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Megaspores and associated palynofloras of Middle Jurassic fluvio-deltaic sequences in North Yorkshire and the northern North Sea: a biofacies-based approach to palaeoenvironmental analysis and modelling

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Abstract: Outcrops of the Early Bajocian, Gristhorpe Member (Ravenscar Group) in North Yorkshire have been subjected to a multi-disciplinary analysis which establishes a key reference section at Yons Nab. Eight micro-biofaces types (MBs) are defined based on counts of transitional marine microfaunas, megaspores and plant-derived debris. Associated palynofloral associations (PAs) are used to qualify the micro-biofacies defined to provide an integrated model for interpreting salinity–freshwater trends associated with deltaic progradation and retreat. Megaspore and small-spore trends within the delta-plain are shown to have been closely linked to peat-mires forming in topographic lows, with variations across the delta-plain attributable to the presence of the semi-permanent and seasonal water tables. A reconstruction of the floodplain–peat-mire depositional setting is proposed where the composition of host vegetation (e.g. ferns, lycopsids) varied in relation to groundwater levels. Biostratigraphic correlation within the Gristhorpe Member is attempted using the base of 'established' delta-plain deposition (megaspore dominant MBs/ spore-dominant PAs) and the top and base agglutinated foraminifera-dominant MBs (brackish). Using these criteria the Gristhorpe Member is modelled in terms of a southward progradation of delta-plain facies into a bay-fill sequence, which persisted at Yons Nab. With the delta-plain established, the MB/PA trends and sedimentology suggest a northward shift towards the higher delta-plain, with seasonal standing water only. The MB/PA model was tested on core samples from the coeval lower Brent Group from northern North Sea well 34/10-B-12 (Gullfaks Field); MB/PA trends are shown to compare closely with those of the Gristhorpe Member at Yons Nab, with the same megaspore/small-spore associations developed within similar lithofacies. On this basis transitional marine, bay-fill and delta-plain deposition are defined in the cored section. These comparative data suggest that the dispersal of megaspore and miospore host floras occurred effectively across the Mid North Sea High, and that they colonized the same niche habitats associated with bay-fill and delta-plain development.

Keywords: North Yorkshire, Middle Jurassic, megaspores, miospores, micro-biofacies, palynofacies, Brent Group

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Fluvio-deltaic sections of the Middle Jurassic, Ravenscar Group (previously known as the 'Estuarine' and 'Deltaic' Series) have been the subject of numerous studies since the turn of the twentieth century, with the publication of papers and monographs focused particularly on its well-preserved plant fossils, including those of A.C. Seward (1900), T.G. Halle (1913), H. Hamshaw Thomas (e.g. Thomas 1922) and T.M. Harris (e.g. his five monographs published between 1961 and 1979). Since the mid-1960s, other studies on the flora have been carried out by C.R. Hill (1987, 1990), H.S. Morgans (see van Konijnenburg-van Cittert & Morgans 1999) and J.H.A. van Konijnenburg-van Cittert (1996). In the majority of these the relationships between the occurrences of plant taxa and the sedimentary rocks from which they were recovered received little attention: associated plant microfossils were also largely excluded from analysis with the exception of Harris (1961), who described dispersed megaspores from the main plant-bearing intervals, and van Konijnenburg-van Cittert, who focused initially (in 1971) on the occurrence of pollen grains in gymnosperm fructifications. Published research on palynomorph assemblages from the Ravenscar Group, i.e. not only small spores and pollen grains (miospores) but also dinoflagellate cysts and other phytoplankton, is limited to summary data from selected deposits. These include the Ellerbeck Formation and Sycarham and Gristhorpe members of the Cloughton Formation (Hancock & Fisher 1981; Butler *et al.* 2005), and the Scarborough to Scalby formations (Hancock & Fisher 1981; Riding & Wright 1989; Butler *et al.* 2005). Despite field and sedimentological evidence for the existence of distinct regressive–transgressive sequences within the Ravenscar Group, no part of it has been subjected to an integrated, multidisciplinary evaluation involving sedimentology, megaspore/micropalaeontological and palynological analyses of closely spaced samples in mudstone–siltstone intervals. The main aim of this paper is to show that such an approach provides a more accurate determination of brackish–freshwater sedimentation associated with delta-top development and flooding than has been established previously. New data obtained from two field sections at Yons Nab and Cloughton Wyke provide an integrated micro-biofacies model which is then applied to a cored section of similar age through part of the Broom and Ness formations in the Gullfaks Field, Viking Graben, northern North Sea.

Geological background

The Yons Nab (Cayton Bay) and Cloughton Wyke successions comprise a small part of the Jurassic rocks of the Cleveland Basin (see Knox *et al.* 1991; Rawson & Wright 1995, 2000; Powell 2010)

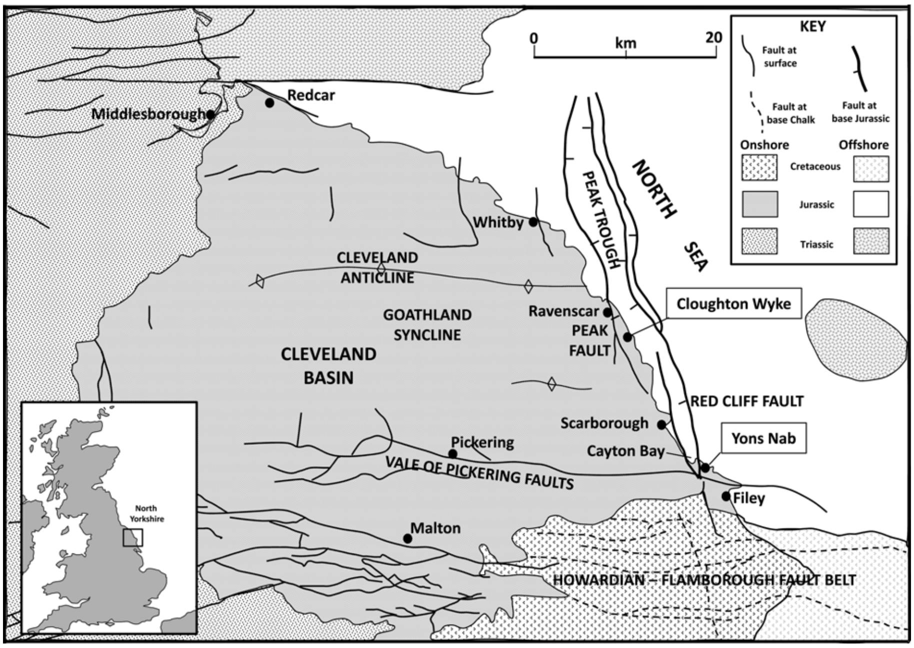

Fig. 1. Geological map of North Yorkshire and adjacent North Sea showing the main structural elements and the location of the sections studied (after Rawson & Wright 1995, modified).

that are exposed along the NE coast of England from north of Redcar to just south of Filey (Fig. 1). The sections examined form part of the Ravenscar Group and are mostly within the Gristhorpe Member of the Cloughton Formation (Fig. 2). The oldest samples are from the Yons Nab Beds, a basal quasi-marine part of the Gristhorpe Member considered by some authors to represent a 'regressive phase' of the Millepore Bed (Bate 1959; Hemingway 1974). For a time the beds were considered to belong to the Lebberston Member of the Cloughton Formation (Hemingway & Knox 1973; Livera & Leeder 1981) but more recently have again been regarded by some geologists (e.g. Rawson & Wright 1995, p. 181), though not all (e.g. Hesselbo & Jenkyns 1995, p. 145), as the basal part of the Gristhorpe Member.

The non-marine deposits of the Ravenscar Group were initially interpreted in terms of an estuarine series (Fox-Strangways 1892) but, by the 1920s, deltaic deposition was being invoked (e.g. Kendall & Wroot 1924; Black 1928, Wilson *et al.* 1934; Hemingway 1949). More recently the debate has been between deltaic and alluvial-plain deposition (e.g. Alexander 1989). Rawson & Wright (2000, p. 8) pointed out that the group shows features that are characteristic of both; nevertheless, the Cloughton Formation is considered to represent 'coal measures facies' with the Gristhorpe Member in the past being the main source of mined coal throughout the district (Rawson & Wright 1995, p. 181; Powell 2010). Associated crevasse-splay sandstones and rootlet beds show a marked thickening trend north from Yons Nab, implying the attainment of extensive delta-top conditions in the Cloughton Wyke area. Channel palaeocurrent data suggest sediment supply from a NE direction (Rawson & Wright 2000). The limited palynological analysis of the Cloughton Wyke section by Hancock & Fisher

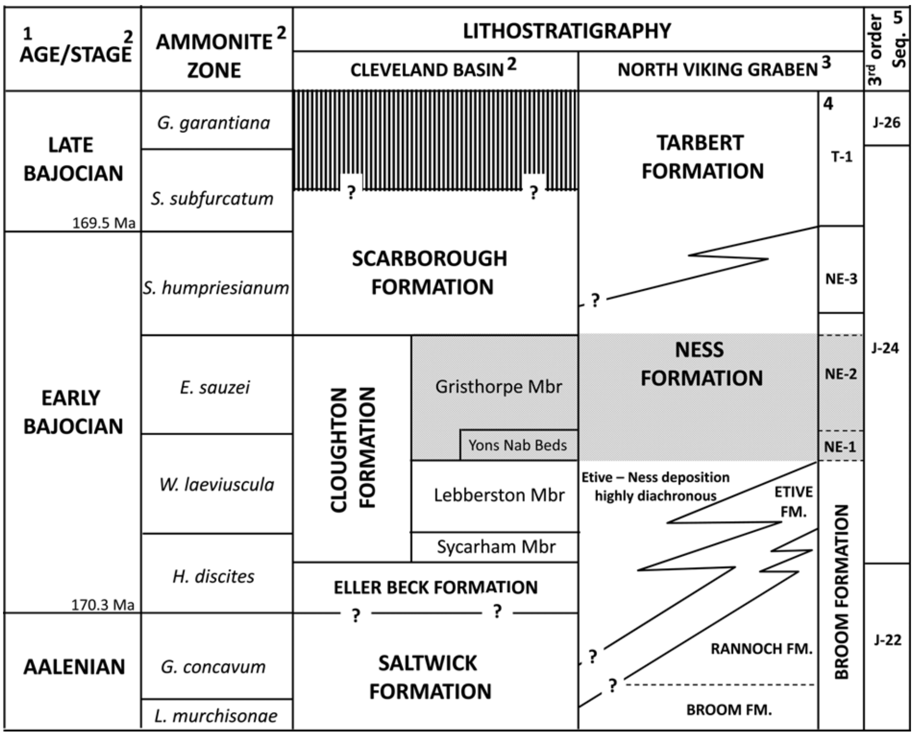

Fig. 2. Middle Jurassic chrono- and lithostratigraphy of North Yorkshire showing the current subdivision of the rocks that comprise the Ravenscar Group, the ammonite zonation and correlation with the litho- and sequence stratigraphy of formations encountered in the North Viking Graben in the northern North Sea. 1, after Gradstein *et al.* (2012); 2, after Hemingway & Knox (1973), Rawson & Wright (1995) and Powell (2010); 3, after Vollset & Doré (1984); 4, Statoil in-house lithostratigraphy (unpublished); 5, third-order sequence stratigraphy after Partington *et al.* (1993).

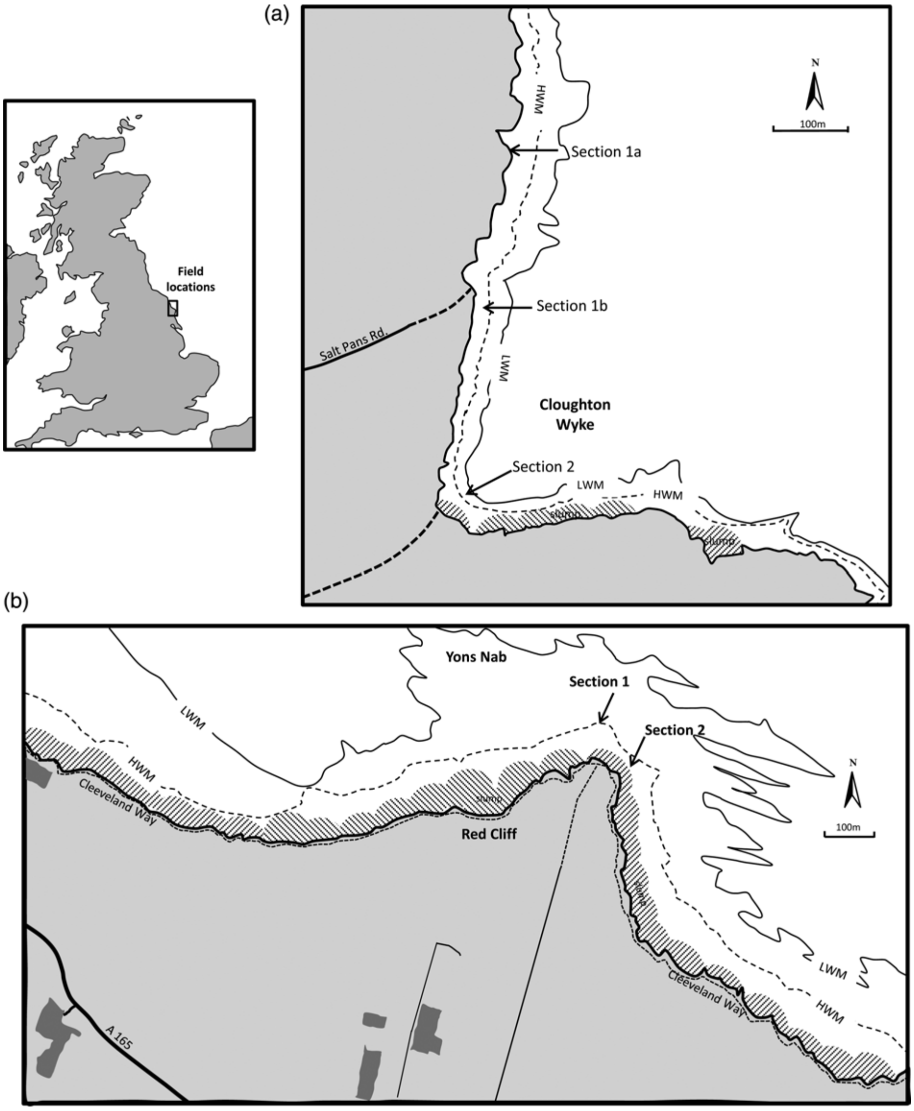

Fig. 3. Location of field sections sampled at (**a**) Cloughton Wyke and (**b**) Yons Nab, Cayton Bay.

(1981) indicates that thin brackish and saline infill occurs within the sequence. Based on previous field and analytical data, therefore, the Gristhorpe Member displays the characteristics of a delta-plain–interdistributary bay sequence close to sea-level.

Field sections analysed and methodology

Sampling

Locations of the field sections logged and sampled at Yons Nab in Cayton Bay and Cloughton Wyke are shown in Figure 3. At the northern tip of the Yons Nab headland the foreshore–lower cliff section exposes the transition of the Yons Nab Beds to the Gristhorpe Member *sensu stricto*: this part of the sequence (Section 1) was logged and sampled. A massive 1 m-thick sandstone forms a prominent ledge in the low cliff ('Upper crevasse-splay sandstone') here, above which a dark carbonaceous claystone marker horizon is developed. This horizon dips gently southeastwards and, at a point some 90 m SE of Section 1, crops out at the base of the cliff. At this location, Section 2, the mid–upper Gristhorpe Member was sampled. A composite sedimentary log for the whole of the Gristhorpe Member at Yons Nab showing sampling positions is presented in Figure 4.

The succession at Cloughton Wyke was logged and sampled at three main locations (Fig. 3a), which required traversing the basal cliff sections at low tide, from 500 m north of the wyke to the embayment further south (essentially following Rawson & Wright 2000, Itinerary 5). The southward dip of beds at this locality renders the Yons Nab/Gristhorpe Member succession accessible for logging and sampling, with the highest beds reached at Section 2. The composite sedimentary log for Cloughton Wyke showing sampling positions is provided in Figure 5.

Processing and analyses

All of the samples collected from the above locations were initially processed using standard volumetric micropalaeontological techniques, which have previously been successful for the extraction of megaspores as well as microfaunal components such as foraminifera and ostracods (see Morris *et al.* 2009). Processing involved firstly the immersion of 80 g of rock in 500 ml 10% w/v hydrogen peroxide solution and gentle 'simmering' on a hot-plate ensuring dissagregation of the matrix: any remaining aggregated material was dried and weighed, this amount being subtracted from the original 80 g total to provide an accurate computation of individual specimen counts per 100 g (see below). This was followed by washing through a 1 mm- and 63 µm-aperture sieve nest and subsequent drying of residues. These were then passed through a nest of standard micropalaeontological sieves and each fraction (1 mm, 500, 250, 125 and 63 µm) was subsequently picked under a stereo-microscope. During picking it became evident that plant debris of various types occurred in such large quantities that it was

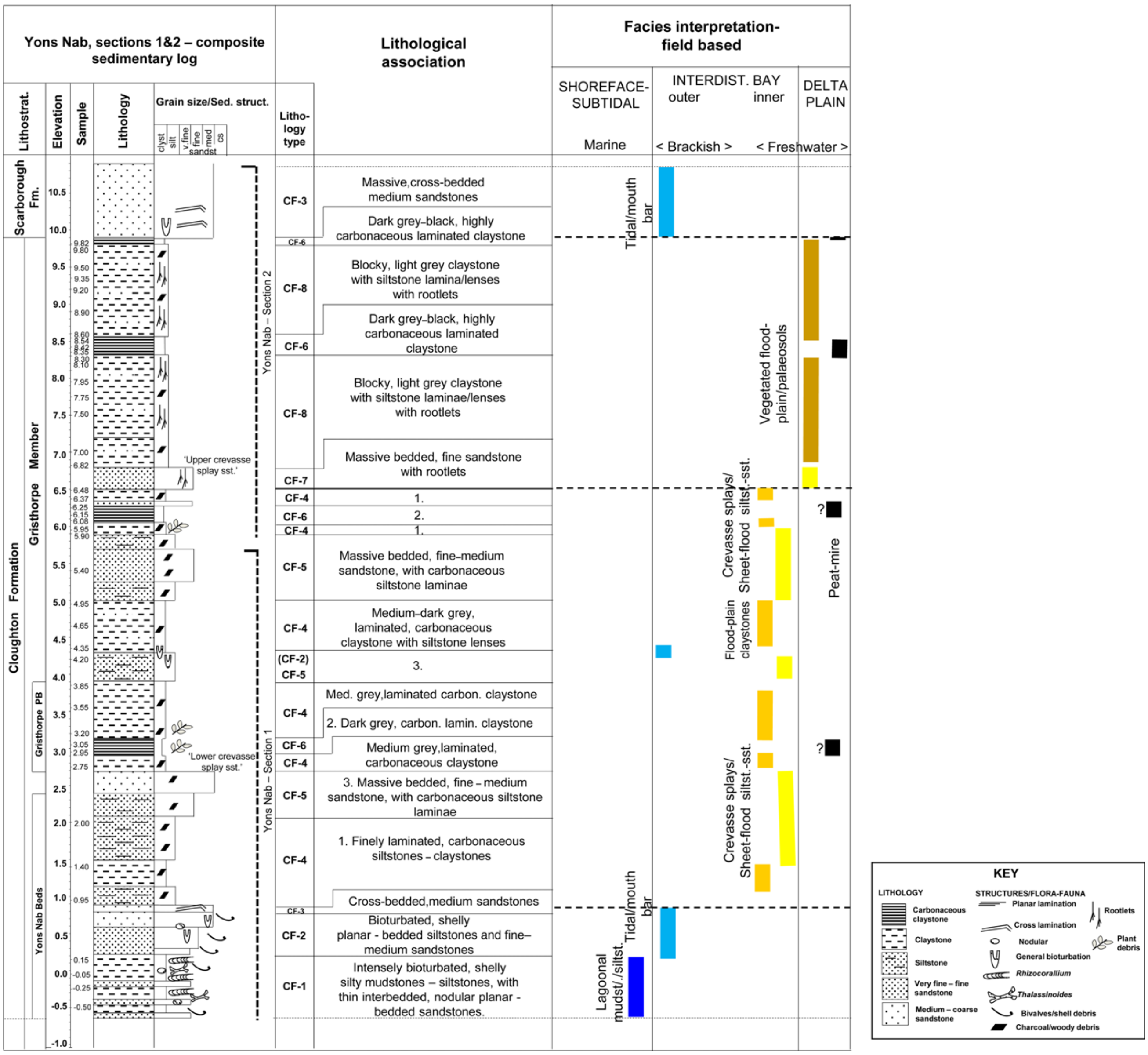

Fig. 4. Composite sedimentary log for Yons Nab showing lithological associations and field-based facies interpretation. PB, plant bed.

impractical to prepare counts for all of the sieved fractions. To gain a quantative assessment of these components the solution was to prepare counts for only the coarser 1 mm and 500 µm fractions. These, along with associated mesofossils (mainly megaspores) in the finer fractions, were normalized to 100 g for the purpose of generating volumetric distribution charts.

Analysis of picked samples involved quantative counts of megaspores and other mesofossils, and plant debris – with the last of these classified informally into two main groups: charcoalified and non-charcoalified. The latter group includes a wide variety of cuticle types, but the bulk occurring in the coarser sieve fractions comprises translucent structured components of stem and leaf tissues, cuticles commonly showing stomata, and nondescript membraneous and amorphous tissues. Other plant components identified include featureless membranous sacs, seed cuticles (some attributable to *Spermatites*) and the annuli of sporangia. Also recorded were nets referable to *Dictyothylakos* that are attributable to leech cocoons (Manum *et al.* 1991).

The majority of the samples from the two localities that were processed for the recovery of megaspores were also prepared for palynological analysis. This was accomplished using standard methods involving HCl and HF, as described previously by Batten & Morrison (1983) and Batten (1999). Selected samples were also processed for megaspores using a procedure different from that described above. This involved initial soaking of rock fragments in flasks of warm water on a hot plate followed by further immersion in warm *c.* 5% $Na_4P_2O_7$ and washing on a sieve with a mesh size of 85 µm, both treatments being repeated as many times as necessary to reduce the bulk of the sample before subjecting the residue to acid digestion in HCl and HF as for the palynological preparations.

The palynofacies data were recorded in two ways. Firstly, in order to obtain a record of the most numerically important of the miospores recovered, 200 specimens were counted from all of the preparations apart from those that proved to be barren or yielded only a few palynomorphs. Secondly, the occurrence of associated plant debris and components other than small spores and pollen grains (i.e. megaspores and fragments thereof, dinoflagellate cysts, acritarchs, non-marine algae including *Botryococcus*, prasinophyte algae, phytoclasts, zooclasts and amorphous organic matter) was recorded using a five-point scale of relative abundance as follows: 1, trace; 2, present; 3, common, 4, very common; 5, abundant (cf. Batten 1973; Kovach & Batten 1994). As on previous occasions when used, this scale was tested several times by counting against 200 palynomorphs in a sample preparation.

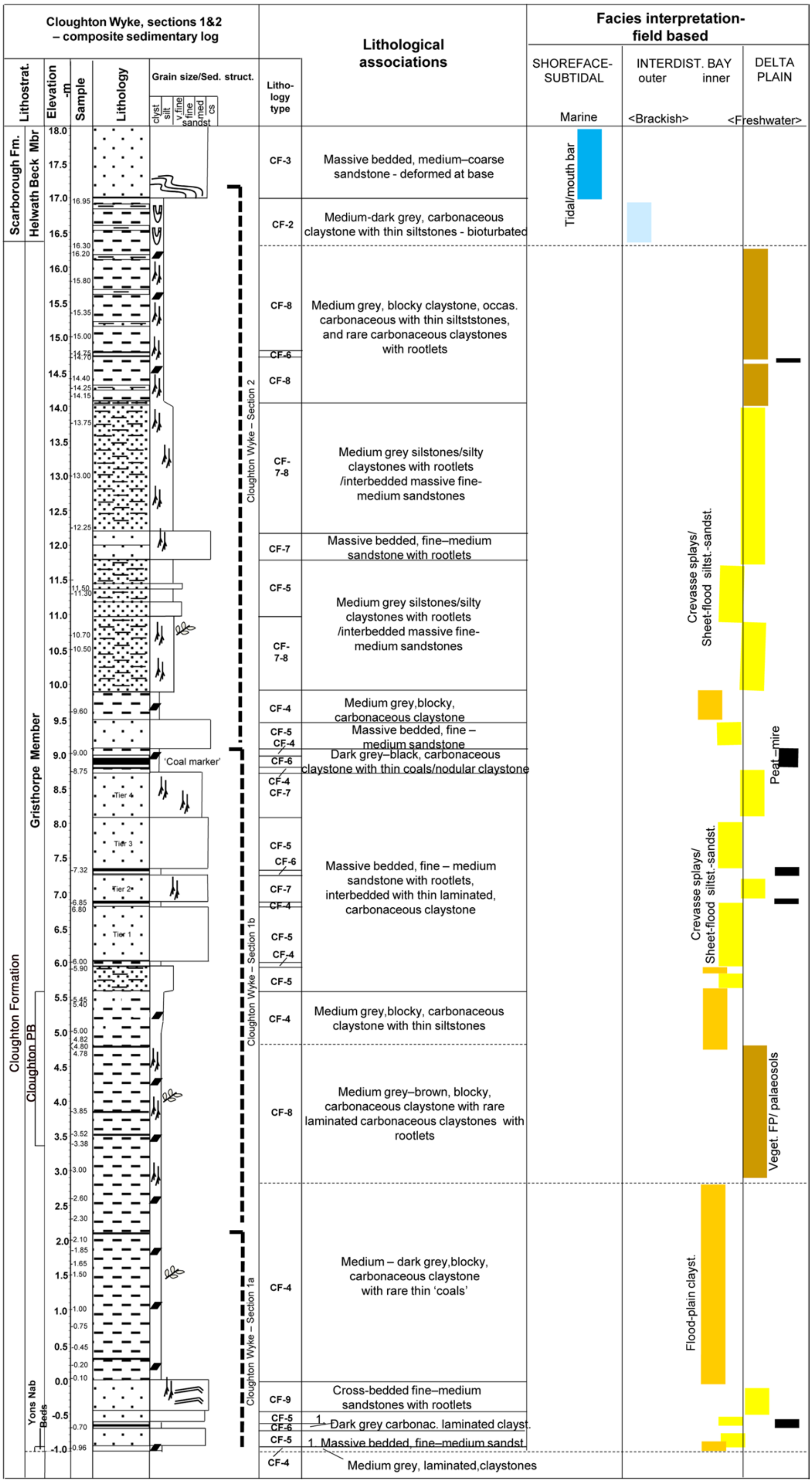

Fig. 5. Composite sedimentary log for Cloughton Wyke showing lithological associations and field-based facies interpretation. For key to lithologies, structures and other symbols, see Figure 4. Veget. FP, vegetated floodplain.

The miospore preparations, together with the micropalaeontological slides, are currently housed in the Aberystwyth University palynological and mesofossil slide collections (catalogue numbers prefixed by QPR and MFP respectively).

Sedimentology

The sedimentological evaluation of the sections studied is based primarily on field observations, which are compared with those of previous workers, notably Hancock & Fisher (1981), Rawson & Wright (1995, 2000) and van Konijnenburg-van Cittert & Morgans (1999). In all of these studies, however, sedimentology logs for the Gristhorpe Member are generalized with little in the way of detailed lithological description. The analysis of the Yons Nab Beds and Gristhorpe Beds of the Gristhorpe Member at Cloughton Wyke by Hancock & Fisher (1981) integrates field observations with palynofacies/palynomorph distributions, providing the most detailed dataset for comparison with our records. In their study, however, the definition of saline intervals relied heavily on the proportion of marine microplankton (dinoflagellate cysts and acritarchs) compared to terrestrially derived spores and pollen grains, whereas our data show that marine elements are always rare, if present at all, the palynomorph assemblages being dominated by spores and pollen in the samples examined (see below).

Yons Nab sedimentary sequence

The composite field log for Yons Nab showing the main lithological associations and sampling horizons (Fig. 4) also includes our facies interpretations. Eight lithological associations (CF, Cloughton Formation) can be defined at this location using field criteria, which can be rationalized into three main facies groups.

(1) Shoreface–subtidal facies, comprising CF-1–3 lithological associations. Shallow-marine indicators clearly evident including the presence of disarticulated bivalve debris, nodules and intense bioturbation, including *Thalassinoides* and *Rhizocorallium*. Specific environments indicated range from lagoons to tidal/mouth bars.

(2) Interdistributary bay facies, CF-4–6 lithological associations. Increased carbonaceous (plant) content in claystones; marine indicators absent apart from limited bioturbation. Environments are interpreted to range from crevasse splay to floodplain. The occurrence of peat-mire deposition based on the characters of CF-6 is questionable.

(3) Delta plain facies, CF-6–8 lithological associations. Predominant claystone sequence with abundant rootlets, including those of *Equisetites*, interpreted to indicate vegetated floodplain/palaeosols: CF-6 indicates probable peat-mire deposition.

The above field interpretation broadly concurs with that of van Konijnenburg-van Cittert & Morgans (1999), who interpreted the transition from the Lebberston Member to the Gristhorpe Member as representing a depositional shift from a fully marine emergent bar to a freshwater floodplain. However, these authors defined a delta-front environment equivalent to the Yons Nab Beds with partly marine characteristics, whereas Rawson & Wright (1995) regarded this unit as 'scarcely marine' and, therefore, better incorporated in the overlying Gristhorpe Member, as noted previously. The absence of clear delta-front progradation was also noted by Hancock & Fisher (1981): both observations are consistent with our field logs, which suggest a transition within the Yons Nab Beds from outer to inner bay-fill. Within the Gristhorpe Member distinguishing bay-fill from delta-top deposition is clearly problematic using field criteria. However, the presence of abundant rootlets throughout the upper section attests to an extended period of partial emergence, which is consistent with the attainment of delta-top conditions.

Cloughton Wyke sedimentary sequence

In common with Figure 4, the composite field log for Cloughton Wyke, showing the main lithological associations and sampling horizons (Fig. 5), also includes our facies interpretations. At this locality lithological associations CF-2 to CF-8, defined at Yons Nab, are also recognized: CF-1, representing marine beds of the Yons Nab Beds, was not sampled because these deposits were inaccessible. An additional lithological association, CF-9, is defined near the base of sequence, this being a cross-bedded fine–medium sandstone with rootlets. Based on field data two main facies groups are defined.

(1) Interdistributary bay facies, CF-4–6 lithological associations with the absence of rootlets. Environments interpreted range from crevasse splay to floodplain. Again the peat-mire deposition based on the characters of CF-6 is questionable within this association.

(2) Delta plain, CF-6–9 lithological associations. A claystone sequence associated with thick crevasse-splay sandstones showing abundant rootlets, interpreted as vegetated floodplain/palaeosols: CF-6 indicates probable peat-mire deposition as at Yons Nab.

The Gristhorpe Member at Cloughton Wyke displays a predominance of delta-plain and inner bay-fill facies associated with a marked thickening of the unit. Evidence for saline (brackish) incursions is lacking, with a high proportion of the thick, crevasse-splay sandstones showing rootlets, indicating deposition closer to distribution channels with partial emergence and plant colonization.

Our facies interpretation compares broadly with that of Hancock & Fisher (1981). However, based on palynological evidence these authors recognized a saline bay-infill sequence some 3 m thick immediately below the massive, tiered sandstone unit.

The sedimentary sequences of the Gristhorpe Member examined at both localities suggest that bay-fill and delta-plain depositional environments predominated. Claystone types, notably those of CF-4 and CF-6, are difficult to assign within these settings without additional analytical data. CF-8 constitutes a high proportion of the sedimentary sequence and is characterized by containing numerous rootlets, but it can only be broadly assigned to a vegetated floodplain in a more proximal, questionably upper delta-plain setting.

Megaspore and plant debris distribution at Yons Nab and Cloughton Wyke

Yons Nab

The results of the micropalaeontological analysis are plotted in Figure 6. In addition to megaspore species and plant debris, agglutinated foraminifera and ostracods are also represented in a few samples, notably from the Yons Nab Beds and in the topmost carbonaceous claystone underlying the Scarborough Formation.

Micro-biofacies types (numbered MB-1 etc.) are shown in the right-hand column. They are assigned on the basis of species composition, abundance levels and diversity, and linked to the presence of cuticles, abundance of charcoal and other types of plant debris. The main component species of megaspores identified in the Gristhorpe Member are illustrated in Figure 7.

Microfaunas occurring in the Yons Nab Beds consist of the ostracods *Pneumatocythere bajociana* and *Praeschuleridea subtrigona*, and agglutinated foraminifera, notably *Ammodiscus yonsnabensis*, which is consistent with previous analyses of the same section by Bate (1959, 1967) and Nagy *et al.* (1983). A reduction in ostracods/calcareous benthics coupled with an increase in *Ammodiscus* through the Yons Nab Beds, represented by MB-7 and MB-8 micro-biofacies, was also documented by Nagy *et al.* (1983). This microfaunal trend, with the increasing predominance

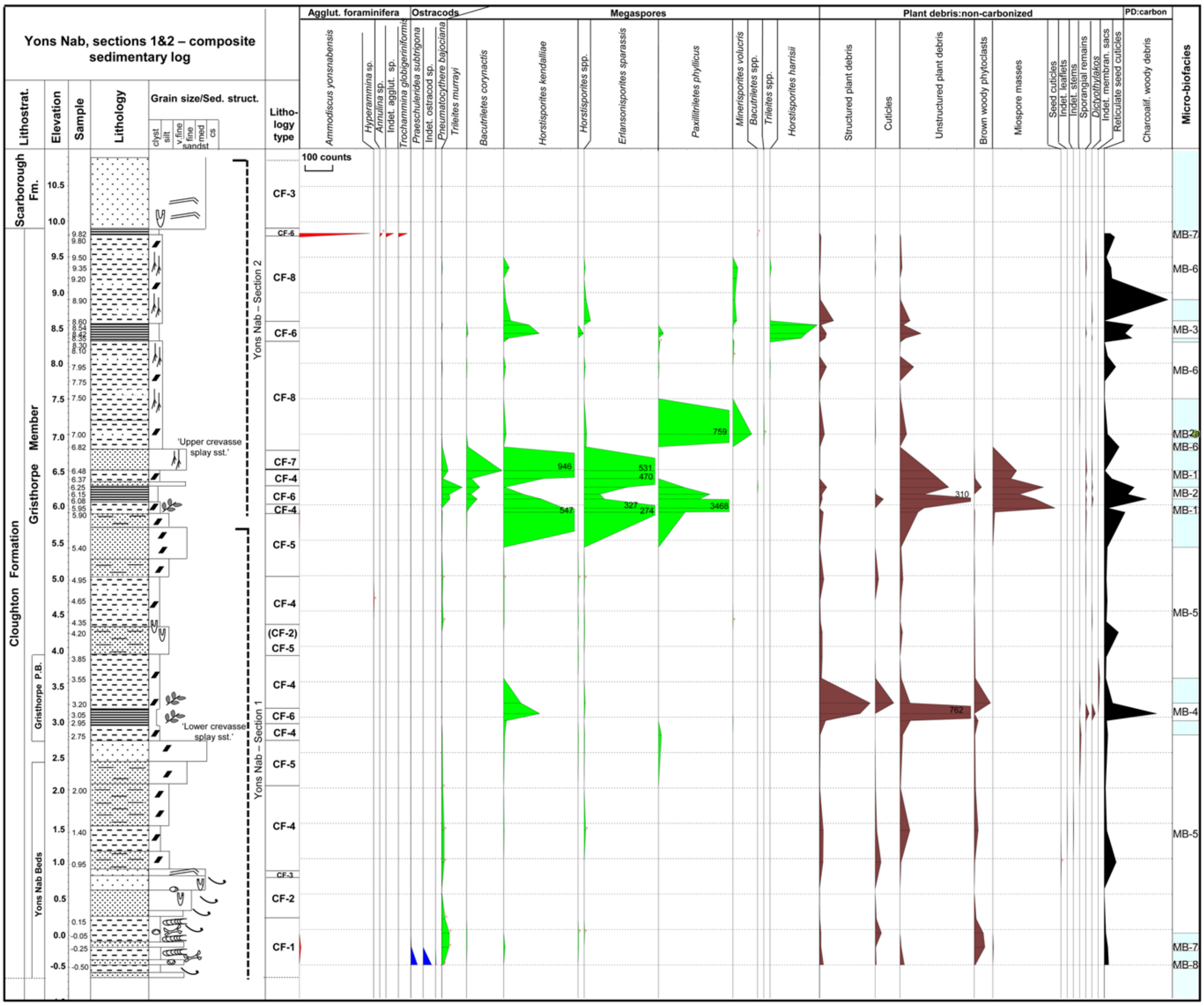

Fig. 6. Micropalaeontological distribution chart and micro-biofacies for the Yons Nab section. For key to lithologies, structures and other symbols, see Figure 4.

of *Ammodiscus yonsnabensis*, is also seen in the transition between the Drake and Rannoch formations in the northern North Sea where it is used to define the changeover from deposition in normal salinities (prodeltaic) to hyposaline (delta-front/interdistributary bay: Nagy & Johansen 1991; Nagy 1992). The similar trend at Yons Nab is interpreted as evidence of the transition from marine- to brackish-bay conditions through the unit. Of note is the reappearance of *Ammodiscus yonsnabensis*, attaining super-abundant levels at the top of the Gristhorpe Member, suggesting a return to brackish-bay conditions. This has not been documented before (see below).

The transition from the Yons Nab Beds to the Gristhorpe Member *sensu stricto* is marked by the changeover to exclusively megaspore- and plant debris-dominated assemblages, assigned to micro-biofacies MB-1 to MB-6 (Fig. 6). Carbonaceous claystones CF-6 and adjacent claystones CF-4 yielded the largest assemblages of megaspores. Associated are high levels of plant debris, both carbonized and non-carbonized. Remarkable, however, is the interval from 5.90 to 6.48 m which displays the greatest megaspore abundances (>1000 specimens/100 g) and diversity, these parameters varying across the claystone sequence between crevasse splay sandstones. Two species of megaspore predominate overall: *Horstisporites kendalliae* and *Erlansonisporites sparassis*, with the small species *Paxillitriletes phyllicus* locally super-abundant. The plant debris profile through this section is also different in displaying the highest numbers of miospore masses. Detailed analysis provides the basis for recognition of a key micro-biofacies type, namely MB-1, with MB-2 intimately associated (Fig. 6). These biofacies represent freshwater deposition within a peat-mire environment, with high groundwater levels suiting plant communities of limited diversity. The absence of rootlets suggests that conditions were not suitable for *Equisetites* or other plants with penetrative root systems. The large numbers of megaspores and the plant debris profile, in particular the abundance of miospore masses, suggest that deposition occurred close to the parent plants, these consisting of both lycopsids and ferns. The absence of discernible remains of lycopsids may be attributable to their poor preservation potential (see Kovach & Batten 1993): nevertheless it is tempting to hypothesize that micro-biofacies MB-1 was developed within lycopsid communities, an interpretation that is supported by palynological evidence (see below).

Two other megaspore events are associated with carbonaceous claystones. These differ in terms of abundance, composition and the plant debris profiles (Fig. 6). The lower CF-6 claystone yields an almost monotypic assemblage of *Horstisporites kendalliae* and abundant cuticles: this horizon, which is associated with the Gristhorpe Plant Bed and an absence of *Equisetites* rootlets, is assigned to micro-biofacies MB-4. The upper CF-6 claystone is within the rooted sequence and referred to micro-biofacies MB-3. It

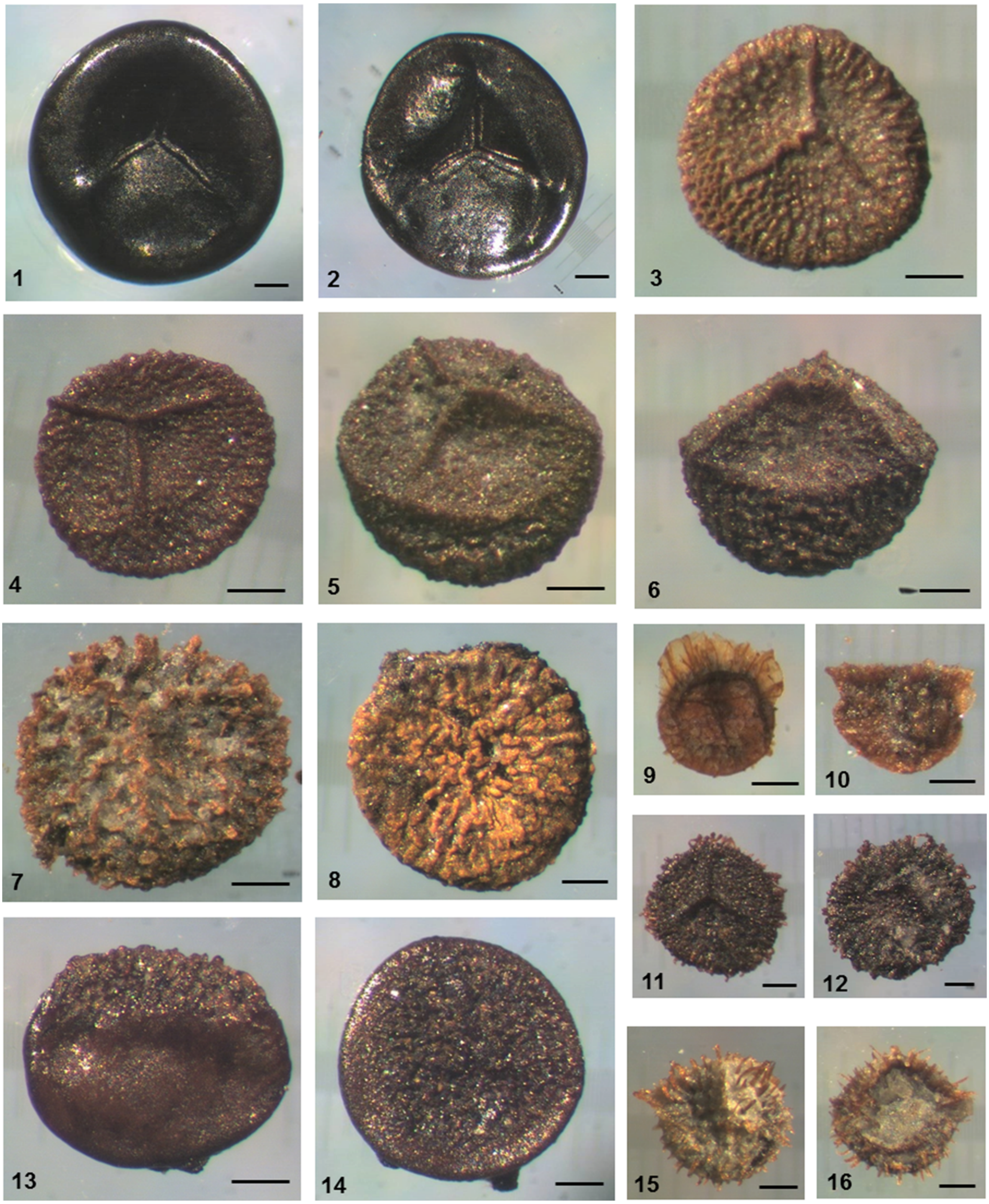

Fig. 7. Representative examples of the numerically more important or otherwise significant megaspores recovered from the Gristhorpe Member, Yons Nab and Cloughton Wyke, and North Sea well 34/10-B-12. Accompanying data are sampling levels at Cloughton Wyke (CW), Yons Nab (YN) and North Sea well 34/10-B-12 (NSW). None has been subjected to HF treatment so several have varying quantities of mineral matter (mainly quartz) attached. Scale bar represents 100 µm. **1, 2,** *Trileites murrayi* (Harris) Marcinkiewicz, CW –0.96 m; proximally compressed specimens. **3, 4,** *Horstisporites kendalliae* (Harris) Kempf; compressed specimens: 3, proximal, NSW 2847.20 m and 4, oblique proximal view, YN 3.2 m. **5, 6,** *Horstisporites harrisii* (Murray) Potonié; oblique proximal and lateral views, YN 8.3 m. **7, 8,** *Erlansonisporites sparassis* (Murray) Potonié: 7, oblique proximal view of specimen with quartz grains attached, YN 6.37 m and 8, proximal view of abraded specimen, NSW 2847.10 m. **9, 10,** *Paxillitriletes phyllicus* (Murray) Hall & Nicolson; lateral view of wetted specimen and oblique proximal view respectively, YN 5.95 m. **11, 12,** *Bacutriletes corynactis* (Harris) Marcinkiewicz: 11, proximal view of partly abraded specimen, YN 6.08 m; 12, proximal view with attached quartz, YN 6.25 m. **13, 14,** *Hughesisporites* sp. cf. *H. variabilis* Dettmann; compressed lateral and proximal views respectively, NSW 2793.56 m. **15, 16,** *Minerisporites volucris* Marcinkiewicz; oblique lateral views, with quartz attached, YN 8.60 m.

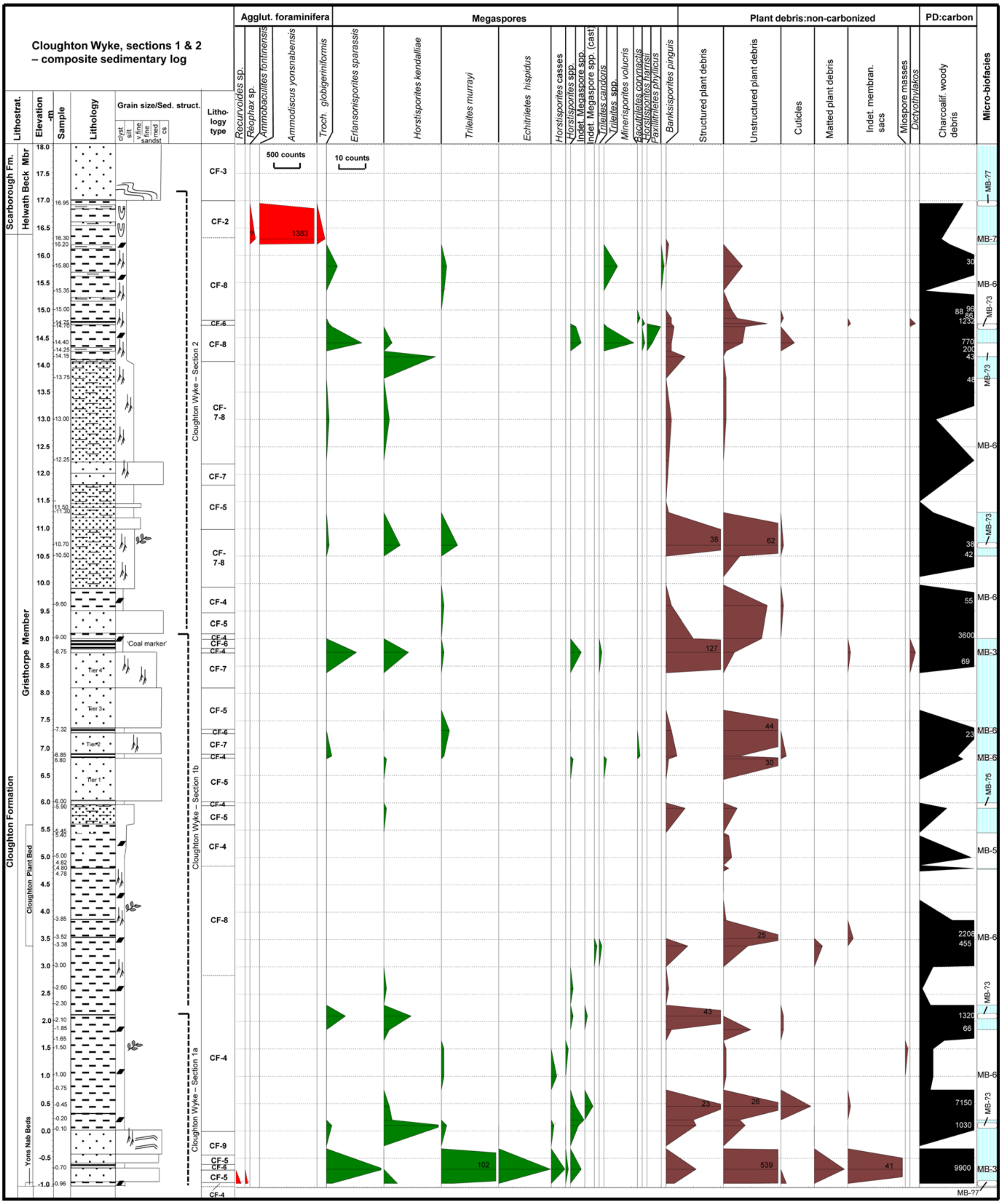

Fig. 8. Micropalaeontological distribution chart and micro-biofacies for Cloughton Wyke section. PD: carbon = plant debris, carbonized. For key to lithologies, structures and other symbols, see Figure 4.

yields abundant megaspores dominated by *Horstisporites kendalliae* and *H. harrisii.* The associated plant debris is similar in composition to that of the intervening claystones.

An additional megaspore influx occurs at 7.00 m, below the base of the rooted sequence. This assemblage differs from the others in being dominated by super-abundant *Paxillitriletes phyllicus* with numerous *Minerisporites volucris* in association (Fig. 6): unlike the underlying MB-2 micro-biofacies, it contains low numbers of *Horstisporites kendalliae* and *Erlansonisporites sparassis*. Nevertheless, since *Paxillitriletes phyllicus* also reaches super-abundant levels in MB-2, this megaspore association is assigned to MB-2a. The above profiles suggest that generically MB-1–4 are closely linked, indicating freshwater deposition in a peat-mire environment.

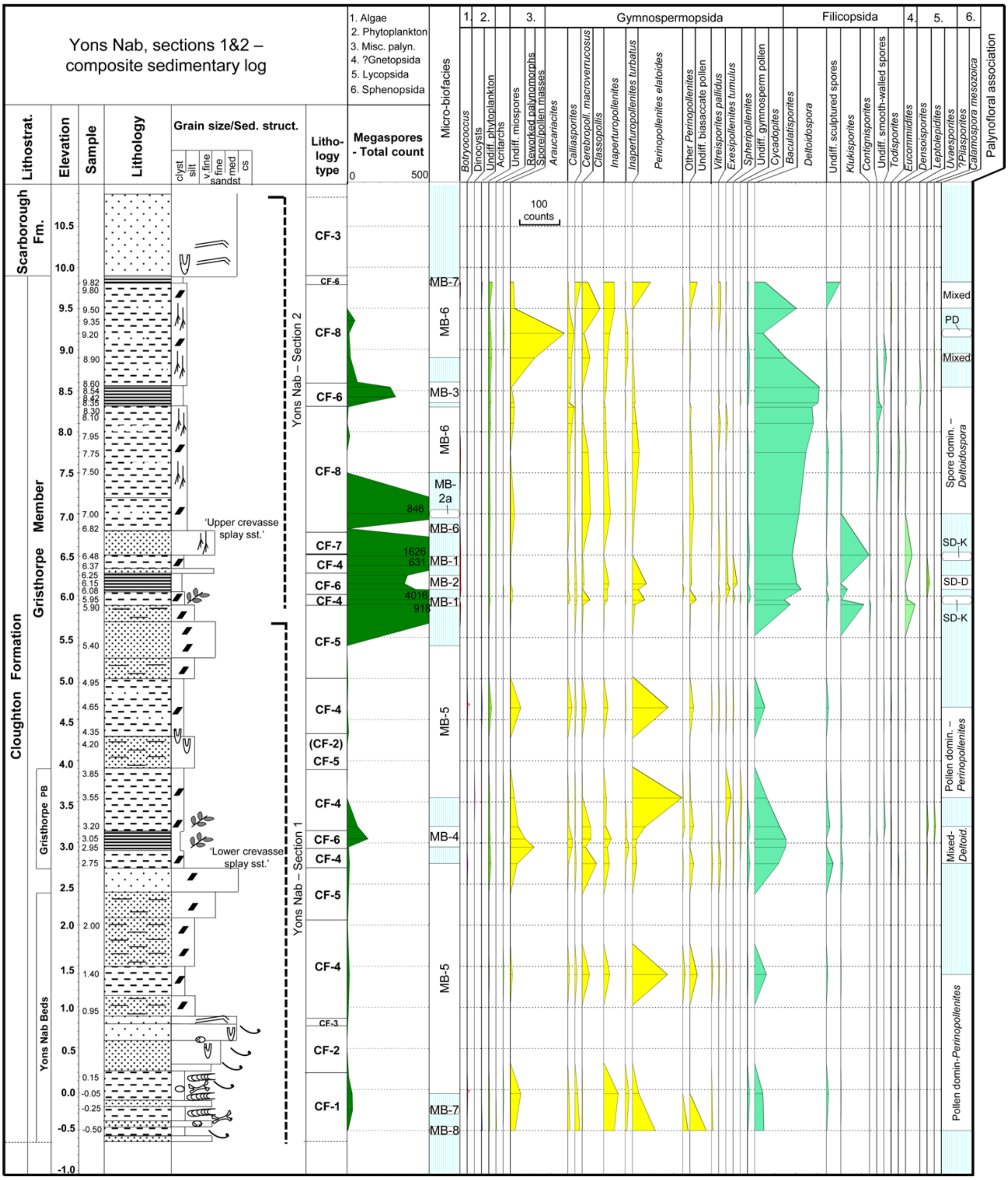

Fig. 9. Total megaspore count, micro-biofacies, palynomorph distributions and palynofloral associations for the Yons Nab section. For key to lithologies, structures and other symbols, see Figure 4. PD, Pollen dominated; SD, Spore dominated; SD-K, Spore dominated – *Klukisporites*; SD-D, Spore-dominated – *Deltoidospora*.

Cloughton Wyke

The results of the micropalaeontological analysis of the Cloughton Wyke succession are plotted in Figure 8 (note that the count scale is increased by ×10 compared to that of Yons Nab). As previously noted, sampling of the lower Yons Nab Beds was not undertaken; however, transitional micro-biofacies represented by MB-7 are tentatively indicated in the lowest sample analysed based on the presence of agglutinated foraminifera. Above this, as at Yons Nab, the transition to the Gristhorpe Member *sensu stricto* is characterized by an increase in megaspore and plant-debris content. Overall, however, the organic matter recovered is dominated by charcoalified detritus with megaspore counts generally low. Peaks, where they occur, correspond to CF-6-type carbonaceous claystones and associated deposits, with the sample at −0.70 m producing the largest assemblage of megaspores. This shows some affinities with those of the Yons Nab Beds at Yons Nab with common specimens of *Trileites murrayi*. Although *Echitriletes hispidus* and *Horstisporites casses* were not recorded at this locality, in overall profile the assemblage has the characteristics of MB-3 micro-biofacies, indicating freshwater, peat-mire deposition.

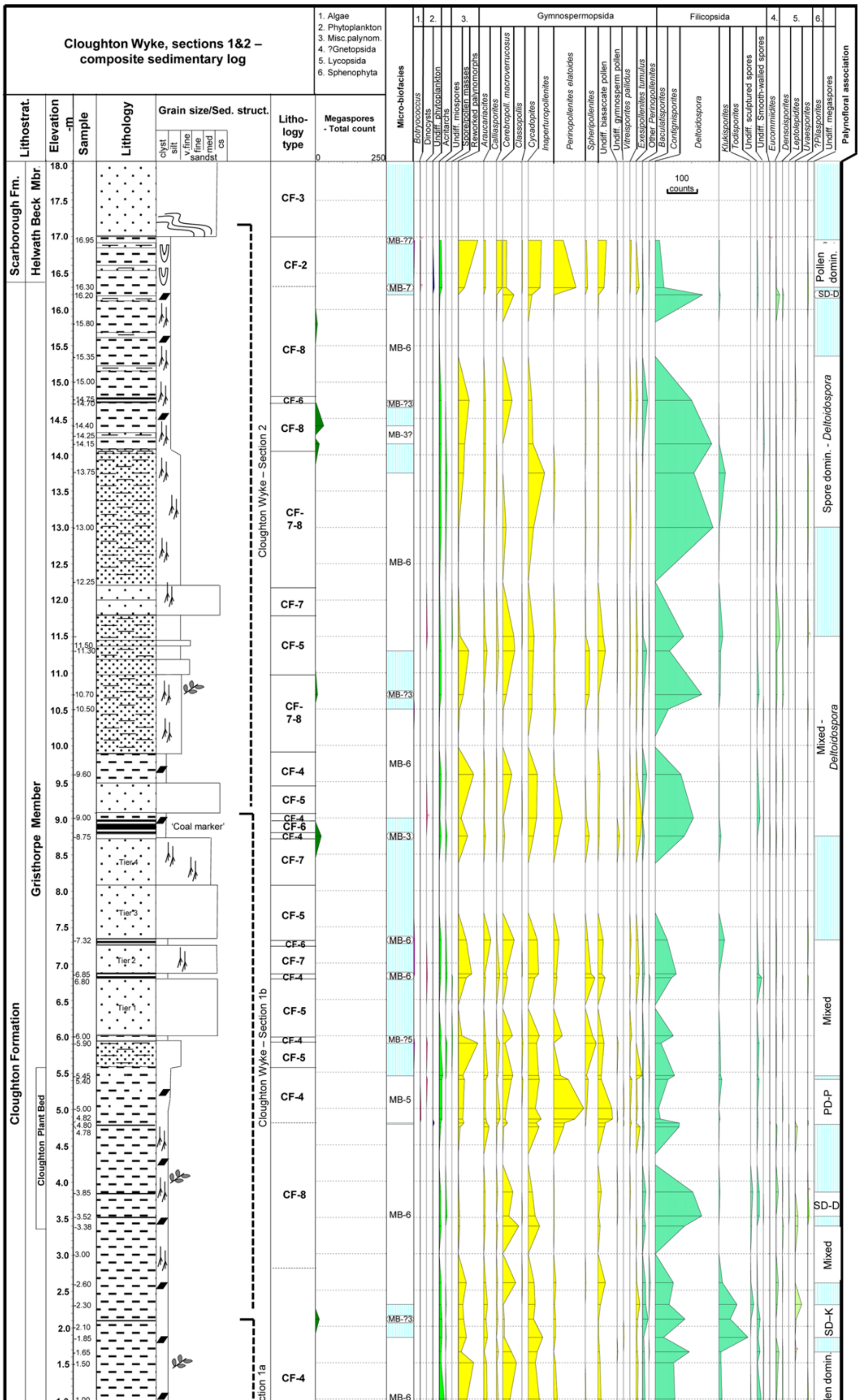

Fig. 10. Total megaspore count, micro-biofacies, palynomorph distributions and palynofloral associations for the Cloughton Wyke section. For key to lithologies, structures and other symbols, see Figure 4. PD-P, Pollen dominated – *Perinopollenites*; SD-D, Spore-dominated – *Deltoidospora*; SD-K, Spore dominated – *Klukisporites*.

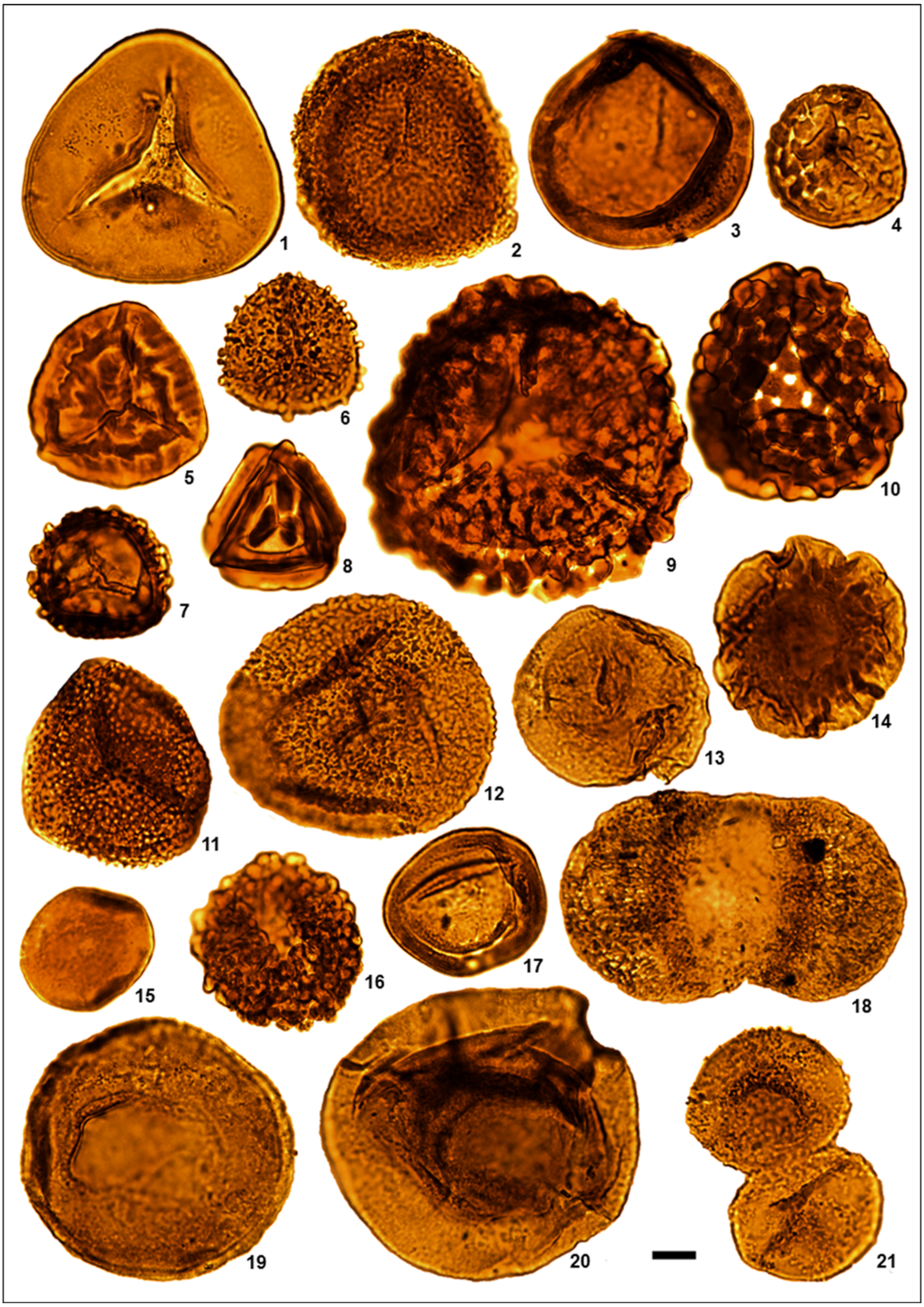

Fig. 11. Selected examples of the miospore components of the palynofacies associated with the Gristhorpe Member including three less common forms that form part of the background palynoflora, indicated by an asterisk (*). Accompanying data are palynological preparation and slide numbers prefixed by QPR, sampling levels at Cloughton Wyke (CW), Yons Nab (YN) and North Sea well 34/10-B-12 (NSW), and England Finder references. Scale bar represents 10 µm. **1,** *Deltoidospora* sp., 3495.2, CW 5.9 m, K38/2. **2,** *Densoisporites velatus* Weyland & Krieger, 3505.2, CW 11.5 m, R45/1. **3,** *Todisporites major* Couper, 3571.2, CW 3.38 m, S47/2. **4,** *Stereisporites* sp. cf. *Sculptisporis aulosenensis* (Schulz) Koppelhus*, 3651.3, NSW 2966.84, V45/1. **5,** *Coronatispora valdensis* Couper*, 3577.2, CW 5.45 m, S35/1. **6,** *Neoraistrickia* sp. cf. *N. gristhorpensis* (Couper) Tralau*, 3651.3, NSW 2966.84, T44/0. **7,** *Leptolepidites equatibossus* (Couper) Tralau, 3520.4, YN 6.48 m, J55/4. **8,** *Striatella* sp. (records combined with those of *Contignisporites* on Figs 9, 10 and 17), 3568.2, CW 2.3 m, J54/0. **9,** *Uvaesporites argentineaformis* (Bolkhovitina) Schulz, 3619.2, YN 8.35 m, N34/2. **10,** *Klukisporites variegatus* Couper, 3568.2, CW 2.3 m, O51/0. **11,** *Sestrosporites pseudoalveolatus* (Couper) Dettmann*, 3616.2, YN 7.75 m, K28/2. **12,** *Osmundacidites wellmanii* Couper (records combined with those of *Baculatisporites* on Figs 9, 10 and 17), 3561.2, CW4, J45/3. **13,** *Perinopollenites elatoides* Couper, 3611.2, YN 3.55 m, F39/1. **14,** *Callialasporites dampieri* (Balme) Sukh Dev, 3566.2, CW 1.85 m, T40/1. **15,** *Exesipollenites tumulus* Balme, 3563.2, CW 1.0 m, V25/1. **16,** *Cerebropollenites macroverrucosus* (Thiergart) Schulz, 3565.2, CW –0.7 m, V17/2. **17,** *Classopollis torosus* (Reissinger) Couper, 3563.2, CW 1.0 m, S24/0. **18,** bisaccate group (*Alisporites*), 3651.3, NSW 2966.84, Q45/3. **19,** *Araucariacites australis* Cookson, 3495.2, CW 5.9 m, K39/0. **20,** *Inaperturopollenites turbatus* Balme (this species is also referred to *Araucariacites* and *Callialasporites* in the literature), 3495.2, CW5.9 m, J29/2. **21,** *Spheripollenites* sp., 3495.2, CW5.9 m, M31/1.

Claystones associated with the 'Coal marker' also show increased megaspore yields with *Erlansonisporites sparassis* and *Horstisporites kendalliae* dominant: again this assemblage is consistent with the characters of the MB-3 micro-biofacies. Other, less pronounced peaks in megaspore yields (e.g. at 2.10 m) are tentatively assigned to MB-3 micro-biofacies, the high fusain levels by comparison with Yons Nab perhaps having led to the 'dilution' of megaspore yields (see below). MB-1 and MB-2 micro-biofacies appear to be absent at Cloughton Wyke. The higher levels of charcoalified woody debris recorded indicate proximity to wildfire events similar to those described for the Bagå peat-mires of Bornholm (Nielsen *et al.* 2010).

The incoming of super-abundant *Ammodiscus yonsnabensis* in the uppermost Gristhorpe Member correlates with the same event at Yons Nab, marking the transition to brackish, bay-fill deposition and the occurrence of micro-biofacies MB-7.

The spatial interrelationships and inferred environments of microfacies defined at Yons Nab and Cloughton Wyke are further evaluated in the following sections on the associated palynofacies.

Palynofacies

The distribution of key palynomorph taxa, including indicators of marine influence, are presented in Figures 9, 10 and 17. Plant debris records are omitted from these plots because of lack of space, and are anyway included in the mesofossil plots (Figs 6, 8 and 16). A key feature of the palynofloras occurring in the Gristhorpe Member is the extremely high proportion of small pteridophyte spores and gymnosperm pollen so that specimen counts of 200 frequently excluded key palaeoenvironmental indicators, such as acritarchs, dinoflagellate cysts and freshwater algae (mainly *Botryoccus*). Such groups, where detected, are plotted as 'present' so that their palaeoenvironmental significance can be evaluated.

Selected examples of numerically significant palynofloral components associated with the Gristhorpe Member are illustrated in Figure 11.

Yons Nab

The results of the palynological analysis are plotted in Figure 9 alongside the total megaspore count and the micro-biofacies categories, previously defined. The Yons Nab succession contains a higher percentage of well-preserved specimens compared to Cloughton Wyke: consequently (as with the megaspores) this section is used for reference purposes.

Based on the gross taxonomic affinities of palynomorphs and their relative abundances, three main Palynofloral Associations (PAs) are recognized in the Yons Nab sequence: Spore-dominated, Pollen-dominated and Mixed (all of the pollen grains have gymnospermous origins: Table 1). Within these categories particular taxa often predominate: these provide a basis for defining sub-categories, as shown in Figure 9.

In the lower section (−0.5 to 4.65 m), including the transitional lithofacies of the Yons Nab Beds, Pollen-dominated PAs are characteristic with *Perinopollenites elatoides* especially numerous (Fig. 9). This abundance of *P. elatoides* suggests the presence of a lowland cupressaceous (taxodiaceous) swamp forest in the vicinity (Table 1). Increases in numbers of filicopsid spores, notably *Deltoidospora* and *Klukisporites*, correlate with higher megaspore counts, especially above the 'Lower crevasse splay sandstone'. Evidence for marine influence/brackish conditions, indicated in the microfaunas (MB7, 8) and lithologies (CF1–3), is very limited, with prasinophyte algae, *Micrhystridium*, and/or questionable (poorly preserved) dinocysts recorded at −0.05, −0.50, 2.75, 3.55 and 4.65 m.

A marked shift in palynomorph composition is seen from 5.90 m in interbedded claystones associated with the 'Upper crevasse splay sandstones'. Here Spore-dominated replace Pollen-dominated PAs, with *Deltoidospora* becoming consistently abundant. Other small spores, notably *Klukisporites* and *Leptolepidites*, are also more numerous, abundances showing a positive correlation with the total megaspore count (Fig. 9): in addition, *Botryococcus* is consistently 'present' through this interval. This palynofloral association,

Table 1. *The spore and pollen (miospore) taxa recorded on Figures 9, 10 and 17 are classified according to families, orders and higher taxa from which they are thought to be derived*

Bryophyta
Undifferentiated sculptured spores in part
Lycopsida
Densoisporites
Leptolepidites
Uvaesporites
Sphenopsida
Equisetales
Calamospora mesozoica
?Pilasporites
Filicopsida
Baculatisporites/Osmundacidites
Contignisporites/Striatella
Deltoidospora
Klukisporites
Todisporites
Undifferentiated sculptured spores in part
Undifferentiated smooth-walled spores in part
?Gnetopsida
Eucommiidites
Pteridospermopsida
Undifferentiated bisaccate pollen in part
Caytoniales
Vitreisporites pallidus
Gymnospermopsida
Inaperturopollenites
Undifferentiated gymnosperm pollen
Cycadales, Bennettitales, Ginkgoales
Cycadopites
Coniferales
Undifferentiated bisaccate pollen in part
Podocarpaceae
Undifferentiated bisaccate pollen in part
Araucariaceae
Araucariacites
Callialasporites
Inaperturopollenites turbatus (see note to caption of Fig. 11.20)
Pinaceae
Cerebropollenites macroverrucosus
Undifferentiated bisaccate pollen in part
Cupressaceae (Taxodiaceae)
Exesipollenites tumulus
Perinopollenites elatoides
Other *Perinopollenites* species
Spheripollenites
Cheirolepidiaceae
Classopollis

The inferred relationships, some of which are more reliable than others, are based on the work of numerous authors including those cited by Nielsen *et al.* (2010, table 3). Specimens questionably identified as *Pilasporites* may be the spores of *Equisetites* (cf. Batten 1968). For convenience *Eucommiidites* is listed under questionable Gnetopsida. Many of the taxa that were only intermittently encountered during counts of 200 miospores per preparation belong to a variety of genera and species that make up the general 'background palynoflora' of the rock units examined. Since they are of little significance in the context of the aims of this paper they have been included in the several undifferentiated groups noted above.

together with the presence of megaspores, strongly suggests freshwater, peat-mire conditions with the source of the spores being ferns and lycopsids fringing and inhabiting the mire.

A reduction in small spores/*Deltoidospora* is evident in the upper Gristhorpe Member from 8.90 m, with Mixed or Pollen-dominated PAs characteristic. The assemblage from the uppermost sample at 9.82 m is comparable to those from the Yons Nab Beds, except for lower counts of *Perinopollenites*: notably the acritarch *Micrhystridium* is present in this sample, which is consistent with the shift back to brackish-marine biofacies, MB7.

Cloughton Wyke

In common with the data from Yons Nab, the results of the palynological analysis of the Cloughton Wyke section are plotted alongside the total megaspore count and the micro-biofacies categories (Fig. 10). Preservation of the miospores is often poor, making identification difficult. Nevertheless, all three main associations defined for the Yons Nab succession are identified at Cloughton Wyke, where there is also a notable shift in spore composition, with *Deltoidospora* frequently being the dominant miospore component.

Mixed or Pollen-dominated PAs characterize the lower section from −0.96 to 4.78 m, with Spore-dominated PAs containing common *Klukisporites* limited to samples at 1.85, 2.10 and 2.30 m (note increase in megaspore count). Compared to Yons Nab, *Perinopollenites* is more common higher in the section, occurring abundantly in samples from 4.80 to 5.40 m. Evidence for brackish-water deposition is lacking, despite the tentative micropalaeontological evidence for MB-7 at −0.95 m.

Mixed PAs occur in claystones below and up to the base of the tiered crevasse splay sandstone unit. However, scarce acritarchs and dinocysts have also been recorded from this part of the succession with, in addition, prasinophyte algae from 5.40 and 5.90 m, suggesting raised salinities on the floodplain; this is consistent with the findings of Hancock & Fisher (1981).

A marked shift in composition is associated with the ‘Coal Marker’ at 8.75–9.00 m, with an increase in the proportion of *Deltoidospora* in Mixed PAs (Fig. 10). Above 12.25 m Spore-dominant PAs are characteristic, resulting from a further increase in numbers of *Deltoidospora*, subordinate *Klukisporites* and other small-spore species. There is a return to Pollen-dominated PAs at 16.30 and 16.95 m; associated with these is an increase in numbers of *Perinopollenites* and the presence of rare acritarchs and questionable (very poorly preserved) dinoflagellate cysts, suggesting the development of brackish conditions, as seen in the micro-biofacies.

Integrated micro-biofacies/palynofacies model and palaeoenvironmental interpretation

Micro-biofacies composition, notably the frequency of megaspores, displays a consistent relationship with PA types, which is key to our interpretation of plant habitat and environment. At Yons Nab an increase in the abundance of *Deltoidospora* and other filicopsid spores through the transition from the Yons Nab Beds to the Gristhorpe Member *sensu stricto* coincides with a positive correlation with megaspore frequency (Fig. 9). Despite this, large numbers of gymnosperm pollen are evident, with Pollen-dominated and Mixed PAs characterizing the lower beds. It is at 5.90 m within the Gristhorpe Member that a marked changeover to Spore-dominated PAs is seen, this also being the level at which megaspores become super-abundant (Fig. 9). From 5.90 to 6.37 m within this assemblage, further changes occur with *Klukisporites* and *Leptolepidites* spore frequencies peaking in association with MB-1 micro-biofacies, where megaspores attain abundance levels exceeding 500 specimens/100 g. Also occurring over this interval are a few representatives of the freshwater alga *Botryococcus*. Specimens of *Deltoidospora* generally dominate assemblages from the rooted claystone sequence above, with localized influxes of gymnosperm pollen (Fig. 9).

At Cloughton Wyke there is a more limited range of micro-biofacies with the apparent suppression of megaspore numbers, previously discussed. Overall, however, the micro-biofacies/palynofloral association profile is comparable to that of the upper Gristhorpe Member at Yons Nab, with *Deltoidospora* occurring prominently in a Mixed–Spore-dominant succession (Fig. 10). Spore-dominated assemblages with increases in numbers of *Klukisporites* and a few lycopsid spores (e.g. *Densoisporites*) show some correlation with megaspore peaks, although background pollen levels (and charcoal) are higher by comparison.

The above interrelationships and the distribution of key components are summarized in Figure 12. Aspects of palaeoecological and palaeoenvironmental observations in a range of palaeobotanical and palynological publications (e.g. Collinson 1988; Skog & Hill 1992; Batten 1996, 1998; Morgans *et al.* 1999; van Konijnenburg-van Cittert & Morgans 1999, among others) and, to a lesser extent, consideration of the habitats of some plant taxa in modern coastal plains and swamps, such as those of the southern and southeastern USA (e.g. Christensen 2000; Mendelssohn & McKee 2000) are reflected in a general way in our interpretation of the palaeoenvironmental significance of the micro-biofacies/palynological associations defined herein. This, in turn, enables refinement of the environmental determinations previously based on field data, including the claystone lithological associations (e.g. CF-1, CF-4: Fig. 4). From the various associations it can be seen that (a) an increase to predominance of agglutinated foraminifera (*Ammodiscus*) defines the marine to brackish trend indicative of tidal mouth deposition, previously observed by Nagy *et al.* (1983); this is also reflected weakly in the palynofloras, with occurrences of the acritarch *Micrhystridium* becoming less common. (b) *Perinopollenites*-dominated assemblages with low megaspore counts characterize inner bay-fill, sheet-flood deposits, suggesting the presence of a cupressaceous (taxodiaceous) swamp forest nearby; initial peat-mire development is indicated by increased numbers of both *Deltoidospora* and megaspores with dominant *Horstisporites* (MB-4). (c) Increased megaspore frequency and diversity associated with Spore-dominant PAs characterize delta-plain conditions; heterosporous plants shedding megaspores inhabited established peat-mires associated with ponds and lakes within this environment, which was also conducive to colonization by ferns represented by *Klukisporites* and other taxa, and the alga *Botryococcus*. On this basis, associated claystone types CF-4 and CF-6 are readily distinguishable from those occurring in the bay-fill sequence. (d) Rooted palaeosols of CF-8 type tend towards Spore-dominated assemblages with abundant *Deltoidospora* spp.. (e) The reappearance of abundant agglutinated foraminifera dominated by *Ammodiscus* (MB-7 micro-biofacies) at the top of the Gristhorpe Member defines marine flooding of the delta-plain.

In Figure 12 the spatial relationships of micro-biofacies and palynofacies are shown in terms of a delta-plain–interdistributary-bay environmental model. The distribution profile of key components, ranging from the higher delta-plain to the embayment shoreface, are indicated in traverses A–B and C–D: it thus represents a complete progradational cycle, as seen at Yons Nab, with new criteria for the recognition of freshwater, delta-plain deposition.

A significant feature of the palynofloras is the very high levels of background gymnosperm pollen in most deposits, including those reflecting the transitional marine environments. This effectively masks subtle changes in non-marine (e.g. *Botrycoccus*, rare *Lecaniella*) and marine (e.g. dinoflagellate cysts and acritarchs) environmental markers, which are much less common. We suggest,

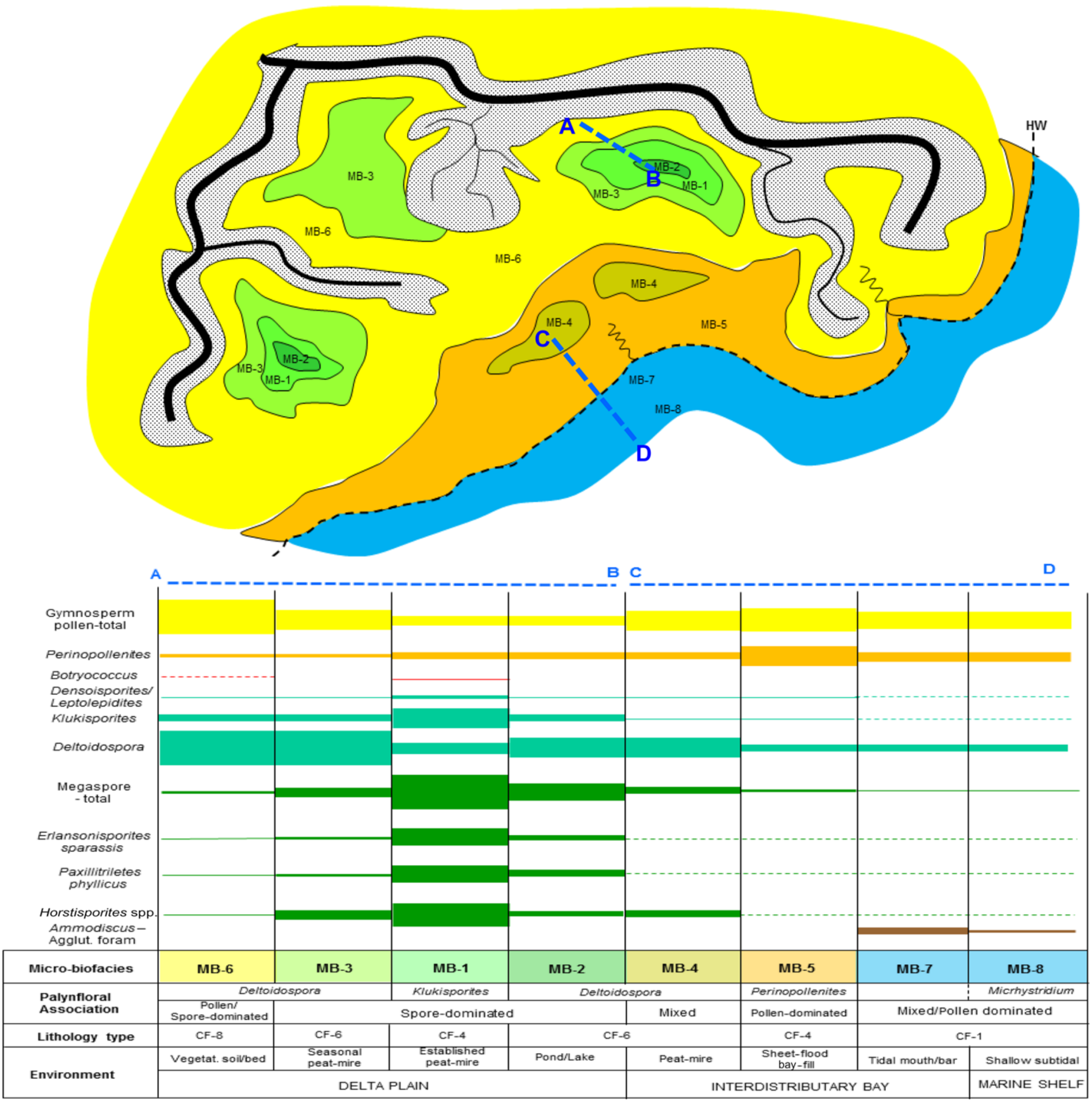

Fig. 12. Relative distribution of key components, micro-biofacies and generalized palynofloral associations for the Gristhope Member. Spatial relationships are rationalized in terms of an interdistributary bay-fill–delta-plain model. Solid black line indicates river distributaries.

therefore, that in such circumstances the changeover from Mixed and Pollen-dominated to Spore-dominated palynofloras, together with an increase in numbers of megaspores, can be a more reliable indicator of non-marine conditions of deposition than the presence or absence of these elements.

Peat-mires and the reconstruction of plant communities

In Figure 12 the development of peat-mires and associated ponds and lakes in topographic lows is highlighted by the MB-1–3/ Spore-dominated associations. Similar mire developments were considered by Nielsen *et al.* (2010) to be important for the deposition of beds rich in organic matter, now represented by coals in the Middle Jurassic Bagå Formation on the Danish island of Bornholm. Palynological analysis of these organic-rich beds within the lake–mire sequence also revealed the predominance of fern spores, with *Deltoidospora* the most abundant of these. Nielsen *et al.* (2010) observed that an increase in fern, bryophyte and lycopsid spores correlated with a decrease in gymnosperm pollen towards the upper parts of the coal-rich beds analysed. These changes were interpreted in terms of a rise in groundwater level, with the development of wetter, open mires favouring the former plant groups.

Changes in groundwater levels can also be invoked using megaspores in our model, with micro-biofacies MB-1 and MB-2 sites located in semi-permanent standing water. Beyond these locations, seasonal variation in groundwater levels may account for the megaspore/small-spore trends indicated along the traverse B–A, with MB-3–6 representing higher ground colonized by sparser fern and lycopsid vegetation (Fig. 12). A reconstruction of the peat-mire setting showing these relationships is depicted in Figure 13. The decline in lycopsids observed in distal mires by Nielsen *et al.* (2010)

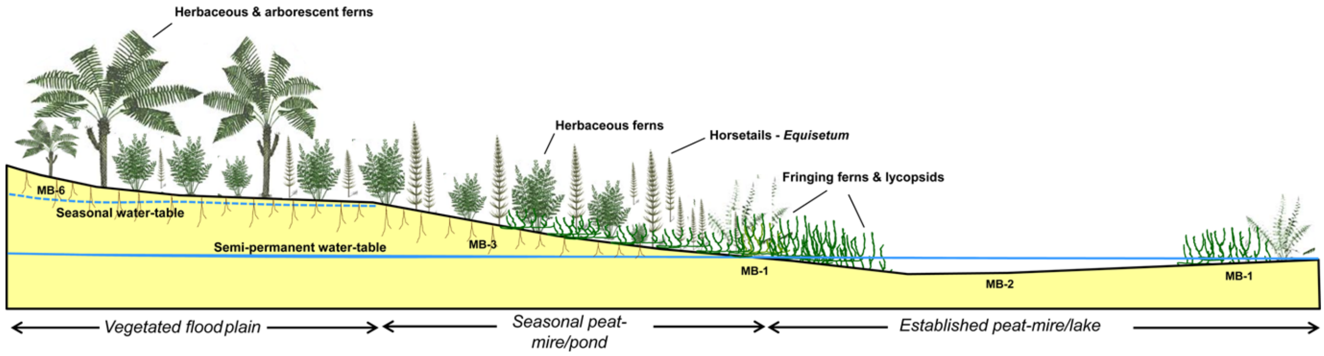

Fig. 13. Schematic reconstruction of the peat-mire depositional setting for the Gristhorpe Member showing habitats of the main plant groups based upon their megaspore/small-spore distribution.

is consistent with our model, which is based on trends in the occurrence of megaspores and *Klukisporites* spp. Unfortunately the recovery of lycopsid microspores is rather sporadic but can provide supporting evidence when present in significant numbers. The possibility exists that some of the abundant small, smooth-walled spores referred to *Deltoidospora* might be lycopsid microspores but positive evidence is wanting.

Our model also shows that established peat-mires with associated water bodies (ponds and lakes) within the delta-plain were the main power houses of megaspore and small-spore generation, with dispersal from these habitats overprinting background levels of allochthonous spores and pollen.

High-resolution correlation using the MB/PA model

Micro-biofacies and palynofacies distributions through the Gristhorpe Member of Yons Nab and Cloughton Wyke are summarized in Figure 14. With deposition occurring within 1 myr and 14 km apart, correlation of units within the Gristhorpe Member relies heavily on defining key depositional events and the most likely lateral facies trends. The MB/PA model defines these more clearly in claystone-dominant sequences by determining the likely base of 'established' delta-plain deposition; also, the definition of brackish biofacies MB-7 effectively brackets the progradational cycle (Fig. 14). Based on these criteria, the lower Gristhorpe Member can be modelled in terms of southwards progradation of delta-plain facies into a bay-fill sequence, which persisted in the Yons Nab area. A major increase in clastic supply, evident from the occurrence of the thick crevasse-splay sandstones at Cloughton Wyke, is likely to have closed the bay-fill phase and established an extensive delta-plain. The two locations labelled 1 on Figure 14 indicate the relative positions of Yons Nab and Cloughton Wyke during this first phase of deposition.

Significant micro-biofacies and palynofacies variations within the delta-plain are evident northwards from Yons Nab to Cloughton Wyke; notably there is a decline in megaspores and associated small spores (*Klukisporites* spp.), although *Deltoidospora* spp. persist in abundance. There is also a marked in increase in charcoal. The high inertinite (charcoal) content associated with the mire deposits of the Bagå Formation is interpreted to represent wildfires of the hinterland vegetation (Nielsen *et al.* 2010). This destabilization of the vegetation cover is considered to have affected the floodplain–mire environment by increased run-off and sediment supply, triggering the onset of plant colonization by pioneering species of ferns and lycopsids. The above micro-biofacies/palynofacies trends are consistent with a shift northwards towards the higher delta-plain, with seasonal standing water and greater wildfire influence on the vegetation. The locations labelled 2 on Figure 14 depict the relative positions of Yons Nab and Cloughton Wyke during this second phase of deposition.

The close of delta-plain deposition, evident from the incoming of MB-7 micro-biofacies in the uppermost Gristhorpe Member appears to be more gradual at Cloughton Wyke, which may be linked to the differences in accommodation rates between the two areas; the presence of a discontinuity separating micro-biofacies in the uppermost Gristhorpe Member of Yons Nab is also a possibility. This flooding event marks the base of the next cycle within the J24 sequence of Partington *et al.* (1993): it culminated in the delta-plain deposition of the Scalby Formation (Upper Bajocian–Bathonian).

Although no regional palynological or megaspore marker species have been identified to assist correlation of units, the inception of the megaspore species *Horstisporites harrisii*, which occurs in the upper Gristhorpe Member at both localities, may have regional biostratigraphical significance (Fig. 14; see below).

Regional application of the MB/PA model to the Brent Group, northern North Sea

In a review of Middle Jurassic, deltaic development in NW Europe, Hancock & Fisher (1981) emphasized the discreteness of individual deltas, each with localized drainage and sediment supply. However, they also highlighted the close similarities in the timing and nature of facies developments. These aspects of deposition were subsequently interpreted by Underhill & Partington (1993) in terms of thermal doming, with plume-head emplacement in the mid North Sea area (see Fig. 15a): phases of uplift and subsidence may, therefore, have occurred simultaneously across the region. This model provides an explanation for the close matches in the vertical sequences of lithologies and sedimentary structures that are particularly evident when comparing delta-top facies of the Brent Group in the northern North Sea with those of the Scalby and Saltwick formations of North Yorkshire, as observed by Hancock & Fisher (1981) who, however, made no reference to the Cloughton Formation despite the fact that the facies of this unit are clearly similar to those of the Broom and Ness formations of the Brent Group.

Although comparative sedimentological studies have been undertaken, sometimes with palynological and other palaeontological input (e.g. Hancock & Fisher 1981; Butler *et al.* 2005), no multidisciplinary research involving megaspores has been carried out previously. As a part of a regional review of the Brent Group, Statoil ASA has recently undertaken integrated palynological and megaspore/micropalaeontological evaluations of the Snorre, Oseberg and Gullfaks field areas of the northern North Sea. However, discussion of the results of this project is beyond the scope of our paper. Consideration here is given only to data from well 34/10-B-12 (Gullfaks Field), which are used to demonstrate: (a) the similarities in palynofloral and megaspore compositions and their associations; (b) the regional potential of the Yorkshire-based biofacies model; and (c) the applicability of outcrop data to core analyses.

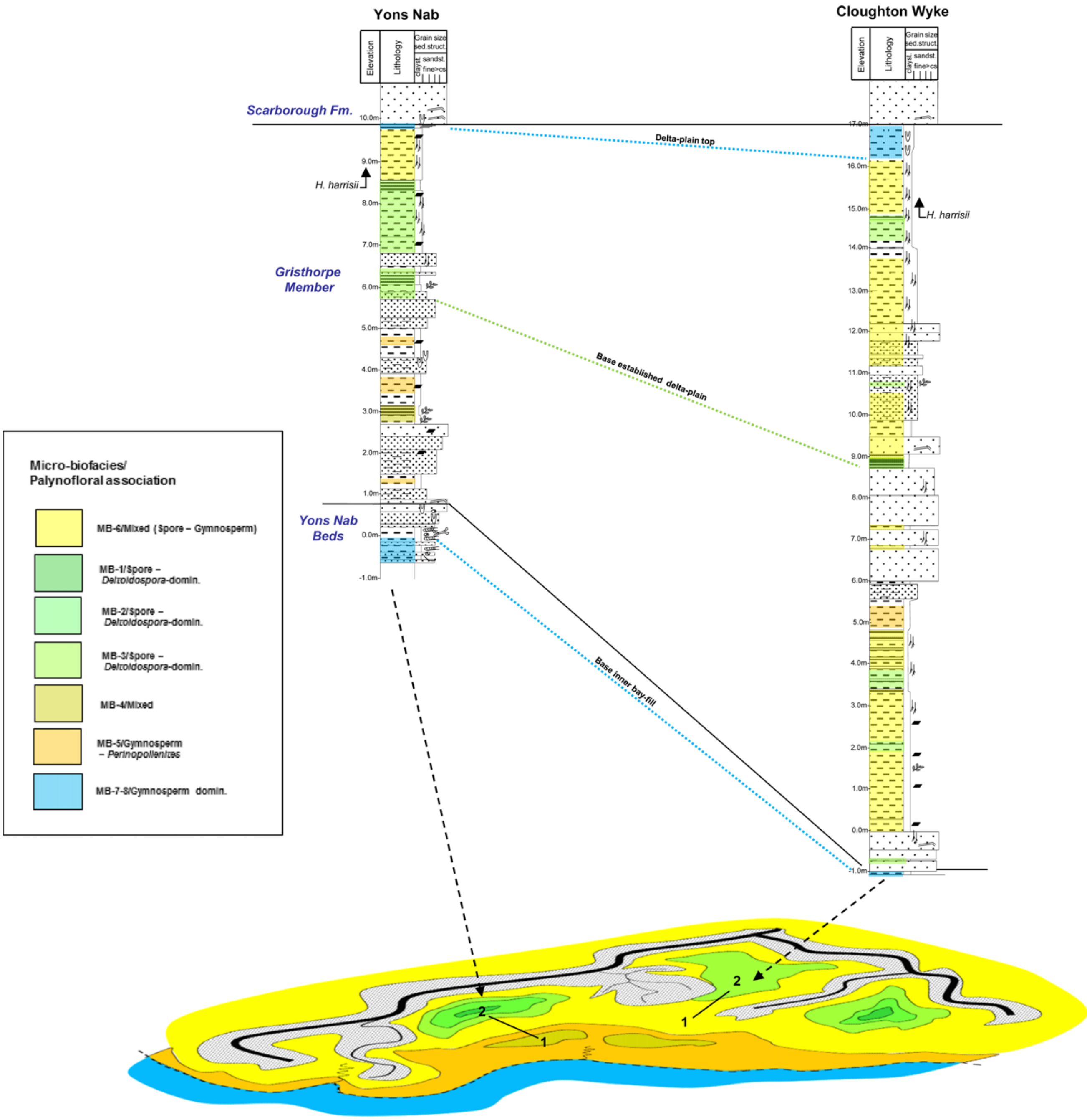

Fig. 14. Micro-biofacies/palynofacies correlation between, and relative locations of, the two field sections within the interdistributary bay-fill–delta-plain model. 1, lower Gristhorpe Member; 2, upper Gristhorpe Member. For key to lithologies, structures and other symbols, see Figure 4. Solid black line indicates river distributaries.

The locations of well 34/10-B-12 and the Gullfaks Field are shown in Figure 15b. Core samples selected from the Broom and overlying Ness formations of the lower Brent Group were analysed for both micropalaeontology/megaspores and palynology using the same preparation and analytical methods as described for the Yorkshire material.

Megaspore distribution and micro-biofacies, well 34/10-B-12

The results of the micropalaeontological analysis are plotted in Figure 16 alongside gamma-ray/bulk density wireline logs, and Statoil in-house lithostratigraphic units. Recovery levels, especially of megaspores, are comparable with those at Yons Nab, as are the quantity and types of plant debris.

The four core samples analysed from the Broom Formation (which incorporates the Rannoch and Etive formations of other authors: e.g. Vollset & Doré 1984; Johnson & Stewart 1985) display the characteristics of MB-7 micro-biofacies; notably the agglutinant foraminifera *Ammodiscus yonsnabensis* predominates at 2963.45 m. This occurrence is consistent with published data from well 34/10–1, also within the Gullfaks Field, presented by Nagy & Johansen (1991). These authors recorded agglutinated assemblages with reducing diversity and increased species dominance of *Ammodiscus yonsnabensis* through the lower Rannoch Formation. This trend, which occurs within their *Ammodiscus–Trochammina* assemblage type, is interpreted as defining the transition from brackish lower delta-front to interdistributary-bay deposition (Nagy & Johansen 1991; Nagy 1992).

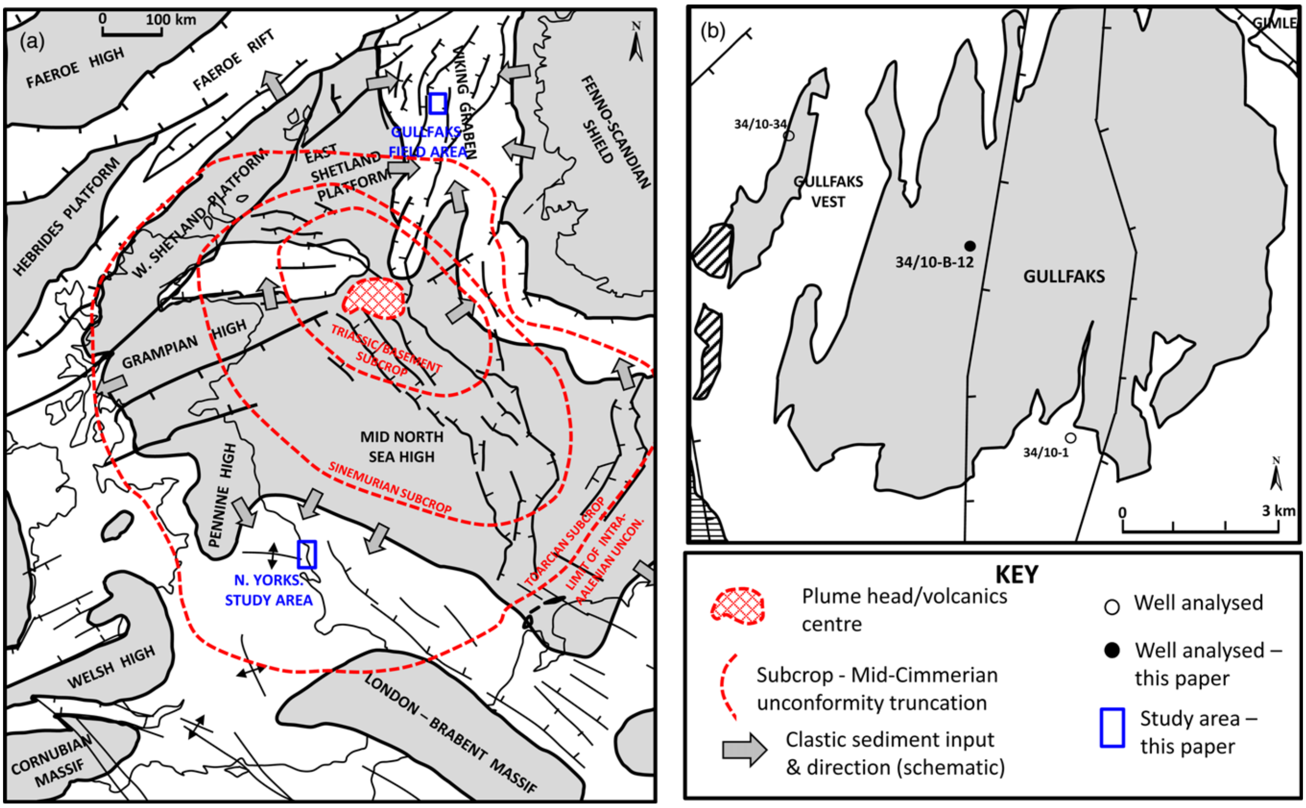

Fig. 15. (**a**) Structural map of the North Sea and surrounding land masses showing the location the Gullfaks Field area and the main source of sediments that comprise the Ravenscar Group in North Yorkshire and the Broom and Ness formations in the Viking Graben. (**b**) Map showing the location of well 34/10-B-12.

Owing to a coring break, no samples were available to evaluate the Broom–lower Ness transition in 34/10-B-12: consequently there is a marked contrast in the composition of the assemblages recovered from core further into the Brent sequence, with the predominance of megaspores and associated plant debris in unit NE-2 of the Ness Formation (Fig. 16). Similarities to megaspore assemblages from the Gristhorpe Member of Yons Nab is striking, with abundant specimens of *Erlansonisporites sparassis* and *Paxillitriletes phyllicus* co-occurring in association with carbonaceous claystones (defined on logs by low bulk density). One significant difference is the reduced numbers of *Horstisporites kendalliae*, although this species is commonly encountered. Overall, the interval from 2908.30 to 2899.95 m is similar to the profile from 5.90 to 6.37 m at Yons Nab, providing strong evidence for the presence of MB-1 and MB-2 micro-biofacies in the sequence. Core analysed above from 2895.65 to 2870.60 m shows a marked reduction in megaspores and associated plant debris, indicating a biofacies shift; the palynofloras suggest that these assemblages occur in a bay-fill sequence and represent MB-5 rather than MB-6 micro-biofacies (see below).

Integrated micro-biofacies and palynofacies, well 34/10-B-12

The results of the palynological analysis are plotted in Figure 17 alongside the total megaspore count and the micro-biofacies categories previously defined. The palynofacies of the samples from the Broom Formation display Mixed (basal sample) or Pollen-dominated PAs, with only a few dinoflagellate cysts indicating raised salinities. However, these assemblages are comparable with those of the Yons Nab Beds and consistent with the MB-7 micro-biofacies association.

By contrast, the palynofloral assemblages from the interval 2916.27–2899.95 m are all dominated by small spores (Spore-dominated PA), with *Deltoidospora* being especially numerous in several of these; the *Baculatisporites*/*Osmundacidites* group is unusually common at 2916.27 m. Comparison with the distribution of megaspores reveals a positive correlation, with *Deltoidospora* frequency similar to that seen within the Gristhorpe Member. Numbers of other spore types, notably species of *Klukisporites*, are reduced in comparison; however, increases in counts of this genus do correspond in part with MB-1 and MB-2 micro-biofacies (Fig. 17).

The return to Pollen-dominated PAs occurs in cores from 2896.50 m, with specimens of *Perinopollenites elatoides* being especially numerous. Along with the decline in megaspores this trend indicates a shift to bay-fill deposition, with assemblages comparable to those of the transition of the upper Yons Nab Beds to the lower Gristhorpe Member *sensu stricto*.

Comparison of the two datasets reveals that the relationship between micro-biofacies and palynofacies established for the Gristhorpe Member has the potential to be applied directly to the Brent Group succession. Application of the Yorkshire model has enabled, in this example, the recognition of transitional marine, bay-fill and delta-plain deposition in a cored sequence (Fig. 17).

These comparative data also have a bearing on the dispersal and colonization of megaspore/small-spore producing floras. Given the 800 km separation of the study areas, the similiarities in megaspore species composition suggest that largely water-borne dispersal of megaspores and their associated microspores occurred effectively across the Mid North Sea High, with relatively rapid colonization of particular niche habitats associated with delta-plain environments when these became available. It follows, therefore, that similiar micro-biofacies and palynofloral associations might be expected in other basins receiving fluvio-deltaic deposition during the Middle Jurassic (e.g. Moray Firth, Norwegian–Danish Basin and Inner Hebrides).

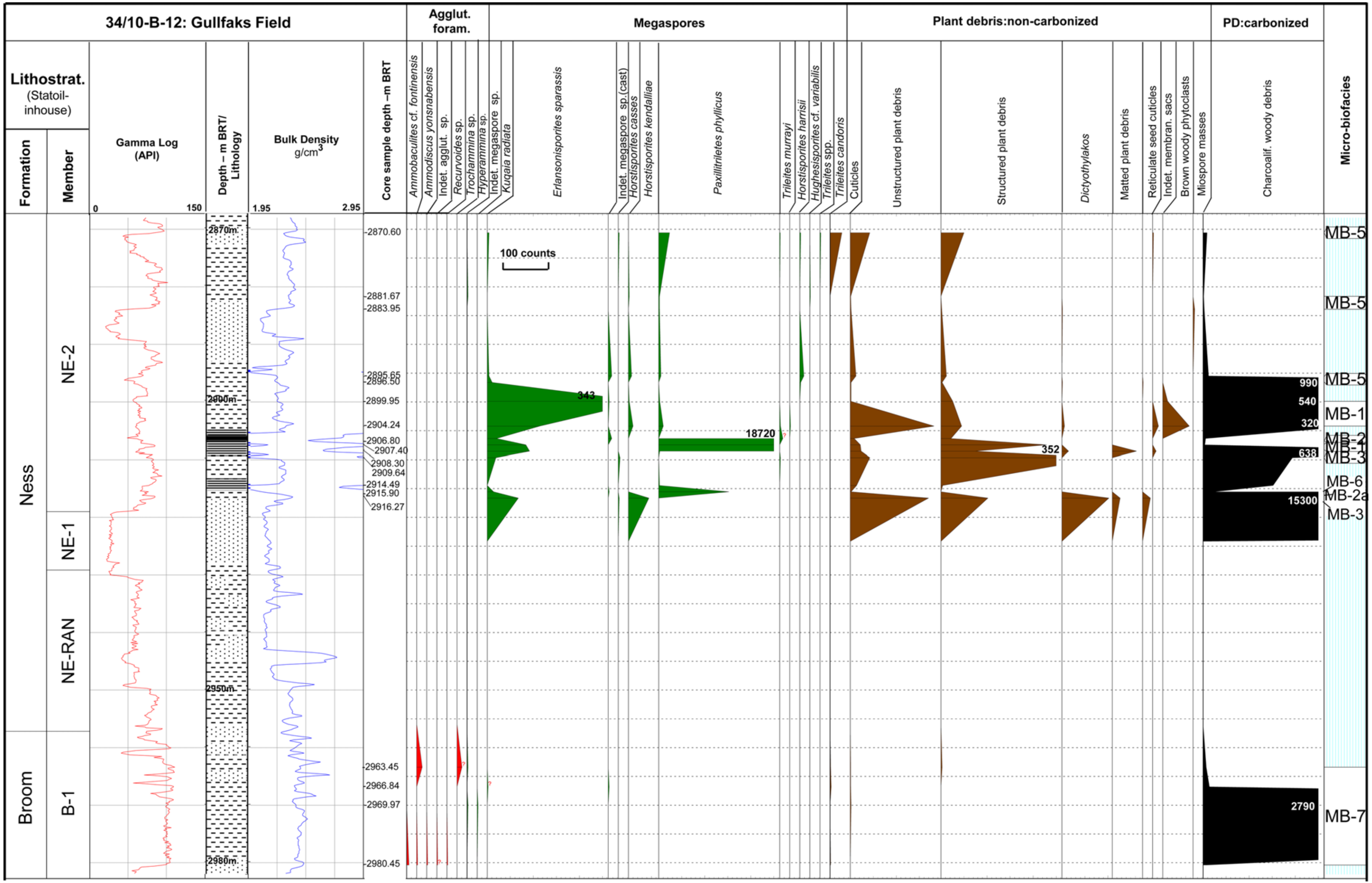

Fig. 16. Micropalaeontological distribution chart and micro-biofacies for the Broom–Ness formations in well 34/10-B-12. PD, plant debris.

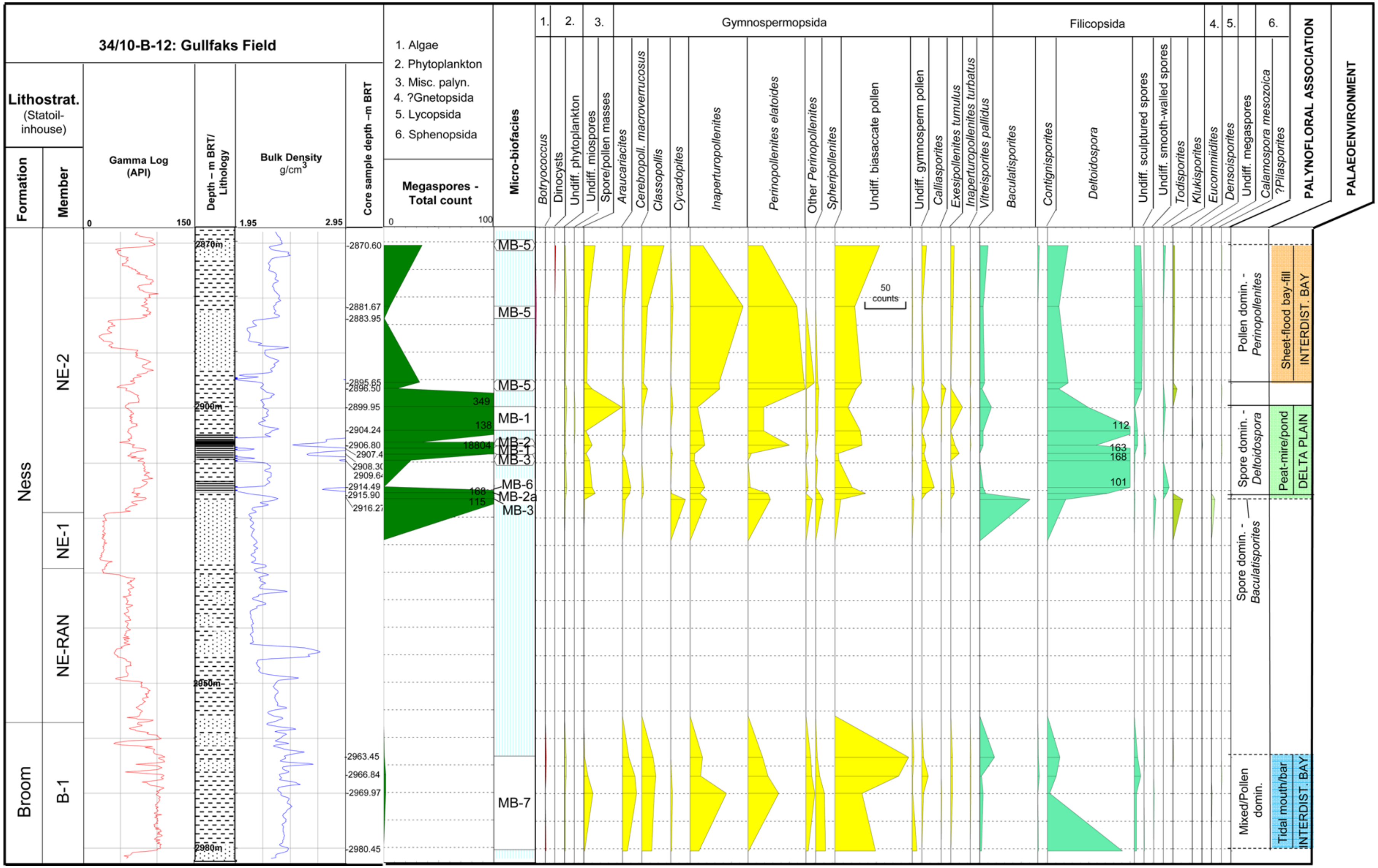

Fig. 17. Total megaspore count, micro-biofacies, palynomorph distributions, palynofloral associations and palaeoenvironmental interpretations for the Broom–Ness formations in well 34/10-B-12.

Biostratigraphic relationship of the Gristhorpe Member and Ness Formation

Two significant changes in megaspore species composition in the Ness Formation are considered to have regional biostratigraphic potential. These are the inceptions of *Horstisporites harrisii*, recorded at 2904.24 m, and *Hughesisporites* sp. cf. *H. variabilis* at 2896.50 m (Fig. 16). The former has its inception in the upper Gristhorpe Member, as noted above, but *Hughesisporites* sp. cf. *H. variabilis* has not been recorded from it. Based on this evidence and on similiarites in gross megaspore composition, the Gristhorpe Member appears to be equivalent to the lower Ness Formation of the central North Viking Graben. This biostratigraphic evidence is consistent with the sequence stratigraphic scheme and biostratigraphic calibration of Partington *et al.* (1993) and Underhill & Partington (1993) who assigned the Ness Formation to the Lower Bajocian, J24 (pars) sequence. These findings, however, conflict with those of Butler *et al.* (2005) who placed the Ness Formation within the late Aalenian, thus pre-dating the Gristhorpe Member. The palynological evidence for this is based on the absence of Early Bajocian marker species *Sentusidinum granulatum* and *Durotrigia filapicata* from the Ness Formation, together with the presence of *Nannoceratopsis triceras* which ranges no younger than earliest Bajocian (Butler *et al.* 2005). Neither *Sentusidinum granulatum* nor *Durotrigia filapicata* has been identified in the Ness Formation of 34/10-B-12. Their apparent absence from the Gristhorpe Member of the present study suggests that these taxa are generally rare and likely to be masked in preparations containing high numbers of miospores.

Although Butler *et al.* (2005) documented *Nannoceratopsis triceras* in the Ness Formation of certain unspecified regions, indicating an Aalenian age, elsewhere it appears to be absent or has not been identified, as in 34/10-B-12 and in other Norwegian sector fields such as Oseberg and Veslefrikk (Morris, personal observation). This discrepancy can be explained partly by the highly diachronous nature of the progradational lower Brent Group, as exhibited at the top Rannoch–Etive/base Ness formations, locally as in the Oseberg Field (blocks 30/6–30/9, Horda Platform; Loseth & Ryseth 2003) and regionally from south to north across the North Viking Graben (see Helland-Hansen *et al.* 1992). In summary, therefore, it is suggested that the Gristhorpe Member shares many of the biostratigraphic characteristics of the Ness Formation, but may only be partly age-equivalent, depending on location within the North Viking Graben.

Conclusions

Outcrops of the Gristhorpe Member at Yons Nab and Cloughton Wyke constitute important reference sections for comparative studies on Middle Jurassic, fluvio-deltaic depositional environments. By using a multi-disciplined approach, the complex interrelationships between plant habitat, megaspore and miospore dispersal, and depositional environment can be determined and applied more accurately. Key to this is the definition of eight micro-biofacies types (MBs) with three qualifying palynofloral associations (PAs), which are tied into a complete fluvio-deltaic cycle at Yons Nab. The defining palynofloral and mesofossil characteristics are:

(1) *Initial regressive bay-fill*: Reduction in marine palynomorphs (including *Micrhystridium*) and microfaunas, with increasing predominance of monotypic agglutinated foraminifera (*Ammodiscus*), marking the marine to brackish trend (MB-8 to MB-7 micro-biofacies).

(2) *Inner bay-fill with increasing fluvio-deltaic influence*: Increase in gymnosperm, *Perinopollenites*-dominated assemblages and more abundant megaspores (MB-5 micro-biofacies).

(3) *Established delta-plain*: Increase in megaspore frequency and diversity and the changeover from Pollen-dominated to Spore-dominated PAs (MB-1–3/MB-6 micro-biofacies).

(4) *Semi-permanent peat-mire and associated vegetated flood-plain*: Marked increase in megaspores with *Erlansonisporites sparassis* and *Paxillitriletes phyllicus* reaching abundant/super-abundant levels; associated are small-spore-dominated PAs, often with numerous *Deltoidospora* and *Klukisporites* (MB-1–3 and MB-6 micro-biofacies).

Throughout the regressive cycle high levels of background gymnosperm pollen are evident which may mask subtle shifts in marine (e.g. acritarchs, dinoflagellates) and non-marine (e.g. *Botryococcus*) palaeoenvironmental markers. Consequently the changeover from Mixed/Pollen-dominant to Spore-dominant PAs, coupled with an increase in megaspores, is shown to be a more reliable indicator of non-marine conditions.

Our data indicate that once the delta-plain was established, megaspore and small-spore generation was linked to peat-mire development, which is likely to have been affected by the positions of both the semi-permanent and seasonal water tables; the described variation in megaspore/small-spore trends suggests a reduction in standing water passing from the lower to higher delta-plain, as seen between Yons Nab and Cloughton Wyke.

The close similarities in MB/PA types between the Gristhorpe Member and the Broom–Ness formations in core from well 34/10-B-12 suggest that the Yorkshire-based model has regional potential and can be applied directly to the Brent Group of the Viking Graben. Finally, comparative data from the two study areas suggest that the dispersal of megaspore and miospore host floras occurred effectively across the Mid North Sea High, with rapid colonization of niche habitats associated with delta-plain development.

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