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

3

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28 **ABSTRACT**

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

51

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

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57 **1. Introduction**

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

81

82 **2. Geological setting**

83 The stratigraphy of the Middle Jurassic Brent Group (Fig. 1A) is largely based on fields in the East
84 Shetland Basin (e.g. Deegan and Scull, 1977; Budding and Inglin, 1981; Cannon et al., 1992;
85 Richards et al., 1993). The Brent Group comprises five formations (Fig. 1A): the Broom, Rannoch,
86 Etive, Ness and Tarbert formations. The basal Broom Formation records lowstand shallow marine
87 sedimentation, with the overlying Rannoch, Etive and Ness formations recording the progradation of
88 an axial, basin-filling, wave-dominated delta under long term, albeit punctuated, forced regression
89 (Olsen and Steel, 2000; Mjøs, 2009, Went et al., 2013). In addition, Wei et al., (2016) identified a
90 tidal signature within the Rannoch Formation c. 50 km to the south-east of the Penguin Cluster in the
91 axial part of the basin, suggesting that the Brent delta was more tidally influenced than previously
92 thought. The uppermost Tarbert Formation records subsequent transgression (cf. Hampson et al.,
93 2004). The study area (Fig. 1B–D) (Domínguez, 2007), lies close to the northern limit of delta
94 progradation (cf. Brown and Richards, 1989; Mitchener, et al., 1992) and differs from the type section
95 seen to the south-west in the Brent Field. Here the section largely lacks coastal plain Ness Formation
96 facies (Fig. 2) and is dominated by Rannoch lower shoreface and Etive upper shoreface, inlet and
97 beachface sandstones (Scott, 1992; Jackson et al., 2010). Ness-like facies are locally recorded in the
98 greater Penguins area, but are poorly developed and are largely expressed by a relatively thin
99 succession of lagoonal shales or thin coals which lack the facies diversity seen to the south (cf. Livera,
100 1989). Biostratigraphic data indicate that the Rannoch–Etive section in the Penguins Cluster area is
101 the approximate chronostratigraphic equivalent of the Ness Formation in the Brent Field c. 40 km to
102 the south.

103 Overall the depositional setting of the Rannoch–Etive section can be compared to modern
104 wave dominated deltas characterised by a relatively low and/or episodic sediment supply and high
105 degree of wave dispersal (Budding and Inglin, 1981). In these settings the fluvial sediment supply to
106 the coast is largely reworked by wave processes (e.g. Domínguez, 1996; Bhattacharya and Giosan,
107 2003) and in extreme cases no mouth bar facies are preserved. Instead, swash bar complexes,
108 analogous to those seen in ebb tidal deltas (Oertel, 1972; Hayes, 1980) reflect the products of mouth
109 bar material reworked between flood events. Following fluvial avulsion deltaic promontories

110 generated by fluvial sediment supply are re-graded to an equilibrium profile adjusted to the ambient
111 wave climate (Bhattacharya and Giosan, 2003). Distributary channels, deflected by longshore
112 sediment transport by waves into a shore parallel orientation, are also prone to reworking by minor
113 shoreline oscillations. Despite the poor preservation potential of mouth bar and distributary channel
114 facies, hyperpycnal/hypopycnal deposits resulting from episodic river flooding may be preserved
115 below fair weather wave base in more offshore settings and may potentially be the only record of the
116 former presence of a nearby river mouth.

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

120

121 *2.1. Rannoch facies*

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

126

127 *2.1.1. Shoreface facies*

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

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

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

161

162 *2.1.2. Fluvial flood deposits*

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

166

167 *2.1.2.1. Muddy graded beds*

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

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

185

186 *2.1.2.2. Structureless mudstones*

187 These beds punctuate the entire Rannoch succession, but are particularly common in the lower part of
188 the section. They occur as discrete cm-scale beds characterised by sharp bases and tops, generally lack
189 a fine scale lamination or bioturbation, and are either structureless or very crudely laminated (Figs 3F

190 and G). The beds are typically flat lying, but also locally drape antiformal wave ripple forms. They
191 punctuate the background Rannoch stratigraphy and do not delineate the boundary between facies.

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

202

203

204 2.2.2.3. *Rhythmic sandstones*

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

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

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

223

224 **3. Material and methods**

225 *3.1. Collection, Processing and Counting*

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

240

241 *3.2. Palynofacies analysis*

242 Previous palynofacies studies have provided useful information for the regional and large-scale
243 stratigraphic and palaeoenvironmental interpretation of the Brent Group (e.g. Parry et al., 1981;
244 Williams, 1992; Whitaker et al., 1992; Batten and Stead, 2005; Sawyer and Keegan, 1996). Here we
245 use palynofacies analysis to provide more focussed interpretations based on targeted sampling of

246 individual beds deposited under different depositional processes. The scheme of Williams (1992) is
247 used here with some modifications and the following categories are applied: Amorphous Organic
248 Matter (AOM), Blackwood, Brownwood, Plant cuticle, Dinoflagellate cysts, Microforaminiferal test
249 linings (Forams), Fresh to brackish water algae (e.g. *Botryococcus* spp.), Leiospheres, Non-saccate
250 Pollen, Saccate Pollen, Megaspores, Spores, *Tasmanites*, Acritarchs, Scolecodonts and Translucent
251 phytodebris. Non-saccate and saccate pollen have been separated to assess more subtle patterns in
252 pollen abundances between samples. 'Translucent phytodebris' refers to particles that are almost
253 transparent to pale yellow in colour but which cannot be assigned to any other category. Such
254 particles probably represent a mixture of broken marine and terrestrial palynomorphs and leaf cuticle
255 fragments, however a more detailed classification is hampered by poor preservation. For extensive
256 discussions of palynofacies analysis and palynofacies categories see Tyson (1995) and Batten and
257 Stead (1995). Counts of 500 particles were conducted under transmitted light; the size cut-off for
258 particles was 15 μm .

259

260 3.3. Data analysis

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

272 To assess broad changes in vegetation through time, sporomorphs have been grouped
273 according to their botanical affinity (Fig. 4). Botanical affinities are well constrained for many, but far

274 from all taxa based on spore/pollen *in situ* (e.g. van Konijnenburg-van Cittert, 1978), wall-
275 ultrastructure and grain morphological studies (e.g. Slater et al., 2015).

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

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

285

286 **4. Results**

287 The studied wells have been correlated based on lithological, gamma ray and neutron density logs
288 (Fig. 4). Spore/pollen assemblages are dominated by typical Jurassic elements (e.g. *Deltoidospora*
289 *minor*, *Classopollis* spp. and *Perinopollenites elatoides*) with 42 spore and 17 pollen taxa.

290 Palynofacies counts are typically dominated by AOM, Blackwood and Brownwood with relatively
291 small quantities of other components. For raw sporomorph and palynofacies count data, see
292 Supplementary Tables 1–2 and for relative abundance sporomorph and palynofacies charts, see
293 Supplementary Figures 1–8.

294

295 4.1. Well 211/13A-8

296 4.1.1. Palynology

297 Fifteen samples were analysed spanning the interval ~3646–3636 m from the lower part of the
298 Rannoch Formation (Fig. 4). From these, 10 samples represent sandstone intervals and five derive
299 from structureless mudstones. All samples were productive with variable levels of preservation;
300 palynofloras were accompanied by generally abundant fresh/brackish-water algae and scarce marine
301 palynomorphs. Raw and rarefied species richness values for each sample (Fig. 4) are relatively

302 consistent through time. Figure 4 reveals few ‘long-term’ abundance and richness shifts in plant
303 groups and individual taxa, suggesting that the vegetation was relatively static during the studied
304 interval.

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

309

310 4.1.2. Palynofacies and *Botryococcus* spp. abundances

311 Black and Brownwood remains are dominant throughout the studied interval. Amorphous Organic
312 Matter displays high relative abundances within structureless mudstones. Dinoflagellates are low in
313 abundance throughout, but are more abundant in the lower part of the studied interval. *Botryococcus*
314 spp. is common throughout the samples, varying in abundance between 6–81%. The palynofacies
315 composition of structureless mudstone and sandstone samples does not vary greatly in core 211/13A-
316 8, for example *Botryococcus* spp. abundances do not correlate strongly with lithology in core
317 211/13A-8, whereas in other cores *Botryococcus* spp. is only abundant within structureless
318 mudstones.

319

320 4.2. Well 211/14-3Z

321 4.2.1. Palynology

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

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

329

330 4.2.2. *Palynofacies and Botryococcus spp. abundances*

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

336

337 4.3. *Well 211/14-3*

338 4.3.1. *Palynology*

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

346

347 4.3.2. *Palynofacies and Botryococcus spp. abundances*

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

352

353 4.4. *Well 211/14-4RE*

354 4.4.1. *Palynology*

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

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

362

363 4.4.2. *Palynofacies and Botryococcus* spp. abundances

364 Black and Brownwood remains dominate in samples from the sandier beds, but in the lowermost
365 sample (structureless mudstone), AOM is the most abundant palynofacies category. Blackwood is
366 generally more abundant within samples from well 211/14-RE compared to other cores.

367 Dinoflagellate cysts comprise a small portion of the total palynofacies count (<1%), but are more
368 abundant within sandstone samples compared to structureless mudstones. *Botryococcus* spp. is only
369 abundant in the lowermost structureless mudstone sample, reaching a relative abundance of 22% of
370 the total palynomorph count.

371

372 4.5. *Sample Ordination*

373 Ordination (NMDS) of samples using sporomorph relative abundance (percentage) data (Fig. 6A–D)
374 demonstrates that samples from interpreted hyperpycnal and shoreface deposits cluster with limited
375 overlap. This pattern is evident when *Botryococcus* spp. is excluded from the data (Fig. 6A), but is
376 slightly more pronounced when this is included (Fig. 6B). This reflects the abundant *Botryococcus*
377 spp. within interpreted hyperpycnal deposits. Bioturbated shoreface samples cluster according to their
378 well, demonstrating spatial variations in palynological assemblages between wells. Structureless
379 mudstone samples are, however, highly similar regardless of their sampled well suggesting that
380 depositional processes and spore/pollen sources (i.e. catchment zones) were similar among
381 hyperpycnite deposit-forming flooding events of different wells. Ordination of samples using
382 presence–absence data (Fig. 6E) also reveals that samples from structureless mudstones cluster
383 relative to shoreface deposits. Structureless mudstone samples therefore display high compositional
384 similarity, regardless of the geographical location of the sampled well. Limited clustering of well is
385 evident in presence–absence plots compared to relative abundance ordinations. This suggests that

386 shifts in abundances of range through taxa are more important than the presence–absence of species
387 among the different wells. When samples of well 211/13A-8 are excluded from the ordinations (Fig.
388 6C–E), interpreted hyperpycnites and shoreface deposits separate slightly more strongly. The
389 northwards progradation direction of the Brent Delta (Richards, 1992; Went et al., 2013) would imply
390 that well 211/13A-8 was located closer to a palaeoshoreline/river mouth compared to other cores and
391 the abundant *Botryococcus* spp. throughout this well, which originates from a non-marine source,
392 supports this.

393

394 **5. Discussion**

395 *5.1. Comparison of structureless mudstones and bioturbated shoreface facies*

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

402 Correlation of cores using combined lithological, gamma ray and neutron density data (Fig.
403 4), demonstrates that the sampled intervals are reasonably coeval and a lack of extensive temporal
404 variation in sporomorph assemblages indicates that environmental change through time was limited.
405 With the exception of core 211/13A-8, abundant *Botryococcus* spp. is confined to structureless
406 mudstones. Abundant *Botryococcus* spp. throughout core 211/13A-8 is suggestive of a more
407 persistent freshwater fluvial input in this well adjacent to the Penguins Cluster in comparison to the
408 wells within the cluster (Fig. 4). Equally, rare *Botryococcus* spp. and common dinoflagellates
409 (including *Nannoceratopsis* spp., *Kallosphaeridium* spp., *Mancodinium* spp., *Evansia* spp.,
410 *Pareodinia* spp. and *Phallocysta* spp.) within palynofacies counts of bioturbated sandy facies of cores
411 211/14-3, 211/14-3Z and 211/14-4RE suggests reduced fresh-water input and more persistent marine
412 shoreface conditions. Spatial variations in *Botryococcus* spp. abundances are probably a result of the
413 proximity of sampled environments relative to avulsive river mouths. Hence, the causes for variation

414 in the distribution and abundances of *Botryococcus* spp. between wells appear linked to spatial
415 variations in river mouth proximity. Marine components were not recorded in palynofacies counts
416 from structureless mudstones, whereas marine components (mostly dinoflagellates) from sandier
417 shoreface lithologies were common. The generally lower relative abundances of Black- and
418 Brownwood remains within structureless mudstones are not considered to be an indicative feature of
419 hyperpycnites here, as these lower relative abundances are due to higher abundances of AOM; when
420 AOM is removed from the palynofacies raw data set prior to calculating relative abundances, Black-
421 and Brownwood relative abundances are generally very similar or slightly higher within interpreted
422 hyperpycnites. The terrestrial content of the structureless mudstones and paucity of marine
423 components would appear to indicate that there was little turbulent mixing of hyperpycnal flows and
424 fluid muds with ambient seawater or that a substantial freshwater wedge was present across these
425 flows as they were depositing.

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

436

437 *5.2. Environmental Reconstruction:*

438 Sporomorph assemblages investigated here are highly similar to regional onshore Middle Jurassic
439 deposits from Yorkshire and the East Midlands of the UK (Couper, 1958; Chaloner, 1968; Chaloner
440 and Muir, 1968; Boulter and Windle, 1993; Hubbard and Boulter, 1997; Butler et al., 2005;
441 Srivastava, 2011; Slater and Wellman, 2015; Slater and Wellman, 2016). Assemblages of the

442 shoreface samples of the Rannoch Formation differ in generally possessing more abundant conifer
443 pollen (e.g. *Perinopollenites elatoides*), which is expected within an offshore setting considering the
444 hydrodynamic properties of conifer pollen (cf. Salter et al., 2002; cf. Stukins et al., 2017). The
445 coniferous flora is dominated by Cupressaceae (*Perinopollenites elatoides* (van Konijnenburg–van
446 Cittert and van der Burgh, 1989; Balme, 1995)) and Cheirolepidiaceae (*Classopollis* spp. (Balme,
447 1995)). Jurassic Cupressaceae trees are frequently interpreted to have inhabited swamp/poorly drained
448 floodplain forests (e.g. Stukins et al., 2013), and Cheirolepidiaceae, a globally common extinct
449 Jurassic gymnosperm, has been interpreted from a range of environments, including dry coastal (e.g.
450 Hughes and Moody-Stuart, 1967; McArthur et al., 2016) and upland settings (e.g. Filatoff, 1975).
451 These trees comprised the canopy together with smaller portions of conifers producing
452 *Spheripollenites* spp. and *Callialasporites* spp. Bisaccate pollen is highly abundant; several better
453 preserved samples demonstrate that *Alisporites* spp. dominate the bisaccate pollen group. *Alisporites*
454 spp. is similar to pollen recovered *in situ* from pteridosperm reproductive structures (e.g. Harris, 1964;
455 Balme, 1995), thus a large portion of bisaccate grains here probably originate from pteridosperms.
456 Such plants probably constituted the mid-storey vegetation. Low-storey vegetation comprised a
457 combination of ground ferns and to a lesser degree, lycophytes. Simple monosulcate pollen grains
458 (e.g. *Cycadopites* and *Chasmatosporites*) occur consistently but in low relative abundances.
459 Reconstructing parent vegetation with certainty based on these taxa is difficult due to their broad
460 botanical affinities (e.g. Balme, 1995); *Cycadopites* is known from the Cycadales, Ginkgoales,
461 Peltaspermales and Bennettitales, and *Chasmatosporites* is known from the Cycadales and Ginkgoales
462 (Frederiksen, 1980; Balme, 1995). Cycad, Bennettitales and ginkgo macrofossils are common from
463 coeval deposits from Yorkshire (e.g. Spicer and Hill, 1979), thus such pollen probably originates from
464 several of these groups.

465 Floras recovered here are dominated by typically warm-adapted groups (e.g.
466 Cheirolepidiaceae); similar findings are recorded from Jurassic palynological investigations of the
467 central (e.g. McArthur et al., 2016) and southern North Sea (e.g. Abbink, 1998; Abbink et al., 2001,
468 2004) and coeval onshore regional deposits (e.g. Couper, 1958; Vajda and Wigforss-Lange, 2009 and
469 references therein; Slater et al., 2015, 2016). Hyperpycnite deposits concentrated within the lower part

470 of the Rannoch Formation may have been a response to the developing climatic seasonality identified
471 from coeval regional deposits of the Cleveland Basin, UK (Morgans et al., 1999). Such seasonality
472 (possibly monsoonal) and/or cyclic climatic changes may have resulted in more flood-prone discharge
473 and higher suspended sediment concentrations conducive to hyperpycnal flows during wet seasons,
474 together with a propensity towards limited fluvial supply and wave reworking during dry seasons.
475 Extensive terrestrial floods with substantial suspended-concentrations may have been linked to the
476 active rifting of the North Sea; short, steep sided drainage basins often present in active rift basins
477 would presumably increase the likelihood of rapid floods (Mulder and Syvitski, 1995; Ichaso and
478 Dalrymple, 2009).

479

480 **6. Conclusions**

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

497

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502

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702

703 **Figure Captions**

704

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

708

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

711

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

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

721

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

728

729 **Fig. 5.** Palynofacies compositions of interpreted hyperpycnite (A–D) and shoreface samples (E–H).
730 A, slide 211/13A-8 11926i (England finder reference T39/1); B, slide 211/14-3Z 12321.7ii (England
731 finder L36/1); C, slide 211/13A-8 11954.5i (England finder Q40/2); D, slide 211/14-4RE 11688.7ii
732 (England finder P29/3); E, slide 211/13A-8 11939.3 (England finder L39/3); F, slide 211/14-4RE
733 11650, (England finder L36/4); G, slide 211/14-3Z 12289 (England finder S54/C); H, slide 211/14-
734 4RE 11662 (England finder L38/4). Scale bar = 100 μm . Note the more abundant *Botryococcus* spp.
735 (red ellipses) and AOM (blue ellipses) within interpreted hyperpyncnites; abundant *Botryococcus* spp.
736 within samples from well 211/13A-8; and more abundant marine components within shoreface
737 samples (e.g. arrow in E).

738

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

742

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

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

748

749 **Supplementary Material**

750

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

753

754 **Supplementary Table 2.** Raw palynofacies count data.

755

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

757

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

759

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

761

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

763

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

765

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

768

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

771

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

774

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

777

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

779

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

781

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

783

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