

1 **Sedimentology and stratigraphy of the Kellaways Sand Member (Lower Callovian),**

2 **Burythorpe, North Yorkshire, UK**

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9

10 **Abstract:** In the Burythorpe area of the Howardian Hills, located on the northern margin of
11 the Market Weighton High, the Callovian succession is represented only by Lower Callovian
12 sediments. These belong to the Kellaways Sand Member (Kellaways Formation), up to 12 m
13 thick, but thinning southwards to 5 m. This contrasts with the more complete Callovian
14 succession (Osgodby Formation) on the Yorkshire coast (Cleveland Basin) which is up to 32.5
15 m thick. At Burythorpe Quarry the Kellaways Sand Member has yielded palynomorphs and
16 ammonites confirming an Early Callovian (Koenigi Zone) age with depositional hiatuses
17 above and below. The sequence consists of a yellow-white, poorly cemented, fine-to
18 medium grained, unimodal uncemented sand (moulding sand) with sparse grey clay beds
19 and laminae, in marked contrast to the broadly coeval Red Cliff Rock Member (Osgodby
20 Formation) of the Cleveland Basin.

21 The depositional environment is interpreted as a tidally influenced shallow sea on
22 the margin of the Market Weighton High, in a shallow sub-tidal regime, similar to the sub-

23 tidal sand-mud lithofacies in the Heligoland region of the present-day North Sea. Winnowing
24 of the sand in highly mobile substrate resulted in a unimodal grain size, lack of impurities,
25 and sparse shelly- and ichnofaunas. However, during quieter water phases, grey clay
26 laminae were deposited at the base of channels, allowing colonisation of the substrate by
27 burrowing ichnofauna and deposition of palynomorphs. Sparse, calcite-cemented tabular
28 beds with a benthic shelly fauna, ammonites, *Planolites* burrows and mudstone rip-up clasts
29 are interpreted as the deposits of periodic storm events. The marked local variation in
30 thickness of the Kellaways Sand Member in the Howardian Hills is probably due to
31 synsedimentary east-west trending faulting related to the Flamborough Fault Zone.

32

33

34 The Kellaways Sand Member (Middle Jurassic: Lower Callovian) succession is exposed at
35 Burythorpe Silica Sand Quarry [NGR: SE 785 658; N 54° 04 39.7' W 00° 48 31.7'] west of the
36 small village of Burythorpe, south of Malton, North Yorkshire. The working quarry, owned
37 by the Yorkshire Mineral Company Ltd., produces resin-coated moulding (foundry) sand. The
38 exposures are of great significance as they provide one of the few examples of Callovian
39 sedimentation on the northern margin of the Market Weighton High (Wright 1978).
40 Furthermore, the succession at Burythorpe exhibits lithofacies that are distinct from the
41 well-exposed Callovian succession (Osgodby Formation) on the Yorkshire coast between
42 Cayton Bay and Scarborough and thus provides a link between sedimentation in the
43 Cleveland Basin, located to the north, and the Market Weighton High (Kent 1955, 1974)
44 where the attenuated Callovian succession is represented by the Kellaways Sand Member
45 (Gaunt *et al.* 1980; Page 1989). The stratigraphically older Kellaways Clay Member of

46 southern England and the stratigraphically higher Cave Rock Member of North Humberside
47 are both absent in the study area.

48 Burythorpe Quarry was first described by Wright (1978) who reported small limonitic
49 concretions in the lower part of the succession that yielded a shelly fauna including the
50 brachiopod *Rhynchonella* sp., the bivalves *Entolium demissum*, *Meleagrinea*
51 *braamburiensis*, *Astarte* sp. and *Pleuromya* sp., and the ammonites *Keplerites* sp. and
52 *Proplanulites* sp. The ammonites indicate an Early Callovian age. Subsequent extensions of
53 the quarry to the south-west has exposed new faces at a low stratigraphical level. This has
54 enabled the study of the sedimentology and biostratigraphy in greater detail. Additional
55 information on the palynostratigraphy and ammonite faunas collected from the quarry
56 provide a more robust biostratigraphy for the Kellaways Sand Member. The integrated study
57 has also enabled a better understanding of the depositional environment and
58 palaeogeography of the Callovian succession in the region.

59

60 **Geological setting**

61

62 Following Page (1989), the Callovian succession at Burythorpe is referred to the Kellaways
63 Sand Member to distinguish it from the Osgodby Formation of the Cleveland Basin located
64 to the north and north-east (Fig. 1). It lies at the southern end of the Howardian Hills, within
65 a wedge-shaped outcrop bounded to the north and south-east by normal faults (Figs 2, 3)
66 (British Geological Survey 2017). The friable moulding sand is distinguished in the field by its
67 fine- to medium-grain size and white to yellow-white colour; large, hard calcite-cemented
68 concretions (locally known as bullions) up to 3 m in diameter are present throughout the

69 succession (Fig. 4). Approximately 3 km to the south of Burythorpe, the member disappears
70 below the overstepping Cretaceous (Chalk Group) unconformity, but it was proved below
71 Upper Jurassic rocks, Carstone and the Chalk Group in the nearby Brown Moor Borehole
72 [NGR SE 8126 6203] (Gaunt *et al.* 1980) and reappears at outcrop before the member is cut
73 out below the Cretaceous unconformity about 15 km to the south of Acklam on the north-
74 western margin of the Market Weighton High. To the south of the Market Weighton High,
75 near South Cave (Fig.1), the Callovian succession is represented by the uncemented sands of
76 the Kellaways Sand Member and the overlying calcareous, shelly Cave Rock Member (Walker
77 1972; Brasier & Brasier 1978; Page 1989).

78 Boreholes drilled by the Yorkshire Mineral Company near the quarry proved the
79 Kellaways Sand Member to be at least 12 m thick, although the upper boundary is not
80 present. However, it thins rapidly southwards to 5.46 m of fine-grained sandstone in the
81 Brown Moor Borehole (Fig. 3) where the member was previously attributed entirely to the
82 Calloviense Zone (Gaunt *et al.* 1980). In this borehole, the member is overlain
83 disconformably by 8.78 m of calcareous mudstone attributed to the Peterborough Member,
84 Oxford Clay Formation (Coronatum to Athleta zones) overlain, in turn, by the Corallian
85 Group. The southward thinning of the Kellaways and Oxford Clay formations in this area is
86 attributed to the positive isostatic feature of the Market Weighton High, and possibly syn-
87 sedimentary faults that influenced sedimentation patterns and thickness trends through
88 much of the Jurassic (Kent 1974; Kirby & Swallow 1987).

89

90 **Sedimentology**

91

92 **Introduction**

93

94 The Kellaways Sand Member was studied in three main faces at Burythorpe Quarry (Fig. 3).
95 These revealed low-angled, scoured channels with white and pale grey, fine- to medium-
96 grained, finely laminated, unconsolidated sand(stone) with thin, dark grey clay(stone) beds
97 and laminae in the lower part of the channels (Figs 4 - 6). The channels show both vertical
98 and lateral accretion. Claystone beds commonly overlie the scoured base of the channels
99 (Figs 4-6) and have yielded wood fragments, and abundant terrestrial and marine
100 palynomorphs (see below). Benthic macrofauna have not been observed within the
101 channels, but there is evidence of sparse vertical *Skolithos* burrows and horizontal burrows
102 (probably *Planolites*) at the base of channels (Fig. 7). Channel bases show post-depositional
103 disturbance with grey claystone wedges injected downwards along microfaults into the
104 underlying sandstone (Figs 5, 6). In contrast to the Yorkshire coastal sections of the broadly
105 coeval Red Cliff Rock Member of the Osgodby Formation (Wright 1968a, 1978; Page 1989;
106 Rawson & Wright 2000; Powell & Riding 2016), the Kellaways Sand Member at Burythorpe
107 has a more uniform grain size and a sparse shelly benthic fauna; furthermore, it lacks pyritic
108 and berthierine ooids.

109 Channel complex 2 (Fig. 8) reveals a scoured channel base with laterally accreted
110 beds at the channel margin passing up to vertical accreted fill with climbing ripples, the
111 latter showing palaeocurrent directions at right angles to channel, that is to the north-north-
112 west. Channel orientation and ripple drift, cross lamination in Burythorpe Quarry indicate a
113 north-northwest orientation for the long axes of the channels, with a predominant
114 palaeoflow in this direction.

115 In contrast with the poorly lithified channel sandstone, thin, hard calcareous-
116 cemented tabular beds occasionally form cap-rocks to the large calcite-cemented

117 concretions (Wright 1978). The calcite-cemented beds are characterised by mudstone rip-up
118 clasts, mudstone-flake conglomerates, wave ripples and sparse *Planolites* burrows (Fig. 9).
119 The large calcite concretions have also yielded sparse ammonites (Fig. 10). Concentric,
120 ferruginous growth lines in incipient concretions cut across the bedding (Figs 6, 11),
121 indicating that the concretions post-date sedimentation and the micro-faulting seen in the
122 lower parts of the channels. More evolved concretions cut across and destroy original
123 bedding features (Fig. 11). Migration of carbonate ions to the concretionary centres may
124 have been initiated by mobilisation of original calcium carbonate cements in the tabular cap
125 rocks.

126

127 ***Interpretation***

128

129 The low-angle, vertically and laterally accreted channels and early diagenetic microfaults
130 bear a remarkable similarity to the inter-tidal and sub-tidal channels described from the
131 present-day North Sea between Heligoland and the north German coast (Reineck & Singh
132 1973). The shelf-sand-mud lithofacies of these authors are interpreted to have been
133 deposited in water depths of between 10-15 m and exhibit many of the features seen in the
134 Burythorpe succession described above. These include finely intercalated, fine-grained sand
135 and mud lithologies, flaser and lenticular bedding, laminated sand and ripple cross-bedding
136 bedding, and shelly storm deposited layers. Reineck & Singh (1973) showed that the
137 intertidal sands in the North Sea were derived from tidal flats located near the coast of
138 Germany. We envisage that the Kellaways Sand Member was deposited on the north-west
139 margins of the Market Weighton High where the sediments were winnowed in a shallow
140 sub-tidal regime, which resulted in deposition of fine- to medium-grained, unimodal sand

141 with few impurities. Low-angle sub-tidal channels were eroded in the sand during ebb tidal
142 flow. During periods of slack-water (waning flow), flocculating clay was deposited at the base
143 of some of the channels, and was also locally interbedded with sand laminae during gradual
144 lateral and vertical fill of the channels. Low angle, lateral accretion cross-bedding at channel
145 margins indicates a sinuous to meandering channel morphology. The presence of marine
146 and terrestrial palynomorphs, together with drifted wood fragments in the claystone beds,
147 suggest deposition in a shallow marine setting close to the alluvial, vegetated hinterland.
148 Dewatering due to sediment loading within the channels resulted in multiple phases of
149 microfaulting and injection of clay laminae downwards along these fractures. Similar sub-
150 tidal sand-mud channels with water escape feature were described by Sellwood (1972,
151 1975) from the Lower Jurassic of Bornholm, although the overall sedimentary regime in that
152 succession was a shallower tidal flat. Middle Jurassic sandstone on the islands of Skye and
153 Raasay, north-west Scotland, is interpreted as a tidal deposit (Mellere & Steel 1996) with low
154 angle channel-fill and dewatering structures. The estuarine, tidal channel-fill deposits in the
155 upper part of the Bearreraig Sandstone Formation (Bajocian) on Raasay exhibit many
156 features seen in the Burythorpe sections. The absence of benthic macrofauna within the tidal
157 channels suggests that the fine- to medium-grained sand substrate was highly mobile
158 because of the high energy tidal regime, so that bottom conditions were not suited to
159 colonisation by benthic fauna. However, sparse vertical and horizontal burrows (Fig. 7)
160 associated with grey clay lamina at the base of some channels indicate the substrate was
161 colonised by burrowing organisms during periods of waning flow.

162 In contrast, the tabular bedded, calcareous-cemented beds, often preserved at the
163 top of the hard concretions, show features typical of storm-induced sedimentation. These
164 include the presence of mudstone rip-up clasts and mudstone conglomerates, large drifted

165 wood fragments, occasional bivalves and brachiopods, and sparse ammonites. Deposition of
166 these 'clastic' elements probably occurred during storm surge-ebb events across the sub-
167 tidal flats. Reineck & Singh (1973) described similar shelly, storm deposited beds within their
168 sub-tidal sand-mud lithofacies in the Heligoland region of the North Sea.

169 The Callovian succession at Burythorpe differs in detail from the broadly coeval
170 succession on the southern flanks of the Market Weighton High at South Cave (Fig. 1)
171 (Brasier & Brasier 1978). In the Humberside area, the Kellaways Sand Member also
172 comprises uncemented sands, but with bands rich in the bivalves *Gryphaea* sp. and *Catinula*
173 sp., as well as byssally attached bivalves (*Oxytoma* and *Meleagrinnella* spp.) with sparse
174 ammonites and abundant belemnites. In addition, the sands are more intensively
175 bioturbated and have a more diverse ichnofauna (including *Ophiomorpha* and
176 *Thalassinoides*) than seen at Burythorpe. The succession at South Cave was interpreted as
177 being deposited in a tidal regime as laterally migrating point bars with macrofauna
178 preserved as lags in the base of channels. This contrasts with the Burythorpe succession
179 where infaunal trace fossils are sparse and the clays at the base of channels are devoid of
180 macrofossils. The latter are, in contrast, preserved in tabular cemented sands along with
181 mudstone rip-up clasts, features reported from the modern North Sea (Reineck & Singh
182 1973). Brasier & Brasier (1978) also noted the absence of flaser bedding and wavy bedding,
183 small-scale ripples or megaripples at South Cave, all sedimentary structures seen at
184 Burythorpe (Figs 8, 9). The differences noted above may be attributed to slower
185 sedimentation rates in a lower energy tidal regime at South Cave, with longer sediment
186 residence time (e.g. as indicated by higher bioturbation and common epifaunal gryphaeate
187 bivalves) compared to a higher energy sub-tidal shoal environment at Burythorpe. Although
188 the successions in both areas suggest that the sands were winnowed and well-sorted in a

189 tidal regime on the flanks of the Market Weighton High, the presence of the postulated
190 Cleveland Basin margin hinge (basin-shelf) line a few tens of kilometres to the north of
191 Burythorpe (Fig. 1) would have created a more hydrodynamically active regime in contrast to
192 the lower energy regime of East Midlands Shelf to the south of Humberside.

193

194 **Biostratigraphy**

195

196 ***Palynology***

197

198 Two samples of clay were collected close to the base and the top of the exposed succession
199 in Burythorpe Quarry for palynological analysis (Riding 2016). Sample 2 (MPA 67359) is a
200 dark grey claystone sampled from the base of a channel (Figs 5, 6) and was collected from
201 the more recent, southerly extension of the quarry at a level approximately 12 m below the
202 top of the quarry face. Given the low regional dip, Sample 2 is stratigraphically lower in the
203 Kellaways Sand Member than Sample 1 and is estimated to be about 3 m above the base of
204 the member. Sample 1 (MPA 63612) was taken from ca 6 m below the top of the northern
205 quarry face, again from a grey clay at the base of a channel (Figs 3, 4); this sample is from
206 the upper part of the member.

207 Both samples yielded relatively abundant palynofloras comprising terrestrially-
208 derived forms (pollen and spores) and indigenous marine elements (largely dinoflagellate
209 cysts and acritarchs). The stratigraphically important taxa are illustrated in Fig. 12, and a list
210 of palynomorphs is given in Appendices 1, 2. All the author citations pertaining to the
211 dinoflagellate cyst taxa mentioned herein are listed in Williams et al. (2017).

212

213 *Sample 2 (MPA 67359)*. This sample produced an abundant organic residue which is
214 dominated by palynomorphs. Plant tissues and wood are present in moderate proportions,
215 and the levels of amorphous organic material are very low (Appendix 2). The palynomorphs
216 are numerous and well-preserved; the principal palynomorph group is gymnosperm pollen
217 (45.0 %), largely bisaccate pollen and *Cerebropollenites macroverrucosus*. Pteridophyte
218 spores are markedly subordinate (8.3 %). The marine elements are dominated by
219 dinoflagellate cysts (41.0 %) of which *Mendicodinium groenlandicum* is by far the most
220 prominent (20.9 %). *Ctenidodinium* spp. and indeterminate forms are also prominent;
221 however, the remainder are relatively sparse (Appendix 1). Other dinoflagellate cyst taxa
222 recognised include *Nannoceratopsis pellucida*, *Pareodinia* spp., *Sentusidinium* spp. and
223 *Tubotuberella* spp. (Appendix 1). Miscellaneous microplankton comprising acritarchs and
224 foraminiferal test linings make up a relatively minor component (5.7%). The occurrence of
225 common and diverse marine palynomorphs is indicative of fully marine depositional
226 conditions.

227 Sample 2 is unequivocally of Callovian age. The range bases of the dinoflagellate
228 cysts *Gonyaulacysta jurassica* subsp. *adepta* (consistent), *Mendicodinium groenlandicum*,
229 *Rigaudella aemula* and *Rhynchodiniopsis cladophora* (and the acritarch *Fromea tornatilis*)
230 are all intra-Callovian, and the range tops of *Ctenidodinium continuum*, *Korystocysta* spp.
231 (common) and *Wanaea acollaris* are typically intra-Callovian (Raynaud 1978; Riley & Fenton
232 1982; Riding 1984, 2005; Riding & Sarjeant 1985; Riding *et al.* 1999; Poulsen & Riding 2003).
233 Furthermore, common *Mendicodinium groenlandicum* is typical of the Callovian (Woollam
234 1980). However, the key biostratigraphically significant dinoflagellate cysts are
235 *Impletosphaeridium varispinosum*, *Kalyptea stegasta* and common *Meiourogonyaulax*
236 *caytonense*. *Impletosphaeridium varispinosum* is a distinctive chorate (spine-bearing)

237 species, which is a reliable marker for the Early Callovian (Herveyi to Calloviense zones)
238 (Riley & Fenton 1982; Riding 2005; Feist Burkhardt & Wille 1992). There is a single report of
239 this taxon from the latest Bathonian (Riding 1987, fig. 4), but this is not thought to be
240 significant. The presence of *Kalyptea stegasta* and common *Meiourogonyaulax caytonense*
241 is also typical of the Early and Mid Callovian (Sarjeant 1959; Davey & Riley 1978; Riley &
242 Fenton 1982; Riding 1987; Powell & Riding 2016). In summary, the occurrence of
243 *Impletosphaeridium varispinosum*, together with forms such as *Rigaudella aemula* and
244 *Rhynchodiniopsis cladophora*, is unequivocally indicative of an Early Callovian age. Sample 2
245 is, therefore, stratigraphically coeval with the Red Cliff Rock Member of the Osgodby
246 Formation in the Cleveland Basin (Wright 1968a, 1978; Page 1989; Powell & Riding 2016).

247

248 *Sample 1 (MPA 63612)*. Sample 1 was collected from a claystone at the base of channel 3 in
249 the northern sector of the quarry (Figs 3, 4); it lies about 4 m above Sample 2. This horizon
250 produced a sparse, poorly-preserved palynoflora. However, the level of organic material is
251 relatively high; the residue is dominated by indigenous wood fragments (~70 %). Jurassic
252 palynomorphs comprise the dinoflagellate cysts? *Gonyaulacysta jurassica* subsp. *adepta*,
253 ?*Mendicodinium groenlandicum* and *Nannoceratopsis pellucida*, the pollen ?*Callialasporites*
254 and *Perinopollenites elatoides*, and the smooth fern spore genus *Cyathidites*. This
255 assemblage is essentially a low-diversity equivalent of the palynoflora from Sample 1. It is
256 hence interpreted as also being of Early Callovian age as it stratigraphically overlies Sample
257 2, is clearly part of the same genetic succession and lacks any markers for the post-Early
258 Callovian interval. The abundance of wood fragments and presence of marine

259 palynomorphs is consistent with a fluvial channel close to a shoreline, and which is within
260 the tidal limit.

261 In summary, both samples in this study yielded palynomorph assemblages indicative
262 of a marine setting and an Early Callovian (Mid Jurassic) age. Sample 2 is Early Callovian in
263 age due to the presence of *Impletosphaeridium varispinosum*, and species such as
264 *Rigaudella aemula* and *Rhynchodiniopsis cladophora*. This sample thus appears to be the
265 equivalent of the Red Cliff Rock Member of the Osgodby Formation. Sample 1 is also Early
266 Callovian in age because it overlies sample 2, is part of the same overall succession and lacks
267 any post-Early Callovian index fossils.

268

269 ***Ammonite biostratigraphy***

270

271 As noted above, benthic and nektonic macrofauna are relatively sparse in the Kellaways Sand
272 Member at Burythorpe. Where present, these macrofossils are restricted to tabular, hard
273 calcite-cemented beds and small concretions in the uppermost part of the member, or within
274 larger, late diagenetic concretions in the lower part of the quarry (Fig. 10). The concretions
275 have been observed *in situ* at various stages of late-stage diagenetic development (Figs 6, 11).
276 However, some of the large (> 1 m diameter) concretions have been moved during quarrying
277 operations to an adjacent part of the quarry and are not *in situ*. Consequently, it is not certain
278 if the some of the large ammonite-bearing concretions are always in their original
279 stratigraphical position. However, it is certain that the concretions were located within the
280 lower to middle part of the member and that, as noted by Wright (1978), the upper part of
281 the concretions often comprises a tabular bedded cap-rock with benthic fauna, mudstone rip-

282 up clasts and wood fragments. Due to the extremely hard nature of the large calcareous
283 concretions in the main quarry, it has not been possible to extract whole specimens from the
284 surrounding matrix; those identified were photographed in the field and compared with
285 published reference material. However, a recent near-surface archaeological excavation in a
286 planned northern extension to the quarry (Fig. 3) exposed small calcareous concretions from
287 the uppermost surface levels of the member, which included fragmentary ammonites and
288 bivalves. Ammonites identified by P.F.R. and J.K. Wright during the current study include the
289 genera *Keplerites*, *Chamoussetia* and *Pseudocadoceras* (Fig. 10). Together with well-
290 preserved samples collected earlier from the quarry by J.K. Wright and R. Myerscough, the full
291 ammonite list is: *Keplerites (Gowericeras) curtilobus* (S.Buckman) (4 specimens); *K. (G.)*
292 *trichophorum* (S. Buckman) (1 specimen); *Keplerites* sp. (microconch); *Proplanulites aff.*
293 *crassiruga* (S. Buckman) (2 specimens); *Chamoussetia phillipsi* Callomon & Wright (4
294 specimens); and *Pseudocadoceras boreale* S. Buckman (2 specimens) (J.K. Wright personal
295 communication 2017). The ammonite assemblage is representative of the Lower Callovian,
296 Koenigi Zone, Curtilobus Subzone (J.K. Wright personal communication 2017) which is broadly
297 coeval with the Red Cliff Rock Member (Osgodby Formation) of the Cleveland Basin (Wright
298 1978; Page 1989; Powell & Riding 2016).

299

300 **Chronostratigraphy**

301

302 The Koenigi Zone, Curtilobus Subzone age for the Kellaways Sand Member (Fig. 12) indicated
303 by the ammonites is earlier than the Calloviense Zone attributed to the equivalent beds in
304 the nearby Brown Moor Borehole (Gaunt *et al.* 1980), although no Calloviense age
305 ammonites were recorded there. The Koenigi Zone age is confirmed by the marine

306 palynomorphs (see above). Studies by Wright (1968b) at Peckondale Hill, near Malton, and
307 cores from the Brown Moor Borehole (Gaunt *et al.* 1980), showed that the overlying Oxford
308 Clay Formation is older (Coronatum Zone) in the Burythorpe-Acklam area (northern margin
309 of the Market Weighton High) compared to the Yorkshire coast sections (Cleveland Basin),
310 where the basal Weymouth Member of the Oxford Clay Formation is earliest Oxfordian
311 (Mariae Zone) in age (Wright 1968a, 1983; Page 1989; Powell & Riding 2016). In the study
312 area (Fig. 13), there is a depositional hiatus between the Koenigi Zone (Kellaways Sand
313 Member) and the Athleta Zone (Oxford Clay Formation), with the Calloviense and Jason
314 zones missing (Page 1989, fig. 10). The northerly younging of the lowermost Oxford Clay
315 Formation and lateral lithofacies changes means that the Upper Callovian Hackness Rock
316 Member (Osgodby Formation) is absent to the south of the Cleveland Basin (Fig. 13).
317 Similarly, the Cornbrash and Cayton Clay formations of the Yorkshire coast are absent below
318 the Kellaways Sand Member in the Burythorpe area (Fig. 13), so that the latter rests
319 disconformably on the fluvial Scalby Formation (Ravenscar Group) of Bathonian age.

320 Terrestrial plant spores and marine palynomorphs are present in high proportions in
321 the clays sampled from the channel bases in the lower and upper parts of the Kellaways
322 Sand Member. As noted above, the occurrence of the marine palynomorph
323 *Impletosphaeridium varispinosum*, together with forms such as *Rigaudella aemula* and
324 *Rhynchodiniopsis cladophora*, is indicative of an Early Callovian age, supporting the
325 ammonite age determination. The Kellaways Sand Member, therefore, represents a
326 relatively condensed Lower Callovian (Koenigi Zone) succession separated, above and
327 below, by depositional hiatuses (Fig. 13).

328

329 **Palaeogeography**

330

331 During the Callovian, the palaeogeography of the Cleveland Basin (Fig.14) was characterised
332 by deposition of high energy, shoreface sands (Osgodby Formation) with a palaeoflow to the
333 south-south-east and south-south-west (Wright 1968a, 1978). The sands are characterised in
334 places (e.g. the Scarborough area and the Hambleton Hills) by a high percentage of iron in
335 the form of berthierene and framboidal pyrite ooids, probably derived from iron colloids in
336 shoreline lagoons that were redistributed offshore by storms (Wright 1978; Powell & Riding
337 2016). Intense faunal bioturbation of the sands indicates a long residence time on the
338 seafloor and a diverse burrowing infauna. The sands forming the lower part of the
339 succession (Red Cliff Rock Member) are thus in marked contrast to the unimodal, fine- to
340 medium-grained grained, non-ferruginous, sparsely bioturbated, tidal channel sands of their
341 approximate equivalents (Kellaways Sand Member) in the Burythorpe/Acklam area. Here,
342 the highly mobile, sub-tidal depositional regime generally precluded bioturbation of the
343 sand lithofacies.

344 Although the provenance of the sand from the Pennine High and Mid North Sea is
345 likely to have been the same for both areas, we attribute the Kellaways Sand Member
346 lithofacies to reworking and winnowing of highly mobile quartz sand in shallow, sub-tidal
347 environments on the northern margin of the Market Weighton High. The orientation of the
348 channels in Burythorpe Quarry and palaeocurrent indicators within the channels indicate
349 palaeoflow to the north-northwest (Fig. 14) in a depositional environment similar to the
350 sand-mud lithofacies of the Heligoland area of the North Sea (Reineck & Singh 1973). The
351 presence of occasional large, drifted wood fragments and abundant terrestrial
352 palynomorphs in the clay laminae of the Kellaway Sand Member suggest that the coastal
353 hinterland was relatively close.

354 The marked variation in thickness of the Kellaways Sand Member from at least 12 m
355 in the Burythorpe outcrop, to 5.5 m in the Brown Moor Borehole located to the south may
356 be due to active northerly downthrow as a syndepositional growth fault across the east-west
357 trending Burythorpe Fault (Fig. 2). East-west trending faults in the Howardian Hills (Fig. 14)
358 are known to pre-date the Cretaceous unconformity as part of the Cimmerian (Late Jurassic
359 to Early Cretaceous) tectonic events (Kirby and Swallow 1987). Syndepositional movement
360 across similar trending faults has been invoked for thickness variations in the Upper Jurassic
361 strata in the Howardian Hills (Wright 2009). Many of these faults were reactivated during the
362 Paleogene.

363

364

365 **Conclusions**

366

367 The Kellaways Sand Member in the Burythorpe area of the Howardian Hills yields
368 palynomorphs and ammonites of Early Callovian (Koenigi Zone) age. The member consists of
369 a yellow-white, poorly cemented, fine-to medium grained, unimodal sand with sparse grey
370 beds and laminae, in marked contrast to the broadly coeval Red Cliff Rock Member
371 (Osgodby Formation) of the Yorkshire Coast. The unimodal grain size, general absence of a
372 cement, and a low percentage of clay fines and other impurities makes it an ideal industrial
373 moulding sand.

374 The Callovian succession in the Burythorpe-Acklam area is relatively thin (ca 12 m
375 thick, thinning southwards to about 5 m) as compared to the more complete Osgodby
376 Formation of the Yorkshire coastal sections in the Cleveland Basin between Scarborough

377 and Cayton Bay, where it is up to 32.5 m thick. In the Burythorpe area, and the Howardian
378 Hills in general, only Lower Callovian strata are present, with depositional hiatuses above
379 and below. Thus, the lowermost Callovian Cornbrash and Cayton Clay formations (Herveyi
380 Zone) of the coastal succession are missing, as are equivalents of the Middle Callovian
381 Langdale and the Upper Callovian Hackness Rock members.

382 The Lower Callovian sands (Red Cliff Rock Member) in the Cleveland Basin, broadly
383 equivalent to the Burythorpe succession, are of a similar thickness (11-12 m) at Cayton Bay
384 and Scarborough, but thicken to the west to reach 14 m in Newtondale south; 18.9 m in
385 Newtondale north and 23 m in the Hambleton Hills (Wright 1968; Powell et al. 1992; Powell
386 & Riding 2016; J K Wright personal communication 2017). These regional thickness
387 variations and the marked local variations in thickness of the Kellaways Sand Member in the
388 Howardian Hills are probably due to differential movement on east-west trending, syn-
389 sedimentary faults associated with the Coxwold-Flamborough Fault Zone (Fig.14).

390 The Kellaways Sand Member in the Burythorpe area is interpreted as having been
391 deposited in a tidally influenced, shallow sea on the northern margins of the Market
392 Weighton High, in a shallow sub-tidal regime, similar to the sub-tidal sand-mud lithofacies in
393 the Heligoland region of the present North Sea. Compared to the more rapidly subsiding
394 Cleveland Basin, located to the north, subsidence on the flanks of the Market Weighton
395 High was significantly less. Winnowing of the sand in highly mobile subtidal channel regime
396 resulted in the unimodal grain size, lack of impurities, and a general absence of benthic
397 faunas and ichnofaunas. However, during quieter water phases, grey clay laminae were
398 deposited, especially at the base of channels, allowing colonisation of the substrate by
399 burrowing organisms. Sparse, calcite-cemented tabular beds with benthic fossils,

400 ammonites, *Planolites* burrows, mudstone rip-up clasts and wood fragments were
401 concentrated during periodic storm events.

402

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404

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410

411

412 **References**

413

414 Brasier, M.D. & Brasier, C.J. 1978. Littoral and fluvial facies in the “Kellaways Beds” on the
415 Market Weighton Swell. *Proceedings of the Yorkshire Geological Society*, **42**, 1-20.

416 British Geological Survey. 2017 (in prep.). *Digital Geological Map of Great Britain 1:10 000*
417 *scale (BGS Geology -10k) data*. Version 3.24. Keyworth, Nottingham: British Geological
418 Survey.

419 Davey, R.J. & Riley, L.A. 1978. Late and Middle Jurassic dinoflagellate cysts. In: Thusu, B.

420 (ed.), *Distribution of Biostratigraphically Diagnostic Dinoflagellate Cysts and Miospores*

421 *from the Northwest European Continental Shelf and adjacent areas. Continental Shelf*
422 *Institute Publication, 100, 31–45.*

423 Feist-Burkhardt, S. & Wille, W. 1992. Jurassic palynology in southwest Germany - state of
424 the art. *Cahiers de Micropaléontologie N.S. 7*), 141–156.

425 Gaunt G. D., Ivimey-Cook, H. C., Penn, I. E. & Cox, B. M. 1980. Mesozoic rocks proved by IGS
426 boreholes in the Humber and Acklam areas. Report of the Institute of Geological
427 Sciences, 79, 1–34.

428 Kent, P. E. 1955. The Market Weighton Structure. *Proceedings of the Yorkshire Geological*
429 *Society, 30, 197-227.*

430 Kent, P. E. 1974. Structural history. *In: Rayner, D. H. & Hemingway, J. E. (eds) The geology*
431 *and mineral resources of Yorkshire.* Yorkshire Geological Society, Leeds, 13–28.

432 Kirby, G.A. & Swallow, P.W. 1987. Tectonism and sedimentation in the Flamborough Head
433 region of north-east England. *Proceedings of the Yorkshire Geological Society, 46, 501-*
434 *509.*

435 Mellere, D. & Steel, R.J. 1996. Tidal sedimentation in Inner Hebrides half-grabens, Scotland:
436 the Mid-Jurassic Berreraig Sandstone Formation. *In: De Batist, M. & Jacobs, P.*
437 *(editors). Geology of Siliciclastic Shelf Seas.* Geological Society Special Publication, **117,**
438 *pp.49-79.*

439 Page, K.N. 1989. A stratigraphic revision for the English Lower Callovian. *Proceedings of the*
440 *Geologists' Association, 100, 363-382.*

441 Pousen, N.E. & Riding, J.B. 2003. The Jurassic dinoflagellate cyst zonation of Subboreal
442 Northwest Europe. *In: Ineson, J.R. & Surlyk, F. (editors). The Jurassic of Denmark and*
443 *Greenland.* Geological Survey of Denmark and Greenland Bulletin, **1, 115–144.**

- 444 Powell, J.H. 2010. Jurassic sedimentation in the Cleveland Basin: a review. *Proceedings of*
445 *the Yorkshire Geological Society*, **58**, 21-72.
- 446 Powell, J.H., Cooper, A.H. & Benfield, A.C. 1992. Geology of the country around Thirsk.
447 *Memoir of the British Geological Survey*, Sheet 52 (England and Wales). 129 pp.
- 448 Powell, J H & Riding, J B. 2016. Stratigraphy, sedimentology and structure of the Jurassic
449 (Callovian to Lower Oxfordian) succession at Castle Hill, Scarborough, North Yorkshire,
450 UK. *Proceedings of the Yorkshire Geological Society*, **61**, 109-133.
- 451 Rawson, P. F. & Wright, J. K. 2000. *The Yorkshire Coast*. Third edition. Geologists' Association
452 Guide 34.
- 453 Raynaud, J.F. 1978. Principaux dinoflagellés caractéristiques du Jurassique Supérieur
454 d'Europe du Nord. *Palinologia número extraordinario* **1**, 387–405.
- 455 Reineck, H.-E & Singh, I.B. 1973. *Depositional Sedimentary Environments with Reference to*
456 *Terrigenous Clastics*. Springer-Verlag, Berlin, 439 pp..
- 457 Riding, J.B. 1984. Dinoflagellate cyst range top biostratigraphy of the uppermost Triassic to
458 lowermost Cretaceous of northwest Europe. *Palynology*, **8**, 195–21.
- 459 Riding, J.B. 1987. Dinoflagellate cyst stratigraphy of the Nettleton Bottom Borehole
460 (Jurassic: Hettangian to Kimmeridgian), Lincolnshire, England. *Proceedings of the*
461 *Yorkshire Geological Society*, **46**, 231–266.
- 462 Riding, J.B. 2005. Middle and Upper Jurassic (Callovian to Kimmeridgian) palynology of the
463 onshore Moray Firth Basin, northeast Scotland. *Palynology*, **29**, 87–142.
- 464 Riding, J.B. & Sarjeant, W.A.S. 1985. The role of dinoflagellate cysts in the biostratigraphical
465 subdivision of the Jurassic System. *Newsletters on Stratigraphy*, **14**, 96–109.

466 Riding, J.B., Fedorova, V.A. & Ilyina, V.I. 1999. Jurassic and lowermost Cretaceous
467 dinoflagellate cyst biostratigraphy of the Russian Platform and northern Siberia, Russia.
468 *American Association of Stratigraphic Palynologists Contributions Series*, **36**, 179 pp.

469 Riding, J.B. 2016. The palynology of the Osgodby Formation (Middle Jurassic) of Burythorpe
470 Quarry, North Yorkshire. *British Geological Survey Internal Report*, **IR/16/028**. 26
471 pp. Riley, L.A. & Fenton, J.P.G. 1982. A dinocyst zonation for the Callovian to Middle
472 Oxfordian succession (Jurassic) of northwest Europe. *Palynology*, **6**, 193–202.

473 Sarjeant, W.A.S. 1959. Microplankton from the Cornbrash of Yorkshire. *Geological*
474 *Magazine*, **96**, 329–346.

475 Sellwood, B.W. 1972. Tidal flat sedimentation in the Lower Jurassic of Bornholm, Denmark.
476 *Palaeogeography, Palaeoclimatology, Palaeoecology*, **11**, 93-106.

477 Sellwood, B.W. 1975. Lower Jurassic tidal deposits, Bornholm, Denmark. In: Ginsberg, R. N.
478 (ed.) *Tidal Deposits: A Casebook of Recent Examples and Fossil Counterparts*. Springer-
479 Verlag, Berlin, 93-101.

480 Walker, K.G. 1972. The stratigraphy and bivalve fauna of the Kellaways beds (Callovian)
481 around South Cave and Newbald, East Yorkshire. *Proceedings of the Yorkshire*
482 *Geological Society*, **39**, 107-138.

483 Williams, G.L., Fensome, R.A. & MacRae, R.A. 2017. The Lentin and Williams index of fossil
484 dinoflagellates 2017 edition. *American Association of Stratigraphic Palynologists*
485 *Contributions*. Series 48, 1097 pp.

486 Woollam, R. 1980. Jurassic dinocysts from shallow marine deposits of the East Midlands,
487 England. *Journal of the University of Sheffield Geological Society*, **7.5**, 243–261.

488 Wright, J.K. 1968a. The stratigraphy of the Callovian Rocks between Newtondale and the
489 Scarborough Coast, Yorkshire. *Proceedings of the Geologists' Association*, **79**, 363-399.

- 490 Wright, J.K. 1968b. The Callovian succession at Peckondale Hill, Malton, Yorkshire.
491 *Proceedings of the Yorkshire Geological Society*, **41**, 325-346.
- 492 Wright, J.K. 1978. The Callovian succession (excluding Cornbrash) in the western and
493 northern parts of the Yorkshire Basin. *Proceedings of the Geologists' Association*, **89**,
494 259-261.
- 495 Wright, J.K. 1983. The Lower Oxfordian (Upper Jurassic) of North Yorkshire. *Proceedings of*
496 *the Yorkshire Geological Society*, **44**, 249-281.
- 497 Wright, J.K. 2009. The geology of the Corallian Ridge (Upper Jurassic) between Gilling East
498 and North Grimston, Howardian Hills, North Yorkshire. *Proceedings of the Yorkshire*
499 *Geological Society*, **57**, 193-216.

500 Appendices:

501 See separate file for Appendix 1 and 2

502

503

504

505 **Figure captions:**

506 Fig. 1. A simplified geological map of the Cleveland Basin and the northern part of the East
507 Midlands Shelf, UK, illustrating the main localities discussed herein and the approximate
508 position, at depth, of the Market Weighton High. Inset map shows general location.

509 Fig.2. A geological map depicting the outcrop of the Kellaways Sand Member near
510 Burythorpe and the location of Burythorpe Quarry. Note the southward thinning of this unit
511 and the unconformable Chalk Group (Cretaceous).

512 Fig.3. A generalised map of Burythorpe Quarry in 2015 indicating the channel complexes
513 illustrated in the figures and the surface exposure (i.e., archaeological excavations) from
514 which many of the ammonite specimens were collected. The map is based on information
515 provided by the Yorkshire Mineral Company Limited.

516 Fig. 4. The north-east face of Burythorpe Quarry illustrating Channel Complex 3 (see Fig. 3).
517 The erosional bases of two channels are shown, together with an *in-situ* concretion.
518 Palynology sample 1 was collected from grey claystone bed at the base of the channel.

519 Fig. 5. A cross-section of Channel Complex 1 at Burythorpe Quarry (see Fig. 3) showing the
520 erosional bases of stacked channels (dashed lines) with a higher proportion of grey

521 claystone beds and laminae at the base of the channels. Note the low-angle lateral accretion
522 and vertical accretion within the channels. The inset shows the detail of clay-filled
523 downward, penetrating microfaults and minor bioturbation at the base of the channel.

524 Fig. 6. Erosive bases of stacked channel margins at Burythorpe Quarry showing gently
525 inclined, finely laminated cross-bedding dipping to the right in the lower channel, with
526 downward penetrating micro-faults. The upper channel-fill shows a bed of clay (palynology
527 sample 2) at the base and an incipient concretion that preserves original cross-lamination.
528 The hammer for scale is 30 cm in length. The section represents the right-hand side of Fig. 4.

529 Fig. 7. Finely laminated, cross-bedding in sand and clay at the base of the upper channel at
530 Burythorpe Quarry (see Fig. 5) showing sparse vertical *Skolithos* and horizontal *Planolites*
531 burrows.

532 Fig. 8. Longitudinal (NE-W) and transverse sections across channel complex 2 at Burythorpe
533 Quarry showing laterally accreted low angle cross-bedding (right) at the channel margin
534 passing to vertically accreted channel fill sand and an overlying claystone plug. Note the
535 inclined climbing ripple cross-lamination at the right in the far face (and inset) at right angles
536 to the channel showing palaeoflow to the north-east.

537 Fig. 9. Tabular calcite cemented storm beds at Burythorpe Quarry showing **(a)** wave ripples,
538 **(b)** mudstone rip-up clasts and wood fragments, **(c)** branching *Planolites* burrows
539 (enlargement of b), and **(d)** mudstone-flake conglomerate. The scale is 1 cm; the hammer in
540 (a) is 30 cm long.

541 Fig. 10. Examples of Lower Callovian (Koenigi Zone) ammonites from Burythorpe Quarry
542 entombed in hard calcareous concretions from the middle part of the Kellaways Sand
543 Member. The scale is in centimetres; coin is 2 cm in diameter.

544 Fig. 11. Examples of medium-size, calcite-cemented concretions in the middle part of the
545 section at Burythorpe Quarry; note the disruptive growth of the concretions that has cut
546 across the sand and clay beds (right) which has obscured bedding (see inset photograph for
547 enlargement). The scale card is in centimetres.

548 Fig. 12. Selected dinoflagellate cysts from palynology sample 2 collected at Burythorpe Sand
549 Quarry (see text for details). The images were all taken using Nomarski Interference
550 Contrast. The specimens are all from slide MPA 67359/2, and are curated in the palynology
551 collections of the British Geological Survey, Nottingham, UK. References for the author
552 citations given can be found in Williams et al. (2017).

553 A. *Nannoceratopsis pellucida* Deflandre 1938. Specimen MPK 14644. Overall length: 82 μm ;
554 maximum width: 44 μm .

555 B. *Kalyptea stegasta* (Sarjeant 1961) Wiggins 1975. Specimen MPK 14645. Overall length:
556 104 μm ; maximum width: 71 μm .

557 C. *Impletosphaeridium varispinosum* (Sarjeant 1959) Islam 1993. Specimen MPK 14646. The
558 cyst body (i.e. excluding processes) is 51 μm x 44 μm .

559 D. *Wanaea acollaris* Dodekova 1975. Specimen MPK 14647. Overall length: 42 μm ;
560 maximum width: 58 μm .

561 E. *Mendicodinium groenlandicum* (Pocock & Sarjeant 1972) Davey 1979. Specimen MPK
562 14648. Maximum length: 42 μm ; maximum width: 60 μm .

563 Fig. 13. Correlation of the Kellaways Sand Formation in the Acklam/Burytorpe area within
564 the Cleveland Basin (Yorkshire Coast) and the East Midlands Shelf, after Wright (1968a),
565 Gaunt *et al.* (1980) and Page (1989). Note the hiatuses above and below the Kellaways Sand
566 Member in the study area, and the northwards younging of the Oxford Clay Formation
567 lithofacies between Burythorpe (Koenigi Zone) and the Yorkshire Coast (base of the Mariae
568 Zone).

569 Fig. 14. Lower Callovian palaeogeography in the Cleveland Basin and the northern part of
570 the East Midlands Shelf. This illustrates the tidally influenced succession in the Burythorpe
571 area, located on the north-west margin of the Market Weighton High, which contrasts with
572 the generally thicker siliciclastic sand lithofacies, locally with ferruginous ooids, in the more
573 rapidly subsiding Cleveland Basin where a more complete Middle and Upper Callovian
574 succession is preserved. The red dashed line illustrates the approximate transition zone
575 between the basin and high, and the probable influence of synsedimentary faulting
576 associated with the Flamborough Fault Zone; the latter, and other, faults are shown by
577 dashed black lines.

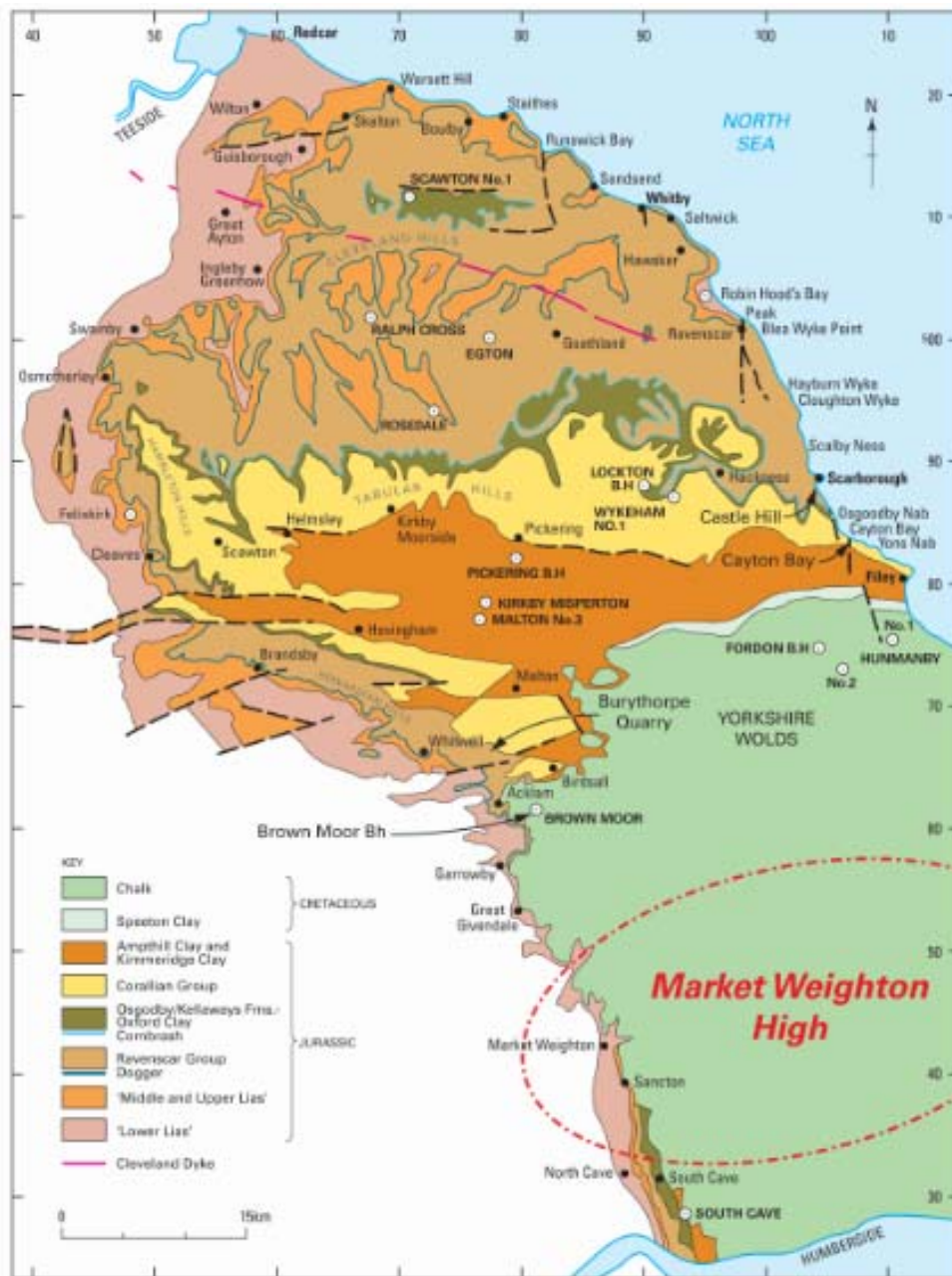


Fig. 1

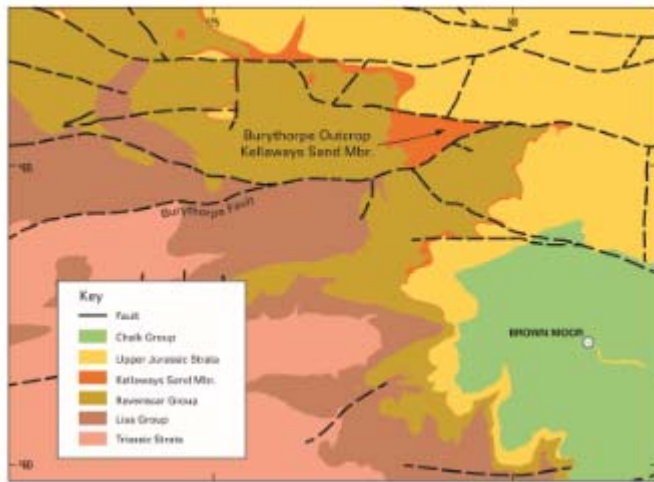


Fig. 2

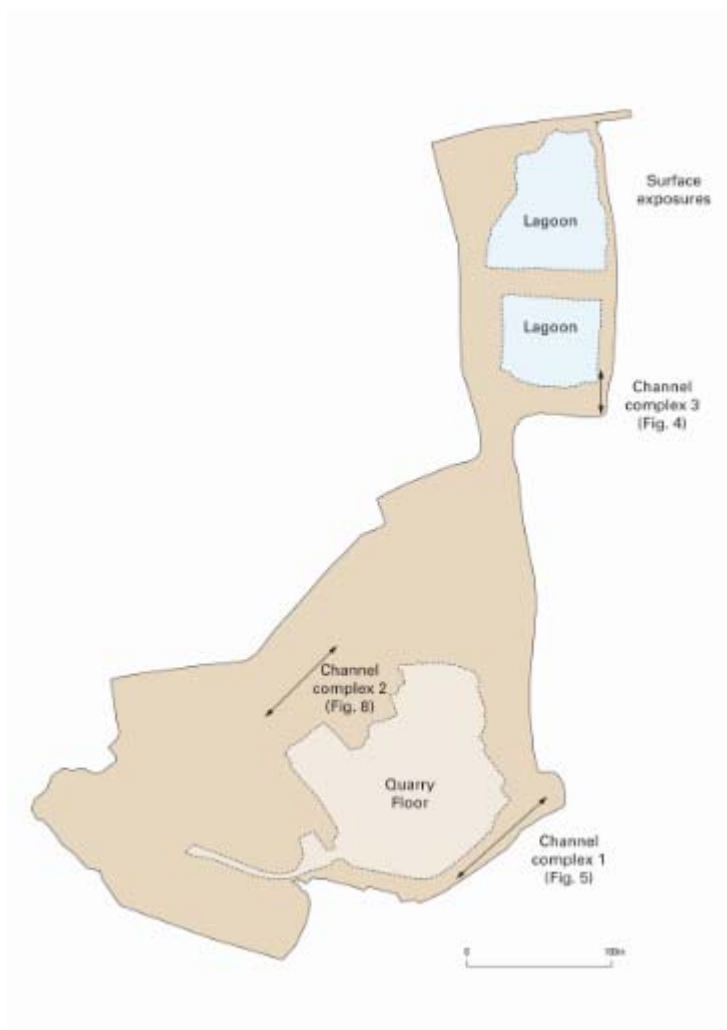


Fig.3



Fig. 4



Fig. 5



Fig. 6

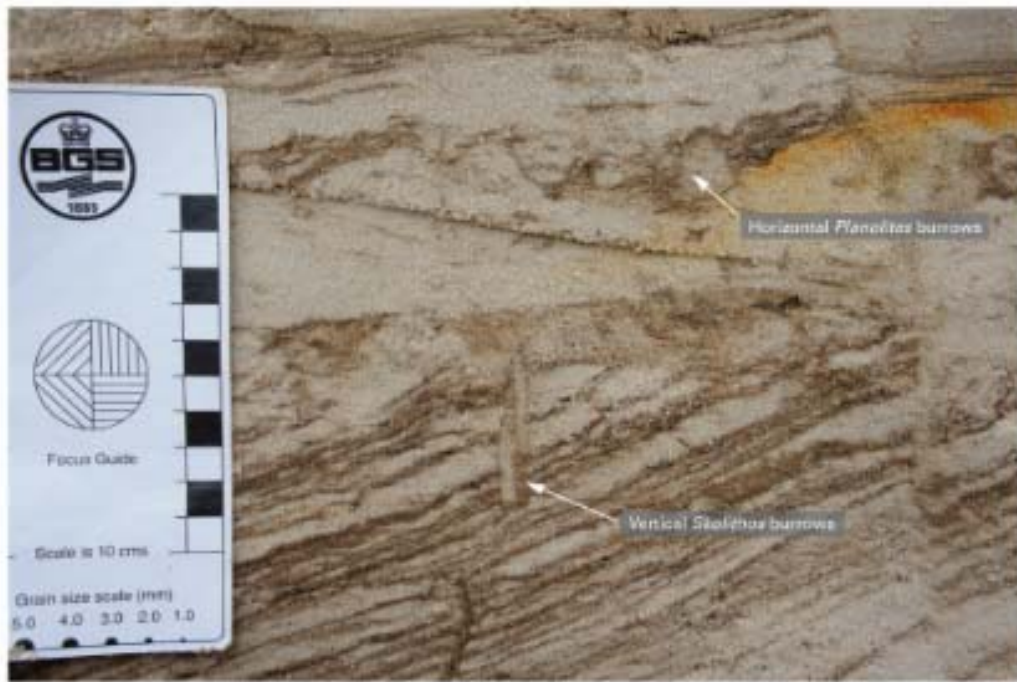


Fig.7

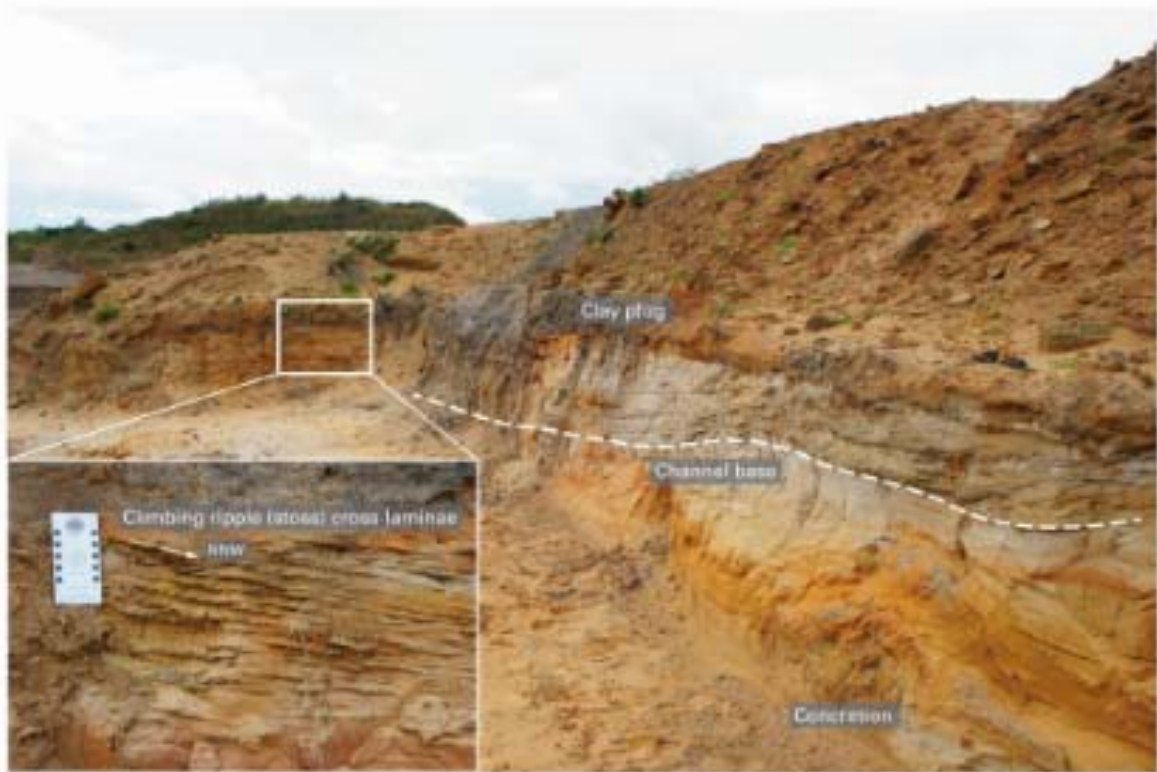


Fig. 8

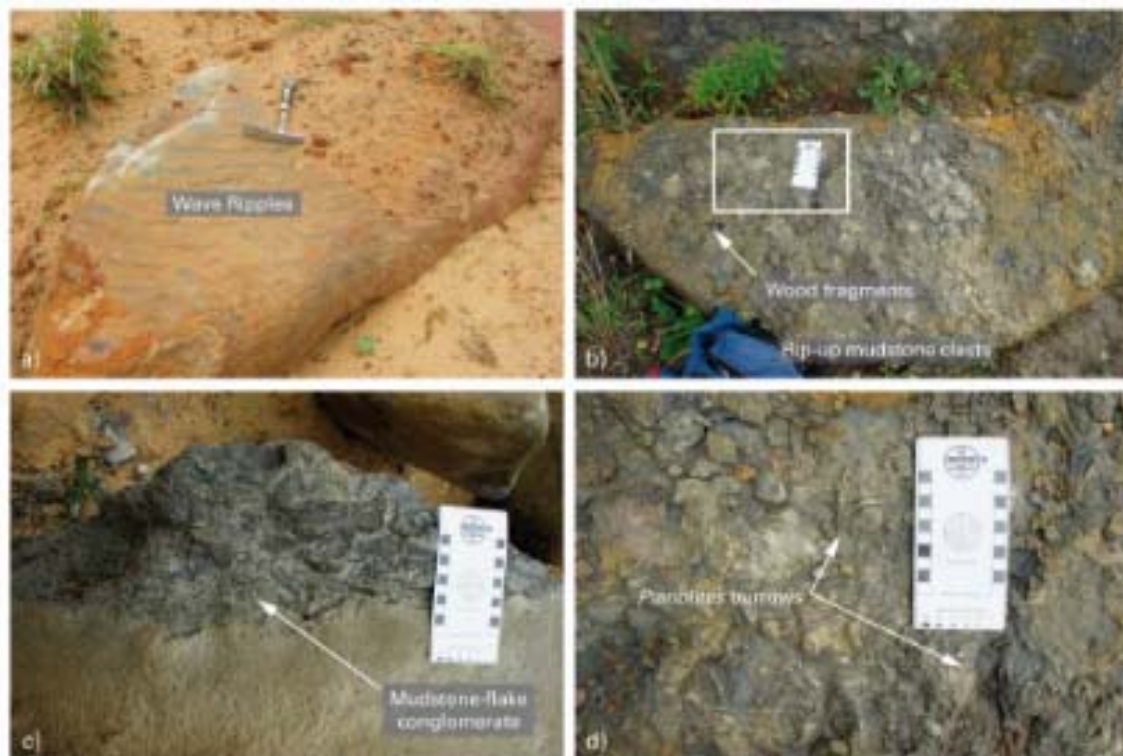


Fig.9



Fig.10



Fig.11

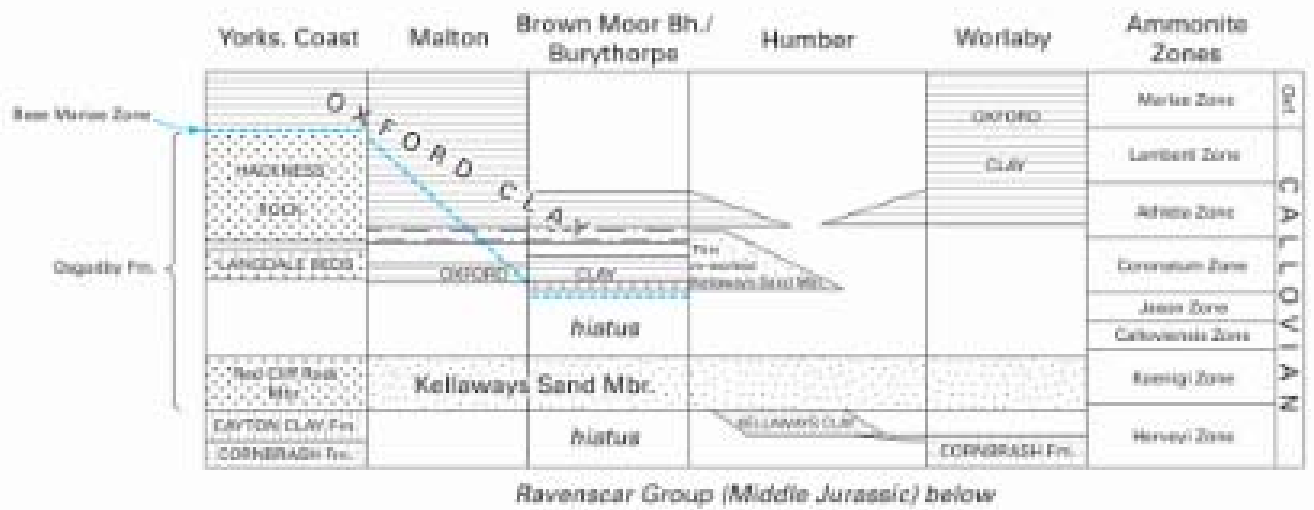


Fig 12

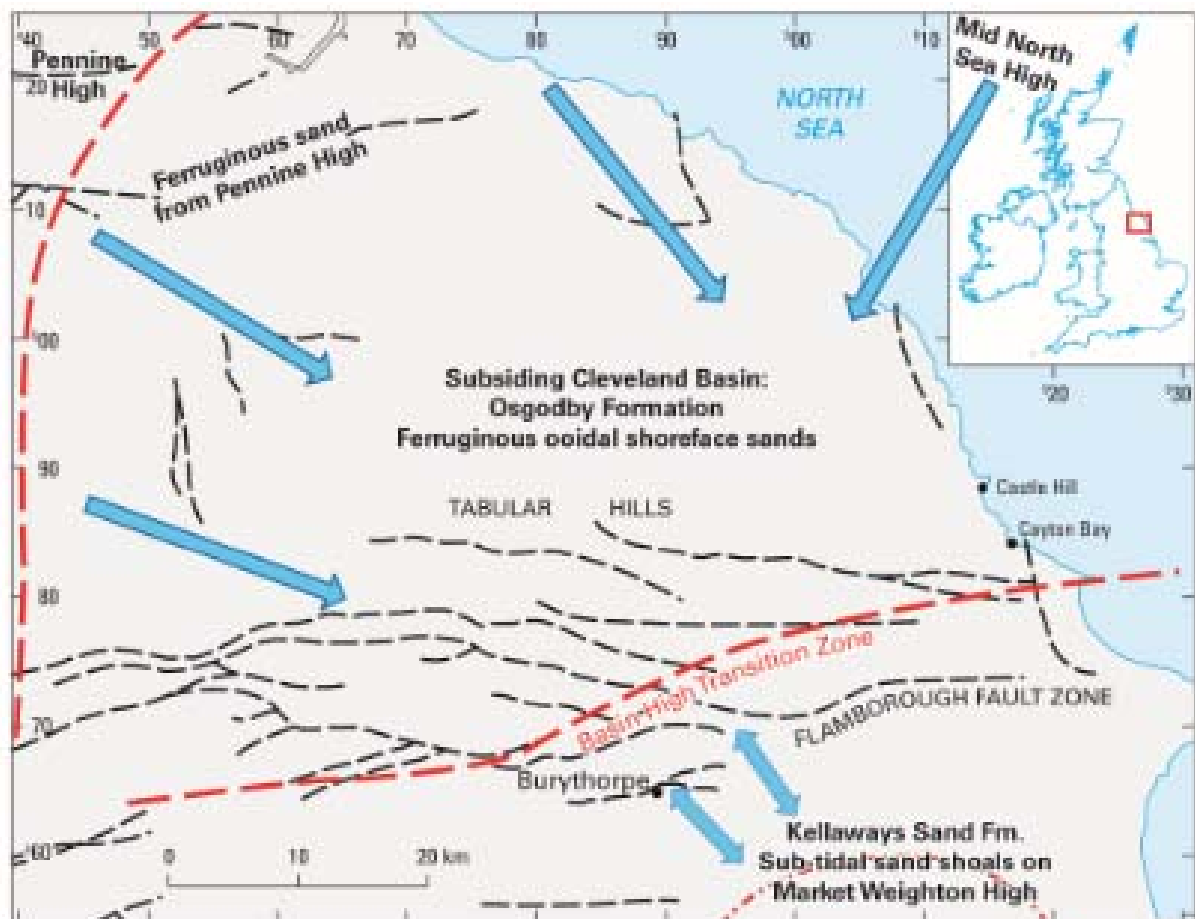


Fig. 13