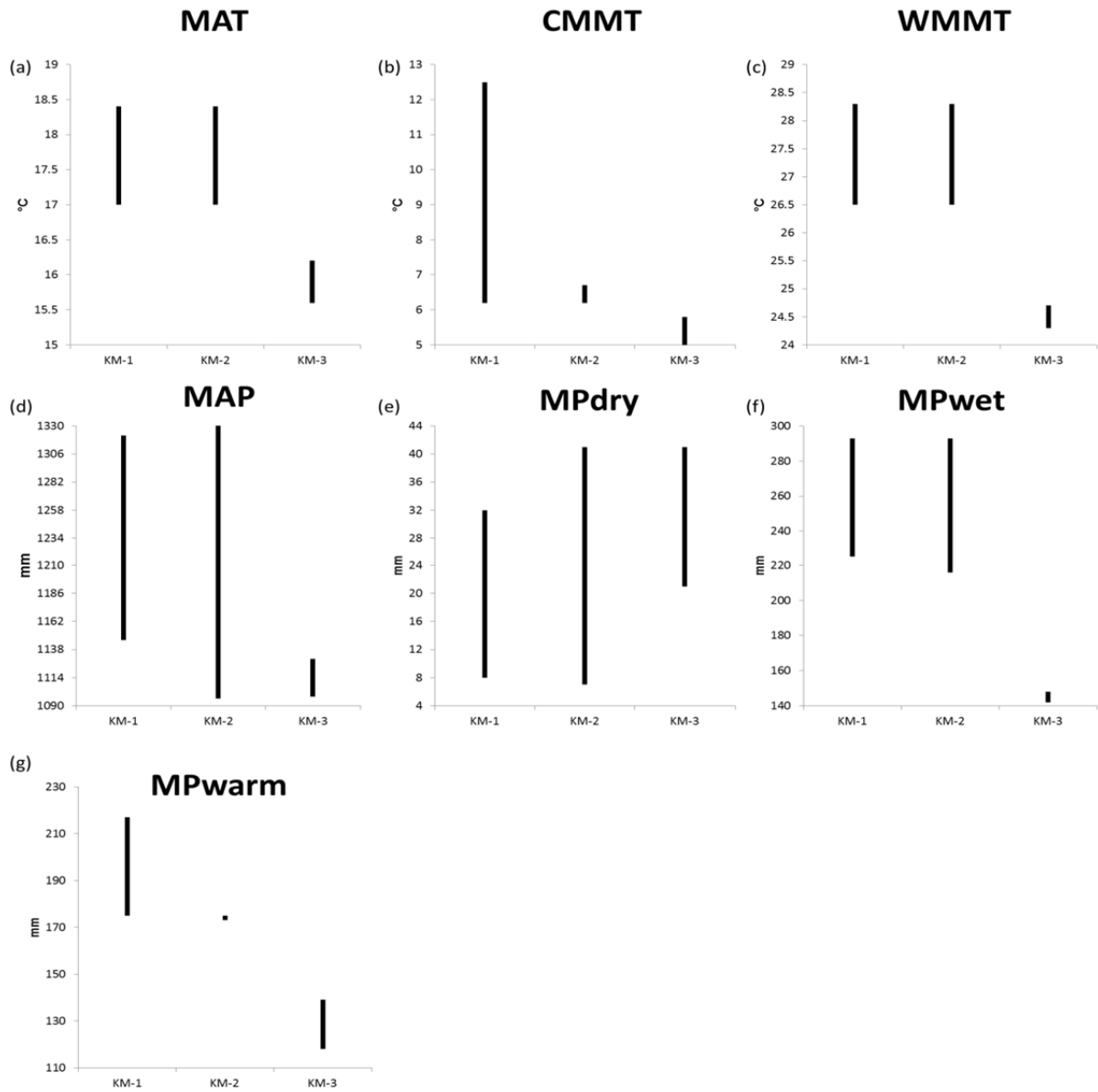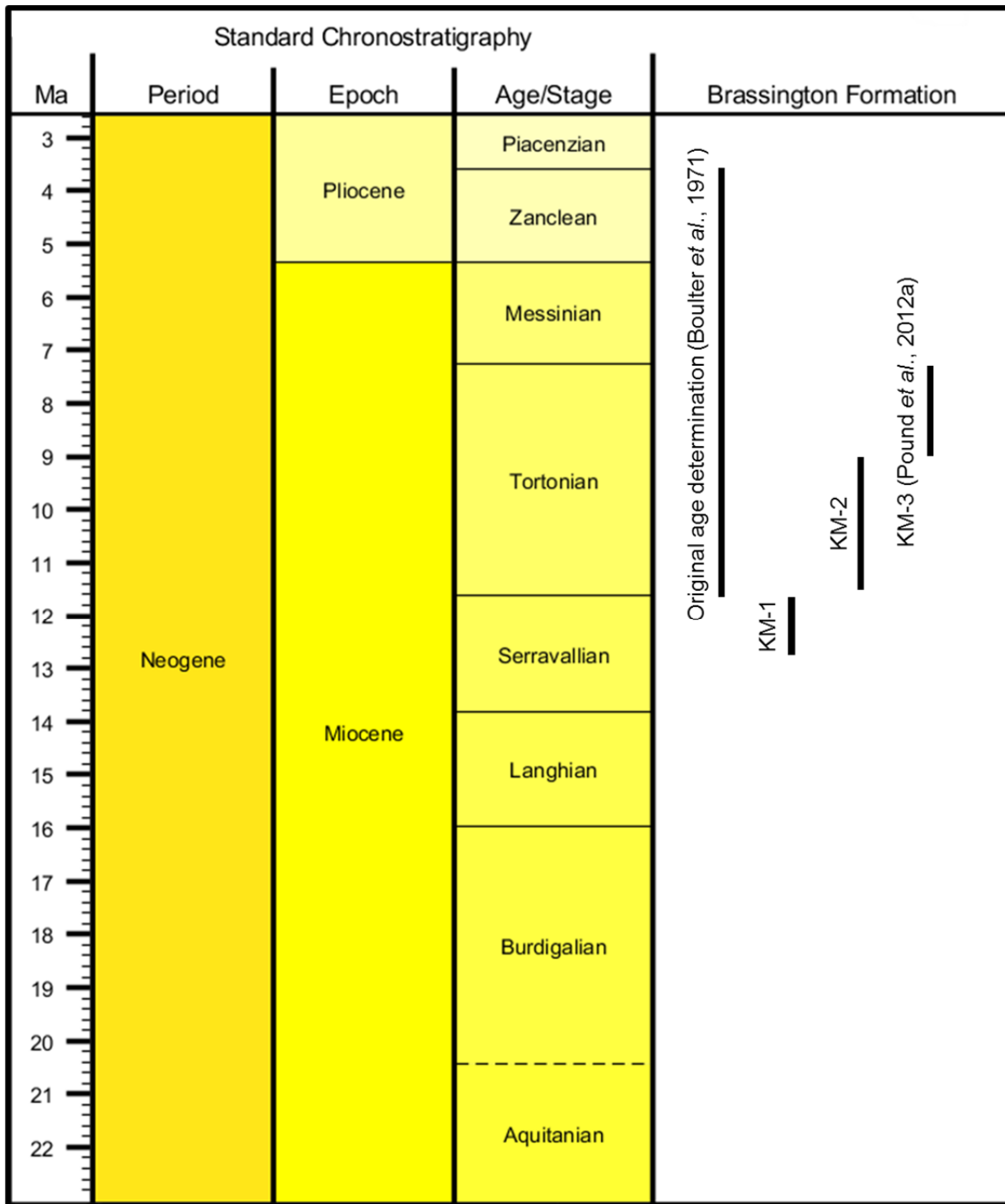
661

662 Figure 6. The palaeoclimatology of the three pollen/spore assemblages from the Kenslow Member

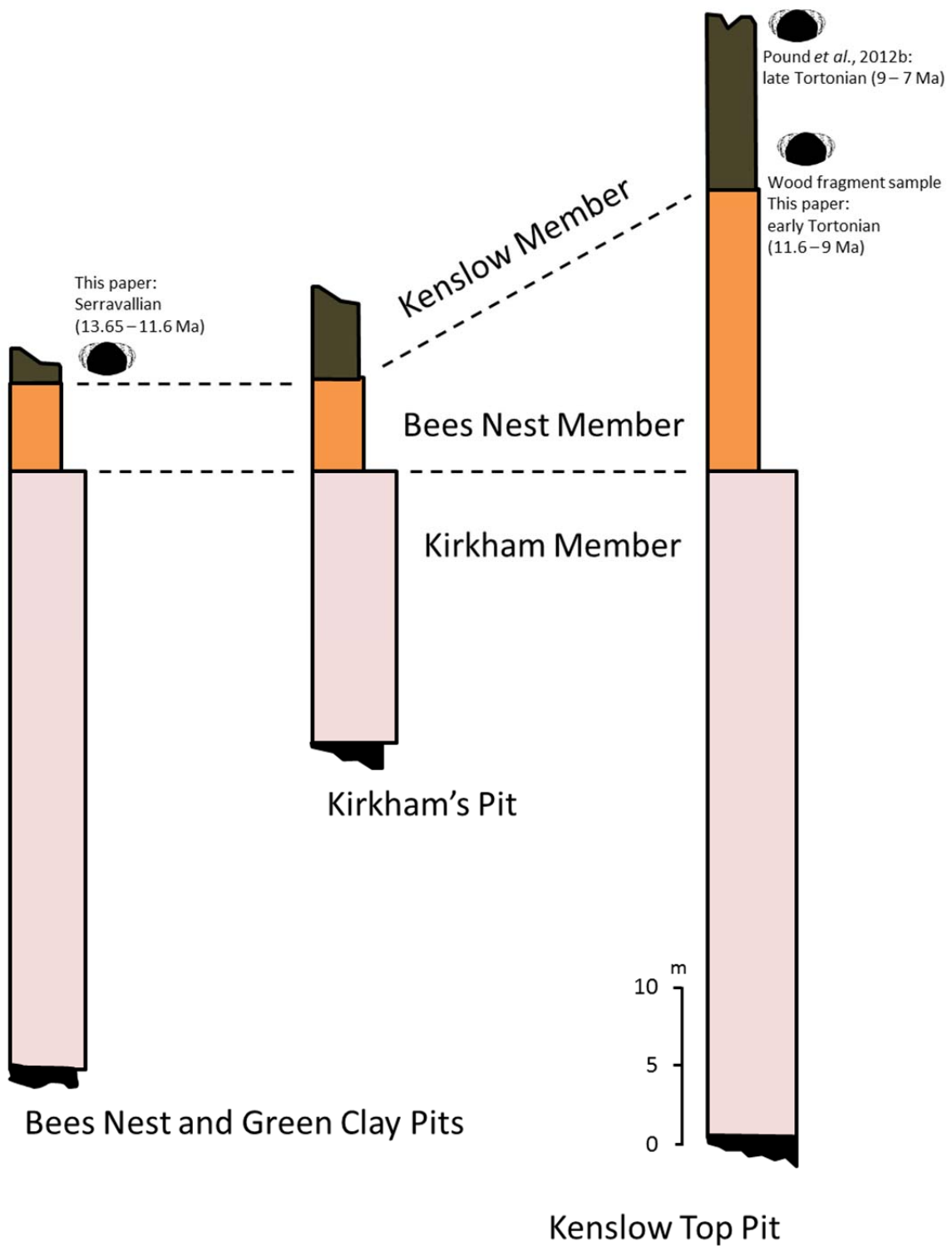663 of the Brassington Formation reconstructed using the Co-existence Approach (CA).

664

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).

670

671   Figure 8. Sketch lithostratigraphical logs of the Brassington Formation at the three main exposures

672   showing the approximate stratigraphical locations of the three pollen/spore assemblages, and their

673   inferred ages. The simplified logs are based on more detailed ones in Walsh et al. (1980). Green Clay

674   Pit is immediately north of Bees Nest Pit (Walsh et al. 1972, fig. 1).

675

676 Appendix 1

677 This appendix lists, in alphabetical order, all valid formally defined palynomorph taxa below the

678 generic level which are mentioned in this contribution with full author citations. Taxonomic names

679 and citations are based upon Stuchlik et al. (2001; 2002; 2009; 2014).

680

681 *Compositoipollenites rizophorous* (Potonié 1934) Potonié 1960

682 *Ericipites baculatus* Nagy 1969

683 *E. callidus* (Potonié 1931) Krutzsch 1970

684 *E. costatus* Grabowska 2014

685 *E. ericius* (Potonié 1931) Potonié 1960

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

687 *I. margaritatus* (Potonié 1931) Thiergart 1938

688 *Leiotriletes wolffii* Krutzsch 1962

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

690 *Symplocoipollenites vestibulum* (Potonié 1931) Potonié 1960

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

692 *Triplanosporites sinuous* Pflug 1952 ex Thomson & Pflug 1953