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Episodic river flooding events revealed by palynological assemblages in Jurassic deposits of the Brent Group, North Sea

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ABSTRACT

Spore and pollen (sporomorph) assemblages from Middle Jurassic marine deposits of the Brent Group in the northern North Sea are investigated to assess temporal and spatial variations in vegetation and depositional processes. Four wells were sampled for palynology from the Penguins Cluster and the Don North East fields through the Rannoch Formation shoreface succession. Hyperpycnite deposits occur throughout, but are concentrated within the lower part of the section. These are expressed by sand-prone beds displaying waxing and waning current motifs, normally graded muddy beds and structureless mudstones. Hyperpycnal/hypopycnal deposits resulting from episodic river flooding represent important sedimentary features as they may be preserved below fair weather wave base in more offshore settings and potentially be the only record of the former presence of a nearby river mouth. The hyperpycnites typically contain abundant *Botryoccocus* spp., Amorphous Organic Matter (AOM) and hinterland taxa with relatively few marine components compared to associated marine shoreface facies. Variations in palynofacies assemblages and *Botryococcus* spp. abundances indicate frequent river mouth avulsion. Ordination of samples using non-metric multidimensional scaling (NMDS) indicates that shoreface samples of the sampled wells are relatively distinct, but hyperpycnite samples are highly similar regardless of their sampled well. This suggests that depositional processes and spore/pollen sources (i.e. catchment zones) were similar among hyperpycnite events across different wells. Abundant bisaccate pollen, *Botryococcus* spp. and AOM within interpreted hyperpycnites suggests sediment mixing along the fluvial drainage path during flooding events. The terrestrial signature of hyperpycnite sporomorph assemblages demonstrates that underflows remained coherent as they descended the shoreface profile with little turbulent mixing with ambient marine waters. Sporomorph assemblages display few large changes through time suggesting vegetation on the adjacent coastal plain was relatively static through the studied interval.

Key Words: Hyperpycnite; Spores and pollen; Rannoch Formation; Palynofacies; Non-metric multidimensional scaling (NMDS); *Botryococcus* spp.

1. Introduction

Hyperpycnite deposits are increasingly recognised in the shallow marine stratigraphic record (Mulder et al., 2003; Zavala et al., 2011). Such deposits provide insights into the processes that operated on ancient shorelines, in many cases providing clues to the former presence of transient river mouths whose shallow water facies have been entirely removed by wave and tidal action. Hyperpycnal flows are negatively buoyant flows that flow along the basin floor due to their higher density, as a result of their particle load compared to the ambient density of the standing water-body (Bates, 1953; Mulder and Syvitski, 1995; Mulder et al., 2003). They form at river mouths during flooding events and can transport substantial volumes of sediment into marine basins (Mulder et al., 2003). Recognition criteria for such deposits are largely based on primary depositional structures indicative of waxing and waning flows (cf. Mulder et al., 2001), although the presence of abundant terrigenous organic matter has also been cited as a diagnostic feature (Zavala et al., 2012). These deposits differ from gravity flows resulting from episodic sediment failure in that they record the fluctuating currents associated with flood events. This contrasts with isolated waning flows resulting from sediment failure episodes. Their differentiation can be important to distinguish between deltaic systems dominated by sediment-laden seasonal flow and those capable of building unstable, failure-prone mouth-bars and delta-fronts, or subject to seismic induced failure. Here we identify the products of river flood events based on sedimentological evidence and subsequently investigate their palynomorph content to provide possible further recognition criteria for these deposits. The study area, located in the Penguins Cluster and the Don North East fields (Fig. 1) occupies the northern limit of the Middle Jurassic Brent Delta of the North Sea Viking Graben; a location which has previously been identified as turbidite-prone (Cannon et al., 1992). We also link sporomorphs (spores and pollen) with botanical groups based on studies of spores/pollen preserved *in situ* within plant reproductive structures (e.g. Balme, 1995) to assess temporal and spatial variations in vegetation and sediment provenance.

2. Geological setting

The stratigraphy of the Middle Jurassic Brent Group (Fig. 1A) is largely based on fields in the East Shetland Basin (e.g. Deegan and Scull, 1977; Budding and Inglin, 1981; Cannon et al., 1992; Richards et al., 1993). The Brent Group comprises five formations (Fig. 1A): the Broom, Rannoch, Etive, Ness and Tarbert formations. The basal Broom Formation records lowstand shallow marine sedimentation, with the overlying Rannoch, Etive and Ness formations recording the progradation of an axial, basin-filling, wave-dominated delta under long term, albeit punctuated, forced regression (Olsen and Steel, 2000; Mjøs, 2009, Went et al., 2013). In addition, Wei et al., (2016) identified a tidal signature within the Rannoch Formation c. 50 km to the south-east of the Penguin Cluster in the axial part of the basin, suggesting that the Brent delta was more tidally influenced than previously thought. The uppermost Tarbert Formation records subsequent transgression (cf. Hampson et al., 2004). The study area (Fig. 1B–D) (Domínguez, 2007), lies close to the northern limit of delta progradation (cf. Brown and Richards, 1989; Mitchener, et al., 1992) and differs from the type section seen to the south-west in the Brent Field. Here the section largely lacks coastal plain Ness Formation facies (Fig. 2) and is dominated by Rannoch lower shoreface and Etive upper shoreface, inlet and beachface sandstones (Scott, 1992; Jackson et al., 2010). Ness-like facies are locally recorded in the greater Penguins area, but are poorly developed and are largely expressed by a relatively thin succession of lagoonal shales or thin coals which lack the facies diversity seen to the south (cf. Livera, 1989). Biostratigraphic data indicate that the Rannoch–Etive section in the Penguins Cluster area is the approximate chronostratigraphic equivalent of the Ness Formation in the Brent Field c. 40 km to the south.

Overall the depositional setting of the Rannoch–Etive section can be compared to modern wave dominated deltas characterised by a relatively low and/or episodic sediment supply and high degree of wave dispersal (Budding and Inglin, 1981). In these settings the fluvial sediment supply to the coast is largely reworked by wave processes (e.g. Domínguez, 1996; Bhattacharya and Giosan, 2003) and in extreme cases no mouth bar facies are preserved. Instead, swash bar complexes, analogous to those seen in ebb tidal deltas (Oertel, 1972; Hayes, 1980) reflect the products of mouth bar material reworked between flood events. Following fluvial avulsion deltaic promontories generated by fluvial sediment supply are re-graded to an equilibrium profile adjusted to the ambient wave climate (Bhattacharya and Giosan, 2003). Distributary channels, deflected by longshore sediment transport by waves into a shore parallel orientation, are also prone to reworking by minor shoreline oscillations. Despite the poor preservation potential of mouth bar and distributary channel facies, hyperpycnal/hypopycnal deposits resulting from episodic river flooding may be preserved below fair weather wave base in more offshore settings and may potentially be the only record of the former presence of a nearby river mouth.

In this paper we examine the sedimentology and palynological signature of the lower portion of the Rannoch Formation in order to investigate the processes that operated in the shallow marine environments distal to the Brent Delta.

2.1. Rannoch facies

The overall facies architecture of the Rannoch and Etive section in the Penguins Cluster is broadly comparable to the type area to the south, albeit of a slightly younger age. This study focusses on the lower shoreface Rannoch section where evidence of hyperpycnal deposits is preserved. The section is typically 30–60 m thick and coarsens-upwards from mudrocks to fine-medium grained sandstones.

2.1.1. Shoreface facies

Bioturbated siltstones and sandstones occur in the basal few meters of the Rannoch section and typically possess a diverse trace fossil assemblage (Fig. 3A) dominated by *Phycosiphon*, *Teichichnus*, *Zoophycos*, *Terebellina* and *Cylindrichnus*. Primary depositional structures are largely absent and belemnite fragments are locally present. These diversely bioturbated, fossiliferous deposits record low energy, open marine deposition following transgressive drowning of the underlying Broom lagoonal system. The sharp boundary with the underlying Broom Formation, and presence of reworked sandstone and mudstone clasts, indicate that the contact likely represents an erosional ravinement surface. This mud-prone interval as a whole records maximum flooding prior to the rapid reversion to normal and subsequent forced regression (Went et al., 2013).

Stratified and burrowed sandstones dominate the Rannoch succession in the study area, and are characterised by successions of generally clean, fine grained sandstones showing a variety of internal fabrics (Fig. 3B–D). Wave formed structures are common, ranging from small scale, combined flow ripples to hummocky cross stratified sandstones with wavelengths visible over the width of core (Fig. 3B), to large scale hummocks identifiable through antiformal lamination and internal angular truncations (Fig. 3C; cf. Richards and Brown, 1986). Discrete bioturbated colonisation surfaces are locally present (Fig. 3D), containing trace fossils such as *Diplocraterion*, *Macaronichnus*, *Palaeophycus* and *Schaubcylindrichnus*. Escape burrows are sporadically distributed. However, in many cases large sections of the Rannoch are characterised by clean, apparently structureless sandstones with an indistinct lamination defined by local mica concentrations. On close inspection, these apparently structureless sandstones can be seen to have a pervasive bioturbation fabric dominated by *Macaronichnus*, or by indistinct cryptobioturbation (cf. Pemberton et al., 2008) which becomes locally better defined where micaceous material is concentrated.

The hummocky cross-stratified beds record episodic deposition under long period waves and combined flows (Southard et al., 1990; Duke et al., 1991; Cheel and Leckie, 1993) on the Rannoch shoreface. Lower in the succession depositional events were sufficiently infrequent to allow the preservation of bioturbated bed tops, but higher in the Rannoch section the uniformly stratified intervals lacking colonisation surfaces are likely to be erosively amalgamated. In the case of the apparently structureless, but intensely bioturbated sandstones it is likely that a large proportion have been overprinted by *Macaronichnus*. This may be indicative of relatively shallow shoreface deposition (Clifton and Thompson, 1978), and would suggest that some shoreface sections were subject to intense infaunal burrowing during fair-weather periods rather than continuous sediment transport, possibly indicating episodic sheltering from wave action (e.g. on the downdrift margins of river mouths or spits).

2.1.2. Fluvial flood deposits

These deposits are sporadically distributed throughout the Rannoch section, commonly occurring as single beds within the background shoreface facies, but locally comprising stacked beds forming intervals of up to a few metres thick.

2.1.2.1. Muddy graded beds

These range in grain size from mudstone to siltstone and rarely to very fine grained sandstone. Muddy graded beds tend to be preserved in the lower parts of the Rannoch section, locally dominating the interval, or interbedded with bioturbated deposits in discrete packages up to a few metres thick. They are characterised by rhythmic stacking of centimetre-scale, normally graded beds which commonly lack any internal fabric, or locally show limited evidence of a planar lamination (Fig. 3E).

These packages could represent: (i) distal, deep water and low energy storm beds deposited below wave base; (ii) storm resuspension of lower shoreface/shelf muds which settled below wave base (Myrow et al., 2002); or (iii) wave enhanced shelf gravity flows (Macquaker et al., 2010). However, their occurrence in discrete packages, general absence of wave formed structures (whilst associated with sediments showing evidence of wave activity) and paucity of biogenic structures (whilst enclosed in bioturbated deposits) suggest that they are the product of dilute turbidity currents which were temporarily focussed into discrete areas of the Rannoch shoreface/delta-front. The sediment load within these packages could have been deposited from decelerating hypopycnal plumes, or bottom-hugging hyperpycnal flows to generate normally graded beds that lack internal fabric. Their discrete packaging within otherwise wave-dominated shoreface facies may therefore reflect the temporary presence of avulsive river mouths which discharged onto the more typically wave-swept Rannoch shoreface.

2.1.2.2. Structureless mudstones

These beds punctuate the entire Rannoch succession, but are particularly common in the lower part of the section. They occur as discrete cm-scale beds characterised by sharp bases and tops, generally lack a fine scale lamination or bioturbation, and are either structureless or very crudely laminated (Figs 3F and G). The beds are typically flat lying, but also locally drape antiformal wave ripple forms. They punctuate the background Rannoch stratigraphy and do not delineate the boundary between facies.

These muds are comparable to the deposits of fluid mud layers identified by Ichaso and Dalrymple (2009), and may be the product of deposition from high density, bottom-hugging flows (cf. Traykovski et al., 2000). The origin of these is enigmatic. The absence of significant tidal indicators in the Brent succession in this area suggests they are not the product of tidal resuspension, and their rare expression draping wave formed structures may indicate post-storm deposition of fluid muds. They appear to be entirely terrestrially derived, but lack the coarser grained fraction and grading that might be expected of suspended sediment deposition from discharging rivers. Instead these deposits may be the product of remobilisation of water saturated muds from coastal plain repositories (such as lakes, lagoons or mud-filled channels) by flooding rivers which transported these dense suspensions onto the Rannoch shoreface.

2.2.2.3. Rhythmic sandstones

These beds are characterised by metre-scale packages of fine-grained sandstone which display a repetitive alternation between current ripple and planar laminated, or laminated and structureless, sandstone (Fig. 3H). They occur in a similar context to the muddy graded beds within otherwise burrowed and wave reworked lower Rannoch deposits.

These sandstones record deposition under fluctuating or surging currents which bear many similarities to sandy hyperpycnites (cf. Mulder et al., 2003; Bhattacharaya and MacEachern, 2009). They are unlikely to represent turbidites resulting from sediment failure, which tend to show structures indicative solely of deceleration (e.g. vertical deceasing grain size (Sumner et al., 2008)), or storm beds, which typically show wave formed structures and tend not to achieve the suspended sediment concentrations that lead to structureless sandstones (e.g. Richards and Brown, 1986). They are instead interpreted as the product of higher energy river mouth flooding than the muddy deposits, and again their occurrence in discrete packages may reflect the temporary presence of an active river mouth on the Rannoch shoreface.

Overall the Rannoch section in the Penguins area shows a dominance of wave processes and no direct evidence of fluvial processes except for the presence of deposits that could be ascribed to river mouth plumes. If these deposits were indeed the product of river mouth processes then a critical test of this would be to examine their palynological composition for evidence of their terrigenous content and how this might contrast with the more open marine facies.

3. Material and methods

3.1. Collection, Processing and Counting

Thirty samples were collected from four wells: 211/13A-8, 211/14-3Z, 211/14-3 and 211/14-4RE through the Rannoch Formation of the Penguins Cluster and the Don North East field, northern North Sea (Fig. 1). Sampling focussed on structureless mudstone and bioturbated beds to compare the palynological signals of the two facies. Rock samples were processed using standard HCl and HF palynological processing techniques. Samples were sieved using a 10 or 15 µm mesh sieve; initial samples were sieved at 10 µm, however no sporomorphs were recorded at <20 µm thus it was deemed adequate to sieve further samples at 15 µm. A minimum of 200 terrestrial sporomorphs were counted from each sample; taxa that were present in slides but not in counts were recorded as ‘p’ in the raw data. *Botryococcus* spp. was counted in addition to sporomorphs; each occurrence of *Botryococcus* spp. was counted as ‘1’ in the raw data. Due to poor preservation in the majority of samples, most bisaccate pollen grains were grouped together. *Quadraeculina anellaeformis* and *Vitreisporites pallidus* were however distinguished from other bisaccates due to their distinctive characters. *Vitreisporites pallidus* is distinct from coniferous bisaccate pollen in that it probably originates from Caytoniales plants

3.2. Palynofacies analysis

Previous palynofacies studies have provided useful information for the regional and large-scale stratigraphic and palaeoenvironmental interpretation of the Brent Group (e.g. Parry et al., 1981; Williams, 1992; Whitaker et al., 1992; Batten and Stead, 2005; Sawyer and Keegan, 1996). Here we use palynofacies analysis to provide more focussed interpretations based on targeted sampling of individual beds deposited under different depositional processes. The scheme of Williams (1992) is used here with some modifications and the following categories are applied: Amorphous Organic Matter (AOM), Blackwood, Brownwood, Plant cuticle, Dinoflagellate cysts, Microforaminiferal test linings (Forams), Fresh to brackish water algae (e.g. *Botryococcus* spp.), Leiospheres, Non-saccate Pollen, Saccate Pollen, Megaspores, Spores, *Tasmanites*, Acritarchs, Scolecodonts and Translucent phytodebris. Non-saccate and saccate pollen have been separated to assess more subtle patterns in pollen abundances between samples. 'Translucent phytodebris' refers to particles that are almost transparent to pale yellow in colour but which cannot be assigned to any other category. Such particles probably represent a mixture of broken marine and terrestrial palynomorphs and leaf cuticle fragments, however a more detailed classification is hampered by poor preservation. For extensive discussions of palynofacies analysis and palynofacies categories see Tyson (1995) and Batten and Stead (1995). Counts of 500 particles were conducted under transmitted light; the size cut-off for particles was 15 μm.

3.3. Data analysis

Non-metric multidimensional scaling (NMDS) was used to assess compositional variation between samples. This is a non-parametric ordination method that uses ranked distances to assess the degree of similarity between samples. Samples that are compositionally similar plot close together and samples that are dissimilar plot far apart. The Bray-Curtis dissimilarity metric was used here as this is considered to perform well in ecological studies (e.g. Harrington, 2008). Repeated runs were undertaken until a convergent solution was reached. NMDS was carried out using PAST (Hammer et al., 2001). For all NMDS plots, taxa that were present in samples but not in counts and singletons (taxa present in only one sample) were excluded from the data to reduce statistical noise. For the abundance matrix, taxon abundances were converted to relative abundances (percentages), so that the count total equals 100 for all sporomorphs in a given sample. For the presence–absence matrix, taxa that were present were scored as '1' and taxa that were absent were scored as '0'.

To assess broad changes in vegetation through time, sporomorphs have been grouped according to their botanical affinity (Fig. 4). Botanical affinities are well constrained for many, but far from all taxa based on spore/pollen *in situ* (e.g. van Konijnenburg-van Cittert, 1978), wall-ultrastructure and grain morphological studies (e.g. Slater et al., 2015).

To assess changes in diversity, raw and rarefied species richness/diversity values are displayed for each sample (Fig. 4). Raw values refer to the number of species in the slide, i.e., including taxa that are present in slides but not in counts. Rarefied values are based on counts of 201 grains. Rarefaction calculations were carried out in PAST (Hammer et al., 2001).

In all analyses, relative abundances of *Botryococcus* spp. were calculated as a percentage of the total number of sporomorphs plus *Botryococcus* spp., and sporomorphs were calculated as 'standard' relative abundances; i.e. percentage values, relative to the total number of sporomorphs counted. Therefore, abundance shifts in *Botryococcus* spp. are recorded, but do not influence sporomorph abundance shifts.

4. Results

The studied wells have been correlated based on lithological, gamma ray and neutron density logs (Fig. 4). Spore/pollen assemblages are dominated by typical Jurassic elements (e.g. *Deltoidospora minor*, *Classopollis* spp. and *Perinopollenites elatoides*) with 42 spore and 17 pollen taxa. Palynofacies counts are typically dominated by AOM, Blackwood and Brownwood with relatively small quantities of other components. For raw sporomorph and palynofacies count data, see Supplementary Tables 1–2 and for relative abundance sporomorph and palynofacies charts, see Supplementary Figures 1–8.

4.1. *Well 211/13A-8*

4.1.1. Palynology

Fifteen samples were analysed spanning the interval ~3646–3636 m from the lower part of the Rannoch Formation (Fig. 4). From these, 10 samples represent sandstone intervals and five derive from structureless mudstones. All samples were productive with variable levels of preservation; palynofloras were accompanied by generally abundant fresh/brackish-water algae and scarce marine palynomorphs. Raw and rarefied species richness values for each sample (Fig. 4) are relatively consistent through time. Figure 4 reveals few 'long-term' abundance and richness shifts in plant groups and individual taxa, suggesting that the vegetation was relatively static during the studied interval.

Perinopollenites elatoides overwhelmingly dominates together with *Classopollis* spp. Bisaccate pollen and *Deltoidospora minor* are also abundant. Simple monosulcate pollen grains (e.g. *Cycadopites* and *Chasmatosporites*) occur consistently within this and all other wells but in low relative abundances. *Vitreisporites pallidus* is generally more abundant in well 211/13A-8.

4.1.2. Palynofacies and Botryococcus *spp. abundances*

Black and Brownwood remains are dominant throughout the studied interval. Amorphous Organic Matter displays high relative abundances within structureless mudstones. Dinoflagellates are low in abundance throughout, but are more abundant in the lower part of the studied interval. *Botryococcus* spp. is common throughout the samples, varying in abundance between 6–81%. The palynofacies composition of structureless mudstone and sandstone samples does not vary greatly in core 211/13A-8, for example *Botryococcus* spp. abundances do not correlate strongly with lithology in core 211/13A-8, whereas in other cores *Botryococcus* spp. is only abundant within structureless mudstones.

4.2. Well 211/14-3Z

4.2.1. Palynology

Six samples were taken spanning the interval ~3755–3741 m from the Rannoch Formation (Fig. 4). Three samples are from sandstone intervals and 3 are from structureless mudstones.

Classopollis spp. and *Perinopollenites elatoides* dominate the basal samples together with *Deltoidospora minor* and unidentified bisaccate pollen, which show relatively low abundances compared to other cores. Interestingly, the sample located at ~3746.5 m depth (fourth sample from the base) is dominated by *Spheripollenites* spp. (53%), and in the topmost sample *Deltoidospora minor* dominates. Raw and rarefied richness values are relatively consistent throughout the studied interval.

4.2.2. Palynofacies and Botryococcus *spp. abundances*

Black and Brownwood dominates within the studied samples. Dinoflagellates occur within sandstone beds and are moderately abundant within the uppermost sample. In the lower part of the section, within the structureless mudstones, AOM is abundant and correspondingly, Black and Brownwood remains record lower relative abundances. *Botryococcus* spp. is also more abundant within structureless mudstones in the lowermost three samples (Fig. 4).

4.3. Well 211/14-3

4.3.1. Palynology

Three samples were taken spanning the interval ~3534–3526 m from the lower part of the Rannoch Formation (Fig. 4). From these, one sample was taken from a sandstone interval and two samples were taken from structureless mudstones. The non-bisaccate group is dominant; of this *Classopollis* spp. is highly abundant in lower samples and *P. elatoides* is highly abundant in the upper sample. Unidentified bisaccate pollen grains are abundant throughout (15–27%) and *Deltoidospora minor* occurs at consistent levels among all samples (18–20%). Raw and rarefied richness records display little change through time (Fig. 4).

4.3.2. Palynofacies and Botryococcus *spp. abundances*

Amorphous Organic Matter is highly abundant in the two structureless mudstone basal samples, reaching 38%, whilst the uppermost sample is dominated by Brownwood. Dinoflagellates were only recorded in the uppermost sandier sample in low abundance. *Botryococcus* spp. is rare in all samples from core 211/14-3, but the highest abundances are within the basal structureless mudstone sample.

4.4. Well 211/14-4RE

4.4.1. Palynology

Six samples were studied for palynology from the section spanning the interval ~3567–3554 m from the Rannoch Formation. Five samples represent sandstone intervals and one derives from a structureless mudstone.

Perinopollenites elatoides and *Classopollis* spp. dominate. Bisaccate pollen grains are highly abundant, particularly within the lowermost two samples. Similarly to other wells, spore abundances are dominated by *Deltoidospora minor*. Raw and rarefied richness values are relatively consistent through time (Fig. 4).

4.4.2. Palynofacies and Botryococcus *spp. abundances*

Black and Brownwood remains dominate in samples from the sandier beds, but in the lowermost sample (structureless mudstone), AOM is the most abundant palynofacies category. Blackwood is generally more abundant within samples from well 211/14-RE compared to other cores. Dinoflagellate cysts comprise a small portion of the total palynofacies count (<1%), but are more abundant within sandstone samples compared to structureless mudstones. *Botryococcus* spp. is only abundant in the lowermost structureless mudstone sample, reaching a relative abundance of 22% of the total palynomorph count.

4.5. Sample Ordination

Ordination (NMDS) of samples using sporomorph relative abundance (percentage) data (Fig. 6A–D) demonstrates that samples from interpreted hyperpycnal and shoreface deposits cluster with limited overlap. This pattern is evident when *Botryococcus* spp. is excluded from the data (Fig. 6A), but is slightly more pronounced when this is included (Fig. 6B). This reflects the abundant *Botryococcus* spp. within interpreted hyperpycnal deposits. Bioturbated shoreface samples cluster according to their well, demonstrating spatial variations in palynological assemblages between wells. Structureless mudstone samples are, however, highly similar regardless of their sampled well suggesting that depositional processes and spore/pollen sources (i.e. catchment zones) were similar among hyperpycnite deposit-forming flooding events of different wells. Ordination of samples using presence–absence data (Fig. 6E) also reveals that samples from structureless mudstones cluster relative to shoreface deposits. Structureless mudstone samples therefore display high compositional similarity, regardless of the geographical location of the sampled well. Limited clustering of well is evident in presence–absence plots compared to relative abundance ordinations. This suggests that shifts in abundances of range through taxa are more important than the presence–absence of species among the different wells. When samples of well 211/13A-8 are excluded from the ordinations (Fig. 6C–E), interpreted hyperpycnites and shoreface deposits separate slightly more strongly. The northwards progradation direction of the Brent Delta (Richards, 1992; Went et al., 2013) would imply that well 211/13A-8 was located closer to a palaeoshoreline/river mouth compared to other cores and the abundant *Botryococcus* spp. throughout this well, which originates from a non-marine source, supports this.

5. Discussion

5.1. Comparison of structureless mudstones and bioturbated shoreface facies

A general trend emerges when comparing the palynological and palynofacies assemblages of structureless mudstones and sandy successions; structureless mudstones are characterised by spikes in AOM and the fresh-brackish water algae, *Botryococcus* spp. (Fig. 5) with generally higher abundances of *Classopollis* spp., bisaccate pollen and lower abundances of *Perinopollenties elatoides*. The structureless mudstones contain very low abundances of marine palynomorphs in palynofacies counts.

Correlation of cores using combined lithological, gamma ray and neutron density data (Fig. 4), demonstrates that the sampled intervals are reasonably coeval and a lack of extensive temporal variation in sporomorph assemblages indicates that environmental change through time was limited. With the exception of core 211/13A-8, abundant *Botryococcus* spp. is confined to structureless mudstones. Abundant *Botryococcus* spp. throughout core 211/13A-8 is suggestive of a more persistent freshwater fluvial input in this well adjacent to the Penguins Cluster in comparison to the wells within the cluster (Fig. 4). Equally, rare *Botryococcus* spp. and common dinoflagellates (including *Nannoceratopsis* spp., *Kallosphaeridium* spp., *Mancodinium* spp., *Evansia* spp., *Pareodinia* spp. and *Phallocysta* spp.) within palynofacies counts of bioturbated sandy facies of cores 211/14-3, 211/14-3Z and 211/14-4RE suggests reduced fresh-water input and more persistent marine shoreface conditions. Spatial variations in *Botryococcus* spp. abundances are probably a result of the proximity of sampled environments relative to avulsive river mouths. Hence, the causes for variation in the distribution and abundances of *Botryococcus* spp. between wells appear linked to spatial variations in river mouth proximity. Marine components were not recorded in palynofacies counts from structureless mudstones, whereas marine components (mostly dinoflagellates) from sandier shoreface lithologies were common. The generally lower relative abundances of Black- and Brownwood remains within structureless mudstones are not considered to be an indicative feature of hyperpycnites here, as these lower relative abundances are due to higher abundances of AOM; when AOM is removed from the palynofacies raw data set prior to calculating relative abundances, Black- and Brownwood relative abundances are generally very similar or slightly higher within interpreted hyperpycnites. The terrestrial content of the structureless mudstones and paucity of marine components would appear to indicate that there was little turbulent mixing of hyperpycnal flows and fluid muds with ambient seawater or that a substantial freshwater wedge was present across these flows as they were depositing.

Within the interpreted hyperpycnites, abundant bisaccate pollen, much of which probably originates from hinterland conifers, in association with abundant *Classopollis* spp. suggests flood events that originated in upland drainage networks. These events also incorporated material from along the flood path to the coast from overbank flooding of lowland floodplains. Abundant *Botryococcus* spp. and AOM in structureless mudstones suggests a fresh/brackish water setting with relatively low energy and low oxygen levels (e.g. relatively stagnant floodplain lakes or lagoons) (see Tyson, 1995; Roncaglia, 2004; Carvalho et al., 2006; Traverse, 2007; Pacton et al., 2011 for discussions regarding environmental reconstructions using AOM) for the environment from which these particles originated (i.e. prior to transportation), which would have been eroded during flooding events.

5.2. Environmental Reconstruction:

Sporomorph assemblages investigated here are highly similar to regional onshore Middle Jurassic deposits from Yorkshire and the East Midlands of the UK (Couper, 1958; Chaloner, 1968; Chaloner and Muir, 1968; Boulter and Windle, 1993; Hubbard and Boulter, 1997; Butler et al., 2005; Srivastava, 2011; Slater and Wellman, 2015; Slater and Wellman, 2016). Assemblages of the shoreface samples of the Rannoch Formation differ in generally possessing more abundant conifer pollen (e.g. *Perinopollenites elatoides*), which is expected within an offshore setting considering the hydrodynamic properties of conifer pollen (cf. Salter et al., 2002; cf. Stukins et al., 2017). The coniferous flora is dominated by Cupressaceae (*Perinopollenites elatoides* (van Konijnenburg–van Cittert and van der Burgh, 1989; Balme, 1995)) and Cheirolepidiaceae (*Classopollis* spp. (Balme, 1995)). Jurassic Cupressaceae trees are frequently interpreted to have inhabited swamp/poorly drained floodplain forests (e.g. Stukins et al., 2013), and Cheirolepidiaceae, a globally common extinct Jurassic gymnosperm, has been interpreted from a range of environments, including dry coastal (e.g. Hughes and Moody-Stuart, 1967; McArthur et al., 2016) and upland settings (e.g. Filatoff, 1975). These trees comprised the canopy together with smaller portions of conifers producing *Spheripollenites* spp. and *Callialasporites* spp. Bisaccate pollen is highly abundant; several better preserved samples demonstrate that *Alisporites* spp. dominate the bisaccate pollen group. *Alisporites* spp. is similar to pollen recovered *in situ* from pteridosperm reproductive structures (e.g. Harris, 1964; Balme, 1995), thus a large portion of bisaccate grains here probably originate from pteridosperms. Such plants probably constituted the mid-storey vegetation. Low-storey vegetation comprised a combination of ground ferns and to a lesser degree, lycophytes. Simple monosulcate pollen grains (e.g. *Cycadopites* and *Chasmatosporites*) occur consistently but in low relative abundances. Reconstructing parent vegetation with certainty based on these taxa is difficult due to their broad botanical affinities (e.g. Balme, 1995); *Cycadopites* is known from the Cycadales, Ginkgoales, Peltaspermales and Bennettitales, and *Chasmatosporites* is known from the Cycadales and Ginkgoales (Frederiksen, 1980; Balme, 1995). Cycad, Bennettitales and ginkgo macrofossils are common from coeval deposits from Yorkshire (e.g. Spicer and Hill, 1979), thus such pollen probably originates from several of these groups.

Floras recovered here are dominated by typically warm-adapted groups (e.g. Cheirolepidiaceae); similar findings are recorded from Jurassic palynological investigations of the central (e.g. McArthur et al., 2016) and southern North Sea (e.g. Abbink, 1998; Abbink et al., 2001, 2004) and coeval onshore regional deposits (e.g. Couper, 1958; Vajda and Wigforss-Lange, 2009 and references therein; Slater et al., 2015, 2016). Hyperpycnite deposits concentrated within the lower part of the Rannoch Formation may have been a response to the developing climatic seasonality identified from coeval regional deposits of the Cleveland Basin, UK (Morgans et al., 1999). Such seasonality (possibly monsoonal) and/or cyclic climatic changes may have resulted in more flood-prone discharge and higher suspended sediment concentrations conducive to hyperpycnal flows during wet seasons, together with a propensity towards limited fluvial supply and wave reworking during dry seasons. Extensive terrestrial floods with substantial suspended-concentrations may have been linked to the active rifting of the North Sea; short, steep sided drainage basins often present in active rift basins would presumably increase the likelihood of rapid floods (Mulder and Syvitski, 1995; Ichaso and Dalrymple, 2009).

6. Conclusions

Whilst the Brent Group has long been considered to be the product of large-scale deltaic progradation (Richards, 1992), and terrestrial palynomorphs are known to be abundant in the Rannoch Formation, this study has identified the bipartite nature of sedimentation within the Rannoch Formation, comprising wave reworked shoreface (with an open marine signature) and the former presence of rivers mouths recorded by flood deposits (with a terrestrial signature). Sediment supply was probably dominated by wet season flooding (possibly monsoonal) and dry season wave reworking of temporary mouth bar constructions. The flood deposits show preservation of terrestrial palynological assemblages within beds which are encased within a fully marine succession. Turbulent mixing with ambient seawater appears to have been minimal, particularly for the fluid mud deposits. The terrestrial assemblages encased in the hyperpycnites are characterised by abundant *Botryococcus* spp. which may indicate flood overspill of lakes and breaching of coastal lagoons. The conifer content is indicative of runoff from extrabasinal areas and direct transport to the coast. Palynology has proven to be a useful tool in identifying hyperpycnite deposits as terrestrial in origin, and provides an indication of the upland to lowland vegetation along the flood water path. The recognition of these processes on the Brent Delta improve our understanding of how the delta advanced at its northern limit as sediment supply became increasingly incapable of maintaining a progradational front across the Viking Graben.

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Figure Captions

Fig. 1. Stratigraphy and maps of the study area. A, Brent Group stratigraphy (Richards et al., 1993); B, map of the North Sea with location of study area; C, regional map of study area, shaded regions represent oil/gas fields; D, well locations, shaded regions represent oil/gas fields.

Fig. 2. Schematic facies architecture of the Brent Group extending from the area of the Brent Field north-eastwards to the area of the Penguins Cluster.

Fig. 3. Representative core facies. A, fully bioturbated, mud-prone facies from the basal part of the Rannoch succession; B, heterolithic Rannoch shoreface storm event beds with bioturbated tops in the lower part of the formation; C, hummocky cross-stratified Rannoch shoreface sandstones characteristic of the main part of the formation; D, Rannoch shoreface storm event beds with bioturbated tops characteristic of the upper part of the formation; E, Muddy graded beds within the lower part of the Rannoch section; F, sharply bounded, structureless mudstone within weakly

bioturbated sandstones; G. structureless mudstone within hummocky cross-stratified sandstone with reworked coaly detritus; and H, sandstone interval showing fluctuations between structureless, weakly stratified and planar laminated fabrics.

Fig. 4. Correlation panel of studied wells. Relative abundances of selected palynofacies and sporomorph groups provided. Abundances of palynofacies categories are relative to all other palynofacies categories; abundances of sporomorphs are relative to all other sporomorphs; abundances of *Botryococcus* spp. are relative to the total number of sporomorphs plus *Botryococcus* spp. Raw and rarefied (at 201 grains) richness values displayed, horizontal grey bars represent 95% confidence intervals for rarefied values.

Fig. 5. Palynofacies compositions of interpreted hyperpycnite (A–D) and shoreface samples (E–H). A, slide 211/13A-8 11926i (England finder reference T39/1); B, slide 211/14-3Z 12321.7ii (England finder L36/1); C, slide 211/13A-8 11954.5i (England finder Q40/2); D, slide 211/14-4RE 11688.7ii (England finder P29/3); E, slide 211/13A-8 11939.3 (England finder L39/3); F, slide 211/14-4RE 11650, (England finder L36/4); G, slide 211/14-3Z 12289 (England finder S54/C); H, slide 211/14-4RE 11662 (England finder L38/4). Scale bar = 100 µm. Note the more abundant *Botryococcus* spp. (red ellipses) and AOM (blue ellipses) within interpreted hyperpycnites; abundant *Botryococcus* spp. within samples from well 211/13A-8; and more abundant marine components within shoreface samples (e.g. arrow in E).

Fig. 6. NMDS ordinations of sporomorph data; A and B, all samples included; C–E, Well 211/13A-8 excluded; A and C relative abundance data, *Botryococcus* spp. excluded; B and D, relative abundance data, *Botryococcus* spp. included; E, presence–absence data, *Botryococcus* spp. excluded.

Fig. 7. Environmental reconstruction along the palaeo-river course based on studied wells. Plant groups and distributions are based on spore-pollen assemblages. Note the heavy rainfall on hinterland environments; low and high stage flows represent ‘normal’ fluvial conditions and ‘flood’ conditions

(i.e. when hyperpycnites are deposited) respectively. The slope gradient from the terrestrial to marine environment is exaggerated to be steeper than reality.

Supplementary Material

Supplementary Table 1. Raw sporomorph count data with botanical affinities of taxa. Taxa that are present in samples but not counts are marked with '+'. Botanical affinities of taxa are displayed.

Supplementary Table 2. Raw palynofacies count data.

Supplementary Table 3. NMDS Axis scores for Fig. 6A.

Supplementary Table 4. NMDS Axis scores for Fig. 6B.

Supplementary Table 5. NMDS Axis scores for Fig. 6C.

Supplementary Table 6. NMDS Axis scores for Fig. 6D.

Supplementary Table 7. NMDS Axis scores for Fig. 6E.

Supplementary Fig. 1. Relative abundance chart of individual sporomorph taxa and *Botryococcus* spp. for well 211/13A-8.

Supplementary Fig. 2. Relative abundance chart of individual sporomorph taxa and *Botryococcus* spp. for well 211/14-3Z.

Supplementary Fig. 3. Relative abundance chart of individual sporomorph taxa and *Botryococcus* spp. for well 211/14-3.

Supplementary Fig. 4. Relative abundance chart of individual sporomorph taxa and *Botryococcus* spp. for well 211/14-4RE.

Supplementary Fig. 5. Relative abundance chart of palynofacies categories for well 211/13A-8.

Supplementary Fig. 6. Relative abundance chart of palynofacies categories for well 211/14-3Z.

Supplementary Fig. 7. Relative abundance chart of palynofacies categories for well 211/14-3.

Supplementary Fig. 8. Relative abundance chart of palynofacies categories for well 211/14-4RE.