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Palaeoecological and possible evolutionary effects of early Namurian (Serpukhovian, Carboniferous) glacioeustatic cyclicity

M. H. STEPHENSON[1], D. MILLWARD[2], M. J. LENG[3] & C. H. VANE[1]

[1]British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK

[2] British Geological Survey, Murchison House, Murchison House, West Mains Road, Edinburgh, EH9 3LA, UK

[3] NERC Isotope Geoscience Laboratory, British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK

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RUNNING HEADER: PALAEOECOLOGY AND NAMURIAN CYCLES

Abstract: Early Namurian (Serpukhovian, Carboniferous), sedimentary cycles in the Throckley and Rowlands Gill boreholes, near Newcastle-upon-Tyne, UK, consist of fossiliferous limestones overlain by (usually unfossiliferous) black mudstone, followed by sandstones and often by thin coal seams. Sedimentological and regional geological evidence suggests that the largest are high amplitude cycles, most likely of glacioeustatic origin. δ^{13}C (bulk organic matter) delineates marine and non marine conditions due to the large difference between terrestrial and marine δ^{13}C, and indicates full marine salinity was only intermittent resulting from glacioeustatic marine transgression superimposed on a background of inundation of freshwater by large rivers, which killed off the marine biota. Palynology suggests that plant groups, including ferns and putative pteridosperms, were affected by changing sea level, and that there is a theoretical possibility of connection between cyclicity and the first appearance of walchiacean conifer-like monosaccate pollen such as *Potonieisporites*. Long term terrestrial and marine increasing δ^{13}C (organic) may reflect the onset of major glaciation in Gondwana, since there is evidence to suggest that the two are coeval, but no specific mechanism can be suggested to link the trends.

Keywords: Carboniferous palaeoecology palynology isotopes

A series of small linked, fault-controlled basins developed across northern and central England in late Devonian and Mississippian times, in response to regional north-south extension (Fig. 1; Chadwick *et al.* 1995; Fraser & Gawthorpe 2003). Initial extension was rapid and fault-controlled with the positions of the basins and blocks determined largely by basement structure. Thick sequences of clastic sediments accumulated in the basins at this time, compared with those on the blocks. This gave way to a more uniform, regional subsidence from late Viséan through Namurian times, though localised faulting still occurred at block margins (Collinson 1988). In the Central Pennine Basin (Central Province), south of the Lake District and Askrigg blocks, the Namurian basin was filled mainly by turbidite and pelagic deposits. The repeated occurrence of goniatite-bearing mudstone bands in this sequence allows a highly-refined Namurian biostratigraphical scheme (Ramsbottom *et al*. 1978; Waters & Davies 2006). By contrast, across the Northumberland-Solway and Stainmore basins, and the Alston and Askrigg blocks, high-frequency ‘Yoredale’-type cyclic sedimentation was established in Asbian times, and persisted into the Namurian (Ramsbottom 1977; Wright & Vanstone 2001). In this area limestone dominates the marine phase, succeeded by clastic sediments deposited from prograding delta systems.

The palaeoenvironments of the terrestrial realm in the Namurian of the central and northern provinces are much less well studied than their Westphalian counterparts, probably because fewer Namurian coals are thick enough to have been exploited. However, the terrestrial macroflora was similar (Cleal & Thomas 1995). Broadly the same spores that dominate the palynological assemblages are also characteristic of the coal swamp forests of the Westphalian of NW Europe, for example, *Lycospora* and *Crassispora*. Present also were fern spores, putative pteridosperm spores (e.g. *Schulzospora*) and larger pollen that can be related to primitive conifers of the

Walchiaceae (e.g. *Potonieisporites;* Poort & Veld 1997) and to the cordaites (e.g. *Florinites;* Falcon-Lang & Scott 2000). The palaeoecology of these plants has been studied exhaustively in rocks of Westphalian age, particularly in relation to coal quality and distribution (e.g. Scott 1979; Phillips & DiMichele 1981), and more recently with regard to climate change and cyclicity (e.g. Phillips & Peppers 1984; Cecil 1990; DiMichele *et al*. 2002; Falcon-Lang & Bashforth 2004).

Studies of palaeoecology in relation to cyclicity in the British Namurian are restricted to palynology in the Central Pennine Basin (e.g. Neves 1958; Turner *et al*. 1994; Davies & McLean 1996), which recognised increased numbers of pollen in marine bands. These phenomena were described by Chaloner (1958) as the 'Neves Effect' and interpreted as due to drowning of coastal lowland plants leading to over-representation by pollen produced by upland plants. However no detailed multidisciplinary studies have been made of palaeoecology and its relationship to climate change and cyclicity in the early Namurian. This is an interesting interval since it was at this time that large scale Carboniferous glaciation began in the Southern Hemisphere (González-Bonorino & Eyles 1995; Isbell *et al*. 2003), and this is linked with increasing frequency and amplitude of glacioustatic sea level changes in NW Europe (Waters & Davies 2006). The onset of glaciation was also linked by Cecil (1990) and Cecil et al. (1993) to farfield climate change that also had a strong influence on sedimentation. Thus the aim of this paper is to document cyclicity and palaeoenvironmental change in early Namurian successions. In order to understand the distribution of marine sediments in the successions we also apply a technique new to mixed Palaeozoic clastic-carbonate successions that involves tracking the $\delta^{13}C$ of sedimentary organic matter.

Geological setting

Stratigraphy

The early Namurian strata of the Throckley (NZ 14557 67617) and Rowlands Gill (NZ 1664 5815) boreholes near Newcastle-upon-Tyne, were analysed for $\delta^{13}C$ (bulk organic matter and wood fragments), palynology, palynofacies, sedimentology and macropalaeontology. The Throckley Borehole is within the Northumberland Trough, and the Rowlands Gill Borehole is south of the Ninety Fathom Fault, and thus is positioned on the Alston Block (Fig. 1). The Namurian strata in the boreholes contain approximately 10 large sedimentary cycles, assigned to the Stainmore Formation, each cycle consisting of fossiliferous limestone overlain by (usually unfossiliferous) black mudstone, followed by sandstone upon which there is a seatrock and then by a thin coal seam. In this paper we focus mainly on two large cycles of the lower, Pendleian-Arnsbergian part of the section, delimited by (in ascending order) the Lower Felltop Limestone, the Coalcleugh Limestone and the Upper Felltop Limestone (Fig. 2).

In the area around Newcastle-upon-Tyne, the Lower Felltop Limestone is around 6 m thick, and includes a fauna of bryozoa, brachiopods and chaetetids (Mills & Holliday 1998; Pattison 1980). The thickness of strata between the Lower Felltop and Upper Felltop limestones ranges from 31 to 65 m, being less on the Alston Block (e.g. Rowlands Gill Borehole) than in the Northumberland Basin (e.g. Throckley Borehole). This sequence is laterally variable, and its lower part is mainly arenaceous, while its upper part is argillaceous. Marine beds also occur, for example the Pike Hill Limestone (or its lateral equivalent the Coalcleugh Limestone), which is correlated with the Coalcleugh Shell Bed on parts of the Alston block. The Pike Hill Limestone/Coalcleugh Limestone is usually argillaceous limestone or shaley calcareous mudstone with ironstone nodules, and ranges between 3.5 and 5 m thick. Fauna from this limestone in the Ouston (BJ 40800 05699) and Throckley boreholes includes clisiophyllid corals, bryozoa, brachiopods and a few bivalves. Thin coals and seatearths also occur in this sequence, for example the Chapel House Coal, which has been worked in the area. The Upper Felltop Limestone is one of the thickest and most persistent limestones in the Namurian of the Newcastle area. It varies between 2 and 7.3 m thick and is pale grey to grey, medium to coarse-grained and crinoidal, with a rich Namurian fauna including rugose corals, bryozoa, brachiopods and rare bivalves.

In the Tyne to Stainmore area to the south of Newcastle, the Lower Felltop Limestone is widely exposed (e.g. in Alston Moor, Rookhopehead and Coalcleugh) as a grey, fine grained limestone varying between 0.3 and 2 m thick. It was used for lime-burning and contains the alga *Girvanella*, as well as brachiopods. Beds above the Lower Felltop Limestone contain a sequence of variable sandstone units named the 'Transgression Beds' by Carruthers (1938) and the Coalcleugh Beds by Dunham (1990). The beds contain flaggy sandstone and ganisters that have been quarried. Dunham (1990) suggested that in places erosion associated with the sandstones has cut out the Lower Felltop Limestone, e.g. in the Derwent Valley. Above the sandstones in the Tyne to Stainmore area are coals including the Coalcleugh Coal which reaches 56 cm in thickness, followed by a series of marine beds which have been measured and described in North Grain Opencast Quarry (NY883448), near Allenheads. The beds there include 60 cm of shale with marine fossils, which correlate with the Coalcleugh Limestone of the Throckley and Rowlands Gill sections, and above this are 6 m of apparently unfossiliferous black micaceous shales. The thickness of the Coalcleugh marine beds to the base of the Upper Felltop Limestone varies between 25 m and 33.5 m (Dunham 1990).

Age

The faunal sequence of goniatites of the Namurian of the Central Pennine Basin does not occur in the Northumberland Basin and Alston Block, and goniatites are extremely rare, thus dating involves reference to palynology, foraminifera and lithostratigraphy.

The lowest studied part of the Throckley Borehole between 358.33 and 243.23 m is assigned to the *capistratus – nitidus* (CN) Biozone (Owens *et al*. 2004) based on the presence of *Bellispores nitidus*, *Cingulizonates* cf. *capistratus* as well as the occurrence of accessory taxa, e.g. *Crassispora kosankei*, *Grandispora spinosa, Microreticulatisporites concavus*, *Rugospora corporata*, *Rotaspora fracta*, *Remysporites magnificus, Tripartites trilinguis* and *T. vetustus*. The top of the section assigned to the CN Biozone is difficult to ascertain because the base of the succeeding zone of Owens *et al*. (2004), the *trigallerus – knoxi* (TK) Biozone, cannot be positioned precisely in this borehole. However Owens *et al*. (2004) mention that *Cingulizonates* cf. *capistratus* disappears at the top of the CN Biozone, and the level of its last appearance is used provisionally to mark this level in the Throckley Borehole.

Perhaps the most distinct palynostratigraphical level in the Throckley Borehole is marked by the first appearance of common *Crassispora kosankei* at 126.5 m. This event, in part, defines the base of the *kosankei – varioreticulatus* (KV) Biozone, and has long been associated with the base of the Kinderscoutian (R1, Owens *et al.* 1977), though Owens *et al.* (2004) now consider it to be late Alportian. The first occurrence of *Lycospora subtriquetra*, slightly lower, at 136 m, suggests that the *subtriquetra – ornatus* (SO) Biozone may extend from 136 to 126.5 m. Owens *et al.* (2004) considered the SO Biozone to span the late Arnsbergian to early Alportian.

By contrast Riley (1992) concluded that foraminifera in the Lower Felltop Limestone in the Rowlands Gill Borehole indicated that the base of the Arnsbergian Substage should be taken at the base of the limestone (Fig. 2). Indirect stratigraphical evidence supports this age assignment. In North Yorkshire, the base of the Arnsbergian Substage can be precisely positioned because of the occurrence of the E2a goniatite *Cravenoceras cowlingense* Bisat in limestone or marine mudstone above the Mirk Fell Ganister (Dunham 1990). The Mirk Fell Ganister has been traced into sandstone underlying the Lower Felltop Limestone in the Brough-under-Stainmore area, south of the present area of study (Dunham 1990).

Thus, there is a conflict between the ages suggested by lithostratigraphical correlation and foraminifera on the one hand, and palynology on the other. The assignment to the CN Biozone of the interval 358.33 – 243.23 m in the Throckley Borehole suggests, through palynological correlation, that the Pendleian extends up to 243.23 m, whereas lithostratigraphic correlation and foraminifera suggest that the Lower Felltop Limestone is Arnsbergian, however a general early Namurian (Serpukhovian) age is clear.

Sedimentology and facies analysis

The sedimentological characteristics and distribution of marine fauna between 105 and 325 m in the Throckley Borehole and between 120 and 222 m in the Rowlands Gill Borehole (after Brand 1987; Mills & Holliday 1998) are shown in Figs. 3 and 4 respectively. Excellent core preservation of the Rowlands Gill Borehole between 135 and 222 m allowed detailed palaeoenvironmental interpretation (Fig. 4). Lack of continuous core prevented similar analysis in the Throckley Borehole. The bulk of the sequence in the Rowlands Gill Borehole is made up of coarsening upward cycles beginning with fissile mudstone and siltstones, which are either unfossiliferous or contain rare marine fossils. These generally become completely unfossiliferous upsection and coarsen up to contain lenses of sandstone with wave ripple marks, before becoming fine-grained sandstone, commonly rooted, toward the top of the cycle. Rooting and a bleached colour indicate that contemporaneous pedogenic processes affected some cycles, suggesting fairly prolonged subaerial exposure. A number of these coarsening upward cycles culminate in thin (1-2 cm thick) coal seams (e.g. at 177 and 200.5 m) which may alternate on a centimetre-scale with thin mudstone beds in places containing marine fossils.

The coarsening-upward cycles are interpreted as delta progradational interdistributary bay fills, the lower finer-grained sediment being the first stages of fill and the last sandier sediment being mouth bar deposits into shallow water. The coals probably formed due to terrestrial plant colonization of emergent mouthbar and other sediment platforms. Alternation of marine sediment and coal at the top of the more complete cycles may relate to small-scale cyclic relative sea level rise which is not expressed in the deeper water facies, or delta sedimentation processes. Limestones in the sequence in the Rowlands Gill Borehole are grey, micritic, muddy and crinoidal and sometimes coarsen up into cleaner bioclastic limestone. The limestones are interpreted to have been deposited at sea level highstands, and the coarsening upward trend is attributed to upward shoaling. The bases of limestone units are often sharp, interpreted as ravinement surfaces, and may be associated with a truncated underlying cycle (chiefly marked by the absence of coal), implying small amounts of erosion.

Intensely bioturbated, greenish, sideritic sandstone units (wave rippled toward the top) with marine and trace fossils (e.g. *Monocraterion*, *Teichichnus*) occur at two levels in the sequence (151 – 157 m and 187 – 189 m). The base of these units is sharp and erosive and may impinge on the upper mouth bar deposits of the coarsening upward cycles. These sandstones are interpreted as deposits of shelf sandbodies driven by tides and marine currents in shallow water.

At three levels (134 to 142.5 m; 142.5 to 146 m; 184.5 to 187 m) are units of fine to medium grained (rarely coarse grained) micaceous, silty or feldspathic sandstones, often with plant fragments and large (metre-scale) cross beds. The bases of these units are erosional and the units are interpreted as having been laid down by distributary channels of varying sizes. The bases of the coarser units may mark the positions of non-sequences.

Organic carbon isotope ratios

Changing $\delta^{13}C$ of bulk organic matter within clastic sequences has been shown to be of value in delimiting marine and non-marine intervals (e.g. Foster *et al*. 1997; Gorter *et al*. 1995; Newmann *et al*. 1973; Maynard 1981) because marine sedimentary organic matter (usually of algal origin) has a different $\delta^{13}C$ value from that of terrestrial organic matter (mainly wood fragments and palynomorphs). In Permian sequences, $\delta^{13}C$ marine organic matter is generally c.–30‰ (Lewan 1986; Foster *et al*. 1997), and $\delta^{13}C$ terrestrial is c.–24‰ (Foster *et al*. 1997). Peters-Kottig *et al*. (2006) measured $\delta^{13}C$ from terrestrial organic matter from plant fossils, cuticles, humic coals and bulk terrestrial material through the Late Palaeozoic. During the late Mississippian and early Pennsylvanian values are around –23.5‰, rising slightly to around –23‰ in the late Pennsylvanian. Values of $\delta^{13}C$ for late Mississippian - early Pennsylvanian marine organic matter are very scarce; Lewan (1986) recorded mean values for the Mississippian of –28.55‰ (4 measurements) and –28.03‰ for the Pennsylvanian (3 measurements).

Migrated hydrocarbons affect $\delta^{13}C$ bulk values particularly if they are markedly different in geochemical origin from the *in situ* material analysed (Stephenson *et al*. 2005). For this study all samples were treated to remove migrated hydrocarbons; samples were then prepared as set out by Stephenson *et al*. (2005), including the separation and $\delta^{13}C$ analysis of microscopic wood fragments (500-1000 µm), liberated by palynological processing. The distribution of values shows that in the mixed marine/terrestrial sequence of the Throckley and Rowlands Gill boreholes, $\delta^{13}C$ (bulk) is most likely a function of the ratio of $\delta^{13}C$ marine organic matter to $\delta^{13}C$ terrestrial (Figs. 3 and 4). The main excursions in $\delta^{13}C$ (bulk) (to a minimum of c.–31‰) correspond with marine intervals as defined by limestone and marine macrofossil distribution, suggesting that known marine rocks contain low $\delta^{13}C$ organic matter. This organic matter is displayed in palynological slides as amorphous organic matter (AOM), which is commonly believed to be of algal origin (e.g. Lewan 1986). $\delta^{13}C$ of microscopic wood fragments ($\delta^{13}C$ wood) from samples split and also analysed for $\delta^{13}C$ (bulk) is substantially the same as $\delta^{13}C$ (bulk) at levels where both were measured (Fig. 3).

Palynology and palynofacies

Pollen and spores are generally poorly preserved but identifiable at least to generic level. Counts of around 150 palynomorphs per slide were taken initially and then each slide was scanned for additional taxa. Yield of palynomorphs is high in all lithologies apart from the purer limestones where residues are dominated by AOM, though palynomorphs are also usually present. In this study of palynomorphs and palynofacies in relation to cyclicity we concentrate on the best developed cycles between the Lower and Upper Felltop limestones. The most common palynomorph types in this section are *Cingulizonates* spp., *Cristatisporites* spp., *Crassispora kosankei*, *Densosporites* spp., *Granulatisporites* spp., *Knoxisporites* spp., *Leiotriletes* spp., *Lycospora pusilla*, *Remysporites magnificus*, *Schulzospora* spp. and indeterminate monosaccate pollen. Rarer taxa include *Knoxisporites stephanephorus, Potonieisporites* spp., *Savitrisporites nux*, *Tripartites vetustus* and various scolecodonts, which are the mouthparts of marine polychaete worms. Pollen and spores are arranged into palaeocommunities by relating them to their parent plants (see Willard *et al*. 1995; Davies & McLean 1996;

DiMichele & Phillips 1996; Table 1, Figs. 5 and 6), and palynofacies elements are grouped as in Table 2. The scheme used was that of Davies & McLean (1996), based in the Namurian of northern England. This scheme was considered generally applicable despite the fact that the plant affinities of most of the palynomorph taxa are known from Westphalian rather than Namurian fructifications. This is because we consider that well-defined and distinct morphotypes e.g. *Lycospora pusilla*, *Potonieisporites novicus*, *Crassispora kosankei*, *Leiotriletes*/*Granulatisporites* and *Schulozospora*, which range through the Namurian into the Westphalian, represent broadly the same conditions throughout that time period. The scheme was, however, slightly modified to include new data about the ecological preferences of cordaites which are known to colonise a wide range of habitats (see Falcon-Lang & Scott 2000) and thus cannot be considered to be primarily extrabasinal. Thus cordaites (represented by *Florinites*) were excluded from the extrabasinal category of Davies & McLean (1996). Within the non-forest mire category of Davies & McLean (1996), *Granulatisporites*/*Leiotriletes* were dominant and showed the most significant trends; they were thus subtracted from that category and displayed separately in Figs. 5 and 6. A similar procedure was followed for *Schulzospora*.

The most common palynomorph group is that of the forest mire. This group is made up almost entirely (>90%) of *Lycospora pusilla* which is unequivocally linked with the coal swamp flora (Willard 1989; Willard *et al.* 1995). The forest mire in turn usually comprises more than 50% of each assemblage (Figs. 5 and 6). Forest mire palynomorphs decrease in number in low yielding limestones which - when palyniferous - yield small fern spores, mainly *Leiotriletes* or *Granulatisporites* (Eble *et al.* 2001). Fern spores additionally tend to be common in the lower parts of coarsening-up cycles (e.g. 208 – 205 m, 192.5 – 190 m and 178-175 m in the Rowlands Gill Borehole) but dwindle in numbers upsection. Colonisers and extrabasinal palynomorphs are rare throughout the section, and seem not to have a pattern that can be related to cyclicity. Contrary to the concept of the 'Neves Effect', extrabasinal palynomorphs do not peak during marine units. *Schulzospora* tends, like fern spores, to be most common in the lower, marine parts of coarsening-up cycles; this is particularly evident in the Rowlands Gill Borehole (Fig. 6). Scolecodonts are most common in sections identified as marine on the basis of marine macrofossils, low $\delta^{13}C$, or high AOM, but limestones do not always yield them. The most common palynofacies elements (Table 2) are AOM, black equant fragments and phytoclasts, and these are strongly related to facies and cyclicity (Figs. 5 and 6). AOM occurs most commonly in limestones or in sediments identified as marine on the basis of marine macrofossils, or at levels with low $\delta^{13}C$, while black equant fragments and phytoclasts, most likely of terrestrial wood origin, are most common in sections without marine macrofossils. At a few horizons, low $\delta^{13}C$ and AOM indicate marine conditions though marine macrofauna are not recorded, for example at 198 m in Rowlands Gill (Fig. 4), thus a combination of $\delta^{13}C$ and AOM may be a valuable indicator of cryptic marine horizons.

Interpretation

Facies analysis suggests that the bulk of sediment between the Lower Felltop and Upper Felltop limestones was deposited in a series of prograding delta lobes, probably related to a southward flowing river system sourced in Laurentia and Baltica (Waters & Davies

2006). However the three main limestones were deposited during major relative sea level rises of several tens of metres, as suggested by the fauna (P. Brand, pers. comm. 2007), and are correlated across the northeast of England, the Vale of Eden and the Midland Valley of Scotland (P. Brand, pers. comm. 2007; Ramsbottom *et al*. 1978). The age of the limestones and their widespread distribution over several tectonic blocks and basins suggests that the sea level rises are likely of glacioeustatic origin. Thinner, cryptic marine horizons marked by rare marine fauna, scolecodonts, low $\delta^{13}C$ values or high amounts of AOM, probably represent shallower, less persistent seas and are not uniquely identifiable palaeontologically, thus it is not possible to verify their lateral extension beyond the boreholes. They may have a variety of origins, including glacioeustacy, or may be related to delta sedimentation processes. Small-scale cyclicity manifested by centimetre-scale alternations between coals and thin marine horizons towards the top of coarsening upward cycles, may have a similar variety of origins.

The $\delta^{13}C$ pattern in both sections (Figs 3 and 4) indicates that marine organic matter is associated with limestones and with beds with marine macrofossils. $\delta^{13}C$ of microscopic wood fragments from samples split and also analysed for $\delta^{13}C$ (bulk) give substantially the same figures as $\delta^{13}C$ (bulk). These samples were mainly unfossiliferous siltstone and mudstone, rather than limestones which yielded too few 500-1000 μ wood fragments for analysis. The congruence of $\delta^{13}C$ values between bulk organic matter and wood fragments, and the lack of AOM in these samples suggests that the sediments were deposited in bodies of water that did not generate marine algal organic matter, though they were close enough to terrestrial environments to receive wood fragments. It seems likely, therefore, that they were deposited in an environment not conducive to marine organisms, perhaps an interdistributary bay open to the sea, but with low salinity water. Thus, the distribution and thickness of low $\delta^{13}C$ sections suggests that full salinity conditions were relatively intermittent.

A possible explanation for this could lie in early Namurian palaeogeography where the Northumberland Trough lay within a complex lowland area amongst uplands or highs in central Scotland, the Southern Uplands and Wales-Brabant (Cope *et al*. 1992; Waters & Davies 2006). Only in the south, in the Central Province, was there permanent deep water. However, fresh river water entered from the north, discharged from large rivers (Collinson 1988; Holdsworth & Collinson 1988), with high potential to reduce salinity, particularly after a certain amount of marine regression, perhaps past a step or barrier. Collinson (1988) and Holdsworth & Collinson (1988) considered salinity to have varied in a similar way in the Central Pennine Basin concluding that it was the chief control on the stratigraphical distribution of goniatites, and that the thick black mudstones between marine bands were deposited in low salinity conditions. A possible modern analogue for these palaeoenvironments is the narrow Strait of Malacca in SE Asia fringed by tropical rainforests with very high rainfall and runoff, but very low erosion and sedimentation rates due to extensive vegetation cover (Cecil *et al*. 1993). Salinity there is very low (two thirds that of normal seawater) due to mixing of high river discharge, and marine biota is rare over large areas of the basin (Cecil *et al*. 1993).

Palynology suggests that terrestrial plant palaeocommunities were similar to those of the later Namurian and early Westphalian. The progradational parts of the sequence, both distal (unfossiliferous low salinity mudstones) and proximal (mouthbar sandstone and coal), are dominated by *Lycospora pusilla* related to tree lycopsids (Willard 1989; Willard *et al*. 1995), probably occupying coastal, perennially-flooded, swamps at various distances from the Throckley-Rowlands Gill area, depending on the extent of progradation. Non forest mire plants were present, probably consisting of less woody herbaceous ferns, sphenopsids and progymnosperms, but the presence of other palaeocommunities and their geographical position with respect to the swamp coastal zone is more speculative, because few patterns are present in the data.

Repeated progradation and transgression appear to have produced a few consistent changes in the terrestrial plant palaeocommunities based on palynology. Fern spores and *Schulzospora* appear to be more common in the lower parts of coarsening-upward cycles, and there appears to be no increase in extrabasinal palynomorphs in marine sections ('Neves Effect'). The trends in fern spores and *Schulzospora* are expressed in all the coarsening upward cycles that were densely sampled above the three major limestone units (Rowlands Gill, 208.36 - 203.64 m, 12 samples; 192.45 - 189.3 m, 7 samples: Throckley 244.14 - 241.25 m, 5 samples). These short sections are abruptly regressive; evidence from macrofauna, AOM and δ^{13}C suggests very rapid reduction in salinity. Though water depth for the lower parts of each cycle is difficult to estimate, it was probably much less than that during limestone deposition. The decrease in salinity probably resulted from the influence of rapidly advancing rivers.

The allochthonous fern spores and *Schulzospora* may represent some aspect of the terrestrial environment that is radically different from the normal forest mire-dominated palaeocommunity. Unlike the latter, ferns require a moist but dryland substrate to establish the gametophyte, and therefore large numbers of ferns in such conditions may be indicative of low or descending water table, which is likely during marine regression. Thus, coastal areas or newly created dry land after regression may have been populated preferentially by small ferns. *Schulzospora* was likely produced by a pteridosperm, an extinct seed-producing, fern-like plant, allied or ancestral to the gymnosperms (Remy & Remy 1955; Potonié 1962; Ouyang 1996; Eble *et al*. 2001) 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. The pteridosperms are a diverse group and thus generalisations cannot be made about their palaeoecology, however early and mid Mississippian pteridosperms appear to have been most common in disturbed settings, including stream levees and drier parts of floodplains in North America, and in volcanigenic landscapes in western Europe (Rothwell & Scheckler 1988), and would have avoided standing water (DiMichele *et al*. 2006). Thus, like ferns, they represent a radically different palaeoecology to the forest mire. This, coupled with their gymnospermous water-independent reproduction strategy made lowlands newly created by regression with declining water table conditions ideal for pteridosperm colonisation.

The fact that extrabasinal palynomorphs do not increase during marine intervals may be due to their extreme rarity in the lower parts of the Throckley and Rowlands Gill boreholes, and in the early Namurian generally (Clayton *et al*. 1977), but even in the later Namurian section of the Throckley Borehole, where extrabasinal palynomorphs are more common, they are concentrated outside marine sections (Fig. 3). It is possible that what are interpreted as extrabasinal plants, including upland habitats, had not yet taken up such a position and were still riverine or littoral, and therefore were affected in the same way as lowland plants during transgression, preventing a ‘Neves Effect’. A strong fluvial influence in the upper part of the Throckley Borehole is indicated by generally low bulk $\delta^{13}C$, AOM and marine fossils, and the presence of large fluvial channel sandbodies (Fig. 3; Dunham 1990; Mills & Holliday 1998), thus it is also possible that fluvial runoff was the strongest source of ‘extrabasinal palynomorphs’ being brought from upland areas around the basin, a phenomenon identified by Muller (1959) in studies of the distribution of saccate pollen in the modern Orinoco delta. In the more distal settings in which the ‘Neves Effect’ has been traditionally identified (Neves 1958; Davies & McLean 1996) such an influence would not be so strong.

Notwithstanding fluvial effects, the main trend of extrabasinal palynomorphs is from very low numbers in the lower parts of both boreholes to higher numbers in the later Namurian, probably reflecting increasing colonisation of habitats (Fig. 3). The most common palynomorph of the extrabasinal group in the Throckley and Rowlands Gill boreholes is *Potonieisporites* which appeared in the earliest Namurian E1 (basal Pendleian) in NW Europe (Clayton *et al*. 1990; Owens *et al*. 2004); a similar inception is suggested in the Rhadames Basin, Libya (Coquel *et al*. 1988), eastern Canada (Utting 1987), and Asia (Ouyang 1996). This apparently synchronous first appearance has prompted the use of monosaccate pollen of *Potonieisporites* as a marker for the basal Namurian worldwide (see for example Jones & Truswell 1992). *Potonieisporites* was probably pre-pollen in that it is unlikely to have germinated through a distal aperture (Poort & Veld 1997; Rothwell & Mapes 2001; see also Zaviolova & Stephenson 2006), but it has been found in association with walchiacean conifer-like plants that had xeric adaptations (Krassilov 1997; Poort & Veld 1997). The earliest macrofossil of this type is of Wesphalian B age (Scott & Chaloner 1983), but it is likely that the early Namurian of NE England, Scotland and parts of Northern Ireland supported walchiacean conifer-like plants based on the presence of *Potonieisporites* (this study; Scott & Chaloner 1983; Whitaker & Butterworth 1978). The origins of conifers such as the Walchiaceae are related to pteridosperms and cordaites (Rothwell 1982), or gnetophytes (Hernandez-Castillo *et al.* 2001) and are interpreted to have evolved in xeric, seasonal environments (Zhou 1994) or upland areas (Falcon-Lang & Scott 2000) capitalising on their water-independent reproduction strategy. Their common appearance worldwide in greater numbers across several ecological zones in the latest Pennsylvanian and Early Permian in the Euramerican region (e.g. in the Autunian of France) is attributed to rapid aridification. However since land plants were originally concentrated on river margins and close to coasts, it seems reasonable to suggest that the ancestors of the Walchiaceae group may have appeared in these areas and later spread to the uplands. Though cordaites have been proposed as upland plants recently (Falcon-Lang 2006; Falcon-Lang & Scott 2000; Falcon-Lang & Bashforth 2004), Krassilov (1997) suggested that a xeric aspect to morphology in cordaites and Walchiaceae may not always suggest an upland habitat, and that walchiacean coniferoids may have had xeric adaptations for intra-littoral environments rather than upland environments. It is interesting to speculate about the early Namurian coincident appearance of walchiacean pollen and high frequency-high amplitude glacioeustatic cyclicity. Pfefferkorn *et al*. (2007) commented that in greenhouse to icehouse transitions, lowland areas are the sources of evolutionary innovation (the ‘Havlena Effect’). If the Walchiaceae evolved from pteridosperms, perhaps xeric-adapted, intra-littoral lowland walchiacean coniferoids were encouraged to develop by repeated appearance of low water-table ecospace following regression. These may have been connected with allopatric speciation related to dryland colonisation of pteridosperm *Schulzospora*-producing plants.

Large scale trends

Cyclic sedimentation appears to affect palaeoecology over short intervals, but overall, the period of study indicates equilibrium, with palaeocommunities such as forest mire continually re-establishing themselves after sea level changes. A similar pattern of equilibrium is present in later sequences of the Westphalian (Falcon-Lang 2003, 2004; DiMichele *et al*. 2002).

However a long term trend in Throckley and Rowlands Gill boreholes is increasing terrestrial $\delta^{13}C$ (Figs. 3 and 4). The trend was examined using bootstrap statistics (Efron & Tibshirani 1993) whereby the slope of a linear fit to the regression line was calculated from 10000 resamples of the depth/ $\delta^{13}C$ data pairs. The median and 95th percentile confidence limits on the slope (median value -0.00428, 95% confidence limits -0.00591 to -0.00294) indicate that the $\delta^{13}C$ trend is significant.

The extended record in the Throckley Borehole shows that the trend extends through much of the Namurian up to the Kinderscoutian - Marsdenian KV palynological biozone. This trend is also mirrored in the lower parts of the boreholes by marine $\delta^{13}C$. $\delta^{13}C$ (terrestrial) has been documented through the Palaeozoic by Strauss & Peters-Kottig (2003) and Peters-Kottig *et al*. (2006). These authors' values come from a large database of samples and broadly show high values of terrestrial $\delta^{13}C$ (–21‰ to –22‰) between the early Mississippian and the Early Permian, attributed to the rise of large vascular land plants and associated burial of carbon in decomposition resistant lignin. Within this period, Strauss & Peters-Kottig (2003) and Peters-Kottig *et al*. (2006) also recognised a period of relatively low values corresponding to the late Mississippian and Pennsylvanian (–22‰ to –24‰), and these were attributed to the physiological response of plants to high atmospheric O_2 concentrations at that time (Berner 2003), in that increased photorespiration due to enhanced O_2 lead to increased carbon isotope fractionation and decreased $\delta^{13}C$. Within the period of depressed values is a long, low-gradient increasing trend that extends from the late Mississippian through the Pennsylvanian (Strauss & Peters-Kottig 2003, fig. 3; Peters-Kottig *et al*. 2006, fig. 1).

The trend in the Throckley and Rowlands Gill boreholes is from c. –24‰ (Pendleian-Arnsbergian, c.327 Ma) to c. –22‰ (late Alportian - ?early Marsdenian, c.323 Ma; numerical dates from Waters & Davies 2006: Figs. 3 and 4), and thus is similar to the Mississippian-Pennsylvanian transition recorded by Strauss & Peters-Kottig (2003) and Peters-Kottig *et al*. (2006). We suggest that this trend probably records global variation because it occurs in both boreholes and because the data come from a random collection of mainly wood fragments at each sampled stratigraphic level and thus are unlikely to be subject to systematic bias or to extreme individual results from unusual habitats. In addition, if the marine and terrestrial realm behave in a linked fashion when responding to global carbon cycle changes as suggested by Strauss & Peters-Kottig (2003), then the congruent trend in marine $\delta^{13}C$ (Figs. 3 and 4) supports the veracity of the $\delta^{13}C$ terrestrial increasing trend. Maturation is known to have minor effects on $\delta^{13}C$ in wood (van Bergen & Poole 2002), but maturation differences between and through the two boreholes are negligible based on palynomorph exine colour. The trend is also unlikely to be related to a change in wood type (e.g. from lycopsid wood to gymnosperm wood upsection) because wood types are not known to vary systemically in $\delta^{13}C$ in this way.

The increasing trend in the Throckley and Rowlands Gill boreholes is, however, difficult to explain. If the depressed values of $\delta^{13}C$ in the late Mississippian and Pennsylvanian are related to high atmospheric O_2, as suggested by Strauss & Peters-Kottig (2003) and Peters-Kottig *et al*. (2006), then a small increase in $\delta^{13}C$ upsection might relate to decreases in atmospheric O_2. However Berner (2003) suggested increasing atmospheric O_2 until the Late Permian.

It is tempting to explain the trend in terms of glaciation since the early Namurian Throckley and Rowlands Gill sequences are approximately coeval with the earliest Carboniferous unequivocal glacial facies in South America, eastern Australia and Tibet (see Isbell *et al*. 2003; González-Bonorino & Eyles 1995; Fielding *et al*. 2008). For example the onset of the first Australian (C1) glaciation of Fielding *et al*. (2008) is dated at approximately 326.5-325.5 Ma (earliest Namurian, Pendleian). However the onset of large-scale glaciation would tend to decrease carbon burial and therefore produce a decreasing $\delta^{13}C$ trend. A glacially-related mechanism that might produce an increasing trend could be minor atmospheric O_2 decrease due to decreased plant growth leading to increasing $\delta^{13}C$.

Conclusions

This study has shown that high amplitude - high frequency cycles, most likely of glacioeustatic origin, produced repeated responses in terrestrial plant groups including ferns and putative pteridosperms, probably due to changing sea level. There may also be a theoretical connection between cyclicity and the appearance of monosaccate pollen such as *Potonieisporites*. It also illustrates the value of $\delta^{13}C$ (bulk organic matter) in delineating marine and non marine conditions due to the large difference between $\delta^{13}C$ marine organic matter (c.–30‰) and $\delta^{13}C$ terrestrial (c.–23‰) and indicates that intermittent full marine salinity conditions resulting from glacioeustatic marine transgression were superimposed on a background of constant inundation by freshwater from the north by large rivers, which killed off the marine biota. Long term terrestrial and marine increasing $\delta^{13}C$ (organic) may reflect the onset of major glaciation in Gondwana, since there is some evidence to suggest that the two are coeval, but no specific mechanism can be suggested to link the trends.

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References

Berner, R. A. 2003. The long term carbon cycle, fossil fuels and atmospheric composition. *Nature*, **426**, 323-326.

Brand, P. J. 1987. Report on specimens collected from the Rowlands Gill Borehole, NZ15NE 276, sited at NZ 1664 5815. BGS Report Number PDS/87/1'' England 20, NZ15NE

Carruthers, R. G. 1938. Alston Moor to Botany and Tan Hill: an adventure in stratigraphy. *Proceedings of the Yorkshire Geological Society*, **23**, 236-253.

Cecil, C. B. 1990. Paleoclimate controls on stratigraphic repetition of chemical and siliciclastic rocks. *Geology*, **18**, 533-536.

Cecil, C. B., Dulong, F. T., Cobb, J. C. & Supardi. 1993. Allogenic and autogenic controls on sedimentation in the central Sumatra basin as an analogue for Pennsylvanian coal-bearing strata in the Appalachian basin. *In*: Cobb, J. C. & Cecil, C. B. (eds.) *Modern and Ancient coal-forming environments*. Geological Society of America Special Paper 286, 3-22.

Chadwick, R A, Holliday, D W, Holloway, S, and Hulbert, A G. 1995. The

Northumberland-Solway Basin and adjacent areas. Subsurface memoir of the British Geological Survey.

Chaloner, W. G. 1958. The Carboniferous upland flora. *Geological Magazine*, **95**, 261-262.

Clayton, G., Loboziak, S., Streel, M., Turnau, E. & Utting, J. 1990. Palynological events in the Mississippian (Lower Carboniferous) of Europe, North Africa and North America, *Courier Forschungs Institut Senckenberg*, **130**, 79-84.

Clayton, G., R. Coquel, J. Doubinger, K.J. Gueinn, S. Loboziak, B. Owens and M. Streel 1977. Carboniferous miospores of Western Europe: illustration and zonation. *Mededilingen Rijks Geologische Dienst*, **29**, 1-71.

Cleal, C. J. & Thomas, B. A., 1995. *Palaeozoic palaeobotany of Great Britain*. Chapman & Hall, London, 295pp.

Collinson, J. D. 1988. Controls on Namurian sedimentation in the Central Province basins of northern England. *In*: Besly, B. M. & Kelling, G. (Eds.) *Sedimentation in a synorogenic basin complex; the Upper Carboniferous of Northwest Europe*. Blackie, Glasgow, 85-101.

Cope, J. C. W., Ingham, J. K. & Rawson, P. F. 1992. *Atlas of palaeogeography and lithofacies*. Geological Society Memoir, **13**, 153pp.

Coquel, R., Doubinger, J. & Massa, D. 1988. Nouvelles données palynologiques sur l'intervalle Carbonifère Viséen/Moscovien Bassin de Rhadamès (Libye). *Revue de L'institute Français du Pétrole*, **43**, 3-16.

Davies, S. J. & McLean, D. 1996. Spectral gamma-ray and palynological characterization of Kinderscoutian marine bands in the Namurian of the Pennine Basin. *Proceedings of the Yorkshire Geological Society*, **51**, 103-114.

DiMichele, W. A. & Phillips, T. L. 1996. Climate change plant extinctions and vegetational recovery during the Middle – Late Pennsylvanian transition: the case of tropical peat-forming environments in North America. *In*: Hart, M. B., (ed.), *Biotic recovery from mass extinction events*. Geological Society Special Publication, **102**, 201-221.

DiMichele, W. A., Phillips, T. L. & Nelson, W. J. 2002. Place vs. Time and vegetational persistence: a comparison of four tropical mires from the Illinois Basin during the height of the Pennsylvanian Ice Age. *International Journal of Coal Geology*, **50**, 43-72.

DiMichele, W. A., Phillips, T. L. & Pfefferkorn, H. W. 2006. Paleoecology of Late Paleozoic pteridosperms from tropical Euramerica. *Journal of the Torrey Botanical Society*, **133**, 83-118.

Dunham, K. C. 1990. *Geology of the Northern Pennine Orefield, Volume 1, Tyne to Stainmore*, 2nd Edition. British Geological Survey, 1990.

Eble, C. F., Greb, S. F., & Williams, D. A. 2001. The geology and palynology of Lower and Middle Pennsylvanian strata in the Western Kentucky Coal Field. *International*

Journal of Coal Geology, **47**, 189-206.

Efron, B. & Tibshirani, R. J. 1993. *An Introduction to the Bootstrap*. Monographs on statistics and applied probability, **57**. Chapman & Hall, London, 436 pp.

Falcon-Lang, H. J. 2003. Reponse of Late Carboniferous tropical vegetation to transgressive-regressive rhythms at Joggins, Nova Scotia. *Journal of the Geological Society*, London, **160**, 643-648.

Falcon-Lang, H. J. 2004. Pennsylvanian tropical rain forests responded to glacial-interglacial rhythms. *Geology*, **32**, 689-692.

Falcon-Lang, H. J. 2006. Vegetation ecology of Early Pennysylvanian alluvial fan and piedmont environments in southern New Brunswick, Canada, *Palaeogeography, Palaeoclimatology, Palaeoecology*, **233**, 34-50.

Falcon-Lang, H. J. & Scott, A. C. 2000. Upland ecology of some Late Carboniferous cordaitalean trees from Nova Scotia and England. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **156**, 225-242.

Falcon-Lang, H. J. & Bashforth, A. R. 2004. Pennsylvanian uplands were forested by giant cordaitalean trees. *Geology*, **32**, 417-420.

Fielding, C. R., Frank, T. D., Birgenheier, L. P., Rygel, M. C., Jones, A. T., Roberts, J. 2008. Stratigraphic imprint of the Late Palaeozoic Ice Age in eastern Australia: a record of alternating glacial and nonglacial climate regime. *Journal of the Geological Society,* *London*, **165**, 129-140

Foster, C. B., Logan, G. A., Summons, R. E., Gorter, J. D. & Edwards, D. S. 1997. Carbon isotopes, kerogen types and the Permian-Triassic boundary in Australia: implications for exploration. *Australian Petroleum Production & Exploration Association Journal*, **1997**, 472-489.

Fraser, A. J. & Gawthorpe, R. L. 2003. *An atlas of Carboniferous basin evolution in Northern England*. Geological Society, London, Memoir **28**.

González-Bonorino, G. & Eyles, N. 1995. Inverse relation between ice extent and the late Paleozoic glacial record of Gondwana, *Geology*, **23**, 1015-1018.

Gorter, J. D., Foster, C. B. & Summons, R. E. 1995. Carbon isotopes and the Permian-Triassic boundary in the north Perth, Bonaparte and Carnarvon Basins, Western Australia. *Petroleum Exploration Society of Australia Journal*, **23**, 21-38.

Hernandez-Castillo, G. R., Rothwell, G. W. & Mapes, G. 2001. Compound pollen cone in a Paleozoic conifer. *American Journal of Botany*, **88**, 1139-1142.

Holdsworth, B. K. & Collinson, J. D. 1988. Millstone Grit cyclicity revisited. *In*: Besly, B. M. & Kelling, G. (eds.) *Sedimentation in a synorogenic basin complex; the Upper Carboniferous of Northwest Europe*. Blackie, Glasgow, 132-152.

Isbell, J. L., Miller, M. F., Wolfe, K. L. & Lenaker, P. A. 2003. Timing of late Paleozoic glaciation in Gondwana: was glaciation responsible for the development of northern hemisphere cyclothems? *Geological Society of America Special Paper*, **370**, 5-24.

Jones, M. J. & Truswell, E. M. 1992. Late Carboniferous and Early Permian palynostratigraphy of the Joe Joe Group, southern Galilee Basin, Queensland, and implications for Gondwana Stratigraphy. *Bureau of Mines and Mineral Resources Journal of Australian Geology and Geophysics*, **13**, 143-185.

Krassilov, V. A. 1997. Syngenesis of xeromorphic plant communities in the Late Paleozoic to Early Cenozoic. *Paleontological Journal*, **31**, 125-134.

Lewan, M. D. 1986. Stable carbon isotopes of amorphous kerogens from Phanerozoic sedimentary rocks. *Geochimica et Cosmochimica Acta*, **50**, 1583-1591.

Maynard, J. B. 1981. Carbon isotopes as indicators of dispersal patterns in Devonian-Mississippian shales of the Appalachian Basin. *Geology*, **9**, 262-265.

Mills, D. A. C. & Holliday, D. W. 1998. *Geology of the district around Newcastle upon Tyne, Gateshead and Consett. Memoir for the 1:50000 Geological Sheet 20*, British Geological Survey. London, HMSO.

Muller, J. 1959. Palynology of Recent Orinoco delta and shelf sediments. *Micropalaeontology*, **5**, 1-32.

Neves, R. 1958. Upper Carboniferous plant spore assemblages from the *Gastrioceras subcrenatum* horizon, north Staffordshire. *Geological Magazine*, **95**, 1-19.

Newmann, J. W. Parker, P. & Behrens, E. W. 1973. Organic carbon isotope ratios in

Quaternary cores from the Gulf of Mexico, *Geochimica et Cosmochimica Acta*, **37**, 225-239.

Ouyang, S., 1996. On the first appearance of some gymnospermous pollen and GSPD assemblages in the sub-Angara, Euramerian and Cathaysia provinces. *Palaeobotanist*, **45**, 20-32.

Owens, B., McLean, D. & Bodman, D. 2004. A revised palynozonation of British Namurian deposits and comparisons with eastern Europe. *Micropaleontology*, **50**, 89-103.

Owens, B., Neves, R., Gueinn, K. J., Mishell, D. R. F., Sabry, H. S. M. Z. & Williams, J. E. 1977. Palynological division of the Namurian of northern England and Scotland. *Proceedings of the Yorkshire Geological Society*, **41**, 381-398.

Pattison, J. 1980. Namurian macrofossils from the 1:50000 sheet 20 (Newcastle-upon-Tyne). *Report of the Palaeontological Department*, IGS, **PDL/80/374**.

Peters-Kottig, W. Strauss, H. & Kerp, H. 2006. The land plant $\delta^{13}C$ record and plant evolution in the Late Palaeozoic. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **240**, 237-252.

Pfefferkorn, H. W., Gastaldo, R., DiMichele, W. A., Kotasa, A., Kotasowa, A., Migier, T., Trzepierczynska, A., Zdanowski, A., Purkynova, E., Simunek, Z., Blake, B. M., Eble, C. F., Gillespie, W. H., Beuthin, J. D. & Shulga, V. F. 2007. Impact of a glacial interval (icehouse climate) on tropical vegetation and plant evoluition. Abstracts of the 16th International Congress on the Carboniferous and Permian, *Journal of Stratigraphy*, **31**, 8-

9.

Phillips, T. L. & DiMichele, W. A. 1981. Paleoecology of Middle Pennsylvanian age coal swamps in southern Illinois/Herrin Coal Member at Sahara Mine No. 6. *In*: Niklas, K. J. (ed.) *Paleobotany, Paleoecology and Evolution, vol. 1*, Praeger, New York, 231-285.

Phillips, T. L. & Peppers, R. A. 1984. Changing patterns of Pennsylvanian coal-swamp vegetation and implications of climatic control on coal occurrence. *International Journal of Coal Geology*, **3**, 205-255.

Poort, R. J.& Veld, H. 1997. Aspects of Permian palaeobotany and palynology XVIII. On the morphology and ultrastructure of *Potonieisporites novicus* (prepollen of Late Carboniferous/Early Permian Walchiaceae). *Acta Botanica Neerlandica*, **46**, 161-173.

Potonié, R. 1962. *Synopsis der sporae in situ. Beihefte zum Geologischen Jahrbuch*, **52**: 204 pp.

Ramsbottom, W. H. C. 1977. Major cycles of transgression and regression (mesothems) in the Namurian. *Proceedings of the Yorkshire Geological Society*, **41**, 261-291.

Ramsbottom, W. H. C., Calver, M. A., Eager, R. M. C., Hodson, F., Holliday, D. W., Stubblefield, C. J. & Wilson, R. B. 1978. A correlation of the Silesian rocks in the British Isles. *Geological Society of London, Special Report* **10**, 1978, 82pp.

Remy, R. and Remy, W. 1955. *Simpliotheca silesiaca* n. gen. et sp. Abhandlungen der Deutschen Akademie der Wissenschaften zu Berlin (Jahrg), **2**, 3-7.

Riley, N. J. R. 1992. Foraminiferal and algal biostratigraphy of Rowlands Gill Borehole, (BGS BH reference NZ15NE/276). *Report of the Palaeontological Department, British Geological Survey*, **Report PDL 92/132R**.

Rothwell, G. W. 1982. New interpretations of the earliest conifers. *Review of Palaeobotany and Palynology*, **37**, 7-28.

Rothwell, G. W. & Scheckler, S. E. 1988. Biology of ancestral gymnosperms. *In*: C. B. Beck (ed.), *Origin and Evolution of Gymnosperms*. Columbia University Press, New York, NY, p. 85-134.

Rothwell, G. W. & Mapes, G. 2001. *Barthelia furcata* gen. et sp. nov., with a review of Paleozoic coniferophytes and a discussion of coniferophyte systematics. *International Journal of Plant Science*, **162**, 637-667.

Scott, A. C. 1979. The ecology of Coal Measure floras from northern Britain. *Proceedings of the Geologist's Association*, **90**, 97-116.

Scott, A. C. & Chaloner, W. G. 1983. The earliest fossil conifer from the Westphalian B of Yorkshire. *Proceedings of the Royal Society of London*, **Series B220**, 163-182.

Stephenson, M. H., Leng, M. J., Vane, C. H., Osterloff, P. L. & Arrowsmith C. 2005. Investigating the record of Permian climate change from argillaceous sediments, Oman. *Journal of the Geological Society, London*, **162**, 641-651.

Strauss, H. & Peters-Kottig, W. 2003. The Paleozoic to Mesozoic carbon cycle revisited:

the carbon isotopic composition of terrestrial organic matter. *Geochemistry, Geophysics, Geosystems*, **4**, Article Number 10, 1-15.

Turner, N., Spinner, E., Spode, F. & Wignall, P. B. 1994. Palynostratigraphy of a Carboniferous transgressive systems tract from the earliest Alportian (Namurian) of Britain. *Review of Palaeobotany and Palynology*, **80**, 39-54.

Utting, J. 1987. Palynology of the Lower Carboniferous Windsor Group and Windsor-Canso Boundary Beds of Nova Scotia, and their equivalents in Quebec, New Brunswick and Newfoundland. *Geological Survey of Canada Bulletin*, **374**, 1-93.

Waters, C. N. & Davies, S. J. 2006. Carboniferous: extensional basins, advancing deltas and coal swamps. *In*: Brenchley, P. J. & Rawson, P. F. (eds.) *The Geology of England and Wales (2nd Edition),* Geological Society, 173-223.

Whitaker, M. F. & Butterworth, M. A. 1978. Palynology of Carboniferous strata from the Ballycastle area, C. Antrim, Northern Ireland. *Palynology*, **2**, 147-158.

Willard, D. A. 1989. Source plants for Carboniferous microspores: *Lycospora* from permineralised *Lepidostrobus*. *American Journal of Botany*, **76**, 820-827.

Willard, D. A., DiMichele, W. A., Eggert, D. L., Hower, J. C. Rexroad, C. B. & Scott, A. C. 1995. Paleoecology of the Springfield Coal Member (Desmoinesian, Illinois Basin) near the Leslie Cemetary paleochannel, southwestern Indiana. *International Journal of Coal Geology*, **27**, 59-98.

Wright, V. P. & Vanstone, S. D. 2001. Onset of Late Palaeozoic glacio-eustacy and the evolving climates of low latitude areas: a synthesis of current understanding. *Journal of the Geological Society*, London, **158**, 579-582.

Zaviolova, N. E. & Stephenson, M. H. 2006. The exine ultrastructure of *Plicatipollenites malabarensis* (Potonié et Sah) Foster, 1975. *Review of Palaeobotany and Palynology*, **139**, 241-252.

Zhou, Y. 1994. Earliest pollen-dominated microfloras from the early Late Carboniferous of the Tian Shan Mountains, NW China: their significance for the origin of conifers and palaeophytogeography. *Review of Palaeobotany and Palynology*, **81**, 193-211.

Figure captions

Fig. 1a. Block and basin distribution in the Namurian, simplified after Fraser & Gawthorpe (2003). Location of the Throckley and Rowlands Gill boreholes shown in Fig. 1b.

Fig. 2. Lithostratigraphy of the Throckley and Rowlands Gill boreholes; and ranges of selected palynomorphs for the Throckley Borehole. Note that palynological and foraminiferal information provide inconsistent dates in the boreholes, thus precise chronostratigraphy cannot be shown, see text. Key to lithologies as in Fig. 3.

Fig. 3. Lithology, $\delta^{13}C$ (bulk), $\delta^{13}C$ (wood fragments) and percentage of extrabasinal pollen in palynological assemblages between 105 and 325 m in the Throckley Borehole.

Fig. 4. Lithology, palaeoenvironmental interpretation and $\delta^{13}C$ (bulk) of the Rowlands Gill Borehole.

Fig. 5. Palaeoenvironmental and palynofacies groups of the Throckley Borehole between the Lower Felltop Limestone and Upper Felltop Limestone (240 to 315 m). Curves show decreasing trends in *Schulzospora* and fern spores through coarsening-upward cycles. Figures for palaeocommunities are raw counts; those for palynofacies are percentages.

Fig. 6. Palaeoenvironmental and palynofacies groups of the Rowlands Gill Borehole between the Lower Felltop Limestone and Upper Felltop Limestone (163 to 213 m). Curves show decreasing trends in *Schulzospora* and fern spores through coarsening-upward cycles. Figures for palaeocommunities are raw counts; those for palynofacies are

percentages

Table 1. Composition of palaeoecological groups between the Lower and Upper Felltop limestones, modified after Davies & McLean (1996).

Table 2. Composition of palynofacies groups.

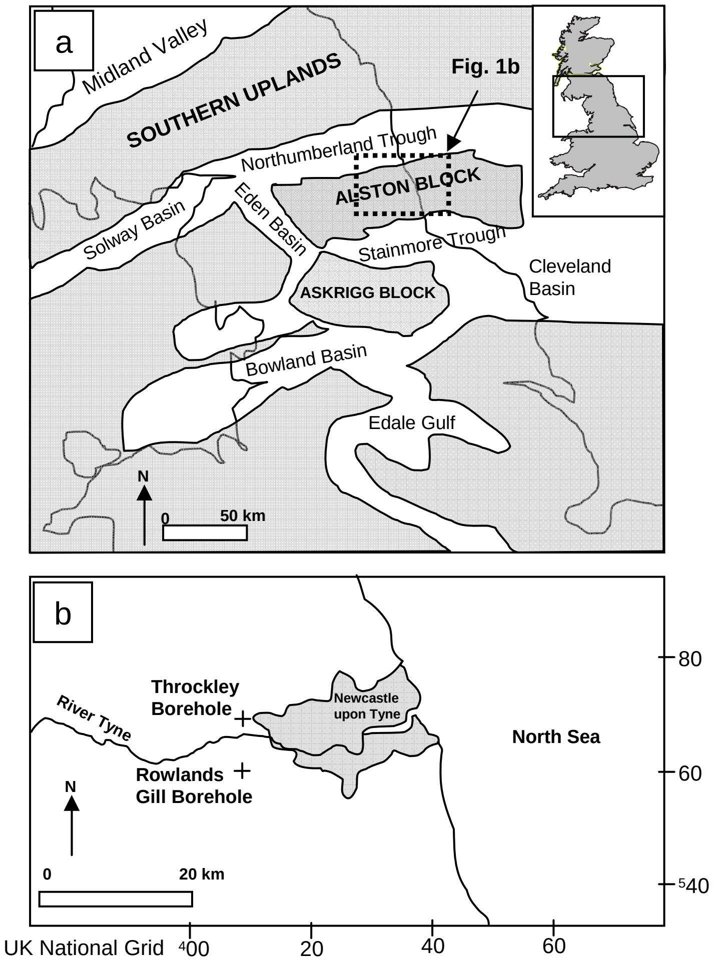

a
Midland Valley
SOUTHERN UPLANDS
Fig. 1b
Northumberland Trough
ALSTON BLOCK
Solway Basin
Eden Basin
Stainmore Trough
Cleveland Basin
ASKRIGG BLOCK
Bowland Basin
Edale Gulf
N
0
50 km
b
Throckley Borehole
Newcastle upon Tyne
River Tyne
Rowlands Gill Borehole
North Sea
N
0
20 km
80
60
540
UK National Grid
400
20
40
60

Fig 1

Fig 2

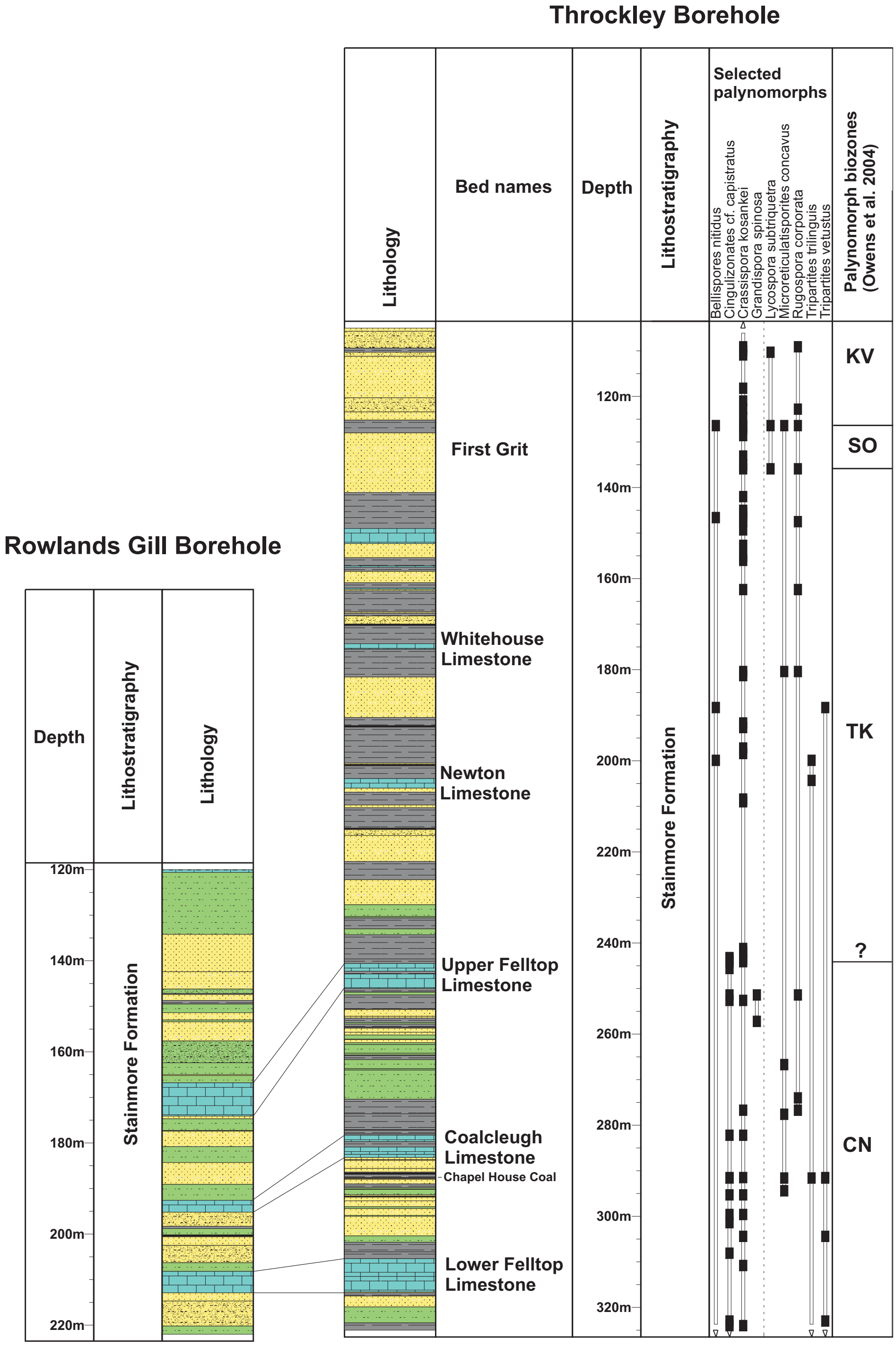
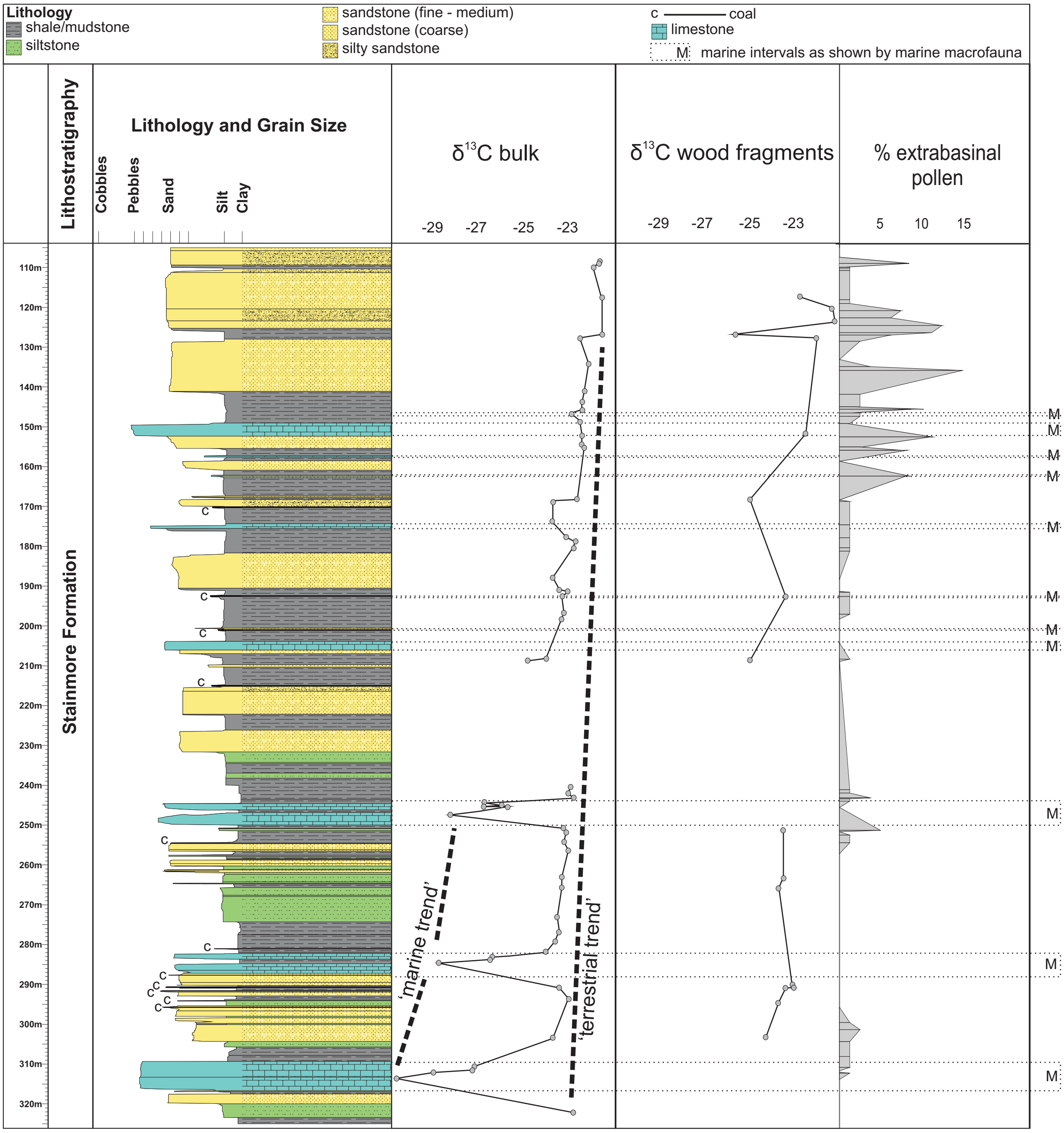

Throckley Borehole
Lithology
Bed names
Depth
Lithostratigraphy
Selected palynomorphs
Bellispores nitidus
Cingulizonates cf. capistratus
Crassispora kosankei
Grandispora spinosa
Lycospora subtriquetra
Microreticulatisporites concavus
Rugospora corporata
Tripartites trilinguis
Tripartites vetustus
Palynomorph biozones (Owens et al. 2004)
First Grit
Whitehouse Limestone
Newton Limestone
Upper Felltop Limestone
Coalcleugh Limestone
Chapel House Coal
Lower Felltop Limestone
120m
140m
160m
180m
200m
220m
240m
260m
280m
300m
320m
Stainmore Formation
KV
SO
TK
?
CN
Rowlands Gill Borehole
Depth
Lithostratigraphy
Lithology
120m
140m
160m
180m
200m
220m
Stainmore Formation

Fig 3


Lithology
shale/mudstone
siltstone
sandstone (fine - medium)
sandstone (coarse)
silty sandstone
c coal
limestone
M marine intervals as shown by marine macrofauna
Lithostratigraphy
Lithology and Grain Size
Cobbles
Pebbles
Sand
Silt
Clay
δ13C bulk
-29
-27
-25
-23
δ13C wood fragments
-29
-27
-25
-23
% extrabasinal pollen
5
10
15
110m
120m
130m
140m
150m
160m
170m
180m
190m
200m
210m
220m
230m
240m
250m
260m
270m
280m
290m
300m
310m
320m
Stainmore Formation
c
c
c
c
c
c
c
c
c
c
'marine trend'
'terrestrial trend'
M
M
M
M
M
M
M
M
M
M
M

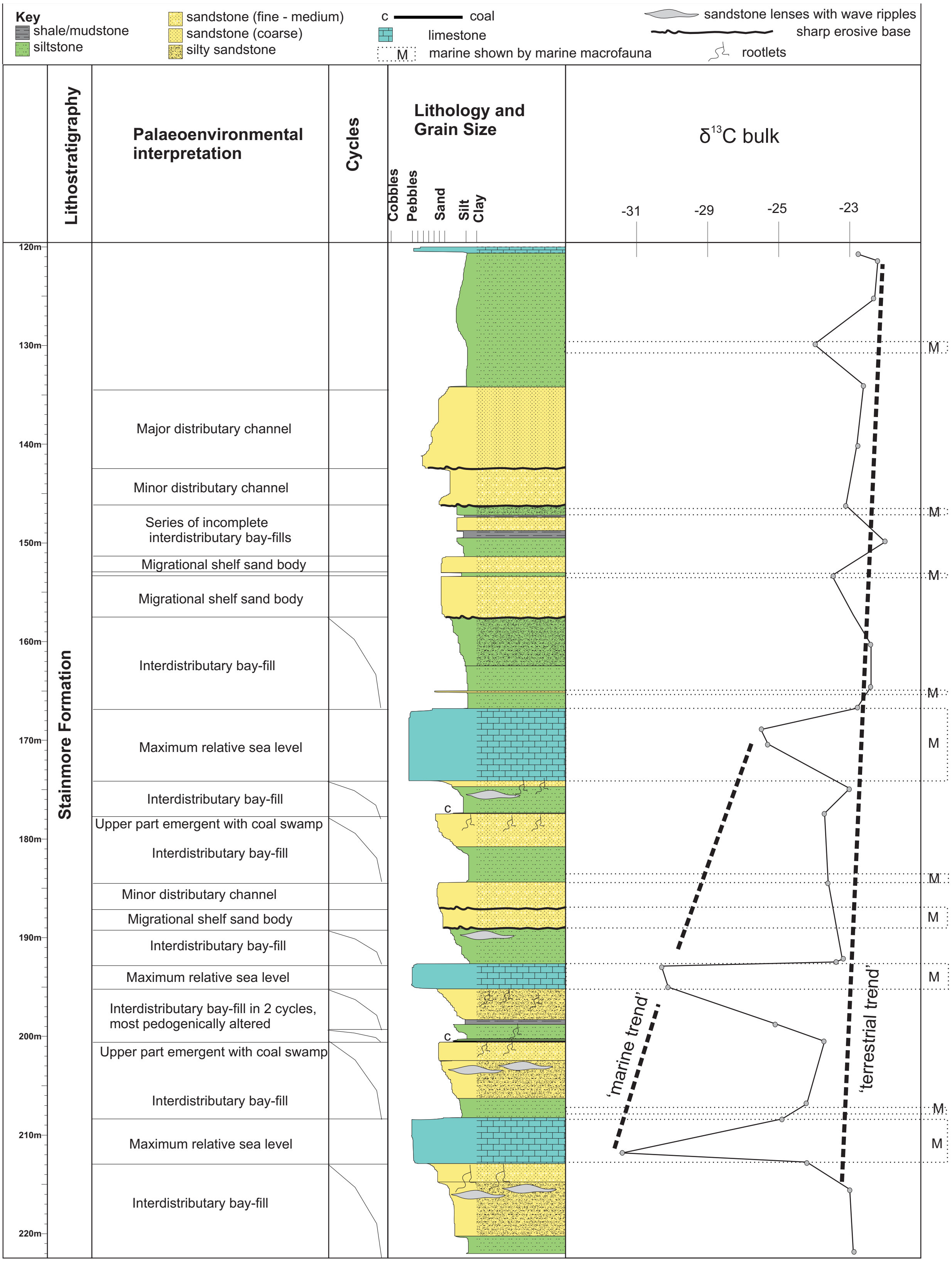

Key
shale/mudstone
siltstone
sandstone (fine - medium)
sandstone (coarse)
silty sandstone
c coal
limestone
M marine shown by marine macrofauna
sandstone lenses with wave ripples
sharp erosive base
rootlets
Lithostratigraphy
Palaeoenvironmental interpretation
Cycles
Lithology and Grain Size
Cobbles
Pebbles
Sand
Silt
Clay
δ13C bulk
-31
-29
-25
-23
120m
130m
140m
150m
160m
170m
180m
190m
200m
210m
220m
Stainmore Formation
Major distributary channel
Minor distributary channel
Series of incomplete interdistributary bay-fills
Migrational shelf sand body
Migrational shelf sand body
Interdistributary bay-fill
Maximum relative sea level
Interdistributary bay-fill
Upper part emergent with coal swamp
Interdistributary bay-fill
Minor distributary channel
Migrational shelf sand body
Interdistributary bay-fill
Maximum relative sea level
Interdistributary bay-fill in 2 cycles, most pedogenically altered
Upper part emergent with coal swamp
Interdistributary bay-fill
Maximum relative sea level
Interdistributary bay-fill
c
c
M
M
M
M
M
M
M
M
M
M
'marine trend'
'terrestrial trend'

Fig 4

Fig 5

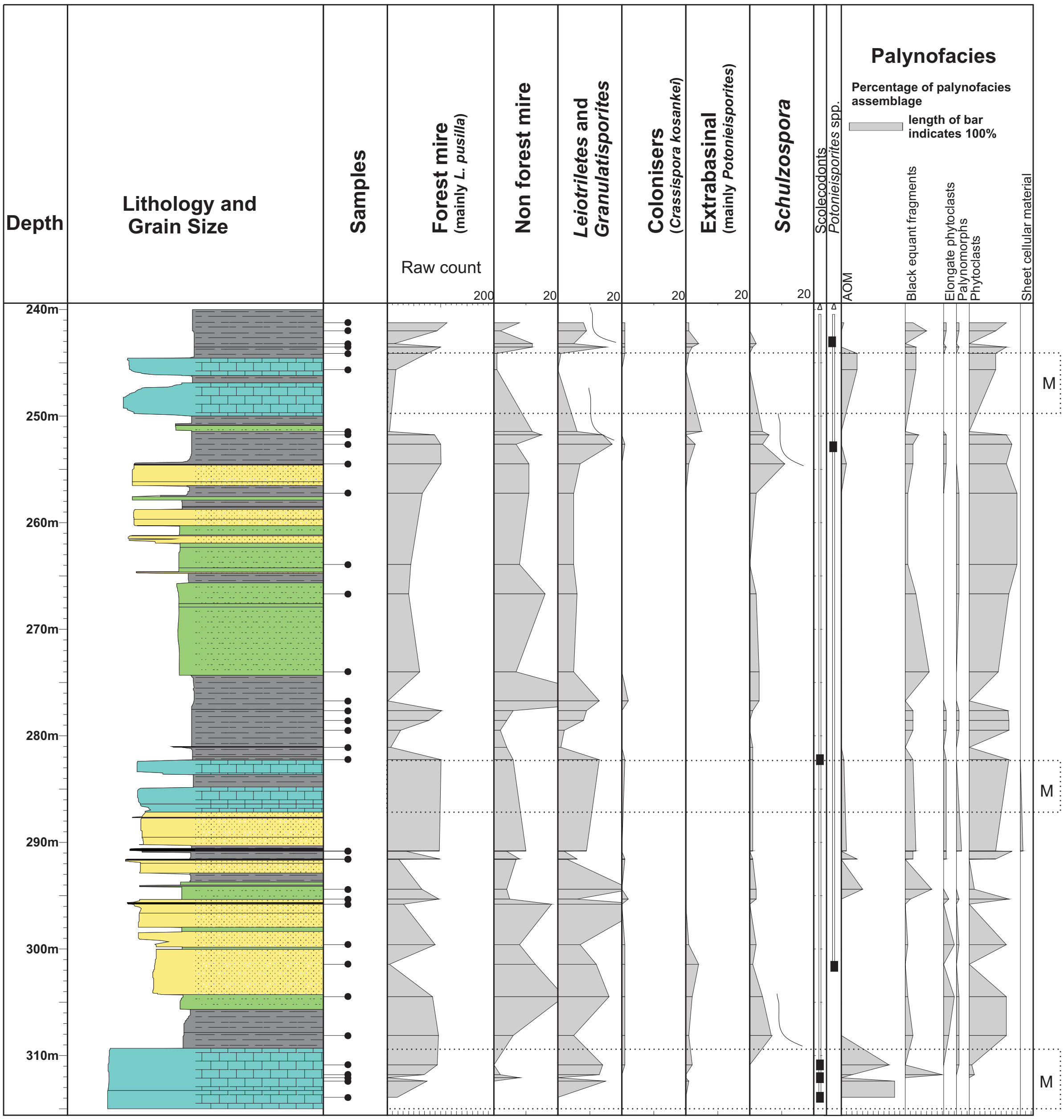
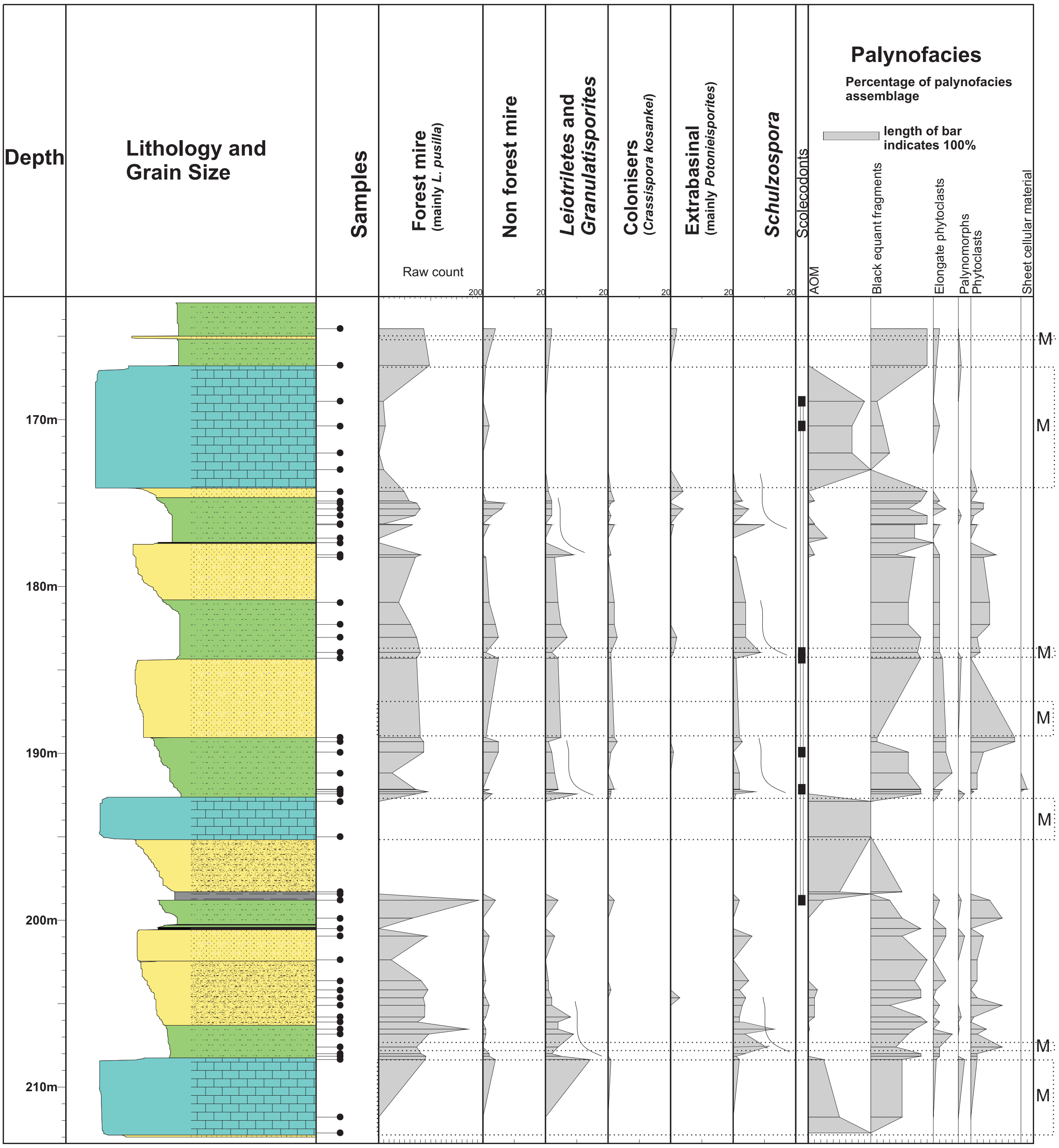

Depth
Lithology and Grain Size
Samples
Forest mire (mainly *L. pusilla*)
Raw count
Non forest mire
Leiotriletes and *Granulatisporites*
Colonisers (*Crassispora kosankei*)
Extrabasinal (mainly *Potonieisporites*)
Schulzospora
Scolecodonts
Potonieisporites spp.
Palynofacies
Percentage of palynofacies assemblage
length of bar indicates 100%
AOM
Black equant fragments
Elongate phytoclasts
Palynomorphs
Phytoclasts
Sheet cellular material
200
20
20
20
20
20
240m
250m
260m
270m
280m
290m
300m
310m
M
M
M

Fig 6


Depth
Lithology and Grain Size
Samples
Forest mire (mainly *L. pusilla*)
Raw count
Non forest mire
Leiotriletes and *Granulatisporites*
Colonisers (*Crassispora kosankei*)
Extrabasinal (mainly *Potonieisporites*)
Schulzospora
Scolecodonts
Palynofacies
Percentage of palynofacies assemblage
length of bar indicates 100%
AOM
Black equant fragments
Elongate phytoclasts
Palynomorphs
Phytoclasts
Sheet cellular material
200
20
20
20
20
20
170m
180m
190m
200m
210m
M
M
M
M
M
M
M

Genera	**Biotic groups**	**Palaeoecological groups**
Lycospora pusilla	Arborescent lycopsids	Forest mire
Cirratriradites rarus	Herbaceous lycopsids	
Densosporites spp. (incl. *D. anulatus*)		
Cingulizonates	Various lycopsids	
Cristatisporites		
Apiculatisporis	Ferns	Non-forest mire
Camptotriletes		
Convolutispora		
Knoxisporites (incl. *K. stephanephorus*)		
Punctatisporites		
Raistrickia		
Retusotriletes		
Savitrisporites (incl. *S. nux*)		
Tripartites (including *T. vetustus*)		
Triquitrites		
Granulatisporites		
Leiotriletes		
Reticulatisporites	Sphenopsids	
Calamospora		
Schulzospora	Pteridospermae	
Crassispora kosankei	Sigillariacaea	Colonisers
Indet. bisaccate pollen	Gymnosperms	Extrabasinal
Indet. monosaccate pollen		
Potonieisporites		
Remysporites spp. (incl. *R. magnificus*)		
Scolecodonts	Polychaete worm	Marine

Table 1

Type	**Description**
Amorphous organic matter (AOM)	Material with no obvious structure
Black equant fragments	Vascular plant origin; probably the result of forest fires or other oxidation.
Palynomorphs	Propagules of largely vascular plant, algal or fungal origin, including spores, pollen, zygospores and fungal spores
Phytoclasts	Vascular plant origin, with some cellular or other structure suggesting lignin or other plant support structures
Elongate phytoclasts	As above, but elongate
Sheet cellular material	Sheets with distinct regular structures; probably cuticle

Table 2