Staithes to Port Mulgrave, North Yorkshire

[NZ 784 189]–[NZ 797 175]

K.N. Page

Introduction

The 3 km stretch of cliffs and foreshore between Staithes and Port Mulgrave exposes the type sections of the Staithes Sandstone Formation and the Cleveland Ironstone Formation, including the Penny Nab Member, and the Mulgrave Shale Member of the Whitby Mudstone Formation. There are also excellent exposures of the Grey Shale Member at the base of the Whitby Mudstone Formation. It provides one of the best exposures in Britain of the Upper Pliensbachian to Lower Toarcian succession, including the Pliensbachian–Toarcian stage boundary. It has been the location for many investigations into the palaeoenvironments and diagenesis of this part of the Lower Jurassic succession in Yorkshire and the source of a rich fossil fauna.

The Cleveland Ironstone Formation that crops out in the Staithes to Port Mulgrave GCR site (Figure 6.14) was historically important as a source of Iron. The remains of mine workings are still visible in the cliffs; mostly at the level of the highest quality seam known simply as the 'Main Seam'. Ore was shipped from Port Mulgrave to the smelters of Tyneside (Rawson and Wright, 1992). In 1920, 6 million tonnes were extracted from the Main Seam in Cleveland (Lamplugh *et al.*, 1920). Arkell (1933) noted that the low lime content of the ore (around 5%), necessitated the extraction of large quantities of limestone for use as a flux. This came from quarries in the Oxfordian Corallian Group of the Pickering district. In the latter part of the 19th century, jet was also mined in the area, with the remains of old adits still visible in the cliff at Thorndale Wyke, where the Top Jet Dogger forms their roofs. The Jet Rock was also quarried on the foreshore and stacks of large nodules, such as the Curling Stones, are still visible as a by-product of this activity (Rawson and Wright, 1995).

Young and Bird (1822, 1828), in their attempt to develop a systematic review of the geology of the Yorkshire coast, lust used the terms 'Staithes Beds' and 'Kettleness Beds' for the lower and upper subdivisions respectively of the (Upper Pliensbachian) Middle Lias, and figured fossils from the Upper Pliensbachign succession of the region. Phillips (1829) provided a detailed section for the Upper Pliensbachian at Staithes, which he divided into a lower Mar'stone Series' and an upper 'Ironstone Series', together with a long list of fossils. Tate and Blake (1876) provided sections which were to prove the basis for most later work, and Wright (1878–1886) also included a detailed section. The results of these early studies, including the work of the [British] Geological Survey (e.g. Barrow, 1888), was reviewed by Fox-Strangways (1892), and additional brief descriptions were provided by Herries (1906a,b). These works remained the basis for the reviews of Buckman (1915) and Arkell (1933). Wilson *et al.* (1934) described a section through the Ironstone Series at Staithes, and Whitehead *et al.* (1952) discussed the petrology of the ironstones. Howarth's (1955) sections have served as the standard stratigraphical framework on which most subsequent work has been based (e.g. Cope *et al.,* 1980a; Hemingway *et al.,* 1969). The lithostratigraphy of the Upper Pliensbachian sequence was revised by Howard (1985) based, in part, on the framework of Powell (1984) and using Howarth's bed numbers.

Tate and Blake's (1876) general description of the Grey Shale Member is useful but incomplete. Howarth (1962a) described the Mulgrave Shale Member and the Grey Shale Member (Howarth, 1973). Further details of both are included in Howarth (1992). Rawson and Wright (1995) published logs of the Staithes Sandstone, Cleveland Ironstone and Whitby Mudstone formations here, based largely on the work of Howarth (1955, 1962a, 1992), and Hesselbo and Jenkyns (1995) published a re-measured section through the Staithes Sandstone, Cleveland Ironstone and the lower part of the Whitby Mudstone formations. Walkden *et al.* (1987) published a graphic log of the Mulgrave Shale Member. All of these used the bed numbers of Howarth (1955, 1962a). Aspects of the sedimentology, petrology, geochemistry and palaeoecology of parts of the succession have been discussed by Hallam (1962a, 1967b), Chowns (1968), Gad *et al.* (1969), Catt *et al.* (1971), Raiswell (1971, 1976), Raiswell and White (1978), Morris, (1979), Greensmith *et al.* (1980, 1983), Coleman and Raiswell (1981), Pye and Krinsley (1986), Myers and Wignall (1987), Knox *et al.* (1990), Young *et* *al.* (1990a), Macquaker and Taylor (1996, 1997), Hesselbo (1997) and Morgans (1999).

Description

The succession dips gently eastward with the oldest part exposed at Cowbar Nab, and the youngest at Port Mulgrave (Figure 6.14). Only a few minor faults interrupt the sequence. The following synthesis of the Redcar Mudstone, Staithes Sandstone, Cleveland Ironstone and Whitby Mudstone formations ((Figure 6.15)a,b and description below) is based primarily on Howarth (1955, 1962a, 1973 and 1992) with additions and modifications based on Howard (1985) and Hesselbo and Jenkyns (1995). Bed numbers for the Whitby Mudstone Formation are taken from Howarth (1962a, 1973), with those for the Pliensbachian succession from Howarth (1955). Details of the lowermost beds are from Howard (1985).

	Thickness (m)
LOWER TOARCIAN SUBSTAGE	
Whitby Mudstone Formation	
Mulgrave Shale Member	
Bituminous Shales (part)	
Serpentinum Zone, Falciferum Subzone	
41: Shale, grey, bituminous, with crushed *Harpoceras* ex grp. *falciferum* (probably including *H. mulgravium*) seen above the Millstones on shore east of Port Mulgrave, towards High Lingrow and in cliff. The base of Bed 41 at Port Mulgrave is effectively a parastratotype for the base of the Falciferum Subzone in Howarth (1992).	5.9 (19 ft 3 in.)
Jet Rock	
Exaratum Subzone	
40: **Millstones**: Giant lenticular calcareous concretions, up to 4.5 m in diameter when seen from above, in grey bituminous shale. *Cleviceras elegans, Hildaites murleyi* and *Dactylioceras* sp., sometimes forming a shell bed. Beds 37–40 encompass the *elegans* Biohorizon.	0.3 (1 ft)
39: **Top Jet Dogger**: Continuous band of argillaceous limestone. *Cleviceras elegans, Dactylioceras* sp..	0.23 (9 in.)
38: Shale, grey, bituminous, with occasional calcareous concretions. The Upper Pseudovertebrae of Howarth (1962a) occur about 0.3 m above the base. *Cleviceras elegans, Harpoceras serpentinum* and occasional *Phylloceras heterophyllum.*	1.54 (5 ft)
37: **Curling Stones**: Calcareous concretions with pyritic skins and a spheroidal shape up to 0.45 m in diameter, in grey bituminous shale. *Cleviceras elegans, Harpoceras serpentinum, Dactylioceras semiannulatum, D. crassoides* and *Phylloceras heterophyllum.*	0.3 (1 ft)
36: Shale, grey, bituminous. *Cleviceras exaratum.* This corresponds to part of the *exaratum* Biohorizon.	1.08 (3 ft 6 in.)
35: **Whalestones**: Large ovoid calcareous concretions up to 3 m long and 1 m thick, with many smaller concretions, including the Lower Pseudovertebrae, in grey bituminous shale. *Cleviceras exaratum* common, with less frequent *Harpoceras serpentinum, Phylloceras heterophyllum* and probably also *Dactylioceras* sp.. Corresponds to part of the *exaratum* Biohorizon.	0.9 (3 ft)

34: Shale, grey, bituminous, with frequent calcareous concretions. *Elegantuliceras elegantulum.* Corresponds to part of the *elegantulum* Biohorizon.	2.7 (8 ft 6 in.)
33: **Cannon Ball Doggers**: Spherical calcareous concretions up to 0.18 m in diameter, with common well-preserved *Elegantuliceras elegantulum* (including macro- and micro-conch forms). Corresponds to part of the *elegantulum* Biohorizon.	0.15 (6 in.)
Grey Shale Member	
Tenuicostatum Zone, Semicelatum Subzone	
32: Shale, grey, with occasional flat calcareous nodules and widespread shell beds, especially near base, full of crushed *Tiltoniceras antiquum. Dactylioceras semicelatum* and *Posidonia radiata* also present. Corresponds to the antiquum Biohorizon.	1.85 (6 ft)
28–31: Shale, grey, with three bands of large calcareous concretions, including a double row at the base, which are often pyritic and contain well-preserved *D. semicelatum,* large belemnites and a nautiloid *Cenoceras astracoides.* This corresponds to the *semicelatum* Biohorizon. The base of Bed 28 is a stratotype, or at least a parastratotype, for the base of the Semicelatum Subzone in Howarth (1992).	3.55 (11 ft 7 in.)
Tenuicostatum Subzone	
20–27: Shale, grey, with several bands of small calcareous nodules and a double band of large calcified lenticular masses, weathering red, at base. Common well-preserved *D. tenuicostatum* in small nodules; the neotype of the species is from Bed 22 (Howarth, 1973). This corresponds to the *tenulcostatum* Biohorizon. The base of Bed 20 is a stratotype, or at least a para-stratotype, for the base of the Tenuicostatum Subzone in Howarth (1992).	2.75 (8 ft 11 in.)
Clevelandicum Subzone	
19c: Shale, grey.	0.81 (2 ft 8 in.)
19b: Shale, grey, including a band of red-weathering lenticles and common *D. clevelandicum.* This corresponds to the *clevelandicum* Biohorizon.	0.05 (2 in.)
19a: Shale, laminated and bituminous.	0.41 (1 ft 4 in.)
18: Shale, grey, with small calcareous concretions and frequent *D. crosbeyi.* This corresponds to the *crosbeyi* Biohorizon. The base of Bed 18 is a stratotype, or at least a parastratotype, for the base of the Clevelandicum Subzone in Howarth (1992).	0.38 (1 ft 3 in.)
Paltus Subzone	
4–17: Shale, grey, with six bands of calcareous and sideritic concretions. Some belemnites and bivalves present.	2.75 (9 ft 1 in.)
3: This level elsewhere (e.g. at Hawsker Bottoms and at Kettleness) yields the lowest typical Toarcian fauna in the region, with *Protogrammoceras paltum* and *Dactylioceras* sp. indet. (Howarth, 1973).	0.08 (3 in.)
UPPER PLIENSBACHIAN SUBSTAGE	
Spinatum Zone, Hawskerense Subzone, Hawskerense Zonule	

2: Shale, dark grey, laminated and bituminous. *Lytoceras* sp. recorded from base at Kettleness.	0.53 (1 ft 9 in.)
1: Shale, grey.	0.51 (1 ft 8 in.)
59–60: Shale, with row of calcareous concretions at top, yielding *Pseudopecten equivalvis* and *Pholadomya.*	0.45 (1 ft 6 in.)
58: **Sulphur Band**: Finely laminated shale with many lenticles of jet.	0.20 (8 in.)
Cleveland Ironstone Formation	
Kettleness Member	
57: Shale, sandy, micaceous, with *Pleuroceras hawskerense.*	0.45 (1 ft 6 in.)
56: Ironstone, with irregular top surface and common *Pleuroceras hawskerense* and very rare *Protogrammoceras turgidulum.*	0.22 (9 in.)
55: Shale with *P. hawskerense.*	1.23 (4 ft)
Elaboratum Zonule	
54: **Main Seam** (top block): Ironstone with branching burrows and concentrations of rolled fossils. Amaltheid ammonites include *Pleuroceras paucicostatum, P. elaboratum, P. apyrenum, Amauroceras ferrugineum* and *A. lenticulare,* with a single example known of the hildoceratid *Canavaria* aff. *cultraroi* (Howarth, 1992).	0.75 (2 ft 6 in.)
Apyrenum Subzone, ?Solare Zonule	
52–53: **Main Seam**(bottom block): Thick ironstone (1.4 m) separated from top block by shale. Burrows are present but concentrations of rolled fossils are rare. Ammonites are uncommon and difficult to extract, but probably include *Pleuroceras paucicostatum.*	1.70 (5 ft 6 in.)
51: Shale, black, hard.	0.45 (1 ft 5 in.)
42–50: **Pecten Seam**: Ironstone, in five bands with shale between and shell beds at some levels.	1.3 (4 ft 2 in.)
41: Ferruginous shale with bivalve shell bed at base.	0.25 (10 in.)
Transiens and *Salebrosum zonules* absent	
Penny Nab Member	
Margaritatus Zone, Gibbosus Subzone	
40: Shale. Crushed *Amaltheus gibbosus.*	0.5 (1 ft 8 in.)
39: **Two Foot Seam**: Ironstone with rare *Amaltheus*ex grp. *margaritatus* and *Pseudoamaltheus engelhardti.*	0.4 (1 ft 3 in.)
36–38: Shale with belemnite-rich band at top and band of calcareous concretions 1.1 m above base yielding *Amaltheus gibbosus, A. margaritatus, Pseudoamaltheus engelhardti* and *Amauroceras ferrugineum.*	2.9 (9 ft 5 in.)
35: **Raisdale Seam**: Ironstone with many *Protocardia truncata* and rare *Amaltheus* cf. *margaritatus.*	0.25 (10 in.)
32–34: Siltstone and shale with pyritic masses in the lower part and a band of calcareous concretions 1.25 m above base. The latter yield *Amaltheus gibbosus,* with *Amauroceras ferrugineum* in the 0.6 m of shale above. The base of Bed 32 is a parastratotype for the base of the Gibbosus Subzone in Howarth (1992).	5 (16 ft 2 in.)
Subnodosus Zone	

31: **Avicula Seam**: Ironstone, fine grained, with pale-green chamositic ooliths, and a 0.1 m-thick mudstone parting in places around the middle. *Amaltheus* ex grp. *margaritatus* and many bivalves, especially *Oxytoma cygnipes* and protocardiid burrows.	0.6 (2 ft)
27–30: Silty sandstone, siltstone and shale with bands of calcareous concretions and a 0.05 m shell bed 0.58 m below top with *Protocardia truncata, Entolium* and other bivalves. *Amaltheus subnodosus, A. striatus* and *A. margaritatus* occur at several levels and are especially abundant in the lowest nodule band (Bed 27a), which yielded the neotype of *A. subndosus* (Howarth, 1958).	6.5 (21 ft 1 in.)
26: **Osmotherley Seam**: Band of small calcareous concretions with *Amaltheus subnodosus, A. striatus* and *A. stokesi,* and many bivalves. The base of Bed 26 is a parastratotype for the base of the Subnodosus Subzone in Howarth (1992).	0.08 (3 in.)
Stokesi Subzone, Nitescens to Celebratum zonules	
24–25: Shale with bands of calcareous concretions, the lowest containing abundant *Amaltheus stokesi* and *A. wertheri.*	2.6 (8 ft 6 in.)
Staithes Sandstone Formation	
Celebratum and *Nitescens zonules*	
23: Shale and sandstone with three bands of calcareous concretions, the middle of which contains *Amaltheus stokesi* and *A. wertheri.*	1.95 (6 ft 4 in.)
17 (part)–22: Thinly bedded sandstones with thin shales and bands of calcareous, and sometimes fossiliferous, concretions. A thin shell-bed at the base yields *Amaltheus stokesi* and *A. wertheri.*	5.5 (17 ft 10 in.)
Occidentale to *Monestieri zonules*	
12–17 (part): Thinly bedded sandstones with some sandy shale and bands of calcareous concretions and lenticles, which often weather red and may be rich in bivalves; *Amaltheus stokesi* present sporadically. The base of Bed 12 is a parastratotype for the base of the Stokesi Subzone in Howarth (1992).	8.5 (27 ft 7 in.)
LOWER PLIENSBACHIAN SUBSTAGE	
Davoei Zone, Figulinum Subzone	
11: Sandstone with bivalve shell beds.	0.3 (1 ft)
10: Shale with scattered calcareous concretions, including abundant *Oistoceras figulinum* in upper 0.3 m and 0. *affligulinum near* the middle.	1.7 (5 ft 6 in.)
4–9: Mainly sandstone alternating with sandy shale. Bivalve-rich shell beds occur near the top, with *Gryphaea* present below: *Oistoceras* sp. recorded from beds 4 and 8. Howard (1985) and Hesselbo and Jenkyns (1995) included Bed 2 in the Figulinum Subzone although without supporting evidence.	6.55 (21 ft 3 in.)
Capricornus Subzone	

1–3: Sandstone forming base of cliff at Cowbar Nab, with sandy shale capped by band of calcareous concretions above. *Androgynoceras lataecosta* var. *pyritosum* figured by Spath (1938, pl. 19, fig. 6) probably came from this level. 2.7	
Oyster Bed: Sandstone, calcareous and ferruginous, with *Gryphaea, Oxytoma* and *Pseudopecten.* Marks the base of the Capricornus Subzone and of the Staithes Sandstone Formation.	0.3
Redcar Mudstone Formation	
Ironstone Shale Member	
Maculatum Subzone	
Shale with some siltstone in upper 7.5 m, and with calcareous nodules and a thin oolitic ironstone 1.5 m above the base. *Androgynoceras maculatum* var. *rigida* from 8 m below sandy series at Staithes figured by Spath (1938).	20.25

The base of the Staithes Sandstone Formation, exposed at Cowbar Nab, is gradational with the underlying Redcar Mudstone Formation. It has been drawn at the base of the 'Oyster Bed' (Howard, 1985), a ferruginous sandstone packed with the bivalves *Gryphaea gigantea, Oxytoma inaequivalvis* and *Pseudopecten equivalvis.* The formation is 28.6 m thick here and superbly exposed to either side of Staithes harbour (Figure 6.16). The lower 12.6 m has been assigned to the Davoei Zone (Capricornus and Figulinum subzones) and the remainder to the lower part of the Stokesi Subzone (Hesselbo and Jenkyns, 1995; Rawson and Wright, 1995). Intensely bioturbated silty sandstones dominate the succession, becoming coarser in the middle of the formation before fining again towards the top. Poorly bioturbated, fine sandstone bands occur at various levels and are thickest (up to about 4 m) in the middle of the formation. They show planar- and cross-lamination and some hummocky cross-stratification (Rawson *et al.,* 1983). The bases of some bear small erosional channels or gutter casts, up to 5 m long and 0.5 m wide, with a predominant east–west trend which is roughly perpendicular to ripple marks in the same sequence (Greensmith *et al.,* 1980). One hummocky cross-stratified unit at about the middle of the formation is associated with abundant intact, but poorly preserved specimens of the crinoid *Balanocrinus gracilis.* Other macrofossils occur sparsely except in some nodules and shelly bands towards the top of the formation. They include the type of *Rudirhynchia huntcliffensis* (Ager, 1956–1967). Scrutton (1996) observed that the more muddy tops of the sandstone beds have a benthos dominated by burrowing bivalves, such as *Protocardia truncata* and *Oxytoma inequivalvis,* the serpulid '*Dentalium*' *giganteum* (Palmer, 2001), and other species. Some assemblages are mixed, especially in coquinas of *Protocardia* which form the nudei for sideritic nodule development. Elsewhere there are current-aligned clusters of belemnites and fragments of driftwood.

The Staithes Sandstone Formation passes up into the shaley mudstones with scattered siderite nodules of the Cleveland Ironstone Formation. The ironstone is superbly exposed from Penny Nab (Figure 6.16) and Brackenberry Wyke. Its base has been taken at the base of a row of scattered siderite nodules with *Amaltheus stokesi.* This marks the lowest of several coarsening-upward cycles within the formation (Rawson *et al.,* 1983; Howard, 1985). The Penny Nab Member comprises four beds of oolitic ironstone (the Osmotherley, Avicula, Raisdale and Two Foot seams) separated by clastics with siderite nodules (Figure 6.17). Except for that beneath the Two Foot Seam, each clastic unit coarsens upwards from silty pyritic shale to argillaceous fine sandstone, and a sharp erosional contact with the ironstone above, marked by reworked and bio-eroded siderite nodules. Macquaker and Taylor (1996, 1997) maintained that the ironstones occur at the top of upward-coarsening successions and are succeeded by units which fine upwards to clay-rich mudstones with phosphate-rich carbonate concretions, in turn overlain by the next coarsening-upwards unit.

Beneath the Raisdale Seam is the 'upper striped bed' of Greensmith *et al.* (1980). This comprises a series of thin laminated siltstones that fine up to dark mudstone, each with a basal erosion surface and often with E–W-orientated gutter casts up to 0.5 m wide and several metres long. The oolitic ironstones are intensely bioturbated at their base, with ooids commonly deformed and broken. Petrologically the ironstones comprise altered berthierine ooids in a more-or-less strongly sideritized muddy matrix (Young *et al.,* 1990a). Catt *et al.* (1971) and Myers (1989) noted that the ironstones have remarkably high thorium–potassium ratios.

The base of the Kettleness Member is taken at a minor erosion surface with occasional phosphatic pebbles at the base of the Pecten Seam. This member is less obviously cyclic in nature than the Penny Nab Member. The Pecten Seam comprises five thin (< 0.15 m) ironstone beds separated by thin silty shale bands, and is almost immediately succeeded by the Main Seam, divided by another thin silty shale into two distinct units. Small, often angular, phosphate clasts are common in the top block of the Main Seam. The top of the member is placed above a minor un-named ironstone seam with a highly irregular top (Bed 56 of Howarth, 1955), which lies just below the top of the Spinatum Zone.

Ammonites are a conspicuous element of the macrofauna throughout the Cleveland Ironstone Formation (Howarth, 1955), providing good biostratigraphical control, although common only at certain levels. Virtually all are members of the Amaltheidae, and include the neotype of *Amaltheus subnodosus* from Bed 27, and possibly that of *Amaltheus striatus* (Howarth, 1958). Howarth (1955, 1992) also recorded single specimens of two species of Tethyan hildoceratid, *Canavaria cultraroi* and *Protogrammoceras turgidulum* (= af *bassanii*), from beds 54 and 56 respectively; these remain unique in the British Lias. The remainder of the macrofauna is dominated by a fairly diverse assemblage of bivalves, listed in Young *et al.* (1990a), together with belemnites, rhynchonellid and terebratuloid brachiopods (Ager, 1956–1967, 1990), and other fossils. These include the type of *Rhynchonelloidea lineata* from near the base of the Pecten Seam. The fauna of the shales of the Cleveland Ironstone Formation generally shows a reduction in benthos diversity compared to that of the Staithes Sandstone Formation beneath, and a greater proportion of pelagic elements, such as ammonites and belemnites. Intact specimens of the crinoid *Hispidocrinus schlumbergeri* have been found in the mudstones of Bed 40, above the Two Foot Seam, while well-preserved stems, cirri, and occasionally crowns, of *Balanocrinus solenotis* are common a little lower in the succession, in the mudstones of beds 32 and 34 (Simms, 1989). Certain fossil species are characteristic of particular units; for instance, the Avicula Seam is characterized by abundant specimens of *Oxytoma* (= *Avicula*) *cygnipes,* whereas the Pecten Seam contains abundant *Pseudopecten equivalvis.* Fossil driftwood from the Penny Nab Member comprised part of a broader investigation of Pliensbachian to Bathonian tree growth-rings by Morgans (1999). The macrofauna of the Kettleness Member is less diverse and more poorly preserved than that of the Penny Nab Member, and is largely confined to the lower part of the Pecten Seam and the top block of the Main Seam. Trace fossils are abundant and diverse at many levels in the Cleveland Ironstone Formation (Young *et al.,* 1990a), particularly in certain of the ironstone seams, and there seems to be a distinction between these assemblages and those seen in the clastic units. They are particularly spectacular in the top block of the Main Seam, where profuse *Rhizocorallium* burrows preserve scratch marks made by the crustaceans that inhabited them (Farrow, 1966). Catt *et al.* (1971) reported a very impoverished microfauna from the Pliensbachian succession of this site, with only occasional specimens of four species of ostracod and a few benthic foraminifera.

The base of the Whitby Mudstone Formation is taken at the base of the Sulphur Band, a 0.2 m-thick, laminated, pyritic mudstone with lenses of jet. The Grey Shale Member is dominated by pyritic, silty, micaceous mudstones with thin, ripple-laminated siltstones and numerous nodule bands in the lower part. Many of these nodules weather distinctly red and can be easily traced across the foreshore and into the cliff. At some levels almost every nodule contains an ammonite; at others they are absent. The base of the predominantly laminated, organic-rich mudstones of the Mulgrave Shale Member is taken here, the type locality, at the base of the distinctive Cannon Ball Doggers (Cope *et al.,* 1980a; Howarth, 1992). The Mulgrave Shale Member is divided into two informal subdivisions. The lower subdivision, the Jet Rock, is characterized by bands of often large nodules (the Whalestones, Curling Stones, and the Upper and Lower Pseudovertebrae), which form a conspicuous feature of the foreshore at Rosedale Wyke. These nodules have formed the subject of several papers. General accounts of the formation and diagenesis of these nodules have been given by Hallam (1962a) and Raiswell (1976). More specific accounts have investigated the spatial distribution, size and orientation of the Curling Stones exposed in *situ* at Port Mulgrave (Raiswell and White, 1978); the diagenetic history of the Cannonball Doggers and Curling Stones (Coleman and Raiswell, 1981); and the trace-element geochemistry of concretionary pyrite (Raiswell and Plant, 1980). The lower part of the upper subdivision, the Bituminous Shales, crops out on the foreshore on the eastern side of Rosedale Wyke and are also well exposed, but mostly inaccessible, in the adjacent cliffs. As their name implies they comprise mainly laminated, organic-rich, mudstones. They contain fewer calcareous nodule bands and a greater abundance of pyrite than the Jet Rock.

Through most of the Grey Shale and Mulgrave Shale members the fauna is dominated by planktonic and nektonic forms, with benthic taxa largely confined to just a few horizons. Ammonites, particularly dactylioceratids and hildoceratids

(Howarth, 1962a, 1973, 1992), are a conspicuous element of the fauna and the site is the type locality for *Dactylioceras tenuicostatum.* Several species of belemnite (Doyle, 1990–1992) and the bivalves *Pseudomytiloides dubius* and *Bositra radiata are* the only other common invertebrate fossils at many levels. Hemingway (1974) noted that *B. radiata* is abundant only in the lower 2 m of the Mulgrave Shale Member, being replaced in higher beds by *P. dubius.* The pseudoplanktonic crinoids *Pentacrinites dichotomus* and *Seirocrinus subangularis* occur rarely in the Bituminous Shales (Simms, 1989). Port Mulgrave was one of the sites examined by Morris (1979) in his palaeoenvironmental investigation of this part of the succession and was also included by Myers and Wignall (1987) in their study of potential correlation between gamma-ray spectrometry and palaeoecological indices. Few vertebrates have been recorded from this site although the organic-rich shales of the Mulgrave Shale Member might be expected to yield well-preserved remains. Benton and Taylor (1984) referred to the skeleton of a crocodilian found here in 1791 and assumed it had fallen from the Alum Shale Member. However, Walleden *et al.* (1987) demonstrated that crocodilians are present in the Mulgrave Shale Member and described a partial skeleton of *Steneosaurus* from the upper part of the Jet Rock.

The jet, which forms such a well-known, but scarce, component of the Mulgrave Shale Member is the product of diagenetically altered driftwood. Hemingway (1974) provided one of the few scientific descriptions of this material. 'Hard' jet, the relatively tough form used in carving, is found in the upper 3 m of the Jet Rock. The more brittle 'soft' jet is found in the Bituminous Shales and elsewhere in the Lower Jurassic succession. It may occur as thin 'seams' or as cylindrical masses with a silicified core in which original cell structure may be well preserved. Rounded quartz and garnet grains, and even an 80 mm-diameter quartzite pebble, have been found lodged in fissures in some pieces of jet.

Interpretation

The succession exposed in the Staithes to Port Mulgrave GCR site differs in only minor respects from those sites at this stratigraphical level elsewhere in the Cleveland Basin. The extensive foreshore exposures have enabled the succession to be studied in detail, and it is the type site for the Staithes Sandstone Formation, the Cleveland Ironstone Formation and Penny Nab Member, and for the Mulgrave Shale Member of the Whitby Mudstone Formation. The abundance of ammonites at many horizons has enabled all of the ammonite zones and subzones from the Maculatum Subzone (Lower Pliensbachian), to the Falciferum Subzone (Toarcian) to be identified at this site. Higher parts of the Toarcian succession are present in the cliffs but are not generally accessible. More detailed biostratigraphical analysis has established the presence of numerous ammonite-correlated 'horizons' and 'zonules' within the subzones (Page, 1995).

Cox (1990) suggested that the succession between Staithes and Port Mulgrave could provide reference sections for the Margaritatus, Spinatum, Tenuicostatum and Serpentinum (formerly Falciferum) zones. Howarth (1992) designated the site as stratotype, or at least parastratotype, for all three subzones of the Margaritatus Zone and for three of the four subzones of the Tenuicostatum Zone. He also suggested that the base of the Hawskerense Subzone could be defined at the base of Bed 55 in the Kettleness Member. However, *Pleuroceras elaboratum* occurs in Bed 54, and was considered by Dommergues *et al.* (1997) to characterize the lower part of the subzone. Information from France and elsewhere indicates the existence of *Pleuroceras* faunas earlier than those recorded from Yorkshire: these correspond to the Transiens and Salebrosum zonules of Dommergues *et al.* (1997). The base of the Apyrenum Subzone was taken by Howarth (1992) at a level higher than that used here. Solare Zonule (basal Apyrenum Subzone) faunas have been recorded from the Pecten Seam at Hawsker Bottoms. The absence of the Transiens and Salebrosum zonules in Yorkshire indicates a non-sequence between the Penny Nab and Kettleness members (Figure 6.11).

There is considerable uncertainty as to the position of the Pliensbachian–Toarcian boundary. The highest unequivocally Pliensbachian species is *Pleuroceras hawskerense* in Bed 57 but the lowest definite Toarcian taxa are not found until Bed 3, almost 1.7 m higher in the succession. Cope *et al.* (1980a) and Howard (1985) placed the Pliensbachian–Toarcian boundary at the base of Bed 58. Howarth (1955) placed the base of the Tenuicostatum Zone immediately above Bed 60, but subsequently (1992) proposed the base of Bed 58 at Staithes, and an equivalent level at Kettleness (Bed 38), as parastratotypes for the base of the Paltus Subzone, and hence the

Toarcian Stage. On current criteria, the Pliensbachian–Toarcian boundary is taken at the base of Bed 3, the level at which the earliest typical Toarcian ammonites occur.

The Mulgrave Shale Member here must have been the source of the unhorizoned holotype of *Harpoceras mulgravium* (Young and Bird, 1822). Despite its name, this was said to be from Whitby, although the poorly localized nature of many specimens collected in the early 19th century certainly does not preclude an origin from Port Mulgrave. Howarth (1992) considered this nominal species to be a synonym of *Harpoceras falciferum.* Evidence from France and Somerset (K.N. Page, unpublished observations) indicates that relatively evolute and slender *Harpoceras* ex grp. *falciferum* such as this are typical of the lower part of the Falciferum Subzone, and that the species can be considered distinct from the later, more involute and stout, *H. falciferum sensu stricto.* This led to the recognition of a Pseudoserpentinum Zonule in France (Elmi *et al.,* 1997), the index fossil of which is considered here to be a synonym of *H. mulgravium.* Howarth (1992) had already considered *Harpoceras pseudoserpentinum* to be an early subspecies of *H. falciferum.*

The superb cliff and foreshore exposures have made this a favoured site for investigating palaeoenvironments and diagenetic processes in the Upper Pliensbachian and Lower Toarcian Staithes Sandstone Formation and Cleveland Ironstone Formation. The vertical grading, planar or low-angle cross-laminations, gutter casts and scours in the Staithes Sandstone Formation have been interpreted as tempestites (Greensmith *et al.,* 1980; Knox *et al.,* 1990). The orientation of the cross-laminations and the gutter casts indicates eastward-flowing storm-surge ebb currents. Wave ripples on the tops of the cross-laminated sands are orientated roughly perpendicular to this. The occurrence of intact crinoids and ophiuroids at certain levels, which clearly represent obrution konservat lagerstatten (Seilacher *et al.,* 1985), support a tempestitic origin. The intervening 'fair weather' deposits often were intensely bioturbated. Knox *et al.* (1990) interpreted the lower part of the Staithes Sandstone Formation as an innermost shelf facies, passing into a middle shelf facies in Bed 17. This may reflect a local transgression but was quickly followed by shallowing, indicated by upward-coarsening, in the succeeding part of the formation. The Cleveland Ironstone Formation was interpreted by Knox *et al.* (1990) as a middle to outer shelf environment, but Hesselbo and Jenkyns (1995) considered the formation to be the best example of a storm-influenced, lower-shoreface, facies in the British Jurassic System. The coarsening-upward cycles, each capped by an erosively based ironstone band, have been interpreted as evidence for repeated episodes of shoaling, leading to deposition of tempestites, followed by transgressions that cut off the sediment supply and allowed the deposition of ironstones. The lack of upward-coarsening in the clastic units beneath the Two Foot Seam suggests that the transgression terminated clastic input before any significant shoaling had occurred. Macquaker and Taylor (1996, 1997) considered that the ironstones and the intervening phosphate-rich units formed during prolonged breaks in sedimentation. The non-sequence between the Penny Nab and Kettleness members is considered to reflect local tectonic movement, rather than the effects of upward shoaling or eustatic change, since on a regional scale this boundary is seen to be markedly unconformable.

There has been considerable debate surrounding the origin of the ironstones (Hallam, 1966, 1975; Chowns, 1968; Catt *et al.,* 1971; Myers, 1989; Young *et al.,* 1990a). Most interpretations have favoured a terrigenous source for the iron, the result of intense subaerial weathering of thorium-bearing kaolinite being considered to account for the high thorium–potassium ratio. Such a weathering regime is perhaps supported by observations of Early and Middle Jurassic tree rings, which were interpreted by Morgans (1999) as evidence for an increasingly seasonal, Mediterranean-type, climate through this interval. However, Young *et al.* (1990a) consider that both iron and thorium may have been enriched on the sea floor during periods of reduced sedimentation through degradation of the background clastic sediment, in a process analogous to the formation of lateritic soils. Textures observed within the ironstone beds probably are not primary but reflect biological mixing and reworking of grainstone and mudstone interbeds, with some further modification by compaction, though the ooids may have been generated concurrently with reworking (Young *et al.,* 1990a).

There is a striking facies change between the sandy micaceous shale at the top of the Cleveland Ironstone Formation and the bituminous Sulphur Band at the base of the Whitby Mudstone Formation. The lower part of the Grey Shale Member is a 'normal shale', as indicated by burrows, benthic invertebrates and the gamma-ray spectrometry (Morris, 1979; Myers and Wignall, 1987). It passes up into a 'restricted shale' facies towards the top of the member and then, fairly abruptly, into laminated bituminous shales of the Mulgrave Shale Member, in which benthic activity is limited or absent and the fauna is dominated by nektonic and pelagic organisms. The lower part of the Mulgrave Shale Member was termed an 'anoxic event' by Jenkyns (1988) and can be traced across much of Europe. It represents a significant extinction event for many benthic organisms (Little, 1996). It shows evidence of considerable stability by comparison with some other organic-rich mudrock sequences (Myers and Wignall, 1987), which has been taken as evidence of greater water depth than the mudrocks above and below. Hallam (1997) suggested a water depth of 50–100 m for the Mulgrave Shale Member, compared with no more than 20 m depth for the Staithes Sandstone and Cleveland Ironstone formations. He estimated that sea level rose at between 0.8 cm and 2.5 cm per ka in early Toarcian times, a figure equivalent to the growth rate of mid-oceanic ridges. This rapid eustatic rise might explain the onset of anoxic conditions at this time throughout much of Europe. The foraminiferan *Reinholdia macfadyeni* occurs in abundance in the Grey Shale Member at Port Mulgrave (Hylton and Hart, 2000), an indicator of deep water (Broumer, 1969) and implying a transgressive event. It disappears at the onset of the low-oxygen conditions of the Jet Rock.

Total organic carbon content of the mudrocks of the Mulgrave Shale Member ranges between 5% and 15% (Kuspert, 1982; Raiswell and Berner, 1985). The organic material in the mudrocks is mainly structureless but includes various microplankton, pollen and spores (Wall, 1965; Hallam, 1967a). Under laboratory distillation these mudrocks yield from 54 to 86 litres of sulphurous oil per tonne (Hemingway, 1974). Calcareous concretions often emit a strong odour of mineral oil when broken open (Arkell, 1933) and cavities, such as ammonite chambers, may also occasionally contain an oil-like hydrocarbon. The development of microbial mats has been invoked to explain certain levels with wavy laminations (O'Brien, 1990) and a similar process may be responsible for peculiar patches of very finely and wavy banded micritic limestone, occasionally found within some of the calcareous concretions. A wide range of different shapes and sizes of concretions are developed within the Jet Rock, and at some levels have a characteristic outer pyritic skin or zoning (Hallam, 1962a; Coleman and Raiswell, 1981). These nodules, which form such a conspicuous element of parts of the Whitby Mudstone Formation, have been the subject of various papers. Hallam (1967b) found a correlation between sediment grain-size and the relative abundance of sideritic and calcitic early diagenetic nodules. Siderite nodules are more abundant in sandier sediment, such as the Grey Shale Member, whereas calcitic nodules predominate in the mudrocks, particularly the Mulgrave Shale Member. Raiswell and White (1978) concluded that the areal distribution of nodules at a particular horizon was random, implying that adjacent nodules had no influence on the growth of each other and did not compete for limited resources during growth. The discovery that some 30% had a long-axis orientation, with a prevailing NNE–SSW trend, indicated that there might be a preferred direction of water transport along bedding planes during compaction. Raiswell (1976) and Coleman and Raiswell (1981) showed that most of the calcite cement in these nodules originated from organic matter in the sulphate reduction zone and that the nodules formed at shallow depth beneath the sediment surface. They also demonstrated two phases of pyrite growth, with sulphate reduction during the second phase providing the carbonate source for nodule growth. The pyrite-skinned nodules (Hallam, 1962a; Coleman and Raiswell, 1981) may be analogous to the pyrite-skinned Coinstone and the Eype Nodule Bed of the Dorset coast (Ensom, 1985b; Hesselbo and Jenkyns, 1995; Hesselbo and Palmer, 1992). Development of the pyritic skin in the Dorset examples has been attributed to diagenesis associated with exhumation and re-burial of the carbonate concretions, although there is no evidence for any hiatus surfaces associated with pyrite-skinned nodules in the Mulgrave Shale Member.

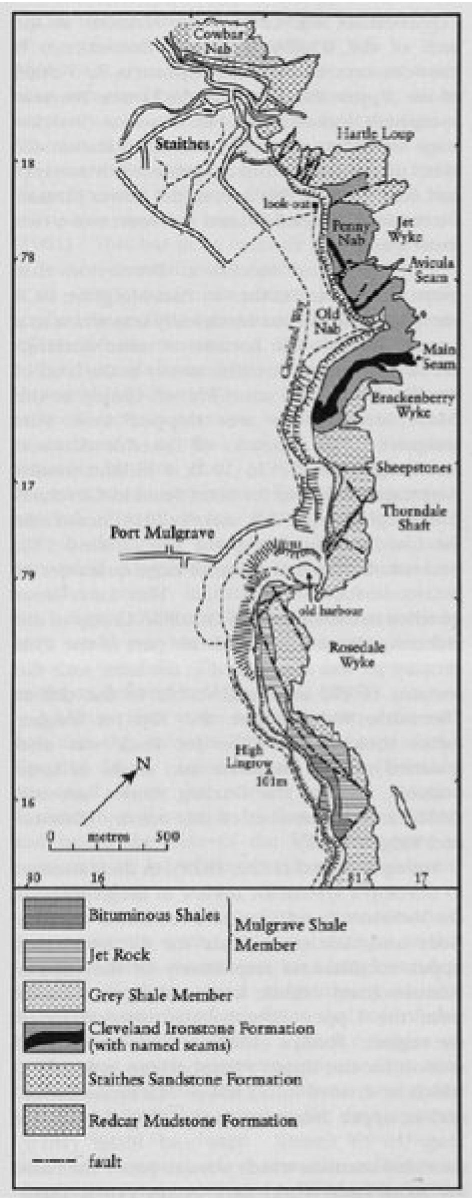
Hemingway's (1974) observations of jet in the Mulgrave Shale Member suggest that rather than being simple compressions of intact logs, many pieces were formed from tree trunks split longitudinally, with these planks then being mechanically rounded prior to burial and compaction. Silicification of the cores of some pieces must have occurred early in diagenesis since these are largely uncompacted. The presence within some pieces of jet of detrital clastic grains suggests that many pieces of wood had already experienced a long period floating at the surface, and occasionally being washed ashore, before they entered this area and sank to the sea floor.

The Toarcian succession seen at this site differs only in very minor respects from correlative sections farther along the Yorkshire coast. Howarth (1962a) recorded total thickness variations for the Mulgrave Shale Member of less than 1 m over a distance of almost 18 km along the coast and was able to correlate individual units over this distance. Similar constancy of thickness was also seen in the Grey Shale Member (Howarth, 1973). The region was tectonically stable throughout this period. In contrast, the Cleveland Ironstone Formation shows marked lateral changes (Figure 6.11), particularly in the thickness of the ironstone seams which thicken to the north-west of Staithes but thin to the south-east at the expense of the intervening clastics (Young *et* ed., 1990a). In addition, the Kettleness Member onlaps unconformably onto the northward dipping Penny Nab Member. The thickening of the ironstone seams to the north-west has been attributed to increasingly low subsidence rates towards the margins of the basin while the southward onlap of the Kettleness Member may relate to movement on the Market Weighton Block ((Figure 5.10), Chapter 5).

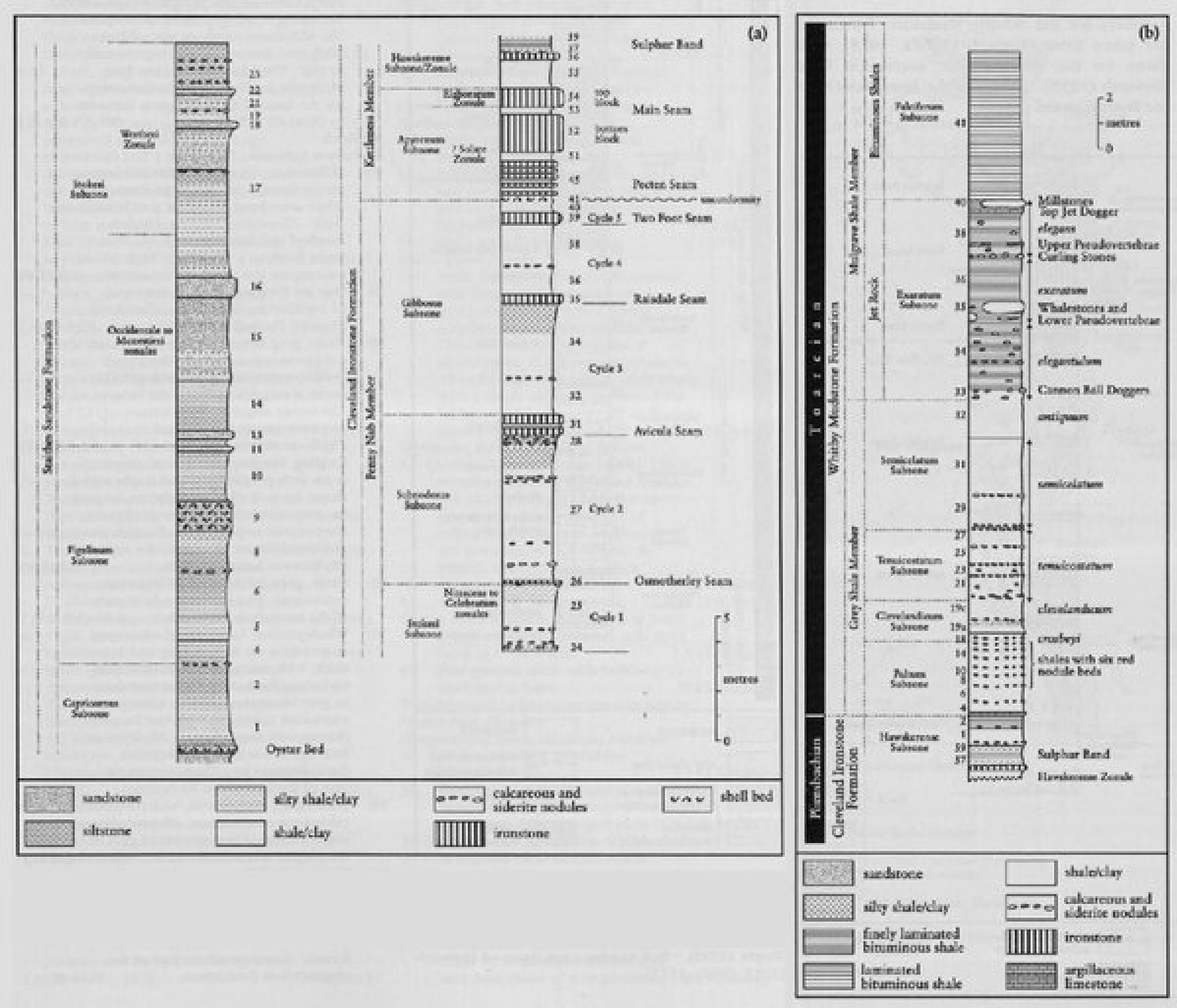
Conclusions

The cliffs and foreshore between Staithes and Port Mulgrave, North Yorkshire expose one of the most complete and accessible Upper Pliensbachian to Toarcian successions in Britain. The Pliensbachian sequence between Staithes and Port Mulgrave, includes the type sections of the Staithes Sandstone and the Cleveland Ironstone formations, and of the Penny Nab Member of the latter formation. Because of the extensive foreshore exposures, accessibility of the site, and often fossiliferous nature of the succession, this site has been the focus of much research into a diverse range of topics covering many aspects of the palaeoecology, sedimentology and diagenesis of the sequence. The results of much of this research have had considerable bearing on the interpretation of other successions elsewhere in the geological record and makes it one of the most important Lower Jurassic reference sections in Britain.

References

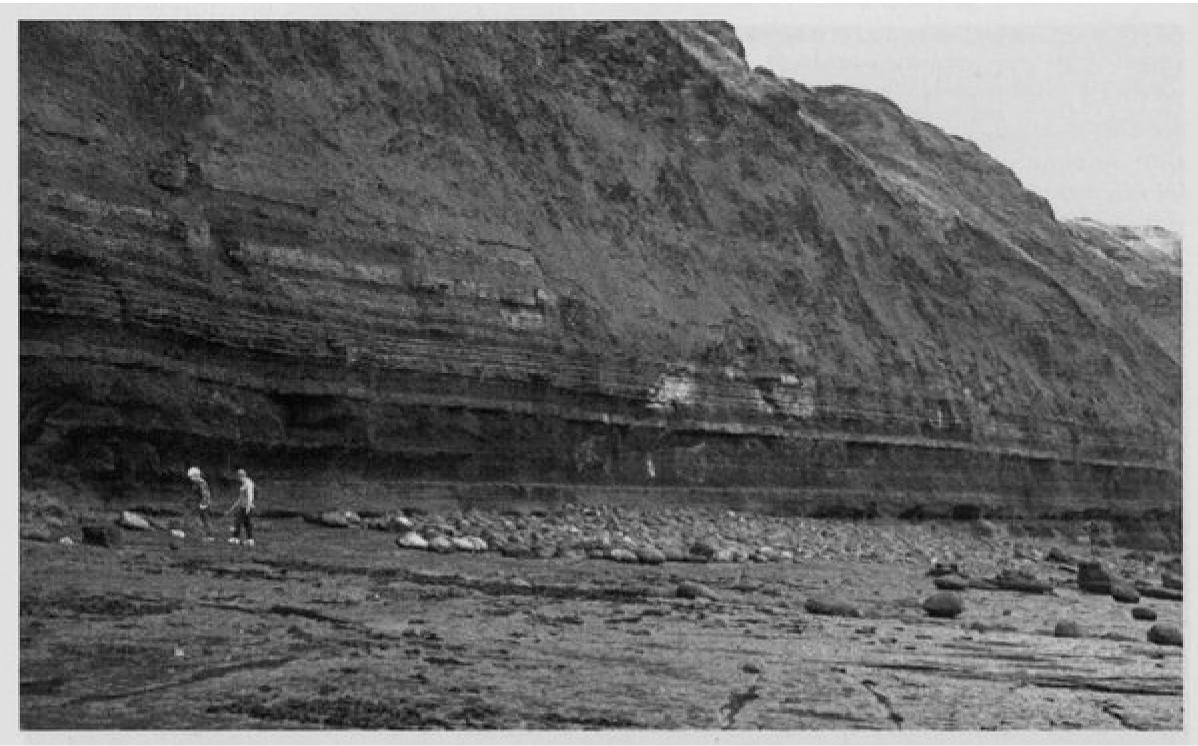


(Figure 6.14) Outcrop map of the main lithostratigraphical units between Staithes and Port Mulgrave. After Rawson and Wright (1992).

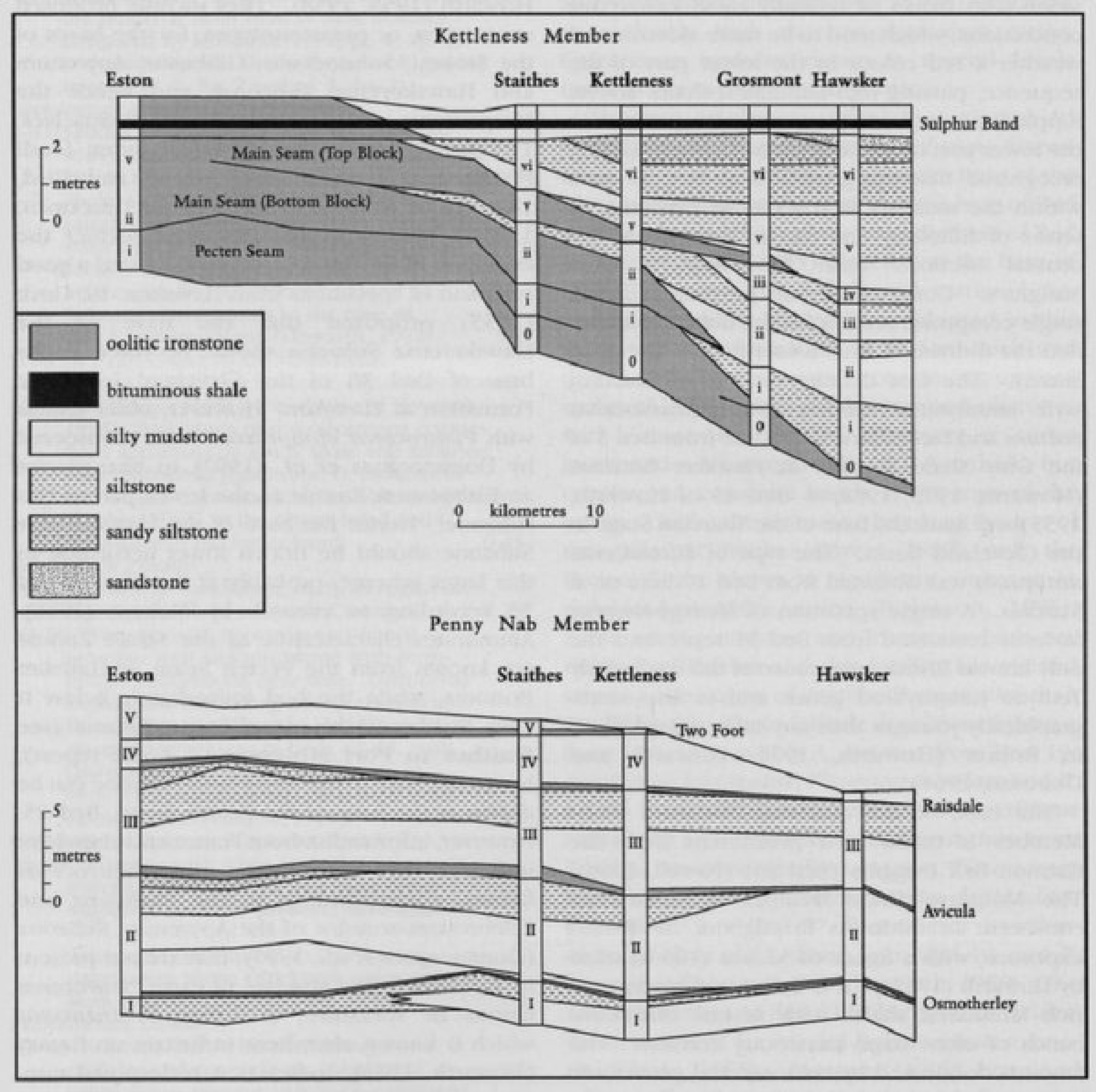


(Figure 6.15) a Section through the Staithes Sandstone and Cleveland Ironstone formations between Cowbar Nab, Staithes, and Rosedale Wyke, Port Mulgrave. After Rawson and Wright (1995). Bed numbers are those of Howarth (1955, 1962a, 1973). The Cleveland Ironstone Formation cycles of Howard (1985) are indicated. b Section through the top of the Cleveland Ironstone and the Whitby Mudstone formations between Cowbar Nab, Staithes, and Rosedale Wyke, at Port Mulgrave. After Rawson and Wright (1995). Bed numbers are those of Howarth (1955, 1962a, 1973).

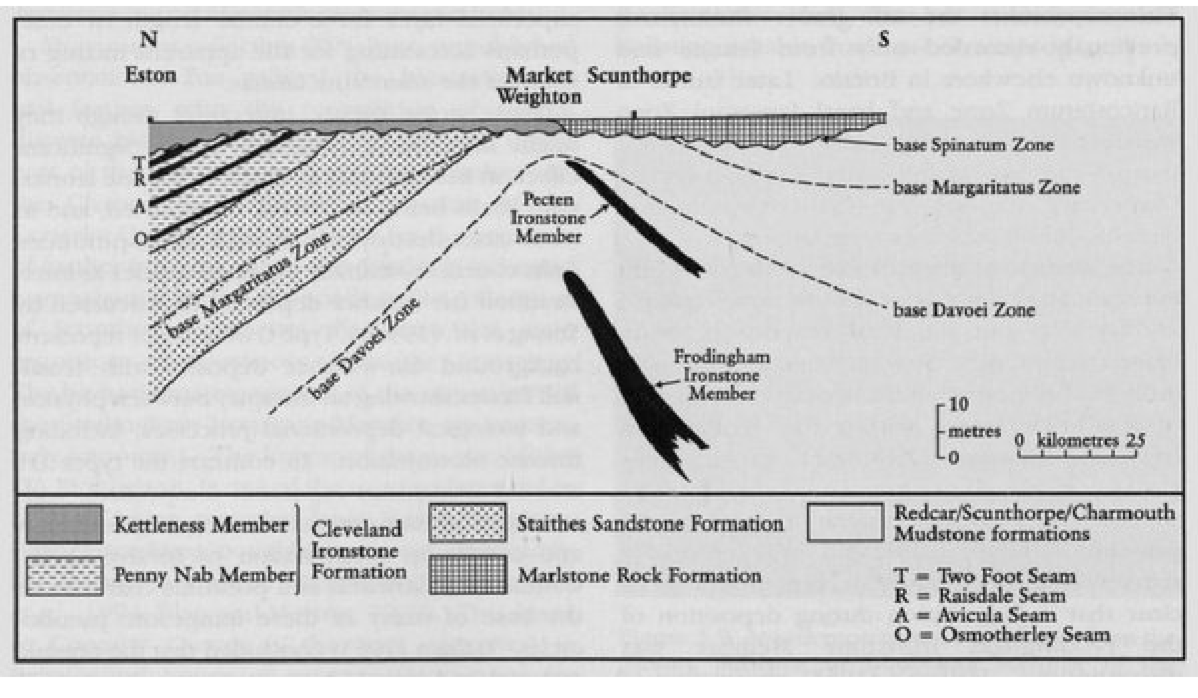
(Figure 6.16) Foreshore and cliff exposures of the Staithes Sandstone Formation, of Stokesi Subzone age, on the west side of Penny Nab, Staithes. Sandstones and sandy mudstones form the steep lower portion of the cliff (mostly in shade) and are overlain by mudstones, siltstones and ironstones of the Cleveland Ironstone Formation, Penny Nab Member (mainly Subnodosus–Margaritatus subzones) in the less steep (and well-lit) upper part of the cliff. (Photo: K.N. Page.)



(Figure 6.17) Silty mudstones and ironstone bands in the Cleveland Ironstone Formation at Penny Nab, south of Staithes. The Two Foot Seam, the six thin ironstones of the Pecten Seam, and the various beds of the Main Seam above can easily be recognized. The higher part of the cliff face is in the Whitby Mudstone Formation. (Photo: M.J. Simms.)



(Figure 6.11) Lateral variation in the Cleveland Ironstone Formation along NW–SE transects between Eston and Hawsker. Datum for the Kettleness Member is the Sulphur Band; datum for the Penny Nab Member is the base of the Two Foot Seam. Roman numerals indicate the cycles of Howard (1985). After Young et al. (1990a).



(Figure 5.10) Schematic section across the Cleveland Basin, Market Weighton High and northern end of the East Midlands Shelf showing the relationship of the Liassic ironstones to the underlying structure. After Howard (1985).