Sedimentology and stratigraphy of the Kellaways Sand Member (Lower Callovian), Burythorpe, North Yorkshire, UK

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

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

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

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

Geological setting

Following Page (1989), the Callovian succession at Burythorpe is referred to the Kellaways Sand Member to distinguish it from the Osgodby Formation of the Cleveland Basin located to the north and north-east (Fig. 1). It lies at the southern end of the Howardian Hills, within a wedge-shaped outcrop bounded to the north and south-east by normal faults (Figs 2, 3) (British Geological Survey 2017). The friable moulding sand is distinguished in the field by its fine- to medium-grain size and white to yellow-white colour; large, hard calcite-cemented concretions (locally known as bullions) up to 3 m in diameter are present throughout the succession (Fig. 4). Approximately 3 km to the south of Burythorpe, the member disappears below the overstepping Cretaceous (Chalk Group) unconformity, but it was proved below Upper Jurassic rocks, Carstone and the Chalk Group in the nearby Brown Moor Borehole [NGR SE 8126 6203] (Gaunt *et al*. 1980) and reappears at outcrop before the member is cut out below the Cretaceous unconformity about 15 km to the south of Acklam on the north-western margin of the Market Weighton High. To the south of the Market Weighton High, near South Cave (Fig.1), the Callovian succession is represented by the uncemented sands of the Kellaways Sand Member and the overlying calcareous, shelly Cave Rock Member (Walker 1972; Brasier & Brasier 1978; Page 1989).

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

Sedimentology

Introduction

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

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

In contrast with the poorly lithified channel sandstone, thin, hard calcareous-cemented tabular beds occasionally form cap-rocks to the large calcite-cemented concretions (Wright 1978). The calcite-cemented beds are characterised by mudstone rip-up clasts, mudstone-flake conglomerates, wave ripples and sparse *Planolites* burrows (Fig. 9). The large calcite concretions have also yielded sparse ammonites (Fig. 10). Concentric, ferruginous growth lines in incipient concretions cut across the bedding (Figs 6, 11), indicating that the concretions post-date sedimentation and the micro-faulting seen in the lower parts of the channels. More evolved concretions cut across and destroy original bedding features (Fig. 11). Migration of carbonate ions to the concretionary centres may have been initiated by mobilisation of original calcium carbonate cements in the tabular cap rocks.

Interpretation

The low-angle, vertically and laterally accreted channels and early diagenetic microfaults bear a remarkable similarity to the inter-tidal and sub-tidal channels described from the present-day North Sea between Heligoland and the north German coast (Reineck & Singh 1973). The shelf-sand-mud lithofacies of these authors are interpreted to have been deposited in water depths of between 10-15 m and exhibit many of the features seen in the Burythorpe succession described above. These include finely intercalated, fine-grained sand and mud lithologies, flaser and lenticular bedding, laminated sand and ripple cross-bedding bedding, and shelly storm deposited layers. Reineck & Singh (1973) showed that the intertidal sands in the North Sea were derived from tidal flats located near the coast of Germany. We envisage that the Kellaways Sand Member was deposited on the north-west margins of the Market Weighton High where the sediments were winnowed in a shallow sub-tidal regime, which resulted in deposition of fine- to medium-grained, unimodal sand with few impurities. Low-angle sub-tidal channels were eroded in the sand during ebb tidal flow. During periods of slack-water (waning flow), flocculating clay was deposited at the base of some of the channels, and was also locally interbedded with sand laminae during gradual lateral and vertical fill of the channels. Low angle, lateral accretion cross-bedding at channel margins indicates a sinuous to meandering channel morphology. The presence of marine and terrestrial palynomorphs, together with drifted wood fragments in the claystone beds, suggest deposition in a shallow marine setting close to the alluvial, vegetated hinterland. Dewatering due to sediment loading within the channels resulted in multiple phases of microfaulting and injection of clay laminae downwards along these fractures. Similar sub-tidal sand-mud channels with water escape feature were described by Sellwood (1972, 1975) from the Lower Jurassic of Bornholm, although the overall sedimentary regime in that succession was a shallower tidal flat. Middle Jurassic sandstone on the islands of Skye and Raasay, north-west Scotland, is interpreted as a tidal deposit (Mellere & Steel 1996) with low angle channel-fill and dewatering structures. The estuarine, tidal channel-fill deposits in the upper part of the Bearreraig Sandstone Formation (Bajocian) on Raasay exhibit many features seen in the Burythorpe sections.The absence of benthic macrofauna within the tidal channels suggests that the fine- to medium-grained sand substrate was highly mobile because of the high energy tidal regime, so that bottom conditions were not suited to colonisation by benthic fauna. However, sparse vertical and horizontal burrows (Fig. 7) associated with grey clay lamina at the base of some channels indicate the substrate was colonised by burrowing organisms during periods of waning flow.

In contrast, the tabular bedded, calcareous-cemented beds, often preserved at the top of the hard concretions, show features typical of storm-induced sedimentation. These include the presence of mudstone rip-up clasts and mudstone conglomerates, large drifted wood fragments, occasional bivalves and brachiopods, and sparse ammonites. Deposition of these 'clastic' elements probably occurred during storm surge-ebb events across the sub-tidal flats. Reineck & Singh (1973) described similar shelly, storm deposited beds within their sub-tidal sand-mud lithofacies in the Heligoland region of the North Sea.

The Callovian succession at Burythorpe differs in detail from the broadly coeval succession on the southern flanks of the Market Weighton High at South Cave (Fig. 1) (Brasier & Brasier 1978). In the Humberside area, the Kellaways Sand Member also comprises uncemented sands, but with bands rich in the bivalves *Gryphaea* sp*.* and *Catinula* sp*.*, as well as byssally attached bivalves (*Oxytoma* and *Meleagrinella* spp.) with sparse ammonites and abundant belemnites. In addition, the sands are more intensively bioturbated and have a more diverse ichnofauna (including *Ophiomorpha and Thalassinoides*) than seen at Burythorpe. The succession at South Cave was interpreted as being deposited in a tidal regime as laterally migrating point bars with macrofauna preserved as lags in the base of channels. This contrasts with the Burythorpe succession where infaunal trace fossils are sparse and the clays at the base of channels are devoid of macrofossils. The latter are, in contrast, preserved in tabular cemented sands along with mudstone rip-up clasts, features reported from the modern North Sea (Reineck & Singh 1973). Brasier & Brasier (1978) also noted the absence of flaser bedding and wavy bedding, small-scale ripples or megaripples at South Cave, all sedimentary structures seen at Burythorpe (Figs 8, 9). The differences noted above may be attributed to slower sedimentation rates in a lower energy tidal regime at South Cave, with longer sediment residence time (e.g. as indicated by higher bioturbation and common epifaunal gryphaeate bivalves) compared to a higher energy sub-tidal shoal environment at Burythorpe. Although the successions in both areas suggest that the sands were winnowed and well-sorted in a tidal regime on the flanks of the Market Weighton High, the presence of the postulated Cleveland Basin margin hinge (basin-shelf) line a few tens of kilometres to the north of Burythorpe (Fig. 1) would have created a more hydrodynamically active regime in contrast to the lower energy regime of East Midlands Shelf to the south of Humberside.

Biostratigraphy

Palynology

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

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

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

Sample 2 is unequivocally of Callovian age. The range bases of the dinoflagellate cysts *Gonyaulacysta jurassica* subsp. *adecta* (consistent), *Mendicodinium groenlandicum, Rigaudella aemula* and *Rhynchodiniopsis cladophora* (and the acritarch *Fromea tornatilis*) are all intra-Callovian, and the range tops of *Ctenidodinium continuum*, *Korystocysta* spp. (common) and *Wanaea acollaris* are typically intra-Callovian (Raynaud 1978; Riley & Fenton 1982; Riding 1984, 2005; Riding & Sarjeant 1985; Riding *et al*. 1999; Poulsen & Riding 2003). Furthermore, common *Mendicodinium groenlandicum* is typical of the Callovian (Woollam 1980). However, the key biostratigraphically significant dinoflagellate cysts are *Impletosphaeridium varispinosum, Kalyptea stegasta* and common *Meiourogonyaulax caytonense*. *Impletosphaeridium varispinosum* is a distinctive chorate (spine-bearing) species, which is a reliable marker for the Early Callovian (Herveyi to Calloviense zones) (Riley & Fenton 1982; Riding 2005; Feist Burkhardt & Wille 1992). There is a single report of this taxon from the latest Bathonian (Riding 1987, fig. 4), but this is not thought to be significant. The presence of *Kalyptea stegasta* and common *Meiourogonyaulax caytonense* is also typical of the Early and Mid Callovian (Sarjeant 1959; Davey & Riley 1978; Riley & Fenton 1982; Riding 1987; Powell & Riding 2016). In summary, the occurrence of *Impletosphaeridium varispinosum,* together with forms such as *Rigaudella aemula* and *Rhynchodiniopsis cladophora,* is unequivocally indicative of an Early Callovian age. Sample 2 is, therefore, statigraphically coeval with the Red Cliff Rock Member of the Osgodby Formation in the Cleveland Basin (Wright 1968a, 1978; Page 1989; Powell & Riding 2016).

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

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

Ammonite biostratigraphy

As noted above, benthic and necktonic macrofauna are relatively sparse in the Kellaways Sand Member at Burythorpe. Where present, these macrofossils are restricted to tabular, hard calcite-cemented beds and small concretions in the uppermost part of the member, or within larger, late diagenetic concretions in the lower part of the quarry (Fig. 10). The concretions have been observed *in situ* at various stages of late-stage diagenetic development (Figs 6, 11). However, some of the large (> 1 m diameter) concretions have been moved during quarrying operations to an adjacent part of the quarry and are not *in situ*. Consequently, it is not certain if the some of the large ammonite-bearing concretions are always in their original stratigraphical position. However, it is certain that the concretions were located within the lower to middle part of the member and that, as noted by Wright (1978), the upper part of the concretions often comprises a tabular bedded cap-rock with benthic fauna, mudstone rip-up clasts and wood fragments. Due to the extremely hard nature of the large calcareous concretions in the main quarry, it has not been possible to extract whole specimens from the surrounding matrix; those identified were photographed in the field and compared with published reference material. However, a recent near-surface archaeological excavation in a planned northern extension to the quarry (Fig. 3) exposed small calcareous concretions from the uppermost surface levels of the member, which included fragmentary ammonites and bivalves. Ammonites identified by P.F.R. and J.K. Wright during the current study include the genera *Kepplerites, Chamoussetia* and *Pseudocadoceras* (Fig. 10). Together with well-preserved samples collected earlier from the quarry by J.K. Wright and R. Myerscough, the full ammonite list is: *Kepplerites (Gowericeras) curtilobus* (S.Buckman) (4 specimens); *K. (G.) trichophorum* (S. Buckman) (1 specimen); *Kepplerites* sp. (microconch); *Proplanulites aff. crassiruga* (S. Buckman) (2 specimens); *Chamoussetia phillipsi* Callomon & Wright (4 specimens); and *Pseudocadoceras boreale* S. Buckman (2 specimens) (J.K. Wright personal communication 2017). The ammonite assemblage is representative of the Lower Callovian, Koenigi Zone, Curtilobus Subzone (J.K. Wright personal communication 2017) which is broadly coeval with the Red Cliff Rock Member (Osgodby Formation) of the Cleveland Basin (Wright 1978; Page 1989; Powell & Riding 2016).

Chronostratigraphy

The Koenigi Zone, Curtilobus Subzone age for the Kellaways Sand Member (Fig. 12) indicated by the ammonites is earlier than the Calloviense Zone attributed to the equivalent beds in the nearby Brown Moor Borehole (Gaunt *et al*. 1980), although no Calloviense age ammonites were recorded there. The Koenigi Zone age is confirmed by the marine palynomorphs (see above). Studies by Wright (1968b) at Peckondale Hill, near Malton, and cores from the Brown Moor Borehole (Gaunt *et al*. 1980), showed that the overlying Oxford Clay Formation is older (Coronatum Zone) in the Burythorpe-Acklam area (northern margin of the Market Weighton High) compared to the Yorkshire coast sections (Cleveland Basin), where the basal Weymouth Member of the Oxford Clay Formation is earliest Oxfordian (Mariae Zone) in age (Wright 1968a, 1983; Page 1989; Powell & Riding 2016). In the study area (Fig. 13), there is a depositional hiatus between the Koenigi Zone (Kellaways Sand Member) and the Athleta Zone (Oxford Clay Formation), with the Calloviense and Jason zones missing (Page 1989, fig. 10). The northerly younging of the lowermost Oxford Clay Formation and lateral lithofacies changes means that the Upper Callovian Hackness Rock Member (Osgodby Formation) is absent to the south of the Cleveland Basin (Fig. 13). Similarly, the Cornbrash and Cayton Clay formations of the Yorkshire coast are absent below the Kellaways Sand Member in the Burythorpe area (Fig. 13), so that the latter rests disconformably on the fluvial Scalby Formation (Ravenscar Group) of Bathonian age.

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

Palaeogeography

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

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

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

Conclusions

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

The Callovian succession in the Burythorpe-Acklam area is relatively thin (ca 12 m thick, thinning southwards to about 5 m) as compared to the more complete Osgodby Formation of the Yorkshire coastal sections in the Cleveland Basin between Scarborough and Cayton Bay, where it is up to 32.5 m thick. In the Burythorpe area, and the Howardian Hills in general, only Lower Callovian strata are present, with depositional hiatuses above and below. Thus, the lowermost Callovian Cornbrash and Cayton Clay formations (Herveyi Zone) of the coastal succession are missing, as are equivalents of the Middle Callovian Langdale and the Upper Callovian Hackness Rock members.

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

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

Acknowledgements

The authors thank Dr. John K. Wright for his help in identifying the ammonite specimens, and for his supportive advice on the manuscript. We are very grateful to Simon Broad and the Yorkshire Mineral Company Limited for allowing access to the quarry and advice on the succession. We thank Ian Longhurst (BGS) for preparing the figures. All authors except PFR publish with the approval of the Executive Director, British Geological Survey (NERC).

References

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

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

Davey, R.J. & Riley, L.A. 1978. Late and Middle Jurassic dinoflagellate cysts. In: Thusu, B. (ed.), *Distribution of Biostratigraphically Diagnostic Dinoflagellate Cysts and Miospores* *from the Northwest European Continental Shelf and adjacent areas.* Continental Shelf Institute Publication, 100, 31–45.

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

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

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

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

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

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

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

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

Powell, J.H. 2010. Jurassic sedimentation in the Cleveland Basin: a review. *Proceedings of the Yorkshire Geological Society*, **58**, 21-72.

Powell, J.H., Cooper, A.H. & Benfield, A.C. 1992. Geology of the country around Thirsk. *Memoir of the British Geological Survey*, Sheet 52 (England and Wales). 129 pp.

Powell, J H & Riding, J B. 2016. Stratigraphy, sedimentology and structure of the Jurassic (Callovian to Lower Oxfordian) succession at Castle Hill, Scarborough, North Yorkshire, UK. *Proceedings of the Yorkshire Geological Society*, **61**, 109-133.

Rawson, P. F. & Wright, J. K. 2000. *The Yorkshire Coast*. Third edition. Geologists' Association Guide 34.

Raynaud, J.F. 1978. Principaux dinoflagellés caractéristiques du Jurassique Supérieur d'Europe du Nord. *Palinologia número extraordinario* **1**, 387–405.

Reineck, H.-E & Singh, I.B. 1973. *Depositional Sedimentary Environments with Reference to Terrigenous Clastics.* Springer-Verlag, Berlin, 439 pp..

Riding, J.B. 1984. Dinoflagellate cyst range top biostratigraphy of the uppermost Triassic to lowermost Cretaceous of northwest Europe. *Palynology,* **8**, 195–21.

Riding, J.B. 1987. Dinoflagellate cyst stratigraphy of the Nettleton Bottom Borehole (Jurassic: Hettangian to Kimmeridgian), Lincolnshire, England. *Proceedings of the Yorkshire Geological Society*, **46**, 231–266.

Riding, J.B. 2005. Middle and Upper Jurassic (Callovian to Kimmeridgian) palynology of the onshore Moray Firth Basin, northeast Scotland. *Palynology*, **29**, 87–142.

Riding, J.B. & Sarjeant, W.A.S. 1985. The role of dinoflagellate cysts in the biostratigraphical subdivision of the Jurassic System. *Newsletters on Stratigraphy,* **14**, 96–109.

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

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

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

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

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

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

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

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

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

Wright, J.K. 1968b. The Callovian succession at Peckondale Hill, Malton, Yorkshire. *Proceedings of the Yorkshire Geological Society*, **41**, 325-346.

Wright, J.K. 1978. The Callovian succession (excluding Cornbrash) in the western and northern parts of the Yorkshire Basin. *Proceedings of the Geologists' Association*, **89**, 259-261.

Wright, J.K. 1983. The Lower Oxfordian (Upper Jurassic) of North Yorkshire. *Proceedings of the Yorkshire Geological Society*, **44**, 249-281.

Wright, J.K. 2009. The geology of the Corallian Ridge (Upper Jurassic) between Gilling East and North Grimston, Howardian Hills, North Yorkshire. *Proceedings of the Yorkshire Geological Society*, **57**, 193-216.

Appendices:

See separate file for Appendix 1 and 2

Figure captions:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

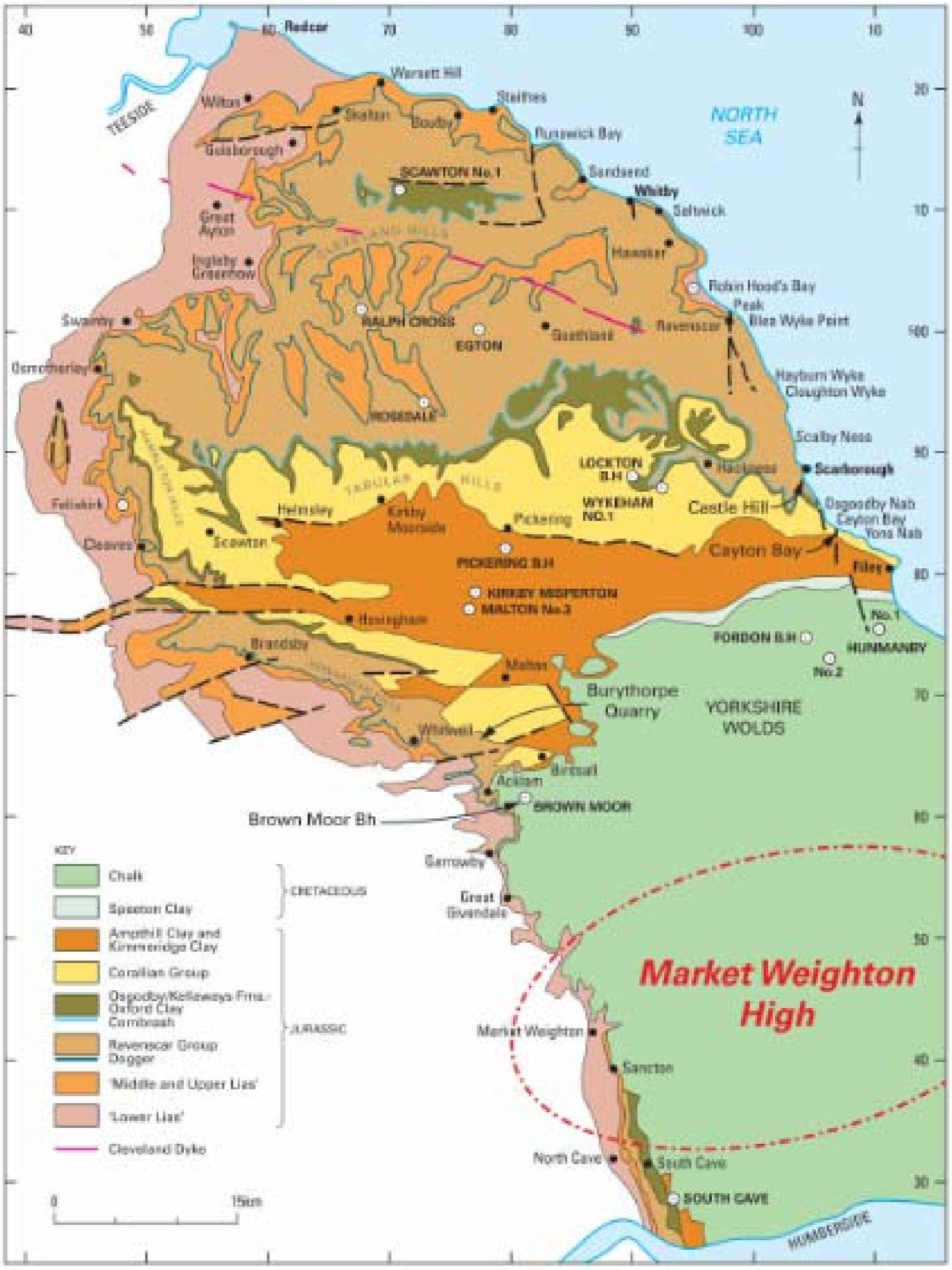
40
50
60
Redcar
70
80
90
100
10
TEESIDE
Wilton
Warsett Hill
Skelton
Boulby
Staithes
Runswick Bay
Guisborough
SCAWTON No.1
Sandsend
Whitby
Saltwick
NORTH SEA
N
Great Ayton
Ingleby Greenhow
Hawsker
Robin Hood's Bay
Peak
Blea Wyke Point
Swainby
RALPH CROSS
EGTON
Goathland
Ravenscar
Osmotherley
Hayburn Wyke
Cloughton Wyke
ROSEDALE
Scalby Ness
LOCKTON B.H
Hackness
Scarborough
TABULAR HILLS
WYKEHAM NO.1
Castle Hill
Osgodby Nab
Cayton Bay
Yons Nab
Felixkirk
Helmsley
Kirkby Moorside
Pickering
Cleaves
Scawton
PICKERING B.H
Cayton Bay
Filey
KIRKBY MISPERTON
MALTON No.3
Hovingham
No.1
FORDON B.H
HUNMANBY
Brandsby
No.2
Malton
Burythorpe Quarry
YORKSHIRE WOLDS
Whitwell
Birdsall
Acklam
BROWN MOOR
Brown Moor Bh
Garrowby
Great Givendale
Market Weighton High
Market Weighton
Sancton
North Cave
South Cave
SOUTH CAVE
HUMBERSIDE
20
10
100
90
80
70
60
50
40
30
KEY
Chalk
Speeton Clay
CRETACEOUS
Ampthill Clay and Kimmeridge Clay
Corallian Group
Osgodby/Kellaways Fms.-Oxford Clay
Cornbrash
JURASSIC
Ravenscar Group
Dogger
'Middle and Upper Lias'
'Lower Lias'
Cleveland Dyke
0
15km

Fig. 1

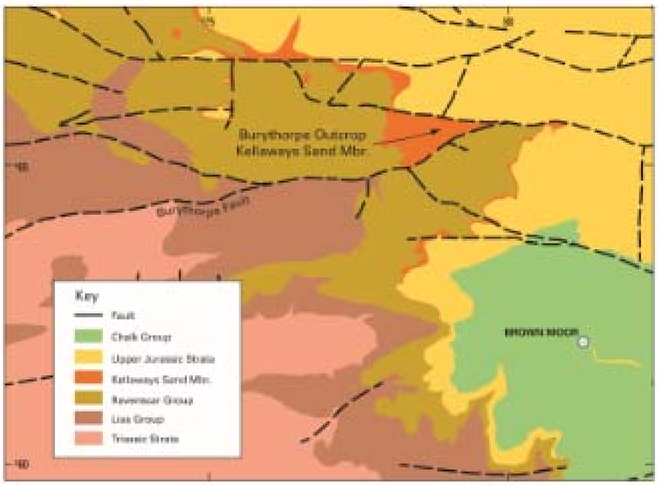
Burythorpe Outcrop
Kellaways Sand Mbr
Burythorpe Fault
BROWN MOOR
Key
Fault
🟩 Chalk Group
Upper Jurassic Strata
Kellaways Sand Mbr.
Ravenscar Group
Lias Group
Triassic Strata

Fig. 2

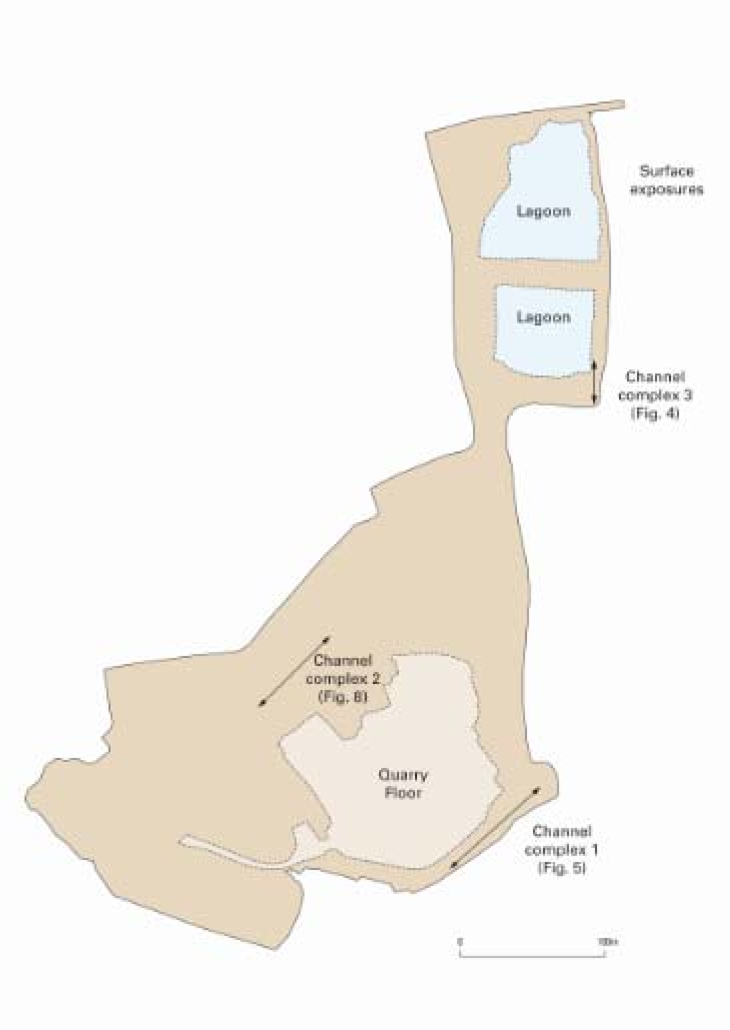
Surface exposures
Lagoon
Lagoon
Channel complex 3 (Fig. 4)
Channel complex 2 (Fig. 8)
Quarry Floor
Channel complex 1 (Fig. 5)
0
100m

Fig.3

Fig. 4

Fig. 5


Incipient concretion
Clay bed.
Base of channel
Clay microfaults at base of channel

Fig. 6


BGS
Focus Guide
Scale is 10 cms
Grain size scale (mm)
5.0 4.0 3.0 2.0 1.0
Horizontal *Planolites* burrows
Vertical *Skolithos* burrows

Fig.7

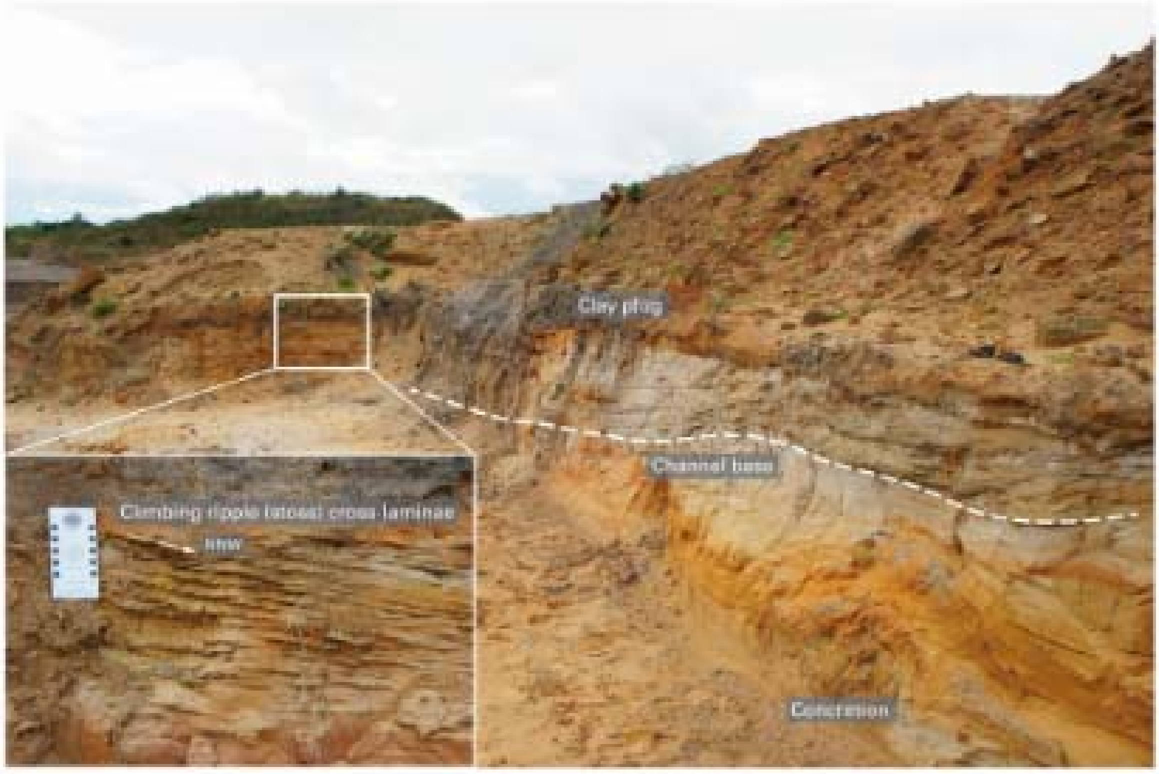
Clay plug
Climbing ripple lateral cross-laminae
ssw
Channel base
Concretion

Fig. 8

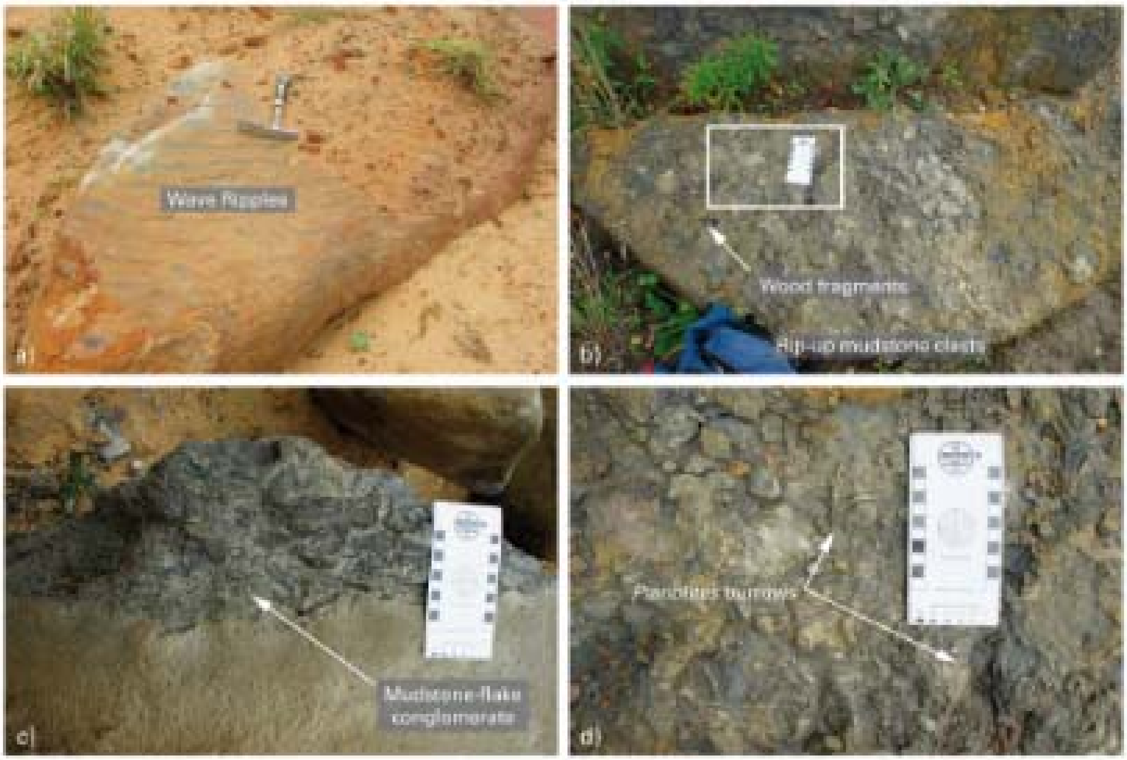
Wave Ripples
a)
Wood fragments
Rip-up mudstone clasts
b)
Mudstone-flake conglomerate
c)
Planolites burrows
d)

Fig.9


Kepplerites sp.
Pseudocadoceras sp.
Cadoceras sp.

Fig.10


Incipient concretions

Fig.11

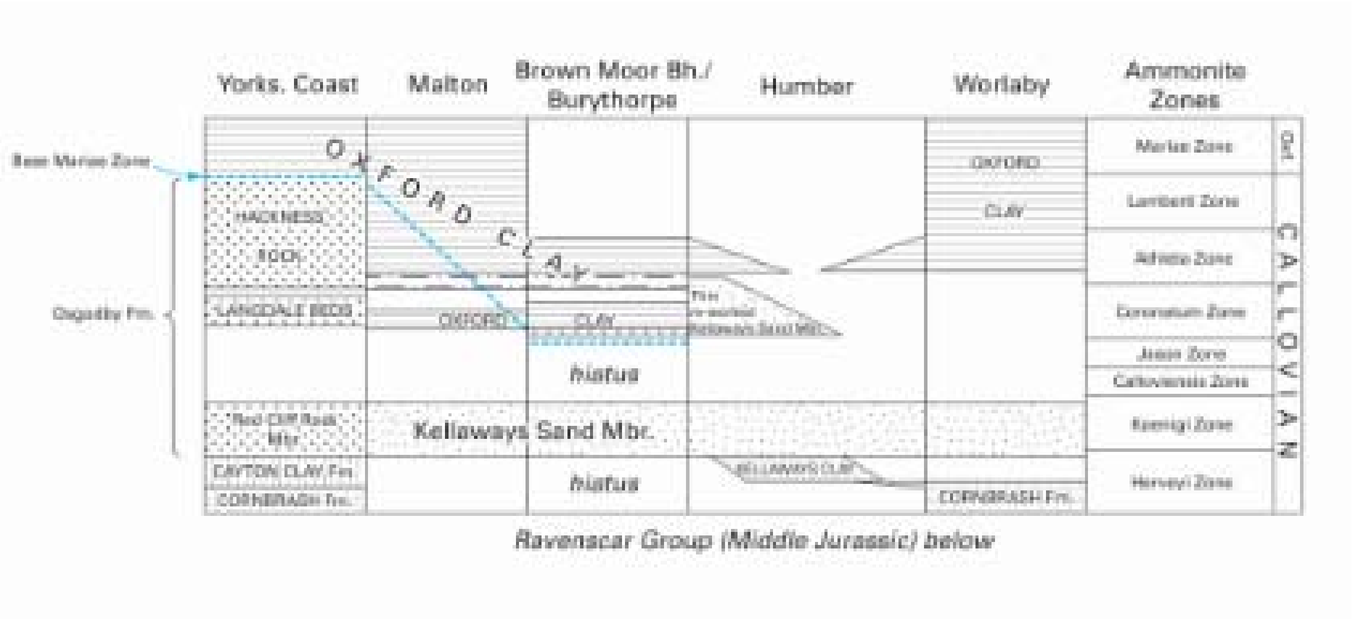
Yorks. Coast
Malton
Brown Moor Bh./ Burythorpe
Humber
Worlaby
Ammonite Zones
Base Mariae Zone
Osgodby Fm.
HACKNESS ROCK
LANGDALE BEDS
Red Cliff Rock Mbr.
CAYTON CLAY Fm.
CORNBRASH Fm.
OXFORD CLAY
OXFORD
CLAY
hiatus
Kellaways Sand Mbr.
Thin re-worked Kellaways Sand Mbr.
KELLAWAYS CLAY
hiatus
OXFORD
CLAY
CORNBRASH Fm.
Mariae Zone
Lamberti Zone
Athleta Zone
Coronatum Zone
Jason Zone
Calloviensis Zone
Koenigi Zone
Herveyi Zone
Oxf.
CALLOVIAN
Ravenscar Group (Middle Jurassic) below

Fig 12

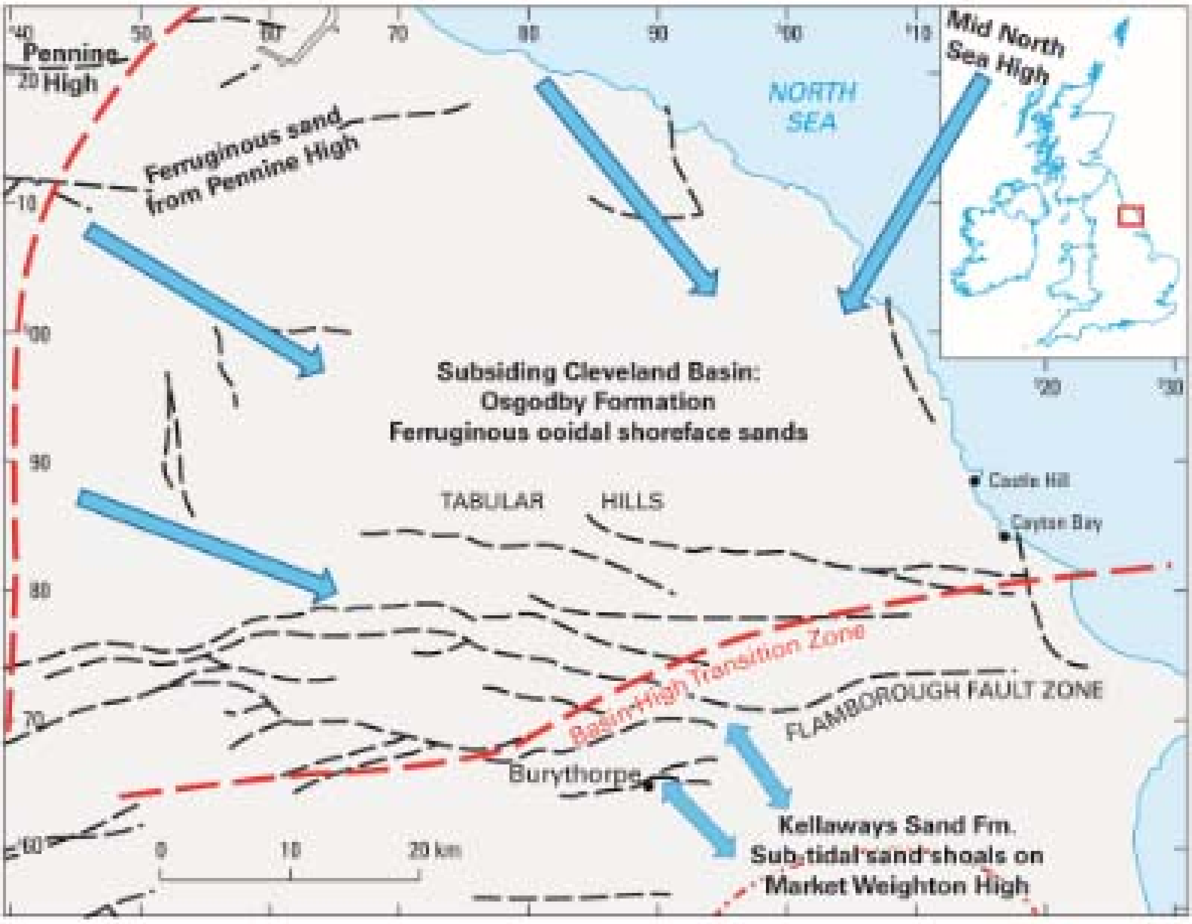
Pennine High
Ferruginous sand from Pennine High
NORTH SEA
Mid North Sea High
Subsiding Cleveland Basin: Osgodby Formation Ferruginous ooidal shoreface sands
TABULAR HILLS
Castle Hill
Cayton Bay
Basin-High Transition Zone
FLAMBOROUGH FAULT ZONE
Burythorpe
Kellaways Sand Fm. Sub-tidal sand shoals on Market Weighton High
0
10
20 km
40
50
60
70
80
90
100
110
120
130
20
10
100
90
80
70
60

Fig. 13