Quantitative palynological analysis of the E_{2a} and E_{2b} goniatite zones (Arnsbergian, Mississippian) in mudstones from the Southern Pennine Basin (U.K.).

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Abstract

We performed a quantitative palynological analysis of Namurian (Late Mississippian) mudstone intervals, potentially prospective for unconventional hydrocarbons. Many palynological studies exist on these stratigraphic intervals in the Widmerpool Gulf and the Edale Basin (sub-basins of the Pennine Basin) very few studies perform full statistical analyses. Using the Carsington Dam Reconstruction C3 Borehole (Carsington DRC3, Widmerpool Gulf) and the Karenight-1 (Edale Basin), we show the combination of quantitative palynological data and detrended correspondence analysis (DCA) can aid biozonation and additionally, provide palaeoecological constraints to the deposits. The studied interval in Carsington DRC3 was assigned to the TK miospore biozone and a hitherto undescribed peak in the fresh water alga *Botryococcus* was recorded. Using relative abundances of hinterland species, mainly from the genus *Florinites*, both boreholes could be correlated and a more confident assignment of an interval containing goniatite Biozone E_{2b} in Karenight-1 was achieved. The techniques used in the current study should be especially valuable for assessing borehole materials where the recovery of macrofossils, like goniatites used as the main biostratigraphic tool in this interval, can be very low. Future studies should focus on the same stratigraphic interval from different sub-basins of the Pennine Basin to further assess the applicability of quantitative palynological analysis combined with DCA as a stratigraphic tool for potentially prospective mudstones.

1. Introduction

In recent years, the Pennine Basin, underlying much of northern England (e.g. Aitkenhead et al., 2002), received renewed attention of industrial and academic researchers following reports some of its Carboniferous successions may be a prospective source of unconventional hydrocarbons (Selley, 1987; Selley, 2005; Selley, 2012; Smith et al., 2010). Especially the Bowland Shale Formation and its lateral equivalent units (e.g. Morridge Formation, Hollywell Shales Formation) have been the target of resource assessments (Andrews, 2013) and tentative exploration programmes (Clarke et al., 2018). These formations were deposited during the late Visean and Namurian (Serpukhovian–Bashkirian) when the Pennine Basin was located in low latitudes (McKerrow and Scotese, 1990) surrounded by two emergent land masses: the Southern Uplands High on its northern and the Wales–Brabant High at its southern edge (Figure 1) (Aitkenhead et al., 2002; Fraser and Gawthorpe, 1990; Waters et al., 2009). During the early Visean, a phase of crustal extension fragmented the earlier deposited Devonian carbonates and the Pennine Basin developed into a patchwork of smaller grabens and half-grabens (Figure 1), separated by fault-bounded carbonate blocks (Gawthorpe, 1987; Lee, 1988).

During the Namurian, the grabens and half-grabens filled with mostly deltaic sediments containing intervals with marine shales, characterized by a bivalve and ammonoid fauna, called marine bands (Bisat, 1923). Some 60 marine bands have been recognized in the Namurian, 45 of which are characterized by the occurrence of a distinct goniatite species (Bisat, 1923; Holdsworth and Collinson, 1988; Ramsbottom, 1977; Ramsbottom et al., 1962). The occurrence of these marine bands is thought to be glacio-eustatically driven (Isbell et al., 2003; Stephenson, 2008; Veevers and Powell, 1987) and during the Pendleian–Arnsbergian, the time of deposition of the sediments that are the subject of the current study, their periodicity is estimated at 111 kyr (Figure 2; Waters and Condon, 2012).

Even though ammonoid biozonation is a robust tool for correlating marine bands (e.g. Bisat, 1923; Ramsbottom, 1977, 1978; Riley, 1993), goniatite occurrence within a eustatic cycle is restricted to the sediments representing the maximum eustatic highstand and/or the sediments deposited during the interval of maximum sea level rise (Gross et al., 2014; Posamentier et al., 1988). Especially in core material goniatite occurrence can be very sporadic, which can hamper confident biostratigraphy. Added complications are the fragmented nature of the Pennine Basin (Figure 1) combined with the poorly constrained extent of Namurian marine bands, as noted by Waters and Condon (2012). Taken together this makes correlation of sedimentary successions in each of the sub-basins often challenging.

Historically, Namurian and Westphalian deposits were of strategic economic importance during the Industrial Revolution (summarized in Waters et al., 2011). Starting in the second half of the twentieth century, large scale palynological studies were undertaken to complement the existing goniatite biostratigraphy using miospores (Butterworth and Mahdi, 1982; Clayton et al., 1977; Mahdi, 1981; Marshall and Smith, 1965; Marshall and Williams, 1967; Nader, 1983; Neves, 1961; Owens and

Burgess, 1965; Owens et al., 2004; Owens et al., 2005; Owens et al., 1977; Ramsbottom, 1981; Smith and Butterworth, 1967; Wagner and Spinner, 1974; Whitaker and Butterworth, 1978a, b)). Hitherto most of these studies focused on qualitative analyses used to erect a miospore biozonation scheme (e.g. Clayton et al., 1977; Owens et al., 2004; Owens et al., 2005) with relatively few investigators publishing providing full palynological counts including assemblage composition plots (e.g. Hawkins et al., 2013). The advantages of miospores as a biostratigraphic tool are that they are very widely distributed, occur in high abundances in terrestrial and marine sequences and require only small amounts of rock material to yield a representative microflora. This is a major advantage especially when studying core material, where the chance of encountering well-preserved macrofossils in high abundance is often very limited.

The aim of this paper is to explore whether high resolution, quantitative, rather than purely qualitative miospore analysis, of Namurian deposits in the Pennine Basin is a viable correlation tool. For this exercise we selected two cores in close proximity, yet in different sub-basins: the Carsington Dam Reconstruction C3 Borehole (Carsington DRC3) in the Widmerpool Gulf and the Karenight-1 Borehole on the Derbyshire High to Edale Gulf transition (Figure 1). The boreholes have overlapping stratigraphies based on goniatite occurrences (Figure 2; Aitkenhead, 1991; Wilson and Stevenson, 1973), but a detailed miospore biozonation is missing at this point.

2. Materials and methods

In total, spore assemblages from 20 Carsington DRC3 samples and 11 Karenight-1 samples were analysed quantitatively. To eliminate the possibility of smearing and caving, a concern for confident miospore biozonation raised by Clarke et al. (2018), only well-cleaned core samples rather than cuttings were used in the current study.

2.1 Sample material

Following a dam failure during the construction of the Carsington Water reservoir (Skempton and Vaughan, 1993), an array of boreholes was drilled to assess fluid movement in the subsurface, one of which was the Carsington DRC3 Borehole (1.63°W; 53.05°N). During the Mississippian, this area was located close to the centre of the Widmerpool Gulf (Figure 1). A total of 38 m of alternating sandstones and mudstones units of the Morridge Formation (Figure 3) attributed to the E_{2a} *Cravenoceras cowlingense*, E_{2a3} *Eumorphoceras yatesae* and E_{2b1} *Cravenoceratoides edalensis* marine bands (Figures 2–3) were cored (Aitkenhead, 1991; Aitkenhead et al. 2002) and investigated in the current study.

Karenight-1 (1.53°W; 53.18°) was drilled in 1973 by Drilling and Prospecting International as a mineral exploration well at the transition of the Derbyshire High to the Edale Gulf (Figure 1). Samples originate from the 234.70–251.89 m interval of carbonate cemented mudstones interdigitated with limestone (250.93–244.50 m) and siltstone (244.5–234.70 m) levels (Figure 4). This interval covers the E_1 (251.89–248.55 m) and E_2 *Eumorphoceras* goniatite zones (Figures 2, 4) of the Bowland Shale

Formation based on goniatite (Dimorphoceratid) occurrences in combination with *Posidonia corrugata elongata* (E_2) and *Leiopteria longirostris* (E_{2b}) (Wilson and Stevenson, 1973).

2.2 Palynological preparation protocol

Approximately 5g of each of the 31 samples (Appendix 1–2) were processed in the Biostratigraphy and Palaeontology Laboratories of The British Geological Survey following the standard maceration protocol using HCl (36%) and HF (40%) to digest carbonates and silicates (Wood et al., 1996). Palynofacies analysis of both boreholes revealed a high abundance of amorphous organic matter, often surpassing 80% (Hennissen et al., 2017). To allow proper spore identification in such AOM rich kerogen isolates, most samples were exposed to fuming nitric acid for a maximum of 2 minutes to remove excess AOM. The resulting residues were strew mounted on microscope slides using Elvacite™ 2044 resin. Routine study of miospores was performed using a Nikon Eclipse Ci-L microscope with a maximum magnification of 1000X. Images (Plates I, II) were taken using a Nikon 80i differential interference contrast (DIC) microscope equipped with a Nikon DS-Fi2 camera. Counts were performed line-by-line keeping track of miospores continuously using a macro-enabled Microsoft Excel™ spreadsheet. When reaching 300 miospores we finished counting the line in progress after which the remainder of the slide was scanned for the occurrence of rare species. In samples with low abundances (<300 miospores), two entire slides were counted (Appendices 1–2).

2.3 Data handling for statistical analysis

Before conducting DCA, we excluded indeterminate palynomorphs and palynomorphs not identified to the genus level. These specimens either lack any diagnostic taxonomic features, other than the presence of a trilete mark (e.g. ‘trilete spores’) or a particular exinal sculpture (e.g. ‘baculate spores’). These informal taxonomic groups potentially unite palynomorphs from very different origins, thriving in different ecological niches. Therefore, the distribution pattern of these groups is not driven by the affinity to certain ecological conditions and their abundance signature carries no information that can be resolved using detrended correspondence analysis (DCA).

For this reason, we also excluded reworked palynomorphs (e.g. chitinozoans): their occurrence is important to assess the amount of reworking encountered in a particular sample, but their palaeoecological significance is low because they are an external addition to the palynological assemblage of the sample.

To allow a comparison of the assemblages from samples in both boreholes, DCA was performed on a composite dataset consisting of the raw counts of samples from both boreholes. To allow meaningful statistical analysis and direct comparison to palaeoecological groupings in the literature (e.g Balme, 1995; Davies and McLean, 1996; Phillips and Peppers, 1984; Scott, 1979) summarized in Table 1, taxa were grouped within their respective genera and converted before conducting DCA (Appendix 3).

2.4 Detrended correspondence analysis (DCA)

DCA was performed on the counting results per genus as given in Appendix 3 using the decorana routine of the *vegan* package (Oksanen et al., 2018) in the R environment (R Core Team, 2013). To establish an appropriate ordination method we carried out an initial DCA analysis and determined the gradient length of variation for the first two DCA axes for the species plots in each borehole separately. For Carsington DRC3 these were 4.43 SD (DCA1) and 8.23 SD (DCA2) while for Karenight-1 these were 4.86 SD (DCA1) and 8.51 SD (DCA2), whereby SD = Standard Deviation units. Because these values clearly surpass 3SD, we consider a unimodal response and we choose DCA over correspondence analysis (CA) following the recommendations by Hill and Gauch (1980) and Leps and Smilauer (2003).

3. Results

As part of a previous study, a palynofacies assessment was conducted on all samples from Carsington DRC3 and Karenight-1 (Hennissen et al., 2017). Based on the combined results of transmitted light microscopy and reflected near-UV fluorescent light microscopy, the most promising samples for a miospore assemblage assessment were selected for the current study. Samples were selected based on spore abundance and the general state of preservation of the miospores. The Carsington DRC3 borehole was situated closer to the source of terrestrial material in the middle of the Widmerpool Gulf while the Karenight-1 borehole was situated further north, in the Edale Gulf, slightly further away from emergent landmasses (Figure 1) resulting in generally lower miospore abundances, but also a poorer preservation state. This is perhaps illustrated best by the presence of coarser, turbiditic intervals in the Carsington DRC3 core (Figure 3), which were not found in the Karenight-1 core (Figure 4).

3.1 Carsington Dam Reconstruction C3 palynological counts

In Carsington DRC3 we assessed the spore assemblages in 20 samples; full counts are included in Appendix 1. In 15 samples at least 300 spores were identified, while in the other five samples two complete slides were counted (SSK45587, SSK45647, SSK46311, SSK46324 and SSK46331). Overall, *Lycospora pusilla* (Plate I, Figures 1–2) is the most abundant taxon (34.1% average). Indeterminate spores and pollen are the second most abundant group (9.2% average) while the alga *Botryococcus* sp. (Plate I, Figures 11–12) is the third most abundant taxon (5.0%). However, *Botryococcus* sp. only appears in three samples (22.99–18.44m) near the top of the studied section in important abundances (SSK45595, 45594 and 45587). In sample SSK45587 (18.44m) the most abundant taxon is *Florinites* sp. (Plate I, Figures 17–18).

3.2 Karenight-1 palynological counts

In the Karenight-1 core 11 spore assemblages were assessed; full counts are included in Appendix 2. In seven samples at least 300 spores were identified, while in the other four samples two complete slides were counted (SSK51175, SSK51184, SSK51199 and SSK53146). When all samples are considered, *Lycospora pusilla* is the most abundant taxon (32.2% average). Indeterminate spores and pollen are the second most abundant group with an average relative abundance of 12.5%. The third most abundant taxon was *Densosporites* spp (11.08% on average) (Plate I, Figures 3–4). In sample SSK51184 (238.86 m) *Florinites* sp. was more abundant (16%) than either *L. pusilla* or *Densosporites* sp.

3.3 Detrended Correspondence analysis

The eigenvalues for the first four axes of DCA and the taxa scores for these axes are given in Table 2, with the taxa with a statistical weight in the upper quartile printed in bold. The statistical weight, or weighting factor (WF) is expressed as an accumulative sum of the relative abundance of a taxon in each sample. *Lycospora* is the most influential taxon in DCA of the combined counts, with a statistical weight of 12.382 around five times higher than *Densosporites* (WF = 2.606), the second most important taxon. *Granulatisporites* (Plate I, Figures 5–6) with a statistical weight of 2.062 is the third most important taxon. It is worth noting *Botryococcus* and *Florinites* are also in the upper quartile of most influential taxa though they occur in relatively few samples and mostly in Carsington DRC3.

The samples and upper quartile taxa, with indication of their palaeoecological affinity, against the first two DCA axes, with an eigenvalue of 0.241 and 0.155 respectively, are plotted in Figure 5. The first DCA axis effectively separates hinterland taxon *Florinites* from coloniser *Crassispora* (Plate I, Figures 19–20). Non-forest mire taxa and forest mire taxa plot on intermediate positions along DCA1. The algal taxon *Botryococcus* has the second highest score along DCA1 while the two upper quartile taxa with an unknown palaeoecological affinity, *Pilosisporites* and *Leiotriletes* (Plate I, Figures 9–10), plot close to each other and *Verrucosisporites* (Plate II, Figures 1–2) on the positive side of DCA1.

The DCA2 axis separates *Botryococcus*, the highest upper quartile score, from *Florinites*, the lowest score. Non-forest and forest mire taxa plot in low scores on the positive and negative side of DCA2 and the coloniser *Crassispora* has a low positive DCA2 score.

Samples from Carsington DRC3 mostly cluster in the upper left quadrant of the DCA plot with low negative scores on the X axis and low positive scores (low negative for SSK4604) on the Y axis. SSK45587, 45594 and 45595 plot away from the main sample cluster. Sample SSK45587 (18.44m) is the only Carsington DRC3 sample with a high positive DCA1 score combined with a negative DCA2 score, because of its high relative abundance (49%) of the genus *Florinites* combined with a low relative abundance (0.45%) of the genus *Lycospora*. Both SSK45594 and 45595 combine high abundances of *Botryococcus* (31% and 39% respectively) with intermediate abundances of the genus *Lycospora* (21% and 25% respectively). Sample SSK46301 plots somewhat out of the main Carsington DRC3 cluster due to its very high relative abundance of *Lycospora* (65%).

Samples from Karenight straddle zero on DCA1 while plotting with low negative scores along DCA2. There are two main outliers: SSK53139 and 51209. Relative abundances of the assemblages in these two samples are characterized by high amounts of *Lycospora* (47% and 50% respectively) combined with low, questionable occurrences of *Densosporites* (0.66 and 2% respectively).

4. Discussion

4.1 Biostratigraphy

Using goniatite biostratigraphy, Carsington DRC3 has been assigned an E_{2a} to E_{2b1} age (Figures 2, 3; Aitkenhead, 1991) while in the Karenight-1 Borehole, the top and bottom of the studied section are not well constrained, but the succession covers an interval that includes the top part of E_{1c}, E_{2a} and E_{2b}, with a questionable occurrence of *Cravenoceratoides edalensis* (E_{2b1}) at around 242 m (Figures 2, 4; Wilson and Stevenson, 1973).

The miospore biozonation of western Europe was established by Clayton et al. (1977) while Owens et al. (1977) focused on the Namurian of northern England and Scotland, a scheme that was later refined by Owens et al. (2004). Following these schemes and using the goniatite biostratigraphy as a lead, Carsington DRC3 should correspond to the *Mooreisporites trigallerus* – *Rotaspora knoxiae* (TK) Miospore Biozone (Owens et al., 2004), formerly the *Stenozonotriletes triangulus* – *R. knoxiae* Biozone (Owens et al., 1977).

The studied interval from the Karenight-1 borehole should mostly cover the same TK Biozone, but its lower boundary may extend into the Pendleian, represented by the *Verrucosisporites morulatus* Sub-Biozone (Vm) of the *Reticulatisporites carnosus* – *Bellispores nitidus* biozone (CN). Its upper boundary may extend into the *Lycospora subtriquetra* – *Apiculatisporis variocorneus* Sub-Biozone of the *L. subtriquetra* – *Kraeuselisporites ornatus* Biozone (Figure 2).

Owens et al. (2002) defines the base of the TK miospore biozone using the appearance of *Punctatisporites giganteus*, *P. pseudopunctatus* and *Stenozonotriletes triangulus* while close to the E_{2a}–E_{2b} boundary, *Mooreisporites fustis* and *Reinschospora speciosa* appear. The upper boundary of the TK biozone coincides with the disappearance of *Rotaspora knoxiae*, *Triquitrites marginatus*, *T. trivalvis* and *Tripartites vetustus* (Owens et al., 2004).

The top of the preceding CN Biozone is characterized by the range tops of *Reticulatisporites carnosus*, *Rotaspora fracta* and *Raistrickia nigra* (Owens et al., 2004). The upper part of this biozone is represented by the Vm Sub-Biozone which is characterized by the appearance of *V. morulatus*.

The base of the SO Biozone succeeding the TK Biozone, with the SV Sub-Biozone at its base, is characterized by the appearance of *Lycospora subtriquetra*, *Kraeuselisporites ornatus*, *Apiculatisporis variocorneus* and *Camptotriletes superbus*. The top of the SV sub-biozone coincides with the range tops of *Schulzospora campyloptera*, *Crassispora maculosa*, *Bellispores nitidus* and *Microreticulatisporites concavus* (Owens et al., 2004).

4.1.1 Miospore Biostratigraphy in Carsington DRC3

The miospore assemblages of Carsington DRC3 are dominated by *Lycospora pusilla*, often surpassing 50% of the total counts, which is a common observation in Namurian deposits of the Pennine Basin and the CN–SO Biozones in particular (e.g. Stephenson et al., 2008). However, a number of the index taxa for the Clayton et al. (1977) and Owens et al. (2004) miospore biozonations summarized above were identified as well. *Stenozonotriletes triangulus* (Plate II, Figures 15–16), though never a very important part of the assemblage, occurs in many samples and has an important range in the studied Carsington DRC3 section co-occurring with *B. nitidus* (Plate II, Figures 9–10), *C. maculosa* and *S. campyloptera* (Plate II, Figures 15–16) (Figure 3). *Bellispores nitidus*, *C. maculosa* and *S. campyloptera* have range tops around the Ansbergian–Chokierian (E_{2c4}–H_{1a1}) boundary and commonly occur in early Namurian deposits (Varker et al., 1990). Though specimens of the genus *Rotaspora* (in SSK45647 and 46331) were recovered, none of them could be identified confidently to the species level. Specimens from the genus *Triquitrites* were kept in open nomenclature (SSK46032 and 46363). *Tripartites nonguerickei* was recovered from (SSK45594, 45628, 46311 and 45621) while unspeciated specimens of the genus *Tripartites* were recovered from SSK46019 (37.10 m).

A single specimen of *Reticulatisporites carnosus* was identified in sample SSK46301 (40.83 m), even though its range top coincides with the CN Biozone (Owens et al., 2004). Because there is no other sign of significant reworking in the assemblage of SSK46301, this specimen was kept in the counts. *Kraeuselisporites ornatus* (Plate II, Figures 13–14), with a range bottom reportedly in the SO Biozone, succeeding the TK Biozone, occurs here in samples SSK45621 (28.94 m), SSK46301 (40.83 m) and SSK46351 (46.08 m). However, none of the other diagnostic taxa for the SO Biozone were reported.

The long range of the index taxon *S. triangulus* alongside *B. nitidus*, *C. maculosa* and *S. campyloptera*, shows that this section is indeed part of the TK Biozone while no confident upper or lower boundary for this biozone can be assigned on the basis of the studied samples. The single occurrence of *R. carnosus* does not warrant an assignment to the SO Biozone, nor does it allow us to confidently assign a lower boundary of the TK Biozone at that level. In Carsington DRC3, *K. ornatus* appears earlier than its previously reported upper Arnsbergian range base in previous European biostratigraphic studies (e.g. Clayton et al., 1977; Owens et al., 2004). However, this observation corresponds to the observations by Utting and Giles (2008) who report an earliest appearance of *K. ornatus* in the *Reticulatisporites carnosus* Assemblage Zone which was dated Pendleian to Arnsbergian from the Canadian Atlantic.

4.1.2 Miospore Biostratigraphy in Karenight-1

The state of preservation of spores in the Karenight-1 Borehole was poor in comparison to Carsington DRC3. This is reflected in the relatively high abundances of indeterminate spores. *L. pusilla* again was the most dominant identified spore, though from SSK51191 to SSK46364 (240.56–234.80m), *Densposporites* sp. became an equally important taxon. In sample SSK51184 *Florinites* sp. was more abundant than both *L. pusilla* and *Densosporites* sp. *Stenozonotriletes triangulus* was identified tentatively only in sample SSK53139. *Schulzospora campyloptera* has a long range within the studied section comparable to Carsington DRC3. The only sample it was not identified in was SSK46364 at the very top of the interval (234.80m). This is the same sample where *Mooreisporites fustis* (Plate II, Figures 19–20) was identified. None of the diagnostic taxa from the SO biozone were identified.

The dominance of *L. pusilla* alongside the long range of *S. campyloptera* suggest a TK assignment of the assemblages from Karenight-1. Hennissen et al. (2017) identified *M. fustis* in SSK51192 while in the current study *M. fustis* was reported at the top of the studied interval Karenight-1. Therefore we can tentatively assign SSK51192 –46364 (240.93–234.80 m) to the E_{2b} goniatite zone following Owens et al. (2004). None of the index taxa of the preceding SO Biozone were identified here and based on the data, we cannot identify the lower boundary of the TK Biozone.

4.2 Palaeoecology of the miospore assemblages

To assess the palaeoecology of the Carsington DRC3 and Karenight-1 assemblages we utilise the palaeobotanical and palaeoecological grouping of Carboniferous miospore genera by Davies and McLean (1996) combined with the DCA. The absolute abundances (Appendices 1–2) and relative abundance plots (Figures 3–4) contain specimens in open nomenclature, marked by a '?' following the figure denoting the abundance. These identifications concern taxa for which we are confident of the genus assignment, but where the state of preservation prevents a confident species assignment. Because the palaeoecological groupings of Davies and McLean (1996) are based on genus assignments rather than species identifications, these specimens in open nomenclature were included in the palaeoecological characterization. Specimens that lack diagnostic features to confidently assign a genus, but are recognized as miospores, were put in the 'Spores indeterminate' group and were consequently not included in any further palaeoecological considerations (see also Paragraph 3.3).

4.2.1 Detrended correspondence analysis (DCA) on the Carsington DRC3 and Karenight-1 cores

The DCA was run on the genus abundances of both boreholes combined (Appendix 3). Genus scores and eigenvalues for DCA analysis are given in Table 2, where genera with a statistical weight in the upper quartile, influencing the DCA the strongest, are indicated in bold. Along the first axis, the DCA analysis separates the hinterland genus *Florinites* and the alga *Botryococcus* on the positive side from the coloniser genus *Crassispora* on the negative side (Figure 5). All miospores related to mire plants plot between these end members and there does not seem to be a clear distinction between non-forest and forest mire spore genera. Along the second DCA axis, *Florinites* at the negative end is separated from *Botryococcus* on the positive end with the forest and non-forest taxa and the colonisers plotting in between without a clear clustering.

In the DCA plot, samples from both boreholes are clearly separated with the bulk of the samples from Carsington DRC3 plotting slightly higher scores on DCA2 and slightly lower scores on DCA2 reflecting mostly a higher abundance of *L. pusilla*. Samples from Karenight-1 overall have slightly higher relative abundances of *Densosporites* sp. resulting in the higher DCA1 scores. This different clustering on the combined DCA plot is possibly a result of the different source of terrigenous material. In the Carsington DRC3 borehole this material is sourced from the Wales-Brabant High and the shales are interspersed with pale grey protoquartzitic turbidites (Waters et al., 2009). In the Karenight-1 borehole, these turbiditic intervals are absent and the terrestrial material was sourced from the Southern Uplands (Waters et al., 2019; Waters et al., 2009).

Lycospora is the dominant genus in both Carsington DRC3 and Karenight-1 with a weighting factor (WF) of 12.382. *Lycospora pusilla*, which on average made up 34 % of the assemblage in Carsington DRC3 and 32% in Karenight-1, was the most commonly encountered species in this study. This spore is derived from tree lycopsids (Willard, 1989; Willard et al., 1995) which occupied coastal, perennially flooded swamps, indicating wet climatic conditions. *Lycospora* was produced by arborescent lepidodendracean lycopods; tall tree-like club mosses that overshadowed lower vegetation (Philips and DiMichele, 1992).

Densosporites the second most important genus (WF = 2.606) and *Cingulizonates* (WF = 1.078) originate from herbaceous lepidodendralean lycopods abundant near raised bogs (Balme, 1995). These raised bogs would receive their water in the form of precipitation rather than from nutrient-rich ground water, resulting in reduced growth of the plants that lived there, thus favouring herbaceous lycopods (Balme, 1995).

Granulatisporites (WF = 2.062) is a genus that was present in all samples from Carsington DRC3, except SSK45587 (18.44m) and all samples from Karenight-1 except SSK51209 (244.93m). It is the miospore of a number of small fern genera and possibly some pteridosperms (Brousmiche, 1983; Eble, 1996). They are indicative of exposed substrates and are not significant in peat formation (DiMichele and Phillips, 1994).

Punctatisporites (WF = 1.741) is a genus that was recovered from all studied samples in Carsington DRC3 and all but one sample (SSK51209, 244.93m) in Karenight-1. Most specimens could not be identified to species level, especially in Karenight-1. The most common species of *Punctatisporites* in Carsington DRC3 was *P. aerarius*, from the *Scolecopteris major* group of the tree fern *Psaronius* (DiMichele and Phillips, 1994).

There is very little reported in the literature about the palaeoecology of the genera *Leiotriletes* (WF = 1.177) and *Pilosisporites* (WF = 0.469). Both genera have previously been interpreted as small fern spores (Hower et al., 1996; Stephenson et al., 2008) and they were classed as Ferns in Davies and McLean (1996).

Botryococcus (WF = 1.123) occurs in relatively low abundances from 55.46 m to 25.40 m in Carsington DRC3 while in the uppermost part of the core (22.99–18.44m) it has very high relative abundances (12–36%). In Karenight-1, *Botryococcus* occurs only in three samples with a maximum relative abundance of 2.03% in SSK51175 (236.7m). In modern environments, *Botryococcus* occurs in lakes and ponds across all latitudes with blooms often recorded from shallow, often partly saline lakes in arid regions (Tyson, 1995 p.309). In saline, evaporitic environments the occurrence of blooms of *Botryococcus* follows heavy rains (Cane, 1976) and productivity pulses seem to be related to freshening of the water (Warren, 1986). Palaeoecologically, in Late Carboniferous deposits in Central Europe, *Botryococcus* has been reported from shallow lakes or littoral environments of deeper lakes (Clausing, 1999).

Calamospora (WF = 1.107) is present in both studied cores but never reaches a relative abundance exceeding 8 %. *Calamospora* is the miospore of various non-forest mire ferns of the Orders Equisetales and Sphenophyllales (Balme, 1995). Bek and Simunek (2005) relate *Calamospora* to the cone genus *Discinites* belonging to tree ferns from the Order Noeggerathiales.

Florinites (WF = 0.999) occurs in very low abundances (≤ 3%) throughout Carsington DRC3, except in the uppermost sample (SSK45587 at 18.44m) where the relative abundance reaches 42%. In Karenight-1, *Florinites* is present in very low abundances throughout except for a conspicuous spike from 240.93 to 236.70 m when its relative abundance rises from 6% up to 16% and back down to 6%. *Florinites* is a large cordaite pollen grain (Falcon-Lang and Scott, 2000). This genus can also represent coniferaleans, as can *Potonieisporites* (Balme, 1995). These pollen genera all represent plants that colonised better drained, extra-basinal slopes in the Carboniferous following the interpretations by Neves (1958) and Chaloner (1958), but cordaites are known to have appeared in mire settings (DiMichele and Phillips, 1994; Smith, 1962).

Other known seed fern prepollen are *Schulzospora* and *Rotaspora* (Balme, 1995). *Schulzospora* (WF = 0.402) was probably produced by a pteridosperm, an extinct seed-producing, fern-like plant, allied or ancestral to the gymnosperms (Eble et al., 2001; Ouyang, 1996; Potonié, 1962) and is similar in morphology to simple conifer-like monosaccate pollen such as *Potonieisporites* and *Caheniasaccites* in having an inflated sac-like extension around the central body.

Crassispora, and in particular *C. kosankei* is a marginal spore throughout both boreholes though it never reaches important relative abundances. This spore is produced by an arborescent sigillariacean lycopod (Davies and McLean, 1996) which is known to be underrepresented in spore assemnblages because of its parent plant has a low spore production rate (Willard and Phillips, 1993).

The last three genera in the upper quartile of genera in DCA *Verrucosisporites* (WF = 0.748), *Convolutispora* (WF = 0.615) and *Colatisporites* (WF = 0.624) are spore genera for which very limited paleoecological information is available other than that they are related to non-forest mire plants (Davies and McLean, 1996). For example, Looy and Hotton (2014) describe *Verrucosisporites* as an undiagnostic morphotaxon for several non-forest mire botanical orders. Because of their low abundances and limited use in previous studies, no major conclusions can be inferred from their distribution pattern.

4.2.2 Palaeoecology of the Morridge Formation spore assemblage in Carsington DRC3

Most samples from Carsington DRC3 plot on the negative end of DCA axis 1 and have low positive scores along DCA axis 2. This clustering reflects the high abundance of *Lycospora* in these samples with *L. pusilla* on average making up 39% of the assemblage. This cluster encompasses all samples that were part of the E_{2a} marine band below E_{2a3} (55.46–28.94m) (Figures 3, 5). Sample SSK46032 (39.55m) plots slightly positive along DCA1, which reflects the highest abundance of *Botryococcus*, plotting at the positive end of DCA1, in this part of the core.

Sample SSK45604 (25.40m) is the oldest sample from E_{2a3} and it plots slightly out of the main cluster reflecting the lower relative abundance of *L. pusilla* (16%). Samples SSK 45595 (22.99m) and SSK45594 (21.48m) plot with distinctly positive DCA1 and DCA2 values. This is a reflection of the highest recorded relative abundances of *Botryococcus*, 39% in SSK 45595 and 31% in SSK 45594 (Figure 3). Finally, sample SSK 45587 plots positive along DCA1 and negative on DCA2. This is a reflection of the maximum relative abundance of *Florinites* at 18.44m.

The E_{2a}–E_{2b} interval of the Carsington DRC3 core consists of mudstones and sandstones of the Morridge Formation (Hennissen and Gent, 2019; Hennissen et al., 2017), part of the Millstone Grit Group, containing fluvio-deltaic deposits sourced from the Wales-Brabant High as opposed to the Bowland Shale Formation where similar deposits are sourced from Southern Uplands (Figure 1 and Waters et al., 2009).

The interval of E_{2a} below E_{2a3} (55.46–28.22m) is characterized by the dominance of typical wetland flora (Turner and Spinner, 1993; Turner et al., 1994) which is reflected by the forest and non-forest mire genera *Lycospora*, *Cingulizonates* and *Densosporites* (Figure 3). During the E_{2a3} interval (26.18–21.48 m) a gradual decline in the relative abundance of *Lycospora pusilla* is noticeable from 33% to 21%. The uppermost sample in the studied section shows a peak in the hinterland genus *Florinites* (49%). This is comparable to what has been described as the 'Neves effect' by Chaloner and Muir (1968) and Chaloner (1958) after Neves (1958); (saccate) upland spores are encountered in higher relative abundances more distally because they are transported into the basin by wind and rivers while the (non-saccate) forest and non-forest mire spores are only dispersed more locally. In the Namurian, this abundance signature has previously been related with maximum flooding surfaces (e.g. Hawkins et al., 2013; Stephenson et al., 2008; Turner et al., 1994) and is consistent with the sedimentary and geochemical observations on the same section by Hennissen et al. (2017). However, in the 22.99–18.44 m interval, there is a spike of *Botryococcus* which is more difficult to interpret. Neves (1961) reported the occurrence of *Botryococcus* in non-marine shales of Yeadonian age in the southern part of the

Pennine Basin while Marshall and Smith (1965) reported *Botryococcus* in Westphalian deposits in the Yorkshire Coalfield. Marshall and Smith (1965) suggest that because of the high abundances and its restricted range, these occurrences can serve as a correlation tool. To assess whether the spikes of *Botryococcus* in the current study can be used as a tool for correlation requires further analysis of contemporaneously deposited sediments from the Widmerpool Gulf and its surrounding sub-basins.

Because of the restricted nature of the grabens and half grabens in the Pennine Basin (Paragraph 1 and Figure 1) with only occasional connection to the main ocean, large salinity fluctuations are to be expected throughout the course of an entire glacio-eustatic cycle (Martinsen et al., 1995). These large salinity fluctuations have been reported in the E_{2a1} and E_{2a2} marine bands of the Widmerpool Gulf, evidenced also by the occurrence of siderite intervals in both turbiditic and mudstone intervals (Gross et al., 2014). In the currently studied section (Figure 3), we found frequent sideritic intervals associated with the turbiditic intervals in E_{2a}, but in E_{2a3} siderite is only reported around 26 m, just below the main peak in *Botryococcus*. This occurrence merits further investigation and the precise significance of this peak cannot be described using the data we currently possess.

4.2.3 Palaeoecology of the Bowland Shale Formation spore assemblage in Karenight-1

In the DCA analysis, the main cluster of Karenight-1 samples plots lower on DCA2 and slightly higher along DCA1 (Figure 5). The samples of the interval 251.89–244.93 m are characterised by relatively low DCA1 scores and the highest recorded DCA2 scores for this borehole. This shows the dominance of *L. pusilla* combined with the higher relative abundance of miospores of the genus *Crassispora*, mostly *C. kosankei*. This spore is considered to be produced by sigillarian plants, capable of colonising habitats that may have been seasonally dry or experienced periods of reduced rainfall (Cecil, 1990; Phillips and Peppers, 1984; Winston, 1990). The true abundance of sigillarian plants is most likely underestimated by relatively low spore production rates (Willard and Phillips, 1993; DiMichele and Philips, 1994), see also Section 4.2.1. This may explain why despite its relatively long range (Serpukhovian to Kasimovian, Clayton et al., 1977), *C. kosankei* is rarely a major component in the studied assemblages (Owens et al., 2004).

In samples SSK 51199 (242.62 m) and 51193 (241.17 m), *C. kosankei* all but disappears from the assemblages and the hinterland ecological group becomes more significant with a relative abundance reaching 3% in SSK 51193 (241.17 m). In the following samples (SSK 51193–51191; 241.17–240.56 m), the forest mire group reaches its maximum abundances (63–70%) while abundances of hinterland specimens rise to 7%. The maximum relative abundance of hinterland species occurs at SSK51184 (238.86 m), which is also reflected in the DCA plot where this sample plots closer to SSK45587, the sample from Carsington DRC3 with the maximum relative abundance for hinterland species. The goniatite biostratigraphy in Karenight-1 is hampered by poor recovery and poor preservation which only allowed for a tentative assignment of biozone E_{2b} (Wilson and Stevenson, 1973). Based on the miospore abundance, a correlation between both cores can be made and the E_{2b} Biozone seems to be somewhat higher in the Karenight-1 Borehole than originally described; most likely around 238.86 m (SSK51184).

Despite the different source areas of the terrestrial material reflected in the clustering of the samples in the DCA plot, common signatures in the relative abundances of certain taxa, notably *Lycospora pusilla* and *Florinites* sp., have been identified. These allow us to refine and enhance existing biostratigraphy and elucidate the palaeoecological conditions at the time of deposition of the Bowland Shale and Morridge Formations in the Widmerpool Gulf and Edale Basin.

5. Conclusions

We studied the miospore assemblages of two boreholes of an overlapping stratigraphic interval in the Namurian of the southern part of the Pennine Basin. The Bowland Shale Formation of the Carsington Dam Reconstruction C3 core covers the E_{2a}–E_{2b} goniatite biozones while the Morridge Formation covers an interval from E_1 to E_2 with only a tentative assignment of E_{2b}. Using statistical analysis of full quantitative counts of the miospore assemblages revealed:

1) That the studied interval in the Carsington DRC3 borehole is part of the TK biozone, which corresponds to the E_{2a}–E_{2b} goniatite biozonation assigned by Aitkenhead (1991).
2) That the studied interval in the Karenight-1 borehole can be assigned to the TK biozone. The occurrence of *Mooreisporites fustis*, appearing near the E_{2a}–E_{2b} boundary (Owens et al., 2004), suggests the SSK51192–46364 (240.93–234.80 m) is part of the E_{2b} goniatite biozone which was only tentatively assigned in previous studies (Wilson and Stevenson, 1973).
3) That the biostratigraphic data is corroborated by the relative abundance signatures of key taxa. Though only poorly preserved specimens of *M. fustis* were described in the current study and by Hennissen et al. (2017); two potentially corresponding peaks in *Florinites* sp. were described in the boreholes. In Carsington DRC3 this peak falls within the E_{2b1} goniatite biozone while in Karenight-1 this peak is part of the E2b biozone above the lower boundary of the provisionally assigned (Wilson and Stevenson, 1973) E_{2b} goniatite biozone.
4) A hitherto undescribed peak in the relative abundance of the fresh water alga *Botryococcus* in Carsington DRC3 (22.99–18.44 m). This palynomorph was not described in those abundances in the more distal Karenight-1 borehole and further analyses of the same stratigraphic interval in different basins is required to assess the importance of the *Botryococcus* peak and whether it has potential as a correlation tool.
5) In Carsington DRC3 *Kraeuselisporites. ornatus* appears earlier than the reported first occurrence in previous biostratigraphic studies (Clayton et al., 1977; Owens et al., 2004).

Acknowledgements

JH publishes with the approval of the Executive Director of the British Geological Survey. Jane Flint is thanked for the preparation of palynological slides. Tracey Gallagher, Scott Renshaw and the staff of the National Geological Repository are thanked for their help accessing cores and facilitating sample collection.

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Figure captions

Figure 1: Location of the two boreholes discussed in the current study, Carsington Dam Reconstruction C3 and Karenight-1, with a reference to current geography (A) and with relation to Mississippian palaeogeography (B; based on Waters et al., 2009). BH = Bowland High; BT = Bowland Trough; CLH = Central Lancashire High; DH = Derbyshire High; EG = Edale Gulf; GT = Gainsborough Trough; LDH = Lake District High; MH = Manx High; WG = Widmerpool Gulf. Contains Ordnance Survey data © Crown Copyright and database rights 2018.

Figure 2 (biostratigraphy in the Carboniferous): Biostratigraphy of the Tournaisian (part) – Westphalian in the British Isles. Chronostratigraphy based on Holliday and Molyneux (2006); ammonoid biozonation of the Tournaisian–Namurian based on Riley et al. (1993), of the Westphalian based on Cleal and Thomas (1996) and Waters et al. (2011); miospore biozonation is based on Clayton et al. (1977), Owens et al. (1977), Butterworth (1984) and Owens et al. (2004). The approximate stratigraphic position of the two boreholes is given in green shading. W. Eur. = Western European; *A.* = *Apiculatisporis*.G. = Goniatites; B. = *Bollandoceras*; Ct = *Cravenoceratoides* K. = *Kraeuselisporites*; U. = *Umbonatisporites*; M. m = *Murospora margodentata*; R. e. = *Rotaspora ergonulii*; A. = *Apiculatisporis*; CDRC3 = Carsington Dam Reconstruction C3.

Figure 3: Stratigraphic range of key index taxa and relative abundances of selected miospore taxa in the Carsington DRC3 Borehole. The DCA plot is based on the results presented in Paragraph 3.3. Ct. = *Cravenoceratoides*.

Figure 4: Stratigraphic range of key index taxa and relative abundances of selected miospore taxa in the Karenight-1 Borehole. The DCA plot is based on the results presented in Paragraph 3.3. Ct = *Cravenoceratoides*.

Figure 5: Detrended correspondence analysis of the samples and upper quartile genera in Carsington DRC3 and Karenight-1.

Table Captions

Table 1: Palaeoecological grouping of miospores following Davies and McLean (1996), based also on data from Scott (1979), Phillips and Peppers (1984).

Table 2: Detrended correspondence analysis (DCA) of Carsington DRC3 and Karenight-1: eigenvalues and taxon scores for the first four axes. Axes DCA1–DCA2 are shown in Figure 5. Taxa with a statistical weight, a reflection of its influence on sample distribution in DCA, in the highest quartile are indicated in bold. Species with high statistical weights and high scores on axes with high eigenvalues are indicator species whereas species having a high statistical weight and low scores on axes with high eigenvalues are cosmopolitan.

Plate Captions

Plate 1. Scale bar is 10µm. Two optical cross-sections are shown per specimen.

1, 2: *Lycospora pusilla*, Carsington DRC3 SSK46301 (30.20m), Slide 1, E. F.: P28/3

3, 4: *Densosporites anulatus*, Carsington DRC3 SSK46363 (55.46m), Slide 3, E. F.: J62/2

5, 6: *Granulatisporites granulatus*, Carsington DRC3 SSK46301 (30.20m), Slide 1, E. F.: K63/0

7, 8: *Punctatisporites* sp., Carsington DRC3 SSK46301 (40.83m), Slide 1, E. F.: M11/

9, 10: *Leiotriletes tumidus*, Carsington DRC3 SSK46301 (30.20m), Slide 1, E.F.: M20/0-3

11, 12: *Botryococcus* sp., Carsington DRC3 SSK45595 (22.99m), Slide 3, E.F.: O24/3

13, 14: *Calamospora breviradiata*, Carsington DRC3 SSK46359 (54.57m), Slide 1, E.F.: C53/1

15, 16: *Cingulizonates bialatus*, Karenight-1, SSK51192 (240.93m), Slide 1, E.F.: H25/3

17, 18: *Florinites* sp., Carsington DRC3 SSK46363 (55.46m), Slide 3, E.F.: E43/0

19, 20: *Crassispora kosankei*, Carsington DRC3 SSK46351 (51.86m), Slide 1, E.F.: S28/2

Plate 2. Scale bar is 10µm. Two optical cross-sections are shown per specimen.

1, 2: *Verrucosisporites verrucosus*, Carsington DRC3 SSK46301 (30.20m), Slide 1, E. F.: N22/2

3, 4: *Grandispora spinosa*, Carsington DRC3 SSK46363 (55.46m), Slide 3, E.F.: T8/1

5, 6: *Colatisporites decorus*, Carsington DRC3 SSK46363 (55.46m), Slide 3, E. F.: N27/1

7, 8: *Schulzospora campyloptera*, Carsington DRC3 SSK45621 (28.94m), Slide 2, E. F.: U28/0

9, 10: *Bellispores nitidus*, Carsington DRC3 SSK45621 (28.94m), Slide 2, E.F.: M20/0-3

11, 12: *Cirratriradites saturni*, Carsington DRC3 SSK46363 (55.46m), Slide 3, E.F.: Q69/0

13, 14: *Kraeuselisporites ornatus*, Carsington DRC3 SSK46331 (46.08m), Slide 1, E.F.: O16/4

15, 16: *Stenozonotriletes triangulus*, Carsington DRC3 SSK46301 (40.83m), Slide 1, E.F.: H21/3

17, 18: *Convolutispora florida*, Karenight 1 SSK51185 (239.19m), Slide 1, E.F.: G61/1

19, 20: *Mooreisporites fustis*, Karenight-1 SSK46364 (234.80m), Slide 5, E.F.: K11/0

Figure

Figure 1

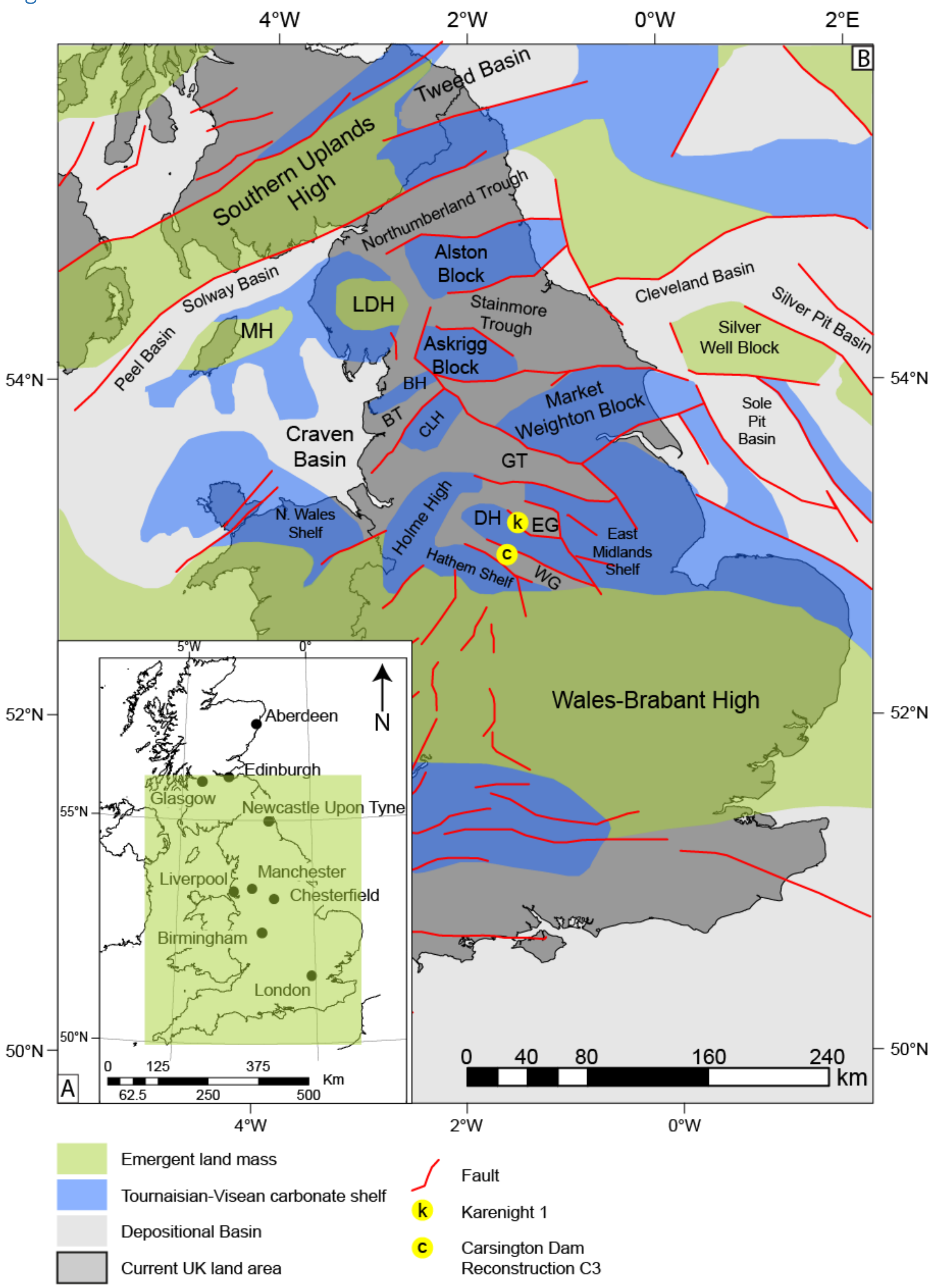
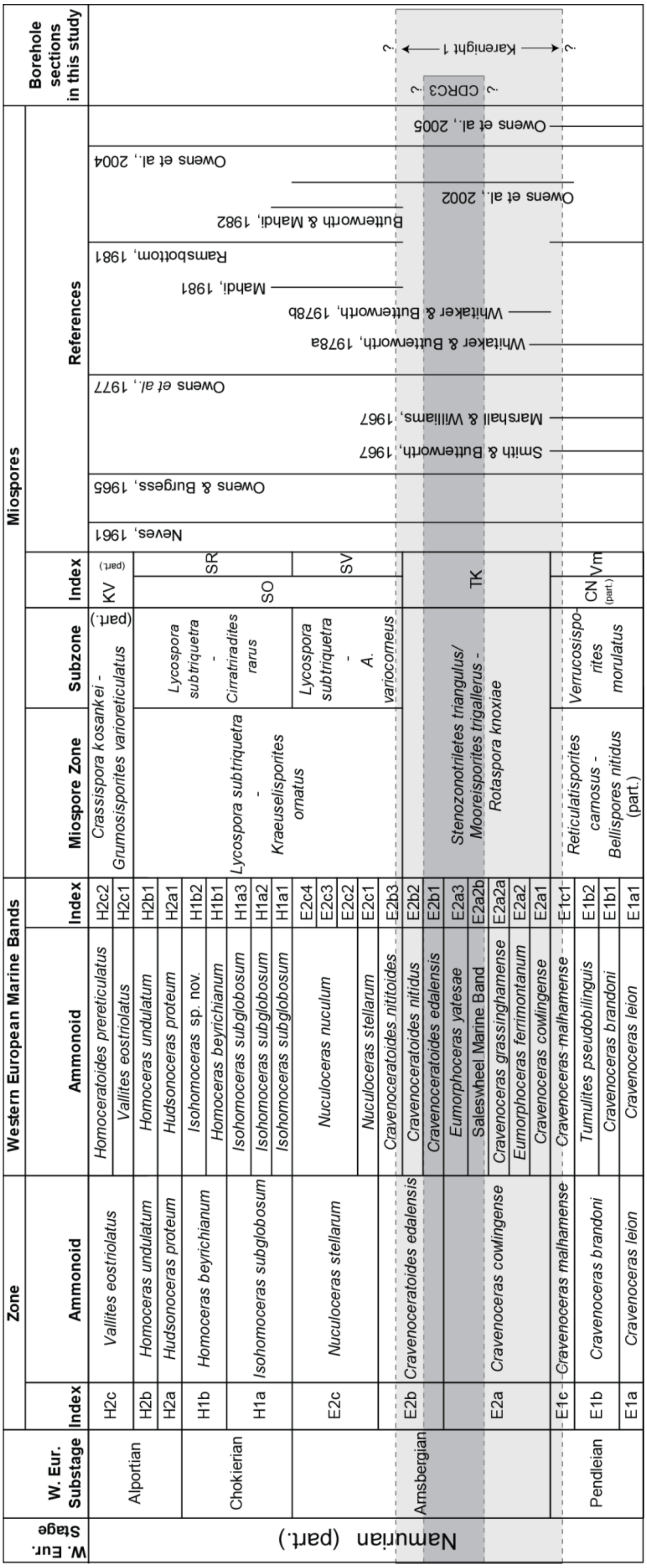


Figure 2



W. Eur. Stage
W. Eur. Substage
Zone
Index
Ammonoid
Western European Marine Bands
Miospores
Miospore Zone
Subzone
References
Borehole sections in this study
Namurian (part.)
Alportian
Chokierian
Arnsbergian
Pendleian
H2c
H2b
H2a
H1b
H1a
E2c
E2b
E2a
E1c
E1b
E1a
Vallites eostriolatus
Homoceras undulatum
Hudsonoceras proteum
Homoceras beyrichianum
Isohomoceras subglobosum
Nuculoceras stellarum
Cravenoceratoides edalensis
Cravenoceras cowlingense
Cravenoceras malhamense
Cravenoceras brandoni
Cravenoceras leion
Homoceratoides prereticulatus
Vallites eostriolatus
Homoceras undulatum
Hudsonoceras proteum
Isohomoceras sp. nov.
Homoceras beyrichianum
Isohomoceras subglobosum
Isohomoceras subglobosum
Isohomoceras subglobosum
Nuculoceras nuculum
Nuculoceras stellarum
Cravenoceratoides nititoides
Cravenoceratoides nitidus
Cravenoceratoides edalensis
Eumorphoceras yatesae
Saleswheel Marine Band
Cravenoceras grassinghamense
Eumorphoceras ferrimontanum
Cravenoceras cowlingense
Cravenoceras malhamense
Tumulites pseudobilinguis
Cravenoceras brandoni
Cravenoceras leion
H2c2
H2c1
H2b1
H2a1
H1b2
H1b1
H1a3
H1a2
H1a1
E2c4
E2c3
E2c2
E2c1
E2b3
E2b2
E2b1
E2a3
E2a2b
E2a2a
E2a2
E2a1
E1c1
E1b2
E1b1
E1a1
Crassispora kosankei - Grumosisporites varioreticulatus (part.)
KV (part.)
Lycospora subtriquetra - Kraeuselisporites ornatus
Lycospora subtriquetra - Cirratriradites rarus
SR
SO
Lycospora subtriquetra - A. variocorneus
SV
Stenozonotriletes triangulus/ Mooreisporites trigallerus - Rotaspora knoxiae
TK
Reticulatisporites carnosus - Bellispores nitidus (part.)
Verrucosisporites morulatus
CN (part.)
Vm
Neves, 1961
Owens & Burgess, 1965
Smith & Butterworth, 1967
Marshall & Williams, 1967
Owens et al., 1977
Whitaker & Butterworth, 1978a
Whitaker & Butterworth, 1978b
Mahdi, 1981
Ramsbottom, 1981
Butterworth & Mahdi, 1982
Owens et al., 2002
Owens et al., 2004
Owens et al., 2005
CDRC3
Kareniqht 1
?

Figure 3

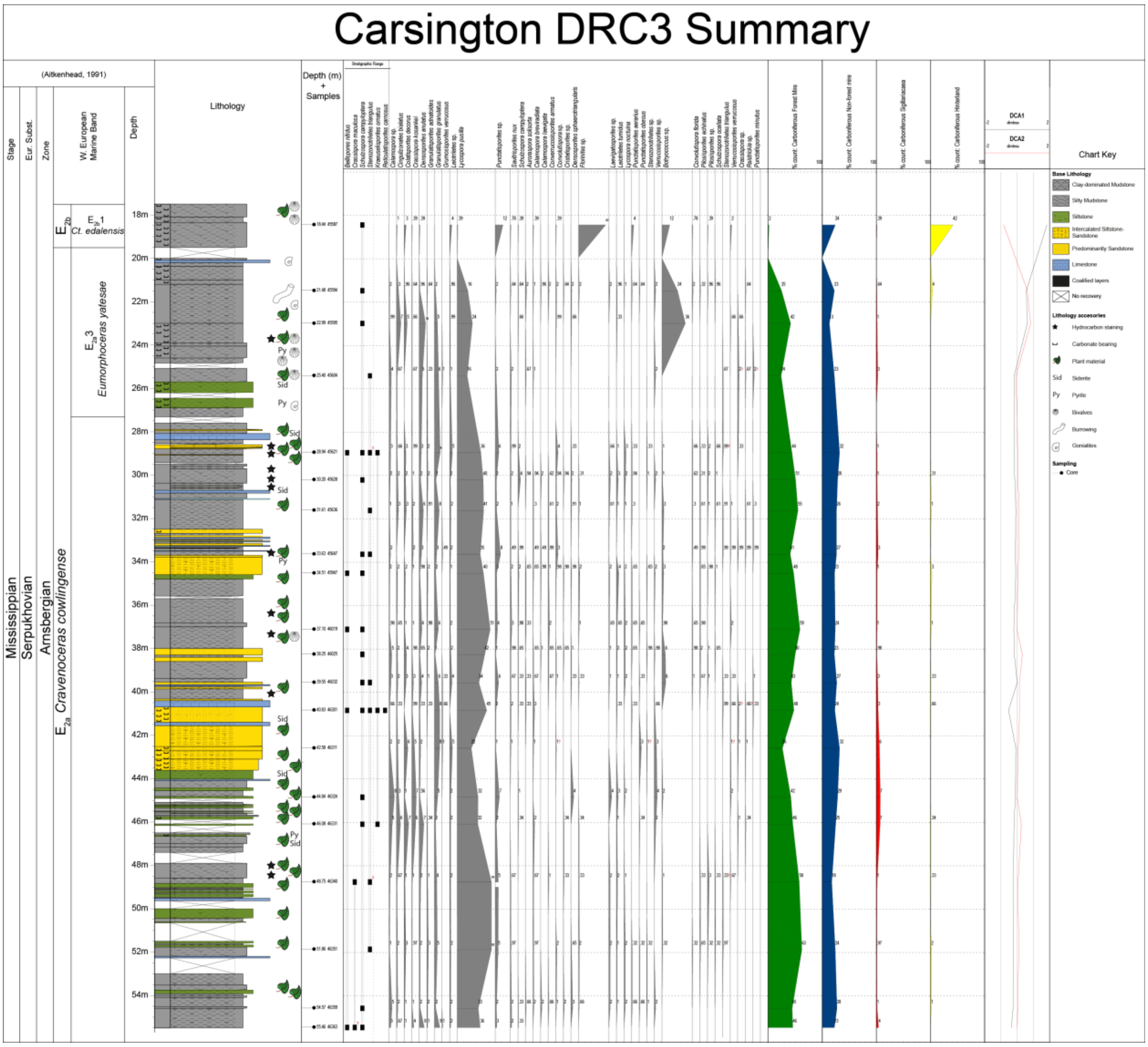
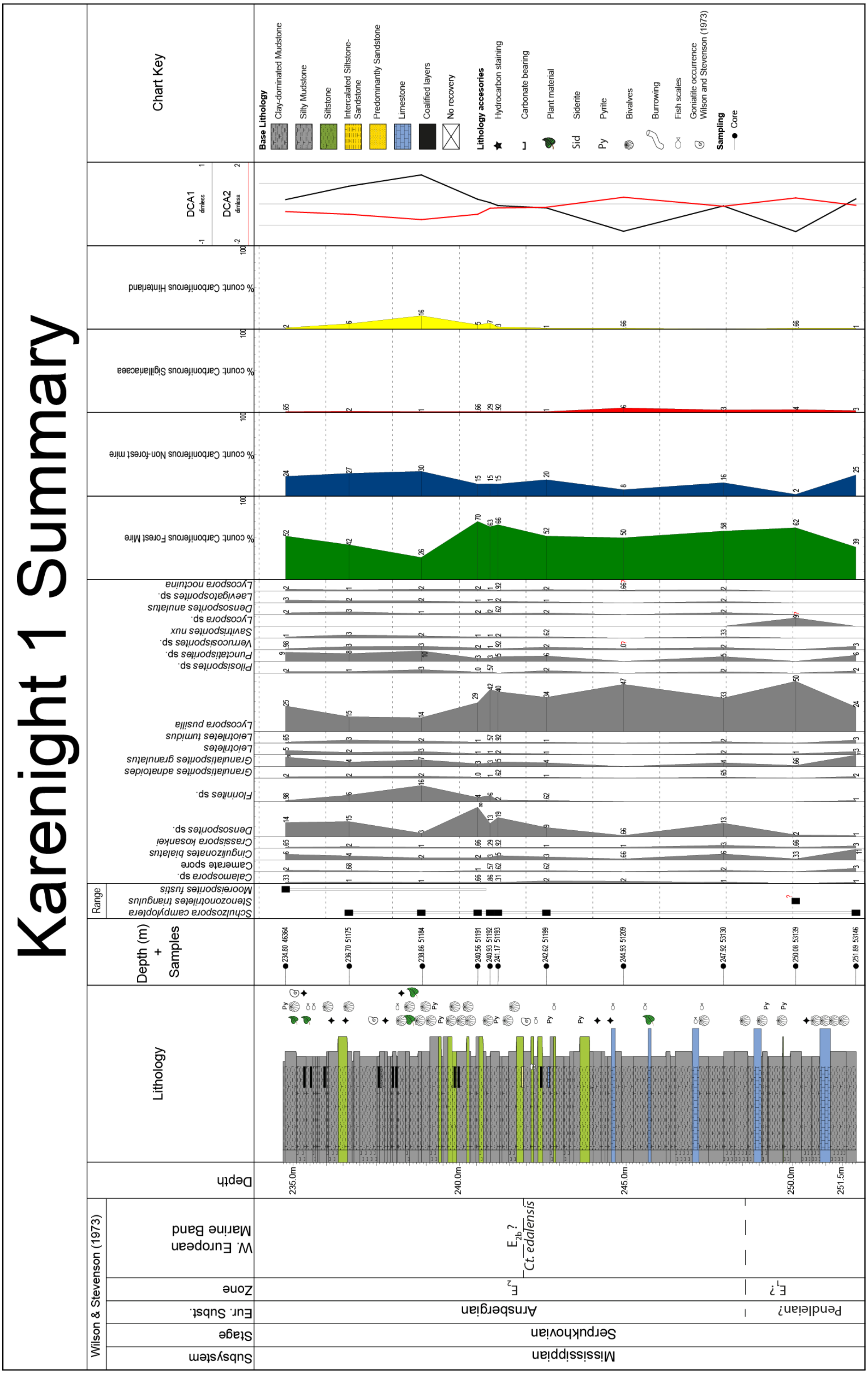
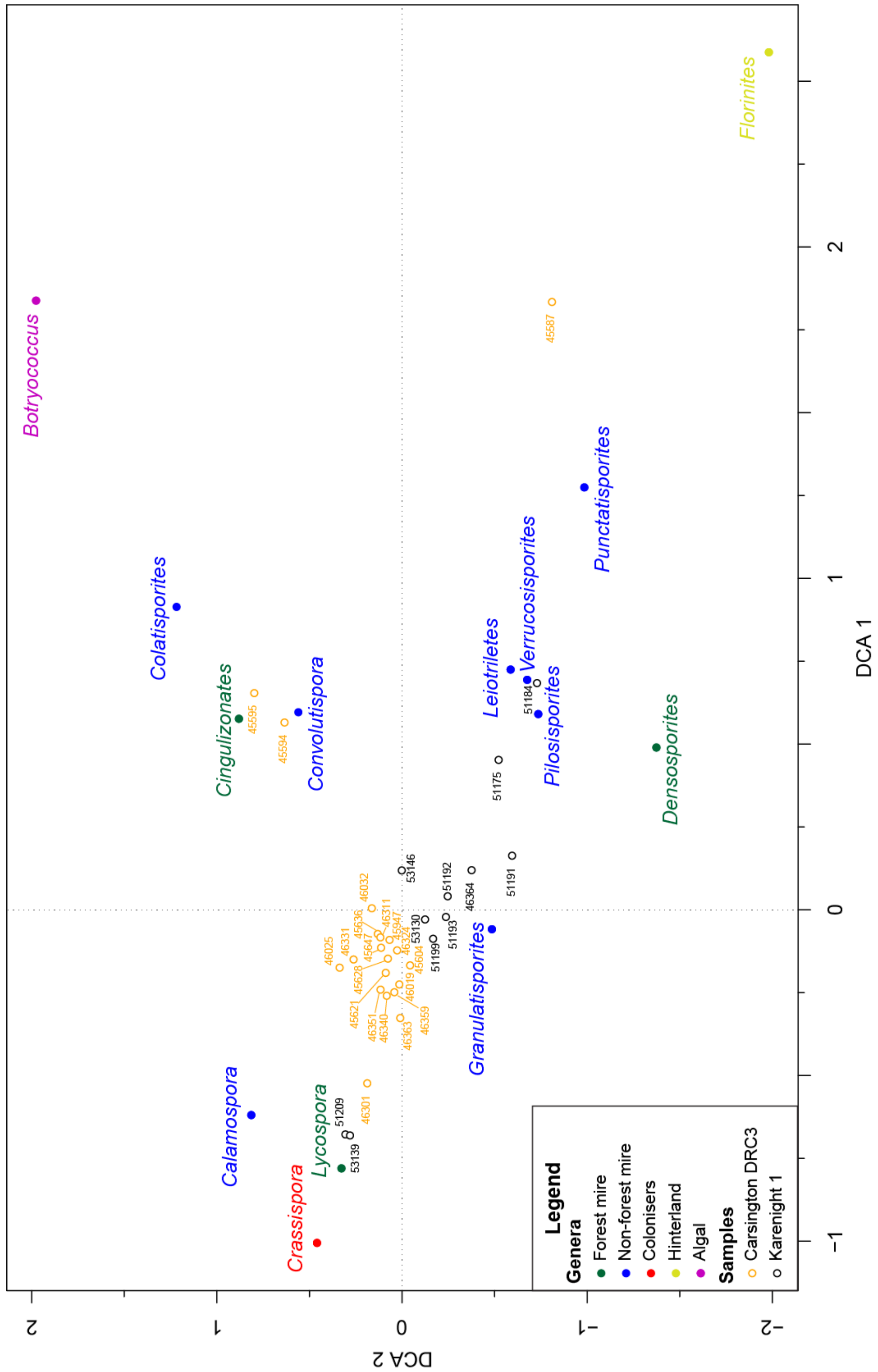

Carsington DRC3 Summary
(Aitkenhead, 1991)
Stage
Eur. Subst.
Zone
W. European Marine Band
Depth
Lithology
Depth (m) + Samples
Mississippian
Serpukhovian
Arnsbergian
Chart Key

Figure 4



Karenight 1 Summary
Chart Key
Base Lithology
Clay-dominated Mudstone
Silty Mudstone
Siltstone
Intercalated Siltstone-Sandstone
Predominantly Sandstone
Limestone
Coalified layers
No recovery
Lithology accesories
Hydrocarbon staining
Carbonate bearing
Plant material
Siderite
Pyrite
Bivalves
Burrowing
Fish scales
Goniatite occurrence Wilson and Stevenson (1973)
Sampling
Core
DCA1
DCA2
% count: Carboniferous Hinterland
% count: Carboniferous Sigillariaceae
% count: Carboniferous Non-forest mire
% count: Carboniferous Forest Mire
Range
Depth (m) + Samples
Lithology
Depth
235.0m
240.0m
245.0m
250.0m
251.5m
Wilson & Stevenson (1973)
W. European Marine Band
Zone
Eur. Subst.
Stage
Subsystem
Mississippian
Serpukhovian
Arnsbergian
Pendleian?
Ct. edalensis

Figure 5



DCA 1
DCA 2
Botryococcus
Florinites
Colatisporites
Cingulizonates
Convolutispora
Leiotriletes
Verrucosisporites
Punctatisporites
Pilosisporites
Densosporites
Granulatisporites
Calamospora
Lycospora
Crassispora
Legend
Genera
Forest mire
Non-forest mire
Colonisers
Hinterland
Algal
Samples
Carsington DRC3
Karenight 1