Jurassic sedimentation in the Cleveland Basin: a review

J.H. Powell

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British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK

(e-mail: jhp@bgs.ac.uk)

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SUMMARY: This review combines two Presidential Addresses (2005; 2006) and aims to provides an up-to-date overview of the stratigraphy and sedimentation of the Jurassic sequence of the Cleveland Basin (Yorkshire), including poorly known data from the western outcrop. These fascinating rocks have been the focus of geological research since the 18th century and have had a profound influence on the development of the geological sciences. Throughout the 20th century, the excellent coastal exposures have acted as a magnet for palaeontologists, stratigraphers, sedimentologists and geochemists, as a natural geological laboratory, and in recent decades, the coastal exposures received increased scientific interest as a result of their analogy with hydrocarbon source and reservoir rocks in the North Sea. Designation of the international Global Stratotype Section and Point (GSSP) for the Sinemurian-Pliensbachian stage boundary in Robin Hood's Bay, the establishment of the Dinosaur Coast, and development of the Rotunda Museum in Scarborough have all given the regional geology additional importance.

The Lias Group (Hettangian to Toarcian age; 199.6 to 175.6 Ma), exposed in the well known coastal sections, is illustrated by the fully cored Felixkirk Borehole, located at the western margin of the outcrop, and is one of the best examples of shallow marine sedimentation in an epeiric shelf-sea setting. It comprises two large-scale, upward coarsening cycles, namely the Redcar Mudstone to Staithes Sandstone cycle, followed by the Cleveland Ironstone to Blea Wyke Sandstone cycle. Within this broad pattern, smaller scale transgressive-regressive cycles are described from stratigraphically expanded and reduced successions. Detailed ammonite biostratigraphy provides a finely calibrated temporal framework to study the variations in sedimentation, which include storm-generated limestones and sandstones ('tempestites') interbedded with mudstone deposited during fair-weather periods. Hemipelagic mud, occasionally organic-rich, reflects deeper-water anoxic events that may indicate a response to global climate change.

In cores, the tempestite beds (Hettangian to Sinemurian) are characterized by sharp bases that, at outcrop, are often masked by downward penetrating burrows. Cyclicity on a centimetre scale in the overlying Pliensbachian 'Banded Shales' may be the result of orbitally induced, climatic cycles. Gradational upward coarsening to the Staithes Sandstone Formation marks a transition to sand-rich tempestite deposits, characterised by low angle and swaley cross-lamination, interbedded with sand-starved units (striped siltstones). The sands were probably deposited from sediment-laden, storm-surge and ebb currents in inner- and mid-shelf settings; the sandy substrate was, at some levels, extensively bioturbated by deposit feeding organisms

that produced a spectacular range of trace fossil assemblages characteristic of shoreface, inner-, mid-, and outer-shelf settings. Intrabasinal tectonics was a controlling factor during deposition of both the Staithes Sandstone and the overlying Cleveland Ironstone (Late Pliensbachian). The influx of sand is attributed to hinterland uplift and increased sediment flux. More marked intraformational uplift during deposition of the Cleveland Ironstone is manifested in a much attenuated succession in the west of the basin (Felixkirk); southwards, towards the Market Weighton High, the Pecten/Main Seam oversteps unconformably onto progressively older beds to rest on the lower part of the Redcar Mudstone Formation. Ironstone, in the form of berthierine ooids and sideritic mud, was deposited during 5-6 cycles (in coastal exposures) of high sea-level stands that cut off siliciclastic influx from the low-gradient hinterland; regressive, upward-shoaling intervals are marked by interbedded, bioturbated siltstone and fine-grained sandstone.

The Toarcian succession (Whitby Mudstone and Blea Wyke Sandstone formations) continues the second upward coarsening cycle in response to increased subsidence, rising sea-level, and an influx of siliciclastic sand. Oxygenated, open marine mud was deposited during the initial deepening phase, followed by bituminous mud, attributed to ocean-water stratification and the establishment of anoxic bottom conditions; in the west of the basin an upward shoaling sequence suggests that water depths were not as great. Recent research on the geochemistry and stable isotope signatures across this early Toarcian interval indicates a widespread, global anoxic event, possibly attributed to the release of methane hydrate on the ocean floor. The Alum Shale Member represents increasingly oxygenated bottom conditions and an upward coarsening motif with passage to the Blea Wyke Sandstone Formation, which is preserved only in the Peak Trough, an actively subsiding graben. Basin uplift accompanied by gentle folding in late Toarcian to Aalenian times removed much of the late Toarcian succession so that the Middle Jurassic Dogger Formation (Aalenian), a complex, condensed, shallow water unit rests unconformably on beds as low as the Alum Shale over much of the Basin.

Deep boreholes and revision mapping by the BGS in the west of the outcrop have allowed a fuller, basin-wide synthesis of the palaeoenvironments and the influence of intra-Jurassic tectonics during Mid- to Late Jurassic times. During Mid-Jurassic times the low-lying, paralic coastal plain, typified by braided and meandering fluvial systems and lacustrine deposits was invaded by marine incursions from the south and east. Each transgressive event was different in its geographical penetration across the coastal plain, resulting in varied lithofacies and palaeoenvironments including ooidal ironstone and lime mud (Eller Beck Formation), peloid and ooid carbonate shoals (Lebberston Member), and tidal sand bars, pelloidal limestones and nearshore marine muds (Scarborough Formation). Trace fossils, including dinosaur footprints, and macro-plant fossils tell us much about the palaeoenvironments on the coastal plain, during this time interval (175.6 Ma – 164.7 Ma) that was characterised by a warm, seasonal climate.

The basin wide transgression and marked global sea-level rise represented by the Cornbrash Formation, marks deposition in a shallow marine environment during the Callovian, followed by sand (Osgodby Formation) and deeper water muds (Oxford Clay Formation) that spread northwards from the East Midlands over the Market Weighton High during the Oxfordian. Subsequent shallowing of the basin resulted in the establishment of a carbonate/siliciclastic platform typified by ooidal shoals, coral patch reefs and sponge spicule-rich marine sands (Corallian Group). Their complex sedimentation pattern was influenced by local infra-Oxfordian tectonics related to the Howardian-Flamborough Fault Belt. Although the Ampthill Clay and Kimmeridge Clay formations, the latter representing the most important regional hydrocarbon source rock, are not well-exposed, recent boreholes in the Cleveland Basin have allowed a much better understanding of the hemi-pelagic marine environment (both oxic and anoxic) during this phase of sedimentation which marks a global sea-level rise. Although well-studied by world standards, the Jurassic sediments of the Cleveland Basin continue to throw up surprises and advances in our understanding of the Earth as a dynamic system over a period of about 30 million years. These studies have directly and indirectly influenced our understanding of the Earth as a system, and have played an important role in educating non-specialists, undergraduates and professional geologists over many decades.

The Jurassic rocks of the Cleveland Basin (Yorkshire) have been a focus of geological research since the 19th century, with studies by William Smith, his nephew John Phillips (1829), George Young and John Bird (1822), Martin Simpson (1884) and the Survey geologist Charles Fox-Strangways (1992, 1915), to name but a few. Throughout the 20th century the excellent coastal exposures have acted as a magnet for palaeontologists, stratigraphers, sedimentologists and geochemists, as a natural geological laboratory, and their study was given additional impetus in the later part of the 20th and early 21st centuries by their analogy with hydrocarbon reservoir and source rocks in the North Sea Basin.

The Jurassic of Yorkshire (Fig. 1) was treated to an authoritative review by past YGS President Professor John Hemingway (Hemingway 1974) and has been the subject of a number of excellent regional summaries and guides (Black 1934*b*; Rawson & Wright 1992, 1996, 2000; Cope 2006). Many of these publications focussed on the superb coastal sections so, in my YGS Presidential addresses (2005, 2006), summarized here, I aimed to present an overview of Jurassic sedimentation in the Cleveland Basin, including relatively recent and unpublished data from the western margin of the basin, an area often overlooked. With such a wealth of scientific publications on these fascinating rocks, I have only been able to focus on key topics, but I hope this paper will provide an up-to-date overview of the geology that will stimulate further research into outstanding problems.

1. STRUCTURAL SETTING

The Cleveland Basin in Jurassic times formed part of a system of shallow epeiric seas and small extensional tectonic basins, linked via the Sole Pit Basin (a half-graben structure) to the North Sea Basin (Fig. 2; Zeigler 1982). The Cleveland Basin was relatively small, and was bounded to the north-east by the Mid-North Sea High and to the west by the Pennine High. To the south lay the East Midlands Shelf, the northern part of which comprised the Market Weighton High (MWH) (Kent 1955), which remained as a relatively stable unfolded block, probably underlain by a granite intrusion (Bott *et al*. 1978; Donato 1993) and characterized by reduced rates of sedimentation throughout the Jurassic. The MWH is an asymmetrical structure over which subsidence and sedimentation rates were reduced; it separated rapid subsidence and higher sedimentation rates to the north, in the Cleveland Basin, from more gradual subsidence to the south in the Lincolnshire area of the East Midlands Shelf (Kent 1955, 1974).

The Mid North Sea High underwent tilting to the southwest in Mid Jurassic times, probably in response to doming associated with the Forties-Piper Volcanic Centre in the central North Sea Basin (Sellwood & Hallam 1974; Zeigler 1982; Underhill & Partington 1993). Mid Jurassic sedimentation in the Cleveland Basin was therefore characterized by marine transgressions that advanced in a north-westerly direction across the Market Weighton High, and by progradation of fluvial and deltaic siliciclastics towards the south-east (Hemingway 1974). The shoreline depositional lithofacies of the Lower Jurassic strata were removed following basin inversion and erosion during the Neogene, but projection of lithofacies and thickness trends suggests that the Early Jurassic shoreline lay around the present-day northern Pennines and Southern Uplands (Fig. 2).

At the regional scale, the Cleveland Basin was affected by a number of extensional faults and probable strike-slip fault complexes (Hemingway 1974; Kirby & Swallow 1987) that roughly define the present–day outcrop (Fig. 3). Some were active during Early and Mid Jurassic sedimentation (Milsom & Rawson 1989; Powell *et al*. 1992). To the south, the east-west trending Asenby–Coxwold-Gilling Graben, the Helmsley-Filey Fault Belt and the Howardian-Flamborough Fault Belt (defining the Vale of Pickering) were intermittently active north of the Market Weighton High during Mid to Late Jurassic times (Kirby & Swallow 1987). The eastern margin of the basin is cut by north-trending structures, such as the Peak Trough and Peak Fault (Milsom & Rawson 1989), the Cayton Bay Fault and the Whitby Fault. The Peak Trough was active in Early Jurassic times and preserves a thicker sequence of Lower Jurassic rocks compared to the surrounding areas. Furthermore, the entire Cleveland Basin was subjected to gentle folding and erosion in late Toarcian time, so that the upper part of the Lias Group was eroded to increasingly lower stratigraphical levels towards the south and southeast of the basin (Black 1934*a*; Hemingway 1974). The western margin of the present-day outcrop is marked by the north-trending Borrowby Graben (Powell *et al*. 1992), which, like the Peak Trough, shows evidence of synsedimentary faulting during the Mid Jurassic. Less evident is the uplift of part of the western outcrop near Roulston Scar (Hambleton Hills) in the Oxfordian, resulting in local erosion of the Oxford Clay (Powell *et al*.1992, fig. 16). A number of the major bounding faults are known to have been active during the Cimmerian orogeny, especially the east-west trending Coxwold-Gilling and Howardian-Flamborough fault belts, which show extension in Oxfordian (Late Jurassic) times (Wright, 2009) and renewed movements in post-Cretaceous times (Kirby & Swallow 1987; Starmer 1995). Petrographic and fission-track analysis suggest that the Middle Jurassic sediments were buried to a depth of about 2 to 3km (Hemingway & Riddler 1982;

Green 1986; Bray *et al*. 1992), prior to inversion and north-south compression during the latest Cretaceous to Neogene. The latter resulted in formation of the complex east-west trending Cleveland Anticline (Fig. 3) and subsidiary folds (e.g. the Lockton Anticline, Goathland Syncline and Robin Hood's Bay Dome) that control the Jurassic outcrop pattern of the North York Moors (Kent 1980*a*, 1980*b*).

2. PALEOGEOGRAPHY

The palaeogeography of the Cleveland Basin is less well known during the Early Jurassic (Lias Group; 199.6 to 175.6 Ma) than at later times. With notable exceptions such as the London Platform, the region then formed part of the broad epeiric sea that covered much of England and Wales and much of western Scotland (Cope *et al*. 1992; Scrutton & Powell 2006; Fig. 2). During sea-level low stands (e.g. late Pliensbachian), however, clastic sediments may have been derived from an emergent Pennine-Caledonian High. Lias Group 'background' sediments mostly comprise mudstones, but regional variations in interbedded coarser grained bioclastic carbonate and siliciclastic sediments, ranging from carbonate dominated in southern Britain (e.g. Blue Lias) to siliciclastic, storm-dominated sediments in the Cleveland Basin, suggest a northerly source area for the siliciclastic sediments. This may have been the Pennine High or land areas in southern Scotland (Fig. 2).

By Mid Jurassic time, uplift of the Mid North Sea High and the northern source areas noted above, coupled with uplift (possibly isostatic buoyancy) over the Market Weighton High, defined a more or less circular Cleveland Basin that was linked intermittently to the East Midlands Shelf to the south and the Sole Pit Basin to the south-east. Marine sedimentation continued in a broad epeiric shelf setting in southern Britain and northwest Europe, but tectonic uplift and North Sea doming/rifting resulted in fluvial progradation from the northwest and northeast (Knox *et al.* 1991) into the Cleveland Basin and deposition in paralic environments ranging from river, lake and delta to estuarine. There is also evidence of 'Millstone Grit' quartz granules in the Aalenian sediments of the Howardian Hills, suggesting a western Pennine source area. Only occasionally did sea-level rise result in marine transgression over the low-lying paralic hinterland. These brief marine transgressions advanced generally northwestwards (Knox 1973; Parsons 1977) over the Market Weighton High, and except for the mid-Bajocian sea-level high (ammonite-bearing Scarborough Formation), they did not extend to the northwest of the present-day outcrop (Fig. 4c).

Rapid (global) sea-level rise throughout Britain during the early Callovian resulted in partial drowning of the Cleveland Basin and widespread marine sedimentation over northern Britain (Fig 8a). Fully marine ammonite faunas indicate connection with the faunal provinces of southern Britain. The Market Weighton High still influenced sedimentation in the region, however, resulting in thinner and distinctive marine calcareous sands during the Callovian (164.7-161.2 Ma) compared to muds on the East Midlands Shelf. Sand was mostly derived from the northwest (Wright 1977), but tectonics resulted in depositional hiatuses and much reworking of sediment during the Callovian, prior to sea level rise that was characterized by the northwards development of deeper water muds (upper Oxford Clay) across the Market Weighton High in the early Oxfordian. During the late Early Oxfordian to early Late Oxfordian, sedimentation in the Cleveland Basin was again distinct from the area south of the Market Weighton High (Rawson & Wright 2000, fig. 3c). Subsidence rates kept pace with sea-level rise and resulted in deposition of distinctive Corallian Group sediments, a complex suite of marine siliceous sands, spiculites, ooidal shoals, micritic limestone and coral/algal patch reefs (Blake & Huddleston 1877; Wilson 1936, 1949; Wright 1972, 1983). This second phase of basin inversion (relative to the gently subsiding East Midland Shelf) resulted in shallower water sedimentation coeval with deeper water muds of the West Walton Formation and Ampthill Clay on the East Midland Shelf and the Seeley Formation in the Sole Pit Basin (Fig. 7). It was not until mid late Oxfordian times that increased subsidence and rising sea-level allowed the mud lithofacies of the Ampthill Clay to spread northward from the Vale of Pickering area (Cox & Richardson 1982). Finally, a major worldwide sea level rise during the Kimmeridgian (Hallam 1988; Haq *et al*. 1988; Herbin *et al.* 1991) resulted in deeper water hemipelagic sedimentation over wide areas of present day Britain, by which time the Cleveland area was no longer an active and distinct tectono-depositional basin.

Relative sea-level changes expressed within the Jurassic succession of the Cleveland Basin are often not in accord with global patterns (Hallam 1988; Haq 1988; Hallam 2001); there is good correspondence with global sea-level rise in the early Hettangian (Calcareous Shales, Redcar Mudstone Formation), early Pliensbachian (Pyritous/Banded Shales; Redcar Mudstone Formation); early Toarcian (Grey Shales/Mulgrave Shale members; Whitby Mudstone Formation) and late Oxfordian (Weymouth Member, Oxford Clay). However, the early Sinemurian, early-late Bajocian and mid-Callovian global sea-level rises are not well expressed. This is due to the effects of local and regional intra-plate tectonics which resulted in hinterland uplift and local basinal subsidence, increased sediment flux and regressive siliciclastic sedimentation (e.g. Ravenscar Group and Osgodby Formation in the Cleveland Basin).

3. BIOSTRATIGRAPHICAL AND CHRONOSTRATIGRAPHICAL FRAMEWORK

Ammonites have traditionally provided the biostratigraphical and chronostratigraphical framework for the Jurassic of the Cleveland Basin, although their absence from the paralic and fluvio-deltaic lithofacies of the Middle Jurassic Ravenscar Group has resulted in an interesting debate on the timing of basin fill during the Bajocian and Bathonian (Leeder & Nami 1979; Riding & Wright 1989; Butler *et al*. 2005).

Ammonite zonation is precise and is based on the benchmark work of Arkell (1933, 1945) and later workers. Up to 65 ammonite zones have been recognized in the Cleveland Basin (Figs 5, 6, 7), together with many subzones that allow fine temporal resolution and correlation throughout Britain (Buckman 1909-30; Dean *et al*. 1961; Howarth 1955, 1962, 1973; Cope *et al*. 1980*a*, *b*; Callomon 1995). The duration of ammonite zones is difficult to determine as rates of extinction and the incoming and acme of new species are likely to have varied through Jurassic time. As a common ‘rule of thumb’, the duration of an ammonite zone was estimated to be about 1 million year (Ma). However, where recent radiometric ages have been determined based on U-Pb and $^{40}Ar/^{39}Ar$ ratios, the duration of Jurassic ammonite zones has been estimated to be between 0.4 and 1.6 Ma (Palfy & Smith 2000), although this duration has been questioned for the Toarcian by McArthur *et al.* (2000), who consider the variation in duration to be much greater.

Ammonites typical of the Boreal (northern) and Tethyan (southern) realms are present in the Cleveland basin as a result of periodic connection between these two palaeobiogeographical provinces via the Faeroes Rift, the Anglo-Welsh Basin, the Paris Basin and the open Tethys Ocean located to the south (Cope 2006). Howarth (1976) recognized the incoming of Tethyan forms during the Early Jurassic, Sinemurian–Aalenian interval. At other times, Boreal faunas were dominant, especially during the Callovian transgression and the Oxfordian, and are typified by cardioceratid and kosmoceratid ammonites (Cope 2006). Of considerable note is the selection of the Global Stratotype Section and Point (GSSP) for the base of the Pliensbachian Stage at Wine Haven, Robin Hood’s Bay (Meister *et al*. 2006), at a level interpreted as coinciding with a major deepening of the sea manifested in the lower part of the Pyritous Shales Member (Redcar Mudstone Formation, Lias Group).

The ammonite zonal scheme in relation to the chronostratigraphy and lithostratigraphy of the Cleveland Basin and correlative strata in the Sole Pit Basin and East Midlands Shelf is outlined in Figures 5, 6 and 7. The zonal scheme is based on the Boreal ammonite distribution, most commonly used in the UK; in this paper ammonite zones are used as chronozones, so their names are capitalized using the Standard Zone terminology species name (e.g. Planorbis Zone), but for ease of reference to the genus and species (e.g. *Psiloceras planorbis*), the names are written as biozones in Figures 5, 6 and 7. Ogg *et al*. (2008) have revised the Jurassic time scale so that the geochronological age of the base of the Jurassic is 199.6 Ma and the base of the Cretaceous is 145.5 Ma, a duration of 54 million years, considerably shorter than earlier estimates of 205.7 Ma (base) and 142.0 Ma (top) and 63.7 years duration (Gradstein & Ogg 1996). However, as a result of Late Cimmerian (latest Jurassic to pre-Cretaceous) erosion (Rawson & Riley 1982), the youngest beds preserved in the Cleveland Basin belong to the Pectinatus Zone, c.151 Ma (Ogg *et al*. 2008), or possibly the higher Pallasioides Zone (Herbin *et al*. 1991) (Fig. 7).

The standard north-west European sequence of Lower Jurassic ammonite chronozones and sub-chronozones for the Hettangian, Sinemurian, part of the Pliensbachian and Toarcian stages has been recognized in the Lias succession in well-exposed coastal sections (Buckman 1909-30, 1915; Bairstow 1969; Howarth 1955, 1962, 1973, 2002). Most of these zones have also been identified in the Felixkirk cores (Fig. 9) (Ivimey-Cook & Powell 1991, fig. 2; Powell *et al*. 1992). The ammonite zonation for the Middle and Upper Jurassic is based on Cope *et al*. (1980*a*, *b*), especially the work of Wright (1980).

Other fossil groups, particularly microfossils, have aided biostratigraphical zonation and correlation, especially with the North Sea Basin and for the paralic and marginal marine successions where ammonites are not present. Bate (1964, 1965, 1967) used ostracods to correlate thin transgressive marine units of the Middle Jurassic Ravenscar Group with the fully marine succession of the East Midlands Shelf. Although less precisely resolved, dinoflagellate cysts were used by Woollam & Riding (1980) to establish up to 16 zones calibrated against the standard north-west European ammonite scheme (76 zones). Dinoflagellates have enabled correlation of the Middle Jurassic succession in the Cleveland Basin with the southern North Sea (Hancock & Fisher 1981) and northern North Sea (Butler *et al*. 2005), and have helped to resolve the age of the Bajocian to Bathonian succession onshore (Riding & Wright 1989).

4. LITHOSTRATIGRAPHY OF THE CLEVELAND BASIN

A brief outline of the lithostratigraphy of the Jurassic succession is presented in this section (Figs 5, 6, 7), and the former nomenclature is shown in Tables 1 and 2. Further details of the succession are presented in later thematic sections (Section 5).

Lower Jurassic sediments comprise the **Lias Group** (Fig 8b) of Hettangian to Toarcian age, with a maximum thickness of 454 m; subdivisions are based on Powell (1984), Knox (1984), Ivimey-Cook & Powell (1991), Howard (1985) and Rawson & Wright (1992). Lias Group sediments (Figs 5, 9) rest conformably on the Upper Triassic (Rhaetian) **Penarth Group** (Benfield & Warrington 1988; Ivimey-Cook & Powell 1991). Black, anoxic, fissile mudstones of the Westbury Formation and the overlying grey-green smectitic claystones of the Cotham Member (Lilstock Formation), both formations of the Penarth Group, were deposited in brackish and restricted lagoons and are dominated by monospecific faunas. The first truly marine interbedded limestones/mudstone beds typical of the Lias Group occur about 10 m below the first marine ammonite fauna represented by *Psiloceras planorbis* (Ivimey-Cook & Powell 1991), which marks the base of the Hettangian Stage in the region (Fig. 9). However, the GSSP for the base of the Jurassic System and the Hettangian Stage is placed at the incoming of *Psiloceras spelae* in the mid-European Tethyan realm, slightly earlier than the '*planorbis* event' in the UK (Page & Bloos 1998; Lucas & Tanner 2007).

4.1 Lower Jurassic Succession

The Lias Group (Figs 5, 9) in the Cleveland Basin is divided into five formations (Powell 1984), described here in ascending order. The **Redcar Mudstone Formation** (c. 283 m thick) forms the greater part of the group, and consists of clay and silt grade siliciclastic sediments interbedded with carbonate-rich shell beds of various types, concretion beds and fine-to medium-grained siliciclastic beds. The coarse-grained beds enable subdivision of the formation into five informal members on the coast (Tate & Blake 1876; Fox-Strangways 1892; Fox-Strangways & Barrow 1915; Buckman 1915; Hemingway 1974; Knox *et al*. 1991; van Buchem & McCave 1989; Hesselbo & Jenkyns 1998; van Buchem & Knox 1998). In upward sequence, these are the Calcareous Shales (with numerous oyster-rich limestone beds), Siliceous Shales (bioturbated, sand-rich beds), Pyritous Shales (pyritous nodules and beds of concretionary siderite), Banded Shales (regular alternations of siltstone and mudstone beds) and Ironstone Shales (iron-rich, silty laminations). However, in the west of the basin, the distinction between the last three members is less apparent. There, a gradational upward coarsening trend within the Pyritous/Banded/Ironstone interval (lower Pliensbachian) is clearly shown on the gamma-ray logs of the Felixkirk Borehole [SE 4835 8576] (Figs 1, 9; Powell & Ivimey-Cook 1991; Powell *et al*. 1992). The formation is considerably thinner (194 m) in the west of the basin. The marked 'saw-tooth' expression of the gamma-ray and sonic geophysical logs in the Calcareous Shales and Siliceous Shales members (Fig. 9) is due to the intercalation of fine-grained 'background' sediments (mudstone) and coarse-grained bioclastic or sand-rich beds that form the characteristic 'benches' in these Hettangian to Sinemurian strata in Robin Hood's Bay (Fig 10a). The origin of these beds is considered in Section 5.

The Ironstone Shales pass gradationally upward with increasing sand-grade sediment to the **Staithes Sandstone Formation** (c. 30 m) (Hemingway 1974; Howard 1985). The formation forms a coastal cliff and inland scarp feature, and consists of grey, yellow weathering, fine- to medium-grained sandstone and siltstone of late Pliensbachian age. On the coast, at Staithes, the upper part of the formation has a higher ratio of siltstone to sandstone than in the western outcrop. Sandstone beds are often characterized by low-angle, wavy and hummocky cross-bedding (Howard 1985), and the beds are often heavily bioturbated with a rich suite of ichnofossils (Figs 10c,f) (Knox *et al.* 1991).

The **Cleveland Ironstone Formation (CIF,** c. 28 m thick**)** and the underlying Staithes Sandstone Formation form a marked mappable feature inland, hence the earlier term 'Middle Lias' for these two formations. The formation, on the coast, is subdivided into a lower Penny Nab Member (Howard, 1984), including five mineable ironstone seams (in upward sequence: the Osmotherly, Avicula, Raisdale and Two Foot seams). The overlying, the Kettleness Member, which includes the Pecten and Main Seam, unconformably oversteps successively younger Lias Group units to the south towards Market Weighton, and to the west (Fig. 16).

Ironstone represents only a small part (c. 30%) of the CIF, which consists of grey mudstone and sandy mudstone interbedded with sideritic and berthierine (chamosite)-rich ooidal ironstone (Sorby 1857; Lamplugh 1920; Hemingway 1951; Whitehead *et al.* 1952; Chowns 1968; Howard 1985). Intervening siliciclastic beds show fine parallel lamination, wave ripple lamination and erosional gutter casts (Greensmith *et al*. 1980; Rawson *et al*. 1983; Howard 1985). The formation is thickest at Staithes, but thins to the south and west where the siliciclastic interbeds are reduced in thickness, and as a result of an intraformational unconformity below the Pecten Seam (Fig. 9), only three seams including the Main Seam are present at Felixkirk, with a total thickness of 9m (Powell *et al*. 1992). This is a result of the Main Seam overlapping the Pecten Seam to rest with overstep on successively older strata to the south. In the Howardian Hills, the formation is only 2m thick (Chowns 1968)

The beds informally known as the 'Upper Lias' comprise the **Whitby Mudstone Formation** and the **Blea Wyke Sandstone Formation** (Rastall 1905; Powell 1984; Knox 1984). The Whitby Mudstone (c. 105 m thick) consists predominantly of grey to dark grey mudstone and siltstone with abundant shelly fossils at some levels. Uplift and erosion prior to deposition of the Dogger Formation in Aalenian times has resulted in the full succession being preserved only in the syndepositional Peak Trough (Milsom & Rawson 1989), where five members are present (Knox 1984). The **Grey Shale Member** (c. 13.5 m max.) comprises the eponymous silty mudstone with beds of calcareous siderite concretions. A change to more anoxic bottom conditions is recorded in the overlying **Mulgrave Shale Member (formerly Jet Rock Member)** (Rawson & Wright 1992) (c. 31 m max.), which consists of fissile, bituminous, dark grey mudstone with abundant ammonites. This unit was long exploited for the mineral jet (dense, water-logged, araucarian wood), mined on the coast and sporadically inland for the manufacture of jewellery (Hemingway 1974, p.174). The **Alum Shale Member** (max. 37 m) is generally less fossiliferous and comprises grey silty mudstone with bands of calcareous and siderite concretions, and bands of phosphatic nodules in the upper part; the shales were formerly worked in large quarries for alum used for 'fulling' wool and in chemical industries (Gad *et al*. 1969; Hemingway 1974). The Middle Jurassic Dogger Formation rests unconformably on this unit over much of the Cleveland Basin (e.g. in the Felixkirk Borehole; Fig. 9). Where the full succession is preserved, the upper part of the Alum Shale Member shows a gradual coarsening upward trend to the overlying **Peak Shale Member** (Knox 1984). The upward coarsening trend continues into the **Fox Cliff Siltstone Member**, comprising muddy siltstone with beds of calcareous and sideritic concretions and with small phosphatic nodules. The coarse-grained end-member of this trend is the **Blea Wyke Sandstone Formation** (18 m max.), comprising grey, mud-rich sandstone (Grey Sandstone Member) passing up to 'cleaner' yellow sandstone (Yellow Sandstone Member). When traced southwards towards the Market Weighton High (MWH), pre-Dogger erosion cuts downwards through the Whitby Mudstone so that the Dogger Formation rests on the Mulgrave

Shale Member in the Brown Moor Borehole (Gaunt *et al.* 1980; Fig 1), located north of the MWH. At Market Weighton, the highest Lower Jurassic strata below the sub-Cretaceous unconformity comprise sandstone with ironstone nodules attributable to either the Cleveland Ironstone Formation or Staithes Sandstone Formation (Whitham *in* Scrutton & Powell 2006).

In the Southern North Sea Basin, the Lias Group is between 200 and 300 m thick, but reaches up to 820 m in the Sole Pit Basin. It thins northwards towards the Mid North Sea High (Lott & Knox 1994). Formations offshore are recognized largely from their geophysical wireline log characteristics (Fig. 5), but are broadly equivalent to the onshore equivalents. Hence, in upwards sequence, the Penda and Offa formations are equivalent to the Redcar Mudstone Formation, the ferruginous and sandy Ida Formation is equivalent to the Cleveland Ironstone and Staithes Sandstone formations, and the Cerdic Formation is equivalent to the Whitby Mudstone Formation. As a result of latest-Toarcian folding, the sandy late Toarcian Phillips Member of the southern North Sea Basin, broadly equivalent to the upward coarsening Blea Wyke Formation, was removed by erosion and is identified only in a few wells (e.g. 47/3b-4; 42/29-1), possibly restricted to extensional rifts similar to the better known Peak Trough (Lott & Knox 1994).

4.2 Middle Jurassic Succession

The **Dogger Formation**, up to 13 m thick (Hemingway 1974), is Aalenian in age (Black 1934*a*; Parsons *in* Cope *et al*. 1980*b*). It rests unconformably on the Lias Group, generally on the Alum Shale Member but disconformably on the Blea Wyke Sandstone (Knox 1984) within the Peak Trough. In coastal sections, the marine Dogger Formation is generally represented by thin ferruginous sandstone, locally rich in berthierine and calcareous ooids. Intense bioturbation is common, and soft-sediment burrows penetrate downward into the underlying, mudstone (Alum Shale). Near Whitby (East Cliff), for example, the Dogger, c. 1 m thick, consists of highly bioturbated, ferruginous sandstone with rounded black phosphatic pebbles, locally with endolithic borings. Inland, the Dogger Formation is a lithologically heterogeneous unit, comprising conglomerate, sandstone, mudstone, ooidal and bioclastic limestone and ironstone, and including marine and brackish lithofacies. When traced southwards towards the northern margin of the Market Weighton High, the Dogger Formation rests unconformably (overstep) on older units of the Lias Group down to the Redcar Mudstone Formation (Hemingway, 1974).

The majority of the Middle Jurassic (Aalenian to Bathonian) succession is represented by the **Ravenscar Group** (240 m max.) (Smithson 1934, 1942; Hemingway 1949; Hemingway & Knox 1973; Lott & Humphreys 1994; Cox & Sumbler 2002) comprising mostly paralic, including fluvial and lacustrine, lithofacies, and three distinctive transgressive marine units (Fig. 6): the Eller Beck Formation, the Lebberston Member of the Cloughton Formation, and the Scarborough Formation. The Ravenscar Group thins rapidly southwards to 57 m in the Fordon Borehole [TA 058 758], south of the Vale of Pickering (Fig. 8b), and a similar thickness was recorded in the Brown Moor Borehole (see below).

The paralic units in the succession (formerly known as 'Estuarine' or 'Deltaic' units; Table 2) comprise the Saltwick, Cloughton and Scalby formations. The **Saltwick Formation** (57 m max.) generally overlies the Dogger Formation, but rests unconformably on the Lias Group (Alum Shales) where the Dogger is absent due to erosion or non-deposition. It consists mostly of medium- to coarse-grained, cross-bedded channel sandstones with fine-grained, planar laminated and ripple cross-laminated sandstone and micaceous mudstone; drifted plant fragments and *in situ* plant rootlets are common in some beds. The **Eller Beck Formation** (c. 8 m max.) represents the first transgressive marine incursion that advanced northwestwards across the basin; it comprises sandstone rich in berthierine ooids, ooidal ironstone and mudstone (Barrow 1877; Knox 1973). The overlying **Cloughton Formation** (85 m) is lithologically similar to the Saltwick Formation, but includes a marine limestone/sandstone unit, the **Lebberston Member** (up to 9 m), which, where present in the south of the basin, divides the formation into a lower **Sycarham Member** and an upper **Gristhorpe Member**. In southern coastal exposures, where the Lebberston Member comprises sandy ooidal limestone and calcareous sandstone, it is know as the 'Millepore Bed' lithofacies. In the Hambleton and Howardian Hills, it is more calcareous, and is referred to as the 'Whitwell Oolite' lithofacies (Richardson, 1912). When traced southwards to the Market Weighton High (e.g. in the Brown Moor Borehole, Gaunt *et al*. 1980), the attenuated sandy paralic Cloughton Formation succession (56 m thick) between the Eller Beck Formation and the Scarborough Formation becomes more 'marine' in character, and includes 16 m of ooidal limestone (in 3 beds) and sandstone with bivalves and scattered ooids.

The **Scarborough Formation** (Bate 1965; Parsons 1977, 1980; Gowland & Riding 1991; Butler *et al*. 2005), marks a major marine transgression over the whole Basin in the early Bajocian. In the coastal type section at Hundale Point (Fig. 27) it is dominated by mud- and sand-rich sediments with thin argillaceous limestones, subdivided into seven members (Table 2; Gowland & Riding 1991). Ammonites such as *Dorsetensia* and *Teloceras,* and marine palynomorphs in the Ravenscar Shale Member, indicate the Humphriesianum Zone (late early Bajocian). In the coastal outcrop, marine siliciclastic sediments with hummocky cross-bedding (e.g. at Ravenscar cliff) and thin silty limestones that yield bivalves (*Gervillella, Pseudomontis, Trigonia, Astarte and Lopha*), belemnites and sparse ammonites, together with a diverse suite of shallow marine trace fossils including *Rhizocorallium*, *Teichichnus* and U-shaped *Diplocraterion* (Hemingway 1974; Miller *et al*. 1984; Gowland & Riding 1991).This contrasts with the different succession in the western outcrops of the Hambleton Hills (Table 2), where a lower unit, the **Brandsby Roadstone Member** , comprising peloidal (faecal peloids) planar cross-bedded limestone, is overlain by medium-grained, fossiliferous sandstone, the **Crinoid Grit Member** (Powell *et al*. 1992).

A return to fluvio-deltaic and paralic lithofacies is marked by **Scalby Formation** (c. 60 m) (Black, 1928; Leeder & Nami, 1979). At the base, the Moor Grit Member consists of medium- to coarse-grained, locally pebbly, cross-bedded, channel sandstone unconformably overlying the Scarborough Formation. It passes gradationally up to the **Long Nab Member**, which is chararcterised by micaceous mudstone and finer-grained sandstone locally with abundant plant remains; channel sandbodies are less common and smaller in size compared to those in the Moor Grit, hence its former name the 'Level-bedded Series' (Hemingway 1974).

The biostratigraphical framework of the Ravenscar Group is poorly constrained. Based on ostracod faunas (Bate 1967), the marine Eller Beck Formation and Lebberston Member are thought to be of late Aalenian-early Bajocian and early Bajocian age respectively, coeval wholly or in part with the Discites Zone of the Lincolnshire Limestone. Sparse ammonites collected from the Scarborough Formation suggest the 'mid-Bajocian' Humphriesianum Zone (Romani to Blagdeni subzones) (Parsons 1977). Correlation of the western inland succession with the typical coastal exposures is, however, tentative, and the Scarborough Formation in the Hambleton Hills may be representative of the early Sauzei Zone (Fig. 6; Parsons 1980). Fluvial and paralic parts of the succession contain few biostratigraphical indicators, but given the ages indicated for the marine units, the Cloughton Formation probably spans the Discites, Laeviuscula and possibly Sauzei zones (Fig. 6; Cope *et al*. 1980*b*). The basal part of the Scalby Formation (Moor Grit Member) on the coast has yielded a dinoflagellate cyst assemblage of probable late Bajocian age (Riding &

Wright 1989); the overlying Long Nab Member ranges from late Bajocian in the lower part to Bathonian in the upper.

The upper boundary of the Ravenscar Group is defined by the base of the marine Cornbrash Formation or, where absent, by the base of the Osgodby Formation (Powell *et al*. 1992; Gaunt *et al*. 1980). The overlying marine succession represents a condensed sequence of Callovian age (Wright 1977), equivalent to the Upper Cornbrash of the succession on the East Midlands Shelf and southwards to Dorset (Page 1989). The latter author renamed the berthierine-rich limestone unit as the Fleet Member of the Abbotsbury Cornbrash Formation, but this name and earlier terminology are used variably in Rawson and Wright (2000), and the traditional name is preferred here (cf. Douglas & Arkell 1932).

The base of the Cornbrash Formation marks the base of the Callovian Stage (Macrocephalus Zone) in the Cleveland Basin. The formation consists of oyster-rich sandy limestone with berthierine ooids. This distinctive unit is about 1 m thick on the coast (Cayton Bay) and up to 3.6 m in Newtondale (Wright 1977; Page 1989), but is absent at Brown Moor on the northern flank of the Market Weighton High (Gaunt *et al*. 1980). The Cornbrash Formation has not been positively identified in the Hambleton Hills, where the basal sandstone (Redcliff Rock Member) of the Osgodby Formation rests directly on the Scalby Formation (Senior 1975; Powell *et al*. 1992). The formation is much thinner than the equivalent Upper Cornbrash of southern England (Page 1989), where it forms a brashy (stoney) soil best suited to growing corn (hence its name). The overlying **Cayton Clay Formation** (formerly 'Shales of the Cornbrash') consists of dark grey calcareous mudstone and siltstone with phosphatic nodules; ammonites indicate the Herveyi Zone (Wright 1978; Rawson & Wright 2000). Recent boreholes (2009) at Knipe Point, near Osgodby, prove up to 4 m of Cayton Clay Formation overlying 1 m of Cornbrash limestone.

Sandstone and siltstone characterize the overlying **Osgodby Formation** (Wright 1978) of Callovian age (Fig. 6). In typical Yorkshire coast sections, the formation was subdivided into the following members, in ascending order: Kellaways Rock (now the Redcliff Rock Member), Langdale Member and Hackness Rock Member (Buckman 1913; Walker 1972; Wright 1968*a*, 1968*b*, 1978). The stratigraphy of the Callovian (and Oxfordian) rocks on the Cleveland Basin has been refined by Wright (1968*a*, 1977, 1978, 1983), particularly for the eastern part of the Basin. Only the Redcliff Rock and the Hackness Rock are present in the Hambleton Hills, where the Osgodby Formation ranges in thickness from 20 to 23 m (Powell *et* *al*. 1992; Frost 1998), and at Brown Moor only 5.5 m of fine- to medium-grained, poorly lithified, bioturbated sand with a marine fauna (belemnites and *Kosmoceras*) are present. Wright's studies, and BGS re-surveys in the western part of the basin (British Geological Survey 1992, 1994), have demonstrated two unconformities within the Callovian succession. At the base, the **Redcliff Rock Member** (Page 1989), named after Red Cliff, Cayton Bay, ranges from 11.5 to 23 m in thickness and consists of orange, yellow and grey, fine- to medium-grained, thick-bedded sandstone, locally with scattered berthierine ooids. Large bivalves and belemnites, often preserved as decalcified moulds and casts, are conspicuous in some beds, particularly in the upper part of the member. Some beds show cross-bedding and the rock is usually soft and decalcified at outcrop. Vertical burrows and burrow-mottling are common in some beds. Bivalves include the oysters *Gryphaea dilobotes and Liostrea* sp., as well as *Chlamys fibrosa, Meleagrinella braamburiensis, Trigonia* sp. and *Unicardium* sp.; rhynchonellid brachiopods are also present. The Redcliff Rock has yielded ammonites indicating the Koenigi Zone (Page 1989) and is equivalent in part to the Kellaways Clay Member of southern England. The **Langdale Member** (Wright 1968*a*, 1978) at Red Cliff, Scarborough [TA 07 84] is locally cut out below the unconformable Hackness Rock. In the Hackness Hills, it consists of about 15 m of greenish brown, fine- to medium grained sandstone and siltstone, often heavily bioturbated with sparse chamosite ooids and clay laminae. On the coast (Castle Hill; Osgodby Nab) a hard, brown fine-grained sandstone bed is present at the base The bivalve fauna is similar to that found in the underlying Redcliff Rock Member, and belemnite guards are also common in places. Ammonites include species of *Erymnoceras*, *Kosmoceras* indicating the upper Coronatum Zone. The sandstone members, together with the overlying Hackness Rock Member, are equivalent in part to the Peterborough and Stewartby members of the Oxford Clay south of the Market Weighton High (Cox *et al*. 1993). The **Hackness Rock Member**, where present, is about 3 m thick, and consists of buff-grey siltstone with alternating soft and hard calcite-cemented bands; fossils include bivalves, belemnites and sparse ammonites, the latter indicating the Athleta and Lamberti zones (Wright 1978; Page 1989).

4.3 Upper Jurassic Succession

The lithostratigraphy of the Upper Jurassic in the Cleveland Basin was established by Fox-Strangways *et al*. (1886) and Fox-Strangways (1892), and was later refined by Wright (1972, 1983, 1996*a*, 1996*b*, 2009), who formalized the nomenclature and provided a detailed chronostratigraphical framework based on ammonite zones (Fig.

7). The base of the Upper Jurassic is defined at the lower boundary of the Oxfordian Stage (Cope *et al*. 1980*b*), which corresponds to the base of the Oxford Clay Formation in the Cleveland Basin. The youngest Jurassic strata in the Cleveland Basin, the Kimmeridge Clay, belong to the Pectinatus Zone (151 Ma) or possibly the overlying Pallasioides Zone of the Tithonian Stage (Herbin *et al.* 1991; Ogg *et al.* 2008). Later Kimmeridgian sediments were removed during the late Jurassic-early Cretaceous Cimmerian earth movements.

The Upper Jurassic rocks are wholly of marine origin and mark a continuation of the major marine transgression that began during the Callovian Stage. Eustatic sea-level rise in north-west Europe (Hallam 1988; Haq *et al*. 1988) was interrupted locally by a regressive phase during the deposition of the Corallian Group, comprising carbonates and calcareous sandstones, but culminated in restricted, basinal environments with anoxic bottom-conditions during the deposition of the bituminous Kimmeridge Clay.

The **Oxford Clay** ranges in thickness from 0 to 44 m and consists of grey-green calcareous mudstone and silty mudstone. South of the Market Weighton High, the formation comprises three members, the Peterborough, Stewartby and Weymouth members in upwards succession, but only the Weymouth Member of early Oxfordian age is present in the Cleveland Basin (Cox *et al*. 1993). The lithology is more silt-rich compared to its occurrence on the East Midlands Shelf, where the formation is about 70 m thick. In the Roulston Scar area of the Hambleton Hills, the absence of the Oxford Clay is the result of uplift and subsequent sub-marine erosion of the Oxford Clay, and in places the underlying Hackness Rock, prior to deposition of the Lower Calcareous Grit.

An abundant ammonite fauna has been collected from a number of levels in the Oxford Clay of the Hambleton Hills, and indicates the Mariae Zone, Scarburgense Subzone (Cox *in* Powell *et al*. 1992). Other sections near the top of the formation have yielded small casts of *Cardioceras praecordatum* Douvillé, proving the later Praecordatum Subzone.

The **Corallian Group** ranges in thickness from 70 m to 150 m and predominantly comprises ooidal and micritic limestone and calcareous, spiculitic, fine-grained sandstone. The group is subdivided into three formations (Wright 1972, 1983, 1996*a*, 1996*b*) separated by disconformities, and spans the upper Lower, Middle and lower Upper Oxfordian stages (Fig. 7: Wright 1980; Rawson & Wright 1992, 2000). Disconformities are also present within the formations over parts of the basin and lateral lithofacies changes have enabled Wright to recognize numerous impersistent members (Fig. 7). The group is equivalent to the mud-rich West Walton Formation and the lower part of the Ampthill Clay of the East Midlands Shelf.

At the base of the group, the **Lower Calcareous Grit (LCG)** crops out along the upper part of the bold, west-facing escarpment of the Hambleton Hills and at classical localities such as Castle Hill (Scarborough) and Filey Brigg (Rawson & Wright 2000). The Lower Calcareous Grit ranges from 22 to 48 m thick in the Hambleton and Howardian Hills, and reaches 50 m on the Yorkshire coast. It consists predominantly of yellow, buff, fine- to medium-grained, calcareous sandstone, with subsidiary beds and concretions of blue-grey, micritic limestone; both lithologies are variably ooidal and peloidal. Siliceous spicules of the sponge *Rhaxella perforata* form much of the clastic component (Sorby 1851; Wilson 1939; Hemingway 1974), and diagenesis of these has produced secondary thin beds of chert, particularly in the lower part of the formation. *Thalassinoides* burrows are very common on bedding planes at some horizons; the backfilled burrows have a higher spicule content and are more resistant to weathering, giving an irregular, nodular appearance to weathered faces. The micritic limestone concretions reach up to 1.5 m diameter, and are locally concentrated in the upper part of the formation (the 'Ball Beds' of Arkell 1945).

The contact between the LCG and the Oxford Clay is gradational, except on the Roulston Scar 'block' where the Oxford Clay is absent. Near Sutton Bank, between [SE 5156 8121] and [SE 5327 8206], the **Oldstead Oolite Member** (Wright 1980) is locally distinguished in the lower part of the LCG. It consists of grey to yellow-grey, bioclastic, ooidal wackestone-grainstone, up to 11 m thick, and cross-bedded in part. The base is an erosive, unconformable junction with the underlying Redcliff Rock Member in the Raven's Gill area [SE 5295 8186] (Fig. 33). To the east, in Shaw's Gill, the Oldstead Oolite overlies Oxford Clay with a sharp base. The proportion of ooids (wackestone texture) decreases gradationally upwards through passage to the spiculitic calcareous sandstone of the 'typical' Lower Calcareous Grit (Powell *et al*. 1992; fig. 16), indicating increasing water depths through time.

The boundary between the LCG and the overlying Hambleton Oolite Member (Coralline Oolite Formation) is gradational in the Hambleton Hills, the percentage of ooids increasing upwards at the expense of spiculitic sandstone. However, farther east around Givendale, Dalby Forest [SE 854 863] and at the Bridestones [SE 878 907], a poorly consolidated yellow sand unit, cross-bedded in part, with calcareous concretions rich in bivalves and brachiopods and termed the Passage Beds Member

(Wright 1972) or Yedmandale Member (BGS 2000), is present below the Hambleton Oolite, which has an erosive base. On the coast, at Filey Brigg, the Passage Beds Member consists of bioturbated calcareous sandstone interbedded with grey limestone. The beds are rich in shell debris, including *Nanogyra* and *Gervillella*. Cross bedding indicates a south-east palaeoflow (Wright 1992). In addition to the fauna noted above, the formation has yielded a benthic assemblage that includes bivalves and brachiopods (A*vicula, Pecten, Trigonia, Modiola, Ostrea* and *Rhynchonelloidea;* Hemingway 1974), but these are rarely well preserved. The carbonate concretions contain the richest fauna and have yielded many large, well preserved ammonites that indicate the Bukowskii Subzone of the Cordatum Zone (Fig. 7; Wright 1980).

The **Coralline Oolite Formation** (Wright 1972) comprises the following five members, in upward sequence: Hambleton Oolite, Birdsall Calcareous Grit, Middle Calcareous Grit, Malton Oolite and Coral Rag (Fig. 7). The estimated thickness of the formation ranges from 60 to 70 m. The Coralline Oolite Formation consists of a varied sequence of grey, predominately ooidal and peloidal limestone (ooidal wackestone to ooidal grainstone texture) intercalated with wedges of buff-yellow, sparsely ooidal, calcareous fine-grained sandstone. Subsidiary lithologies include micritic limestone and reefal boundstone rich in corals and algae. Over most of the Cleveland Basin, from Scarborough in the east to Northallerton in the west, the stratigraphical relationship of the members assumes a ‘layer-cake’ sequence (Wright 1972; Hemingway 1974, fig. 53). As the formation is traced from the north-west of the district to the south-east and beyond to the Howardian Hills, however, lateral changes in lithofacies are prevalent, particularly in the lower three members (Fig. 7). South-east of Murton Common [SE 509 885], the Hambleton Oolite is separated into ‘upper’ and ‘lower’ leaves by the intervening Birdsall Calcareous Grit (Wright 1972). On parts of Byland Moor, south of Cold Cam [SE 542 813], the ooidal limestones cannot be traced and there is a continuous sequence of calcareous spiculitic sandstone from the top of the Lower Calcareous Grit through the Birdsall Calcareous Grit up to the base of the Middle Calcareous Grit (Fox-Strangways *et al*. 1886; Powell *et al*. 1992), the last being marked by a topographical feature. The top of the formation is defined by the base of the Upper Calcareous Grit (Wright 1972) which rests disconformably on the Coral Rag Member.

The **Hambleton Oolite Member** (up to 34 m thick) caps the escarpment of the Hambleton Hills and forms extensive dip slopes north of Pickering on the North Yorks Moors. It consists of pale grey to white ooidal limestone (packstone to grainstone texture), with a variable proportion of quartz sand, peloids and fragmented shells; chert nodules are common in places. Thin beds of calcareous sandstone with scattered ooids are present in the southern part of the outcrop. Cross-bedding and shallow scours are locally common in the ooidal limestone and the beds are frequently penetrated by circular, vertical burrows, up to 1 cm in diameter. Wright (1972) showed that the oolite member splits into an upper and lower leaf in parts of the Hambleton Hills (Powell, *et al*. 1992) and in the Howardian Hills (S. Price *pers. comm.* 2008; Wright 2009). Penecontemporaneous slump structures and injection phenomena (Fig 10b; Hemingway & Twombley 1963; Powell *et al*. 1992) are locally present at Shaw's Gate Quarry [SE 5233 8236] and Old Byland Grange Quarry [SE 5454 8567]. The fauna includes the ammonites *Cardioceras, Goliathiceras, Aspidoceras* and *Perisphinctes*, as well as sporadic bivalves including *Exogyra, Lima, Astarte, Ostrea, Modiola* and *Pholadomya*. Echinoids are common in some beds and include *Cidaris, Nucleolites* and *Hemicidaris* (Hemingway 1974). Rare specimens of *Rhaxella perforata* and a brittle-star have been collected. Ammonites indicate an age ranging from the Cordatum Subzone to the Vertebrale Subzone, spanning parts of the Cordatum and Densiplicatum zones (Fig. 7; Wright 1972). As noted above, the sharp erosive base of the Hambleton Oolite on the coast suggests a disconformity, and Wright (1972) has demonstrated that where the Passage Beds Member is absent in the west of the outcrop, the Costicardia Subzone is missing.

The **Birdsall Calcareous Grit Member** (Cordatum Subzone) is a yellow-buff, calcareous, fine-grained spiculitic sandstone with scattered ooids and lenses of grey chert, which was deposited coevally with the Hambleton Oolite. It is up to 12 m thick in the Hambleton Hills, but reaches 30 m in the Howardian Hills to the south, suggesting a provenance from that direction. Nodular texture is common and is due to abundant silica-rich *Thalassinoides* burrow-fill; *Chondrites* burrows are locally present in thin-bedded siltstone. The Birdsall Calcareous Grit has yielded the subzonal ammonite *Cardioceras cordatum* (Wright 1972, 2009) as well as bivalves, including *Chlamys fibrosa*.

The Birdsall Calcareous Grit is well exposed between Cleave Dyke Quarry [SE 507 863] and Boltby Scar [SE 506 857], but wedges out along the main escarpment south of Boltby Scar, and also along the Caddell valley, so that the upper and lower 'leaves' of the Hambleton Oolite are not distinguishable there (Powell *et al*. 1992, fig. 18).

The **Middle Calcareous Grit Member** (Wright 1972) crops out in the south-east of the Hambleton Hills, on Byland Moor [SE 54 81], where it is about 12 m thick. It is similar in lithology to the Birdsall Calcareous Grit, and the rock is often decalcified at outcrop, so that only relict ooids can be seen. The unit probably belongs to the upper part of the Vertebrale Subzone and the lower part of the Maltonese Subzone (Figs 7, 36; Wright 1980).

The **Malton Oolite Member** (up to 20 m thick), formerly known as the Osmington Oolite, separates the Middle Calcareous Grit from the stratigraphically higher Coral Rag Member (Figs 7, 36; Wright 1972), and comprises variably shelly, ooidal limestone. Quarries in the Malton area show large scale cross-bedding, indicating deposition as laterally migrating ooidal shoals, similar to parts of the present-day Bahama Banks (Twombley 1964). Sparse ammonites indicate the Antecedens Subzone (Wright 1972; Rawson & Wright, 1992).

The uppermost unit, the **Coral Rag Member** (up to 9m thick), belongs to the Parandieri Subzone (Wright 1972), and comprises coral-algal patch reefs, coral-shell inter-reef debris and micritic limestone; both fore-reef and off-reef bioclastic (ooidal-coral-shell) debris with the echinoid *Hemicidaris* and the oyster *Lopha* are common. Isolated patch reefs had a relief of up to 3.5 m high above the surrounding substrate (Twombley 1964; Hemingway 1974). Similar patch reefs are found in the Ayton area [TA 002 856] (Hemingway 1974), although Rawson & Wright (2000) regarded this locality as uppermost Malton Oolite. There, colonial corals include *Thamnasteria*, *Isastraea*, *Rhabdophyllia* and *Thecosmilia*, in life position and as abraded fragments. In the Hambleton Hills, the member was formerly seen in a small inlier exposed by quarrying of the overlying Upper Calcareous Grit at Snape Hill Quarry [SE 508 787]. Fox-Strangways *et al*. (1886, p. 367) recorded up to 1.4 m of Coral Rag ('crystalline limestone') with the colonial coral *Thecosmilia annularis*, the echinoid *Hemicidaris florigemma* and the oyster *Lopha gregarea*. Farther east, Twombley (1964) recognized a similar micrite-biomicrite facies rich in corals, echinoids and bivalves, which he interpreted as a back-reef facies that developed to the north of a reefal boundstone facies typically found in the Howardian Hills.

As the name suggests, the **Upper Calcareous Grit Formation** marks a return to spiculitic sand sedimentation. It is between 12 and 15 m thick and consists of very fine- to fine-grained, calcareous, spiculitic sandstone and siltstone, with abundant beds of clayey, micritic limestone in the middle of the unit. In the Asenby – Coxwold Graben, the clayey carbonate lithofacies is at least 6 m thick and is equivalent to the **North Grimston Cementstone** facies of Wright (1972, 1980), who assigned it to the Nunningtonense subzone. Farther east, in the Kirkdale to Pickering outcrop, the formation was divided into three members by Wright (1972), spanning the Nunningtonense Subzone to early Serratum Zone. In upward sequence, these are the **Newbridge Member**, **Spaunton Sandstone** and **Snape Sandstone**. The Newbridge Member consists of buff, thin-bedded siltstone, marl and fine-grained sandstone. The Spaunton Sandstone is a buff, thin-bedded, bioturbated, calcareous sandstone with abundant sponge spicules and siliceous nodules. The fauna includes belemnites and sparse bivalves. Ammonites collected from the Spaunton Sandstone indicate the Glosense Zone (Wright 1983; Sykes & Callomon 1979; Cox *in* Powell *et al*. 1992). The Snape Sandstone Member is about 8 m thick, and consists of buff, flaggy, cross-laminated siltstone and fine-grained sandstone with abundant ammonite fragments and, locally, bioclastic limestone. Ammonites collected from the Snape Sandstone indicate the Serratum Zone of the Upper Oxfordian (Wright 1972, 1980; Cox *in* Powell *et al*. 1992). The junction between the Upper Calcareous Grit and the overlying Upper Jurassic clays (Ampthill Clay and Kimmeridge Clay formations) is a burrowed, gradational boundary (Cox & Richardson 1982)

In the Cleveland Basin, the Kimmeridge Clay was formerly thought to overlie the Upper Calcareous Grit directly (Fox-Strangways *et al*. 1886), but more recent studies of outcrops and borehole cores from the western end of the Vale of Pickering (Cope 1974; Richardson *in* Institute of Geological Sciences 1974; Pyrah 1977; Cox and Richardson 1982; Wignall 1993) show that mudstone (c. 48 m thick) with subsidiary beds and nodules of siderite, equivalent to the **Ampthill Clay** of southern England and spanning the Upper Oxfordian Serratum, Regulare and Rosenkrantzi zones (Fig. 7), is present between the top of the Corallian Group and the base of the Kimmeridge Clay. The Ampthill Clay is probably present at depth in the Asenby-Coxwold Graben, and its correlative, the Woodward Formation, has been proved (22-90 m thick) in the southern North Sea (Cox *et al*. 1987; Lott & Knox 1994).

An abrupt change in geophysical log signatures at the top of the Corallian Group in the Hunmanby Borehole (Fig. 34) suggests that the Ampthill Clay is faulted out here (Whittaker *et al*. 1985), but an attenuated succession (25 m thick) is present in the Brown Moor Borehole below the Cretaceous unconformity (Fig. 34). The Ampthill Clay has yielded infaunal and epifaunal bivalves, gastropods and echinoid spines, suggesting that it was deposited in an oxic shallow marine environment in response to rising sea-level and increased subsidence of the Cleveland Basin, as mud and silt sediments spread to the north of the basin in Serratum Zone time, about 157 Ma (Fig. 37). The presence of co-eval mud-dominated sediments of

Tenuiserratum Zone age (equivalent to the uppermost Coralline Oolite Formation) towards the south (Brown Moor Borehole; Fig. 34) indicates the gradual diachronous younging of mud sedimentation to the north as the basin gradually subsided.

The **Kimmeridge Clay** (Baylei to Pectinatus and Pallasioides zones) is the youngest Jurassic formation in the Cleveland Basin (Fig. 7). The Kimmeridge Clay succession comprises, shelly mudstone, often bioturbated, interbedded with bituminous (oil-rich) mudstone; abundant small *"Discinisca latissima"* and ammonite fragments are preserved in some beds. The succession represented by the Cymodoce, Mutabilis, Eudoxus, Autissiodorensis, Elegans, Scitulus and Wheatleyensis zones comprises cycles of mudstone, bituminous mudstone, and coccolith-rich limestone (Fig. 38). Above the Eudoxus Zone the formation becomes, overall, more calcareous and less fissile; hard beds with low gamma-ray and high sonic signatures comprise coccolith-rich limestone laminae. Outcrops are sparse, but dark grey fissile mudstone with yellow-brown weathering, organic-rich laminae crop out in the east of the Asenby-Coxwold Graben, and in the Vale of Pickering where the Ampthill and Kimmeridge formations form low ground, largely covered by superficial deposits; they have also been proved in a number of groundwater and hydrocarbon exploration boreholes (Fox-Strangways *et al.* 1886; Falcon & Kent 1960; Cox 1982; Cox *et al*. 1987; Herbin *et al*. 1991, 1993, 1995). The Kimmeridge Clay is intermittently exposed in the Vale of Pickering below thin Devensian till near Low Pasture House [SE 5540 7830], Riseborough Bridge [SE 7568 8428] and at Brink Hill [SE 540 786] where it was worked for brick clay. Comparison of the Kimmeridge Clay sequences recorded in boreholes in the Vale of Pickering and the southern North Sea (Cox *et al*. 1987; Herbin *et al*. 1991, 1993) suggests that the beds at Brink Hill are younger than the Eudoxus Zone. Ammonites collected from the uppermost Kimmeridge Clay in boreholes on the north side of the Vale of Pickering (Herbin *et al*. 1991) suggest the Pallasioides Zone (Fig. 7).

On the coast, the Kimmeridge Clay is overlain unconformably by the Speeton Clay Formation (Lower Cretaceous) at Speeton Sands [TA 140 763], where c. 10 m of dark grey, finely laminated mudstones contain ammonites that indicate the Hudlestoni to lower Pectinatus zones (Rawson & Wright 2000). The unconformity represents a considerable time gap, spanning the late Kimmeridgian (Pectinatus Zone and higher) and the Portlandian, plus the early part of the Cretaceous, so that the Upper Ryazanian 'D' Beds of the Speeton Clay rest on the Kimmeridge Clay.

The Kimmeridge Clay represents the main source of hydrocarbons in the northern part of the North Sea, where it has been buried to greater depths and at higher pressure than onshore and hence is mature enough to allow migration of lighter hydrocarbons to reservoir rocks such as the Brent sandstones (Herbin *et al*. 1993). Although the Kimmeridge Clay in the Cleveland Basin and Sole Pit Basin is bituminous, it is not sufficiently mature to have been a major source of hydrocarbons in these areas.

The Fordon No. 1 Borehole (Falcon & Kent 1960) proved 385 m of Kimmeridge Clay, but this figure has been questioned by Cox *et al*. (1987) who noted that the Ampthill Clay was included in the total thickness in this borehole; they suggest that the total thickness of the formation in the Vale of Pickering is about 305 m. However, the unit is much thicker here than the attenuated and eroded succession south of the Market Weighton High where, below the unconformable Cretaceous Carstone Formation, 7.5 m of Kimmeridge Clay belonging to the Baylei and Cymodoce zones, overlie the Ampthill Clay (Gaunt *et al*. 1992). The formation thickens southwards, reaching c.115 m in The Wash area (Gallois 1994).

Lateral lithofacies changes and attenuation of the Ampthill/Kimmeridge Clay succession southwards towards the Market Weighton High are illustrated by the Hunmanby [TA 131 759] and Brown Moor [SE 813 620] boreholes (Fig. 34) (Whittaker *et al.* 1985). At Hunmanby, the logs suggest that the Kimmeridge Clay lithofacies did not extend northwards until Cymodoce Zone times, whereas farther south at Brown Moor, near Market Weighton, the Ampthill Clay lithofacies extends from Tenuiserratum Zone times (Malton Oolite equivalent) to Serratum Zone times, the Kimmeridge Clay being highly attenuated or not present due to pre-Cretaceous erosion over the high. However, the sharp boundary (Fig. 34) between the Corallian Group and the overlying mudstone of Cymodoce Zone age (c.f. lower Kimmeridge Clay) may indicate a faulted boundary here, with the Ampthill Clay cut out.

Offshore in the Southern North Sea Basin (Fig. 7), the post-Callovian succession (200-300 m thick) is defined as the Humber Group (Lott & Knox 1994). The subtle lithostratigraphical characteristics that allow the sequence to be subdivided onshore are not so apparent in the offshore geophysical logs. Offshore equivalents of the Corallian Group are represented by calcareous sandstone overlain by ooidal limestone (Corallian Formation; 70-100 m thick), but this passes laterally southwards to the mudstone dominated Seeley Formation (equivalent to the West Walton Formation of the East Midlands Shelf). Overlying these is the Woodward

Formation (c. 50 m thick), a mudstone unit of late Oxfordian age broadly equivalent to the Ampthill Clay (Cox *et al.*1993), overlain by the Kimmeridge Clay Formation, which is about 250 m thick in the Sole Pit Basin.

5. JURASSIC SEDIMENTATION IN THE CLEVELAND BASIN: INTERPLAY OF TECTONICS, RELATIVE-SEA LEVEL AND CLIMATE

The Jurassic succession of the Cleveland Basin, with its broad record of terrestrial, shallow marine and relatively deep-water sedimentation, provides an opportunity to assess the relative importance of the role of global and relative sea-level change, tectonics, climate and sediment flux over about 49 million years of Earth history (Hettangian 199.6 Ma to Late Kimmeridgian 150.8 Ma) (Ogg *et al*. 2008). However, application of the concepts of classical sequence stratigraphy (Van Wagoner *et al.* 1988; Haq *et al.* 1988) is difficult because successions preserved in the Cleveland Basin do not record the full range of tectonic and environmental settings. The Early Jurassic marine succession (Lias Group), for example, does not show the shoreline or terrestrial lithofacies, and conversely the non-marine units of the Ravenscar Group cannot be traced laterally to shoreline and deeper water facies. Consequently, for a large part of the succession, only changes in relative sea-level such as upward shoaling parasequences, cycles and breaks in sedimentation can be deduced (van Wagoner *et al*. 1988; Knox *et al*. 1991; Coe 1995). Generally, it is not possible to trace these events laterally to show coastal onlap or offlap, or subaerial unconformities in coeval settings. We can, however, interpret the fluctuation in relative sea-level within the Cleveland Basin from the sedimentary record, and assess the importance of global sea-level fluctuations against the role of intra- and extra-basinal tectonics. Comparison of the much studied coastal exposures with lesser known areas in the west of the basin throws more light on the palaeogeography and tectonics, especially in Mid-Jurassic times.

In this section, the relative importance of these intra- and extra-basinal factors will be assessed against an outline of significant events, and their sedimentological characteristics illustrated by the Jurassic succession.

5.1 Lias Group: tempestites, shoaling cycles, and anoxia

A shallow epicontinental sea extended throughout northwest Europe in Late Triassic times, following deposition of the brackish to shallow marine Penarth Group

(Warrington *in* Powell *et al*. 1992; Ivimey-Cook & Powell 1991). The Lias Group was deposited as two major, upward shoaling cycles: the Redcar Mudstone to Staithes Sandstone cycle and the Cleveland Ironstone to Blea Wyke Sandstone cycle (Knox *et al.* 1991). The first cycle has been subdivided into 3 second-order cycles by Van Buchem & Knox (1998), represented by the Planorbis-Liasicus, Liasicus-Jamesomi and Jamesoni-Ibex intervals, the base of each cycle marking a significant rise in sea-level. Hesselbo & Jenkyns (1995, 1998) recognized smaller, third-order cycles of about 300-500 Ka, which approximate to the estimated duration of many ammonite zones and subzones, and suggest a link between cyclicity, sea-level change and extinction or faunal turn over. Each of the third-order cycles was further subdivided into a number of smaller scale cycles or parasequences that were deposited in response to tectonic control and sediment flux. These cycles can be recognized in the gamma-ray and sonic geophysical logs of the Felixkirk Borehole (Fig. 9) (Ivimey-Cook & Powell 1991).

The Hettangian to early Pliensbachian Redcar Mudstone comprises stratigraphically expanded and reduced successions (van Buchem & McCave 1989; Ivimey-Cook & Powell 1991). Background sedimentation was predominantly hemipelagic mud, but during periods of low sedimentation rates, condensed sequences rich in iron ooids, glauconite or winnowed shell fragments were deposited, especially on highs such as the Market Weighton area. Early Hettangian fair-weather sedimentation (lower Calcareous Shales) is represented by hemipelagic mud, but periods of deposition within fairweather wave base are indicated by thin, winnowed laminae comprising thin shelled bivalves (Fig. 11a). The absence of bioturbation at this level suggests that sedimentation rates were high and/or that the substrate was not sufficiently oxygenated for colonization by epifauna and infauna. However, the gamma–ray inflections of the Felixkirk Borehole log (Figs 9, 11a) indicate a significant change up-sequence. The upper part of the Calcareous Shales is characterized in this borehole (Fig. 9) and in coastal exposures at Redcar and Robin Hood's Bay by 0.10 m to 0.40 m thick and, exceptionally, 1 m thick, beds of coarser grained calcareous siltstone and fine-grained sandstone beds with abundant bivalve fragments and disarticulated shells (mostly *Gryphaea*) in various orientations (Fig. 11b,c). The coarse-grained beds have sharp bases, often with erosional scours, but the junction often appears gradational due to downward penetrating burrows (especially *Chondrites*) that give a superficial appearance of gradational upward shoaling (Sellwood 1970). Multiple cycles are also present (Fig. 11d,c) and the tops of these beds show a sharp return to background mud sedimentation, although occasional winnowed siltstones are present in the upper few centimetres. These beds are interpreted as the result of storm-generated waves and bottom currents that redeposited calcareous sand from the nearshore zone as bioclastic sand layers (tempestites) resulting from powerful storm-surge and ebb currents (Aigner & Reineck 1982). The storm-generated beds were deposited rapidly and punctuate the quieter, slower background sedimentation represented by grey mud and silt, often rich in nektonic ammonite/belemnite faunas (Buckman 1915; Bairstow 1969; Ivimey-Cook & Powell 1991; Knox *et al.* 1991; van Buchem & McCave 1989). Deposition was in the form of laterally continuous bioclastic sheet sand, traceable over many kilometres, possibly resulting from major hurricanes driving sea water onto the coastal zone (storm surge), followed by ebbing offshore bottom currents (with erosional bases) or sediment suspension clouds.

Similar ‘tempestite’ beds characterize the overlying Siliceous Shales, the base of which corresponds to the mid Turneri Zone in the Felixkirk Borehole but is slightly higher at Robin Hood’s Bay (Hesselbo & Jenkins 1995). As the name suggests, the coarse-grained beds comprise fine-grained sand but few shells. Sedimentary structures such as scoured basal contacts and low-angle cross-lamination indicate high-energy bottom currents (Fig. 12). However, the primary sedimentary structures are often obscured by extensive bioturbation, including *Diplocraterion*, *Rhizocorallium, Teichichnus* and *Chondrites* burrows that ‘piped’ sediment downward, below the scoured erosional base, again giving a superficial appearance of an upward shoaling succession (Fig. 12). There is no indication that the individual coarse tempestite beds represent upward coarsening (shallowing) sequences (Sellwood 1970). The change from the shell-rich to sand-rich storm beds suggests provenance of the coarse-grained fraction from different shoreface facies or was perhaps a result of greater sand flux into the nearshore zone during the late Sinemurian. Although early Lias Group sedimentation is characterized by alternating hard/soft beds in both southern England and the Cleveland Basin, the Redcar Mudstone differs markedly from the climate- or diagenetically controlled ‘rhythmic couplet’ sedimentation (Blue Lias) of the Dorset and South Wales provinces (Hallam 1964; House 1985; Weedon 1986; Weedon & Jenkyns 1990). Sedimentation in the Cleveland Basin was influenced by tectonic uplift of the Pennine High hinterland (Fig. 2), increased siliciclastic sediment flux and storm events that redistributed coarser material (bioclasts and sand) offshore from the nearshore sublittoral zone. The presence of iron-rich ooids and glauconite (Fig. 11c) in some of the sandy layers suggests shoaling conditions during condensed phases, possibly a result of a relative sea-level fall (Knox *et al*. 1991; Hesselbo & Jenkyns 1995). The change in storm sedimentation sequences from the lower part of the Calcareous Shales to the Siliceous Shales as seen in the Felixkirk cores is summarized in Fig. 12.

5.1.1 Early Pliensbachian sea-level rise and climatically induced sedimentation

The Sinemurian-Pliensbachian boundary (base Jamesoni Zone) marks a major sea level rise (Sellwood 1972; Knox *et al*. 1991; Hesselbo & Jenkyns 1995; van Buchem & Knox 1998) and is reflected clearly in the 'smooth' gamma and sonic log interval above 164.38 m depth in the Felixkirk borehole (Fig. 9). The same deepening event is clearly visible in the GSSP section at Wine Haven, Robin Hood's Bay (Knox *et al*. 1991; Meister *et al*. 2003). The global sea-level rise is manifested in deposition of dark grey to black hemipelagic mud, deposited in quiet bottom conditions that resulted in local anoxia on the sea-floor, below storm wave base. Coarse-grained storm layers are absent, but the sediment interface was not wholly anoxic or inimitable to life as semi-infaunal bivalves such as *Pinna* sp. are found partially buried, *in situ*, together with pyritized burrows and concretions and a nektonic fauna of pyritized belemnites (locally current aligned) and ammonites. The last include the zonal fossil *Echioceras raricostatum* in the lower part. Partial burial of large *Pinna* shells in life position indicates rapid sedimentation rates in a distal offshore setting.

The section in Robin Hood's Bay and the Felixkirk Borehole logs show a gradual increase in the sand:mud ratio above the Taylori Subzone, in the form of discrete pale/dark banding, and the lower part of the Ironstone Shales is locally known as the 'Banded Shales' (van Buchem & McCave 1989). Sand is present as thin (2-3cm) graded and delicately laminated beds, but unlike the Siliceous Shales, there is no evidence for erosive traction currents. The Banded Shales represent distal hemipelagic sedimentation with silt and fine-grained sand being introduced into the deeper parts of the basin. Isolated lenses of sand preserved as large 'gutter casts' with low angle cross-lamination suggest periodic fluxes of sand that were dispersed offshore from the littoral zone. Again in contrast to the Siliceous Shales, these sand lenses are not bioturbated, suggesting rapid sedimentation rates and little time for colonization by benthic and infaunal organisms. Lighter bands probably represent the fallout of plankton and silt-grade sediment during more intense weathering of the hinterland. Regular banding in these beds has been attributed to alternating climatic cycles (van Buchem *et al*. 1992, 1994); analysis of the cycles suggest a regular periodicity, possibly linked to orbitally induced Milankovitch climatic cycles of perhaps 26 Ka periodicity (precession cycles). In contrast to the cycles induced by storm events in the lower part of the succession (Calcareous Shales and

Siliceous Shales), the Banded Shales cycles are therefore probably the result of astronomically induced climatic variations.

A glauconitic-ooidal bed at the base of the Ibex Zone (Figs 9, 14) in Robin Hood's Bay marks a depositional hiatus at the top of the Banded Shales, and the overlying Ironstone Shales show a strong upward-coarsening gamma-ray signature as pulses of sand were deposited offshore as distal pro-delta deposits, a precursor to progradation of the littoral sands of the overlying Staithes Formation (near base of the Davoei Zone; Fig. 9).

5.1.2 Sandy tempestites and upward shoaling cycles

The base of the Staithes Sandstone at 94.85 m in the Felixkirk Borehole and Bed 1 at Staithes (Howarth 1955; Powell 1984; Howard 1985) marks an influx of shallow marine sand that extended over much of England during late Pliensbachian times (Davoei Zone). Individual beds have shallow, scoured erosive bases and parallel and low-angle cross-lamination, and were deposited as extensive sublittoral and shoreface sands. Sand influx was probably due to shallowing of all the English sub-basins (e.g. Wessex Basin, East Midlands Shelf, Cleveland Basin) as a result of tectonic uplift of the source areas. The effects of this relative sea-level fall are more pronounced over the Market Weighton High and the East Midlands Shelf where the Staithes Sandstone equivalents (and the lower part of the Cleveland Ironstone) were removed by erosion prior to deposition of the Marlstone Rock Formation (broadly equivalent to the Cleveland Ironstone) in Spinatum Zone times (Fig. 16; Howard 1985).

Sand-rich tempestites typified by the Staithes Sandstone beds are sheet-like in general form, with planar, low-angle and hummocky cross stratification; some beds have wave-rippled tops (Figs. 10 c, f,). Erosional gutter casts at the base of tempestite beds (Fig. 10d) indicate an east to west palaeoslope, and internal low-angle cross-lamination measurements suggest that dominant storm-surge currents flowed predominantly to the east. Sheet sands were deposited by storm-surge-ebb currents that re-distributed sand from the nearshore zone to offshore locations (Howard 1985). Consequently, beds often have sharp erosive bases, occasionally with shelly lags (Fig. 10e). Low angle cross-lamination and hummocky cross-stratification represent reworking by waning, wave-generated, oscillatory currents (Nottvedt & Kriesa 1987). These sedimentary structures are locally destroyed by intense bioturbation where the residence time of the sand was longer and the substrate colonized by infaunal organisms (Plate xx). However, where sedimentation rates were high, the internal structures are well preserved. The location offshore below fair-weather wave base also aided preservation of the internal structures (Plate xx). Ichnofossil (trace fossil) assemblages provide a further insight into palaeoenvironmental conditions during 'Staithes time' (Seilacher 1967; Howard 1985; Knox *et al*. 1991). Assemblages from shoreface environments are dominated by deposit feeders such as *Chondrites* and *Planolites*, which exploited nutrient-rich laminae as opposed to clean sand (Fig. 10f); assemblages from innermost shelf environments, below fair weather wave-base, are characterized by dwelling burrows of infaunal deposits feeders such as *Skolithos, Diplocraterion* and those with specialist sediment-mining behaviours such as *Rhizocorallium*, *Asterosoma* and *Thalassinoides.* Distinctive sediment-mining burrows, such as *Siphonites* and *Teichichnus,* are present in the mid-shelf zone; the outer shelf assemblage is again typified by traces of sediment mining activities of deposit feeding organisms.

Upward coarsening (shoaling) cycles in the Staithes Formation are well displayed between Bed 17 (Howarth 1955) and Bed 23 near Penny Nab, Staithes (Howard 1985). These trends are also apparent in the attenuated sequence in the Felixkirk cores (Fig. 9, above 82 m depth; Fig. 10d) and are interpreted as progradation of shoreface and inner-shelf sands during rising sea-level as accommodation space increased on the shelf, a pattern seen also in the overlying Cleveland Ironstone cycles.

5.1.3 Transgressive cycles and iron-rich lagoons

The Cleveland Ironstone Formation comprises a succession of ooidal ironstone (formerly mined seams) separated by mudstone and fine-grained sandstones. These fine-grained sediments were deposited in laterally extensive lagoons and shallow littoral seas during a period of much reduced input of terrigenous, siliciclastic sediment, probably as a result of rising sea-level (second-order rise) during the Margaritatus Zone, which blanketed the geomorphologically low-lying hinterland. The late Pliensbachian appears to have been a time of reduced tectonic uplift of the surrounding landmass, including the Pennine High and the Mid-North Sea High, which were the main sources of clastic sediment from Hettangian to early Pliensbachian time. However, Chowns (1966) showed that the ironstone-rich succession was deposited over a long time period (i.e. it is a condensed sequence) and included a major phase of folding and erosion that produced an intraformational unconformity below the Pecten Seam (base *Spinatum* Zone) (Chowns 1966;

Hemingway 1974; Howard 1985). The ironstone seams and the intervening siliciclastic sediments thin towards the south (Market Weighton High) and the west (towards the basin margin) (Figs 15, 16, 18). In addition, the five seams below the base Spinatum Zone unconformity are cut out successively southwards as result of uplift that removed up to 25 m of beds (Figs. 18,19). Flexuring of the shallow marine basin may also have contributed to extensive shallow water conditions over the shelf during this period, and may have been related to gentle isostatic uplift of the Market Weighton High where the 'sub-Spinatum unconformity' is most pronounced (Howard 1985) (Fig. 16). In the west of the basin, only the Osmotherly and Avicula seams are present below the Main Seam unconformity, represented by thin, condensed units exhibiting burrowing and boring, consistent with a long period of accumulation with little siliciclastic sediment input (Fig. 19).

The coastal succession at Penny Nab (Howarth 1955; Howard 1985; Knox *et al* 1991) is generally characterized by upward coarsening (shoaling) siliciclastic cycles, namely mudstone, siltstone and fine-grained sandstone (with tempestite laminae) capped by transgressive, berthierine-rich ooidal ironstone. The latter have sharp erosional bases, commonly with reworked bored siderite and phosphatized nodules and occasional shelly lags, overlain by intensely bioturbated ooidal ironstone. Berthierine (formerly chamosite) ooids are set in a matrix of microcrystalline siderite; ooids commonly exhibit crushing and unravelling of concentric layers (spastolithization) (Marley 1857; Hallimond 1925; Chowns 1966; Hemingway 1978, fig. 45). Iron, in colloidal form, was probably derived from dissolution of lateritic soils as a result of marine flooding of the low-lying hinterland during punctuated periods of sea-level rise. The Cleveland Basin lay at about 30 degrees north during late Pliensbachian times, within the equatorial zone, and a hot climatic regime conducive to lateritic weathering is likely (cf. warm seasonal climate during the early Mid Jurassic; Morgans *et al.* 1999). Iron colloids may have been introduced into the shallow marine lagoons by rivers draining from the hinterland areas or through marine flooding of deeply laterized coastal areas; preservation of colloidal iron would have required reducing anoxic conditions, possibly a result of high levels of organic matter in the bottom sediment (Curtis & Spears 1968).

The lower part of the succession (Penny Nab Member, 19 m) on the coast, includes four upward coarsening (shoaling) parasequences, generally capped by transgressive ironstones (Osmotherly, Avicula, Raisdale and Two Foot seams) and an incomplete cycle between the Two Foot Seam and the unconformable base of the Pecten Seam (base Spinatum Zone) (Fig. 15). A typical cycle pattern is illustrated by the Avicula to Raisdale interval (Howarth 1955; Chowns 1966; Howard 1985; Knox *et al*., 1991). The Avicula Seam (Fig. 17a,b) was deposited during a marine transgression and comprises berthierine–rich, ooidal ironstone with a basal lag deposit that includes worn bivalve fragments and reworked and bored siderite mudstone nodules with pyritized rims. The overlying upward coarsening (shoaling) phase comprises laminated mudstone with thin, graded, low-energy tempestites ('striped beds') locally, and with east-west orientated gutter-casts (Greensmith *et al*. 1980) produced by strong, storm-generated, erosive, helicoidal bottom currents that flowed down a gentle eastward dipping palaeoslope. Similar gutter-casts are seen in the 'striped siltstones' immediately below the Raisdale Seam (Fig.17c), which, in turn, marks the next punctuated sea-level rise and marine transgression. Microfacies analysis of the Cleveland Ironstone (Macquaker & Taylor 1996) confirmed systematic upward-coarsening and upward-fining unit at various scales; the small-scale upward-coarsening trends (0.1 – 1.0 m thick) are attributed to shoaling parasequences whist the large –scale (1.0 - 3.0 m thick) upward-fining and upward-coarsening packages are interpreted as retrogradational and progradational units, respectively. Ironstone beds are interpreted as marking the interval (sequence boundary) between progradational and retrogradational units; phosphate-rich horizons probably represent maximum flooding surfaces across the shallow lagoons.

Up sequence, the Kettleness Member (10 m thick), which includes the Main Seam, oversteps successively younger Lias Group units to the south towards Market Weighton, and to the west (Fig. 16). Just north of the Market Weighton High, at Whitwell-on-the-Hill, it rests unconformably on beds as low as the Redcar Mudstone, but can be traced southwards over this structure to the East Midlands Shelf where it is equivalent to a highly condensed iron-rich sandstone unit, the Marlstone Rock Formation. In turn, the Marlstone Rock Formation can be traced southwards to the Wessex Basin where it is represented by the Dyrham Siltstone (Cox *et al*. 1999). In the Cleveland Basin, the condensed succession mostly comprises the Pecten and Main seams with thin siltstones, but south of Osmotherly even the Pecten Seam is cut out below the unconformity (Frost 1998), so that the Main Seam rests unconformably on siliciclastic beds above the Avicula Seam (Figs 16, 18,19). Overall, the Kettleness Member/Marlstone Rock succession marks a basin-wide shallowing phase. The base 'base Spinatum unconformity', south and westerly thinning, and condensed ooidal ironstone seams suggest that shallowing is attributable to regional tectonic uplift rather than global sea-level fall. Condensed sequences of ironstone and siliciclastic sediments indicate that the hinterland areas were not uplifted nor supplying large volumes of sediment to the basin. If, as noted above, the iron was derived from the weathering of thick lateritic soils, it is likely that the marginal areas were geomorphologically low lying, so that minor sea-level rises that characterize the transgressive ironstone parasequences (small-cycles) extended over a wide geographical area. The presence of intensely bioturbated horizons, ooidal ironstone, sub-rounded phosphatic pebbles, locally bored surfaces and a prolific benthic fauna confirm shallow-water conditions. Minor isostatic tectonic fluctuations (e.g. uplift of the Market Weighton High) would therefore have had a profound effect over a wide area.

5.1.4 Subsidence, anoxia and a second major shoaling cycle

The Toarcian 'Upper Lias' succession marks a second major shallowing cycle (cf. Redcar Mudstone to top Staithes Sandstone cycle) comprising the Whitby Mudstone to Blea Wyke Sandstone formations (Dean 1954; Hallam 1967*a*; Powell 1984; Knox 1984). Following a relatively quiescent tectonic phase during the late Pliensbachian, the early Toarcian (Tenuicostatum Zone) was a period of major basin subsidence throughout England. More rapid subsidence of the Cleveland Basin, resulting in relatively deeper open water conditions during deposition of the Grey Shales Member (Tenuicostatum Subzone), was accompanied by increased sediment flux. Fluctuating oxic and slightly anoxic bottom conditions are present through the Grey Shales but increasingly higher levels of organic carbon are present from the Semicelatum Subzone (Figs 9, 20) through the Exaratum Subzone (Falciferum Zone), spanning the uppermost Grey Shales and the 'Jet Rock' (Mulgrave Shale Member). The high organic carbon content has been long recognized as indicating ocean-wide anoxia at the sediment-water interface (Hallam 1967*a*, 1967*b*; Morris 1979; Jenkyns 1988; Jenkyns & Clayton 1997). Minor shoaling cycles with striped siltstone laminae (Figs 17d, 20) suggest that water depths were in the region of tens of metres, similar to depths for the Siliceous Shales. However, anoxia on the ocean floor may have been due to a density-stratified ocean (O'Brien 1990) with little overturn of the water column, resulting in stagnant bottom conditions. Prolific ammonite faunas testify to oxygenated water above, conducive to nektonic faunas. The cause of the Toarcian Oceanic Anoxic Event (OAE) anoxia during Exaratum Subzone time in NW Europe has been the subject of much debate. Hesselbo *et al*. (2000) demonstrated that isotopically light carbon isotopes were present ocean-wide and they attributed this to a discharge of methane from the overturn of gas hydrate (a solid ice-like substance rich in biogenic methane found today on deep continental marine margins, e.g. Antarctica). Further studies using osmium, carbon and strontium isotopes (Jenkyns *et al*. 2002; Cohen *et al*. 2004; Kemp *et al.* 2005) have demonstrated a sharp negative excursion in isotope ratios, such as the short-lived carbon ($\delta^{13}C_{org}$) isotope excursion within the Exaratum Subzone that is broadly coincident with a high osmium ($^{187}Os/^{188}Os$) isotope ratio excursion (Fig. 20). The marked change in organic carbon isotope ratios occurs in three marked steps at the base of the Falciferum Zone (Exaratum Subzone) and these steps are inferred to coincide with a marked reduction of benthic species in 'shifts' of minus 67% and minus 50%. High $\delta^{13}C_{org}$ values result from an increase in the burial of biogenic carbon whereas low $\delta^{13}C_{org}$ values result from oxidation of carbon in the sediment or introduction of reduced carbon. Kemp *et al*. (2005) attribute the anoxic phase to the release of carbon dioxide into the atmosphere as a result of overturn of methane hydrates normally trapped as a solid phase on the ocean floor. Both methane and, its oxidation product carbon dioxide, are significant 'greenhouse gases' and their release into the atmosphere may have caused global warming, in turn causing higher ocean temperatures, sea-floor anoxia and extinction of benthic, planktonic, and nektonic species worldwide. The high osmium isotope ratio over this interval was interpreted by Kemp *et al.* (2005) to have resulted from warm-climate, lateritic weathering of the hinterland (c.f. the origin of iron colloids in the Cleveland Ironstones). A subsequent fall in the osmium isotope ratio was interpreted to be due to subsequent take up of carbon dioxide in the atmosphere through the incorporation of the gas in the formation (weathering) of lateritic soils. However, alternative explanations have been proposed, first that the rapid negative $\delta^{13}C_{org}$ value excursions are attributable to recycling of isotopically light carbon from the lower water column in a local euxinic (oxygen-starved) epeiric sea (McArthur et al., 2000; Wignall *et al*. 2006), and secondly, based on fossil leaf stomatal frequency, the fluctuations in carbon dioxide and the injection of isotopiocally light carbon into the atmosphere is a result of the release of thermogenic methane into the atmosphere generated through the intrusion of Gondwana coals by dolerites in the Karoo-Ferrar region (McElwain *et al*. 2005)

Renewed influx of fine-grained terrigenous siliciclastics kept pace with gradual subsidence of the basin during deposition of the overlying Alum Shales Member under more oxygenated conditions (Pye & Krinsley 1986). Periods of lower sedimentation rate are indicated by bands of phosphatic nodules in the upper part of the unit. A paucity of benthic fauna compared to typical Lias mudstones may have been due to climatic conditions. A shallowing, upward-coarsening trend and a concomitant increase in burrowing benthic fauna (including brachiopods and bivalves) (Knox 1984) is seen in the uppermost Toarcian sediments, only locally preserved (e.g. Peak Trough) below the Dogger unconformity. Within the Peak Trough and its onshore extension at Blea Wyke (Fig. 23), the shoaling trend (Figs 21,

22) is indicated by the Peak Mudstone and Fox Cliff Siltstone and the uppermost unit of the Lias Group, the Blea Wyke Sandstone. The latter comprises fine-grained sandstone, and like much of the late Pliensbachian Staithes Sandstone, is heavily bioturbated, the reworking destroying most of the primary sedimentary structures. However, low-angle cross bedding (southwards palaeocurrent) is present, as well as scoured erosive surfaces with bivalve fragments (*Trigonia*; *Nerinea*), indicating deposition in the littoral zone. As in Staithes Sandstone times, the shallowing trend is attributed to regional tectonic uplift, probably doming of the Mid-North Sea High (Sellwood & Hallam 1974; Underhill & Partington 1993) and the Pennine highlands, rather than global sea-level fall.

5.2 Early-Mid Jurassic intra-basinal tectonics and heterolithic condensed marine sedimentation

Regional tectonics (doming and related uplift) that resulted in shoaling marine environments during deposition of the late Toarcian Lias Group succession continued during early Aalenian times. The Cleveland Basin was gently folded during a compressional event in late Moorei Subzone to early Opalinum Subzone times (Black 1934*a*; Hemingway 1974), which resulted in erosion of unconsolidated and semi-consolidated mud and sand. Up to 60 m of mud, silt and sand (uppermost Lias Group) was eroded in the central coastal areas (e.g. Whitby) and in the Hambleton Hills, where variable thicknesses of the Alum Shales are preserved below the Dogger Formation or, where that formation is absent, below the erosive base of the Saltwick Formation (Powell *et al*. 1992; Frost 1998). Southwards, towards the Market Weighton High, the Lias formations become thinner and the group is eroded down to lower stratigraphical levels (Redcar Mudstone Formation).

The Dogger Formation is a heterolithic unit deposited as a condensed succession over a considerable period of time (Opalinum Zone to Murchisonae Zone) and probably over the whole basin, although in some areas, e.g. Botton Head and along parts of the western escarpment, it was removed by erosion prior to deposition of the fluvio-deltaic Saltwick Formation. Despite intense bioturbation and reworking of this predominantly ferruginous, berthierine-rich sandstone unit, two subdivisions have been defined within the formation, namely a lower Opalinum Zone succession in the east of the basin, and a Murchisonae Zone succession that oversteps it, in the west (Macmillan 1932; Black 1934*a*; Rastall & Hemingway 1939, 1940, 1941, 1943, 1949; Hemingway 1974). However, some of the Dogger sands represent homogenized

Opalinum Zone sediments reworked as a palimpsest unit in late Murchisonae time. The relationship between the Dogger Formation and the underlying and overlying beds is critical in unravelling its depositional history. Near Whitby (East Cliff), where the Dogger unconformably overlies the Alum Shales (Fig. 17e), the presence of downward penetrating soft-sediment burrows (*Thalassinoides*), backfilled with Dogger sand and phosphatic pebbles that were 'piped' up to 25 cm into the underlying Alum Shale muds, indicates that the latter were still relatively unconsolidated in this area during deposition of the Dogger. This suggests that the post-Toarcian compressional folding and subsequent erosion of semi- or un-consolidated sediment took place over a short time interval, or perhaps that the compressional folding was ongoing from late Toarcian times as a result of Mid North Sea volcanic doming. The Peak Trough (Milsom & Rawson 1989), a narrow syn-depositional graben that preserves the uppermost Lias at Blea Wyke Point (Fig. 23), may have resulted from transtension rather than compression during this tectonic event. Furthermore, the top of the Dogger sandstone at Blea Wyke and Whitby East Cliff is penetrated by carbonaceous-lined plant rootlets from the overlying paralic Saltwick Formation, demonstrating that the Dogger sands were also poorly consolidated when the Saltwick fluvio-delatic sediments were deposited.

In the west of the basin, where the Dogger is thought to be mostly of early Murchisonae Subzone age (Hemingway, 1974), the formation varies laterally over a few tens of metres from ferruginous berthierene-rich ooidal ironstone to ferruginous sandstone and cross-bedded ooidal limestone at Cleave Quarry [SE 497 828] (Powell *et al.* 1992; Fig. 29). Ooidal limestone is also present in the Mowthorpe area [SE 67 68], where there is a thick development of bi-modal, trough cross-bedded bioclastic limestone that includes the bryozoan *Collapora* [formerly *Haploecia*] *straminaea*, which is more usually associated with the Bajocian Lebberston Member (J Ford *pers comm*. 2007). These atypical carbonates, preferentially preserved in small shallow sub-basins, indicate the presence, locally, of a Dogger carbonate platform in Murchisonae times. Carbonate shoal deposits are preferentially preserved and may once have been more widespread ooidal banks that formed on shoaling highs and were subsequently swept offshore to accumulate in local downwarps. In the Howardian Hills, well-rounded calcareous mudstone pebbles and phosphatic pebbles (Spy Hill lithofacies) are found together with fossil wood 'raffle' in some of the more typical ferruginous sandstones, which here include quartz granules that were probably derived from the Carboniferous Millstone Grit, suggesting a westerly provenance from the Pennine highlands. In the west of the basin, there is no evidence, such as downward penetrating burrows, that the underlying Alum Shale muds were unconsolidated during deposition of the Dogger, probably due to longer residence time and early diagenesis of the folded Lias Group sediments in the west. Lithification of these pre-Dogger sediments is further indicated by the presence, in the Cold Moor area [NZ 558 002], of rounded, bored concretions containing Toarcian ammonites (including *Dactylioceras*, *Hildoceras* and *Harpoceras*) and other derived Toarcian ammonite clasts (Black 1934*a*), which show that the Whitby Mudstone sediments (down to the stratigraphical level of the Grey Shales Member) had, in contrast to the soft sediment burrows at Whitby, gone through early diagenesis and were lithified prior to the pre-Dogger tectonic folding, uplift and erosion.

Locally, in the Rosedale area [SE 729 946], the Whitby Mudstone was deeply eroded into a series of shallow 'boat-shaped' depressions, about 500 m long by 30 m wide (Marley 1870). The depressions were filled with a distinctive Dogger lithofacies, a 'magnetite' ironstone (now shown to be a form of ferric, chronstedtite spinel; Hemingway 1974) overlain by ferruginous sandstone (Fox-Strangways *et al*. 1885; Rastall & Hemingway 1949). The iron ore probably represents a condensed, remanié deposit of early Opalinum Zone times that was preserved locally in shallow depressions on the pre-Dogger sea-floor.

The regional depositional setting of the enigmatic highly variable Dogger unit is outlined below:

(a) Compressional and transpressional folding of poorly consolidated muds, at least in the upper part of the sediment profile; transpression and local rifting resulted in the preservation of latest Toarcian Blea Wyke sands locally in the Peak Trough, but elsewhere up to 60 m of relatively unconsolidated sediment was removed in late Toarcian to earliest Aalenian times.

(b) In the west of the basin, uplift resulted in the development of local submarine highs within fairweather wave-base; here, during Murchisonae times, warm water ooidal shoals developed with an abundant shelly fauna that included bivalves, gastropods, solitary corals and bryozoa. These carbonate platform deposits were probably more extensive than the present outcrop; mobile carbonate sediments were preserved in local sub-basins on the lithified undulating pre-Dogger sea floor. Erosion to lower stratigraphical levels, including erosion of the the Grey Shale Member, reworked already lithified carbonate concretions and phosphatic nodules, which often contain Toarcian ammonites, as a basal conglomeratic lag deposit in the Cold Moor area [NZ 558 002].

(c) Uplift of the hinterland, balanced by basin subsidence, resulted in the southward and esatward progradation of the Middle Jurassic rivers and delta fronts. During the late Opalinum to Murchisonae zones, siliciclastic sediments were deposited in a pro-delta, shallow marine environment characterized by reworking of earlier carbonate platform shoals; iron colloids, in the presence of plant remains derived from the adjacent floodplains, were precipitated in shallow lagoons. Reworking in a shallow, restricted, partly anoxic tidal regime produced berthierine ooids interbedded with ferruginous sandstones. An abundant benthic infauna resulted in intense bioturbation and mixing of the sandy sediments. In places, the underlying Toarcian sediments were still poorly consolidated, enabling crustaceans to develop back-filled burrows into the underlying muds.

(d) Locally, the nearshore shallow lagoons became stagnant, resulting in deposition of laminated black mudstones. On adjacent highs, coeval sediments include trough cross-bedded sandstones with phosphatic pebble lags.

(e) Southward and eastward advance of the rivers and deltas and high sediment flux from the doming hinterland resulted in infilling of the Dogger shelf, lower relative sea-level and colonization of the floodplains by plants, resulting locally in rootlet penetration from plant-rich mires through to the Dogger sands. Basin subsidence in post-Dogger, late Aalenian times was paced by uplift of the surrounding areas and a high siliciclastic sediment flux, so that the coastal plain remained above sea-level until the late Aalenian marine transgression (Eller Beck Formation) that advanced from the south (Fig. 4a).

5.3. Mid-Jurassic paralic sedimentation in a rapidly subsiding basin: transgressions versus regressions

Differential subsidence in the Cleveland Basin, as compared to the East Midlands Shelf, was more pronounced from Aalenian to latest Bathonian times (175.6 – 161.2 Ma), but was at its greatest during the early Bajocian to mid Bathonian, when up to 300 m of fluvial, paralic and thin marine sediments were deposited (Ravenscar Group). During this interval, however, sedimentation rates kept pace with subsidence to fill the available accommodation space. This balance of sedimentation versus subsidence maintained the fluvial to paralic coastal plain in the region at or close to sea-level, so that relatively small increases in sea-level resulted in marine transgressions across large parts of the basin or, in the case of the late Aalenian Eller Beck Formation transgression and especially the Bajocian Scarborough

Formation transgression, throughout the whole basin. At other times, such as during the early Bajocian Lebberston transgression, the northern part of the basin remained above sea-level (Fig. 4b).

The Saltwick Formation was deposited in Murchisonae to Concavum zone times when paralic (i.e. fluvial, deltaic and brackish lagoonal) conditions were rapidly established throughout the basin as result of rapid uplift of the hinterland and high sediment flux from the north and west (Fig. 28). From the present-day coastal exposures to the western escarpment, muds and fluvial sands were deposited rapidly in river channel and interdistributary environments on the coastal plain, where the interfluves were colonized by plants, locally forming peaty mires thick enough to form thin coals.

The Ravenscar Borehole (Fig. 26) illustrates a typical Saltwick succession; initial progradation of muds and fine-grained sands across the low-gradient coastal plain, followed by progradational fluvial and deltaic sands in distributary channels. These sand-dominated, stacked distributary channels pass upwards to an interbedded mud and sand succession that illustrates a change to more isolated channel sands, some meandering and laterally accreted, intercalated with marshy overbank muds, frequently colonized by a diverse plant assemblage (Murchison 1832; Harris 1953; Morgans *et al*. 1999; van-Konijnenburg & Morgans 1999). Overall upward-fining of sediments in the borehole suggests rapid subsidence and high initial sedimentation rates, followed by a lowering of the geomorphological gradient, reduction in accommodation space and a resultant change to low-sinuosity meandering streams. If this trend is true for the basin in general, the lowering of the gradient may reflect rising sea-level in late Aalenian times that peaked during the Eller Beck marine transgression (Knox 1973; Powell & Rathbone 1983).

The transgressive Eller Beck Formation illustrates the subtle balance between paralic and fully marine environments across the basin (Fig. 4a). The sea advanced from the south across the Market Weighton High, depositing micritic lime mud in shallow lagoons; the resulting unit was formerly known as the Hydraulic Limestone. A mixed lime mud and ooidal, ferruginous sand lithofacies was deposited to the north, in the Hambleton Hills (Powell *et al*. 1992), marking a boundary with the ooidal ironstone and ferruginous sand lithofacies to the north (Fig. 4a). Detailed sedimentological studies of the Eller Beck Formation (Knox 1970, 1973; Hemingway 1974) show that the iron was derived in colloidal form from a lateritic hinterland subject to warm, humid weathering, and was deposited in shallow lagoons under anaerobic, reducing conditions (cf. Cleveland Ironstone, Dogger ironstone). Ooids indicate that the lagoons were influenced by tidal currents that resulted in oscillation and aggradation of individual berthierine (formerly chamosite) ooids. Dispersed ooids were also incorporated into the overlying sand member that is characteristic of the upper part of the Eller Beck Formation. Palaeocurrent analysis (Knox 1973) suggests influx of sand from the north that was reworked in a shallow shoreface and tidal regime in the north of the basin (e.g. Goathland [NZ 833 022]). Later, these marine ferruginous sand lithofacies extended to the south of the Hambleton Hills where they overlie the earlier micritic limestone lithofacies (Powell & Rathbone 1983).

The gamma-ray log of the Ravenscar Borehole (Fig. 26) shows the lower part of the overlying Sycarham Member (Cloughton Formation) to be dominated by minor channel sands and overbank coastal plain muds. However, the upper part of the Sycarham succession is represented by a sharp-based sand unit marking a major progradation of fluvio-deltaic sand. These sands represent stacked, erosively based channels similar to those seen in the lower part of the Saltwick Formation at Whitby West Cliff (Knox *et al*. 1991), and were deposited by a major river, at least in the Ravenscar area (Alexander 1986). The major river channels may have been aligned, in this area, close to the axis of a major channel system that persisted through Aalenian to early Bajocian times (Alexander 1986), although Hemingway (1974) proposed that the marked difference in the channel-sand dominance east and west of the Whitby Fault (trace of the River Esk) was due to later, probably Cenozoic transcurrent fault movement.

Relative sea-level rise in Laeviuscula Zone times (Butler *et al.* 2005) resulted in a second transgression and deposition of the Lebberston Member (Cloughton Formation), with lithofacies similar to those in the Eller Beck Formation, i.e. sands to the north and carbonates to the south. However, the marine influence in the north of the basin is much less pronounced, being restricted to thin ferruginous, locally shelly, sands and sideritic sands and thin limestone, as seen in coastal exposures (Cloughton Wyke and Yons Nab). This marine transgression advanced from the south. In the Howardian Hills, near Whitwell-on-the Hill, it is represented by ooidal and peloidal limestone (grainstone) up to 9 m thick, with an abundant shelly benthic fauna that includes the bryozoan *Collapora* [*Haploecia*] *straminea*; hence the local names, Whitwell Oolite and Millepore Bed, ‘millepore’ being an early name given to this bryozoan. Shallow tidal conditions are indicated by bi-directional cross-bedding, and in places colonial corals (*Thamnasteria and Thecosmilia*) are present with bivalves and gastropods. However, the Lebberston transgression was short lived as a result of progradation of fluvial and paralic sands and muds from the north. Based on their ostracod faunas, the carbonates are thought to be of Discites Zone age, equivalent to the Lincolnshire Limestone carbonate platform of the East Midlands Shelf (Bate 1964, 1967). On the coast, the transgressive and regressive lithofacies can be clearly seen at Yons Nab [TA 084 844], where the carbonate-rich 'Millepore Bed' is overlain by mudstones and sandstones with thin limestones termed the Yons Nab Beds, with a marine fauna that includes crinoid ossicles, bivalves and ostracods (Bate 1959,1967; Whyte & Romano, 2006*b*). However, the marine beds disappear rapidly northwestwards along the coast, and this trend is paralleled inland where the Lebberston Member thins northward from 9 m thick in the Howardian Hills to less than 1 m in the Hambleton Hills, and cannot be traced north of a line from Whitby to Osmotherly (Hemingway 1974; Powell *et al*. 1992; Frost 1998). South of the Market Weighton High, the transgression is represented by the Cave Oolite [SE 91 31] (Neale 1958).

Lower delta plain environments with thin crevasse-splay sandstones and muddy flood plain deposits, characterized by a 'saw-tooth' gamma ray profile, typify the Gristhorpe Member (Cloughton Formation) in the Ravenscar Borehole (Fig. 26). Diverse and abundant plant remains have been described from the coastal plain and delta top sediments (van Konijnenburg-Cittern & Morgans 1999). Interfluves were colonized by a very diverse fauna (up to 260 plant species identified), including horsetails (*Equisetum*), ferns, conifers, cycads and tree ferns, with 15 species of *Ginkgo* alone (Harris 1953). Plants rapidly colonized the substrate and stabilized the interfluves, resulting in high sinuosity and meandering channels. Classic localities at Hayburn Wyke, Cloughton Wyke and Whitby are famous for the preservation of drifted plants deposited in shallow, freshwater pools, and for rooted, *in situ* specimens of *Equisites* (Black 1929; Harris 1953; van Konijnenburg-Cittern & Morgans 1999). Charcoal, in the form of fusain among the drifted plant remains, has been interpreted as evidence of forest fires that periodically destroyed the forest canopy, and growth ring studies suggest that the climate was humid, sub-tropical and seasonal (Morgans *et al*. 1999; Hesselbo *et al*. 2003). Thin coals were developed on the flood plain in shallow mires; downward penetrating rootlet traces and siliceous seat-earths resemble those more familiar in the Carboniferous Coal Measures (Fig.17f). These 'Moor Coals' were worked locally for use in smelting ironstone and in lime kilns (Wandlass & Slater 1938; Owen 1970*b*). Coals, with underlying rootlet beds and seatearths, occur in the Cloughton Formation and Scalby Formation and have been exploited inland from bell-pits and shafts such as Boars Gill [SE 5188 8084] where black mudstone and coal in spoil from an old bell-pit indicates coal of workable thickness. Also, in the west of the Asenby-Coxwold Graben, opencast coal exploration boreholes around Burtree House [SE 482 768] have confirmed the presence of the two coal seams worked in the late 18th century at the former Birdforth Colliery (Fox-Strangways *et al*. 1886; Owen 1970*a*; Hemingway & Owen 1975).

Connection with the open Tethys Ocean was only achieved during the Scarborough Formation transgression (Bate 1965; Parsons 1977, 1980; Gowland & Riding 1991; Butler *et al*. 2005), a major sea-level rise in the early Bajocian. The coastal type section at Hundale Point (Fig. 30) is dominated by mud- and sand-rich sediments with thin argillaceous limestones, subdivided into seven members (Gowland & Riding 1991). Ammonites such as *Dorsetensia* and *Teloceras,* and marine palynomorphs in the Ravenscar Shale Member, indicate the Humphriesianum Zone (mid Bajocian). In the coastal outcrop, marine siliciclastic sediments with hummocky cross-bedding (e.g. at Ravenscar cliff) and thin silty limestones that yield bivalves (*Gervillella, Pseudomontis, Trigonia, Astarte and Lopha*), belemnites and sparse ammonites, together with a diverse suite of shallow marine trace fossils including *Rhizocorallium*, *Teichichnus* and U-shaped *Diplocraterion* (Hemingway 1974; Miller *et al*. 1984; Gowland & Riding 1991), suggest depositional conditions of a littoral sandy embayment passing offshore to calcareous mud (Fig. 4c). A different palaeogeographical setting is suggested for the western outcrops of the Hambleton Hills (Fig. 31), where peloidal (faecal peloids) planar cross-bedded limestone (Brandsby Roadstone) is overlain by medium-grained, fossiliferous sandstone (Crinoid Grit) (Powell *et al*. 1992). The limestone exhibits bi-directional planar cross-bedding, suggesting deposition in a tidal lagoon. The overlying sandstone also shows tidal influences such as bi-directional trough cross-bedding and current ripples with surface *Gyrochorte* burrows (Powell 1992). The Scarborough Formation is absent over the Market Weighton High, and the thicker ammonite-bearing marine muds and sands (up to 20 m) on the coast suggest that the transgression came from the east (open marine). The Hambleton Hills were the site of shallow, tidally influenced carbonate lagoons that gave way to shallow tidal marine sands derived from the north, a probable precursor to the influx of the fluvio-delatic system (Moor Grit Member and Scalby Formation) that unconformably overlies the Scarborough Formation over the whole of the basin. South of Scarborough, the formation thins to 6 m at White Nab, 3 m at Yons Nab and Gristhorpe Bay [TA 085 842], but is only 1.5 m thick in the Fordon Borehole [TA 058 758], suggesting a shoreline to the south (Fig. 4c).

It seems probable that there is a significant time gap at the base of the overlying Moor Grit Member (Scalby Formation). During this interval there was a lowering of relative sea-level, emergence of the basin, and erosion and uplift of the hinterland that resulted in high sediment influx from the north, as indicated by the marked lithofacies changes at the Scarborough Formation-Moor Grit boundary across the basin. The basal sand body of the fluvio-deltaic Scalby Formation is well exposed and best known from coastal outcrops (Cloughton Wyke and Black Rocks, Scarborough). On the coast, the Moor Grit is characterized by a low gamma-ray signature (Fig. 26) and typically comprises stacked sets of large-scale trough cross-bedded, medium- to coarse-grained sandstone deposited by a large braided or low-sinuosity river (Nami 1976; Nami & Leeder 1978; Leeder & Nami 1979; Livera & Leeder 1981; Kantorowicz 1985). Large-scale bedforms include laterally accreted channel sandstones with log impressions and pebble lags indicating high current velocities (Black 1928). In South Bay, Scarborough, and south of Hundale Point, sequentially stacked river channels pass up to mud-rich, level bedded units with only occasional laterally accreted channels (Nami & Leeder 1978). Interfluvial beds reveal tetrapod and sauropod dinosaur footprints (Hargreaves 1913; Sargeant 1970; Whyte & Romano 1993; Romano & Whyte 2003; Whyte & Romano, 2006*a*) and 'dinoturbation' structures that the latter authors attributed to large saurian reptiles producing thixotropically contorted laminae below their footfalls (Fig. 27a).The coarse-grained stacked channels in the Moor Grit are mostly confined to the coastal exposures orientated northwest-southeast, and palaeocurrent measurements suggest a major river channel axis in this orientation, with sediment derived from the northwest and north. Elsewhere, the Moor Grit unit is definitely not a 'grit'; for instance in the Hambleton Hills, on the east of the outcrop, it comprises a texturally mature, fine- to medium-grained white sandstone, lacking major channels or laterally accreted bedforms (Powell *et al.* 1992). This tabular sand lithofacies was probably deposited by sheetflows on the interfluves between the major fluvial channels seen in the coastal exposures, which, though better known, are atypical. The texturally mature quartzitic sandstone of the inland outcrop suggests a distant provenance and deposition by a major river system. Large-scale, stacked fluvial channels seen in the northwest trending coastal sections at Hundale Point and south of Scarborough may have been controlled by subsidence associated with penecontemporaneous extensional subsidence within the Peak Trough.

Waning river velocity and reduced sediment flux is clearly seen across the whole basin in the upper part of the Scalby Formation. The upper 'level-bedded' Long Nab Member is mudstone-dominated and is characterized by deposition in meandering low-velocity rivers, muddy interfluves and fresh- to brackish-water lakes. North of Scalby Mills, the curved meander traces of point bar deposits (Nami &

Leeder 1978) can be clearly seen from the cliff top (Fig. 27b); cross-sections in the cliff reveal low angle, laterally accreted point bar sands and mud-filled abandoned channels, together with laterally persistent thin sandstones with ripple marks representing crevasse-splay and overbank deposits that accumulated in shallow fresh water and brackish lakes; sphaerosiderite is a common early diagenetic structure in mud influenced by fluctuating, slightly acidic groundwaters (Kantorowicz 1990).

Studies of well-exposed sections of the Long Nab Member on the Yorkshire coast (Black 1929; Leeder & Nami 1979) have concluded that it was deposited in a spectrum of sub-environments, including meandering channels, marshes and flood basins on an alluvial plain. However, subsequent reports of *Ophiomorpha* burrows, together with bioturbation and mud-grade sediments in channel-fill deposits (Livera & Leeder 1981), supported by the discovery of marine microplankton (Hancock & Fisher 1981), have suggested at least some degree of marine influence. On the basis of detailed sedimentological and palynofacies investigations of the coastal succession, Fisher & Hancock (1985) reinterpreted the upper part of the Scalby Formation as a saline-influenced delta-plain, interrupted by small distributary channels, some of which may have been tidal. However, it is not known whether this marine-influenced lithofacies extended over the whole of the basin, and based on the westward marine incursions in the fully marine units such as the Scarborough Formation, it might have been restricted to the current-day coastal sections.

A major sea-level rise in Callovian times (Herveyi Zone) resulted in marine incursion from the south and east across the Market Weighton High, flooding the low-gradient coastal plain. This major sequence boundary marks the demise of fluvial and deltaic sedimentation due to a world-wide sea-level rise (Haq *et al*. 1988) and increased subsidence of the Pennine landmass. The lower Cornbrash Formation of southern England is absent (Page 1989), indicating that marine flooding of the Cleveland Basin occurred slightly later during Herveyi Zone time. Bioturbation in the topmost Scalby mudstones and *Rhizocorallium* burrows that penetrate downwards from the berthierine ooidal limestone (Cornbrash Formation) (Wright 1977; Rawson & Wright 2000) indicate that the sea transgressed rapidly across a still poorly lithified, low-gradient coastal plain. The condensed succession represented by the Cornbrash limestone with its abundant oysters (*Lopha marshii*) at Cayton Bay [TA 0765 8405] indicates low levels of sediment flux to the littoral coastal plain during the transgression.

5.4 Mid-Late Jurassic carbonates, corals and ooid shoals

The high Middle and Upper Jurassic succession is characterized mostly by calcareous sandstone and limestone that form the spectacular cliffs of Castle Hill, Scarborough, the high ground of the North York Moors and, in the west, the escarpment of the Hambleton Hills. The major sea-level rise in Callovian times marked a return to marine sedimentation that continued for the remainder of the Jurassic, about 20 million years, culminating in relatively deeper water sedimentation of the Kimmeridge Clay in a broad epeiric sea. The Callovian, Oxfordian and Kimmeridgian succession is best known from the early pioneering studies of Fox-Strangways (1892 and references therein), and from Arkell (1933, 1945) and the extensive publications of Wright (1968*a*, 1972, 1977, 1978, 1983, 1992, 1996*a*, 1996*b*, 2009). Wright's detailed studies, and re-surveys of part of the Hambleton Hills by the BGS (Powell 1982, 1992) have demonstrated penecontemporaneous tectonic uplift and erosional unconformities in a seemingly conformable sequence (Coe 1995) (Figs 7, 33). Representative geophysical logs for the Hunmanby and Brown Moor boreholes, illustrating the lateral variation southwards towards the Market Weighton High, are shown in (Fig. 34).

As noted above, the Cornbrash Formation was deposited during the marine transgression at the base of the Callovian Stage (Herveyi? Zone), but its absence from the outcrop in the Hambleton Hills (Senior 1975; Powell *et al*. 1992) suggests that the initial marine transgression did not reach that far west. The overlying Cayton Clay Formation, albeit thin over most of the basin, probably marks the maximum flooding across the fluvio-deltaic plain (Wright 1977; Senior 1975; Coe 1995). The only exposure in the Hambleton Hills was in Northwoods Slack [SE 4982 8920], noted by Fox-Strangways *et al*. (1886, p. 43). Senior (1975) logged sections through this part of the sequence and noted that Fox-Strangway's locality was no longer exposed, but he recorded several small exposures of grey bioturbated, fossiliferous mudstone with bivalve fragments (c.1 m) at the base of the Osgodby Formation sandstone.

The overlying sandy marine Osgodby Formation, and the intra-formational tectonics that resulted in its component members being separated by local unconformities, have been described in detail by Wright (1968, 1978,1992). The unconformities at the base of the Langdale Member and at the base of the Hackness Rock are well developed on the coast between Castle Hill, Scarborough [TA 05 89] and Cunstone

Nab [TA 10 83] (Wright 1968a, fig.3) and in the Hambleton Hills (Powell *et al.*1992). The lower two members, the Redcliff Rock and overlying Langdale Member represent an upward coarsening succession deposited in a shallow-water, littoral environment, probably the subtidal shoreface zone passing offshore to finer-grained siliciclastics in the south-east of the basin.

Shallow marine siliciclastic sedimentation continued through the Callovian, but was interrupted by tectonic events that caused gentle basinal uplift and flexure, non-deposition and erosion, a precursor to early Oxfordian tectonics. Consequently, some of the Callovian ammonite zones are missing. In the Hambleton Hills, the Langdale Member of the Osgodby Formation (Wright 1978) is absent, so the upper member of the formation, the Hackness Rock (Athleta-Lamberti zones) rests unconformably on the Red Cliff Rock Member (Koenigi Zone) with strata representing up to three ammonite zones missing. Callovian to early Oxfordian uplift and erosion is manifested in the area between Whitestone Cliff and Raven's Gill (Fig. 33), where the Oxford Clay and underlying Hackness Rock are cut out by a low-angle, overstepping unconformity at the base of the Lower Calcareous Grit (see below).

A global rise in sea-level in Late Jurassic times (Cope *et al*. 1992; Haq *et al*. 1988) is marked in the Cleveland Basin by the change in facies at the base of the Oxford Clay (Weymouth Member, Mariae Zone), which represents deeper water sedimentation and a continuation of the major marine transgression that began in the Callovian Stage. The later arrival of Oxford Clay lithofacies in the Cleveland Basin, compared to the East Midland Shelf, was due to lower subsidence rates north of the Market Weighton High. Furthermore, the global eustatic sea-level rise in north-west Europe (Hallam 1975, 1988; Haq *et al*. 1988) was interrupted in the Cleveland Basin by a regressive low sea-level stand during deposition of the Corallian Group.

Early Oxfordian sedimentation (Oxford Clay and Lower Calcareous Grit) represents an upward coarsening (shallowing) succession consisting of grey-green mudstone and silty mudstone passing gradationally up to calcareous siltstone and sandy limestone. The benthic fauna of the Oxford Clay includes sparse, small bivalves (*Meleagrinella* sp., *Oxytoma* sp., *Gryphaea* sp., *Nuculoma* sp. and *Rollierella* sp.) and the gastropod *Dicroloma* sp. The fine-grained lithology of that formation, the absence of current structures, the paucity of its benthic fauna, and the presence, locally, of a nektonic fauna that includes belemnites (*Hibolites* sp.) and ammonites (*Quenstedtoceras mariae* (d'Orbigny), C*ardioceras scarburgense* (Young and Bird) and *Peltoceras (Parawedekendia*) sp.), all suggest an offshore, moderately deep-water environment of deposition. However, some beds, especially in the lower part, are heavily bioturbated, with abundant *Chondrites* burrows and *Planolites* burrows, indicating an oxygenated sea-floor.

In the Hambleton Hills, the marked local unconformity below the Lower Calcareous Grit reflects the continuation of tectonic activity that resulted in depositional hiatuses during the Callovian (Fig. 7). This is most pronounced in the south-east of the Hambleton Hills, where uplift and tilting of the Roulston Scar 'block' resulted in the Lower Calcareous Grit resting unconformably (overstep) on the Red Cliff Rock (Osgodby Formation) (Figs 7, 33). The absence of the Oxford Clay between Sutton Bank and Raven's Gill along the main escarpment, and also at Hood Hill [SE 504 813], demonstrates uplift and subsequent sub-marine erosion of the Oxford Clay, and in places the Hackness Rock, prior to deposition of the Oldstead Oolite, the ooidal limestone developed locally at the base of the Lower Calcareous Grit (Wright 1983; Powell *et al*. 1992). This area appears to have been an uplifted block, tilted gently towards the north, since the Oxford Clay thins gradually southwards towards Roulston Scar [SE 5110 8153], but is present between Raven's Gill and Shaw's Gill, where a penecontemporaneous post Oxford Clay-pre Lower Calcareous Grit fault is invoked (Fig. 33). Uplift and erosion must have been short-lived because the Oxford Clay and the overlying Lower Calcareous Grit have yielded ammonites of the Mariae Zone and Cordatum Zone (Bukowskii Subzone), respectively, in the Shaw's Gill area [SE 507 834] (Powell 1982; Powell *et al*. 1992, fig. 18). Clay pellets in the unconsolidated sand at the top of the Redcliff Rock between Whitestone Cliff and Raven's Gill may have been derived from the Oxford Clay during the erosive phase that removed both the Oxford Clay and the Hackness Rock and reworked the top of the Redcliff Rock (Powell 1982). The unconformity is equivalent to five ammonite zones and represents rapid erosion of marine mud and sand representing a considerable time span (Cope *et al*. 1980*b*, fig. 8).

A broad, shallow carbonate platform was established across the Cleveland Basin area during mid Oxfordian times, contrasting with more rapid subsidence and deeper water sedimentation across the East Midlands Shelf. The spicule-rich calcareous sandstones and micritic, bioclastic, reefal and ooidal limestones that comprise the Corallian Group (70 to 150 m) were deposited in a warm, shallow sea during a relative sea-level low stand.

Where the Oxford Clay is present, away from the Roulston Scar 'block', the gradational upward-coarsening across the boundary between the Oxford Clay and the Lower Calcareous Grit,, together with the shelly benthic fauna, abundant sponge spicules and *Thalassinoides* burrows in the latter suggest sedimentation under shallower water conditions than prevailed during deposition of the underlying Oxford Clay. The paucity of small-scale sedimentary structures in the Lower Calcareous Grit is due to intense bioturbation of the substrate soon after deposition; *Thalassinoides* burrows with a higher spicule content are well preserved on bedding planes, but intense bioturbation within individual beds has produced a homogeneous fabric. Despite the general absence of primary current structures, the lithological and faunal characteristics indicate deposition in shallow to moderate depths (c. 10 to 30 m) in the offshore zone.

Development of the Oldstead Oolite Member (Wright 1980; Powell *et al*. 1992) at the base of the formation near Roulston Scar [SE 5156 8121 to 5327 8206] was probably due to the development of a shallow water ooidal shoal lithofacies on a sub-marine high that developed in response to the local tectonic uplift this area (see above), the Oldstead Oolite being deposited in turbulent conditions on the south-eastern flanks of the Roulston Scar ‘block’, which formed the palaeohigh. Cross-bedding, ooidal grainstone texture and basal erosional scours indicate shoaling conditions, within wave-base. A decrease in the proportion of ooids (wackestone texture) at the top of the member suggests gradually increasing water depths through time during the deposition of the Lower Calcareous Grit.

Shallowing of the sea, with a change in benthos (sparse *Rhaxella* spicules) and the development of dynamic, tidally influenced ooidal shoals, is reflected in the overlying Coralline Oolite Formation. The lowermost member, the Hambleton Oolite, has a gradational base and in places passes laterally into spiculitic calcareous sandstone of the Birdsall Calcareous Grit (Wright 1972), indicating the lateral discontinuity of migrating ooid shoals and passage offshore to siliciclastic lithofacies. This relationship reflects the original depositional environment of migrating ooidal shoals passing into slightly deeper water environments typified by the spiculitic sand ‘background’ sedimentation.

Detailed studies of the Corallian succession in the Howardian Hills by Wright (2009) have shown that the broadly east-west fault system in the Howardian Hills and Vale of Pickering was locally tectonically active during the mid Oxfordian (c.f. Roulston Scar in the Hambleton Hills). Penecontemporaneous extensional movement on the Coxwold-Gilling faults resulted, locally, in marked changes in thickness and lithofacies with areas of uplift and erosion along the Corallian ridge notably at Gilling East and between Malton and North Grimston (Wright 2009, fig. 13)

The distribution of lithologies, fauna and facies suggest that the Coralline Oolite Formation was deposited in a warm shallow sea that covered an extensive carbonate platform, across which ooid shoals prograded offshore (south-eastwards) from the nearshore zone situated to the north of the district. Micritic carbonates developed in sheltered lagoons that were protected, in part, by coral-algal patch reefs during deposition of the Coral Rag Member (Reeves *et al*. 1978). Intercalation of ooidal carbonates and calcareous sandstones in the lower part of the formation, and lateral passage to increasingly siliciclastic-dominated lithofacies to the south-west, suggest a south-easterly transition from nearshore to offshore zones.

Ooidal limestone (packstone to grainstone texture) lithofacies (e.g. Hambleton Oolite) with a variable proportion of quartz sand and fragmented shells are typified by cross-bedding and shallow scours. Multidirectional cross-bedding azimuths suggest that the oolite shoals were deposited in an oscillating tidal current regime. Soft-sediment deformation structures, such as the slump structures and injection phenomena locally present at Shaw's Gate Quarry [SE 5233 8236] and Old Byland Grange Quarry [SE 5454 8567] in the Hambleton Hills, might have resulted from the displacement of pore-waters held in the semi-lithified sediments during seismic activity associated with local tectonic uplift in the Roulston Scar area in early Oxfordian times. However, some of the convoluted sandy beds, particularly the basal bed at Shaw's Gate Quarry, have features such as convoluted clasts, erosive bases and planar, truncated, upper bedding surfaces, that indicate deposition as submarine debris flows.

Temporal relationships between the ooidal (Hambleton Oolite Member) and variably spiculitic calcareous sandstone (e.g. Birdsall Calcareous Grit Member) lithofacies in the Hambleton Hills are difficult to resolve because of the paucity of ammonite faunas. The overall lithofacies distribution of these two members, as deduced from their outcrop pattern, indicates a depositional environment ranging from shallow-water ooid shoals in the north of the Cleveland Basin, interdigitating with, and passing offshore to marine siliciclastics towards the south-east. Similar lithofacies have been described from the modern-day Great Bahama Bank, Andros Island and the Arabian Gulf (Purdy 1963; Bathurst 1975, p.135; Black 1980; Hine *et al*. 1981). The lithological characteristics of the ooid lithofacies, taken together with the low-dipping, multidirectional cross-bedding and shallow scours, suggest periodic migration of oolitic shoals on a shallow-water carbonate platform, influenced by waves and oscillating tidal currents. Sparse vertical burrows indicate temporary stability of the substrate that allowed colonization by infauna.

The pattern of fluctuating sea-level is repeated with deposition of the Middle Calcareous Grit Member, Malton Oolite Member and Coral Rag Member which together form the second upwards shallowing cycle in the Corallian Group. Shell beds composed of *Myophorella hudlestoni* in the Middle Calcareous Grit (Vertebrale Subzone; Wright 1980), together with *Rhizocorallium* burrows and cross-bedding, suggest a high-energy, shallow-marine environment of deposition (Hemingway 1974). The shoaling cycle is capped by the Malton Oolite and Coral Rag members. Large-scale foresets and a paucity of benthic faunas in the Malton Oolite indicate large mobile laterally migrating ooidal shoals, similar to parts of the present-day Bahama Banks (Twombley 1964), formed during strong flood and ebb storm surges and preserved as mega-dune foresets. The Coral Rag comprises locally developed coral-algal patch reefs, coral-shell inter-reef debris, and micritic limestone deposited in back-reef lagoons.

As sea-level rose towards the end of Corallian Group deposition, the Upper Calcareous Grit Formation was deposited in slightly deeper water across the Market Weighton High and northwards into the Cleveland Basin. Very fine- to fine-grained, highly calcareous, spiculitic sand and silt, with abundant beds of clayey lime-mud in the middle of the unit, was deposited in moderate depths on the shelf in nearshore to offshore environments. Increased rates of subsidence and global sea-level rise around Serratum Zone time resulted in ‘drowning’ of the shallow siliciclastic and carbonate platform, with the deposition of mud (Ampthill Clay and Kimmeridge Clay) in deeper water environments.

5.5 Late Jurassic global sea-level rise and sea-floor anoxia

Global sea-level rise during the late Oxfordian is manifested in the Ampthill and Kimmeridge Clay formations, which are the youngest Jurassic units in the Cleveland Basin. The marked change in lithofacies from shallow-water carbonates and nearshore siliciclastics, represented by the uppermost Corallian Group, to oxic shallow marine mudstones with thin carbonate beds and nodules (Ampthill Clay), passing upward to organic-rich mudstones (Kimmeridge Clay), reflects subsidence of the Cleveland Basin and deeper-water conditions during late Oxfordian and

Kimmeridgian times. Infaunal and epifaunal bivalves, gastropods and echinoid spines suggest that the Ampthill Clay was deposited in an oxic shallow marine environment. Oxic and anoxic (organic-rich) bottom conditions then alternated as the platform subsided during deposition of the Kimmeridge Clay; pelagic and hemipelagic muds were deposited from suspension across the former platform and into the current-day North Sea, in response to a major worldwide sea-level rise (Haq *et al*. 1988). Muds were deposited in rhythms indicating fluctuating relatively oxic and anoxic bottom conditions. The geophysical logs of the Hunmanby Borehole (Cox & Gallois 1981; Whittaker *et al.* 1985) illustrate the 'saw-tooth', small-scale sedimentary rhythms (Fig. 38). These couplets comprise brown-black, bituminous fissile mudstone (anoxic; kerogen-rich) and overlying medium-grey and pale grey calcareous mudstone (oxic). Anoxic and oxic sea-bed conditions are indicated by fossil associations with increased levels of bioturbation and infaunal bivalves during more oxic periods (Wignall 1990). Free-swimming fauna such as ammonites, fish and marine reptiles were preserved after death during periods of sea-floor anoxia, resulting in their exceptional preservation. Restricted circulation and high organic productivity in the Tethys Ocean during the late Kimmeridgian (post-Eudoxus Zone) led to deposition and preservation under anoxic bottom conditions of organic-walled phytoplankton, which following burial in the northern North Sea Basin and the formation of kerogen, generated hydrocarbons (Gallois 1976; Herbin *et al*. 1993). Earlier depositional models attributed the high organic content to high-levels of phytoplankton productivity (algal blooms) (Gallois 1976). However, Weedon *et al*. (2004) calculated the organic productivity over time and concluded that the 'Kimmeridge sea' was no more productive than modern-day continental shelves, and consequently that the high organic content (3.8% Total Organic Carbon) was due to a dilution or absence of terrigenous siliciclastics sediment entering a semi-restricted basin. If this was the case, it suggests a geomorphologically subdued hinterland with very little erosion of terrigenous material, perhaps akin to the southern margins of the present-day Arabian Gulf, but with more anoxic bottom conditions (cf. the Black Sea).

The non-turbulent and cyclical anoxic bottom conditions resulted in fine preservation of ammonites such as *Amoeboceras* sp. (Ampthill Clay), *Pictonia* sp., *Aulacostephanus fallax* and *Rasenia evolata*, and these have enabled detailed biostratigraphical zonation and correlation with the North Sea and Europe (Herbin *et al*. 1995). The Kimmeridge Clay cycles have been attributed to astronomical (Milankovitch) cycles (Weedon *et al*. 1999; Weedon *et al*. 2004) with the larger (2-4 m wavelengths) representing orbital obliquity (c. 41,000 year periodicity) and the smaller wavelength cycles (1-2 m wavelengths) to precession cycles (c. 26,000 year periodicity). Studies based on sequence stratigraphy (Wignall 1991; Taylor *et al*. 2001; Williams *et al*. 2001) have recognized between 9 and 11 depositional cycles in the North Sea and adjacent areas, with silt-dominated units in the centre of the basin representing lowstand conditions during which siliciclastic sediment by-passed the shallow shelf. The thin and siltier succession through the Elegans to Wheatleyensis zones may have represented significantly shallower basin conditions than during the earlier Mutabilis to Eudoxus zones (Fig. 38). During the late Kimmeridgian (Bolonian of Cope 1993), this upward shallowing trend is reflected in the Late Cimmerian tectonic uplift (Rawson & Riley 1982) that resulted in a basin wide sea-level fall.

Water depth and depositional conditions for the Kimmeridge Clay have been the topic of much debate (Cope 2006). Early workers (Irwin 1979; Tyson *et al*. 1979; Myers & Wignall 1987) postulated relatively deep water and fluctuating oxic-anoxic conditions on the sea-floor as the oxic-anoxic boundary migrated vertically above and below the sediment-water interface. Wignall (1989) also proposed that storm events ripped up intraclasts and fine-grained clastic sediments, which were re-deposited in deeper parts of the basin, thereby oxygenating the bottom sediments. This implies that water depths, at least at the basin margins, were within storm-wave base (c. 30 m depth). It is generally accepted that the 'Kimmeridge Basin' was 'restricted' relative to full ocean circulation to some degree, and some authors (Hallam 1975; Aigner 1980) proposed deposition in stagnant conditions of shallow water depths of about 10 m rather than the c. 100 m or so postulated by Tyson *et al*. (1979) and others.

The unconformity between the Kimmeridge and Speeton clays was a result of latest Jurassic sea-level fall (Haq *et al*. 1988) coupled with the Late Cimmerian earth movements (Rawson & Riley 1982) that led to a tensional (rifting) tectonic phase during latest Jurassic to earliest Cretaceous times, probably in response to sea-floor spreading in the Atlantic Ocean (Rawson 2006).

6. CONCLUSIONS AND FURTHER STUDY

The Jurassic Cleveland Basin, by virtue of its diverse lithofacies, tectonic evolution, excellent coastal exposures and analogues to North Sea hydrocarbon plays, is one of the most studied sedimentary basins in NW Europe. Pioneering research in the geological sciences, supported through the Yorkshire Philosophical Society (later the Yorkshire Geological Society), were stimulated by the early researches by William Smith and his nephew John Phillips. Later academic and practical studies on the coast (e.g. Young & Bird 1822; Phillips 1829, 1858), combined with the search for energy and industrial minerals (coal, ironstone, alum, jet, building stone and aggregates) in the 18th and 19th centuries, paved the way for the Geological Survey Primary Survey at '6 inches-to-the-mile scale' by Fox-Strangways and Barrow in the late 19th century, which laid the foundations to our understanding of the basin in its broadest context.

Our knowledge has been refined over the last 100 years or so through the advent of high resolution biostratigraphy, geochemistry, sedimentology and sequence stratigraphy, heavy mineral studies, and more recently cyclostratigraphy and stable isotope geochemistry, techniques that may lead to an astronomical timescale for the deeper water marine successions. Academic research has focussed on the well-exposed coastal sections, but new data is still emerging from detailed studies of the inland exposures and deep hydrocarbons boreholes. The latter, combined with detailed biostratigraphy and stable isotope geochemical studies, are likely to provide a better understanding of the influence of the Earth's orbit and Milankovitch cylicity on sedimentation and diagenesis. These advances will no doubt lead to a better understanding of the palaeoceanography, sedimentation and evolution of the Cleveland Basin. However, there is still a place for detailed geological mapping, three-dimensional modelling and multidisciplinary sedimentological/petrological/biostratigraphical studies of parts of the succession that we still do not fully understand, such as the origin of the Jurassic ironstones, the nature of sea-bed anoxia, palaeoceanography, the influence of the Howardian-Flamborough Fault Belt on Jurassic sedimentation north of the Market Weighton High, intra-Jurassic tectonics, palaeoclimates and atmospheric gasses, and the evolution of flora and fauna. These and no doubt many new, avenues of research will ensure that the Cleveland Basin remains a focus of geological research and training, thereby attracting leading international scientists to reveal more about this fascinating period of Earth's history – here in Yorkshire!

c.22 k words

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Figure & Table Captions (see separate list)

References (see separate list)