Marine Permian of England

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Chapter 3

North-east England (Durham Province)

INTRODUCTION

Most of the GCR sites documented and discussed in this chapter lie within perhaps 30 km of the original western shoreline of the late Permian Zechstein Sea and north of the Cleveland High (Figure 1.2). There is no evidence of a connection with the Bakevellia Sea at any time during the first two main sedimentary cycles (EZ1 and EZ2) and only limited evidence of a brief connection with the Vale of Eden inland sedimentary basin during Cycle EZ3 (but see Holliday, 1993 and Smith, in press).

The Cleveland High (Figure 1.2) projected eastwards into the basin a few kilometres south of Darlington and strongly influenced sedimentation during Cycle EZ1 and part of Cycle EZ2. It was a broad, gentle, topographical feature where subsidence may have been relatively slightly slower than that to the north and south, and it remained emergent until eventually buried by onlapping sediments of the Edlington Formation. Following its burial, the Cleveland High appears to have exerted little or no effect on sedimentation and Cycle EZ3, and later English Zechstein strata in the Durham and Yorkshire provinces are similar to each other.

Rather more than half of the designated marine Permian sites are in the Durham Province and several of these are large complex coastal or inland exposures of international importance; amongst these outstanding sites are the Blackhalls Rocks coast section, the Claxheugh Rock – Ford Quarry section, Fulwell Hills Quarries and the unrivalled coastal cliffs between (and including) Trow Point (South Shields) and Whitburn.

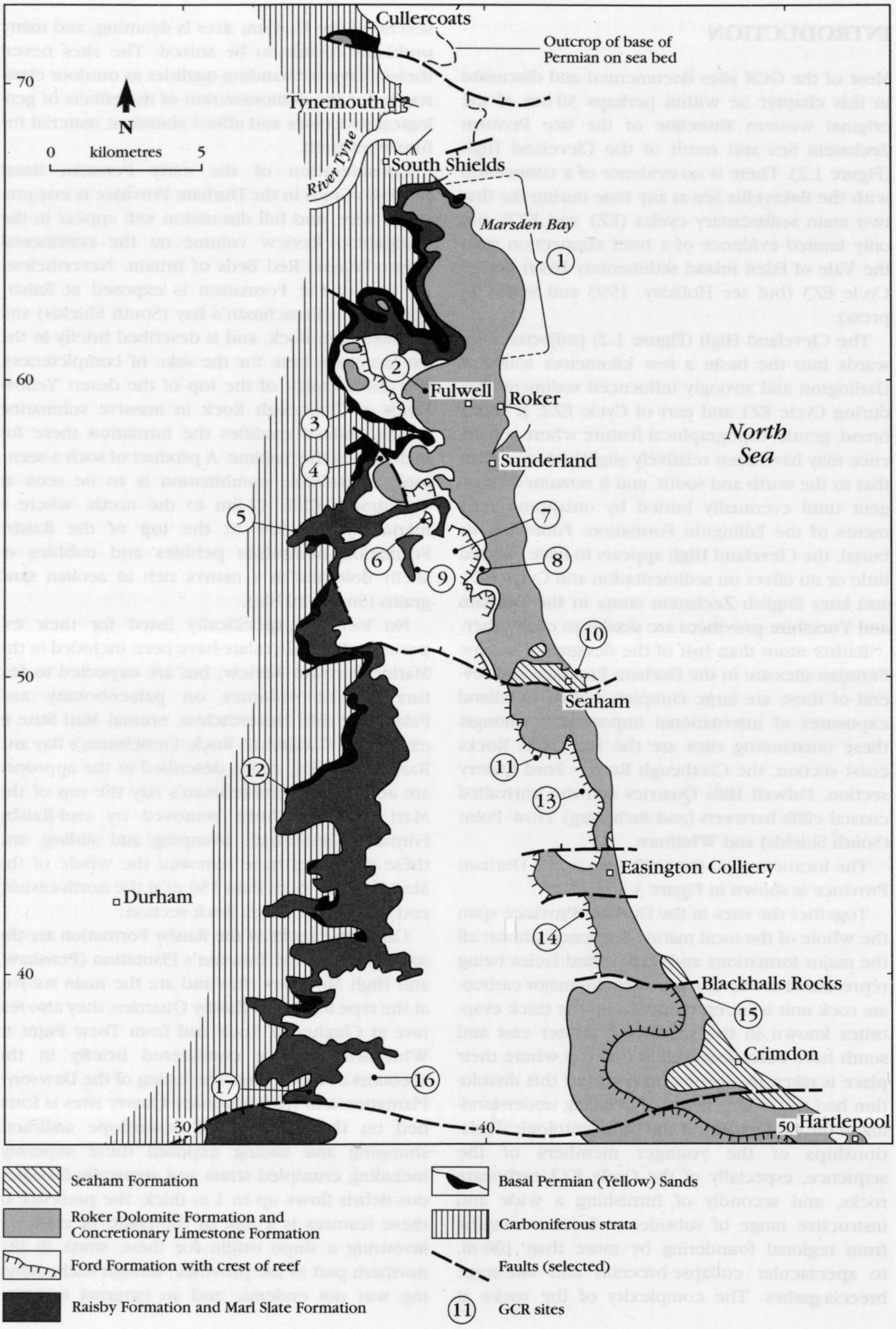
The location of all the GCR sites in the Durham Province is shown in Figure 3.1.

Together the sites in the Durham Province span the whole of the local marine sequence, almost all the major formations and their varied facies being represented at one or more sites. No major carbonate rock unit is unrepresented, but the thick evaporites known in the subsurface farther east and south have been dissolved at outcrop where their place is taken by dissolution residues; this dissolution had the effects firstly of delaying understanding of the stratigraphical and sedimentological relationships of the younger members of the sequence, especially of the Cycle EZ2 carbonate rocks, and secondly of furnishing a wide and instructive range of subsidence features ranging from regional foundering by more than 100 m, to spectacular collapse-breccias and late-stage breccia-gashes. The complexity of the rocks at several of the Durham sites is daunting, and many problems remain to be solved. The sites nevertheless have outstanding qualities as outdoor classrooms for the demonstration of the effects of geological processes and afford abundant material for future research.

Consideration of the early Permian Basal (Yellow) Sands in the Durham Province is inappropriate here, and full discussion will appear in the companion Review volume on the continental Permo-Triassic Red Beds of Britain. Nevertheless, the top of the Formation is exposed at Raisby Quarries, in Frenchman's Bay (South Shields) and at Claxheugh Rock, and is described briefly in the site accounts here for the sake of completeness. The involvement of the top of the desert Yellow Sands at Claxheugh Rock in massive submarine sliding, indeed qualifies the formation there for inclusion in this volume. A product of such a seemingly improbable combination is to be seen at Tynemouth Cliff, 12 km to the north, where a marine debris flow at the top of the Raisby Formation comprises pebbles and cobbles of shelly dolomite in a matrix rich in aeolian sand grains (Smith, 1970c).

No localities specifically listed for their exposures of the Marl Slate have been included in the Marine Permian Review, but are expected to feature in the volumes on palaeobotany and Palaeozoic fish. Nevertheless, normal Marl Slate is exposed at Claxheugh Rock, Frenchman's Bay and Raisby Quarries, and is described in the appropriate accounts. At Frenchman's Bay the top of the Marl Slate has been removed by end-Raisby Formation submarine slumping and sliding, and these processes have removed the whole of the Marl Slate for more than 150 m at the north-eastern end of the Claxheugh Rock section.

Carbonate rocks of the Raisby Formation are the sole subject at the Dawson's Plantation (Penshaw) and High Moorsley sites and are the main subject at the type locality at Raisby Quarries; they also feature at Claxheugh Rock and from Trow Point to Whitburn and are considered briefly in the accounts of those sites. The listing of the Dawson's Plantation and High Moorsley Quarry sites is founded on the evidence of downslope sediment slumping and sliding exposed there superbly, including crumpled strata and atypically fossiliferous debris flows up to 1 m thick; the presence of these features is a link in the chain of evidence favouring a slope origin for these strata in this northern part of the province, though such slumping was not endemic and an external initiating


Cullercoats
Outcrop of base of
Permian on sea bed
70
Tynemouth
N
0 kilometres 5
River Tyne
South Shields
Marsden Bay
1
2
60
Fulwell
Roker
3
North
Sea
Sunderland
4
5
7
6
8
9
10
50
Seaham
11
12
13
Easington Colliery
Durham
14
40
Blackhalls Rocks
15
Crimdon
16
17
30
40
50
Hartlepool
Seaham Formation
Roker Dolomite Formation and
Concretionary Limestone Formation
Ford Formation with crest of reef
Raisby Formation and Marl Slate Formation
Basal Permian (Yellow) Sands
Carboniferous strata
Faults (selected)
11
GCR sites

stimulus such as an earth tremor has been inferred (Smith, 1970c). Raisby Quarries afford a complete eponymous sequence through the formation, and have been freely cited in the literature since 1914; they are famous for the unusual presence of thick primary limestone and for an extensive suite of secondary minerals. Fossils (especially some large brachiopods such as *Horridonia*) are locally well-preserved in Raisby Quarries, but evidence of the widespread slumping low and high in the formation has not been recognized here. The thin Raisby Formation at Trow Point is unusual for its evidence of prevalent bioturbation and for the presence, at its top, of a spectacularly complex mass of slide-blocks (olistoliths) of Raisby Formation strata; at Frenchman's Bay most of the formation is inferred to have been removed by the same episode of massive submarine sliding (the Downhill Slide, named after Downhill Quarry, West Boldon) and the largest of the slide-blocks is about 72 m long and 7.5 m thick.

Rocks of the Ford Formation are amongst the most varied of the Magnesian Limestone sequence and feature in more scheduled sites than those of any other late Permian rock-unit in the Durham Province; this is mainly because of the renowned fossil content of the shelf-edge reef which extends from Sunderland to Hartlepool (Figure 3.1) and has attracted attention for almost two centuries. Each of the main sub-facies of the reef is represented at one or more GCR sites and together the several reef sites provide a cross-section through most of the reef and afford full opportunities for further research. The scheduled exposures are reasonably representative of the reef as a whole, but reefs are notoriously variable and surviving unscheduled reef exposures such as those at Dalton-le-dale (NZ 408476), Easington Colliery (NZ 434438), Beacon Hill (Hawthorn) (NZ 442453) and Castle Eden Dene (NZ 4440) reveal other aspects of the reef not clearly seen at the scheduled sites. Details of the lithology, biota and structure of the reef are given in the individual site accounts, which draw extensively on historical records and on more recent work by Aplin (1985), Hollingworth (1987) and the author (Smith, 1981a; 1994).

Landward (west) of the reef, dolomitized carbonate rocks of the Ford Formation are exposed in three scheduled sites, including Ford Quarry where the reef/backreef contact is uniquely clearly exposed, and Gilleylaw Plantation Quarry (Silksworth) where a lagoonal patch-reef is overlain by shallow-water oncoidal dolomite of a type known at only two other localities in the Magnesian Limestone. The third site, Trimdon Grange Quarry, exposes diagenetically altered backreef or lagoonal oolite several kilometres west of the reef, but this widespread facies is under-represented in the Durham site network and Trimdon Grange Quarry has to be viewed in conjunction with other exposures such as those in the local nature reserves at Bishop Middleham (NZ 3332) and Wingate (NZ 3737) quarries.

Seaward of the reef, the youngest and in some respects the most enigmatic accepted member of the Ford Formation is exposed at and between Trow Point and Frenchman's Bay, South Shields. This, the thin but distinctive Trow Point Bed, is present here in both its peloid/oncoid and columnar-stromatolitic modes, which are also known from cored boreholes immediately offshore, as well as in many North Sea hydrocarbon boreholes and, far to the east, in surface exposures and boreholes in Germany and Poland.

The youngest carbonate rock-unit doubtfully assigned to Cycle EZ1, and therefore to the Ford Formation, is the Hesleden Dene Stromatolite Biostrome, superbly exposed at Blackhalls Rocks and less well seen at Hawthorn Quarry. At the latter the biostrome is seen to rest on an erosion surface cut onto the shelf-edge reef of the Ford Formation and is overlain by supposed Roker Dolomite. The doubts about the age of the biostrome stem from the local presence of fragments of it in collapse-breccias thought to be related to the dissolution of the Cycle EZ1 Hartlepool Anhydrite, and therefore younger than at least part of the latter. However, the approximate aerial coincidence of the reef and biostrome, plus their faunal affinities, slightly favour a Cycle EZ1 age rather than a Cycle EZ2 age for the biostrome, unless its fauna was derived. The exposures of

Figure 3.1 The distribution of Permian marine rocks in the Durham Province, showing the location of Permian marine GCR sites: 1, Trow Point to Whitburn Bay; 2, Fulwell Hills Quarries; 3, Hylton Castle Cutting; 4, Claxheugh Rock, Cutting and Ford Quarry; 5, Dawson's Plantation Quarry, Penshaw; 6, Humbledon Hill Quarry; 7, Tunstall Hills (north); 8, Tunstall Hills (south) and Ryhope Cutting; 9, Gilleylaw Plantation Quarry; 10, Seaham; 11, Stony Cut, Cold Hesledon; 12, High Moorsley Quarry; 13, Hawthorn Quarry; 14, Horden Quarry; 15, Blackhalls Rocks; 16, Trimdon Grange Quarry; 17, Raisby Quarries. The map is based on Smith (1980b, fig. 9).

dolomitized algal stromatolites and cobble-boulder conglomerate at Blackhalls Rocks are particularly impressive and throw much light on contemporary geography and processes.

The carbonate rocks of Cycle EZ2 form almost all the coastal cliffs in the Durham Province and are the main interest in the outstanding site stretching south-eastwards from Trow Point, South Shields to Whitburn Bay; they comprise the predominantly shallow-water shelf and uppermost slope carbonates of the Roker Dolomite Formation and the roughly synchronous slope dolomites and limestones of the Concretionary Limestone Formation. Equivalent strata are unknown in the Yorkshire Province except in boreholes, so that the northern Durham cliffs and quarries are the only large-scale surface exposures available for detailed study of the complex sedimentology and diagenesis of these Cycle EZ2 strata. They are also the only places where the spectacular effects of large-scale foundering may be clearly related to the dissolution of former thick evaporites.

There are no GCR sites in which the Roker Dolomite Formation is the main interest, but it is present incidentally and with its normal lithology and fauna, at Whitburn, Seaham, Hawthorn Quarry, Blackhalls Rocks and in the Ryhope Cutting (as collapse-breccia). At Blackhalls Rocks and Hawthorn Quarry the formation displays no evidence of having foundered onto the underlying biostrome, implying that the Cycle EZ1 anhydrite did not overlap the reef here, but the formation has foundered by perhaps 50–100 m at the Ryhope and Seaham exposures. At Ryhope the collapse-brecciated Roker Dolomite is within 200 m of the reef-front, supporting the evidence from other localities such as West Boldon (NZ 3561), Easington Colliery and Horden that the Hartlepool Anhydrite once lay against the reef at Ryhope even if it did not overlap it. The Seaham exposure is of interest in that the uppermost few metres of the formation have been much fractured and dedolomitized, probably by the formation and dissolution of a complex network of evaporite veins related to the formerly overlying Fordon Evaporites. Large exposures of gently foundered Roker Dolomite extend northwards from the Seaham site and form the coastal cliffs at Roker (NZ 4059) and Whitburn (NZ 4161); here it overlies the well-known Cannon-ball Limestone near the contact with the Concretionary Limestone Formation. The Roker Dolomite lies in its normal stratigraphical position at Hartlepool, where thick Cycle 1 anhydrite has resisted dissolution.

Carbonate rocks of the Concretionary Limestone Formation are the sole interest at the Fulwell Hills Quarries and in the Marsden Bay to Whitburn area of the Trow Point to Whitburn GCR site. Faces preserved in the formerly vast complex of quarries at Fulwell Hills are remarkable for the great range of calcite concretions for which this formation is justly famous, and incidentally display sedimentological evidence favouring a submarine slope origin for these strata; they also include fish-bearing calcite-laminites, a characteristic shared with equivalent beds at Marsden Bay from which fossil fish were first collected from this formation. The Fulwell Hills sections display ample evidence of foundering through dissolution of the former underlying Hartlepool Anhydrite, but the evidence of foundering is especially dramatic and inescapable at Trow Point and Frenchman's Bay where almost completely brecciated dedolomitized Concretionary Limestone overlies the thin dissolution residue of the Hartlepool Anhydrite. Farther south, the effects of the major foundering are spectacularly displayed in Marsden Bay, where late-stage collapse of large dissolution-induced cavities is believed to have been the cause of a number of massive subvertical 'breccia-gashes' or 'breccia-pipes'. The main phase of foundering was Palaeocene or earlier, judging from the mutual relationship of foundered ?Roker Dolomite and the *c.* 58 million-year old Hebburn or Monkton Dyke, the crop of which was discovered recently on the coast at Whitburn by Mr G. Fenwick.

The Marsden Bay section, though extensively calcitized in addition to the brecciation, is still mainly of dolomite and comprises a mid-slope complex of interbedded sapropelic organic-rich fine laminates, graded turbidites and slumped beds (including oolite grainstones translated from the Roker Dolomite shelf). These strata and their associated secondary effects (calcitization and foundering) continue in the coastal cliff south of Lizard Point where they merge gradually with shelly carbonate rocks inferred to have been formed in oxic conditions in the upper part of the basin-margin slope.

The Concretionary Limestone rocks exposed at Fulwell Hills and in the Trow Point to Whitburn GCR site are reasonably representative of this most variable of formations, and include the foraminifer–gastropod–bivalve–ostracod-rich rocks that abound in high-slope facies such as those in coastal cliffs a few hundred metres south of Lizard Point. They are, however, relatively poor in calcite spherulites such as typify rocks of this formation in most inland exposures in the South Shields to Whitburn area. They nevertheless afford unrivalled opportunities for the study of the sedimentology and complex diagenesis of the formation and for observing the profound effects of the dissolution of thick underlying evaporites.

The insoluble remains of the youngest Cycle EZ2 strata – the Fordon Evaporites – comprise the striking Seaham Residue and are the main feature of the northern end of the Seaham site; they also crop out at the south end of the Blackhalls Rocks site. Both exposures illustrate graphically the effects of evaporite dissolution on underlying and overlying carbonate rocks, though the Fordon Evaporites were probably thinner there than the Hartlepool Anhydrite at Trow Point and Frenchman's Bay and the foundering was correspondingly less disruptive. The residue at Seaham is many times thicker than that of the Hartlepool Anhydrite, implying that the Fordon Evaporites contained a much higher proportion of insolubles, and it has been strongly contorted by plastic flow (perhaps whilst the evaporites, probably including salt, were still present).

Light is thrown here on the depositional environment of the Fordon Evaporites by the sedimentary features of an ooidal limestone in the Seaham Residue at Seaham, which was probably formed at or very near contemporary sea level. Undissolved Fordon Evaporites (mainly salt) have been recorded in a borehole 12 km ENE of Sunderland (Smith and Taylor, 1989) and are about 15–30 m thick in northern County Cleveland, approximately 25 km along strike from Seaham.

Carbonate rocks of Cycle EZ3 crop out in only limited areas of the Durham coast, mainly in synclines at Seaham and north and south of Blackhalls Rocks; all are estimated to have foundered by at least 120 m as a combined result of the dissolution of the Hartlepool Anhydrite and the Fordon Evaporites. At its type locality in the walls of Seaham Harbour, the Seaham Formation is mainly of thin-bedded limestone with a restricted biota and a range of shelf-type sedimentary structures, but both there and to the south of Blackhalls Rocks it also features bizarre calcite concretions similar to some of those in the Concretionary Limestone Formation farther north. Foundering is expressed by medium-scale tilting and dislocation of blocks of the Seaham Formation at its main exposures, and at Seaham was accompanied or followed by the creation of breccia gashes that contain fragments of strata (including the Rotten Marl) that are now otherwise eroded from the area.

The main features of the GCR Marine Permian sites in the Durham Province are summarized in Table 3.1, and the approximate stratigraphical positions of most of them are shown in Figure 3.2.

TROW POINT (SOUTH SHIELDS) TO WHITBURN BAY (NZ 388383–410612)

Highlights

The sea cliffs of this classic site (box 1 in Figure 3.2) provide the key to understanding much of the Magnesian Limestone sequence. In the north, from Trow Point to Frenchman's Bay, lowest beds exposed include the Yellow Sands, Marl Slate and Raisby Formation, and these are overlain, in turn, by (1) the unique algal Trow Point Bed, (2) the dissolution residue of the Hartlepool Anhydrite, (3) collapsed and brecciated Concretionary Limestone strata and (4) possible lower beds of the Roker Dolomite Formation; the upper part of the Raisby Formation was affected by massive submarine slumping (the 'Downhill Slide') and at both Trow Point and Frenchman's Bay contains piles (olistostromes) of large slumped masses (olistoliths). Slightly higher strata exposed between Frenchman's Bay and Lizard Point are almost all of the Concretionary Limestone and feature both spectacular evidence of foundering and brecciation and also primary sedimentary lamination, turbidites and submarine slumps. Strata from Lizard Point southwards are mainly less-obviously affected by foundering and brecciation but feature abundant evidence of sedimentation higher on an unstable submarine slope and contain an important but restricted range of shelly fossils.

Introduction

The bewilderingly varied Permian sedimentary rocks exposed in the sea cliffs between Trow Point and Whitburn Bay, Tyne and Wear, are mainly of the Concretionary Limestone Formation but also include glimpses of the Yellow Sands (1.2 m+) and Marl Slate (0.1–1.5 m) in Frenchman's Bay, extensive exposures of the Raisby Formation (up to 13 m) between Trow Point and Frenchman's Bay and intermittent views of possible Roker Dolomite in cliffs and rock platforms from Whitburn southwards. In northern parts of the site, the Raisby Formation is seen to be overlain by the unusual

Table 3.1 Main geological features of the marine Permian GCR sites in the Durham Province of the English Zechstein

DURHAM PROVINCE		
	Site	**Interest**
Cycle 3 Seaham Formation	Seaham	Type section; complex calcite concretions; *Calcinema;* crinkled algal stromatolites; foundered strata
	Blackhalls Rocks	Calcite concretions; foundered, partly collapse-brecciated
Cycle 2 Seaham Residue (of Fordon Evaporites)	Seaham	Type section; distinctive lithology; plastic deformation; dedolomites
	Blackhalls Rocks	Incidental occurrence
Roker Dolomite Formation	Seaham	Typical lithology passing up to dedolomitized brecciated rock at top
	Blackhalls Rocks	Typical lithology
	Ryhope Cutting (part of Tunstall Hills south)	Partly dedolomitized collapse-breccia with infiltrated cavity-fill
	Hawthorn Quarry	Slightly atypical lithology, partly dedolomitized; collapse-brecciated in east
Concretionary Limestone Formation	Fulwell Hills quarries	Bizarre calcite concretions; Fulwell Fish-bed and other laminites; foundered strata
	Trow Point to north end of Marsden Bay, South Shields	Dedolomitized collapse-breccias with infiltrated cavity-fill
	Marsden Bay, South Shields	Interbedded laminated and turbiditic dolomitized slope carbonate mudstones to grainstones; calcite concretions; dedolomites; foundered strata and breccia-gashes
Cycle 1 Residue of Hartlepool Anhydrite	Trow Point to Frenchman's Bay, South Shields	Typical evaporite-dissolution residue underlying collapse-breccias
	Ryhope Cutting (part of Tunstall Hills south)	Near-reef evaporite-dissolution residue; evidence of past plastic flow
?Ford Formation, Heselden Dene Stromatolite Biostrome	Blackhalls Rocks, Hawthorn Quarry	Coarse conglomerate of rolled blocks of dolomitized reef boundstone overlain by dolomitized algal laminites with spectacularly large domes
Ford Formation, Trow Point Bed	Trow Point	Type section of Trow Point Bed; a distinctive thin unit of marine oncoids, peloids and columnar stromatolites, partly dedolomitized
Ford Formation, shelf-edge reef facies	Claxheugh Rock, Cutting and Ford Quarry, Hawthorn Quarry, Humbledon Hill Quarry, Hylton Castle Cutting, Stony Cut (Cold Hesledon), Tunstall Hills (N and S), Horden Quarry	Massive mainly dolomitized fossiliferous reef boundstone, comprising several sub-facies: reef-base at Claxheugh Rock and Humbledon Hill; basal coquina at Tunstall Hills (N); reef-core at Claxheugh Rock, Cutting and Ford Quarry, Hylton Castle, Humbledon Hill and Tunstall Hills (N and S); reef-backreef contact at Ford Quarry; reef-flat at Hawthorn Quarry and Stony Cut; reef talus at Tunstall Hills (S); reef fissures at Tunstall Hills (N); reef crest at Ford Quarry, Horden Quarry and Stony Cut; reef-top erosion surface at Hawthorn Quarry. Humbledon Hill Quarry and Tunstall Hills are renowned historical faunal sites

Table 3.1 *(continued)*

	DURHAM PROVINCE	
	Site	**Interest**
Ford Formation, backreef facies	Claxheugh (Ford) Cutting and Ford Quarry	Reef-backreef contact; sparingly fossiliferous dolomitized mudstone/wackestone with allochthonous slide-blocks or olistoliths (best seen in cutting)
	Gilleylaw Plantation Quarry, Silksworth	Dolomitized ooid grainstones overlain by shelly algal-bryozoan patch-reef; coarse oncoids and lamellar stromatolites at top
	Trimdon Grange Quarry, Trimdon	Typical cross-laminated shallow-water ooid grainstones, extensively replaced by calcite after secondary ?anhydrite; bioturbated
Raisby Formation	Raisby Quarries	Type locality; thick primary limestones; diagenetic breccia; mineralized
	Dawson's Plantation Quarry	Debris flow near base of formation; typical lithology; spatulate listric joints and fractures
	High Moorsley Quarry	Typical lithology with thin debris flow and evidence of large-scale downslope sediment sliding; mineralized; cambered (Quaternary feature)
	Trow Point	Typical lithology; much evidence of bioturbation; major submarine slide-plane overlain by debris flow with exceptionally large slide-blocks (olistoliths)
Marl Slate	Claxheugh Rock, Frenchman's Bay	Typical lithology; was locally fluidized and injected downwards into fissures; partly removed by submarine sliding
	Raisby Quarries	Typical lithology; thins against crest of ridge in Basal Permian Sands
Basal Permian Sands (mainly pre-Cycle 1)	Claxheugh Rock, Frenchman's Bay, Raisby Quarries	Typical lithology; top involved in submarine slide-breccia at Claxheugh Rock; remains of fluidized Marl Slate in fissures at Claxheugh Rock; forms ridge in floor of Raisby Quarry and at head of Frenchman's Bay

and exceptionally persistent Trow Point Bed (0–0.60 m), the sole representative of the Ford Formation which was probably more than 100 m thick only 6 km to the west, and this bed is succeeded by the thin (0–0.15 m) dissolution residue of the Hartlepool Anhydrite.

All beds of the Concretionary Limestone have foundered by the former thickness of the dissolved anhydrite (?100 m+ at Marsden) and have responded in a number of ways ranging from barely disturbed (especially in higher parts of the formation) to completely brecciated and dedolomitized; the limestone collapse-breccias at the base of the formation are particularly resistant and are mainly responsible for the ruggedness of the coast between Trow Point and the northern end of Marsden Bay, whereas the less resistant overlying dolomite has been differentially eroded to form Marsden Bay and its neighbour to the south. Farther south, varied secondary limestones, though less resistant than the massive collapse-breccias, have given rise to a variety of lower sub-vertical cliffs and minor bays, and, by their recession, to exceptionally wide rock platforms off Whitburn (=White Burn, an allusion to the white-capped breakers that occur here during certain combinations of tide and weather).

The cliffs, especially those between Trow Point and Lizard Point and around Byer's Hole and Byer's Quarry some distance farther south, have featured freely in the literature. Early mentions were by Winch (1817), who recorded the discovery by

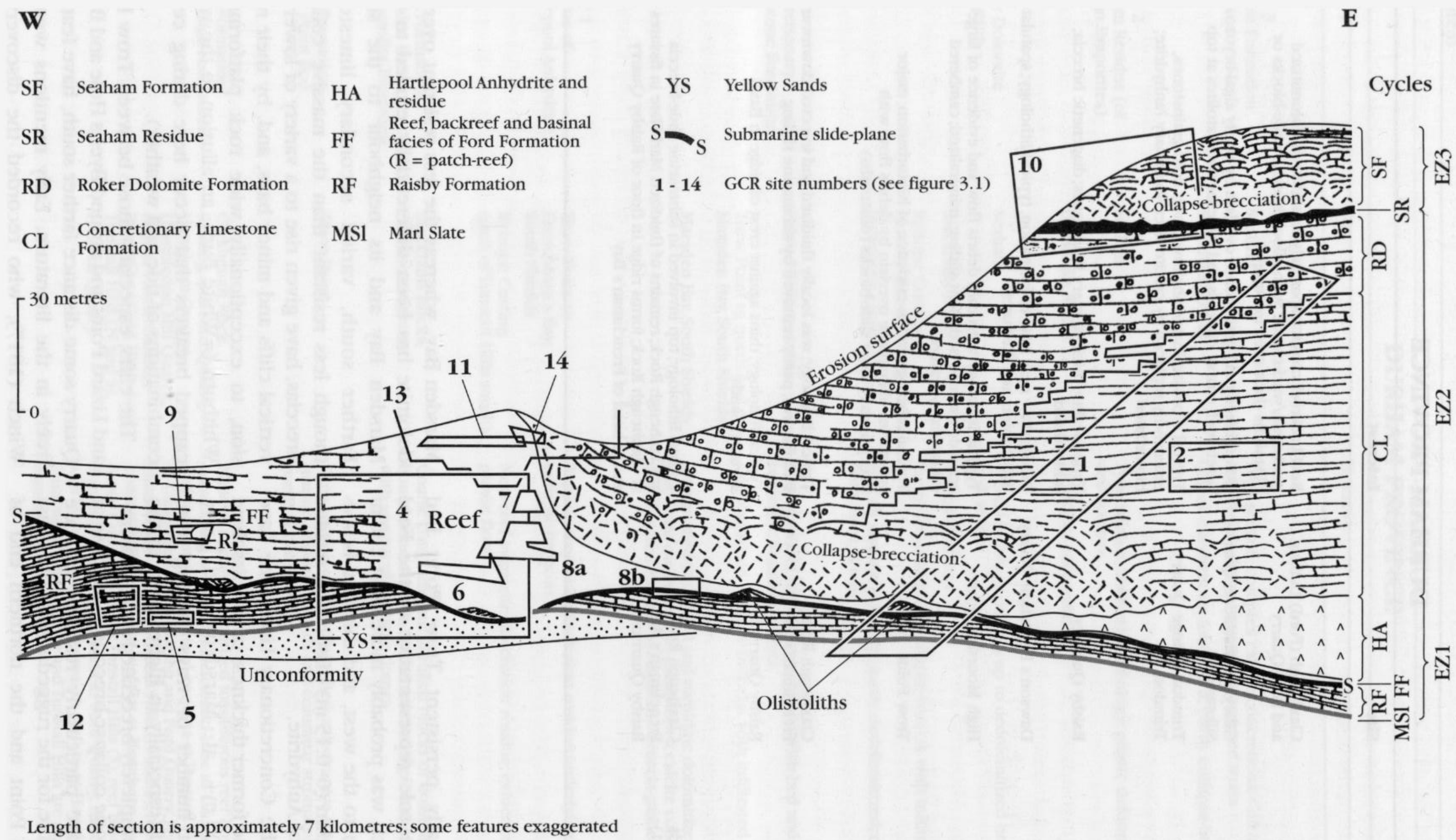


Figure 3.2 Approximate stratigraphical position of GCR marine Permian sites in the northern part of the Durham Province of north-east England (diagrammatic). Some sites in the southern part of the Durham Province cannot be accommodated on this line of section and have been omitted. The Hartlepool Anhydrite would not normally be present so close to the present coastline but is included for the sake of completeness.

Nichol of flexibility in dolomite laminites in Marsden Bay, and by Sedgwick (1829) who also noted the flexibility and graphically described the rocks there, concentrating on the disturbance and brecciation. Bivalves from Byer's Quarry were figured and/or cited by Howse (1848), King (1850) and Logan (1967) and fish remains were found in Marsden Bay in 1836 or 1837 by Miss Green (Kirkby, 1864; Howse, 1891); Howse briefly described the whole section. Clapham (1863) published analyses of three varied samples from Trow Point, Browell and Kirkby (1866) analysed limestone from Byer's Quarry, and Trechmann (1914) gave analyses of specimens from both these locations. Lebour (1884) reviewed the 'gash-breccias' and Card (1892) investigated the flexibility of dolomite laminites from Hendon and Marsden. The sections from Trow Point to Marsden Bay were then exceptionally fully described and illustrated by Woolacott (1909, 1912), who claimed to recognize evidence of low-angle thrusting, a theme returned to by Trechmann (1954), but this interpretation was not generally accepted and the evidence has been reinterpreted by Smith (1970a, c, 1985a) as more consistent with large-scale submarine slumping and collapse-brecciation. Burton (1911) published details of cavity-fill and chert in the breccias at Trow Point and elsewhere.

More recent works include brief reviews of the collapse-breccias by Hickling and Holmes (1931) and Smith (1972), complete geological map coverage on a scale of 1:10560 (Smith, 1975a, b; Land and Smith, 1981, based on fuller notes and scale drawings of all the cliffs and lodged in the fieldnote files of the British Geological Survey), several illustrations and interpretative drawings of strata at Trow Point and in Marsden Bay by Pettigrew (1980) and detailed analyses of a number of rocks from Trow Point and near the Grotto in Marsden Bay by Al-Rekabi (1982). Lastly, Braithwaite (1988) published photomicrographs of samples from near the Grotto and from nearby Marsden Hall Quarry, and discussed the origin of many of the secondary (diagenetic) features in the Concretionary Limestone exposed there. All the northern exposures have also been visited repeatedly by geological excursion parties and numerous guides and excursion reports have been published by local and national geological societies (e.g. Smith, 1973a).

Description

The scheduled site comprises the steep sea cliffs and rock-shore platforms extending uninterruptedly for about 6.5 km between the north side of Trow Point (NZ 667384), South Shields and The Bents (NZ 409613) at Whitburn (Figure 3.3). For the purposes of description it is convenient to divide the site into several sectors, which are described from north to south and the rocks in the order in which they are encountered; summaries of the geology of key parts of these sectors were given by Smith (1975a, b).

Sector 1: Trow Point to Frenchman's Bay, inclusive (Figure 3.4)

Despite great lateral variation, these cliffs display a broadly uniform sequence that has been described partly or wholly by Woolacott (1909), Trechmann (1954), Smith (1970a, c, 1973a) and Land and Smith (1981); the sequence is shown below:

	Thickness (m)
Drift deposits, including boulder clay	up to 6.00
---- unconformity ----	
Concretionary Limestone Formation, mainly brecciated, with much internal sediment (cavity-fill)	up to 11.00
Hartlepool Anhydrite Formation (dissolution residue of)	0–0.15
Ford Formation, Trow Point Bed; peloidal dolomite and dedolomite with oncoids and columnar stromatolites	0–0.60
Raisby Formation, low-slope facies, with disturbed (slumped) beds (0.75–8 m) overlying a discordant slide plane cut into undisturbed beds	0–15.00
Marl Slate (Frenchman's Bay only)	0.10–1.50
Yellow Sands (Frenchman's Bay only)	1.20+

The relationships of the several stratigraphical units are shown diagrammatically in Figure 3.5.

The Concretionary Limestone Formation here mainly comprises a massive, resistant breccia of angular fragments of thinly interbedded laminated and unlaminated calcite mudstone (dedolomite) in

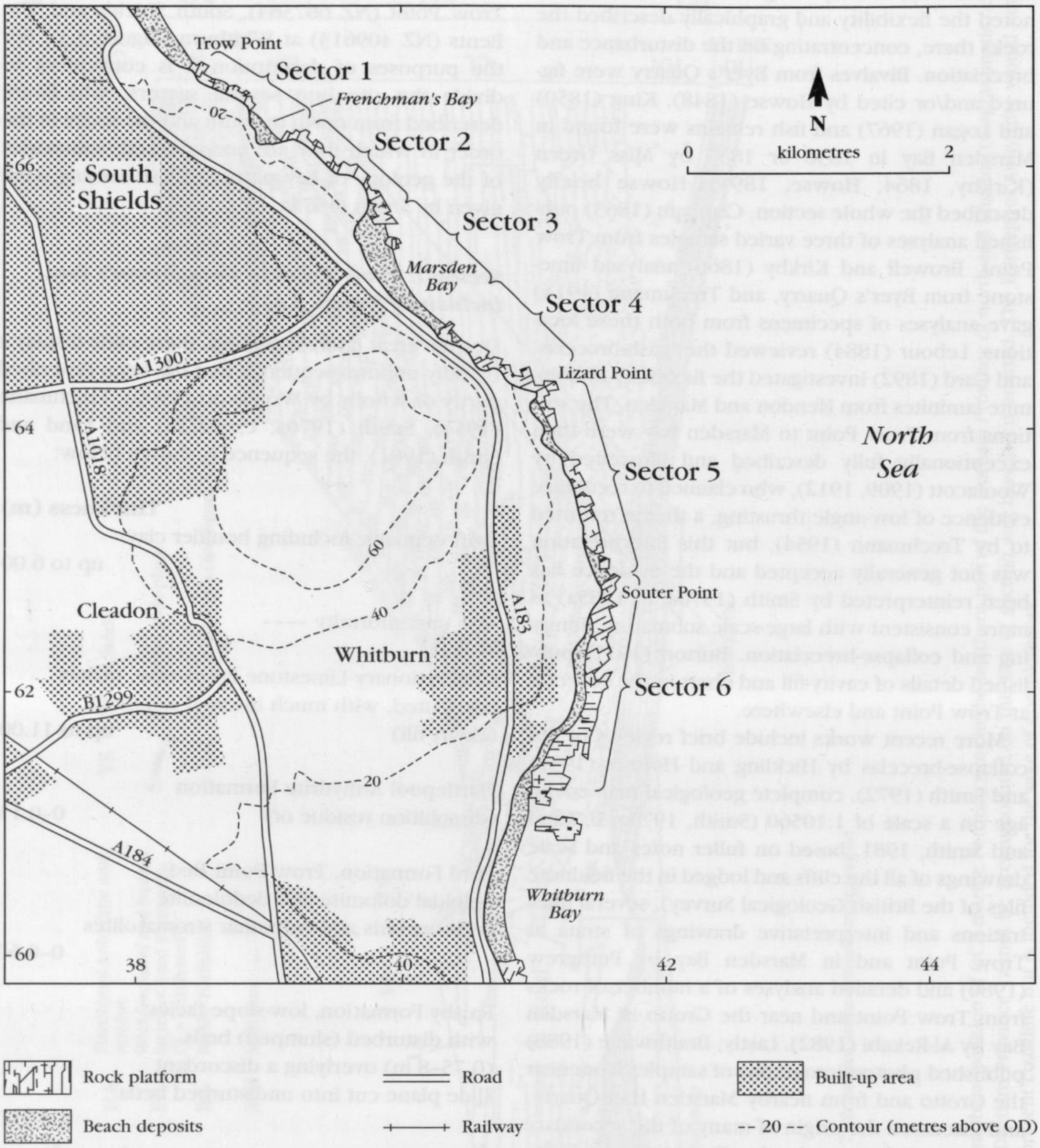


Figure 3.3 Location of the Trow Point to Whitburn Bay GCR site, showing the sectors described in the text.

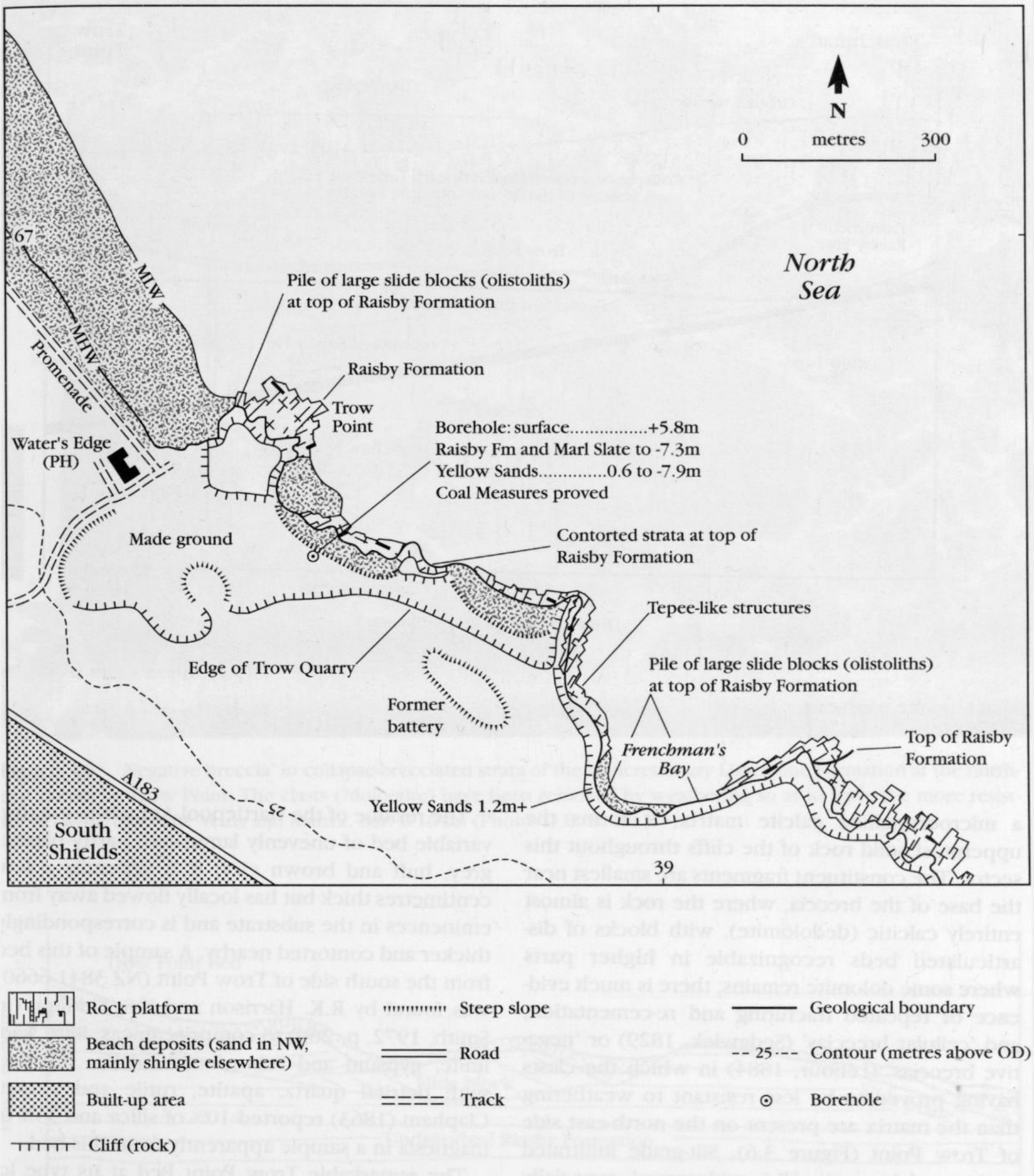


Figure 3.4 The Trow Point to Frenchman's Bay sector, showing the main features of geological interest. In general, strata above high-tide level are collapse-brecciated rocks of the Concretionary Limestone Formation and those below are of the Raisby Formation.

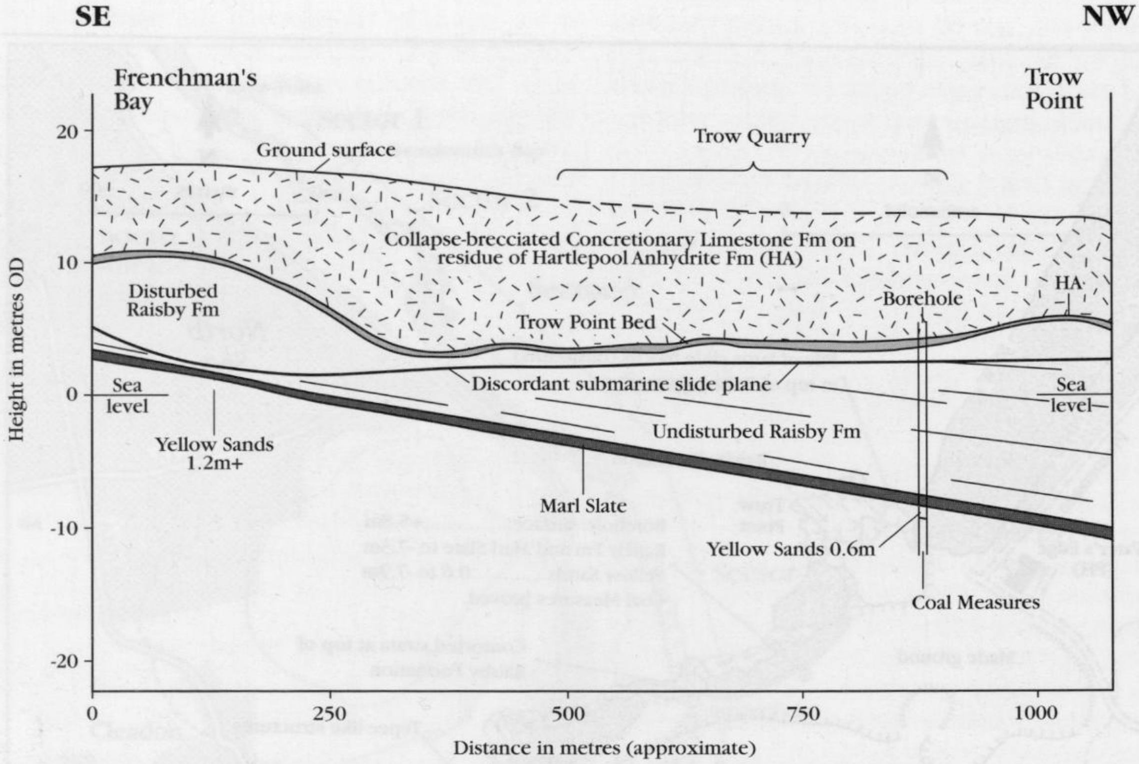


Figure 3.5 Stratigraphical relationships of Permian rock units in the Trow Point to Frenchman's Bay sector, as seen from the north-east.

a microcrystalline calcite matrix; it forms the uppermost solid rock of the cliffs throughout this sector. The constituent fragments are smallest near the base of the breccia, where the rock is almost entirely calcitic (dedolomite), with blocks of disarticulated beds recognizable in higher parts where some dolomite remains; there is much evidence of repeated fracturing and re-cementation, and 'cellular breccias' (Sedgwick, 1829) or 'negative breccias' (Lebour, 1884) in which the clasts having proved to be less resistant to weathering than the matrix are present on the north-east side of Trow Point (Figure 3.6). Silt-grade infiltrated laminar calcite cavity-fill is widespread, especially near the base of the breccia, and contains clasts of detached roof-rocks; the fill bears abundant evidence of intermittent accumulation punctuated by episodes of contortion, tilting and brecciation. The well-documented report of grains of the Yellow Sands in cavity-fill at Trow Point (Burton, 1911) cannot now be verified but is puzzling in view of the known depth of at least 13 m to the top of the 0.6 m Yellow Sands Formation there.

The residue of the Hartlepool Anhydrite is a thin variable bed of unevenly laminated, partly plastic, grey, buff and brown clay; it is generally a few centimetres thick but has locally flowed away from eminences in the substrate and is correspondingly thicker and contorted nearby. A sample of this bed from the south side of Trow Point (NZ 3841 6660) was found by R.K. Harrison and K.S. Siddiqui (in Smith, 1972, p. 260) to comprise micas, illite, kaolinite, gypsum and subordinate calcite, together with detrital quartz, apatite, rutile and zircon; Clapham (1863) reported 10% of silica and 35% of magnesia in a sample apparently from this bed.

The remarkable Trow Point Bed at its type locality has been described in detail by the writer (Smith, 1986). It comprises up to 0.6 m of buff dolomite with subordinate grey limestone (dedolomite), and drapes the underlying hummocky substrate (Figure 3.7) with primary dips of up to 40° and a local relief at Trow Point of about 3 m; in the sector as a whole, its relief relative to the base of the Raisby Formation is at least 14 m. The deposit commonly comprises two beds and is thickest in

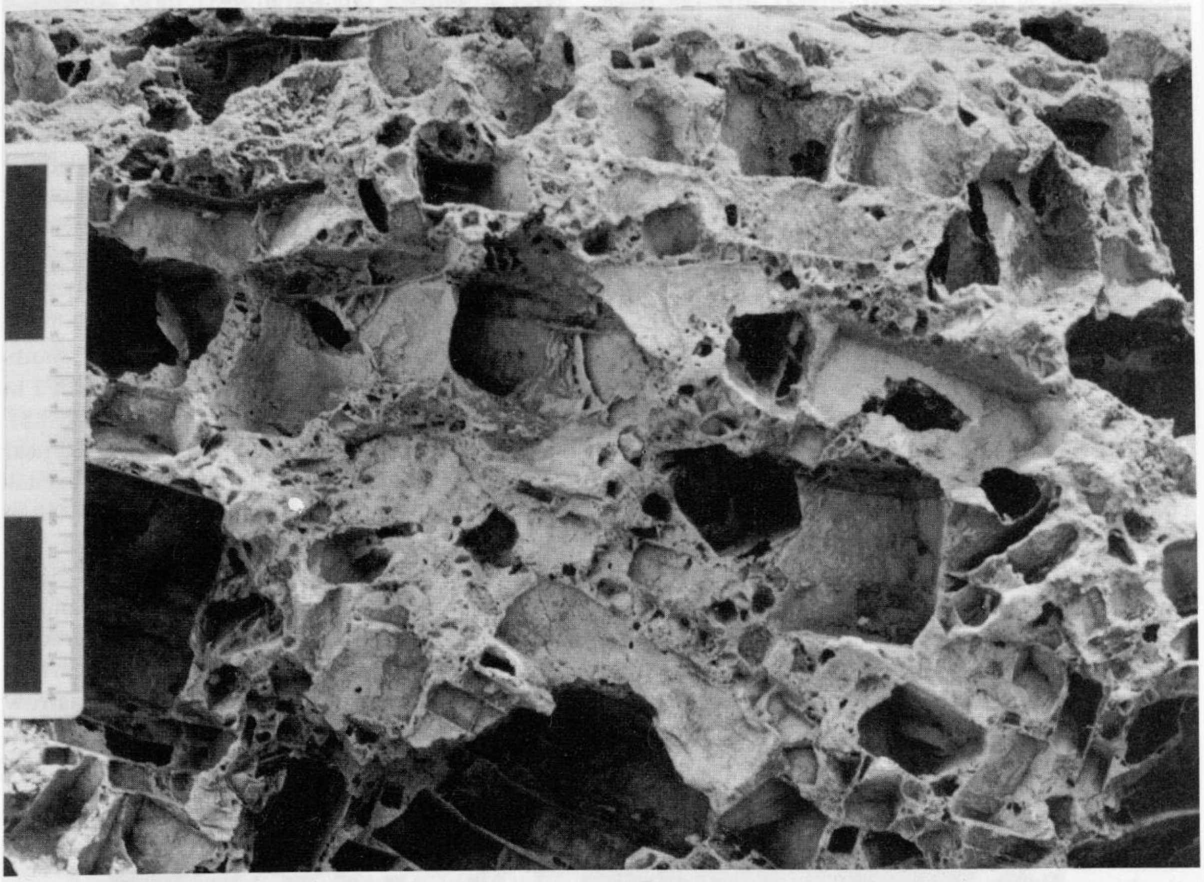


Figure 3.6 'Negative breccia' in collapse-brecciated strata of the Concretionary Limestone Formation at the north-east corner of Trow Point. The clasts (?dolomite) have been removed by weathering so as to leave the more resistant network of calcite veins and matrix. Bar: 0.16 m. (Photo: D.B. Smith.)

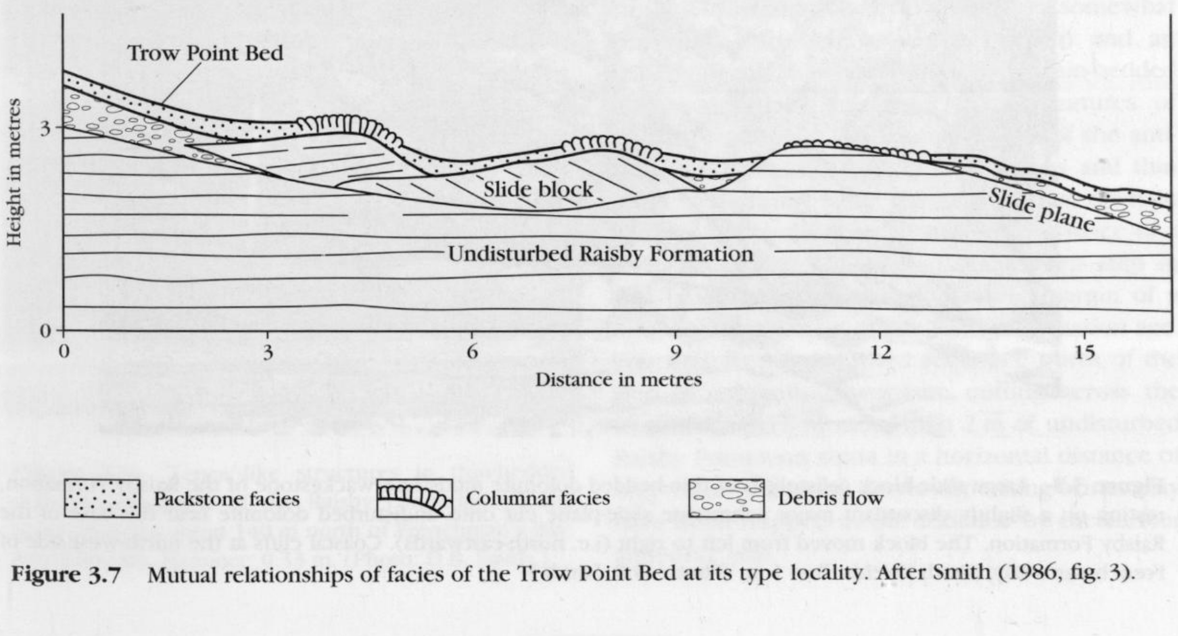


Figure 3.7 Mutual relationships of facies of the Trow Point Bed at its type locality. After Smith (1986, fig. 3).

the hollows where it is mainly an unsorted or poorly-sorted peloid-oncoid packstone; intervening eminences bear one or, more commonly, two layers of radial arrays of narrow (0.01–0.05 m) columnar stromatolites individually up to 0.15 m tall. The packstones contain up to 2% of quartz silt and fine sand and a restricted marine assemblage of foraminifera and ostracods.

The Raisby Formation comprises a disturbed sequence up to about 8 m thick and an underlying undisturbed sequence up to about 11 m thick. The disturbed sequence is extremely varied in thickness, and, where thickest (as at Trow Point and along the south side and head of Frenchman's Bay) is composed of large slide-blocks (many contorted) of buff thin-bedded dolomite lying on a discordant surface interpreted as a major synsedimentary submarine slide plane (Smith, 1970c) (Figure 3.8). Pockets between, beneath and above the slide-blocks are filled with an unsorted mixture of dolomite clasts in a vuggy (i.e. containing many small cavities) dolomite matrix, and similar rock, with scattered slide-blocks or olistoliths, forms a single continuous bed commonly 0.6–1.5 m thick in the cliffs between Trow Point and Frenchman's Bay (Smith, 1970c, plate 2, fig. 2; Pettigrew, 1982, plate 7). The largest slide-block seen by the writer is at the head of Frenchman's Bay and measures about 72 m long and 7.5 m thick; it was also noted by Woolacott (1909, figs 2, 12) and Trechmann (1954, fig. 5), who both interpreted it as a thrust mass. Other slide-blocks, including that illustrated by Pettigrew (1982, fig. 12), contain up to 6.5 m of deformed Raisby Formation strata.

Undisturbed Raisby Formation strata beneath the disturbed sequence have been proved by a borehole (NZ 3847 6652) to be thickest near Trow Point, but they are cut out progressively south-eastwards by the slide plane and are less than 1 m thick at the head of Frenchman's Bay (Figure 3.5). Upper beds, about 5 m of which are exposed near Trow Point, are cream and buff, very finely crystalline dolomites in slightly uneven beds 0.05–0.2 m thick; many feature abundant evidence of bioturbation. The rocks contain small bioclasts, including foraminifera, bivalves, crinoid columnals and obscure plant remains, and also scattered to abundant oval to irregular calcite-lined cavities after former anhydrite; Lee (1990) noted narrow calcitized zones around these cavities. Trechmann

Figure 3.8 Large slide-block (olistolith) of thin-bedded dolomite mudstone/wackestone of the Raisby Formation, resting on a slightly discordant major submarine slide-plane cut onto undisturbed dolomite near the base of the Raisby Formation. The block moved from left to right (i.e. north-eastwards). Coastal cliffs at the north-west side of Frenchman's Bay, South Shields. Bar: 1 m. (Photo: D.B. Smith.)

(1914, p. 245) analysed a sample of the Raisby Formation from Trow Point and reported a dolomite content of 97.19%, and Lee (1990) determined the isotopic composition of secondary limestone from near the top of the formation and found it to be closely comparable with that in the overlying collapse-breccias. Lower beds of the Raisby Formation are exposed progressively southeastwards, where there is less evidence of bioturbation, fewer cavities, and local traces of graded bedding. Unusual features include tepee-like structures up to 0.5 m high on the shore platform (NZ 3888 6631) about 140 m north of Frenchman's Bay (Figure 3.9) and a complex of low-angle intersecting minor movement planes in the cliff (NZ 3886 6629) slightly farther south (Smith, 1994, plate 4); these terminate sharply upwards at the base of the disturbed beds, here only a few metres above the base of the formation.

Marl Slate is exposed periodically around much of Frenchman's Bay, depending on beach accumulations and rockfalls; it is up to 1.5 m thick on the south side of the bay but thins to 0.1–0.3 m at the head of the bay where onlap against a ridge of Yellow Sands is apparent, and is up to 0.8 m thick in the north of the bay. It is a dark grey pyritic finely laminated argillaceous dolomite, with a thin dolomite bed near the top, and abundant fish scales.

Figure 3.9 'Tepee'-like structures in thin-bedded dolomite mudstone of the Raisby Formation on the shore platform about 140 m north of Frenchman's Bay, South Shields. Hammer: 0.33 m. (Photo: D.B. Smith.)

The oldest Permian rocks of this sector are the early Permian Yellow Sands, which lie at the foot of the cliffs at the head of Frenchman's Bay and form a ridge up to 1.2 m high; their base is not exposed. The sands are of normal lithology for this formation and cross-bedding is inclined mainly northwards; only the uppermost 5–10 cm of the formation is cemented.

Sector 2: Frenchman's Bay to Velvet Beds (Figure 3.10)

The general rock sequence in this 800 m sector is similar to that in Frenchman's Bay, but the Yellow Sands and Marl Slate lie below beach level and the uppermost few metres of the Raisby Formation are exposed only in the north and in a small sharp anticline 200–300 m farther south-east (Land and Smith, 1981). Collapse-brecciated, largely dedolomitized Concretionary Limestone up to 10.5 m thick makes up most of the cliffs in the sector, and has been sculpted into a range of rugged shapes including natural arches; breccias similarly make up the low promontory of Velvet Beds, named after the fine quality of grass formerly present on the thin drift capping.

The most complete sequence in this sector lies in the small anticline, where the dissolution residue of the Hartlepool Anhydrite lies immediately beneath the collapse-breccia and is up to 15 cm thick. The Trow Point Bed, here 0.05–0.60 m thick, is mainly oncoidal but includes ooidal dolomite and unusually narrow columnar stromatolites; in the northern limb of the anticline it cloaks the hummocky upper surface (relief 1.5 m) of the Raisby Formation that here comprises a somewhat enigmatic disturbed sequence (1–4 m) and an underlying undisturbed sequence of thin-bedded finely crystalline dolomites (5 m). Features of unusual interest in the southern limb of the anticline are widespread replacive patches and thin veins of pink and white baryte and some chert in all beds below the residue, and the presence of a well-marked, SSE-facing, 4 m high, steep step in the Trow Point Bed that may be a margin of a minor slump canyon of late Raisby Formation age. The base of the disturbed sequence north of the step is unusually discordant, cutting across the truncated edges of more than 2 m of undisturbed Raisby Formation strata in a horizontal distance of only 10 m. The rising baryte-depositing brines may have been trapped in the anticline by the former anhydrite seal.

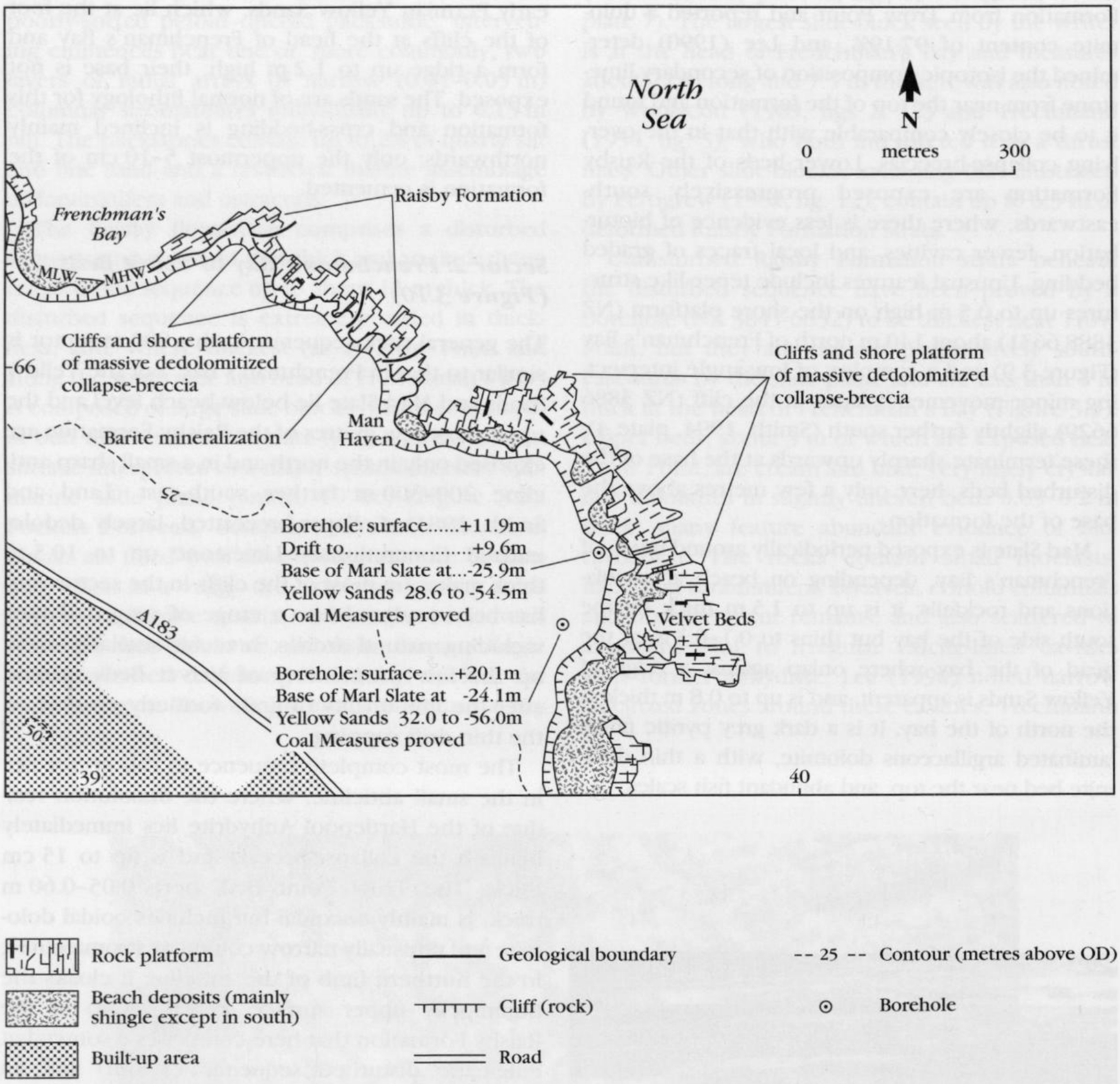


Figure 3.10 The Frenchman's Bay to Velvet Beds sector, showing the main features of geological interest. Except in Frenchman's Bay and in an anticline *c.* 100–200 m north of Man Haven, all the strata are collapse-brecciated rocks of the Concretionary Limestone Formation.

Sector 3: Marsden Bay (Velvet Beds to Marsden Rock) (Figure 3.11)

The broad sweeping curve of Marsden Bay is backed by 15–30 m subvertical cliffs cut in foundered lower strata of the Concretionary Limestone Formation. The response to foundering was extremely varied, with severely collapse-brecciated rocks dominating the northern and southern flanks of the bay and with less dislocated and less altered rocks in the middle. Strata below the so-called 'Flexible Limestone', including the collapse-breccias, were traditionally classified as 'Post-reef Middle Magnesian Limestone' (i.e. Ford Formation) but were reclassified as part of the Concretionary Limestone Formation following detailed mapping and the discovery of a typical Cycle EZ2 fauna in turbidite lags well below the 'Flexible Limestone' (Smith, 1971a).

The disposition of strata in Marsden Bay was dramatically illustrated by Woolacott (1909, plate 2, fig. 8), partly reproduced here as Figure 3.12; drift,

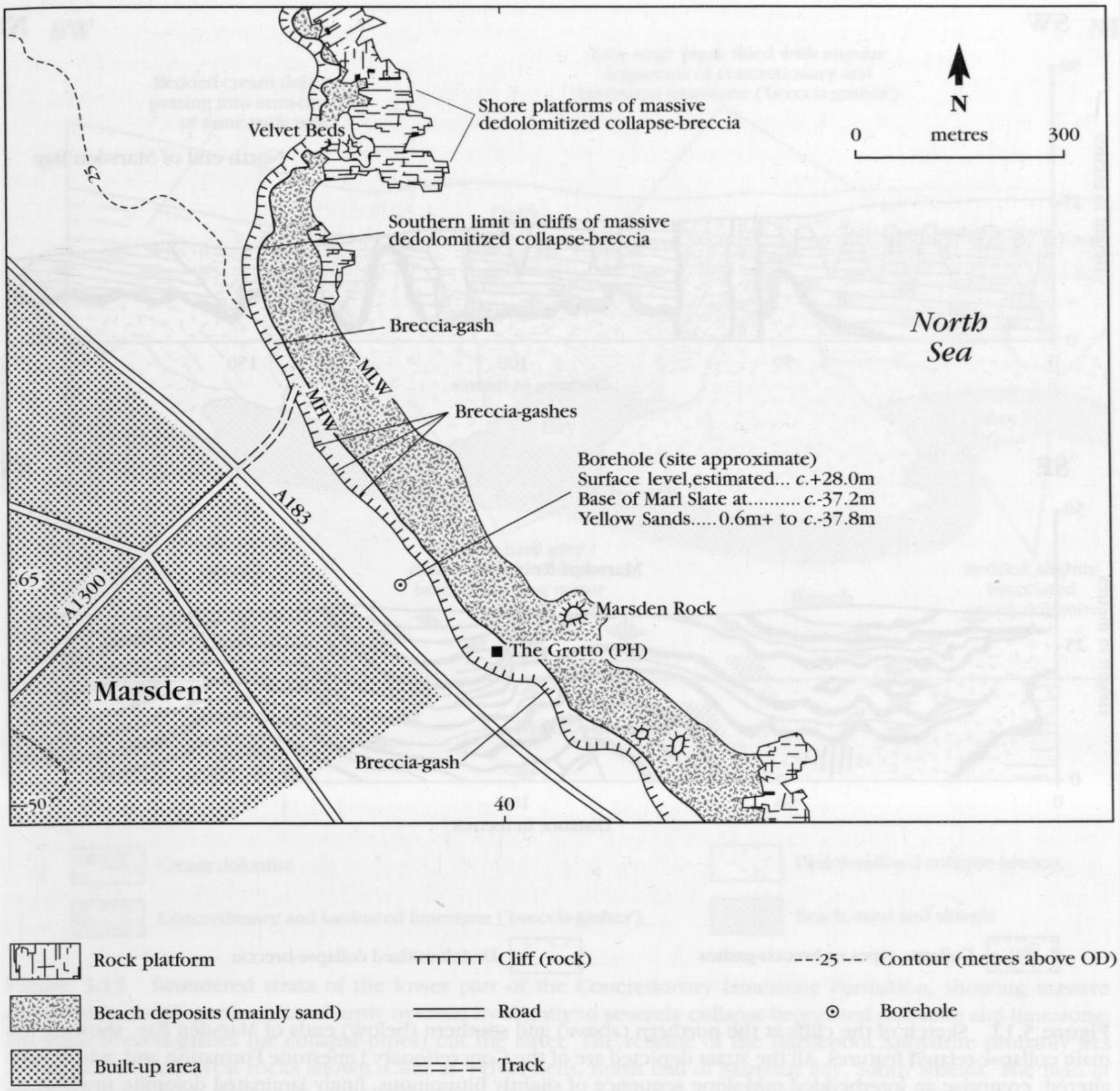


Figure 3.11 The Velvet Beds to Marsden Rock sector, showing the main features of geological interest. All exposed solid strata are of the Concretionary Limestone Formation.

not shown by Woolacott, is generally less than 2 m thick and is a sparingly pebbly silty deposit known locally as the Pelaw Clay.

Massive, dedolomitized collapse-breccias like those between Trow Point and Velvet Beds continue southwards into the north flank of the bay, with the top of the Raisby Formation lying an estimated 5–15 m below beach level at Velvet Beds and the top of the Yellow Sands lying at 24.1 m below Ordnance Datum at the site of the nearby Harton Borehole (NZ 3966 6564). Strata on average dip gently south-eastwards and the sharp and jagged top of the collapse-breccias gradually declines below beach level; the breccias are overlain by about 54 m of cream, buff and grey dolomites and limestones that have been variably dislocated and contain many late-stage 'breccia-gashes' (Figure 3.13) filled with fragments of host rocks and of strata now otherwise eroded off. The most spectacular breccia-gashes are a few metres across and have vertical sides, but some are much larger and have been involved in complex multi-stage foundering and brecciation; the gashes are circular, linear or cruciform in plan.

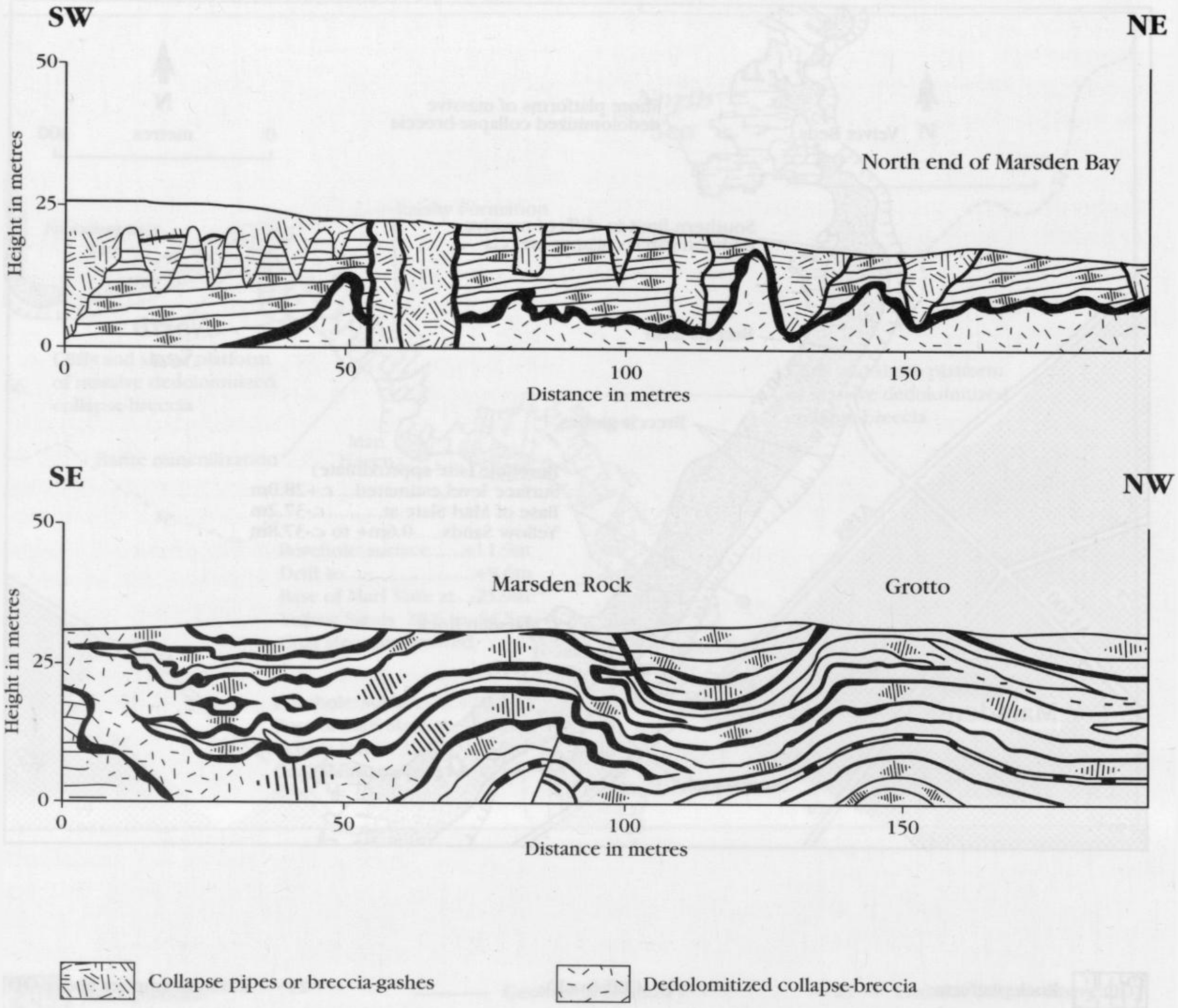


Figure 3.12 Sketch of the cliffs at the northern (above) and southern (below) ends of Marsden Bay, showing the main collapse-related features. All the strata depicted are of the Concretionary Limestone Formation and, where least altered, comprise an interbedded mid-slope sequence of slightly bituminous, finely laminated dolomite mudstones, and sparingly fossiliferous turbiditic and/or slumped dolomite packstones and grainstones. Where severely altered, much of the rock is a hard crystalline secondary limestone (dedolomite). Sketch after Woolacott (1909, plate 2). See Figure 3.13 for detailed distribution of rock types near Velvet Beds.

Least altered and least-brecciated rocks in Marsden Bay comprise a thinly interbedded sequence of plane-laminated dolomite mudstones and dolomite wackestones, packstones and grainstones. The laminites comprise couplets (commonly 15–25 per centimetre), each composed of a carbonaceous film and a thicker dolomite mudstone layer; they contain no shelly fauna but fish remains were recorded (Kirkby, 1864; Howse, 1891) from the 'Flexible Limestone' here, a particularly finely laminated 3–4 m bed that first appears high in the cliff in the northern part of the bay and dips below the beach south of the Grotto (Figure 3.12). Most of the unlaminated beds are a few millimetres to a few centimetres thick and are of silt-grade dolomite; some are graded or reverse-graded. Other unlaminated beds are up to 4 m thick, and comprise dolomite packstones and grainstones (at least some ooidal) that feature a wide range of overfolds, contortions and shear-planes and commonly overlie a slightly discordant erosion surface or slide-plane; some of these thicker units have a basal lag concentrate of gastropods, bivalves and ostracods. Lenses of chert are not

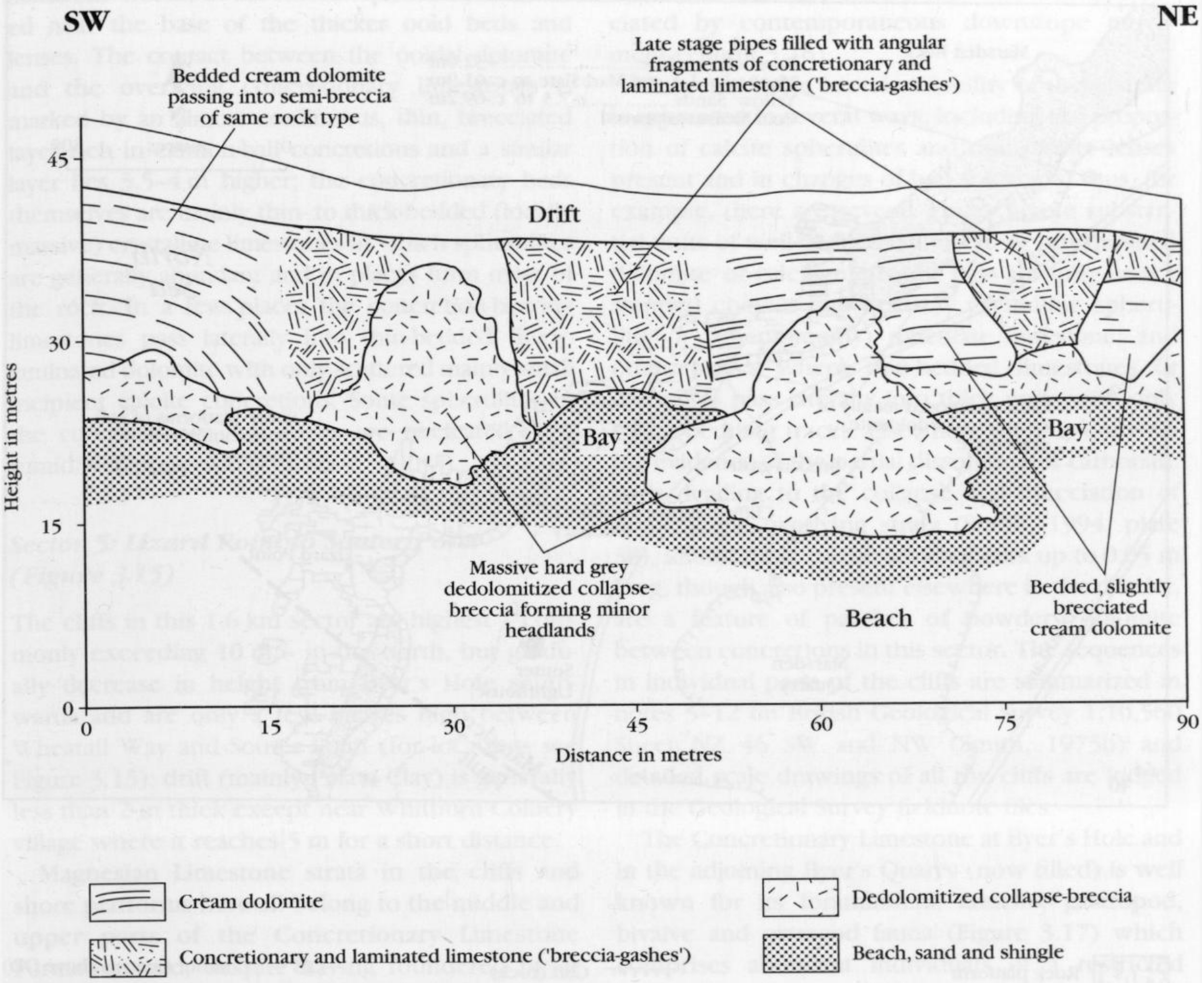


Figure 3.13 Foundered strata of the lower part of the Concretionary Limestone Formation, showing massive dedolomitized collapse-breccias sharply overlain by slightly to severely collapse-brecciated dolomite and limestone; late-stage breccia-gashes (or collapse-pipes) cut the latter. The residue of the Hartlepool Anhydrite probably lies 2–5 m below the lowest rocks shown. Cliffs at Velvet Beds, north end of Marsden Bay, South Shields. The field of view lies near the northern end of the cliffs shown in Figure 3.12 (upper section). After Smith (1994).

uncommon, and irregular to ovoid cavities after former replacive and displacive anhydrite are widespread and locally abundant.

In addition to passing laterally into collapse-breccias, all the dolomite rocks locally pass laterally into secondary, grey or brown, crystalline limestone, which also forms a thick concretion-rich bed high in the cliffs in the northern part of the bay and forms much of the cliff and parts of the stacks near the Grotto.

Sector 4: Marsden Rock to Lizard Point (Figure 3.14)

The geology of this 1.1 km sector of the GCR site is poorly documented in the literature, but the north-western end was included in Woolacott's (1909) drawing of strata in Marsden Bay and the whole sector was summarized by the writer (Smith, 1975a) in notes 1–5 on Geological Survey 1:10,560 Sheet NZ 46 SW; drawings and more detailed descriptions are in the fieldnote files of the British Geological Survey. The subvertical cliffs are generally 15–25 m high but locally approach 30 m, and drift (mainly Pelaw Clay) is generally 0.5–1.5 m thick.

The sequence in the north-western part of the sector is a continuation of that in Marsden Bay, with partly to severely dislocated collapse-brecciated laminated and unlaminated cream dolomites and

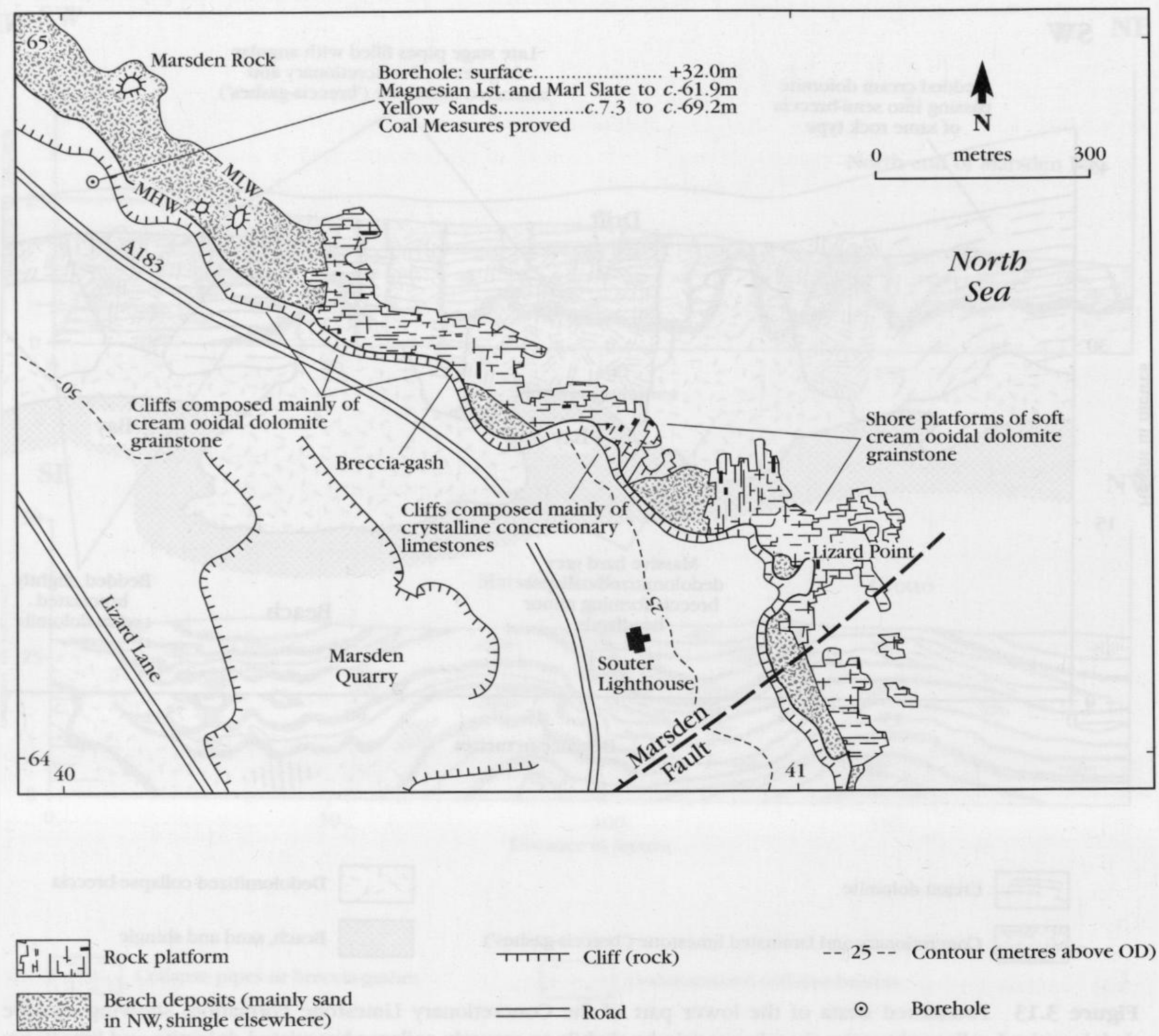


Figure 3.14 The Marsden Rock to Lizard Point sector, showing the main features of geological interest. All exposed solid strata are of the Concretionary Limestone Formation. For further details of strata see British Geological Survey 1:10,560 Sheet NZ 46 SW.

grey to brown secondary limestones forming most of the cliffs; sparingly shelly, vaguely bedded, dolomite ooid packstones/grainstones, however, form the basal few metres of a relatively undisturbed sequence from about 130 to 200 m south-east of the Grotto.

Rocks forming the cliffs in most of the central and southern parts of the sector mainly comprise up to 20 m of vaguely-bedded to massive, altered dolomite ooid packstones/grainstones, but these are overlain by concretionary limestones from about 600 to 725 m north-west of Lizard Point. These limestones reappear at the cliff top about 400 m north-west of Lizard Point and dip gently south-eastwards so as gradually to form the whole cliff; they are at least 14 m thick. The packstones and grainstones are divisible into a variable lower unit in which they are unevenly coarsely interbedded with discontinuous sheets and lenses (?rafts) of laminated dolomite mudstone (some contorted and sheared), and a more uniform 9 m upper unit. Both units contain scattered to abundant bivalves, gastropods and ostracods which, in the lower unit, are concentrated near the base of the thicker ooid beds and lenses. The contact between the ooidal dolomite and the overlying concretionary limestones is marked by an almost continuous, thin, brecciated layer rich in cannon-ball concretions and a similar layer lies 3.5–4 m higher; the concretionary beds themselves are mainly thin- to thick-bedded (locally massive) crystalline limestones in which spherulites are generally abundant and in places form most of the rock. In a few places the concretion-bearing limestones pass laterally into thin-bedded finely-laminated dolomite with only scattered mainly small incipient calcite concretions. Some spherulites in the concretionary limestones are nucleated onto tumid well-preserved bivalves.

Sector 5: Lizard Point to Souter Point (Figure 3.15)

The cliffs in this 1.6 km sector are highest - commonly exceeding 10 m - in the north, but gradually decrease in height from Byer's Hole southwards and are only a few metres high between Wheatall Way and Souter Point (for locations see Figure 3.15); drift (mainly Pelaw Clay) is generally less than 2 m thick except near Whitburn Colliery village where it reaches 5 m for a short distance.

Magnesian Limestone strata in the cliffs and shore platforms here all belong to the middle and upper parts of the Concretionary Limestone Formation and, despite having foundered by at least 100 m through the dissolution of the Hartlepool Anhydrite, are mainly structurally simple and only locally collapse-brecciated; north of the Lizards Fault they comprise a gently rolling strike sequence totalling perhaps 20–25 m thick but an additional 10–15 m of strata may be present to the south of the fault. Cliffs in the most northerly 150 m of the sector, at and immediately south of Lizard Point, are almost entirely of thin-bedded to massive crystalline limestone (mainly spherulitic), and thick-bedded to massive spherulitic limestone forms the cliffs at Souter Point and for about 100 m to the north. Between these stretches the cliffs are mainly composed of a laterally variable interbedded sequence of unlaminated and laminated mainly thin-bedded grey limestone, grey and brown (locally red and black) spherulitic limestone and lenticular to relatively persistent thick beds of cream finely crystalline to powdery dolomite (some possibly of altered oolite); most of the latter, and many of the thick unlaminated limestone beds, have been weakly to strongly contorted and locally brecciated by contemporaneous downslope movement (Figure 3.16).

The remarkable lateral variability of these strata is expressed in several ways, including the proportion of calcite spherulites and thin calcite lenses present and in changes of bed thickness; thus, for example, there are several places where substantial units of well-bedded laminated or unlaminated dolomite- or calcite-mudstone pass abruptly or at a stepped contact into coarsely crystalline spherulitic or (uncommonly) reticulate limestone, and other places where thin-bedded limestones or dolomites pass laterally into thick units with only vague bedding traces. Elsewhere there is convincing evidence of the partial dissolution of carbonate beds, leading to the collapse and brecciation of immediately overlying strata (Smith, 1994, plate 30). Idiomorphic calcite scalenohedra up to 0.05 m long, though also present elsewhere in the district, are a feature of patches of powdery dolomite between concretions in this sector. The sequences in individual parts of the cliffs are summarized in notes 5–12 on British Geological Survey 1:10,560 Sheet NZ 46 SW and NW (Smith, 1975b) and detailed scale drawings of all the cliffs are lodged in the Geological Survey fieldnote files.

The Concretionary Limestone at Byer's Hole and in the adjoining Byer's Quarry (now filled) is well known for its foraminifera, annelid, gastropod, bivalve and ostracod fauna (Figure 3.17) which comprises abundant individuals of a restricted range of species; well-preserved remains of plants have also been reported (Trechmann, 1914). The fauna was noted and listed by Howse (1848, 1858), King (1850), Kirkby (1858), Trechmann (in Woolacott, 1912), Logan (1967), Pattison (Geological Survey internal reports 1967; 1977) and Pettigrew (1980); both King and Logan figured several specimens from here, including some designated as types or syntypes. Additionally, King (followed by Logan who used many of King's specimens) cited 'Souter Point, Marsden' as a bivalve source locality, though it is possible that he meant Lizard Point. Howse (1848) noted the exceptional preservation of bivalve shells at Byer's Quarry, where the original shell has been replaced by crystalline calcite, in contrast to most Magnesian Limestone fossils which are known only from casts; Kirkby (1858) noted that the ostracods, too, are locally exceptionally well-preserved and abundant (see also Pettigrew, 1980, plate 13).

Analyses of grey limestones from Byer's Quarry (Browell and Kirkby, 1866; Woolacott, 1912;

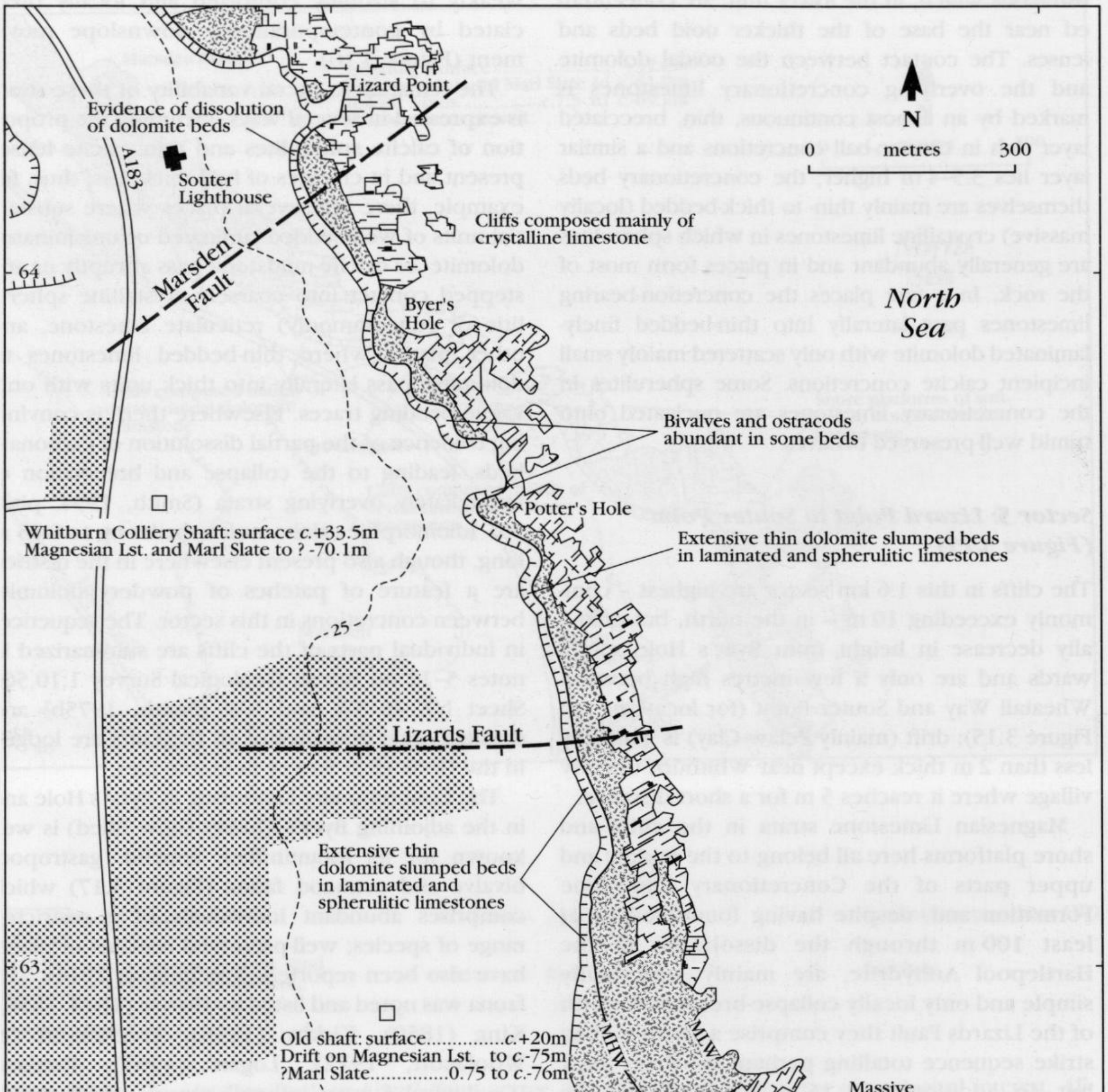


Figure 3.15 The Lizard Point to Souter Point sector, showing the main features of geological interest. All exposed solid strata are of the Concretionary Limestone Formation. For further details of strata see British Geological Survey 1:10,560 Sheet NZ 46 SW.

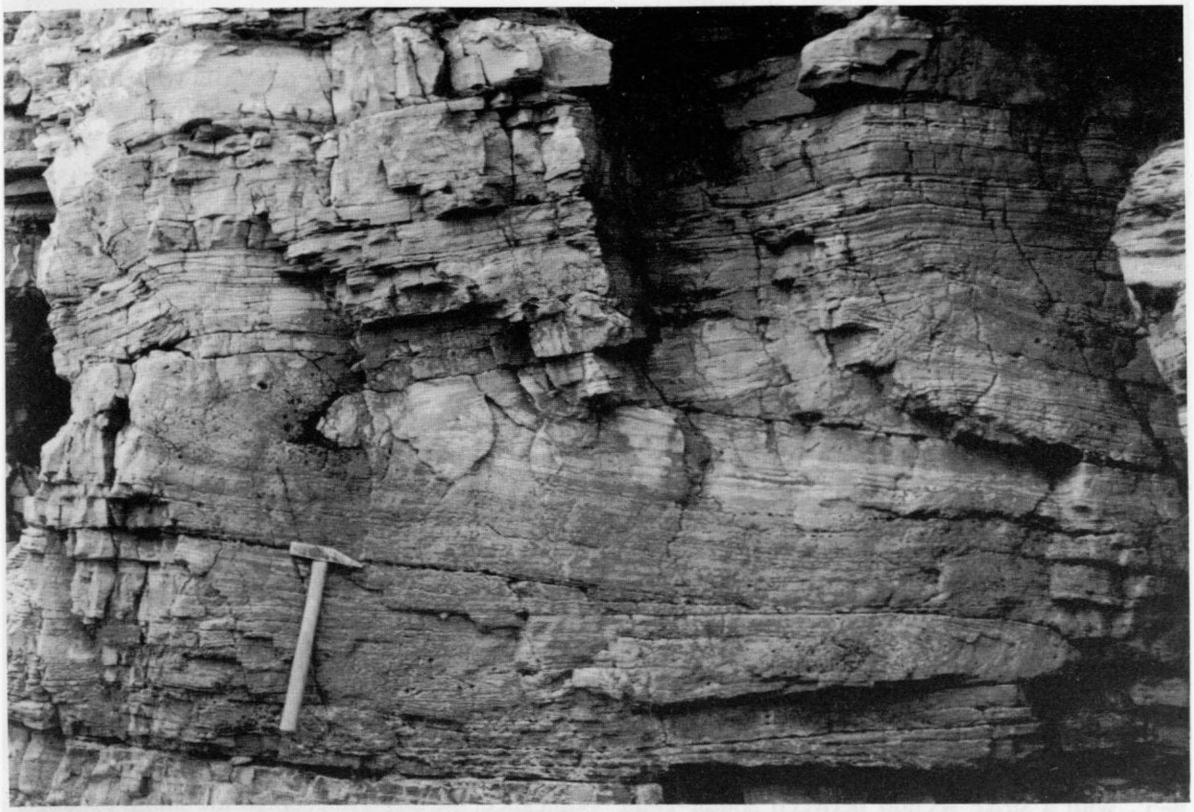


Figure 3.16 Tight slump folds in high-slope thin-bedded calcite mudstones of the Concretionary Limestone Formation. Coastal cliffs *c.* 500 m south of Potter's Hole, Whitburn Colliery. Hammer: 0.33 m. Reproduced by permission of the Director, British Geological Survey: NERC copyright reserved (NL 138).

Figure 3.17 *Kirkbya permiana* (Jones), a typical ostracod from high-slope calcite mudstones of the Concretionary Limestone Formation. Top of coastal cliffs on the south side of Byer's Hole, Whitburn Colliery. Bar: 0.43 mm. (Photo: Sunderland Museum TWCMS: P1004.)

Trechmann, 1914) show that they are amongst the purest limestones in the area, with calcium carbonate contents ranging from 96.94 to 98.04% (three analyses); an interbedded brown friable bed analysed by Trechmann had a calculated composition of 93.2% of dolomite and 5.8% of calcite.

Sector 6: Souter Point to Whitburn Bay (Figure 3.18)

The cliffs in this most southerly sector (1.6 km) of the Trow Point to Whitburn Bay site are generally 6–10 m high, of which drift forms the uppermost 2–3 m from Souter Point to about 150 m north of White Steel; the drift then thickens gradually southwards so as to form the whole of the cliff from a point about 250 m north-east of The Bents. The thin drift in most northern parts of the sector is mainly of the sparingly stony Pelaw Clay but that in the south also includes Durham Lower Boulder Clay and interbedded laminated clay and sand and features widespread and locally intense contortion and involution (Smith, 1981c, fig. 6).

Foundered Magnesian Limestone strata in this sector are structurally and lithologically more varied than in the sector to the north but are similarly gently rolling; dip is generally eastwards at perhaps 3–5°, with a strike section between Souter Point and Rackley Way Goit passing southwards into a broad shallow apparent syncline with its axis about 50 m south of White Steel. Breccia-gashes occur at intervals throughout the sector and, together with several minor faults, are particularly well-exposed in the cliffs and wide shore platforms in the south of the sector (see Geological Survey 1:10,560 Sheet NZ 46 SW and notes and scale drawings in British Geological Survey fieldnote files).

Strata in the strike section north of Rackley Way Goit are probably about 12–15 m thick and belong to the upper part of the Concretionary Limestone Formation; they are lithologically and faunally similar to those exposed in the sector to the north and display comparably extreme lateral and vertical variation. Limestones in the cliffs in the most northerly 450 m of the sector (and locally elsewhere) have been partly to severely brecciated to depths of as much as 4 m below rockhead, probably by Devensian periglacial cryoturbation; drift erratics are mixed with angular limestone debris in the uppermost metre or so of this brecciated sequence.

Strata in the apparent syncline south of Rackley Way Goit total perhaps 20 m and may belong partly or wholly to the Roker Dolomite Formation. They are mainly of thin- to thick-bedded porous, cream, saccharoidal dolomite (probably mainly altered oolite) and include a spectacular basal 5 m bed packed with mutually-interfering 0.05–0.25 m calcite spheroids; this bed, which could be assigned either to the Concretionary Limestone or the Roker Dolomite, may equate with the famous Cannon-ball Rocks' at Roker, 2.5 km farther south. Highest strata in the sector occupy a breccia-gash at the eastern tip of White Steel (NZ 4133 6192) and include dolomite laminites (?algal stromatolites) and remarkable cellular massive limestones interpreted by Dr G.M. Harwood (pers. comm. 1988) as compressed bivalve coquinas.

The subvertical Hebburn (or Monkton) tholeiite dyke, previously not known to crop out in the coastal area, was discovered in 1993 in the cliffs (NZ 4108 6156) of this sector by Mr G. Fenwick of Sunderland University. The dyke and its effects on the host-brecciated limestone are now being investigated.

Interpretation

The Magnesian Limestone rocks of the Trow Point to Whitburn Bay site together constitute a unique assemblage of exposures of truly international significance; the display of submarine slump products in the most northerly sector ranks high in such features anywhere in Britain, the overlying Trow Point Bed is unique in its extent and its range of mixed coated grains and sessile stromatolites, and the effects of evaporite dissolution on overlying Cycle EZ2 carbonate strata are spectacularly exposed between Trow Point and Lizard Point; where least affected by collapse brecciation, the Cycle EZ2 rocks bear striking evidence of carbonate deposition on an unstable submarine slope. The Yellow Sands, Marl Slate and undisturbed lower beds of the Raisby Formation are normal for those formations and require no special comment.

Disturbed beds of the Raisby Formation

The compelling evidence of lateral movement of large masses of bedded dolomite at the top of the Raisby Formation at Trow Point and in Frenchman's Bay was recognized and illustrated by Woolacott (1909, 1912) and Trechmann (1954), who attributed it to tectonic thrusting and interpreted the underlying plane of discontinuity as a thrust plane. The inferred directions of movement of the displaced masses were inconsistent with regional compressive forces however, as was the

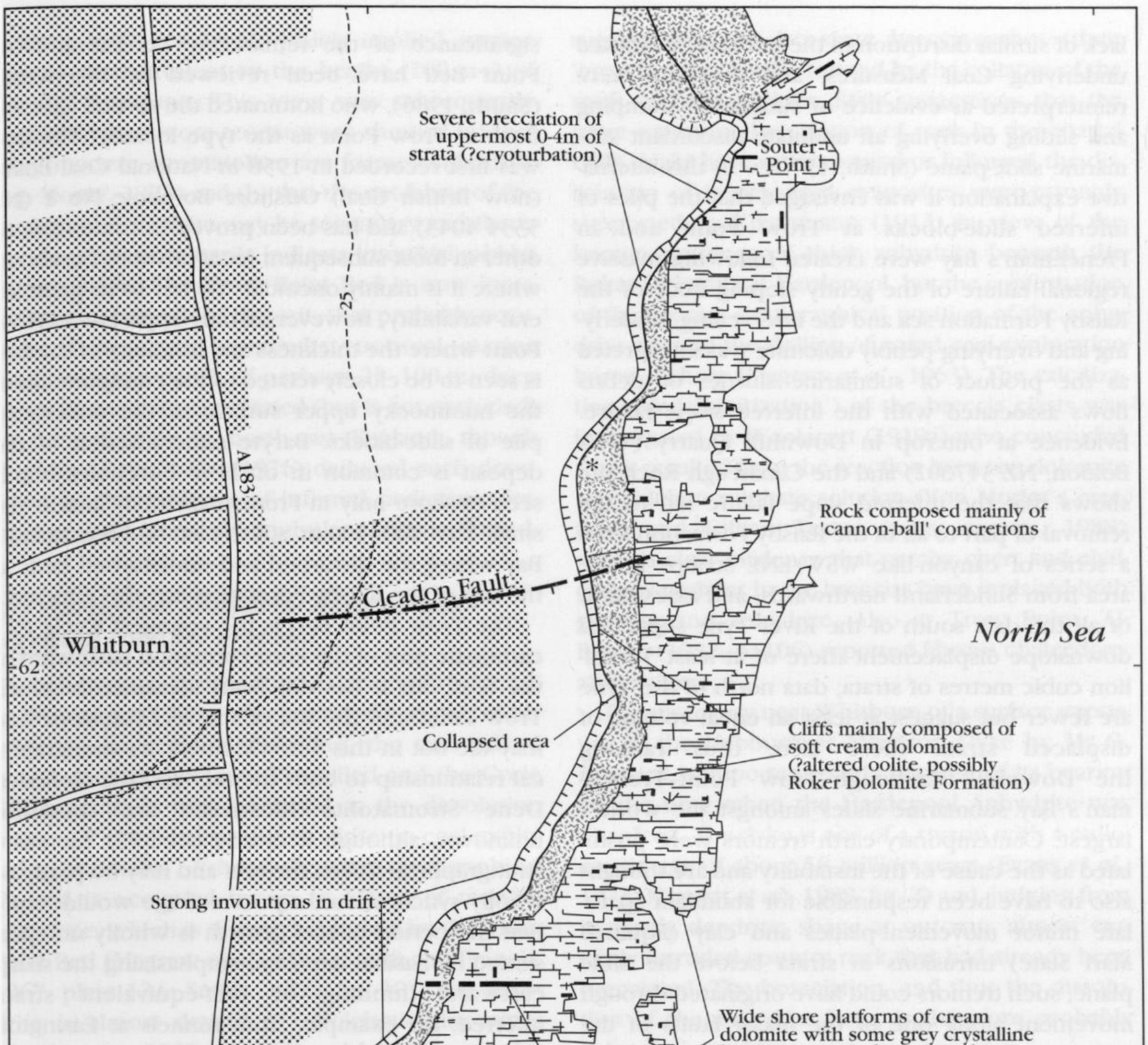


Figure 3.18 The Souter Point to Whitburn Bay sector, showing the main features of geological interest. All exposed strata north of Rackley Way Goit (*) are of the Concretionary Limestone Formation but those to the south may include lower beds of the Roker Dolomite Formation.

lack of similar disruption in the intensively worked underlying Coal Measures, and the data were reinterpreted as evidence of submarine slumping and sliding overlying an undulate discordant submarine slide-plane (Smith, 1970c). In this alternative explanation it was envisaged that the piles of inferred slide-blocks at Trow Point and in Frenchman's Bay were created following massive regional failure of the gently sloping floor of the Raisby Formation sea and the intervening, underlying and overlying pebbly dolomite was interpreted as the product of submarine slurries or debris flows associated with the inferred slope failure. Evidence at outcrop in Downhill Quarry (West Boldon, NZ 347602) and the Claxheugh Rock site shows that the inferred slope failure led to the removal of part to all of the Raisby Formation from a series of canyon-like WSW/ENE scoops in the area from Sunderland northwards, and assessment of all the data south of the River Tyne suggested downslope displacement there of at least 50 million cubic metres of strata; data north of the Tyne are fewer but suggest at least an equal volume of displaced strata there also, thus ranking the Downhill–Claxheugh–Trow Point–Frenchman's Bay submarine slides amongst the world's largest. Contemporary earth tremors were postulated as the cause of the instability and are thought also to have been responsible for abundant spatulate minor movement-planes and clay (liquified Marl Slate) intrusions in strata below the slide plane; such tremors could have originated through movement along one of the major faults of the region, perhaps the Ninety Fathom Fault. An alternative interpretation, by Lee (1990), is that the slope-failure may have resulted from a major decline of sea level following deposition of the Raisby and Ford formations.

Regardless of the cause of the Downhill Slide, it might be supposed that the downslope submarine movement of so vast a volume of sediment would generate a substantial tsunami, though it is not clear if or how such an event would be recorded in the rock record or if it could be distinguished from the record of the event itself. A thin unit of sandstone or siltstone has been reported at the appropriate stratigraphical level in a number of coal exploration boreholes off the Durham coast, and the possibility that this may be the product of a tsunami cannot be excluded.

Trow Point Bed

The distribution, character and environmental significance of the remarkably persistent Trow Point Bed have been reviewed by the writer (Smith, 1986), who nominated the several cliff sections at Trow Point as the type locality. The bed was first recorded in 1958 in National Coal Board (now British Coal) Offshore Borehole No 1 (NZ 5334 4043) and has been proved in some form or other in most subsequent local offshore boreholes where it is mainly oncoidal; the key to its great lateral variability, however, is only apparent at Trow Point where the thickness and lithology of the bed is seen to be closely related to the configuration of the hummocky upper surface of the underlying pile of slide-blocks. Baryte mineralization of the deposit is common in offshore boreholes but is seen onshore only in Frenchman's Bay and in the small bay 200–300 m south-east of Frenchman's Bay where the disturbed and undisturbed beds at the top of the Raisby Formation are also affected.

The Trow Point Bed is the youngest Cycle EZ1 carbonate unit of the Ford Formation basinward of the reef, but it has not been identified between Trow Point and the toe of the reef foreslope and may die out in this 5 m-wide belt. Its stratigraphical relationship to both the reef and the Hesleden Dene Stromatolite Biostrome are therefore unknown, although it clearly occupies the same stratigraphical slot as the reef and may be partly or wholly synchronous; a post-reef age would imply that the period of reef growth is wholly unrepresented by basinal deposits, emphasizing the sharp eastward thinning of reef-equivalent strata inferred, for example, from tunnels at Easington Colliery some 22 km to the south (Smith and Francis, 1967, fig. 21).

Farther afield, equivalents of the Trow Point Bed have been reported immediately beneath the Cycle EZ1 anhydrite at depth in North Yorkshire and parts of the Southern North Sea Basin (Taylor and Colter, 1975), in boreholes and surface outcrops in northern Germany (Füchtbauer, 1968; Richter-Bernburg, 1982) and in widely spaced boreholes in Poland (e.g. Peryt and Peryt, 1975; Peryt and Piatkowski, 1976). The provings in Germany suggest that the bed there is probably closely comparable with the Trow Point Bed but the Polish occurrences are somewhat thicker and more varied.

The environmental interpretation of the Trow Point Bed is a matter of lively debate. Smith (1970a), influenced by then prevailing views on the uniquely peritidal growth of columnar algal stromatolites and of net-fabric sulphate rocks, initially inferred that the bed formed near contemporary sea level, which implied marine drawdown equivalent to the height (100 m+) of the reef foreslope. This view was subsequently modified when more recent work showed (a) that many modern stromatolites are formed subtidally (e.g. Monty, 1973) and (b) that the net-fabric of the Hartlepool Anhydrite may be secondary and therefore does not necessarily indicate intertidal sabkha accumulation. The Trow Point Bed is now interpreted as a basin-floor deposit, that probably accumulated slowly in somewhat unusual marine conditions at a depth of perhaps 25–100 m; deep drawdown is not necessitated (but is not excluded) on the evidence in north-east England, though Peryt and Piatkowski (1976) deduced such drawdown on the evidence of inferred pedogenic features in the supposedly equivalent beds in Poland.

The Hartlepool Anhydrite Residue and overlying collapse breccias

Though previously described as 'a sort of mylonite' by Woolacott (1909), who regarded it as part of his evidence for regional thrusting, the thin mixed layer between the Trow Point Bed and the Cycle EZ2 breccias is now accepted as the dissolution residue of the Hartlepool Anhydrite; in coal exploration boreholes offshore, the same stratigraphical interval is occupied by up to 150 m of massive anhydrite, which is directly underlain by the Trow Point Bed (Magraw *et al.*, 1963; Smith and Francis, 1967, plate 13A; Smith, 1986, fig. 10). The anhydrite is almost devoid of siliciclastic impurities (Trechmann, 1913, p. 243), which accounts for the remarkable thinness of the residue at most localities.

The varied and spectacular breccias of the cliffs between Trow Point and Lizard Point have been noted and described by Winch (1817), Sedgwick (1829), Howse and Kirkby (1863), Lebour (1884), Woolacott (1909, 1912, 1919a), Hickling and Holmes (1931), Trechmann (1954) and Smith (1972, 1985a, 1994). The brecciation and associated mineralogical changes are greatest in the lowest 10–30 m of the formation and diminish unevenly upwards, but there are places where large blocks of strata have foundered with relatively little brecciation or alteration, and other places where severe brecciation and diagenetic changes extend well up into the formation and even into the overlying Roker Dolomite Formation. Sedgwick (1829) was the first to deduce that fracturing and cementation of many of the breccias had taken place repeatedly, and Howse and Kirkby (1863) were the first to suggest that the late-stage breccia-gashes (their 'breccia-dykes') were formed by the collapse of the roofs of large cavities. Early suggestions that the more extensive brecciation of rock in the coastal cliffs might have accompanied or followed the dissolution of interbedded evaporites were strongly supported by Trechmann (1913) in view of the known presence of thick anhydrite beneath the Roker Dolomite at Hartlepool, but the confirmation of the precise stratigraphical position of the anhydrite awaited the drilling of cored coal-exploration bores offshore (Magraw *et al.*, 1963). The calcitization ('dedolomitization') of the breccia clasts was investigated by Woolacott (1919a) who concluded that it resulted from the reaction between dolomite and calcium sulphate solution (Von Morlot's reaction) and Gillian Tester (pers. comm., 1988) records clear evidence that patchy chert and chalcedony nodules in the breccias have replaced both gypsum and anhydrite. Also at Trow Point, Al-Rekabi (1982, p. 106) reported fibrous chalcedony after calcite.

The discovery near Whitburn of a surface exposure of the Hebburn or Monkton Dyke by Mr G. Fenwick is important partly because of its bearing on the time when the Hartlepool Anhydrite was dissolved. The dyke is one of a swarm with a radiometric age of about 58 million years (Evans *et al.*, 1973; Mussett *et al.*, 1988, fig. 2) and, judging from its partly dendritic shape at outcrop, almost certainly intruded country rock that had already been brecciated. The brecciation, and thus the dissolution of the anhydrite here, is therefore probably Paleocene or older.

Cavity-fill in the breccias was first mentioned by Burton (1911) and has since been found to be extensive, and Hickling and Holmes (1931) recorded stalactitic cavity lining. Smith (1972) has drawn attention to the critical influence on the shape and size of breccia clasts played by the creation in basal post-evaporite carbonate rocks of a dense rectilinear network of sulphate veins, itself possibly related to high-pressure fluid injection following burial-related expulsion of formation brines or dehydration of primary gypsum.

The evaporite–dissolution collapse-breccias of north-east England all lie east of the shelf-edge reef of the Ford Formation, and occupy a NNW/SSE belt that extends for 2–5 km beneath the North Sea. Farther to the east and deeper, increasing thicknesses of anhydrite remain undissolved and overlying Concretionary Limestone rocks are progressively less brecciated. West of the present coastline the Concretionary Limestone in northern

Durham passes into the Roker Dolomite and the character of the breccia clasts, as seen in the Ryhope Cutting GCR site, changes accordingly. The collapse-breccias between Trow Point and Lizard Point are amongst the most convincing of their type anywhere in Britain; other excellent (but generally less accessible) exposures of such breccias are in coastal cliffs between Ryhope and Horden (Smith, 1972) and in the Wear Gorge at Sunderland.

Although foundering and collapse following evaporite dissolution are now regarded as the main cause of brecciation in the Concretionary Limestone Formation, there are a number of places in the coastal cliffs (as, for example, just south of Lizard Point) where collapse-brecciation has resulted from the dissolution of carbonate beds (Smith, 1973a, 1994) and many places where partial to complete brecciation has been caused by interstratal carbonate dissolution and stylolite formation during late diagenesis (Braithwaite, 1988). Finally, as in the sector south of Souter Point, local severe brecciation of beds near rockhead appears to have been caused by intense periglacial cryoturbation.

Sedimentology and diagenesis of the Concretionary Limestone Formation

Some aspects of the sedimentology of the Concretionary Limestone are touched on in the account of the Fulwell Hills Quarries site, but most of the critical evidence on which current interpretations are founded is superbly exposed in the cliffs between Velvet Beds and Souter Point. Here, as the sector accounts and literature (Smith, 1970a, 1971a, 1980a, b, 1985a; Smith and Taylor, 1989) show, least-altered strata in the north comprise interbedded finely laminated and unlaminated graded carbonate mudstones in which grainstones and packstones with an exogenous fauna locally form discordant sheets and lenses, whilst strata farther south contain fewer laminites but many disturbed beds with an abundant benthic fauna. These features, coupled with others seen in quarries and borehole cores, have led to interpretation of the Concretionary Limestone as a submarine slope deposit, with strata exposed north of Lizard Point being formed mainly in anoxic or semi-oxic conditions on middle parts of the slope, below an oscillating pycnocline, and those to the south being formed in oxic conditions (i.e. above the pycnocline) higher on the slope and perhaps towards its top (Smith, 1994). In this interpretation, the laminites are envisaged as quiet-water deposits, perhaps as annual couplets (summer sapropel, winter carbonate mud), the graded unlaminated beds are seen as distal turbidites and the disturbed beds are viewed as proximal to medial submarine slumps that may pass downslope into the turbidites. The overall picture is of a gentle subaqueous slope several kilometres long on which differentially high carbonate mud productivity and sedimentation on the upper part resulted in inherent oversteepening and endemic sediment instability. The mud may have been derived by winnowing of the grainstone shoals and back-barrier lagoon of the equivalent shelf facies (i.e. the Roker Dolomite) and the shoals presumably were also the source, through shelf-edge and high-slope failure, of the grainstone sheets and lenses in the mid-slope domain in Marsden Bay as far south as Lizard Point.

Diagenetic changes in the Concretionary Limestone are discussed in the account of the Fulwell Hills site, and most of the secondary features seen in the Fulwell exposures are seen also in the cliffs between Velvet Beds and Souter Point; they were considered in detail by Al-Rekabi (1982) who illustrated and analysed rocks from Marsden Bay and by Braithwaite (1988) who deduced a long and complex diagenetic history. Calcite concretions in the Whitburn to Marsden area are predominantly spherulitic, lacking, however, some of the great range of concretionary patterns seen at the Fulwell Hills site and in coastal cliffs at Hendon (Sunderland). From this point of view, therefore, the Whitburn–Marsden cliffs are perhaps not the best place for the study of these enigmatic structures.

Future research

Although most major aspects of the geology of this remarkable stretch of coastal cliffs and shore platforms have been investigated during the last few years, and several aspects have been researched in detail, many parts of it remain poorly understood and much remains to be discovered. In particular, the detailed sedimentology and local stratigraphy and variation of the Concretionary Limestone are worthy of further detailed research, as are the nature and ecology of the indigenous fauna of the Concretionary Limestone and the diagenetic history of the collapse-breccias.

Conclusions

This very extensive GCR site is of international importance because it constitutes a unique set of exposures which display firstly, a whole range of marine Permian depositional features which characterize the western margin of the Zechstein Sea in north-eastern England, and secondly, the post-depositional effects of evaporite dissolution and associated foundering.

Notable are the Trow Point Bed, which can be traced eastwards across the Zechstein Sea into Germany and Poland, the Hartlepool Anhydrite dissolution residue, and the foundered and brecciated Concretionary Limestone beds. Within these strata are found an important but restricted shelly fauna, much of it transported from more congenial environments nearer to the land.

The section has long been studied, and much of it has been well documented in the literature. However, many parts still remain to be studied and understood, so that there is a need for future research, particularly on the sedimentology of the Concretionary Limestone, its associated fauna and the diagenetic history of the foundered strata.

FULWELL HILLS QUARRIES (MAINLY SOUTHWICK QUARRY) (NZ 3859)

Highlights

The several preserved quarry faces in the Concretionary Limestone of Fulwell Hills, Sunderland (box 2 in Figure 3.2), are representative of more than 40 former exposures. They contain a unique range of complex and spectacular calcite concretions, including some claimed to simulate organic structures such as those of some corals and blue-green algae, and have yielded many fish remains from a thin bed near the base of the exposed sequence; the fish include *Acentrophorus varians* (Kirkby), this being the type locality. The rocks are unevenly gently folded and fractured, probably mainly by differential foundering caused by dissolution of the formerly underlying thick Hartlepool Anhydrite.

Introduction

The vast complex of quarries in the Concretionary Limestone of Fulwell Hills, in the north-western outer suburbs of Sunderland, has long been justly famous for its bewildering array of bizarre calcite concretions. Quarrying started before 1746 and ceased in 1957. In that time almost all the concretion-bearing beds were removed from an area exceeding a 0.5 km^2, largely for lime burning and building purposes; much of the output was transported by wagonways to ships on the River Wear, 2 km to the south.

Only a few of the many faces once worked have been preserved, but records of 36 faces examined in 1954 are lodged in the fieldnote files of the British Geological Survey. About 26 m of strata are now visible, out of a former total of about 35.7 m, and are thought to lie in about the middle of the Concretionary Limestone Formation. Concretions from Fulwell are to be found in many museums, with substantial collections at the Hancock Museum (Newcastle upon Tyne), Sunderland Museum, Nottingham University and the British Museum of Natural History; Abbott (1914) also cites collections at Oxford and Aberdeen University museums and museums at Haslemere and Copenhagen. They feature strikingly in many local walls and buildings, and in hundreds of private and public gardens in the South Shields and Sunderland areas.

The calcite concretions of Fulwell Hills were first noted by Winch (1817) and described in more detail by Sedgwick (1829); they were further described, classified and freely illustrated by Abbott (1907, 1914), Holtedahl (1921) and Tarr (1933). Briefer descriptions and attempts (so far not wholly successful) to explain the genesis of the concretions in the formation as a whole have been made by Garwood (1891), Woolacott (1912, 1919a, b), and Holmes (1931), and a detailed study on calcitization and compaction in rocks of the formation was made by Braithwaite (1988). Browell and Kirkby (1866) and Trechmann (1914) published much-quoted analyses of a selection of rocks from Fulwell Quarries and the site is also the type locality of the Fulwell Fish-Bed from which Kirkby (1863, 1864, 1867) recorded two species of fish. Finally, Fulwell Quarries and other local localities in these strata have been mentioned and/or illustrated in a number of regional accounts (Trechmann, 1925; Smith, 1970a, 1980b, 1994; Pettigrew, 1980) and for many years they have been a favourite venue for excursion parties whose visits have been recorded in the proceedings of various learned societies. Drift deposits formerly present at about +45 m O.D. on the north side of the hills contained a gravel lens interpreted by Howse (1864) and Woolacott (1897, 1900a, b) as a Quaternary raised beach, and Kirkby (1860) describes sand-filled pipes up to 3.5 m deep in the underlying limestone here.

Tarr (1933, p. 268) waxed lyrical over the limestones of Fulwell Quarries and wrote 'This exposure should be permanently preserved as one of the most outstanding examples of nature's ability to build artistically in stone'. The faces to which he referred have, unfortunately, long since disappeared, but those now preserved are reasonably representative of the many formerly available for study.

Description

Most of the several quarries on Fulwell Hills (including Fulwell Quarry itself) have been filled and partly or wholly landscaped, though a number of small faces have survived in addition to those scheduled for preservation. The quarries were worked under a number of names, but the main preserved faces are in the former Southwick Quarry; the scheduled areas are shown on Figure 3.19.

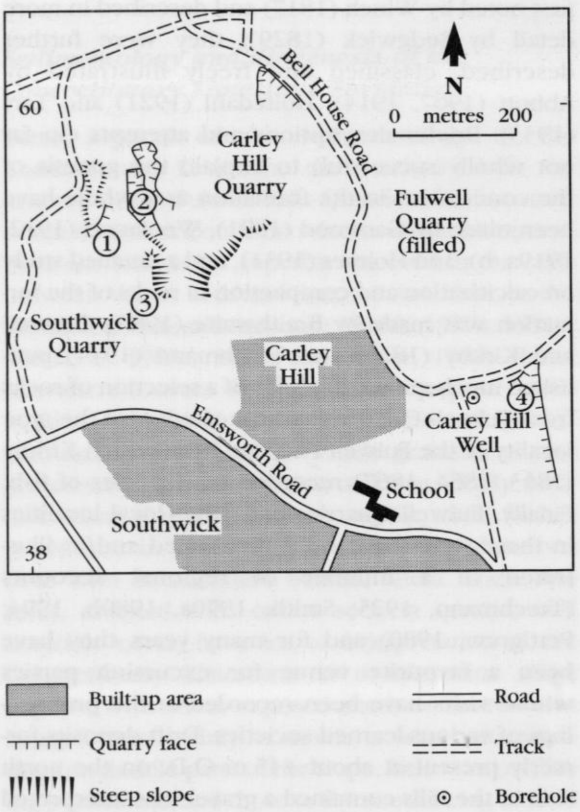


Figure 3.19 Preserved faces within the complex of former limestone quarries on Fulwell Hills, Sunderland; numbers refer to quarry faces described in the text.

The Concretionary Limestone strata of the Fulwell Hills Quarries totalled about 35.7 m in thickness, and comprise four main lithological units; the general sequence formerly visible is shown below.

	Thickness (m)
Drift, mainly red-brown, silty, stony clay, but with patches, sheets and lenses of limestone brash, gravel, sand and laminated clay	0–6.0
---- unconformity ----	
Limestone, grey and brown, very finely crystalline, mainly finely and evenly laminated, but with many thin unlaminated beds (some graded), interbedded with and passing into subordinate very finely saccharoidal, cream and buff dolomite; the laminated limestones contain abundant, but patchy, coarse, radially crystalline, brown calcite, including coarse spherulites, and many displacive lenses and tongues of white calcite; the unlaminated limestones contain patchy, radial/concentric calcite concretions and the dolomites contain scattered to abundant subspherical to lobate calcite concretions. Marked lateral variation	*c.* 21.0
Limestone, grey and brown, very finely to very coarsely crystalline, mainly finely and evenly laminated, but with many thin unlaminated beds (some graded) and with a widespread 0.5 m bed of cream and buff, very finely saccharoidal dolomite 2.4–2.9 m from top. Most of the limestone is massive and comprises a wide range of spectacular reticulate, lobate and spherulitic calcite concretions, with some lateral passage into finely saccharoidal dolomite containing scattered to abundant subspherical and/or lobate calcite concretions; some beds deformed by submarine slumping	*c.* 7.6
Limestone, grey and buff, very finely crystalline, mainly very finely and evenly laminated, but with some thin	

unlaminated beds (some graded); scattered, coarse, radial calcite crystals in the laminated beds, and small subspherical calcite concretions in the unlaminated beds	1.8–2.0
Dolomite, cream-grey, very finely saccharoidal, soft	5.5+

Of these units, the uppermost is by far the most laterally variable; even when many faces were fully exposed, correlation between sections was uncertain unless the faces were either very close or in contact; most parts of this unit are now obscured. In contrast, the 7.6 m unit comprises relatively laterally extensive thick and massive beds that could be traced readily with the aid of the recessive 0.5 m dolomite bed; this 7.6 m unit was the main quarrying target and the floor of the quarry widely followed its base. The 1.8–2 m bed near the base of the sequence is the 'Flexible Limestone' of the literature, although only the thinnest laminae here are noticeably flexible; it includes, near the top, the slightly bituminous Fulwell Fish-Bed discovered and recorded by Kirkby (1863, 1864, 1867) but which is only very sparingly fossiliferous in the solitary section now exposed. The lowest unit is the Great Marl Bed of the quarrymen (Woolacott, 1912) although Kirkby (1863, 1864, 1867) and Browell and Kirkby (1866) used the term in a different (perhaps the original and more correct) sense for a bed at the base of the 21 m unit.

Except in the fish-bed, fossils are very uncommon at Fulwell but a few were recorded by Kirkby from near the base and top of the Flexible Limestone, from four levels low in the 7.6 m unit and from a single level high in this unit; they comprise the conifer *Ullmannia frumentaria*, obscure plant remains, and the nektonic fish *Acentrophorus varians* (Kirkby) and *Acrolepis* (rare); Pettigrew (1980) records that whole *Acentrophorus* (0.04 m), for which this is the type locality, have been found within the visceral cavity of the much larger (0.25–0.35 m) predatory *Acrolepis*. Kirkby (1864) commented that only the fish-bed was worth examining for fossils and that fish discoveries in other beds were almost invariably accidental and made in the course of quarrying. Although bivalves commonly form the nucleus of (or lie within) concretions in the Marsden and Roker areas, none have been found in the Fulwell Hills Quarries (Woolacott, 1912).

Almost all the strata in the Fulwell Hills Quarries (including those in faces now covered) are gently folded and fractured, with dips of up to 40°, but generally 5 to 10°; a few small almost-completely brecciated areas also occur, mainly in faces now covered. The pattern of folds and fractures appears to be random, and is unrelated to well-documented structures in underlying coal workings.

The calcite concretions in the rocks at Fulwell Hills Quarries are bewilderingly varied, but there is a general tendency for the most complex types to be concentrated in the 7.6 m unit where they characterize beds traceable for some hundreds of metres. The most spectacular concretions are in the laminated limestones and comprise three-dimensional reticulate combinations of rhythmic bands and radial calcite crystals on scales ranging from millimetres to several decimetres (depending on the spacing of nucleation centres); spaces between the concretionary calcite are either empty or partly to wholly occupied by powdery cream dolomite which, in places, contains calcite scalenohedra up to 0.05 m long. Many of the concretions in the laminated limestone are clearly spatially and genetically related to joints, cracks and bedding planes, but others appear to be unrelated to such features; as Sedgwick (1829, p. 95) noted, the lamination commonly passes uninterruptedly through the concretions, although slight disruption is common. Concretions also persist through many of the thin unlaminated beds, whereas the thicker unlaminated beds are mainly of dolomite and are either concretion-free or patchily contain rod-like, lobate, or subspherical ('cannon-ball') types (Figure 3.20); some of the last exceed 0.3 m in diameter. Analyses by Browell and Kirkby (1866), Garwood (1891) and Trechmann (1914) showed that the calcite concretions contain up to about 22% of dolomite and that the dolomite between the concretions is slightly calcitic; thin sections (Trechmann, 1914, p. 237 and plate 36, fig. 5) reveal that the dolomite in the concretions forms inclusions in the calcite and that the 13% of calcite in the dolomite of the Great Marl Bed is concentrated in narrow veins. Most of the limestone beds display traces of a complex diagenetic history, and evidence of leaching, stylolitization and partial auto-brecciation is widespread; infiltrated and crystalline cavity-fill commonly have reduced the secondary porosity created by leaching and brecciation.

The site contains several faces of which four are especially noteworthy (1–4 in Figure 3.19); three are in the former Southwick Quarry and one in an unnamed quarry (not Carley Hill Quarry) on the east side of Carley Hill.

Figure 3.20 Mutually interfering subspherical calcite concretions ('cannon-balls') in a matrix of fine-grained dolomite. Note the parallel bedding traces preserved on the surface of some of the concretions. Loose specimen from floor of Southwick Quarry. Reproduced by permission of the Director, British Geological Survey: NERC copyright reserved (NL 130).

Face 1. This upstanding rock-face is about 10 m high and 70 m long; it is overlain by quarry spoil which obscures much of the south-western part of the exposure. Strata (about 18.6 m in total) dip north at up to about 20° and comprise several thick to very thick beds of hard concretionary limestone separated by relatively continuous, but generally thinner, beds of softer cream dolomite; the base of the section is probably slightly above the top of the Flexible Limestone and the sequence exposed comprises most of the 7.6 m unit and the lower beds of the 21 m unit. The limestone beds are mainly finely laminated and feature a wide range of highly complex calcite concretions, including many reticulate types; strong contemporaneous slump contortion is a feature of one of these beds a few metres above ground level on the south-east corner of the face. Most of the dolomite beds contain subspherical non-radial calcite concretions and some contain particularly fine examples of radially-crystalline large calcite lobes.

Face 2. This face surrounds a large excavation in the quarry floor. Strata in it dip generally northwards, in continuation of Face 1, and comprise about 25.5 m of beds of which the uppermost 13 m lie in the 21 m unit and the remainder form the 7.6 m unit and the Flexible Limestone; only the extreme top of the Great Marl Bed is exposed. Interest in this face centres on the Flexible Limestone exposed near the south-west end of the face, and the sparingly fossiliferous Fulwell Fish-Bed near its top.

Face 3. Strata in this face dip southwards at about 5° and comprise about 16 m of much the same sequence as Face 1; finely plane-laminated crystalline limestone predominates, with some calcite crystals exceeding 0.2 m in length. A 5.5 m bed of cream dolomite in the middle of the sequence is atypically thick, however, and is probably the 'Great Marl Bed' of Kirkby (1867); it should not be confused with the bed at the base of the sequence that was accorded the same name by Woolacott (1912) and Trechmann (1914).

Face 4. This comprises two main parts, a small section along the northern side of the old quarry and a long and somewhat overgrown face on the east side. Interest focuses on the small northern face, which furnishes one of the best exposures of complexly reticulate calcite concretions in which the spatial influence of cracks, joints and bedding planes is especially clear. This face is in massive limestone near the top of the 7.6 m unit. The long eastern face is mainly in this unit together with basal beds of the 21 m unit (total about 14 m), and displays both the rolling character of the strata and the great lateral variability of the limestones; the intervening soft cream dolomite beds are more uniform and persistent, as in faces 1–3. In common with many faces in the quarry complex, rockhead in the north of this face features evidence of cryoturbation and large slabs of limestone are embedded in the overlying drift.

Interpretation

The calcite concretions of Fulwell Hills are renowned worldwide for their complexity and variety, and the quarry faces preserved there contain a unique blend of unusual concretionary forms on a wide range of scales; equivalent strata are widely exposed in quarry and coastal cliff sections between South Shields and Whitburn and also at Hendon (a southern district of Sunderland), but none exhibit quite the range exhibited at Fulwell. The Flexible Limestone at Fulwell is generally less flexible than at Marsden, where its flexibility was first noted by Nichol (reported by Winch, 1817), but it is generally richer in fish remains. The cause of the flexibility is not known, but the fineness of the lamination and the preservation of bituminous films and fish remains points to slow accumulation under anoxic conditions well below wave-base.

All the strata exposed in the Fulwell Hills Quarries lie wholly within the Concretionary Limestone Formation as redefined by Smith (1971a), though the 'Great Marl Bed' at the base of the sequence was formerly classified (e.g. Woolacott, 1912; Trechmann, 1914) as Middle Magnesian Limestone. Records of the Carley Hill Well (NZ 3872 5951) in the south of the quarry complex show interbedded marl (i.e. soft dolomite) and laminated limestone to 26 m below the quarry floor, suggesting that at least 22 m of the Concretionary Limestone Formation lies below the Flexible Limestone here. The base of the 0.1 m Marl Slate lies in the well at a depth of 58 m (about −3.4 m O.D.) and the Yellow Sands lie at 95.8 m (about −41.2 m O.D.).

The Concretionary Limestone (up to 120 m) is the thickest carbonate formation of the English Zechstein sequence and its land outcrop spans most of the area between the reef and the present coast (Woolacott, 1912, fig. 5, which mistakenly includes the Seaham Formation); coal exploration boreholes have shown that the formation also crops out on the sea floor (or beneath drift) for several kilometres east of the present coast (Smith, 1994, fig. 34), and extends farther eastwards in the subsurface.

Interpretation of the stratigraphical relationships of the Concretionary Limestone Formation is complicated by its great lateral variability, lack of outcrop continuity and complex foundering, but the writer (Smith, 1970a, 1971a, 1980a, b, 1994) believes that it is co-extensive with the slope facies of the Cycle EZ2 carbonate unit and passes upwards and westwards into a shelf facies represented by the Roker Dolomite; the beds exposed at Fulwell Hills probably were formed on about the middle of the slope, in anoxic water below a basin-wide oscillating pycnocline. The proximity of Fulwell Hills Quarries to the reef at West Boldon shows that the shelf facies may have been less than 2 km wide here. The foundering of the Concretionary Limestone results from the dissolution of the formerly underlying thick (?100 m+?) Hartlepool Anhydrite and is undoubtedly the cause of most of the folds, fractures and brecciation seen in the Fulwell Hills Quarries. Other sedimentological and subsidence features of the formation are further discussed in the account of the coast sections at Marsden Bay, and it will suffice to note here that a slope origin for the Fulwell Hill strata is consistent with the evidence of submarine slumping seen in Face 1 and of the prevalence of thin unlaminated beds (many graded) that are interpreted (Smith, 1970a, 1971a, 1980a, b, 1994) as turbidites.

The origin of the calcite concretions in the Concretionary Limestone has been the subject of endless speculation, but remains uncertain. Sedgwick (1829) recognized that the concretions were secondary and that most of them were formed after much of the rock was partly or fully lithified, and Garwood (1891) showed that the chemical changes could have taken place in a closed system and resulted from a major redistribution ('segregation') of components rather than from the large-scale introduction or removal of matter. Later workers (e.g. Woolacott, 1912, 1919a; Trechmann, 1914; Holmes, 1931; Tarr, 1933) have pondered on the detailed chemistry of the profound mineralogical changes and speculated on the possible involvement of former organic matter, calcium sulphate and other salts; Shearman (1971) and Clark (1980, 1984) considered the possible role of sulphate-reducing bacteria. The petrography, geochemistry and evolution of the Concretionary Limestone in general (but not specifically at Fulwell Hills Quarries) was reviewed in detail by Al-Rekabi (1982) and Braithwaite (1988), who give full references.

Future research

The regional distribution, stratigraphical relationships and sedimentology of the Concretionary Limestone Formation are reasonably well known, although Fulwell Hills Quarries yield only a small part of the evidence on which this understanding is based. The quarries, however, remain a unique repository of almost the full range of concretions in this enigmatic formation, and the exposures here are an essential part of any further studies of the origin of these bewildering structures and of the rocks as a whole. Now that extraction of limestone has ceased, this is no longer a good site for the study of fossil fish, though good specimens are still to be found by the lucky or diligent searcher.

Conclusions

The Fulwell Hill Quarries complex is an internationally important GCR site. The site is justly famous for the enormous range of spectacular calcite concretions which characterize the aptly named Concretionary Limestone, as well as for the Fulwell Fish-Bed for which this is the type locality. It also features a range of structural features caused by the dissolution of the underlying Hartlepool Anhydrite. The origins of the concretions are still poorly understood and therefore this site provides essential exposures for their future study.

HYLTON CASTLE CUTTING (NZ 3594 5862–3611 5888)

Highlights

This small road cutting provides the best and most readily accessible exposure of the lower core of the shelf-edge reef of the Ford Formation. The rock is almost entirely of dolomite and comprises an apparently haphazard crudely-bedded assemblage of masses of hard reef-rock separated and surrounded by shelly rubble; ?algal encrustations are widespread in the hard reef-rock, and steeply dipping ?algal sheets occur in a number of places.

Introduction

The cutting accommodates Rotherfield Road near Hylton Castle, in the north-western outskirts of Sunderland, and was dug in 1955; it exposes about 15 m of exceptionally varied reef dolomite of the Ford Formation, mainly of the lower reef-core facies, and was recorded in detail by the writer (Smith, unpublished Geological Survey fieldnotes, 1955). Preliminary excavations below the floor of the cutting and nearby sewer trenches revealed that the reef-rocks in the cutting were underlain by a typical highly fossiliferous basal coquina.

Large collections from the excavations and cutting led to long fossil lists by Pattison (unpublished Geological Survey report, 1966). More recently, additional collections from the cutting by Hollingworth (1987, table 4) were used (with other data) in his reconstruction of the lower reef-core palaeocommunity (1987, fig. 6.12) which was reproduced by Hollingworth and Pettigrew (1988, fig. 8) in a palaeontological account of the cutting (their locality 1, pp. 40–44). This reconstruction was also reproduced by Hollingworth and Tucker (1987, fig. 5).

The GCR site is at the side of a public highway and great care should be taken both to minimize the risk of personal injury and to avoid causing inconvenience or danger to passing traffic.

Description

The position of the site and of its geological features (including some that are now no longer visible) is shown in Figure 3.21. The rock face in the cutting is about 120 m long and up to 6 m high and its base rises north-eastwards by about 15 m; in

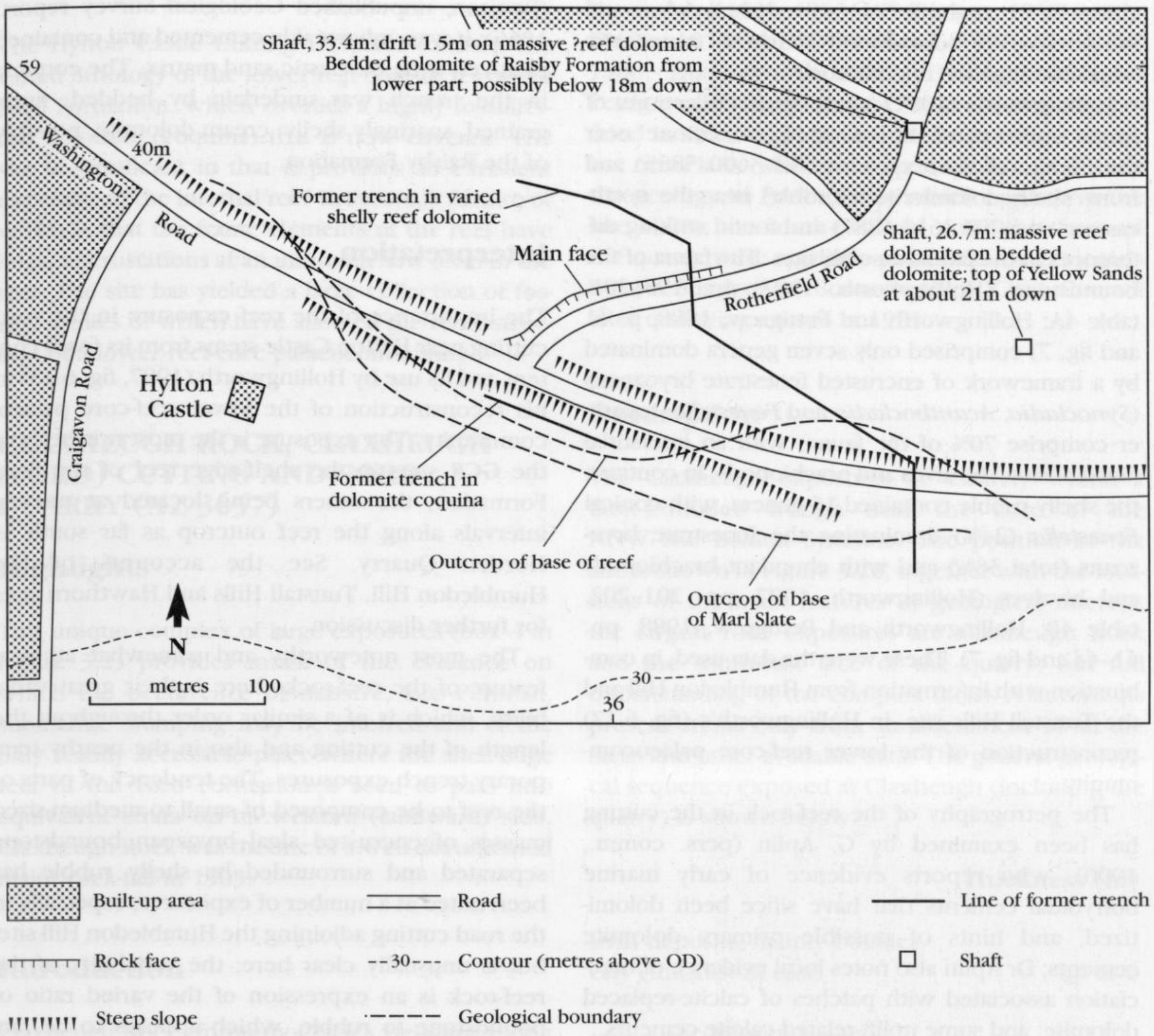


Figure 3.21 Hylton Castle (Rotherfield Road) Cutting and its immediate surroundings, showing the main features of geological interest.

conjunction with former excavations below road level, a section about 20 m thick was exposed, and further information was gained from a number of deep manhole shafts.

The present exposures are mainly in the north wall of the cutting and comprise an extremely varied complex of masses of autochthonous dolomite boundstone, many draped by laminar (?algal) sheets, separated by lenses and pockets of shelly, rubbly reef debris; from a distance the rock has a crude, low-dipping bedded appearance of a type generally found in the reef-flat sub-facies high in the reef and uncommon at this low level in the reef. The boundstone masses are irregular to compressed subspherical in shape (though many are poorly defined) and are commonly 0.5–1 m across (exceptionally 2.5 m); some are concentric; they are composed of dense, hard, cream-buff, finely crystalline dolomite with a sparse bryozoan–brachiopod fauna and widespread (but patchy) concentric ?algal encrustations which in places make up most of the rock. The laminar dolomite sheets are up to 0.3 m thick and some are vertical for 1 m or more; most appear to be contemporaneous coatings of boundstone masses, but some have hints of a bilateral structure and could be fissure-fill. The rubbly pockets between the boundstone masses make up a small to large proportion of the reef according to locality and comprise cream-buff, dolomitized shell debris and fine bryozoan boundstone detritus; concentric ?algal coatings are uncommon.

Hollingworth (1987) made large collections of fossils from a patch of 'laminated boundstone' near the middle of the exposure (NZ 3600 5885) and from 'shelly dolomicrite' (?rubble) near the north-eastern end (NZ 3610 5887) and found striking differences in the faunal assemblages. The fauna of the boundstone (Hollingworth, 1987, pp. 198–201, table 4A; Hollingworth and Pettigrew, 1988, p. 41 and fig. 7) comprised only seven genera dominated by a framework of encrusted fenestrate bryozoans (*Synocladia, Acanthocladia* and *Fenestella*, together comprise 70% of the fauna) with an interstitial fauna of small bivalves and brachiopods. In contrast, the shelly rubble contained 15 genera, with conical *Fenestella* (24%) dominating the fenestrate bryozoans (total 36%) and with abundant brachiopods and bivalves (Hollingworth, 1987, pp. 201–202, table 4B; Hollingworth and Pettigrew, 1988, pp. 41–44 and fig. 7). These were the data used, in combination with information from Humbledon Hill and the Tunstall Hills site, in Hollingworth's (fig. 6.12) reconstruction of the lower reef-core palaeocommunity.

The petrography of the reef-rock in the cutting has been examined by G. Aplin (pers. comm., 1990), who reports evidence of early marine botryoidal cements that have since been dolomitized, and hints of possible primary dolomite cements; Dr Aplin also notes local evidence of brecciation associated with patches of calcite-replaced dolomite, and some uplift-related calcite cements.

The great lateral and vertical variability of the reef dolomite in the cutting was also a feature of reef dolomite temporarily exposed in nearby sewer trenches (see Figure 3.21 for location) which exposed up to 4 m of unpredictably mixed boundstone and shelly rubble (Smith, unpublished Geological Survey fieldnotes, 1955). As in the main cutting, algal encrustations and lamellar drapes were seen to be extremely patchy.

The basal reef coquina is no longer exposed in the Rotherfield Road Cutting, but was seen in 1955 in temporary excavations below road level at the junction of Rotherfield Road and Washington Road and also, at a slightly lower level, in a WNW–ESE sewer trench (NZ 3593 5879–3601 5875) on the opposite (south) side of Washington Road (Figure 3.21). The rock exposed in these excavations was a pale cream accumulation of well-preserved brachiopods and bivalves, with relatively few bryozoans and no recognizable algal encrustations (Pattison, unpublished Geological Survey report, 1966); it was only weakly cemented and contained relatively little bioclastic sand matrix. The coquina in the trench was underlain by bedded, finer-grained, sparingly shelly, cream dolomite, possibly of the Raisby Formation.

Interpretation

The importance of the reef exposure in the road cutting near Hylton Castle stems from its fossil content and its use by Hollingworth (1987, fig. 6.15) in his reconstruction of the lower reef-core palaeocommunity. The exposure is the most northerly of the GCR sites in the shelf-edge reef of the Ford Formation, the others being located at uneven intervals along the reef outcrop as far south as Horden Quarry. See the accounts of the Humbledon Hill, Tunstall Hills and Hawthorn sites for further discussion.

The most noteworthy and somewhat atypical feature of the reef-rocks here is their great variability, which is of a similar order throughout the length of the cutting and also in the nearby temporary trench exposures. The tendency of parts of the reef to be composed of small to medium-sized masses of encrusted algal–bryozoan boundstone separated and surrounded by shelly rubble has been noted at a number of exposures, especially in the road cutting adjoining the Humbledon Hill site, but is unusually clear here; the variability of the reef-rock is an expression of the varied ratio of boundstone to rubble, which appears to be random apart from the strong hint of roughly horizontal bedding. The abundance of ?algal encrustations on bryozoan and other frame elements is also unusual at this relatively low level in the reef, and prompts the question of whether a concentrated reef sequence might be present here; this in turn poses the question of whether the faunal assemblages here might not be fully representative of low-reef faunas as a whole.

Future research

The Rotherfield Road Cutting, having been examined by Hollingworth (1987), appears to offer little immediate scope for further detailed research. It remains an excellent and convenient place where the internal structure of the shelf-edge reef may be examined, and from which the abundant and varied fauna may be collected.

Conclusions

The Hylton Castle Cutting GCR site exhibits the varied lithology of the lower reef-core facies of the Ford Formation, which overlies a highly fossiliferous dolomite (coquina) that is now covered. The site is significant in that it provides an excellent exposure of the internal reef structure, a feature of which is that the frame elements of the reef have ?algal encrustations at an unusually low level in the reef. The site has yielded a large collection of fossils, studies of which have allowed the reconstruction of a lower reef-core palaeocommunity.

CLAXHEUGH ROCK, CLAXHEUGH (FORD) CUTTING AND FORD QUARRY (NZ 3657)

Highlights

This unique complex of large exposures (box 4 in Figure 3.2) provides much of the evidence on which the occurrence of massive, late Permian, submarine slumping may be inferred and is the only readily accessible place where the shelf-edge reef of the Ford Formation is seen to pass into equivalent strata on its western (landward) side. Claxheugh Rock was the site of a well-documented major rock-fall in 1905.

Introduction

Claxheugh Rock (formerly Clack's Heugh = a crag in Mr Clack's property) and the adjoining cutting and quarry lie on the south side of the River Wear in the western outskirts of Sunderland; together the three exposures reveal parts of the Basal Permian (Yellow) Sands, Marl Slate, Raisby Formation and Ford Formation. The sections are the type locality of the Ford Formation, the shelf-edge reef of which was formerly almost completely exposed in cross-section.

The rock faces of the Claxheugh complex of exposures, plus the nearby, but now filled, Claxheugh and Ford (old) quarries, have received more attention in the literature than any other late Permian Marine GCR site. The references range from brief mentions (e.g. Sedgwick, 1829; Howse, 1848, 1858; King, 1850; Howse and Kirkby, 1863; Kirkby, 1866; Lebour, 1884, 1902; Trechmann, 1931) to longer accounts of one or more aspects of the various exposures (e.g. Browell and Kirkby, 1866; Woolacott, 1903, 1905, 1912, 1918; Trechmann, 1925, 1945, 1954; Logan, 1967; Smith, 1969b, 1970a, c, 1981a; Pryor, 1971; Pettigrew, 1980; Hollingworth, 1987; Holling-worth and Pettigrew, 1988). The earlier references were confined to Claxheugh Rock and the railway cutting, but most later workers, were also able to discuss the geology of Ford Quarry which opened in the late 1920s; the south-east and north-east faces of the quarry were specially preserved for geologists by the Sunderland Borough (now City) Council after quarrying ceased in 1971.

Description

The Claxheugh exposures lie entirely within a fault-bounded trough near the core of the NNW–SSE Boldon Syncline. The position of the site is shown in Figure 3.22, together with the locations of the main features of geological interest; the largest rock exposures are Claxheugh Rock and the south-east face of the quarry, but full understanding of the complex facies relationships present stems only from an assessment of all the faces and other available data. The general geological sequence exposed at Claxheugh (including the quarry) is shown below.

	Thickness (m)
Drift deposits, mainly boulder clay (thickest in east)	up to 6
----- unconformity ------	
Ford Formation, reef and backreef facies; at least	55
Raisby Formation, slope facies, with slide-plane and patchy slide-breccia (0–2 m) at top	0–8
Marl Slate	0.77–0.90
Basal Permian (Yellow) Sands (about 18 m seen)	up to ?58
----- unconformity -----	
Upper Coal Measures (Westphalian C)	

The relationships of the several stratigraphical units in the main faces are summarized in Figure 3.23, which was based on drawings made before

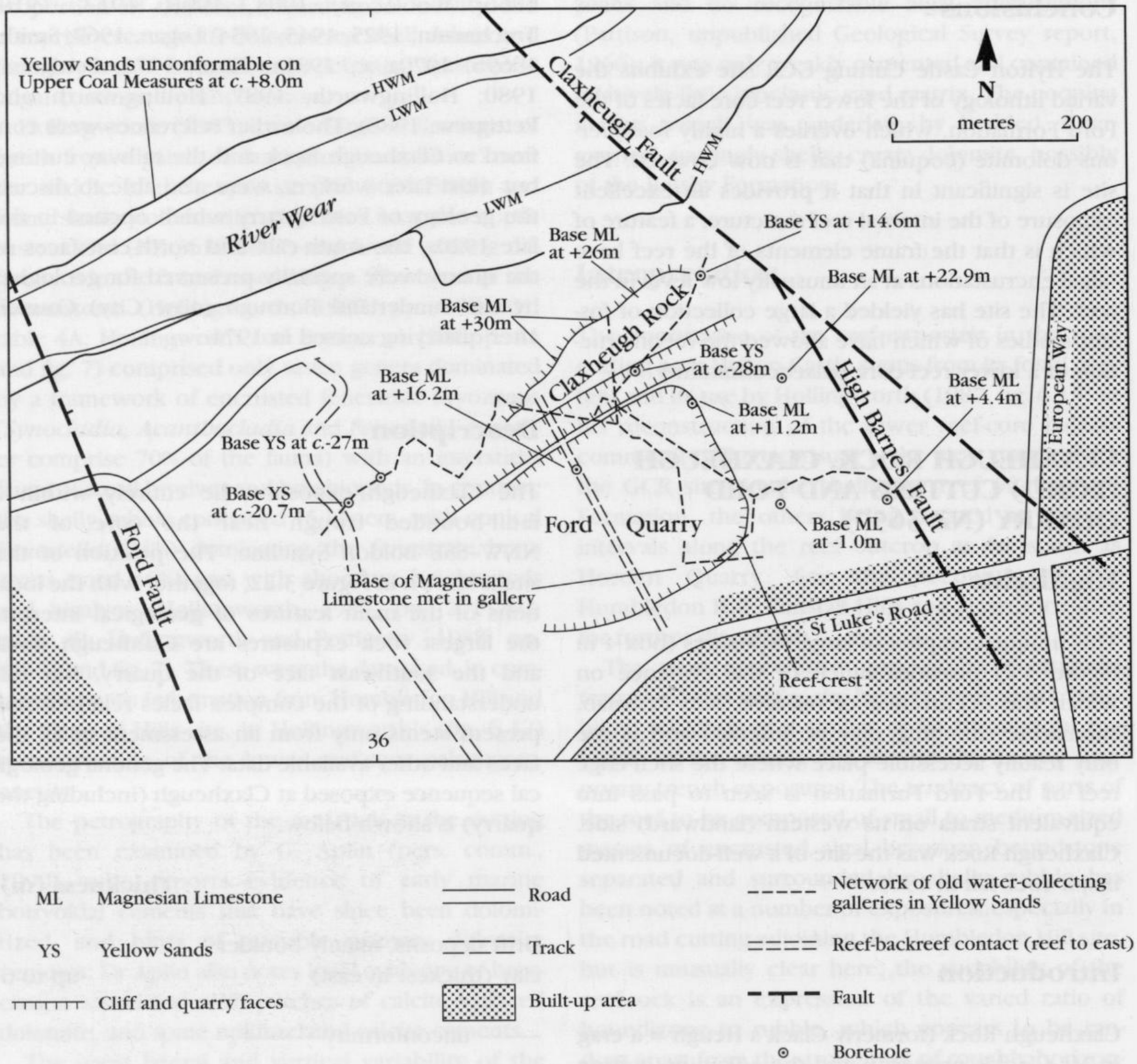


Figure 3.22 Claxheugh Rock, Cutting and Ford Quarry, showing the position of the main features of geological interest.

the partial filling of the quarry. Details of the main Permian units follow.

Basal Permian (Yellow) Sands

The ?early Permian aeolian Yellow Sands are almost at their thickest (about 58 m) beneath Claxheugh Rock; upper parts of the formation here were investigated in detail by Pryor (1971), who classified the weakly-cemented sand as a fine- to medium-grained subarkose with scattered to abundant coarse grains and large-scale, tangential trough cross-stratification. Pryor noted quartz and potassic feldspar contents of 88% and 8%, respectively, and determined a mixed cement of dolomite and calcite with a little illite.

Boreholes have shown that about half of the Yellow Sands at Claxheugh lie below river level. The formation is of special interest here because it was exploited for water by a local factory from which a complex system of galleries was driven south-eastwards deep into the hill along the local water table (Figure 3.22). Tests by Browell and Kirkby (1866) showed that the sand is remarkably porous, with one cubic foot (0.028 m^3) of the deposit able to hold 10 pints (3.41 litres) of water.

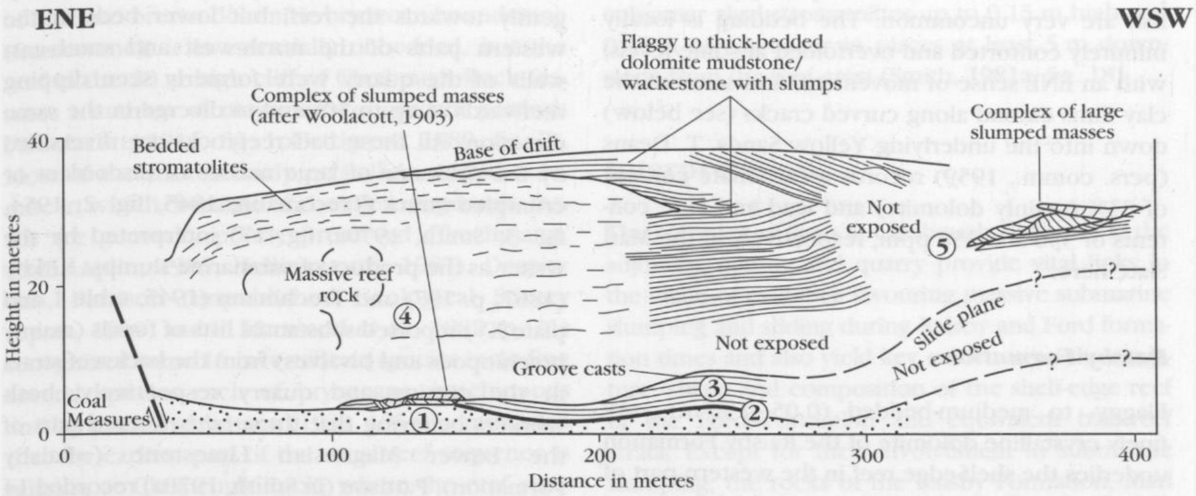


Figure 3.23 Section of strata at Claxheugh Rock, Cutting and Ford Quarry, based on Smith (1970a, fig. 17).

The top of the Yellow Sands at the north-eastern end of the Claxheugh Rock section slopes steeply south-southeastwards (Trechmann, 1954) and boreholes in the quarry floor show that this slope continues for some distance and takes the reef/sand contact from about +26 m O.D. at outcrop at the north-east end of Claxheugh Rock to about +11 m only 150 m farther south, and to about –3 m O.D. in the south of the quarry (Figure 3.24); because of this decline, the base of the limestone was intersected in the most southerly part of the water-gathering gallery.

Marl Slate

This comprises finely laminated, buff and grey, slightly carbonaceous, dolomitic shale with laminae, lenses and thin beds (some partly contorted) of brown, carbonaceous, plastic clay; scales of

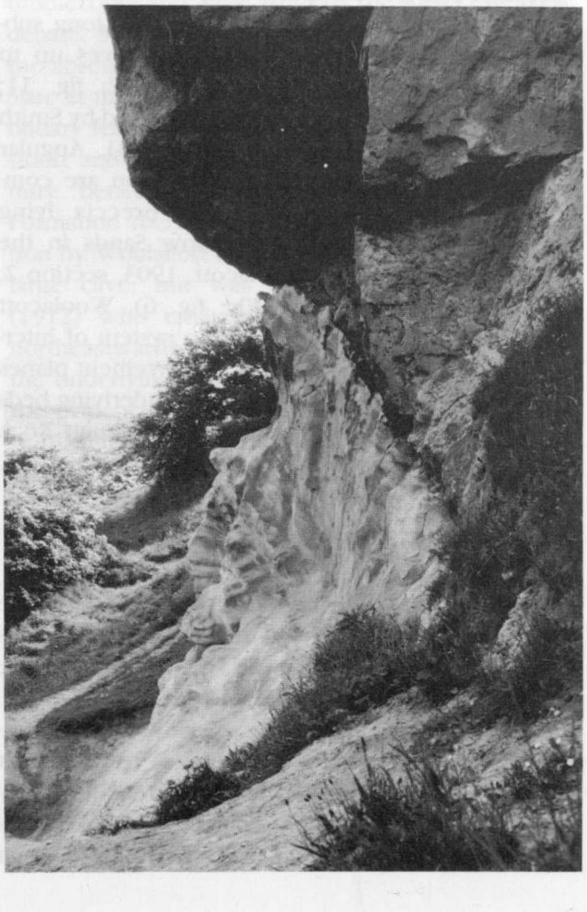


Figure 3.24 Steeply south–south-eastwards sloping contact between Basal Permian Sands (pale) and dolomite boundstone of the Ford Formation reef. The slope is interpreted as the northern flank of an east-northeastwards trending submarine slide canyon (Smith, 1971c). The field of view is about 18 m high. (Photo: D.B. Smith.)

palaeoniscid fish are scattered sparingly, but whole fish are very uncommon. The bedding is locally minutely contorted and overfolded at some levels, with an ENE sense of movement, and some of the clay films extend along curved cracks (see below) down into the underlying Yellow Sands. T. Deans (pers. comm., 1959) records a carbonate content of 33% (mainly dolomite) and lead and zinc contents of 330 and 350 ppm, respectively in the Marl Slate here.

Raisby Formation

Flaggy- to medium-bedded (0.05–0.30 m) very finely crystalline dolomite of the Raisby Formation underlies the shelf-edge reef in the western part of the Claxheugh Rock section, and thickens west-southwestwards to more than 8 m (Figure 3.23). The formation was not identified in Ford Quarry, but may have been present and unrecognized in the deep north-west corner (now filled), beneath comparable back-reef strata of the Ford Formation. Some bedding planes bear a thin layer of brown, dolomitic clay and others are slightly stylolitic; a sparse foraminifer–bivalve–brachiopod fauna is present. The truncated top of the formation at the south-western end of the section bears long sub-parallel and divergent WSW/ENE grooves up to several metres long (Woolacott, 1912, fig. 11; Trechmann, 1945), which are interpreted by Smith (1970c) as score marks (groove-casts). Angular fragments and blocks of the formation are complexly intermixed in a coarse breccia lying between the reef and the Yellow Sands in the centre of the section (Woolacott, 1903, section 2, reproduced by Smith, 1970c, fig. 6). Woolacott (1903, section 3) also recorded a system of intersecting curved cracks and minor movement planes that cut the Raisby Formation and underlying beds at the south-western end of the Claxheugh Rock section, but do not extend into the overlying reef.

Ford Formation

This is the main marine stratigraphical unit in the Claxheugh–Ford Quarry complex, and comprises reef and backreef facies; the reef is slightly more than 200 m wide and comprises several sub-facies.

The backreef facies is exposed in the south-western part of the quarry and of the adjacent cutting and comprises at least 55 m of buff, very finely crystalline dolomite in relatively even beds commonly 0.1–0.25 m thick. Only the uppermost 18–20 m of these beds are now visible, and dip gently towards the reef, but lower beds in the western parts of the north-west and south-east walls of the quarry were formerly seen dipping reefwards at up to 30° and to diverge in the same direction. All these backreef-rocks are diversified by the presence of large masses of discordant or crumpled strata (Trechmann, 1945, fig. 2; 1954, fig. 3; Smith, 1970a, fig. 17) interpreted by the writer as the product of submarine slumps. Kirkby (1867, p. 197) and Trechmann (1945, table 1 and plate XV) reported substantial lists of fossils (mainly brachiopods and bivalves) from the backreef strata in the cutting and quarry respectively, both workers believing that these beds formed part of the Lower Magnesian Limestone (=Raisby Formation); Pattison (in Smith, 1970a) recorded 14 species from these beds in the quarry, and Logan (1967) also cited the cutting as a collection locality. Trechmann's list included several forms that he then claimed to be new to the English Zechstein, but the number of 'new' species has declined with more recent studies by Logan (1967), Pattison (unpublished Geological Survey reports, 1969) and Hollingworth (1987). Hollingworth recorded a patch of crinoid debris in the cutting and remarked that the quarry fauna listed by Trechmann indicated an unlithified soft substrate (see also Hollingworth and Pettigrew, 1988, p. 46). Trechmann (1954) noted that the 'Lower Limestone' (= the Ford Formation backreef strata of this account) in Ford Quarry contained nodules and layers of chert that are 'full of Foraminifera and fragments of bryozoa that are not seen in the enclosing dolomite'. Logan (1967), using specimens of shelly 'Lower Magnesian Limestone' (probably the Ford Formation of this account) from the Trechmann collection from Ford Quarry, described and figured hypotypes of *Streblochondria? sericea* (de Verneuil) and *Cleidophorus? hollebeni* (Geinitz).

The reef facies of the Ford Formation forms the bulk of Claxheugh Rock and the easternmost two-thirds of the cutting and quarry; the contact between the reef and backreef beds is only slightly gradational (Smith, 1981a, figs 5, 6) and was formerly seen to be almost vertical for the whole original height (about 35 m) of the south-east face of the quarry (Figure 3.23). Almost all of the reef-rock in the quarry is of reef-core sub-facies, with a passage into reef crest and uppermost reef slope sub-facies along the north-eastern fringe; a few metres of roughly bedded rock at the top of the main faces may be of reef-flat sub-facies.

The reef-core sub-facies comprises a great mass of buff and brown dolomitic bryozoan boundstone (framestone); it is essentially unbedded, but the reef in the 20 m high cliff of Claxheugh Rock features a number of major sub-concordant partings (Woolacott, 1914, fig. 1; Pettigrew, 1980, fig. 7). Most of the rock is finely crystalline, turbid dolomite in which, because of complex diagenesis, fossils are generally poorly preserved (Trechmann, 1945; Aplin, 1985; Hollingworth, 1987). Despite this, Pattison (unpublished Geological Survey report, 1969, and in Harwood *et al.*, 1982, p. 21) recognized some 16 invertebrate species including several species each of bryozoans, brachiopods and bivalves. Trechmann (1931, 1954) commented that the earliest part of the usual reef sequence is missing at Claxheugh Rock, where the reef rests on a deeply scoured surface of Raisby Formation, Marl Slate and Yellow Sands and no coquina is present. Hollingworth (1987) and Hollingworth and Pettigrew (1988) considered that the abundance of epifaunal genera in the reef is consistent with a lithified substrate and reported that bryozoans such as *Acanthocladia* were stiffened and given extra bulk by laminar algal encrustations. A faunal transect of the upper part of the reef-core in the cutting was given by Hollingworth (1987, fig. 6.35) and Hollingworth and Pettigrew (1988, fig. 9).

The reef-core and ?reef-flat dolomite boundstone in the cutting contains a number of vertical tension fissures up to 0.5 m across and 3 m deep (Aplin, 1985, pp. 90–94), that have not been recognized in the nearby quarry. Aplin reports that the fissures are lined with laminated dolomite of possible algal origin, and that some have cores filled with bioclastic debris; he infers from this fill that the fissures were opened whilst the reef was growing.

In the easternmost part of the cutting and quarry, the crudely bedded uppermost part of the reef-core is seen to increase in dip from almost horizontal to up to 50° (Smith, 1981a) as it passes through the reef crest into the uppermost part of the reef slope. The rock here is a crumbly, saccharoidal dolomite boundstone and comprises a highly varied mixture of *in situ* and detached masses of bryozoan boundstone (framestone), complexly anastomosing laminar ?algal sheets and cavity-fill, and pockets of shelly rubble that are locally rich in gastropods, the brachiopod *Dielasma* and the nautiloid *Peripetoceras*; most organisms in the rock are algal-encrusted, and encrustations probably comprise more than 70% of the whole. Many of the laminar sheets bear laterally-linked stromatolite hemispheres, and outward and upward-elongated columnar algal stromatolites up to 0.15 m high and 0.05 m across occur in places at least 5 m downslope from the reef crest (Smith, 1981a, fig. 18).

Interpretation

The complex of faces at Claxheugh Rock and in the adjoining cutting and quarry provide vital links in the chain of evidence favouring massive submarine slumping and sliding during Raisby and Ford formation times and also yield key evidence on the structure, shape and composition of the shelf-edge reef of the Ford Formation and equivalent backreef strata. Except for their involvement in submarine slumping, the rocks of the Raisby Formation, Marl Slate and Yellow Sands here are normal for the district and require no special comment.

Evidence bearing on submarine slumping and sliding

The unusual relationships of strata at the base of the Claxheugh Rock section have been commented on by most of the authors listed in the introduction to this account and were formerly the subject of lively debate. Most of the early authors recognized that the absence of the Raisby Formation and the Marl Slate at the north-east end of the section was a secondary feature caused by their removal after deposition and several inferred an erosional unconformity beneath the 'Shell Limestone' (= Ford Formation reef). A briefly-held alternative explanation by Woolacott (1903) invoked the collapse of a large cave, but was superceded by Woolacott (1912) who envisaged massive destructive east-northeastwards thrusting of the reef over and into the underlying strata. Trechmann (1945) accepted the evidence of thrusting, but clearly had reservations and, in 1954, diffidently suggested that the missing 30 m or so of the lower part of the reef might have been represented by anhydrite, since dissolved. None of these explanations fully accounted for all the facts, however, and this shortcoming led to a new interpretation (Smith, 1970c) in which the Raisby Formation, Marl Slate and the uppermost part of the Yellow Sands here were thought to have slid away downslope (east-northeastwards), leaving a deep slide-canyon which was subsequently filled and buried by the Ford Formation. This interpretation accounts for the scoremarks and matching ridges (= groove casts) between the Raisby and Ford formations, the breccia of Raisby Formation, Marl

Slate and Yellow Sands debris and the overall relationships, but leaves unexplained the enigmatic later growth of a major shelf-edge reef at right angles to the trend of a large, linear sea-floor hollow. Similar features and abnormal stratigraphical relationships were formerly visible in Downhill Quarry (NZ 348601) 3 km NNW of Claxheugh, and large allochthonous masses of Raisby Formation strata, interpreted as slide-blocks (olistoliths), are present downslope at the coastal site at Trow Point and Frenchman's Bay, South Shields. The whole event and its field expression constitute the Downhill Slide.

Woolacott's (1903, Section 2) faithful recording of a particularly complicated part of the Claxheugh Rock section underlines the importance for geologists of making full records of what they see, even if they cannot interpret or understand it; the exposure was covered by debris from the 1905 landslip, but Woolacott's drawing and description were invaluable in the reinterpretation by Smith (1970c) of the history of the area late during Raisby Formation time. Similarly, Trechmann's (1945, fig. 2; 1954, fig. 3) sketches of the south face of the quarry accurately record discordances that he interpreted as evidence of tectonic thrusting, but which are now regarded as submarine slide-planes overlain by allochthonous slide-blocks. These features are still visible, however, and furnish eloquent evidence of the effect of submarine sliding and slumping on partly-consolidated carbonate muds; the exposures of slumped beds in the Ford Formation in the cutting are even more spectacular and convincing (Smith, 1994, plate 10).

Ford Formation

Although advanced diagenesis has obscured many primary details of the shelf-edge reef of the Ford Formation, and made it an indifferent locality for the study of its biota, the south-east face of Ford Quarry is the only place where a fairly complete cross-section of the reef may be seen and is the only place where the reef–backreef transition is readily accessible. The reef is seen to be at least 200 m wide at this point, but the seaward margin is not exposed.

The shelf-edge reef is also a feature of the GCR site at Hylton Castle to the north, and, to the south, of the sites at Humbledon Hill, Tunstall Hills (north and south), Stony Cut (Cold Hesledon), Hawthorn Quarry and Horden Quarry. Aspects of reef distribution, structure, fabric, biotas and diagenesis at these localities are discussed in the relevant accounts. The aspect for which the reef at Ford Quarry is especially noteworthy is that the north-east face is the best exposure of algal-dominated, nautiloid-rich reef crest and high reef slope dolomite and is the only reef exposure containing columnar stromatolites. The presence of large, rolled, detached blocks here is indicative of phases of high energy.

The exposure of the reef–backreef contact is important for a number of reasons. Firstly, it shows that the landward edge of the reef was sharp, with very little relief, proving that the reef surface was barely higher than the backreef sea floor and that backreef carbonates accumulated at the same rate as the reef grew upwards. Secondly, the virtual absence of reef debris in backreef beds implies little erosion and sediment transport landwards across the top of this part of the reef. Thirdly, the general verticality of the contact shows that the landward edge of the reef remained geographically static whilst the seaward margin prograded; the reef therefore became wider with time.

Finally, the exposed backreef strata themselves are unique in being composed of altered carbonate muds and in containing a fairly varied and abundant invertebrate fauna that includes bryozoans and brachiopods. All the other exposures of backreef strata of this age in north-east England are predominantly of altered oolite grainstones with a sparse bivalve–gastropod fauna. The presence of reefwards-displaced allochthonous slide-blocks in these beds is also unique to Ford Quarry and the cutting, and shows that the backreef sea floor sloped towards the reef and was repeatedly unstable. The reasons for these various differences are not known, but Smith (1994) has speculated that they may have arisen because the reef here grew across the floor of a WSW/ENE submarine slide-canyon at least 30 m deep and the sea here may therefore have been deeper than in most other places.

Future research

Most aspects of the several formations exposed at this complex of exposures have been subject to detailed research in recent years and there seems little scope for further detailed studies in the immediate future; an exception is the backreef facies of the Ford Formation, which presents a number of anomalies noted in the text.

Conclusions

This GCR site is the type section of the Ford Formation and is of international importance in that it shows an almost complete section through the late Permian shelf-edge reef and its passage into equivalent backreef strata to the west. It is particularly important in displaying evidence of penecontemporaneous late Permian submarine sliding and slumping on a large scale. This site has been extensively described in the literature and has been the subject of recent research. It is essential therefore that exposures at the site be preserved for further study and for other educational purposes.

DAWSON'S PLANTATION QUARRY, PENSHAW (NZ 3355 5464–3375 5487)

Highlights

This quarry (box 5 in Figure 3.2) contains a superb exposure of a submarine debris flow that lies a few metres above the base of the Raisby Formation. Though generally less than a metre thick, the debris flow displays great lateral variation; it is part of an extensive, but discontinuous, thin sheet of disrupted strata that became unstable and moved east-northeastwards down the marginal slope of the Zechstein Sea. One or more earthquakes may have triggered the movement. The quarry also features many curved joints and minor movement planes, similarly possibly caused by contemporary, but slightly later earth movements.

Introduction

Dawson's Plantation Quarry, Penshaw, exposes about 7 m of limestones and dolomites of the Raisby Formation and contains a thin disturbed sequence interpreted as a submarine proximal turbidite or debris flow. The disturbed bed lies low in the face and perhaps 5–8 m above the (unexposed) base of the formation; it was first reported by Smith (Geological Survey fieldnotes for 1:10,560 Sheet NZ 35 SW, 1953) and later described more fully and interpreted as the product of a complex episode of downslope movement of partly-lithified sediment (Smith, 1970c). The deposit was re-examined in greater detail by Lee (1990), who recognized evidence of three closely-spaced pulses of downslope movement.

Description

The quarry is about 300 m long and lies along the south-east margin of Dawson's Plantation (Figure 3.25); it is cut into the north-west facing escarpment of the Raisby Formation and most beds dip regularly and gently east-northeastwards. The general sequence is given below.

	Thickness (m)
Dolomite, buff, finely crystalline, in irregular beds 0.05–0.30 m thick, gradational base	*c.* 1.0
Calcite mudstone, buff, in slightly irregular beds 0.03–0.1 m thick except in lowest 0.6 m where several more regular beds are 0.1–0.15 m thick; apparently barren	*c.* 2.5
Limestone breccio-conglomerate, grey, and associated grey wackestones, packstones and grainstones; very varied, locally shelly; base sharp and conformable	up to 0.9
Interbedded (thinly in lowest 0.4 m) buff, finely crystalline, dolomite and subordinate grey calcite-mudstone, sparingly shelly	0.9
Very thinly (0.002–0.02 m) unevenly interbedded grey calcite-mudstone and buff finely crystalline dolomite; sparingly shelly	1.6+

The breccio-conglomerate (proximal turbidite or debris flow) may be traced in the quarry face for about 250 m (Figure 3.26); it thins and becomes less pebbly south-westwards. The lithology of the deposit was investigated by Lee (1990) who identified six main rock types that are present in a roughly consistent, but laterally varied sequence:

6 (at top) Calcarenite, upwards-fining, interbedded with host calcite mudstones
5 Fine calcirudites and pebbly calcarenites, grading up into calcite- and then dolomite mudstones
4 Coarse, poorly-sorted, calcirudite, containing subspherical to tabular clasts
3 Calcirudite/calcarenite, upwards-fining
2 Slightly to severely deformed, interbedded calcite- and dolomite mudstones
1 Calcirudite, clast-supported, well-rounded calcite mudstone clasts

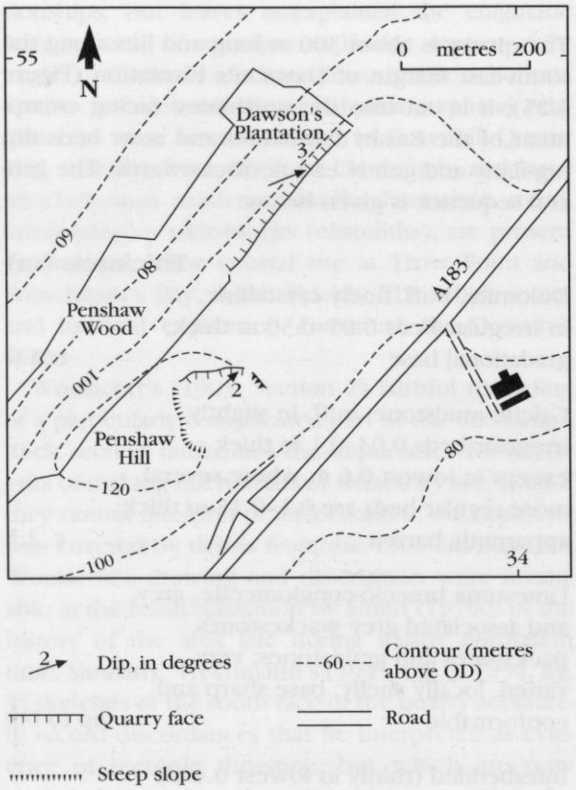


Figure 3.25 Dawson's Plantation Quarry, Penshaw, and its environs.

Lee noted penecontemporaneous erosion surfaces within the deposit, particularly below units 3 and 5, and carefully documented its lateral variability (Figure 3.27). He interpreted this variability as at least partly caused by complex channelling and reworking, the trend of the channels (and therefore the direction of sediment transport) being difficult now to determine; fresher surfaces in 1953 had previously revealed clast imbrication and deformation patterns suggestive of south-west to north-east sediment transport (Smith, 1970c, p. 7). Bioclasts, especially productoids, are much more abundant in the debris flow than in enclosing strata and, though some are deformed, are commonly unusually well preserved. Smith (1970c) has speculated that this good preservation may have resulted from rapid burial of the whole animals rather than slow accumulation of more fragile disarticulated valves and empty shells. Lee (1990) noted a good size correlation between lithoclasts and bioclasts and commented that skeletal remains are most abundant in the finer-grained calcirudites and calcarenites.

In addition, to the debris flow, the Raisby Formation in Dawson's Plantation Quarry features abundant, intersecting, curved low-angle joints and minor rotational movement planes (Smith, 1970c). Most of these are concave-upwards, with a tendency to grade downwards into bedding-plane slips; they cut all strata, including the debris flow.

Interpretation

Dawson's Plantation Quarry contains, without doubt, the best-exposed and most impressive proximal turbidite or debris flow in the Magnesian Limestone. Related disturbed strata are widespread (although not ubiquitous) at about the same stratigraphical level in north-east Durham; they vary greatly in character from place to place, ranging from graded turbidites, as at the former Downhill Quarry (NZ 348601), to coarse breccias composed of slide-blocks up to several metres across as at the High Moorsley Quarry site (Smith, 1970c). Most of the disturbed strata are more fossiliferous than beds above and below, presumably because of rapid deposition, and almost all yield evidence of early sea-floor lithification of the carbonate muds. The rarity of disturbed strata at most other levels in the formation argues against inherent sediment instability through natural oversteepening of the deposition slope and may point to a brief phase of instability caused by contemporary local earth movements.

The low-angle curved joints and minor movement planes in the Raisby Formation at Dawson's Plantation Quarry are similar to others at many northern exposures of these strata, including the Claxheugh Rock site and sea cliffs in Sector 1 of the Trow Point to Whitburn Bay site. At these two localities the joints are truncated upwards at the base of the late Raisby Formation submarine slide sequence, suggesting that they too may have resulted from contemporary earth movements.

Future research

The sedimentology of the Raisby Formation has recently been investigated by Lee (1990, 1993) and there is little immediate scope for further research on this aspect of Dawson's Plantation Quarry. The transported fauna in the disturbed bed and related fall-out deposits, however, are likely more closely to represent the total contemporary benthos than the sparse, selectively-preserved fauna of undisturbed Raisby Formation strata and could repay further study.

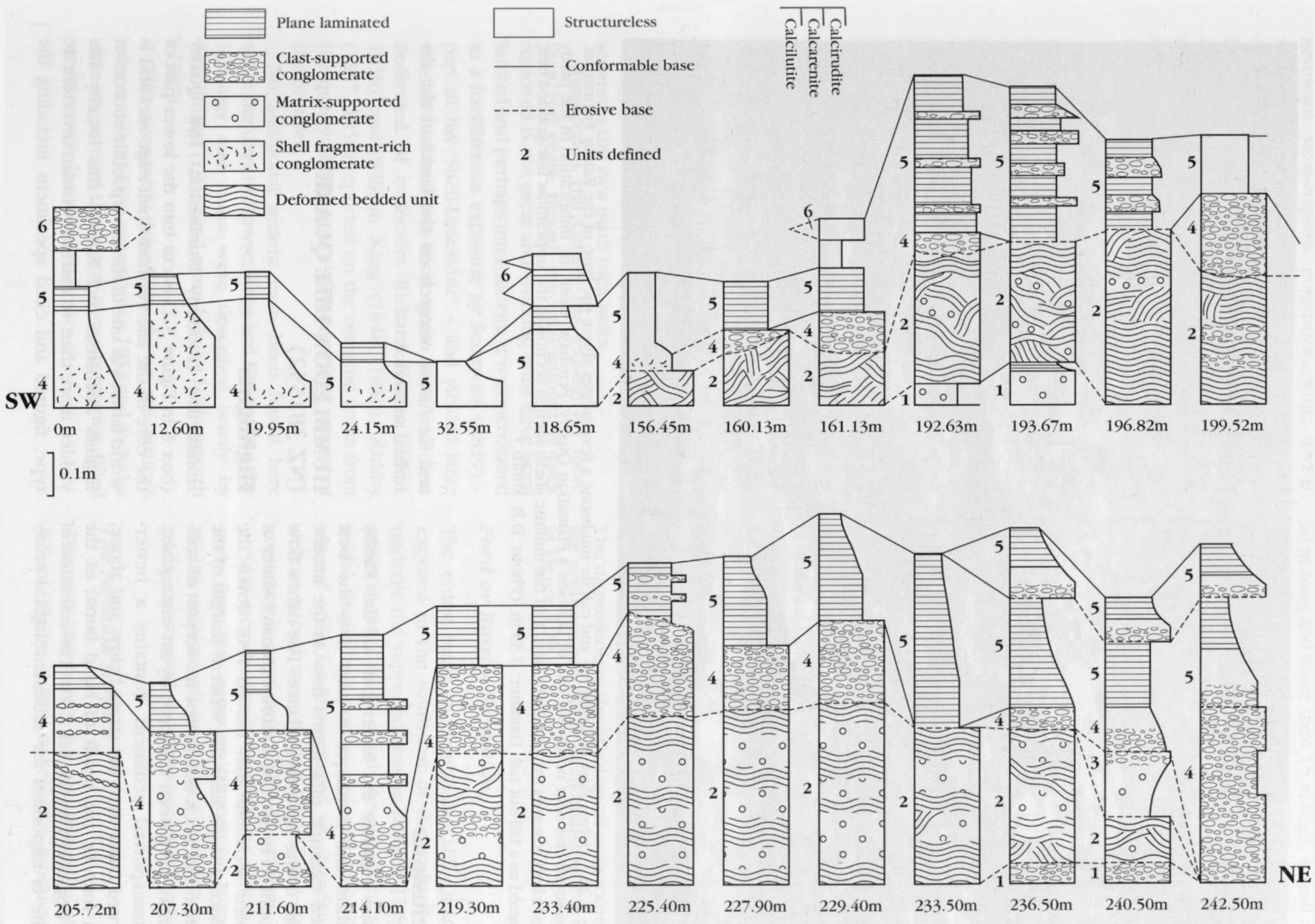


Figure 3.27 Disturbed strata in the Raisby Formation at Dawson's Plantation Quarry, showing their lateral variation. After Lee (1990, fig. 2.21).

Figure 3.26 Debris flow of dolomite- and calcite mudstone a few metres above the base of the Raisby Formation. View to south-east near north-east end of Dawson's Plantation Quarry, Penshaw. Note the imbrication in the partly rounded clasts towards the top of the unit, and the mollusc shells seen in section in the uppermost fine-grained bed, interpreted as a fall-out tail. Hammer: 0.33 m. (Photo: D.B. Smith.)

Conclusions

This site exposes the lower part of the Raisby Formation and is unique in that it is the best exposed example of a debris flow in the marine Permian of the Durham Province. The debris flow is thought to be part of a more extensive sheet of disrupted sediment that moved ENE down the depositional slope near the western margin of the Zechstein Sea. Such downslope movement of sediment may have been triggered by an earthquake. The transported sediment contains a better-preserved fauna than the strata below and above, which may be the result of rapid burial of the shelly organisms on the sea floor. The retention of this site is important for sedimentological study and for future research on the fauna of the disturbed sequence.

HUMBLEDON HILL QUARRY (NZ 381552)

Highlights

Humbledon (formerly Humbleton) Hill Quarry (box 6 in Figure 3.2) is cut into the lower part of the core of the late Permian shelf-edge reef and is world famous as one of the most prolific sources of English Zechstein reef faunas; this locality has yielded more than 40 marine Permian invertebrate type, figured and cited specimens including the brachiopod *Stenoscisma humbletonensis* (Howse) which has been recorded at only one other locality in the region, and the cyclostome bryozoan *Stomatopora voigtiana* (King, 1850) which is thought to be unique world-wide. The quarry contains the best exposure of the contact between the reef and underlying bedded dolomite and, in conjunction with newer roadside sections on the north side of the hill, it provides a transect about 200 m long through the lower part of the reef.

Introduction

Humbledon Hill is a well-known local landmark in the south-western inner suburbs of Sunderland; it is smoothly rounded, roughly circular in plan and 250–300 m across. The hill forms a prominent link in a chain of grassy knolls that mark the position of the shelf-edge reef of the Ford Formation, and the quarry is cut into the steep ENE-facing slope of the hill, not far from the presumed seaward face of the reef; it exposes a thickness of about 15 m of rock in the main excavation and scattered smaller excavations below and above increase the exposed thickness to more than 25 m. Most of the exposed rock is reef dolomite, but the lowest few metres are of sparingly fossiliferous dolomite of uncertain stratigraphical affinity; an apparent erosion surface separates the two main rock units.

Humbledon Hill Quarry has existed for more than 160 years, though the total amount of rock removed is not great and working must have been limited and perhaps intermittent; it was mentioned as a fossiliferous exposure by Sedgwick (1829) – part of his 'Shell-Limestone' – and yielded large numbers of fossils to those great rivals and most dedicated of collectors Richard Howse (1848, 1858) and William King (1848, 1850). Kirkby (1857, 1858) reported on the ostracod fauna from the quarry and Logan (1967) described several of the bivalves.

No additional genera have been found here since the days of Howse, King and Kirkby, but the lithology and fauna were described briefly by Trechmann (1945) and more fully by Hollingworth (1987).

This account is based mainly on the writer's observations of the quarry since 1953 and includes data on parts of the quarry now overgrown, filled or otherwise inaccessible.

Description

The main face of Humbledon Hill Quarry is about 90 m long and more than 15 m high; it, and a little of the adjoining hillslope, comprise the site. The location of the main features of geological interest are shown in Figure 3.28. Parts of the quarry face and much of the hillslope are obscured by vegetation and most of the former quarry floor has been enclosed in private gardens.

The geological sequence in and around the quarry is shown below.

	Thickness (m)
Ford Formation, reef-facies	25+
?Erosion surface	
Ford or Raisby Formation, in south of quarry	2+
Gap	?4–10
Magnesian Limestone (probably mainly Raisby Formation) with Marl Slate at base. Proved beneath drift in nearby well and borehole (two differing records)	82 or 87
Yellow Sands (proved in borehole)	3+

The disposition of the lithological units exposed in the southern part of the main quarry face is shown in Figure 3.29.

Ford or Raisby Formation

The oldest rocks in Humbledon Hill Quarry are exposed in the south-east of the main face and underlie the supposed erosion surface. They comprise about 2 m of evenly level-bedded saccharoidal cream-buff porous dolomite (possibly an altered oolite) with scattered to abundant shell debris; a bed near the middle of the exposed sequence is extremely shelly. Trechmann (1945, p. 341) recorded seven invertebrate genera apparently from this exposure (though his wording is slightly ambiguous), including a bryozoan, brachiopods, a gastropod and two species of bivalves.

The ?erosion surface

This undulate surface has a visible relief of about 0.5 m (Figure 3.29); no erosion products were

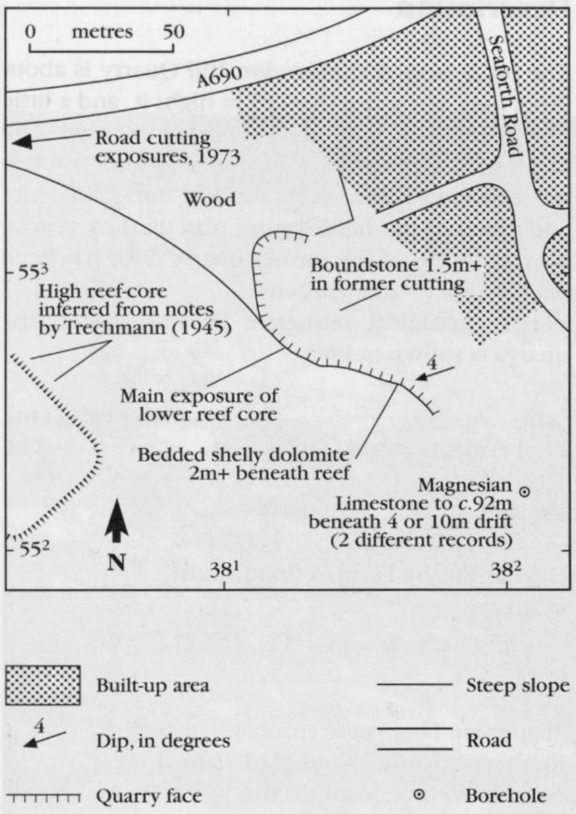


Figure 3.28 Humbledon Hill Quarry and its immediate surroundings, showing the position of the GCR site and the main features of geological interest.

noted on the surface, but overlying dipping rubbly shelly dolomite displays strong onlap. A former 2 m cutting in the quarry floor revealed no bedded dolomite, indicating that the erosion surface in the quarry as a whole has a minimum relief of 2 m.

Ford Formation, reef-facies

Details of the reef-rock in the quarry are somewhat obscured by vegetation and quarry waste, but two main rock types are present: (a) massive hard dolomitized autochthonous bryozoan boundstone (framestone/bafflestone) in ovoid bodies up to several metres across, and (b) tongues, sheets and pockets of crudely bedded dolomitized shelly rubble. The two rock types appear to be randomly distributed relative to each other and both contain scattered cavities after former secondary sulphates.

The biota for which this quarry is renowned is divided unequally between the boundstone and the shelly rubble. Work by Pattison (unpublished British Geological Survey report; Pattison, 1978) on fossils from the adjoining road cutting to the north-west showed that comparable boundstone bodies there contain a relatively low-diversity fauna dominated by *in situ* pinnate bryozoans and small pedunculate brachiopods (Figure 3.30), and Hollingworth (1987, pp. 211–213) broadly confirmed this from smaller collections made in the

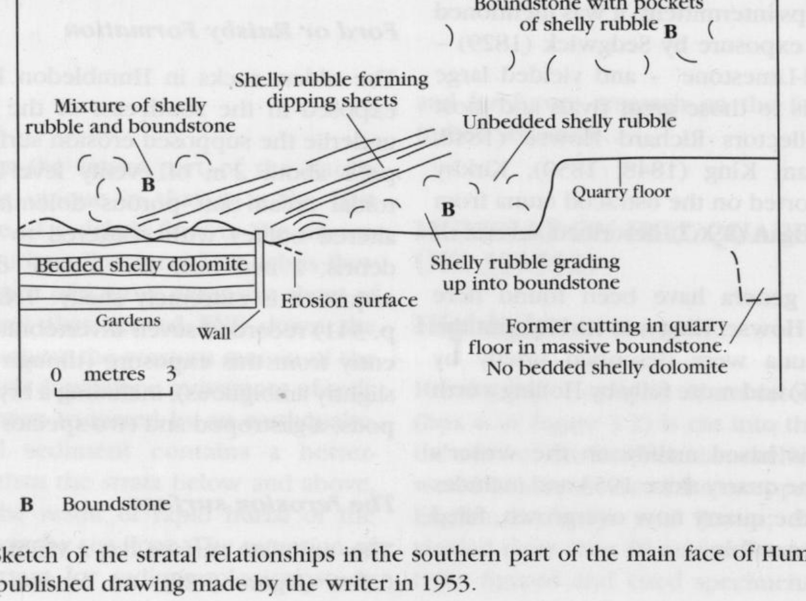


Figure 3.29 Sketch of the stratal relationships in the southern part of the main face of Humbledon Hill Quarry, based on an unpublished drawing made by the writer in 1953.

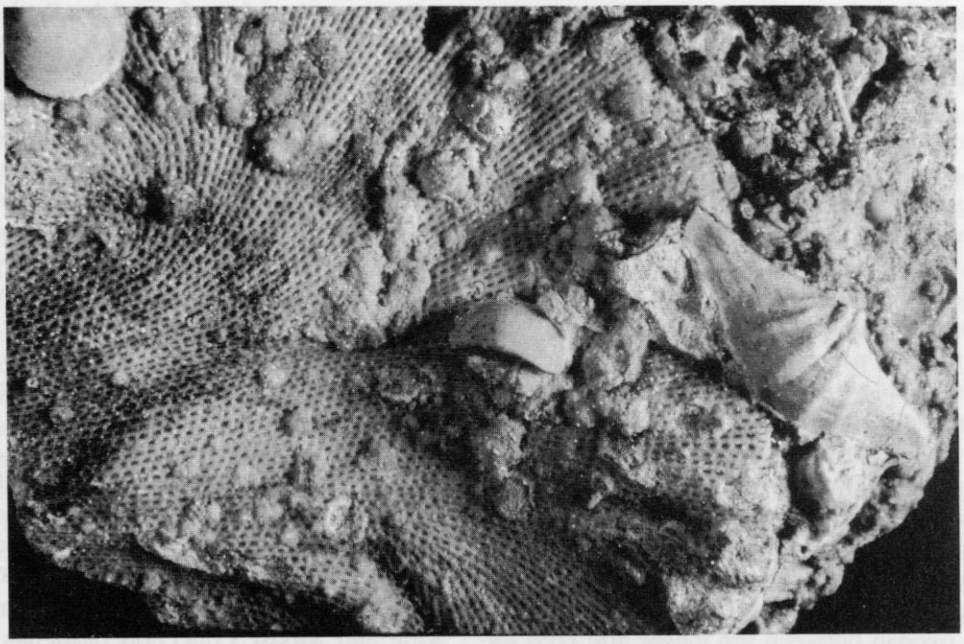


Figure 3.30 Typical elements of the fauna of the boundstone bodies in reef dolomite in Humbledon Hill Quarry, comprising the pinnate bryozoan *Fenestella retiformis* and the pedunculate brachiopods *Dielasma elongatum* and *Pterospirifer alatus*. Field of view about 67 × 100 mm. (Photo: N.T.J. Hollingworth.)

quarry. In contrast, Pattison showed that the enveloping rubble exposed in the cutting contains a highly diverse assemblage of bryozoans, brachiopods, bivalves, crinoids and gastropods. Hollingworth (1987, pp. 212, 216) recorded a similar biota in reef rubble in the quarry, and noted that none of the bryozoan colonies in the rubble were in life position. He inferred that many organisms clearly lived here and were not originally inhabitants of the boundstone bodies. Trechmann (1945) recorded large rolled productids in 'mushy and porous' rock (i.e. rubble) near the base of the reef, and noted that the overall biota remained roughly constant throughout the main face, but became considerably less diverse in small exposures towards the top of the hill behind and above the quarry.

Interpretation

Humbledon Hill Quarry is especially important (a) as the prime source of more than 40 late Permian type, figured and cited marine invertebrate fossils and (b) as one of the best exposures of lower reef-core rocks in the shelf-edge reef of the Ford Formation. Because of the current restrictions on access, the historical aspect is the more important, but the record of the reef-core has assumed additional significance following the unique light thrown on the reef structure by exposures created during the widening of the adjoining road to the north-west in 1973 (see below).

The erosion surface and underlying strata

The significance of the inferred erosion surface beneath the reef at Humbledon Hill Quarry is unknown, and its assessment is complicated by the uncertain stratigraphical age of the underlying bedded dolomite. Similarly uneven inferred erosion surfaces separate reef and underlying beds at an exposure (NZ 3805 5489) some 370 m south of the quarry and also at the Gilleylaw Plantation Quarry site, Silksworth, at both of which the surface has a local relief of about 2 m. Truncation surfaces, indeed, underly reef-rocks at most places where the base of the reef is exposed; in several such exposures the truncation has been ascribed to massive pre-reef submarine slumping (Smith, 1970c), but the thickness of underlying Zechstein strata in these exposures is much less than that at

Humbledon Hill and Silksworth and this explanation may not be appropriate.

The uncertainty regarding the age of the strata immediately beneath the reef in Humbledon Hill Quarry precludes complete understanding of the local stratigraphy and geological history and needs to be resolved; Kirkby (1870) and Woolacott (1912) attributed these beds to the 'Compact Limestone' and 'Lower Limestone' (both now Raisby Formation), respectively, but Trechmann (1945) clearly considered them to be part of the reef; Smith (1969a, 1971b, 1994) tentatively classes them as pre-reef Ford Formation. The argument for a Raisby Formation age presumably was based on their superficial lithological similarity to known Raisby Formation strata beneath the reef at Down Hill, Hylton Castle (not the SSSI) and Claxheugh Rock, but a high content of shell debris is very unusual in upper parts of the Raisby Formation; the faunal list given by Trechmann has little bearing on the problem because of the high species overlap between the Raisby and Ford formations. The argument for a Ford Formation age is based mainly on the height of these strata above the base of the Marl Slate; this is shown by the well and borehole at the adjoining Humbledon Hill Pumping Station to be about 82 or 87 m (two differing records), which greatly exceeds the maximum proved thickness of about 50 m of undoubted Raisby Formation strata in the environs of Sunderland and is comfortably thicker than the maximum exposed thickness of about 45 m of Raisby strata in the general area. Though arguments based on thickness alone are unlikely to be conclusive in a sequence so demonstrably variable as the Magnesian Limestone, the author believes that the thickness and faunal abundance evidence together support a Ford Formation age for the sub-reef strata at Humbledon Hill Quarry. The thickness of these strata is not known, but they exceed 5 m at their main exposure in the sides of Newport Dene (NZ 385542), 1.2 km SSE of Humbledon Hill; they may have been more than 50 m thick in parts of the Sunderland area (Smith, 1994). Farther south, the reef overlies at least 20 m of lagoon-type dolomite in Castle Eden Dene (NZ 4339).

Ford Formation, reef-facies

The importance of the collections of fossils from Humbledon Hill cannot be over-emphasized; they formed a disproportionately large part of King's (1848, 1850) source material and are now housed at University College, Galway, where they provide an invaluable reference set. The collection was fully curated and catalogued by Pattison (1977). None of the genera named by King was unique to Humbledon Hill, though Howse (1848) erected the species *Terebratula humbletonensis* (later referred to *Camarophoria* by Howse (1858) and now *Stenoscisma humbletonensis* by more recent authors), which at that time had not been recorded elsewhere, but which was later reported from Tynemouth by King (1850). Humbledon Hill (presumably the quarry) was listed by Howse (1848, 1858) as a source (though not the only source) of almost 40 genera of Permian marine invertebrates and Trechmann (1945) listed 46 genera from there. Ostracods from Humbledon Hill were described and figured by Kirkby (1857, 1858) and the quarry supplied material to the Kirkby Collection of other Magnesian Limestone fossils, housed at the Hancock Museum, Newcastle upon Tyne. Many specimens of bivalves from Humbledon Hill, including some from both the King and Kirkby Collection (Hancock Museum), were cited and illustrated by Logan (1967). More recently, the quarry was cited as the only source in the world of the bryozoan *Stomatopora voigtiana* (King, 1850) by Taylor (1980) and as one of the sources of the crinoid *Cyathocrinites ramosus* (Schlotheim) described by Donovan *et al.* (1986). The precise source within the quarry of the type, figured and cited specimens is not clear from the literature, but it is probable that most were collected from the rubbly parts of the main face.

The variability of the reef-rock at Humbledon Hill Quarry was first noted by Howse (1848), who mentioned 'hard somewhat crystalline' and 'earthy and rubbly' varieties; Trechmann (1945) referred to both massive and mushy varieties. Presumably these equate with the autochthonus boundstone and shelly rubble mentioned earlier. The widening of the adjoining road exposed a 125 m transect through the reef a short distance west (i.e. landward in a palaeoenvironmental sense) of the quarry (Smith, 1981a, 1994; Hollingworth, 1987) and revealed that the boundstone there forms discrete to grouped ovoid masses up to several metres across (but generally 1–2 m) that are embedded randomly in the shelly rubble; they increase in proportion towards the ENE (i.e. towards the quarry and reef crest). This key exposure, taken in conjunction with that of the quarry, shows that this part of the reef, when formed, comprised patchily distributed bryozoan thickets or compound colonies, each with a low-diversity specialized associated biota and a relief of a few decimetres, lying on and in (and subsequently covered by) a variable mosaic of bioclastic debris derived from and supporting a highly diverse invertebrate community.

Many of the bryozoans in the boundstone masses are thickly invested with lamellar encrustations, which doubtless contributed bulk and stiffening (and possibly cement), but no evidence of contemporaneous cementation of the shelly rubble has been recorded. Some of the boundstone masses are themselves coarsely concentrically layered, presumably as a result of intermittent growth.

The fauna of the reef-rock at Humbledon Hill Quarry is typical of that of the lower and middle parts of the reef-mass, and was assigned by Hollingworth (1987) to the lower reef-core; the Humbledon Hill exposures, together with that at Hylton Castle site, provide the basis for his portrayal of a typical lower reef-core community (Hollingworth, 1987, fig. 6.12; Hollingworth and Pettigrew, 1988, fig. 8). The reef-base coquina, commonly found elsewhere beneath the reef, is absent at Humbledon Hill, and Trechmann's (1945) record of faunal impoverishment at the top of the hill suggests that high reef-core rock is present and may imply that the reef is unusually thin (and perhaps condensed) here. The lack of evidence of strong contemporaneous erosion in the reef and fossils at Humbledon Hill and similar exposures, and of sedimentary structures in the rubble, points to accumulation in relatively low-energy conditions below wave base (Smith, 1981a; Hollingworth, 1987) and is consistent with Hollingworth's assessment of the living conditions of the faunal community.

Neither the biota nor the structure of the reef dolomite in the quarry provide evidence of proximity to the reef slope, which therefore probably lay at least 30 m east of the main exposure.

The isolation of Humbledon Hill from other known areas of late Permian reef-rock, coupled with its rounded outlines, invited speculation that it might be a link in a chain of reef knolls (Trechmann, 1913, 1925, 1945); the newly-exposed reef-rock along the north side of the hill shows no evidence of lateral passage into bedded rocks or of an approach to a reef margin, however, and it now seems more likely that the knoll-like form of the hill is an erosional feature in an otherwise relatively continuous shelf-edge reef. Similar doubts regarding two rounded hills of reef-rock between West Boldon and Hylton Castle were resolved in 1959 when temporary excavations in the floor of the intervening valley revealed almost continuous reef-rock. The reef is known to form an east-facing NNW/SSE belt extending from West Boldon to Hartlepool, and may once have extended farther; it marks the seaward margin of the carbonate rocks of Sub-cycle 2 of English Zechstein Cycle 1 (Figures 1.4, 3.1 and 3.2). Other GCR sites in rocks of the shelf-edge reef are at Hylton Castle Cutting (Sunderland), Ford Quarry, Cutting and Claxheugh Rock (Sunderland), Tunstall Hills (Sunderland), Stony Cut, Hawthorn Quarry and Horden Quarry; each reveals aspects and parts of the reef that are different from those seen at Humbledon Hill, though the fauna at Humbledon Hill and Tunstall Hills have much in common.

Future research

Restrictions on access now hinder research on all aspects of the reef-rocks in Humbledon Hill Quarry, though many features formerly seen in the quarry may still be seen and investigated in the adjoining road cutting. Opportunities for fossil collecting are now severely limited, but large numbers of fossil specimens from the quarry are available for study at the British Museum of Natural History, the Hancock Museum (Newcastle upon Tyne), Sunderland Museum, University College (Galway) and the British Geological Survey, Keyworth.

Conclusions

The site is internationally famous for its fauna. It has yielded a rich variety of invertebrate fossils characteristic of the English Zechstein reef; in particular, the bryozoan *Stomatopora voigtiana* (King, 1850) is considered to be unique worldwide. The site was formerly one of the best exposures of lower reef-core rocks in the Ford Formation and of the erosion surface immediately beneath the reef. Although access to the site is now restricted, it remains one of major importance for the study of late Permian reef faunas in the Durham Province.

TUNSTALL HILLS, SUNDERLAND; MAIDEN PAPS AND THE TUNSTALL HILLS (ROCK COTTAGE EXPOSURE) (NZ 3954)

Highlights

The twin mounds of Maiden Paps at the north-west end of Tunstall Hills (box 7 in Figure 3.2) are probably the best-known topographical expression of the shelf-edge reef of the Ford Formation and also contain a number of the most important exposures of fossiliferous reef-rock; these include a large exposure of reef-core in the more southerly mound, which also features several steeply-dipping laminar sheets and tension gashes. The nearby 'Rock Cottage' exposure is unique in revealing highly fossiliferous primary limestones at the base of the reef, which bear evidence of contemporary sea-floor cementation. More than 50 type, cited and illustrated fossils are from Tunstall Hills, and at least two species of fossil invertebrates carry the name *tunstallensis*.

Introduction

Maiden Paps are two prominent local landmarks (see Hollingworth, 1987, appendix D, fig. 3) in the southern outer suburbs of Sunderland; they form part of a chain of knolls that mark the position of the shelf-edge reef of the Ford Formation between West Boldon (NZ 3460) and Horden (NZ 4341). The hilltops are excellent vantage points for viewing the close relationship between the local geology and scenery and afford a superb view to the west of the low-lying floor of the former glacial Lake Wear and its associated drainage channels.

Reef-rocks, mainly of limestone, but some of dolomite, make up all the exposures at Maiden Paps and total perhaps 35 m in thickness. The more northerly of the mounds is mainly grass-covered and now bears only a single small quarry exposure of shelly dolomite near its northern extremity; in contrast, the southern mound bears many exposures including a north-facing quarry cliff of reef limestone (8 m+). Slightly farther south is the famous 'Rock Cottage' exposure of reef-base limestone coquina.

The shelly rocks of Tunstall Hills have been known since the writings of Winch (1817) and Sedgwick (1829) and, together with those at Humbledon Hill, were the main collecting ground for Howse (1848, 1858), King (1848, 1850) and Kirkby (1857, 1858, 1859); few additional species have been found here since 1860, though long lists were given by Trechmann (1945), Logan (1967), Pattison (internal Geological Survey report, 1966) and Hollingworth (1987). Hollingworth also gave a faunal list from the 'Rock Cottage' exposure, where some of the gastropods have retained part or all of their original colour (Hollingworth, 1987; Hollingworth and Tucker, 1987; Hollingworth and Pettigrew, 1988).

Analyses of the reef-rocks were given by Aplin (1985), who also illustrated (p. 378) the main face and discussed the complex diagenetic history of the reef. Burton (1911), Woolacott (1912) and Trechmann (1945) noted the presence of coarse, frosted, quartz sand grains in fissures in the main face and the origin and filling of the fissures was discussed by Smith (1981b) and Aplin (1985). The diagenesis of the coquina at the base of the reef in the 'Rock Cottage' section was detailed by Tucker and Hollingworth (1986) and Hollingworth and Tucker (1987), who also drew conclusions on some general aspects of early reef history.

Working of the quarries ceased more than a century ago, but the discovery of the 'Rock Cottage' reef-base limestone by Hollingworth in 1983 was followed by NCC-funded excavation to help in GCR assessment and the exposure has since been enlarged and fenced by the Sunderland Borough (now City) Council.

Description

Rock exposures at and near Maiden Paps include the main face cut into reef-core limestone on the north side of the southern mound, a small quarry (NZ 3910 5472) in reef slope dolomite at the foot of the north slope of the northern mound and the small exposure of basal coquinoid limestone (NZ 3910 5432) high on a wooded slope about 70 m south of 'Rock Cottage' (shown on Ordnance Survey maps as 'Tunstall Hills Cottage'). The position of the above exposures is shown in Figure 3.31 which also shows the positions of several minor exposures.

The north face of the main quarry (a) is about 8 m high and 30 m across, but the exposure also extends a short distance south-eastwards on the north-east side of the hill and rather farther southwards on the west side (Figure 3.31). Although at first sight almost unbedded, close inspection reveals hints that parts of the rock, like that at Humbledon Hill and Hylton Castle Cutting, may comprise rounded 1–3 m masses of bryozoan boundstone that are separated and surrounded by vaguely bedded shelly rubble; in places small *Dielasma* shells in life position form dense swarms attached to boundstone masses that were, by inference, already lithified.

The abundance of fossils for which Tunstall Hills was noted in the past is less noteworthy now,

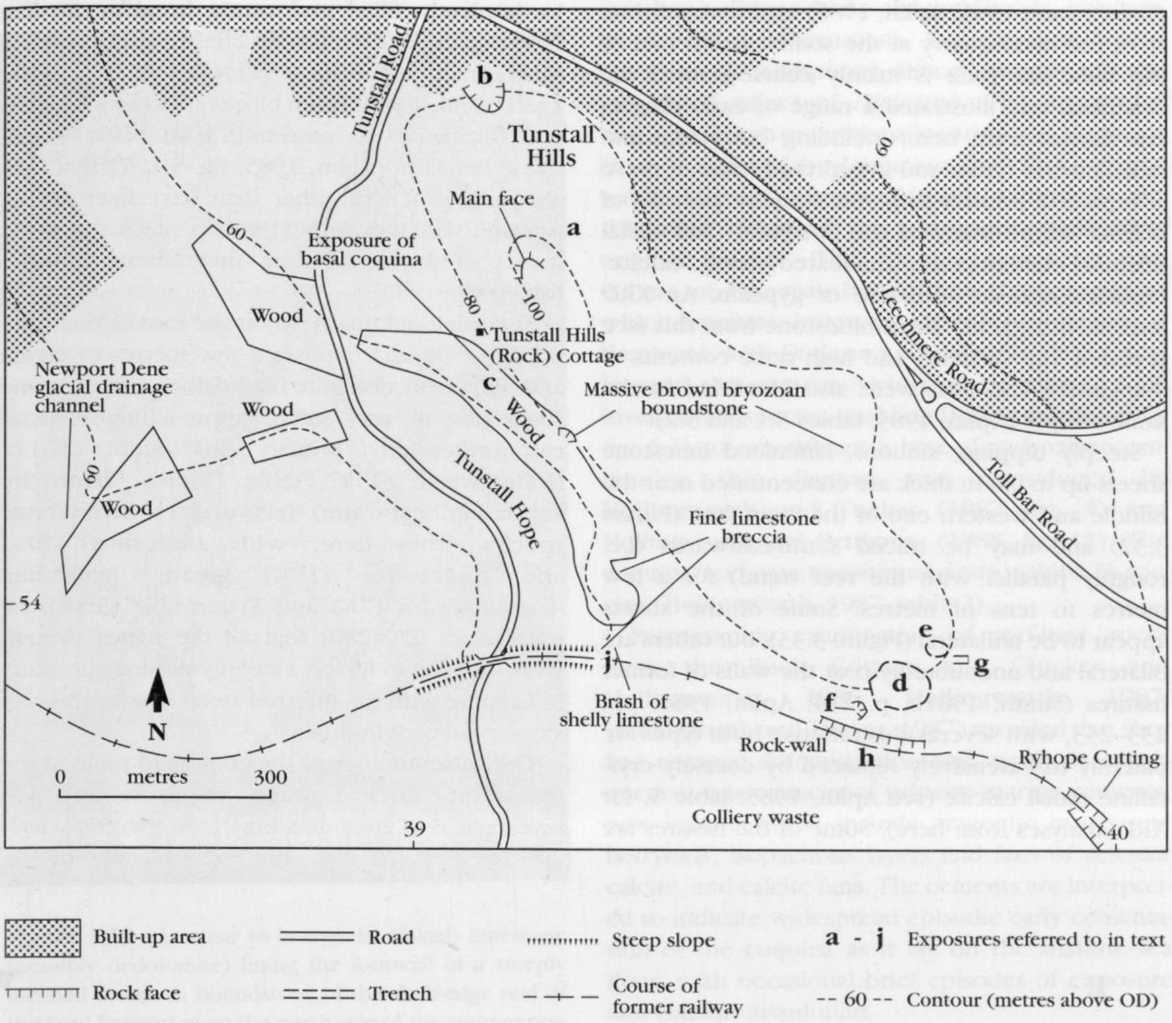


Figure 3.31 Tunstall Hills (north and south), showing the position of the main exposures and features of geological interest.

though locality citations in the early (and some of the later) works were generally limited to 'Tunstall Hills' or 'Tunstall' and the precise point of origin cannot now be identified. These localities, presumably, though not undoubtedly, referring to Maiden Paps, were a source of more than 50 type, cited and/or illustrated individuals for King (1848, 1850), almost 40 for Howse (1848, 1858) and more than 40 for Trechmann (1945) who gave some precise locality details; Logan cited the hills as a source of almost 30 species of bivalve and illustrated several from here. The main face (a) yielded 16 species to Hollingworth (1987, table 7), with *Dielasma* forming 38% and *Bakevellia* (*Bakevellia*) 21% of the fauna; he described the assemblage as of low diversity, with less than 10% of bryozoans, and combined the data from here with that from the main quarry at the south-eastern end of the hills and from Humbledon Hill, to reconstruct a model of a reef-core palaeocommunity (Hollingworth, 1987, fig. 6.15, reproduced as fig. 6 in Hollingworth and Tucker, 1987 and as fig. 16 in Hollingworth and Pettigrew, 1988). Fossil preservation ranges from poor to extremely good, even in single specimens. In several substantial parts of the face, particularly near the centre-top, bryozoan and other frame-building elements are thickly coated with concentric ?algal encrustations that locally form almost all of the rock.

Most of the rock in the main face and adjoining exposures is of hard, crystalline, brown, ferruginous limestone with abundant coarse radial calcite

(Trechmann, 1945; Aplin, 1985). Aplin noted that, as in the main quarry at the south-eastern end of the hills, the rock is mainly coarse-grained; he described and illustrated a range of early diagenetic fabrics from here, including botryoidal and radial-fibrous types, and interpreted some of these as replaced, primary aragonite cements possibly of marine origin; many of the botryoidal and radial fibrous cements are nucleated onto calcite-replaced nodular anhydrite or gypsum. An XRD analysis of algal bryozoan bindstone from this face revealed 100% calcite, and high trace contents of manganese and iron were also identified in the same sample (Aplin, 1985, tables 5.1 and 5.2).

Steeply dipping, sinuous, laminated limestone sheets up to 0.6 m thick are concentrated near the middle and western end of the main face (Figure 3.32) and may be traced south-eastwards (i.e. roughly parallel with the reef trend) for a few metres to tens of metres. Some of the sheets appear to be unilateral (Figure 3.33), but others are bilateral and undoubtedly coat the walls of former fissures (Smith, 1981b, p. 174; Aplin, 1985, pp. 233–253, with several illustrations); both types are patchily to extensively replaced by coarsely crystalline radial calcite (see Aplin, 1985, table 5, for XRD analyses from here). Some of the fissures are incompletely filled and retain irregular median voids; others contain frosted, coarse quartz sand grains (Burton, 1911; Woolacott, 1912; Trechmann, 1945), fallen blocks of reef-rock (some now thickly coated; see Smith, 1994, plate 15) and a few bioclasts (Aplin, 1985, fig. 5.12C) that may also have fallen in rather than have been in life position. Hollingworth (1987, p. 220) found no fossils of fissure-dwelling invertebrates in the fissure fill.

The small old quarry (b) at the foot of the more northerly mound exposes a few metres of cream and buff shelly dolomite boundstone with a strong suggestion of very steep (approaching vertical) east-northeasterly ?primary dips (Smith, 1981a). Hollingworth (1987, table 13, his 'Electricity Substation' exposure) recorded 14 invertebrate species from here, with *Dielasma* (40%) and *Bakevellia* (18%) greatly exceeding *Acanthocladia* (7%) and *Synocladia* (5.5%); he noted (pp. 279–280) that all the forms present were adapted to life on a steeply-sloping substrate, in keeping with the inferred steep dips of this reef slope palaeoenvironment.

The palaeontology of the coquinoid rocks at the important 'Rock Cottage' exposure (c) was investigated in great detail by Hollingworth (1987)

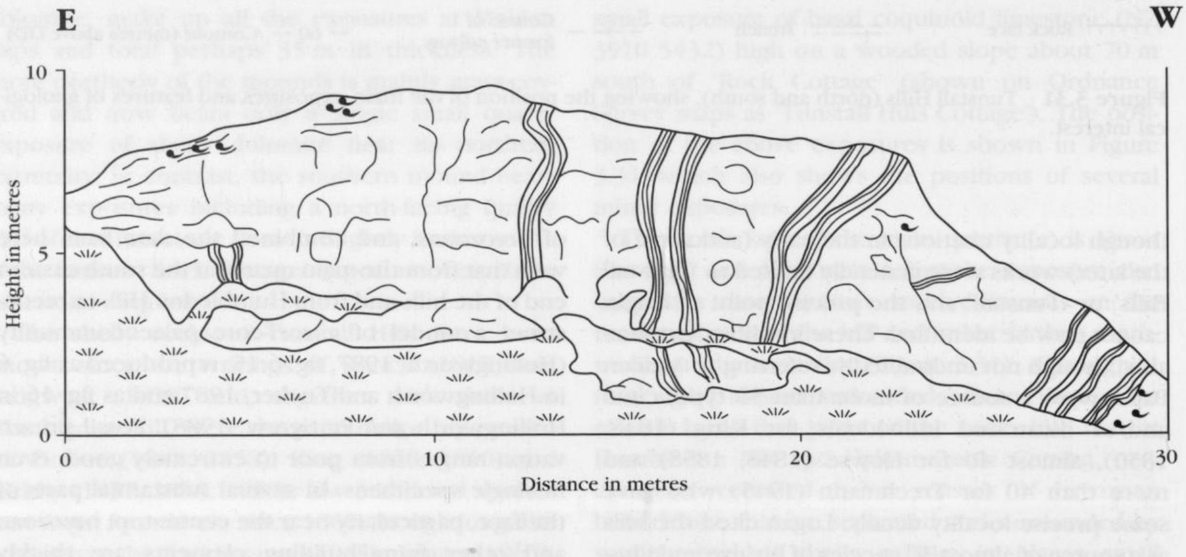


Figure 3.32 The main quarry face on the north side of the more southerly of Maiden Paps, Tunstall Hills. Most of the rock is brown bryozoan boundstone, locally with profuse encrustations. At least two of the tension gashes have partial central voids. Simplified from a sketch by Aplin (1985, p. 378).

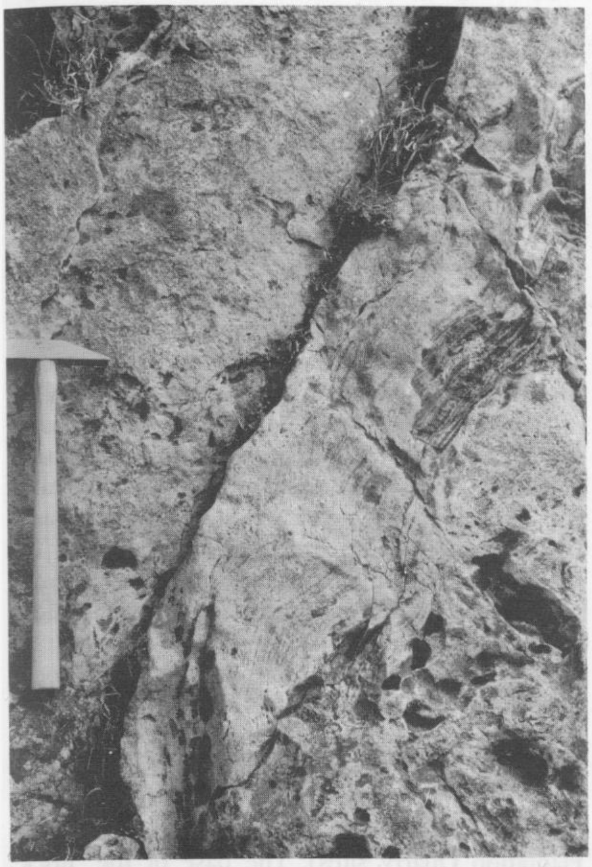


Figure 3.33 Laminar to botryoidal (?algal) limestone (possibly dedolomite) lining the footwall of a steeply inclined fissure in boundstone of the shelf-edge reef of the Ford Formation on the north side of the main exposure at Tunstall Hills (north). Hammer: 0.33 m. (Photo: D.B. Smith.)

and their petrology was described by Tucker and Hollingworth (1986) and Hollingworth and Tucker (1987). The base of the coquina is not exposed, but the lowest part of the new excavation lies only a few metres up the hill from temporarily exposed, sparsely fossiliferous, well-bedded 'dolomicrite'; the outcrop of the coquina may be traced south-eastwards for about 100 m, but then ends abruptly at the High Barnes fault which has an estimated downthrow south of 25 m. According to Hollingworth (1987, pp. 170–173), the coquinoid limestone comprises a crumbly basal unit (0.6 m+) of 'pale cream to buff, well-bedded, calcified coquina overlain by dark brown, iron-rich, partially decalcified coquina' (about 2 m) which, in turn, is succeeded by about 3 m of 'slightly more massive buff-brown, crystalline coquina'. The basal unit has a diverse biota of brachiopods, bivalves, gastropods and bryozoans, but the dark brown limestone is composed almost entirely of the articulated valves of *Dielasma*. The uppermost unit contains an exceptionally varied and abundant fauna dominated by *Dielasma*, and also contains teeth of two genera of fish (*Janessa* and *Wodnika*); some of the gastropods retain their original colours. The coquina passes up into 0.4 m+ of bryozoan boundstone (framestone) in which fenestrate bryozoans (mainly *Fenestella*) are dominant, with *Dielasma* persisting in abundance. In total the coquina yielded the remains of 23 invertebrate species, enabling Hollingworth (1987, fig. 6.3) to reconstruct a base-of-reef palaeocommunity; this diagram was reproduced by Hollingworth and Tucker (1987, fig. 4) and Hollingworth and Pettigrew (1988, fig. 15). The coquina/reef-core transitional strata yielded 26 species (Hollingworth, 1987, table 2).

Petrographic examination of reef-base rocks from the Rock Cottage site (Tucker and Hollingworth, 1986; Hollingworth, 1987; Hollingworth and Tucker, 1987) revealed that they had escaped dolomitization and, partly in consequence, retain traces of primary marine cements, now calcite; these include aragonite crusts and botryoids, isopachous layers and fans of acicular calcite, and calcite fans. The cements are interpreted to indicate widespread episodic early cementation of the coquina as it lay on the shallow sea floor, with occasional brief episodes of exposure and cement dissolution.

Interpretation

The shelf-edge reef of the Ford Formation features in, or is the main constituent of, seven GCR sites in north-east England, each exposing different subfacies; taken together they reveal much of the structure, character and history of the reef. The designated sites are scattered unevenly along the outcrop, and comprise (from the north) Hylton Castle road cutting, Claxheugh Rock and adjoining exposures, Humbledon Hill, Tunstall Hills (both ends), Stony Cut, Hawthorn Quarry and Horden Quarry (Table 3.1); in general the more northerly sites expose the low and middle parts of the reef and the southern sites expose the higher parts.

Some information on the distribution of the reef is given in the accounts of the other reef sites herein, and was summarized by Trechmann (1925, plate 15) and Smith (1981a, fig. 9). There are, however, still many places where the information is too poor to allow precise delineation and the maps, accordingly, are locally little more than speculative; this is particularly so in low-lying areas, where the ridge or topographic step that normally indicates the position of the reef is missing and thick drift deposits cover the rock. The correspondence between topography and reef is generally good at Tunstall Hills, however, with the north-west to south-east ridge probably closely following the reef slope on its eastern side; some erosion of the western side has undoubtedly reduced the width of the reef there, but the hills as a whole are only a little narrower than the usual 300–600 m reef width. The inferred correspondence between the eastern side of the ridge and the reef foreslope is strongly supported by the presence of Cycle EZ2 collapse-breccias in the Ryhope Cutting at the south-eastern end of the hills and by the observed juxtaposition of the reef slope with post-reef collapse-breccia in hill-slope exposures at Easington Colliery (NZ 436437) and Horden (NZ 435417).

In greater detail, Tunstall Hills are important as one of the two main source localities of fossils reported on by King, Howse, Kirkby, Trechmann, Logan and Hollingworth, though locality information given by the early authors was generally vague. The exceptionally large collections of well-preserved fossils made by Hollingworth from the precisely located 'Rock Cottage' exposure is especially significant for the light it throws on the palaeocommunity of the reef-base coquina; this exposure is also noteworthy for the evidence of early cementation and the inference of shallow-water deposition of the coquina uniquely preserved here (Tucker and Hollingworth, 1986; Hollingworth and Tucker, 1987). Though lacking a framework and therefore not being a true reef, the cemented coquina nevertheless provided a firm substrate upon which the succeeding reef could be constructed.

The main face (a) of reef-core limestone affords by far the best exposure of steeply-dipping laminar sheets in the Cycle EZ1 reef and is one of the two main exposures investigated by Aplin (1985) in his study of coarsely crystalline partly secondary reef limestones. The origin of the laminar sheets remains somewhat uncertain because, although some are clearly bilateral fissure-fill, others that are lithologically similar lack deposits on a hanging wall and may be primary reef-surface encrustations (Smith, 1981a; Aplin, 1985). The fissures presumably resulted from tension caused by unequal support around the reef crest and the steep (50–90°) upper reef slope, and their presence is an additional indicator of early cementation of the reef; similar fissures occur in comparable parts of many major shelf-edge and barrier reefs, including the famous Capitan Reef of New Mexico and West Texas. Aplin's exhaustive study of the laminar limestone sheets suggested that they were mainly early and of marine origin, but that some could be inorganic subaerial flowstones (speleothems); this latter interpretation, coupled with the presence of ?wind-blown quartz sand grains in at least one fissure, suggests a phase or phases of subaerial exposure of the reef (Trechmann, 1945; Aplin, 1985).

The host limestones at Maiden Paps, like those in the main quarry at the south-east end of Tunstall Hills, were thought by Aplin to have resulted from the calcitization of partly dolomitized limestones and are therefore, in part, dedolomites; many of the fabrics, he commented, are probably neomorphic replacements of primary aragonite and high magnesium-calcite.

The topographically high level of the 'Rock Cottage' exposure (about +78 m O.D.) and the presence of sparingly fossiliferous dolomite a few metres lower provides further evidence of the marked primary relief of the base of the reef (see interpretation of the Humbledon Hill and Gilleylaw Plantation Quarry sites). The base of the 'Rock Cottage' exposure lies an estimated 103 m above the Marl Slate, in an area where the intervening Raisby Formation is unlikely to be more than 50 m thick and the Yellow Sands to be no more than a few metres thick; it follows that at least 50 m of bedded dolomite of the Ford Formation probably underlies the reef-base at 'Rock Cottage'.

Future research

The overall structure and stratigraphical position of the reef-rocks here are still only poorly understood and require further investigation (though this would probably necessitate drilling or the creation of additional surface exposures), and the age and origin of the fissure-fill and other laminar sheets remains uncertain.

Conclusions

The site is one of a series of GCR sites which highlight the shelf-edge reef of the Ford Formation in north-east England. This series includes a number of important exposures of fossiliferous reef-rock, and one exposure of the underlying reef-base coquina. Both reef-core and reef slope rocks are exposed, the former comprising masses of bryozoan-rich rocks surrounded by shelly rubble, and the latter characterized by very steeply-dipping, sparingly shelly dolomites and limestones. The coquina contains a varied and abundant fauna, which has allowed workers to reconstruct a base-reef community. The former shape of this part of the reef and its relationship to the surrounding rocks is still not well understood, and further study is required. Although exposures are now limited, the preservation of this site is important for the overall understanding of late Permian reef development.

TUNSTALL HILLS (SOUTH-EAST END) AND RYHOPE CUTTING (NZ 395538–399537)

Highlights

The group of exposures (boxes 8a and 8b in Figure 3.2) at the south-eastern end of Tunstall Hills is unique in including a readily accessible large exposure of debris-rich foreslope beds of the shelf-edge reef of the Ford Formation, here overlain by massive *in situ* reef. Slightly east of the reef is an excellent exposure of the younger residue of the Hartlepool Anhydrite Formation, which is in turn overlain by rocks of the Roker Dolomite Formation; the latter were almost totally brecciated (broken up) by foundering for at least 50 m when the anhydrite was dissolved by percolating groundwater.

Introduction

The exposures of reef-rock here form an integral part of the ridge that extends south-eastwards for almost a kilometre from Maiden Paps; they comprise one large and several small quarries cut into the hill itself and a rock-wall cut into the base of the southern extremity of the hill to accommodate a former railway. The quarries are all in massive reef dolomite and limestone with a relatively varied fauna dominated by bryozoans, brachiopods, gastropods and bivalves, and the rock-wall is in eastward-dipping reef debris and interbedded low reef slope deposits, the latter with their own distinctive assemblage of fossils.

The off-reef exposure is in a former railway cutting some 220–270 m ESE of the easternmost exposures of reef-rock; it comprises 2 m+ of bedded reef-equivalent dolomite overlain by 1–6 m of powdery and brecciated dolomite which, in turn, is succeeded by foundered collapse-brecciated Roker Dolomite. The north-western part of the cutting was preserved and re-excavated by the local council for research and teaching purposes when the remainder of the cutting was filled in 1981.

Early references to the reef-rocks at Tunstall Hills are too imprecise for locations mentioned to be identified now, though it is possible that all the various exposures were grouped together for reporting purposes; if this were so, fossils from the south-eastern end of the hills could have been included in the fossil lists published by, for example, King (1848, 1850), Howse (1850, 1858) and Kirkby (1857, 1858, 1859). Analyses of reef-rock by Trechmann (1914, p. 241) seem likely to be from the large quarry at this end of the hills, however, and brief comments on the reef-rock in this same quarry were made by Trechmann (1945, p. 344). Logan (1967, plate 4) later cited the quarry as the source of a hypotype of *Bakevellia* (*Bakevellia*) *ceratophaga* (Schlotheim) and Smith (1971b) summarized the main features of the geology. Further details were given in a series of excursion guides and reports (e.g. Smith, 1973a, 1981d) and by Smith (1981a, 1994). Finally, the petrology and diagenesis of the reef-rocks here were investigated in depth by Aplin (1985) and the faunal communities in the reef were analysed and discussed by Hollingworth (1987) and Hollingworth and Pettigrew (1988).

The earliest detailed reference to rocks in the railway cutting was by Trechmann (1954, p. 198), who listed the fauna in the lowest beds exposed and interpreted the overlying powdery dolomite breccia as 'a sort of mylonite' associated with a thrust plane; this dolomite was later reinterpreted as the dissolution residue of the Hartlepool Anhydrite by Smith (1971a, 1972) and the overlying breccia was interpreted as the foundered remains of the Cycle EZ2 carbonate unit.

The nomenclature used in this account follows traditional practice except that, to avoid confusion, the term 'Ryhope cutting' is restricted to the former railway cutting at Ryhope and the former half-cutting starting some 220 m farther WNW is referred to as the 'rock-wall'.

Description

The several parts of the site at the south-east end of Tunstall Hills and the Ryhope Cutting are shown in Figure 3.31, which also shows the main features of geological interest.

Exposures of reef-rocks of the Ford Formation

These comprise the main quarry ('d' in Figure 3.31), two smaller quarries (e, f), a trench (g) and a large artificially steepened rock wall (h); the position of a number of minor additional exposures (j) is also shown in Figure 3.31. The mutual relationship of exposures (d to h) is shown in Figure 3.34.

The main quarry (d) is about 80 m across and exposes up to 15 m of massive buff to brown algal–bryozoan boundstone (framestone/bafflestone) with several sinuous anastomosing thin sheets of complexly laminar bindstone that dip eastwards at 15–70°; western parts of the quarry are interpreted as lying in the reef-core with eastern parts approaching the mid reef slope (Smith, 1981a, fig. 3; Hollingworth, 1987, fig. 1.6; Hollingworth and Pettigrew, 1988, fig. 4). The fauna of the main quarry was listed by Pattison (Geological Survey internal report, 1966) and Hollingworth (1987, table 8), and was discussed by Hollingworth (1987) and Hollingworth and Pettigrew (1988, their locality 7, 'Tunstall Hills East'); Hollingworth showed that the fossil assemblage is broadly typical of the reef-core, with *Dielasma* being numerically dominant (34%) and fenestrate bryozoans totalling 16%. Many of the fossils are unusually well preserved in the limestones (Smith, 1981a; Aplin, 1985; Southwood, 1985; Hollingworth, 1987; Hollingworth and Pettigrew, 1988) and Smith (1981a) and later authors have speculated that the structures in these partly secondary rocks might have been inherited from primary fabrics that are less clear in the intervening dolomite stage.

Most of the rock in the main quarry is of coarsely crystalline, iron-stained limestone with very coarse replacive calcite spherulites concentrated along the western side (Trechmann, 1914, 1945; Aplin, 1985). Trechmann (1914, p. 241) quoted three analyses of limestone from this quarry and one photomicrograph (plate 36.4) and Aplin (1985, table 5.1) presented two analyses and several photomicrographs (figs 5.4, 5.4, 5.6, 5.8, 5.9, 5.17C and 5.18B); calcite was shown to be predominant in all five rocks analysed, with less than 4% of dolomite in each, but extensive petrographic examination by Aplin of these and other rocks

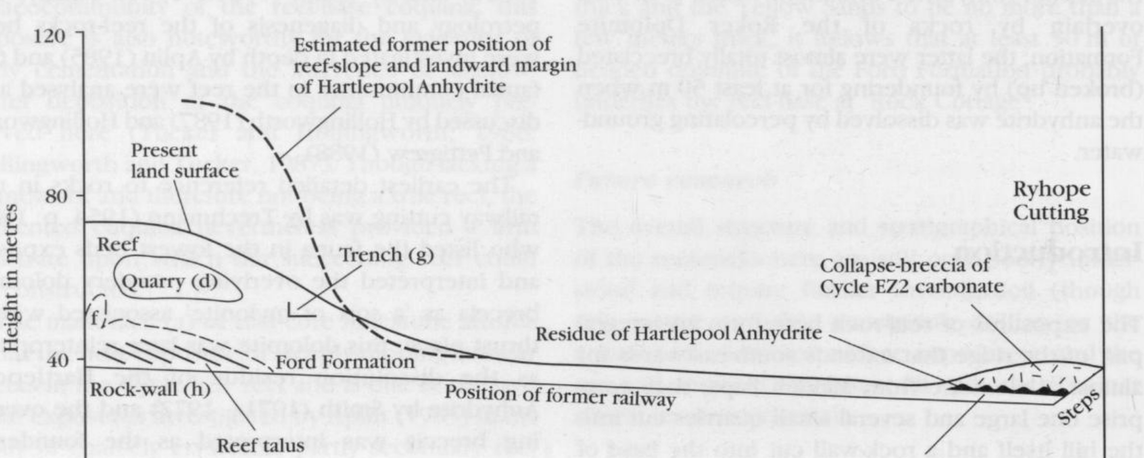


Figure 3.34 Relationships of reef and off-reef (including post-reef) strata at the south-east end of Tunstall Hills and in the Ryhope Cutting (diagrammatic). See Figure 3.31 for the location of the various exposures.

from the quarry revealed a complex diagenetic history and at least some calcite replacement of dolomite and gypsum/anhydrite. Preservation of primary fabrics is generally good in much of the limestone and reveals evidence of former marine botryoidal and fibrous ?aragonite cements (Aplin, 1985); complex ?algal encrustations coat many of the bryozoan frame elements (Smith, 1981a, fig. 26; Aplin, 1985, fig. 5.6) and in places form most of the rock (Figure 3.35). Boundstone masses such as characterize the reef-core at Humbledon Hill are fewer here, though an excellent example of a 1.8 m concentric algal–bryozoan subspherical mass lies in the extreme south-east corner of the quarry. The sinuous laminar bindstone sheets are mainly less than 0.2 m thick and some extend for the full height of the quarry face; some appear to be unilateral, having accreted only basinwards, but others appear to be bilateral and presumably coat the walls of fissures in a fully lithified host rock.

The small old quarry ('e' in Figure 3.31; NZ 3975 5394) situated a short distance north-east of the main quarry, is cut mainly into hard, massive, brown, crystalline, slightly dolomitic limestone similar to that in the main quarry and is interpreted as reef-core facies approaching the middle of the reef slope. The rock appears to be formed mainly of hard, crystalline bryozoan boundstone (framestone/bafflestone) with pockets and irregular sheets of shelly rubble; the rubble dips predominantly south-eastwards at 10–25°, but local westward dips also occur. The fauna of the quarry has not been specially studied, but crinoid debris is abundant locally. Very coarse calcite spherulites form much of the rock near the south-east corner of the quarry.

The small old quarry ('f' in Figure 3.31; NZ 3964 5386) immediately south-west of the main quarry lies at a lower topographical and stratigraphical level and exposes massively rubbly high-foreslope reef talus. The major clasts in the talus are of algal–bryozoan boundstone superficially similar to that in the main quarry, but work by Aplin (1985) shows that the limestone is generally more finely

Figure 3.35 Dense ?algal encrustations in reef boundstone in the main old quarry (d) at the south-east end of Tunstall Hills. Delicate bryozoan frame elements form less than 5% of the rock. Coin: 26 mm across. (Photo: D.B. Smith.)

crystalline and that, paradoxically, primary fabrics are less well preserved; the limestone contains abundant dolomite relics. Aplin states (p. 260) that the talus interdigitates westwards into *in situ* reef-rock, here represented by unbedded dolomite algal–bryozoan boundstone in a large face that extends westwards from the small quarry.

The trench ('g' in Figure 3.31; NZ 3978 5392) lies about 40 m north-east of the main quarry and topographically slightly lower. It is about 1.5 m deep and is cut into brown (iron-stained) crystalline bryozoan boundstone (framestone/bafflestone) with hints of a gentle north-easterly dip and much coarsely spherulitic calcite. Hollingworth (1987) and Hollingworth and Pettigrew (1988, their locality 8) fully describe and discuss the brachiopod-dominated fauna and doubtfully assign the trench rocks to the reef crest sub-facies (see Interpretation); some of the bryozoans are especially well preserved and were thought by Hollingworth (1987) to be in life position. A full faunal list was given by Hollingworth (1987, table 9).

The rock wall ('h' in Figure 3.31; NZ 3964 5382–3971 5380) is about 70 m long and up to 8 m high and is cut in dolomitized reef talus deposited on the lower part of the reef-foreslope; the talus comprises a crudely eastward-dipping (20–35°) accumulation of debris derived from higher parts of the reef slope (including the crest), together with the remains of an indigenous fauna (Smith, 1981a). Tumbled blocks of bryozoan and bryozoan–algal boundstone form more than half the rock (Smith, 1981a, figs 8, 23) and lie in a matrix of finer rubble. The blocks, some more than 3 m across, contain a mid- to high-slope fauna dominated by brachiopods and bryozoans, but the finer rubble contains a much more varied fossil suite; careful collecting by Hollingworth (1987) from a representative pocket of shelly rubble here enabled him to distinguish the allochthonous from the indigenous brachiopod and bivalve fauna, and allowed reconstruction of a reef talus palaeocommunity (Hollingworth, 1987, fig. 6.34, reproduced as Hollingworth and Tucker, 1987, fig. 8 and Hollingworth and Pettigrew, 1988, fig. 17). Faunal lists were given by Pattison (Geological Survey internal report, 1966) and Hollingworth (1987, table 19).

The remaining substantial reef-related exposures ('j' in Figure 3.31, NZ 3926 5395–3929 5394) lie in a separate group some 400 m WNW of the rock wall and are of several different rock types; diagenetic changes and extensive brecciation have obscured much of the primary character of the rocks, but they include both dolomite and limestone. Fragments in the brecciated rocks are mainly less than 0.1 m across, though some exceed 0.3 m, and algal-type lamination is present in some. Extremely fossiliferous calcitic dolomite (possibly basal coquina) is abundant in hillside brash (NZ 3929 5395) at the eastern end of this group of exposures.

Exposures of rocks of the Ford, Hartlepool and Roker formations in Ryhope Cutting

This preserved remnant (NZ 399537) of a former 300 m-long railway cutting reveals the following sequence.

	Thickness (m)
Roker Dolomite Formation (foundered):	
Breccia of subrounded to angular fragments up to 0.30 m across (but mainly less than 0.05 m) of grey and buff calcite- and dolomite-wackestone/?grainstone in a matrix of fine-grained carbonate; much laminar cavity-fill, especially in lower part; base markedly uneven, relief 2–4 m	7+
Inferred residue of Hartlepool Anhydrite Formation:	
Breccia of small, soft, angular fragments of cream finely saccharoidal dolomite in a cream powdery matrix; strong flow-lines in places and several laccolith-type intrusions into overlying breccia (most now covered); sharp rolling base (relief 3 m), partly truncating underlying strata	1–6
Ford Formation, off-reef beds:	
Dolomite brachiopod-bryozoan wackestone, cream-buff, in gently folded thick beds; partly dedolomitized at top at north-west end of cutting (T.H. Pettigrew, pers. comm., 1981)	2+

The bedded dolomite at the base of the section is sparingly to moderately fossiliferous and is notable for containing *Neochonetes davidsoni* which is typical of off-reef Ford Formation strata; faunal lists were given by Trechmann (1954, p. 198) and Hollingworth (1987, table 20), and T.H. Pettigrew (pers. comm., 1981) also records ?*Astartella* and *Permophorus costatus*. No reef-derived debris other than bioclasts has been noted in this dolomite. Judging from the record of strata encountered in Ryhope Colliery shaft nearby (NZ 3989 5353), Cycle EZ1 strata are here about 85 m thick, of which the Raisby Formation is unlikely to exceed 50 m.

The top of the bedded dolomite in the preserved faces has some of the characteristics of an erosion surface, with slopes reaching 70° (T.H. Pettigrew pers. comm. 1981); in the cutting as a whole, before filling, the surface was generally gently and unevenly rolling and had a total relief of at least 4 m in all directions.

The overlying soft breccia, mainly 1–2 m thick in the preserved exposures, but thickening to 6 m where intruded into the overlying hard breccia (see Smith, 1994, fig. 44), was seen in the former cutting to thin south-eastwards to 0.1–0.3 m; it was probably from here that Trechmann (1954) recorded stellate gypsum clusters. This was the bed regarded by Trechmann as marking a thrust plane, and later reinterpreted (Smith, 1972) as the residue of the Hartlepool Anhydrite. The harder calcitic breccia is interpreted as the foundered remains of the Cycle EZ2 carbonate formation, here probably of Roker Dolomite facies.

Interpretation

The advantage of the exposures at the south-east end of Tunstall Hills and in Ryhope Cutting lies in their close grouping, which provides not only a convenient view of the rocks themselves, but also of their mutual relationships; the reef-rocks furnish unambiguous and unique evidence that the reef-core prograded basinwards (i.e. eastwards) over earlier reef talus and the rocks east of the reef show that the succeeding 50 m+ Hartlepool Anhydrite formerly approached to within 200 m of the reef foreslope.

Reef-rocks

The relationship between the reef and the local topography has been discussed in the account of the exposures at the north-western end of Tunstall Hills and the correspondence is particularly close at the south-eastern end; here, notwithstanding the probable erosion of some of the landward margin of the reef, it is clear that the group of quarries lies in the core of the reef, towards its seaward margin; equally clearly, the exposures of bedded reef talus show that bed by rough bed, the front of the reef migrated basinward as it built upwards, so that the reef-core extended out over the former reef foreslope.

Relationships between reef, topography and stratigraphy are less clear on the south-west side of the valley of Tunstall Hope, where the main shelf-edge reef undoubtedly forms much of the high ground at Tunstall village and to the south, but is difficult to delineate. Similarly, the presence of Tunstall Hope makes it impossible to relate the shelf-edge reef directly to the reef-rocks exposed in the nearby old railway cutting (NZ 388538) at High Newport, though these were probably formed as a patch-reef in the Ford Formation lagoon (Smith, 1981a; Hollingworth, 1987).

In greater detail, rocks in the main quarry (d), the small quarry (e) and trench (g), together comprise a partial transect from mid reef-core to near the middle of the reef foreslope, though Hollingworth's tentative identification of reef crest lithofacies in the trench is difficult to reconcile either with some aspects of the biota or with the lithology. The main quarry is doubly important in that, together with the exposures of reef-core at the northern end of Tunstall Hills and at Humbledon Hill, it yielded the fossils upon which Hollingworth (1987, fig. 6.15) was able to reconstruct the reef-core palaeocommunity.

The main quarry is also important in being one of the two main exposures (the other being at the northern end of the hill) where the reef is of coarse-grained limestone, rather than the more usual dolomite, and in which primary fabrics are well preserved; from his detailed studies Aplin (1985, p. 305) concluded that the coarse-grained limestone was produced by the calcitization of partially dolomitized limestone and is thus partly dedolomite. 'Some fabrics' he wrote, 'were regenerated during dedolomitization, but many of the fabrics observed are thought to be secondary replacements of primary aragonite and a high-Mg calcite'.

The small quarry (f) is also important mainly because of Aplin's work; he identified it as one of the main places in the shelf-edge reef where the rock is composed of finely crystalline limestone in which primary fabrics are poorly preserved. Aplin (p. 305) concluded that these limestones are dedolomites and resulted from the reaction of the former dolomite with meteoric fluids during or after Mesozoic/Tertiary uplift.

The rock-wall (h) is important in being the only large surface exposure of the talus aprons of the shelf-edge reef in north-east England. An underground exposure of the reef talus has been recorded in the walls of tunnels through the reef at Easington Colliery 10 km to the SSE (Smith and Francis, 1967, pp. 136–137 and 169). The lithology and biota of the rock at the two exposures is generally similar.

The presence of rocks resembling collapse-breccias at exposure (j) is enigmatic, and the brecciation could be entirely diagenetic in origin; if they are collapse-breccias it implies the former presence here of abundant soluble rocks, presumably secondary anhydrite, which would be difficult to account for by present views of the local palaeogeography.

Off-reef Ford Formation and later rocks

Ryhope Cutting, in addition to providing evidence of the former proximity to the reef of Hartlepool Anhydrite, is important in being one of only four places where the basin-floor bedded equivalent of the reef is known to be exposed. The apparent absence of reef-derived detritus other than bioclasts is particularly noteworthy here in view of the short distance (less than 200 m) between the exposure and the toe of the reef slope. The base of the reef-equivalent strata is not exposed, so that their thickness is not known, but comparable strata proved in the Easington Colliery tunnels are 9–15 m thick (Smith and Francis, 1967, p. 137), indicating a very sharp eastward thinning of the off-reef strata. Farther east, at Frenchman's Bay and Trow Point (South Shields), reef-equivalent strata appear to be absent.

The other exposures of basin-floor rocks of probable reef age are in the floor of Ryhope Dene (NZ 4131 5170) 2.5 km SSE of the cutting and at Dene Holme (NZ 454404), Horden; all are different from each other, both lithologically and faunally, though a link is the common presence of chonetoid brachiopods and nodosariid foraminifera. A number of exposures of sparingly shelly, bedded dolomite in the East Boldon area, 8 km NNW of the cutting, may also be in reef-equivalent strata basinward of the reef, but stratigraphical relationships cannot be proved; if these rocks are of the same age as the reef, the reef foreslope may not be as high in the northern part of its course as the 100 m or so inferred from the spatial relationships of reef and succeeding strata in the Hawthorn–Easington area farther south (Smith, 1981a).

Future research

The structure, palaeontology, ecology and petrology of the reef have recently been investigated in considerable detail, so that there is presently little scope for further broadly based research into these aspects. There remains, however, considerable doubt regarding the relationship of the reef to enclosing and underlying strata, especially in the High Newport and Tunstall areas, and these aspects are worthy of further investigation; delineation of the reef–backreef boundary, for example, and identification of the age of subreef strata (Raisby Formation or Ford Formation?) would help to reduce the present uncertainties, and the possibility that collapse-breccias may be present at exposure (f) deserves investigation in view of its considerable palaeogeographical implications.

East of the reef, scope for further research undoubtedly exists into the sedimentology, distribution and biota of basinal strata of reef age, and determination of the age of bedded, shelly dolomite east of the reef in the East Boldon area would be extremely helpful in reconstructing the contemporary palaeogeography. Further research is also required on the petrography and origin of the supposed residue of the Hartlepool Anhydrite in Ryhope Cutting, and on the overlying inferred collapse-breccias.

Conclusions

The varied rocks in these two readily accessible groups of excavations at the south end of Tunstall Hills include *in situ* reef limestone and dolomite that can be seen to have prograded over its own earlier detritus and, in the cutting, one of the few exposures of fossiliferous basinal rocks equivalent in age to the shelf-edge reef. Detailed study of the reef-rock in the western group of excavations has revealed a complex history of mineralogical changes, and study of the abundant fauna in the reef detritus (talus) has yielded vital clues to the assemblage and lifestyle of the many invertebrate organisms that lived there.

The presence of an inferred residue of Hartlepool Anhydrite directly overlying the reef-equivalent beds in the cutting, is important in showing how close the anhydrite must once have approached to the steep seaward slope of the reef, although the anhydrite was almost certainly wholly younger.

The reef-rocks have been researched in detail but there remains the question of the relationship of the reef to the surrounding strata, the petrography of the residue of Hartlepool Anhydrite, and the origin of the collapse-breccias, presently considered as part of the Roker Dolomite Formation.

For these reasons, the site is an important link in the understanding of reef growth and progradation in the late Permian, and the style of sedimentation along the western margin of the Zechstein Sea.

GILLEYLAW PLANTATION QUARRY (NZ 375537)

Highlights

Though small, the old quarry (box 9 in Figure 3.2) in Gilleylaw Plantation, Silksworth, is the best remaining exposure of a late Permian marine patch-reef in the Durham Province of north-east England. The reef forms part of the Ford Formation and rests discordantly on bedded dolomite also probably of the Ford Formation; the quarry is cut into the northern end of the patch-reef and is the source (or one of the sources) of more than 20 type, figured or cited genera of marine invertebrates and of several growth-forms of supposed marine algae.

Introduction

Gilleylaw Plantation Quarry lies amongst trees at the northern end of a long low north–south hill at Silksworth in the south-western outer suburbs of Sunderland. The hill is probably roughly co-extensive with the patch-reef exposed in the quarry and has also been quarried along much of the northern part of its western side. Quarrying ceased long ago.

A quarry at Silksworth was mentioned by both Howse (1848, 1858) and King (1848, 1850), but no details were given and its exact site is unknown; it seems likely, however, that this quarry is that in Gilleylaw Plantation because both authors quote substantial fossil lists and Gilleylaw Plantation Quarry is much more fossiliferous than the others. Silksworth was also the source of many fossil specimens in the Kirkby collection, housed at the Hancock Museum, Newcastle upon Tyne. The quarry was not mentioned again in the literature until Smith (1958, 1981a) briefly described the section and illustrated oncoids and several other algal growth-forms from there, and Logan (1967) illustrated lectotypes of several species of late Permian bivalves from Gilleylaw. Most recently, a detailed faunal and ecological analysis was given by Hollingworth (1987).

Strata exposed in Gilleylaw Plantation Quarry comprise a lower unit of unevenly-bedded soft saccharoidal dolomite, a median unit of varied reef dolomite (a mixture of algal–bryozoan boundstone and shelly rubble) and a thin upper unit of thin-bedded pisoidal (oncoidal) dolomite. Early authors (e.g. Howse, 1848; King, 1850) apparently believed the reef-rock to be an outlying erosional relic of the main 'Shell-Limestone' reef, then thought to be 1.3–5 km wide; the present view that it is more likely to be a patch-reef in the lagoon landward of a much narrower main reef was proposed by Smith (1981a) and supported on palaeontological grounds by Hollingworth (1987).

After lying unused for over a century, the quarry was filled with builders' rubble during the early 1980s; it was subsequently re-excavated following representations by staff of the Planning Department of the Sunderland Borough (now City) Council acting in consultation with staff of the Nature Conservancy Council and Sunderland Museum and Art Gallery. The floor of the quarry is now occupied by a house and garden, but the face remains available for study by prior permission of the occupants.

Description

The position and shape of Gilleylaw Plantation Quarry are shown in Figure 3.36, which also shows the location of the main features of geological interest. The faces of the quarry total about 60 m in length and the main face is up to 11 m high; parts of the face are obscured by vegetation and soil.

The general geological sequence in the quarry is shown below.

	Thickness (m)
Ford Formation, oncoid facies	up to 1.3
Ford Formation, probable patch-reef	up to 5.5
?Erosion surface	
?Ford Formation, backreef (lagoonal) facies	up to 5.2

The disposition of the lithological units exposed in the south and east faces of the quarry is shown in Figure 3.37.

?Ford Formation, backreef (lagoonal) facies

Strata beneath the ?erosion surface at Gilleylaw Plantation Quarry comprise unevenly thick-bedded cream and buff porous saccharoidal dolomite that

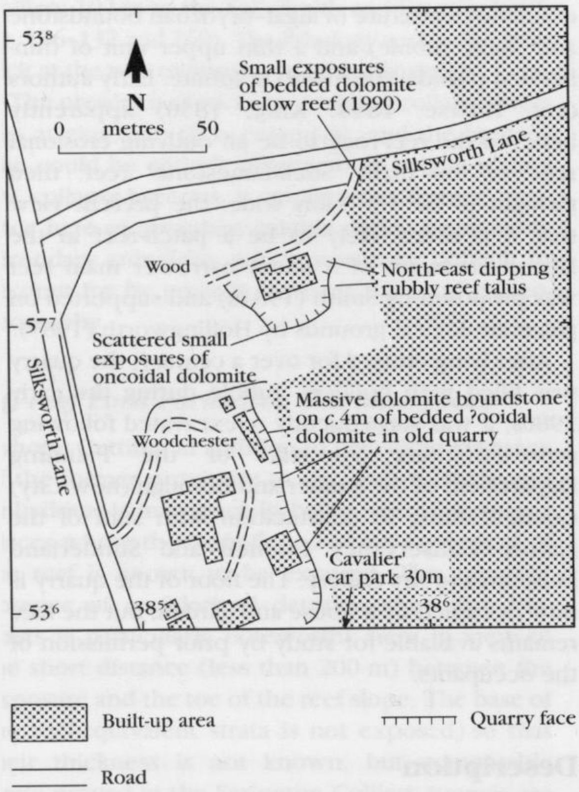


Figure 3.36 Gilleylaw Plantation Quarry and its immediate surroundings, showing the position of the main features of geological interest.

contains sparingly scattered molluscan bioclasts and many empty or thinly calcite-lined cavities up to 10 cm across after secondary anhydrite; the rock is probably an altered ooid grainstone. These strata may be divided into two main units, the lower (*c.* 2.8 m+) of which comprises rock that is variably bedded and rather vuggy, and the upper (3–3.5 m) comprises clearly bedded rock with continuous beds 0.1–0.4 m thick and only local wedging-out. Beds just above the base of the upper unit feature two mound-like structures (Figure 3.37); the larger of these is about 3 m across and 0.7 m high and has a confused (possibly brecciated) mainly dolomite core, and the other (Figure 3.38) is about 1 m across and 0.4 m high and has a core of dense grey limestone (?dedolomite). The mounds contain no obvious organic framework, but are clearly contemporaneous and they may be small algal patch-reefs.

The ?erosion surface

The inferred patch-reef is separated from the underlying bedded dolomite by a sharp break interpreted as an erosion surface (Figure 3.37). This has a relief in the quarry of more than 2 m, and sharply truncates beds beneath it on the east face where it dips north-eastwards at about 20°; its precise position and relief on the remaining (mainly inaccessible) faces is less clear. Hollingworth (1987) noted no evidence of contemporaneous cementation beneath the ?erosion surface.

Ford Formation, probable patch-reef

The inferred patch-reef at Gilleylaw Plantation Quarry occupies most of the upper part of the main face and comprises a varied mixture of massive dolomitized algal–bryozoan boundstone and subordinate dolomitized shelly rubble (Figure 3.37). The boundstone is a dense hard rock (bafflestone/framestone) in which scattered pinnate and straggling bryozoans are partly to thickly encrusted by fine concentric ?algal coating; in a massive 1.5 m bed in the south face such encrustations exceed 90% of the bulk of the rock. Only a restricted range of invertebrates is found in the boundstone masses but the shelly talus, exposed mainly in the east face of the quarry, contains a varied and abundant invertebrate fauna. The biota includes some genera that are absent or very uncommon in the main shelf-edge reef and lacks some common reef forms such as *Horridonia* and *Cyathocrinites* (Hollingworth, 1987); a full list by Hollingworth shows the striking difference between the faunal assemblages of the two rock types in the Gilleylaw reef and also between the overall biota of the inferred patch-reef and that of the main shelf-edge reef.

The association of massive bryozoan–algal boundstone and shelly rubble in the Gilleylaw reef is not unlike that in parts of the main shelf-edge reef, at the Humbledon Hill site for example, and it must be assumed that most of the type, figured and cited genera listed in the early works were specimens collected from the shelly rubble.

Ford Formation, oncoid facies

Up to 1.3 m of irregularly thin-bedded grey and buff oncoidal dolomite was formerly exposed at the top of the slope above the south face of the quarry where it rested with pronounced onlap on the uneven surface of the underlying patch-reef (Figure 3.37). These beds are now mainly covered, but many small exposures and loose blocks may still be found; they appear to contain no invertebrate remains.

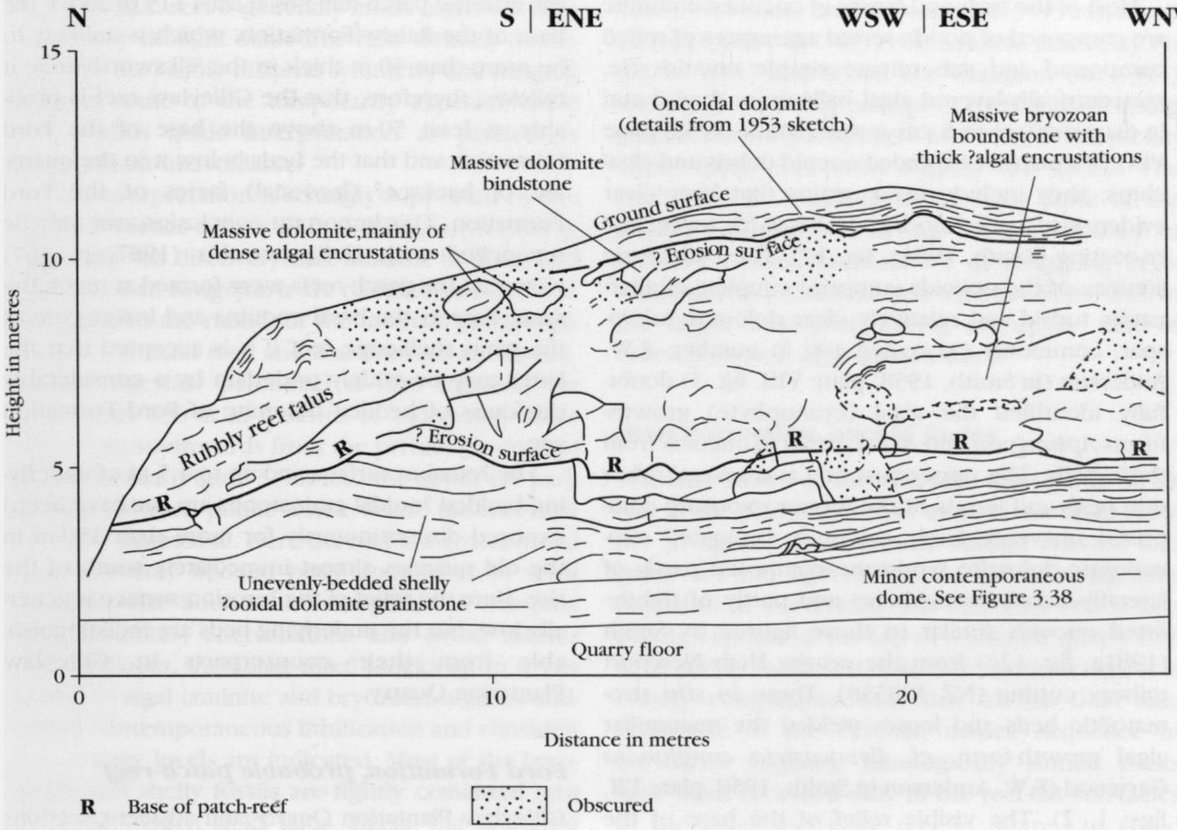


Figure 3.37 Sketch of patch-reef in the east and south faces of Gilleylaw Plantation Quarry, incorporating some details of strata formerly exposed, but not now visible.

Figure 3.38 Contemporaneous minor mound-like structure in backreef dolomite of the Ford Formation in the south face of Gilleylaw Plantation Quarry. Bar: 0.32 m. (Photo: D.B. Smith.)

Most of the beds and lenses of oncoidal dolomite are composed of poorly-sorted aggregates of rolled compound and subordinate simple oncoids (ie. concentrically-layered algal balls more than 2 mm in diameter) up to 5 cm across (Smith, 1958, plate VIA) in a matrix of abraded oncoid debris and algal chips; they include many grains that bear clear evidence of one or more episodes of fracturing and re-coating (Smith, 1981a, fig. 17). The concentric laminae of the oncoids comprise couplets of alternately turbid and relatively clear dolomite microspar, commonly exceeding 100 in number. F.W. Anderson (in Smith, 1958, plate VIII, fig. 3) doubtfully identified the algal (cyanophyte) growth-forms *Aphralysia* and *Bevocastria* in oncoids from these beds. The uppermost bed and several other thin beds and lenses of the former exposure comprised unevenly finely sinuously laminated stromatolitic dolomite bindstone composed partly of laterally-linked hemispheres and partly of tightly-fitted oncoids similar to those figured by Smith (1981a, fig. 12c) from the nearby High Newport railway cutting (NZ 388538). These *in situ* stromatolitic beds and lenses yielded the mammillar algal growth-form, cf. *Bevocastria conglobata* Garwood (F.W. Anderson in Smith, 1958, plate VII, figs. 1, 2). The visible relief of the base of the oncoidal dolomite was about 0.6 m.

Interpretation

Gilleylaw Plantation Quarry is of major importance as (a) the most accessible and complete exposure of a late Permian inferred marine patch-reef in the Durham Province and (b) the prime source of more than 20 type, figured and cited specimens of late Permian marine invertebrate specimens and algal growth-forms. It is also the first locality in Britain from which late Permian marine oncoids were illustrated, though some of the beds from which these were obtained are no longer fully exposed.

The erosion surface and underlying strata

These are closely comparable with the erosion surface and underlying strata exposed in Humbledon Hill Quarry in the main reef 1.7 km NNE of Gilleylaw Plantation Quarry and comments made in the Humbledon Hill account apply equally here. Judging from the record of strata proved in Silksworth Colliery South Shaft (NZ 3766 5404) located some 350 m NNE of the quarry, the base of the inferred patch-reef lies at least 115 m above the base of the Raisby Formation, which is unlikely to be more than 50 m thick in the Silksworth area; it follows, therefore, that the Gilleylaw reef is probably at least 50 m above the base of the Ford Formation and that the beds below it in the quarry are of backreef (lagoonal) facies of the Ford Formation. This important conclusion can only be reconciled with Hollingworth's (1987, p. 367) view that the patch-reefs were formed at much the same time as the basal coquina and lower core of the main shelf-edge reef if it is accepted that the latter may be widely underlain by a considerable thickness of bedded dolomite of Ford Formation age.

The ?erosion surface and up to 4.5 m of underlying bedded ?ooidal grainstones are (or have been) exposed discontinuously for more than 150 m in the old quarries almost immediately south of the site. Here the relief of the ?erosion surface is generally low, but the underlying beds are indistinguishable from their counterparts in Gilleylaw Plantation Quarry.

Ford Formation, probable patch-reef

Gilleylaw Plantation Quarry and adjacent sections provide the most readily accessible exposures of a late Permian inferred patch-reef in the Durham Province of north-east England; such bodies are concentrated in the Silksworth area and are not known farther south. The only other permanently exposed large inferred patch-reef is in an abandoned railway cutting (NZ 387538) at High Newport, about 1.2 km farther east; it differs from the Gilleylaw reef in a number of respects and is, on balance, less varied. Both bodies are only a few metres thick. Other, smaller, reef bodies have been noted in temporary excavations around Silksworth by Smith (1971, 1981a, 1994) and Hollingworth (1987) and it is probable that they number some scores or perhaps hundreds in total; some are wholly embedded in shelly lagoonal ooid grainstones.

The doubts about whether the reef-rocks around Silksworth are truly patch-reefs stem from the generally poor quality of most of the exposures and from the lack of exposure between Silksworth and the main shelf-edge reef complex. The early view that the reef-rock at Silksworth is part of the main reef was presumably based on lithological and faunal similarities, and in the absence of firm evidence to the contrary, cannot yet wholly be refuted; however, the discovery by Smith (1981a) that the main reef is generally much narrower than previously thought made this view difficult to sustain and the visible bilateral symmetry and fringing talus of some of the temporarily exposed, small reef bodies made interpretation as patch-reefs seem almost unavoidable.

This interpretation is strongly supported by the faunal evidence advanced by Hollingworth (1987), especially his discovery that infaunal bivalves and the bryozoan *Kingopora* are relatively much more abundant in the rubble of the inferred patch-reefs than in the main reef, and that crinoids are absent.

The Gilleylaw patch-reef is also exposed for more than 150 m in a series of old quarry faces stretching southwards from the private grounds of Woodchester (Figure 3.36) into the upper car park of 'The Cavalier' public house where the reef-rock is readily accessible. Here the reef is a coarsely and very unevenly bedded body dominated by hard buff dolomite boundstone composed of complex algal laminites, encrustations and ovoid masses and, in places, including tilted blocks up to 0.5 m across of algal laminite and bryozoan–algal boundstone; contemporaneous lithification and considerable energy levels are indicated. Most of the bryozoans and shelly fossils are tightly cemented into the rock, which lacks talus sheets, but scattered pockets and lenses contain many small gastropods and bivalves. The overall appearance and composition of the reef-rock in the 'Cavalier' car park is much like that of the reef-flat sub-facies of the main shelf-edge reef at Townfield Quarry (NZ 434438, Easington Colliery) and at the Hawthorn Quarry site, and similar shallow-water deposition seems likely.

In summary, the evidence suggests that whilst construction of the main shelf-edge reef was actively proceeding a short distance to the east, the shallow ooid-dominated floor of the backreef lagoon was, in the Silksworth area, dotted with bun-shaped patch-reefs ranging from less than 1 m to (exceptionally) several scores or hundreds of metres across. In time, perhaps through building up to sea level, slight sea-level fall and/or a salinity increase, the tops of the larger patch-reefs evolved to become inhospitable (?hypersaline) algal flats.

Although patch-reefs in the Durham Province are restricted to the Ford Formation in and around Silksworth, hundreds of patch-reefs occur in dolomitized open shelf ooid grainstones of the Wetherby Member of the Cadeby Formation in the Yorkshire Province (Smith, 1974a, b, 1981b, 1989); striking examples of the Yorkshire patch-reefs are exposed in the GCR sites at Cadeby Quarry (SE 5200), Newsome Bridge Quarry (SE 379514), South Elmsall Quarry (SE 483116), Ashfield Brick-clay Pit (SK 515981) and Wood Lee Common (SK 5391) and the mutual relationships of reefs and enclosing grainstones are particularly well seen in the picturesque lanes of Hooton Pagnell (SE 4808). The patch-reefs in Yorkshire differ from those in the Durham Province in having cores composed of sack-like masses ('saccoliths') of straggling bryozoans almost without laminar encrustations, and, in the larger examples, having an upper unit of coarsely domed algal stromatolites.

Ford Formation, oncoid facies

The importance of this thin unit rests partly on its role as the prime source of most of the small number of figured late Permian marine oncoids and partly on the light it throws on contemporary depositional conditions. The oncoidal bed is also poorly exposed at the top of a disused quarry (NZ 3759 5354) some 160 m farther south, where it is closely comparable with that in the GCR site. Elsewhere in the Permian marine sequence of north-east England, lithologically similar rocks have been recorded only in the reef-flat sub-facies of the main shelf-edge reef in Stony Cut (Cold Hesledon) Cutting (NZ 418473) (Smith and Francis, 1967, p. 133) and in exposures of reef-flat rocks at Yoden (NZ 4315 4176) (Smith and Francis, 1967, p. 139 and plate XB); superficially similar pisoids at the top of the Boulder Conglomerate of the Hesleden Dene Stromatolite Biostrome at the Hawthorn Quarry and Blackhalls Rocks sites may have a different origin from those at Gilleylaw, Cold Hesledon and Yoden.

Modern oncoids comparable with those at Gilleylaw are formed in a range of peritidal and shallow-water environments near the hypersaline margins of tropical seas such as the Persian Gulf and the Red Sea. The reworked Gilleylaw oncoids presumably accumulated as lenses and sheets of fine gravel on a shallow or peritidal reef-flat in comparable latitudes; the abundant evidence of fracturing, abrasion and re-cementation points to some contemporaneous lithification and to at least moderate energy levels at times, and the apparent absence of a shelly fauna is consistent with an atypical (either high or low) salinity. These inferences on the palaeoenvironments of the oncoids suggest a sharp and considerable change of conditions from those under which the underlying patch-reef was formed, although a shallowing water level and partial exposure may have sufficed.

Despite the presence of algal influences on the formation of the oncoids, the lamination of many of them lacks undoubted organic growth-forms and at least partial inorganic precipitation (as in some modern pisoids formed in unusual environments, such as splash-cups and surge pools) cannot be wholly excluded.

Future research

There are uncertainties and substantial gaps in our knowledge and understanding of most aspects of the Gilleylaw patch-reef and the light it throws on the late Permian sedimentary and stratigraphical evolution of the area. Aspects in particular need of detailed research are listed below.

1. The lithology and diagenetic history of the three main rock units exposed in Gilleylaw Plantation Quarry and also in the car park of 'The Cavalier' public house.
2. The stratigraphical position of the Gilleylaw reef and its relationship (if any) to the main shelf-edge reef and the significance of the presumed erosion surface. If it can be proved that the reef is both well above the base of the Ford Formation and roughly synchronous with the basal coquina and lower core of the main shelf-edge reef, present interpretations of the local late Permian stratigraphy will need to be reconsidered.
3. The nature and origin of the apparently contemporaneous minor mounds in beds underlying the reef.

Conclusions

The massive and rubbly dolomite of this small historic quarry contains an abundant and varied marine fauna, and much evidence of the former presence of marine algae. The massive rock is interpreted as a patch-reef and the rubbly dolomite is thought to be talus at the margin of the reef. The reef overlies a minor erosion surface of unknown significance and is surrounded by shallow-water lagoonal oolites which contain many other small patch-reefs in the Silksworth area. The upper surface of the reef is also an erosion surface, and is overlain by a thin deposit of marine pisoliths.

The detailed sedimentation and stratigraphical position of the patch-reefs are still relatively unknown, and further research is needed, as outlined above. The preservation of Gilleylaw Plantation Quarry is essential both to achieve this aim and to safeguard an example of a patch-reef formed in the late Permian backreef lagoon.

SEAHAM (NZ 4349)

Highlights

This coastal site (box 10 in Figure 3.2) is the type locality and by far the best surface exposure of both the Seaham Formation and the Seaham Residue, and is one of the best places in Britain for observing the effects of evaporite dissolution; it is also the best surface exposure of the highest beds of the Roker Dolomite Formation. The Seaham Formation here is unusual in its content of several thick units rich in calcite spherulites, some exceptionally large, and the Seaham Residue, the dissolution residue of the Cycle EZ2 (Fordon) evaporites, is at its thickest and most spectacular.

Seaham harbour is of interest in being an artificial anchorage created between 1828 and 1831 by the hollowing-out of a former limestone headland. An original Stephenson locomotive was used until the late 1950s on harbour maintenance work and a paddle tug, *The Eppleton Hall*, for many years plied the South Dock of the harbour before becoming an exhibit at the maritime museum in San Francisco.

Introduction

The south-eastward dipping rocks at Seaham are the highest Permian strata exposed on the Durham coast. They occupy a gentle asymmetric downfold on the north side of the Seaham Fault, a major west to east dislocation that has a northerly downthrow of about 200 m in Coal Measures rocks beneath the harbour, but perhaps only a small fraction of that in the overlying Permian strata. The sequence exposed comprises the uppermost part of the Roker Dolomite Formation (8 m+), the Seaham Residue (up to 9 m) and, at the top, the Seaham Formation (about 31 m). Breccia-gashes in the eastern part of the north wall of the North Dock contain foundered debris of higher strata including red 'marl' (mudstone/siltstone) and blocks of cellular limestone that may be the remains of calcitized evaporites. Fossils abound in the Seaham Formation (locally in rock-forming proportions) and comprise two species of bivalve and the supposed alga *Calcinema* (formerly *Filograna*) *permiana* (King); the same two species of bivalve have been found in the local Roker Dolomite beds.

The complex of exposures at Seaham was virtually ignored in the literature until the formal definition of the Seaham Beds and Seaham Residue by Smith (1971a); the name Seaham Beds was subsequently changed to Seaham Formation. The rocks of the Seaham Formation (Smith *et al.*, 1974) were informally known by Trechmann (1954) as the *Filograna* beds and were generally regarded as part of the Concretionary Limestone Formation (e.g. Woolacott, 1912; Trechmann, 1925). This attribution was accepted by Smith (in Smith and Francis, 1967), but was shown to be incorrect by Taylor and Fong (1969); these authors discovered calcite concretions in cores of late Permian marine limestones at two different levels separated by evaporites in boreholes in North Yorkshire and disclosed that those at the higher level were associated with the diagnostic biota of the Seaham Formation. Magraw (1975) proposed the term 'Upper Nodular Beds' for concretion-bearing limestones at about the level of the Seaham Formation in a number of partly cored, offshore coal exploration boreholes, but this name has found little favour.

The exposures of Roker Dolomite at Seaham lie towards the northern end of the designated area (Figure 3.39), and the top of the formation rises gradually northwards. These rocks were classified by Trechmann (1931) as Post-reef Middle Magnesian Limestone (=Ford Formation of modern usage), but their position immediately below the Cycle EZ2 Seaham Residue and above the inferred residue of the Cycle EZ1 Hartlepool Anhydrite in the nearby Seaham Borehole (Smith, 1971a) shows that this view cannot be correct.

The inferred presence of the residue of the Hartlepool Anhydrite in the Seaham Borehole, if correct, implies that all the Permian strata exposed at Seaham have foundered as a result of the dissolution of perhaps 120 m of underlying evaporites.

Description

Seaham (NZ 4349) lies on the east coast of County Durham some 8 km south of Sunderland; the position of the GCR site there is shown in Figure 3.39, together with the geological boundaries and the position of the main features of geological interest.

The general geological sequence in the designated area at Seaham is:

	Thickness (m)
Drift deposits, mainly boulder clay and beach deposits	up to 8
------unconformity------	
Red mudstone/siltstone (Rotten Marl) occupying breccia-gashes	up to ?4
Seaham Formation (EZ3Ca), seen mainly in the harbour walls and at Red Acre Point	30-31.5
Seaham Residue (of the Fordon Evaporites, EZ2E), seen mainly in cliffs from the war memorial northwards	up to 9
Roker Dolomite (EZ2Ca), seen mainly from Red Acre northwards	8+

Roker Dolomite Formation

This formation lies at the base of the sequence exposed at Seaham, its top first appearing at beach level about 300 m SSE of Featherbed Rocks and rising cumulatively until it crops beneath drift about 350 m north of the designated area; beyond this the cliffs for several hundred metres are composed solely of drift on Roker Dolomite.

The Roker Dolomite Formation in the northern part of the site and in the cliffs to the north is composed mainly of fine-sand grade, hollow ooids (Trechmann, 1914, plate 37(5)), and generally is a cream to buff porous rock with less than 2% of calcite. The uppermost 1–5 m of the formation, however, is a hard, finely crystalline, grey limestone (dedolomite) with a network of fractures that in places is so dense that the rock has become a breccia; internal sediment is locally abundant in this breccia. The fractures, which doubtless once were filled with anhydrite, gypsum or salt, diminish in number downwards, and the proportion of dedolomite similarly diminishes until limestone forms only narrow selvedges alongside the downwards-tapering cracks. There is also clear evidence, in the form of irregular to stellate calcite-lined cavities up to 0.1 m across, of the former presence of abundant replacive and intergranular anhydrite.

Where least altered, the Roker Dolomite at Seaham exhibits a range of shallow-water sedimentary structures and has yielded two species of bivalves (*Liebea* and *Schizodus*) (Trechmann,

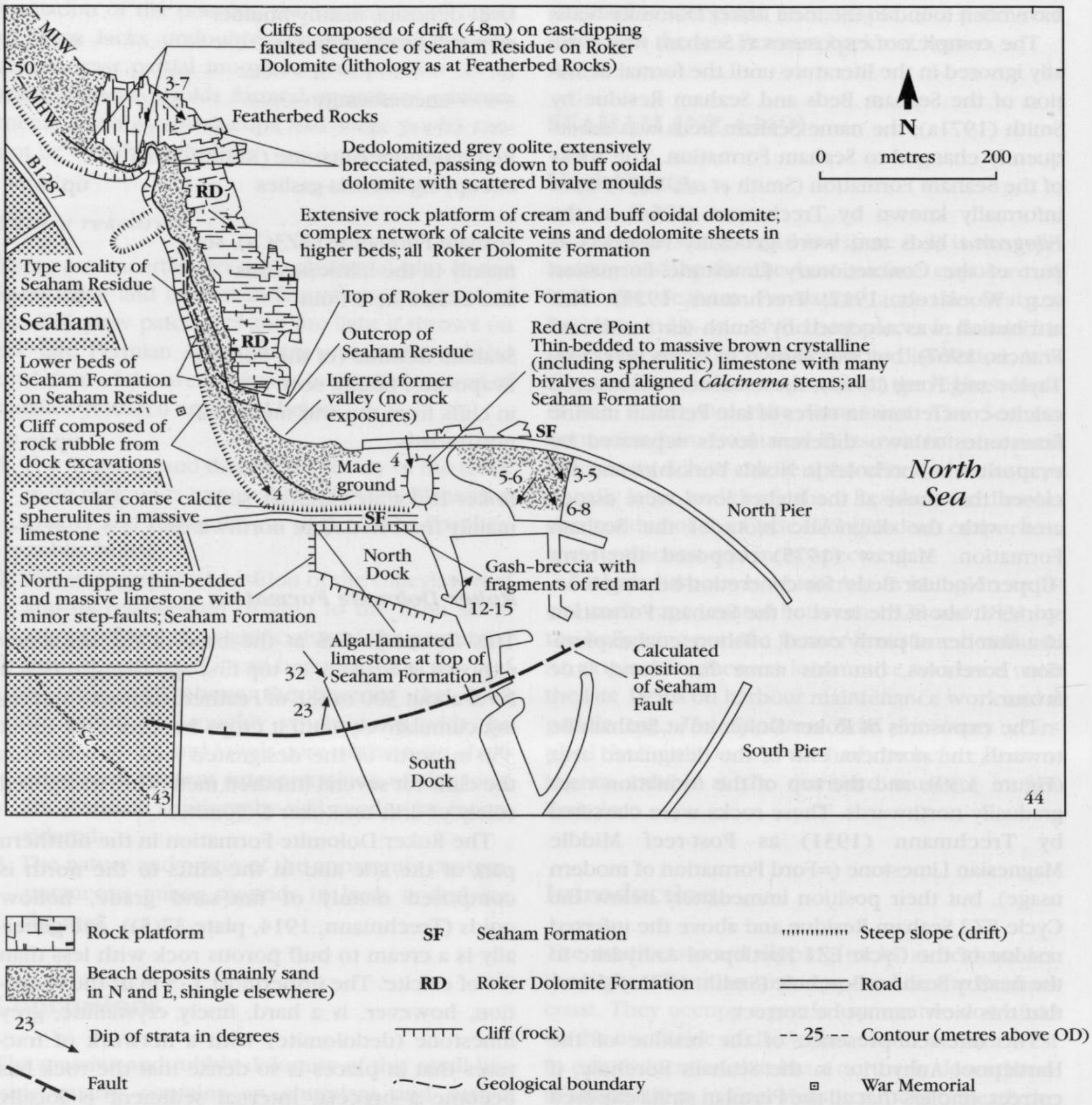


Figure 3.39 The Seaham GCR site, showing the position of the main features of geological interest.

1914, p. 235) from 'a mass of rock isolated from the cliff-section' (presumably Featherbed Rocks).

The contact between the Residue and the Roker Dolomite is generally sharp and smoothly rounded at the southern end of its outcrop and has a local relief of up to 2 m; this relief diminishes towards the northern end of the site, where the contact is generally less sharp and locally interdigitates.

Seaham Residue

The Seaham Residue is not seen in the harbour walls, but its top is exposed at the foot of the cliffs about 200 m NNW of North Dock (dependent on the height of beach gravel) and rises gradually northwards for more than 200 m before cropping out beneath drift at the top of the cliff near

Featherbed Rocks; much of the bed, however, is visible almost as far north as the former Vane Tempest Colliery (NZ 425502), well north of the GCR site, as a result of several minor downfolds and small step faults.

The Seaham Residue was identified and defined by Smith (1970a, 1971a) and further described and illustrated by Smith (1972). It is thickest in the cliffs at Red Acre where it is also strongly contorted (Figure 3.40); despite great lateral variation, the residue has a roughly uniform general sequence exemplified in the cliff face (NZ 4303 4973) some 210 m south of Featherbed Rocks.

	Thickness (m)
Residue, mainly yellow-buff, comprising a weakly layered and partly contorted heterogeneous clayey dolomite or dolomitic clay with scattered small angular fragments of limestone. Top generally sharp, but uneven, relief up to 1 m	1–2.5
Limestone, white, grey and buff, thin-bedded and flaggy, partly contorted, an altered ooid grainstone, with thin beds of yellow-buff clayey ?residue	0.8–1.1
Limestone, off-white, ooidal, finely cross-laminated, with possible bivalve moulds	1.0–1.2
Residue, buff in uppermost part grading down to buff-grey, grey-buff and brown, comprising an upper unit (up to 1.2 m thick) of strongly contorted flaggy and thin-bedded limestone (partly ooidal) passing down to contorted calcareous clay and clayey dolomite with scattered to abundant angular blocks of altered ooid grainstone; some of the latter are cross-laminated and contain flat-pebble conglomerates	1.5–5.0

Traced northwards, the Seaham Residue thins gradually to 2–3 m and is less contorted and varied.

Seaham Formation

The several rock walls of Seaham harbour, Red Acre Point and the cliff section from 155 m to the north, together constitute the type locality of the Seaham Formation (Smith, 1971a); in general, the lower parts of the formation are exposed north of the harbour and the higher parts in the harbour walls. No single continuous section exposes the whole formation and the overall sequence (based on Smith, 1994) has been pieced together from several sections separated by minor faults and stretches of unexposed ground.

	Thickness (m)
Limestone, grey and brown, finely crystalline, hard, thin-bedded, unevenly algal-laminated, with abundant stellate and rectilinear cavities after former sulphate	1.2–1.5+
Limestone, buff, grey and brown, finely crystalline to finely saccharoidal, hard, flaggy to thick-bedded, but with discontinuous beds of calcite concretions and of limestone. Mainly thin-bedded, with symmetrical low amplitude massive coarsely-crystalline ripples, shallow cut-and-fill structures, low-angle planar and tabular cross-lamination and abundant graded bedding. *Calcinema*, *Liebea* and *Schizodus* at most levels, partly in rock-forming proportions	*c.* 27–28.5
Dolomite (exposed in cliffs from about 180 to 300 m NNW of the north-west corner of North Dock), cream and buff, soft, finely saccharoidal, mainly thin-bedded, with *Calcinema, Liebea* and *Schizodus*	*c.* 1.8+

Calcite concretions occur almost throughout the Seaham Formation, but are most abundant slightly above the middle where they merge patchily to form massive spherulitic beds individually up to 3 m thick (Figure 3.41); most of the spherulites are only a few millimetres to centimetres across, but in places they exceed 0.2 m in diameter and completely obscure primary sedimentary features. Seaham is the best and most readily-accessible place to study these concretions.

The tiny stick-like tubular remains of *Calcinema* are present in enormous numbers in much of the rock, and form dense swarms aligned roughly WSW/ENE to west to east at some levels; at other levels however, they appear to be disposed randomly or to form complex swirls.

The algal-laminated (stromatolitic) limestone at the top of the Seaham Formation is exposed for only a few metres on the north side of an artificial

Figure 3.40 Strong contortions in the lower part of the Seaham Residue at the type locality, showing detached blocks of cross-laminated ooid grainstone (middle) and the lowest part of the bedded ooid grainstones that here form a median unit in the Residue. Hammer: 0.33 m. (Photo: D.B. Smith.)

terrace, high in the north-west corner of the North Dock; although such algal-laminites are widespread in subsurface provings at this horizon, this small surface exposure is unique in north-east England.

The minor faults seen cutting the Seaham Formation in the dock walls may be partly tectonic in origin, and related to the proximity of the Seaham Fault, but most of them probably resulted from fracturing of the brittle rocks when the underlying Fordon Evaporites were dissolved. Total brecciation such as is seen in the Cycle EZ2 collapse-breccias is uncommon in the Seaham Formation, but step-faults, partial brecciation and contortion are widespread; an excellent section displaying some of these features is seen in the west wall of the North Dock. It is important to bear in mind that all the strata exposed at Seaham have also foundered by at least 100 m because of the dissolution of the Cycle EZ1 Hartlepool Anhydrite and that some dislocation in the Seaham Formation may have resulted from this cause.

Red mudstones/siltstones (Rotten Marl)

The Rotten Marl is well known in boreholes in County Cleveland (e.g. Marley, 1892), and is extensive on the sea bed off the Durham coast (Smith, 1994). Surface exposures of this formation are known, however, only as fragments in a few breccia-gashes in coastal cliffs between Ryhope (NZ 4152) and Crimdon (NZ 4837), and one of these was excellently exposed (NZ 4327 4950) near the eastern end of the north wall of the North Dock. About 4 m of fragmented, soft red-brown, argillaceous siltstone and silty mudstone were formerly seen here; it contained a number of large angular blocks of pale grey cellular limestones that may be the carbonate framework of the Billingham Anhydrite (EZ3A) or (less likely) cellular dolomite from the Sherburn Anhydrite (EZ4A); the former separates the Rotten Marl from the underlying Seaham Formation, but has been dissolved from all surface outcrops, and the latter overlies the Rotten Marl and has also been dissolved.

The uppermost 2–3 m of the breccia-gash were removed when a new road was constructed in 1980, and much of the remaining Rotten Marl has since been obscured by landscaping; the remainder of the breccia-gash, however, may be seen from the footpath along the northern lip of the North Dock, where the gash is about 7 m wide.

Interpretation

The site at Seaham is of national importance both as a reference section and for teaching purposes; several features exposed there are unique either in north-east England or in Britain as a whole, and the exposures together provide an unrivalled expression of the effects on carbonate rocks of the dissolution of interbedded and pervasive evaporites. The main features of interest and importance are discussed on pages 93–5.

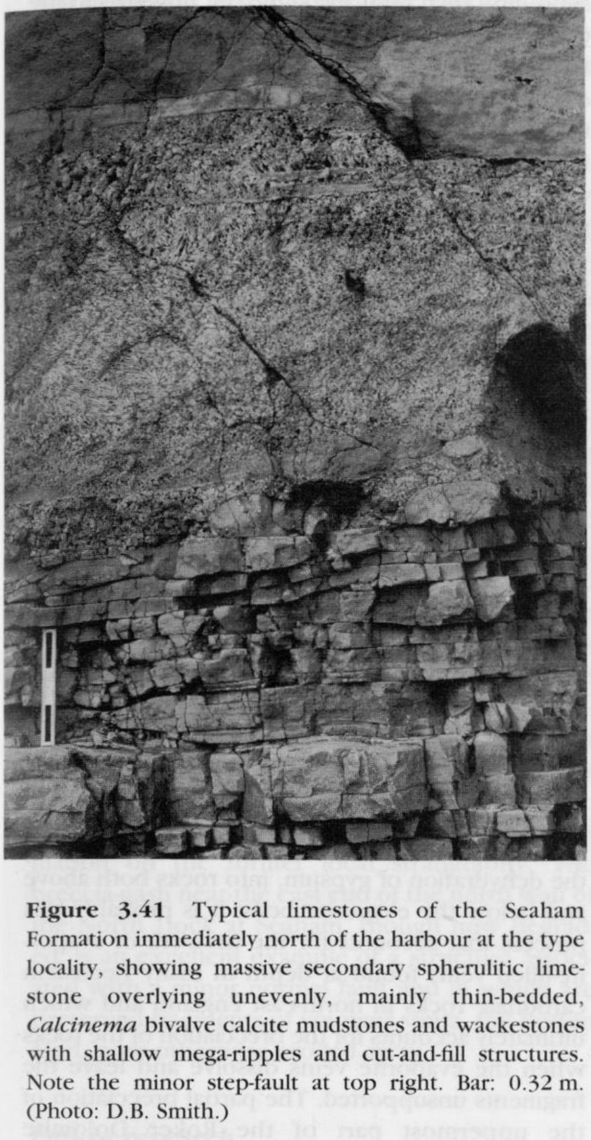


Figure 3.41 Typical limestones of the Seaham Formation immediately north of the harbour at the type locality, showing massive secondary spherulitic limestone overlying unevenly, mainly thin-bedded, *Calcinema* bivalve calcite mudstones and wackestones with shallow mega-ripples and cut-and-fill structures. Note the minor step-fault at top right. Bar: 0.32 m. (Photo: D.B. Smith.)

Roker Dolomite Formation

The clear exposures of the uppermost beds of the Roker Dolomite Formation at the northern end of the Seaham site are unique in north-east England and their protection is important on this account alone; there are, moreover, no readily available records of cored boreholes through this part of the sequence, although it has been cored in confidential commercial boreholes at several places in Cleveland. The discovery by Trechmann (1914) of *Liebea* and *Schizodus* in these rocks at Seaham is also important in providing corroborative evidence that they are not part of the unfossiliferous post-reef Middle Magnesian Limestone as had been claimed previously.

Seaham Residue

The Seaham Residue at Seaham is a superb example of an evaporite dissolution residue, certainly one of the best in the British Isles and ranking highly amongst such features in western Europe; poorer exposures occur beneath the Seaham Formation in coastal cliffs north of Crimdon Park (NZ 4837), Blackhalls Rocks (NZ 4638) and Easington Colliery (NZ 4343). Its great lateral variability in thickness and composition, its commonly gradational contacts with the underlying and overlying strata and its local strong contortion are all typical of evaporite dissolution residues, and combine to make the main exposure a most valuable teaching section.

The stratigraphical affinities of the Seaham Residue leave no doubt that it is equivalent to the Fordon Evaporite Formation (Cycle EZ2), which, approximately along strike in North Yorkshire, is about 15–30 m thick and comprises interbedded anhydrite and halite with subordinate carbonate and siliciclastic rocks. The absence of red and grey siliciclastic rocks in the Seaham Residue, plus the presence of underlying Roker Dolomite, shows that it is not the residue of the Edlington Formation into which the Fordon Evaporites pass landwards (i.e. westwards). The unusually great thickness of the residue, although enhanced at Seaham by lateral flow into a minor anticline, presumably indicates that these evaporites had a high content of insoluble material.

Seaham Formation

The Seaham exposures were chosen as the type locality of the Seaham Formation because of the apparent permanence and ease of access of the various faces and the nearly complete coverage of the whole thickness of the formation; no other exposure offers these advantages. The sedimentary features and biota at Seaham harbour are generally typical of the formation in north-east coastal districts (so far as may be judged from limited alternative exposures) and, except for the graded bedding, are comparable with those in the equivalent Brotherton Formation in Yorkshire and the Plattendolomit in Germany. The removal of some important faces and the covering-up of others during the subsequent construction of a road along the north wall of North Dock was particularly unfortunate, but still left the best overall exposure of these rocks. Other exposures of the formation lie in the coastal cliffs north of Crimdon Park (NZ 4837) (the only other large section), near Blackhall Colliery (NZ 4639), Easington Colliery (NZ 4443) and Dawdon Colliery (NZ 4347), and in the valley of Seaton Burn (NZ 413503), Seaham.

The calcitic concretions and massive beds of spherulitic limestone at Seaham have much in common with those of the Cycle EZ2 Concretionary Limestone of the Fulwell and Carley Hill Quarries at Sunderland and also of several other localities in the Cleadon–Marsden–Sunderland area; the main difference is that those at Seaham generally do not feature the fine parallel primary lamination of their Concretionary Limestone counterparts and white crystalline calcite is much less common. Striking exposures of coarse calcite spherulites lie low in the cliffs (NZ 4315 4951) immediately north of the harbour, where much of the rock is a massive coarsely crystalline limestone. Calcite spherulites are also abundant in parts of the Seaham Formation at its other main exposure in coastal cliffs north of Crimdon Park, but are smaller and less striking.

The composition and petrography of the Seaham Formation were investigated as part of wider studies by Al-Rekabi (1982) and Braithwaite (1988), who present illustrations (including photomicrographs) of several of the rock types present. Both authors inferred a late phase of leaching and partial internal collapse. Al-Rekabi concluded (albeit diffidently) that at least some of the radial calcite concretions may have had a sulphate precursor, but this view was disputed by Braithwaite who concluded that most of the late (i.e. post-burial) calcite replaced a range of earlier carbonate rock types without a sulphate intermediary or precursor.

Structural and petrographical effects of evaporite dissolution

The main structural effects of evaporite dissolution at Seaham cannot readily be seen, but their overall effect may be inferred from evidence visible at other exposures along the north-east coast and from reconstructions of regional stratigraphic relationships from boreholes in Yorkshire (Smith, 1974b; Taylor and Colter, 1975); these data show that all the strata exposed on the coast at Seaham must have foundered by more than 100 m as a result of the dissolution of the Cycle EZ1 Hartlepool Anhydrite. Farther north, study of cliff sections around Sunderland, Whitburn and Marsden shows that the fracturing and brecciation caused by such foundering die out upwards in the Cycle EZ2 Concretionary Limestone and Roker Dolomite formations, but that the less obvious effects persist upwards in the form of broad open folds and scattered faults. Presumably some such folds and faults have affected the sequence exposed at Seaham, but cannot now be distinguished from possible tectonic dislocation associated with the formation of the Seaham Fault and from the effects of the removal of the Fordon Evaporites.

The less severe effects of the dissolution of the Fordon Evaporites take the form of numerous minor faults and folds that break up much of the Seaham Formation into blocks commonly only a few metres across; most of the faults are normal and stepped, but a few reverse faults are present and also some minor troughs. Complete brecciation of parts of the Seaham Formation occurs locally, but is not as widespread as that noted in foundered Cycle 2 strata (Smith, 1972). Late stage breccia-gashes are similarly less common than in Cycle EZ2 rocks.

The relative importance of the varied processes leading to brecciation in rocks associated with evaporites varies greatly from place to place and embraces fracture by and the injection of pressurized formation fluids, including those liberated by the dehydration of gypsum, into rocks both above and below the evaporite beds; it is probably this process that accounts for the network of evaporite-filled veins found at depth in many Zechstein carbonate rocks in north-east England and which ultimately accounts for the brecciation of the rocks when the evaporite veins dissolve and leave the fragments unsupported. The partial brecciation of the uppermost part of the Roker Dolomite Formation in the northern part of the site probably results from this process.

The petrographical effects of evaporite dissolution on the carbonate rocks at Seaham have not been studied in detail, but appear mainly to have resulted in dedolomitization. This process here has widely converted the uppermost part of the Roker Dolomite from soft, porous, ooidal dolomite into hard, dense limestone; the effect is general in the uppermost 1–3 m, but dies out downwards. The basal dolomitic parts of the overlying Seaham Formation have also locally been dedolomitized.

The dedolomitization of the uppermost part of the Roker Dolomite Formation presumably was caused by the reaction of the dolomite with pervasive calcium sulphate-rich solutions. These may have been released during burial by the dehydration of primary gypsum, but more probably originated during uplift when the anhydrite was hydrated and the resulting gypsum was dissolved by phreatic groundwaters.

Breccia-gashes

Most of the known breccia-gashes (under a variety of names such as gash-breccia and breccia-pipe) are in the Concretionary Limestone, but a few at Seaham and in cliffs to the north of Crimdon Park are in the Seaham Formation. Work on equivalent Cycle EZ3 strata in Yorkshire (Smith, 1972; Cooper, 1986) has shown that such gashes probably form through the collapse of caves located at the intersection of joints or faults, and propagate upwards until they choke with debris. According to Cooper, this choking occurs when the pipe is 5–10 times the original height of the cave, through the stoping of angular fragments of roof rock. The end results of this process are near-vertical bodies of breccia, some with slight fault displacement, composed of fragments of wall rock, but also commonly including fragments of rocks from strata since removed by erosion; such breccia-gashes are analogous to small faulted-in outliers, and afford valuable information on the former local stratigraphy. The breccia-gash near the east end of the north wall of the North Dock at Seaham, though now degraded, is an excellent example of a structure associated with a minor normal fault and in which are preserved fragments of younger strata, the Rotten Marl, now otherwise eroded away.

Future research

Although the broad outlines of the geology of the natural and man-made cliffs at Seaham are reasonably well known and understood, many details remain uncertain and would amply repay further research. Amongst the more fundamental aspects in need of investigation are (a) the geochemistry and petrology of the Seaham Residue, with the aim of determining the character, thickness and depositional environment of the Fordon Evaporites of which it is the insoluble remains, and (b) the precise thickness and sedimentology of the Seaham Formation, with the aim of accurately documenting this formation at its type locality and of attempting to deduce its depositional environment.

Conclusions

The coastal site at Seaham contains the highest Permian strata exposed on the Durham coast, and is the type locality of both the Seaham Residue and the Seaham Formation. This is a classic site for the study of post-depositional changes in sedimentary sequences. The site exhibits a range of features including unusually large calcite concretions in the Seaham Formation, together with the only known clear exposure of the top of the Roker Dolomite Formation. Of particular significance are the well-exposed remains of former evaporite beds since removed by dissolution. The evaporites resulted from the evaporation of the Zechstein Sea, producing salt and anhydrite concentrates. These were later taken back into solution by invading groundwater, leaving an insoluble residue and causing collapse of the overlying strata. In particular, breccia-gashes, which contain fragments of rocks which have elsewhere been eroded from the area, were created. The site is therefore of major importance in observing post-depositional changes in the Permian rocks of Durham.

STONY CUT, COLD HESLEDON (NZ 4171 4724–4186 4744)

Highlights

This shallow cutting (box 11 in Figure 3.2) uniquely exposes a transect from the reef-flat to the crest of the shelf-edge reef of the Ford Formation. The reef-flat rocks are exposed in the south-west and central parts of the cutting and comprise a partly crudely-bedded mixture of *in situ* and reworked shallow-water reef dolomite; this passes north-eastwards into massive reef dolomite in which successive positions of the reef crest appear to be marked by sharply steepening thin sheets of laminar (?algal) dolomite.

Introduction

Stony Cut is a disused cutting on a former colliery wagonway and exposes up to 3 m of varied reef dolomite of the Ford Formation beneath a thin cover of Late Devensian boulder clay. The reef-rock is exposed for about 260 m (Smith, 1962) and is divisible into a reef-flat sub-facies (about 190 m seen) in the south-west and a reef crest sub-facies in the north-east; the latter is important as one of only four places where the crest of the Ford Formation reef is now exposed.

The cutting gave valuable insight into the disposition of reef sub-facies as originally identified by Smith (1958) and was later described in more detail by Smith and Francis (1967) and Smith (1981a). The palaeontology of the reef here was investigated by Hollingworth (1987), who reported marked differences between the fauna of the reef-flat and reef crest sub-facies and a striking north-eastwards increase in faunal abundance and diversity. Aplin (1985) reviewed the petrology and diagenesis of the reef-rock and discussed the origin of laminar ?algal encrustations and laminar fissure-fill in north-eastern parts of the cutting.

Description

The position of Stony Cut is shown in Figure 3.42. The rock faces are generally only 1–2 m high and are commonly overgrown and obscured in high summer; the floor of the cutting falls gently north-eastwards at about the regional dip in the Magnesian Limestone, and the north-eastern end of the cutting coincides with the edge of the strong topographic bench that marks the basinward margin of the Ford Formation reef.

Dolomitized reef-flat rock in the south-western part of the exposure is buff algal–bryozoan boundstone with lenses and pockets of oncoids (coated reworked algal chips) and skeletal debris. The rock

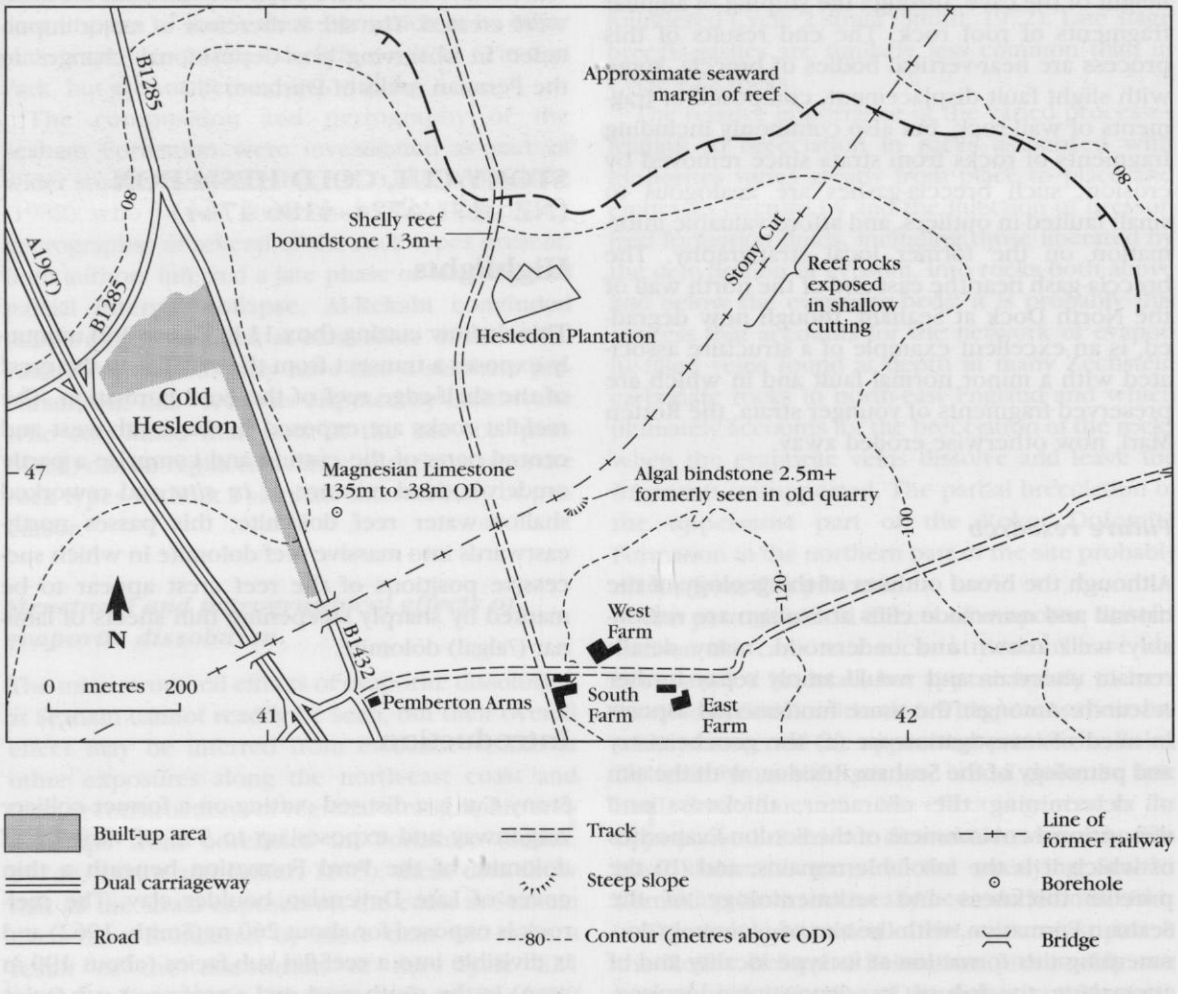


Figure 3.42 Location of Stony Cut, Cold Hesledon.

is generally unbedded and is a heterogeneous assemblage of mutually interfering masses up to 0.5 m across of boundstone (some rolled) and abundant draped sheets of laminar ?algal bindstone; the boundstone masses have a sparse framework of ramose bryozoans (almost exclusively *Acanthocladia* according to Hollingworth, 1987) which are thickly to very thickly coated with concentric ?algal encrustations (Smith, 1958, plate VIB, and 1981b, fig. 12 A,B).

Central parts of the cutting, extending for more than 100 m, are in crude and very uneven thick-bedded dolomitized algal–bryozoan boundstone; this includes many minor primary boundstone domes (some rolled), a wide variety of complex laminar (?algal) sheets and encrustations, and scattered to abundant lenses and pockets of fine boundstone debris, skeletal remains and oncoid rudstone. The overall dip is roughly parallel with the floor of the cutting, but is widely varied and local primary dips of up to 30° in all directions testify to contemporary reef-top relief of up to 1 m.

The dolomitized reef-rock in the north-easternmost 70 m of the cutting is, by contrast, relatively uniform. It contains less skeletal and boundstone debris and mainly comprises massive ***in situ*** brown-buff algal-bryozoan boundstone divided into steeply dipping panels a metre or more thick by thin finely laminar sheets. The boundstone has a sparse framework of ramose and fenestrate bryozoans, most of which are thickly coated with fine concentric ?algal encrustations that locally form up to half of the rock (Aplin, 1985, p. 385). Some of the thin laminar sheets are subvertical to vertical and were interpreted by Aplin as fissure-fill, but many are gently north-east dipping at the top of the section and steepen sharply to up to 85° below (Smith, 1981a; Aplin, 1985) (Figure 3.43); these appear to be algal coatings of reef masses or successive positions of the reef crest and remains of algal filaments were identified in such laminite by Aplin (1985, fig. 2.16C).

Early selective fossil collections from Stony Cut by Pattison (in Smith and Francis, 1967, p. 133) were augmented by more detailed sampling by Hollingworth (1987); both authors noted a sharp north-eastwards increase in faunal abundance and diversity and Hollingworth (1987, fig. 6.38) convincingly illustrated this trend and showed that the increase is not uniform, but is interrupted by a low-diversity belt in central parts of the cutting where bryozoans are less common. Hollingworth noted that *Acanthocladia* persists across the full width of the reef tract, but is accompanied by *Dyscritella, Synocladia* and *Fenestella* in the north-eastern sector; a number of species of gastropods, bivalves and brachiopods are also confined to this sector. He commented that the absence or rarity of infaunal and quasi-infaunal forms suggested a measure of contemporaneous lithification of the substrate, supporting the evidence of such lithification by the rolled boundstone blocks and reef gravels (Smith, 1981a).

Figure 3.43 Laminar ?algal bindstone sheets with high primary east-northeastwards dip, in reef boundstone of the Ford Formation near the north-east end of Stony Cut, Cold Hesledon. The sheets are thought to mark the temporary position of the upper part of the reef foreslope and grade upwards into the reef-crest and reef-flat dolomite. Hammer: 0.33 m. (Photo: D.B. Smith.)

Interpretation

The complex and varied rocks of Stony Cut provide a unique transect across much of the shelf-edge reef of the Ford Formation; this reef extends sinuously from near Sunderland to West Hartlepool and also features in the GCR sites at Hylton Castle, Claxheugh Rock, Humbledon Hill, Tunstall Hills, Ryhope, Hawthorn Quarry and Horden Quarry. Indications from topography, the exposures in the cutting and from other excavations nearby suggest that the reef at Cold Hesledon may be about 400 m wide, compared with estimates of 250–400 m in the Sunderland area and at least 300 m at Hawthorn Quarry. The only other transects are at the Claxheugh Rock site, where the rocks are probably somewhat older, at the Hawthorn Quarry site where the reef-rock is probably of about the same age, but is now partly covered, and in Castle Eden Dene where much of the section is almost inaccessible.

The lithology of the heterogeneous roughly-bedded carbonate rocks in most of the cutting, together with their indigenous and derived fauna, strongly suggests that they were formed on a sub-horizontal, but somewhat rugged reef-flat under water no more than a few metres deep and perhaps at times intertidal (Smith, 1981a; Aplin, 1985; Hollingworth, 1987). Salinity was probably normal to slightly above normal, and energy slight to high according to location and weather conditions. Other, larger, sections in reef-flat dolomite are in the Hawthorn Quarry site and in Townfield Quarry (NZ 4343 4380), Easington Colliery.

The sections at Hawthorn Quarry (now covered) and Horden Quarry, provided the key to understanding Stony Cut, for they showed (a) that massive boundstone at the self-evident reef crest at the two quarries was lithologically and faunally indistinguishable from that in the north-eastern part of the Cold Hesledon cutting and (b) that boundstone at the progradational reef crest, as in the cutting, is divided into steeply-dipping panels by thinner upwards convex steeply-dipping laminar sheets (Smith and Francis, 1967, especially plate IX; Figure 3.47) that strike parallel with the reef foreslope. The origin of these laminar sheets is uncertain and some could fill former tension gashes like those in reef-rock at the Maiden Paps site, Tunstall Hills, Sunderland. The author believes, however, that their upwards-and-outwards convexity is more in keeping with a succession of reef crest ?algal coatings and if this is so, they indicate reef foreslopes approaching vertical and an extremely sharp reef crest. From his analysis of the biota at and near the supposed reef crest here, Hollingworth (1987) inferred that these rocks were formed subaqueously in turbulent water slightly deeper than that covering the reef-flat, and that the vicissitudes of reef growth provided a wide range of ecological niches that were exploited by the abundant and varied invertebrates. The origin of the thick concentric encrustations that freely coat the skeletal framework here and in many other parts of the Ford Formation reef were discussed by Smith (1981a), who concluded that they were probably formed by blue-green algae.

Future research

The palaeontology, ecology and petrology of the rocks in Stony Cut have all quite recently been investigated in detail (Aplin, 1985; Hollingworth, 1987) and there is little immediate scope for further work on these aspects. The curved laminar sheets near the inferred reef crest are worthy of further research, however, because of their importance and probable significance in the interpretation of reef crest and high reef slope morphology and evolution.

Conclusions

This site comprises a unique cross-section from the reef-flat to the crest of the shelf-edge reef of the Ford Formation. It is additionally important in that it is now one of only four places where the crest of the reef is exposed. Reef-flat carbonate rocks in the form of sub-horizontally bedded dolomite, sharply pass into steeply-dipping laminar sheets at this crest. Indications that the reef-flat was subject to very shallow water, possibly intertidal conditions, are the presence of oncoids, of algal encrustations on the reef-building framework and of large rolled boulders of reef-rock that had already become hard.

HIGH MOORSLEY QUARRY (NZ 334455)

Highlights

High Moorsley Quarry (box 12 in Figure 3.2) is typical of many exposures in the much-quarried Magnesian Limestone (Permian) escarpment and exposes a representative section of the lower part of the Raisby Formation (formerly the Lower Magnesian Limestone). In addition, it contains a spectacular submarine debris flow, other evidence of contemporaneous, mass downslope sediment movement and a coarse, mineralized breccia.

Secondary features in the quarry include evidence of markedly widened major joints, the opening of which probably resulted from cambering and/or mining subsidence.

Introduction

High Moorsley Quarry is cut into the west-facing Permian escarpment a short distance south-west of High Moorsley village and exposes about 17 m of the lower part of the Raisby Formation. The rocks exposed are typical of this formation in north-east England, and include an inferred slide-breccia and a debris flow; secondary calcite–marcasite mineralization is a feature of the northern part of the quarry. The general section and the mineralization at High Moorsley Quarry were noted by Francis (1964) and in Smith and Francis (1967, p. 109), and details of the debris flow and slide-breccia were given by Smith (1970c). Lee (1990) presented isotopic analyses of several rock types from the quarry and discussed their diagenetic history.

Description

The position of High Moorsley Quarry is shown in Figure 3.44; the main exposures of the Raisby Formation are in the high, east face of the quarry, but the breccias and debris flow are best exposed in the north of the quarry.

The generalized section in the quarry (from the top) is given below.

Bed		Thickness (m)
7	Dolomite mudstone, coarsely mottled buff and grey-buff, mainly in uneven to lenticular nodular wavy beds 0.15–0.30 m thick in lowest 1.6 m where patchily bioturbated, 0.15–0.20 m beds above; some auto-brecciation	*c.* 5.1
6	Dolomite mudstone, buff with grey-buff patches, in even to wavy beds mainly 0.05–0.15 m thick but becoming thick-bedded in places, partly finely nodular; some beds bioturbated; sharp planar base	*c.* 1.4
5	Dolomite mudstone, finely mottled buff and grey-buff, partly unevenly laminated, strongly bioturbated, one bed, planar base	0.1
4	Dolomite mudstone/wackestone, buff and grey-buff, thick-bedded in the north but mainly in varied uneven to lenticular beds 0.10–0.20 m thick with some boudin-like structures; some beds dip at up to 7° in large cross-sets; ripple-like linen-fold fluting (WSW–ENE, relief 0.10 m, wavelength 0.50–0.80 m) 0.60–0.80 m above base	*c.* 2.3
3	Breccio-conglomerate, buff and grey-buff, comprising ill-sorted sub-rounded to tabular dolomite mudstone clasts up to 0.15 m across (some WSW–ENE imbrication) in a varied matrix of skeletal dolomite mudstone, wackestone and packstone; locally clast-free in uppermost 0.05–0.25 m. Discontinuous, forming at least three discrete 5–10 m-wide lenses (?lobes) in about 60 m along the north-east face of the quarry	0–0.6
2	Dolomite mudstone, buff and grey-buff, mainly in very uneven to lenticular beds 0.05–0.15 m thick, with linen-fold fluting (?nearly symmetrical ripples, relief 0.05–0.10 m) *c.* 0.30 and 0.80 m beneath the scoured top, several to many penecontemporaneous sub-concordant glide-planes, and with scattered large penecontemporaneously folded and brecciated patches (more in north than south).	*c.* 4.0
1	Calcite mudstone, mottled in shades of grey, mainly in finely augen-nodular beds 0.01–0.06 m thick with sub-stylolitic contacts; scattered poorly-preserved molluscan debris; partly broken-up by penecontemporaneous brecciation. Normal top not exposed	1.5+

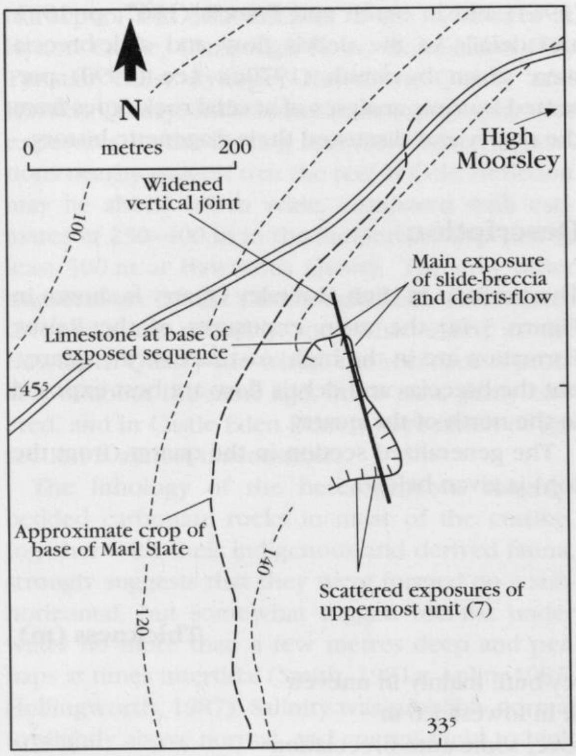


Figure 3.44 High Moorsley Quarry and its immediate surroundings, showing the main features of geological interest.

Judging from small exposures at the north and south ends of the designated area, and from topographical features, the floor of the quarry lies less than 5 m above the base of the Raisby Formation.

All the dolomite rocks in the quarry contain scattered to abundant, irregular to ovoid, calcite-lined cavities after replacive anhydrite, and small calcite laths after anhydrite are also present; manganese dioxide speckles and dendrites are widespread. Most beds are lithologically varied when traced laterally. Beds 1 and 2 are slightly to severely broken-up into irregular blocks, slices and lenses up to 10 m across and 3 m thick, and are interpreted (Smith, 1970c) as comprising a slump- or slide-breccia caused by downslope movement of a mass of fairly-well lithified strata; crumpling and slight truncation of bedding in otherwise apparently undisturbed parts of this disrupted sequence (Figure 3.45) show that some bedding-plane sliding was on an unusually large scale. Heavy calcite–marcasite mineralization of parts of the breccia implies that many inter-block cavities remained at least partly empty of sediment after movement ceased, but M.R. Lee (in letter 1990) believes that the association is coincidental and that the mineralization may be related to later tectonic brecciation. Limestone from bed 1 was analysed for its isotopic composition and strontium content by Lee (1990), who reported lower carbon and oxygen values than is normal for dolomite rocks in this formation, but a higher strontium content. Bed 3 was interpreted as a proximal turbidite (= debris flow) (Smith, 1970c), overlain by a fall-out tail from a suspension cloud. The breccia ranges from clast-supported to matrix-supported and is very variable in thickness; it appears to thin out southwards in the east face. Two clasts from this bed were interpreted by Lee (1990) to have been at one time composed of replacive anhydrite, but their isotopic composition was found to be almost the same as that of normal dolomite rocks in the quarry.

Conspicuously wide, sub-vertical joints in the north and south faces of the quarry are probably a response to massive cambering along the escarpment, but may have been further widened by differential mining subsidence; they cause inherent instability in parts of the east face. Other widened joints trend WSW–ENE in the east face.

Interpretation

High Moorsley Quarry is important because it provides a representative section of the Raisby Formation in this part of County Durham; both the lithology and scanty biota are typical of those in many abandoned quarries in the escarpment, and the debris flow and slide-breccia are characteristic of a disturbed sequence commonly found 3–7 m above the base of the formation. Together they throw much light on the depositional environment of the Raisby Formation.

The Raisby Formation is the first major carbonate unit of the English Zechstein sequence in the Durham Province, and is up to about 73 m thick in some eastern parts of County Durham. Generally, however, it is considerably thinner, and is unlikely to have been more than 50 m thick at High Moorsley. At outcrop in eastern Durham and

Figure 3.45 Crumpled bedding in the lower beds of the Raisby Formation near the north end of the east face of High Moorsley Quarry, with evidence of contemporaneous truncation at the top of the disrupted beds. Hammer (middle top): 0.33 m. (Photo: D.B. Smith.)

adjoining areas it is almost everywhere a carbonate mud rock, and is mainly dolomitized. Judging from the distribution of similar rocks in Yorkshire (Smith, 1974b, 1989, fig. 6), it accumulated mainly on the gentle marginal slopes of the Zechstein Sea and passed westwards into a belt of shallow water dolomitized packstones/grainstones formed on a progradational carbonate shelf. Such shelf rocks have since been eroded from the Durham Province, but may, by selective storm winnowing, have been the source of some or most of the hemipelagic carbonate muds deposited on the slopes (i.e. now the Raisby Formation).

The evidence of sediment instability forms another part of the argument favouring a slope location for the deposition of the Raisby Formation at outcrop in northern Durham and Tyne and Wear, and was summarized by Smith (1970c, 1985); both the debris flow and the slide-breccia are textbook examples of their kind, though the exposure of the latter could be improved by the clearance of debris.

The exposures at High Moorsley Quarry are representative of disturbed strata at about this stratigraphic level for more than 40 km between offshore boreholes east of Blyth (NZ 8231) and the village of Ludworth (NZ 358413) and it seems likely that most of the disturbance was caused by an external stimulus such as an earthquake shock or a closely spaced group of shocks; instability through natural over-steepening seems to be excluded by the limited stratigraphic range and absence of widespread turbidites such as characterize the Concretionary Limestone Formation in, for example, Marsden Bay (Trow Point to Whitburn Bay GCR site). The abundance of bioclasts in the matrix of the debris flow has been attributed to rapid burial and consequent escape from predation.

Future research

The sedimentology and diagenesis of the complex rocks of the Raisby Formation at High Moorsley Quarry have recently been investigated by Lee (1990) and there is little immediate scope for further research on these aspects.

Conclusions

The site is notable for the exposure of the lower part of the Raisby Formation, comprising dolomites and limestone typical of the sequence found in Durham, together with well-exposed interbedded slide-breccia and debris-flow units, a characteristic feature of strata close to the base of the formation. These are indicative of the movement of sediment down an inclined depositional surface as a result of instability, perhaps triggered by earthquake shocks. This site, together with Dawson's Plantation Quarry, is one of the best exposures of evidence of downslope sediment slumping and sliding low in the Raisby Formation, and needs to be preserved for this reason.

HAWTHORN QUARRY (NZ 4346)

Highlights

Hawthorn Quarry (box 13 in Figure 3.2) is one of the largest exposures of late Permian reef-rocks in north-east England and the only exposure in which their contact with overlying strata is seen; unique exposures formerly recorded, but no longer available, revealed the overall profile of the basinward crest of the reef and its juxtaposition with downfaulted or foundered younger strata to the east.

Introduction

Hawthorn Quarry, which ceased working in 1985, exposes the basal beds of the Roker Dolomite Formation (15 m+), the whole of the Hesleden Dene Stromatolite Biostrome (22–26 m, including a basal 0–4 m boulder conglomerate) and the uppermost 15 m of the shelf-edge reef of the Ford Formation. Exposures available up to mid-1958, but now quarried away or covered, showed that the eastern (basinward) crest of the reef crossed the eastern end of the quarry (Smith, 1962), and boreholes drilled in about 1974 proved reef-rock to a depth of at least 44 m below the then quarry floor at about +49 m O.D.

The strata exposed in Hawthorn Quarry dip generally southwards at less than 5° and there are no major folds or faults in any of the strata now visible. The pre-1958 exposures, however, revealed a complex 80° reverse shatter belt abutting and trending parallel with the reef crest, which brought down brecciated, ooidal dolomite on the basinward side.

The rocks at Hawthorn Quarry have been discussed and illustrated by Smith and Francis (1967), Smith (1973b, 1981a), Kitson (1982, petrography), Aplin (1985, petrography of the reef) and Hollingworth (1987, palaeontology of the reef); their interpretation has changed little during the period covered, the main development being the revealing of the boulder conglomerate between the reef and biostromal laminites in about 1980 as the quarry extended gradually westwards. A provisional faunal list for the reef-rock was given by Pattison (in Smith and Francis, 1967, p. 134) and the fauna was analysed in detail by Hollingworth (1987, pp. 258–266).

Description

Hawthorn Quarry (NZ 4346) is cut into an east-facing slope near the Durham coast, about 3 km south of Seaham; the boundaries of the quarry are shown in Figure 3.46, together with the geological boundaries and the position of the main features of geological interest.

The general geological sequence in and around the quarry is given below.

	Thickness (m)
Soil on Durham Lower Boulder Clay	0–5
Gravel, partly calcreted, present only near entrance in east of quarry and in minor rockhead depressions	0–4
------unconformity------	
Roker Dolomite Formation	up to 15
Hesleden Dene Stromatolite Biostrome, with boulder conglomerate at base in west of quarry	*c.* 22–26
------erosion surface------	
Ford Formation, reef-facies, in floor of quarry	*c.* 15+

The disposition of the various lithological units within the quarry site is shown in Figure 3.47.

Ford Formation, reef-facies

Dolomite rocks of this unit are exposed in the lowest levels of the quarry, where they are up to 15 m thick; a borehole in the quarry floor proved an additional 29 m of reef dolomite (Figure 3.47), but its total thickness here may exceed 100 m. The reef comprises a complex assemblage of autochthonous masses of bryozoan and algal boundstone

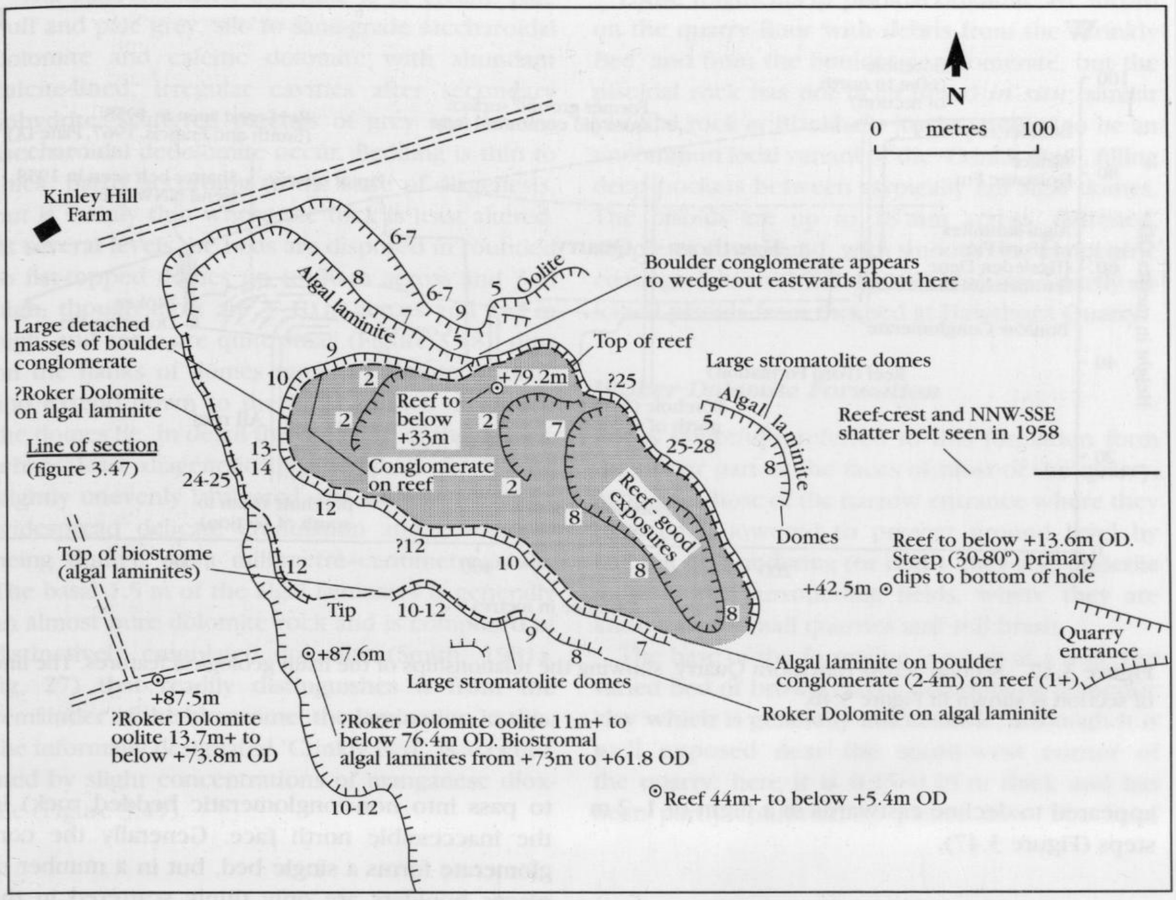


Figure 3.46 Hawthorn Quarry, showing the location of the main features of geological interest.

separated and surrounded by sheets and pockets of shelly detritus (Smith, 1981a, pp. 169–174); laminar (at least partly algal) encrustations and ramifying laminar sheets abound and locally form most of the rock, and a few rolled blocks (some coated) also occur. The reef-rock has a general roughly horizontal thick bedding, with primary dips of up to 30° traceable for a few metres. Pattison (in Smith and Francis, 1967, p. 134) gave a provisional faunal list for reef-rock from Hawthorn Quarry and this has been supplemented by a full faunal analysis by Hollingworth (1987), who distinguished between assemblages in the boundstone masses and surrounding ?algal laminites. Aplin (1985) gave details of the petrography and diagenesis of the rock.

Unique exposures formerly visible (Figures 3.46 and 3.47) near the quarry entrance revealed the reef crest, where successive reef-flat beds bent sharply over to dip east-northeastwards at up to 90° down the reef front (Smith and Francis, 1967, plate 9; Smith, 1973b, 1981a); similarly steep dips were encountered in a nearby borehole, proving that the reef front maintained a high angle to a depth of at least 35 m below the crest. In inaccessible parts of the former exposures, the reef crest

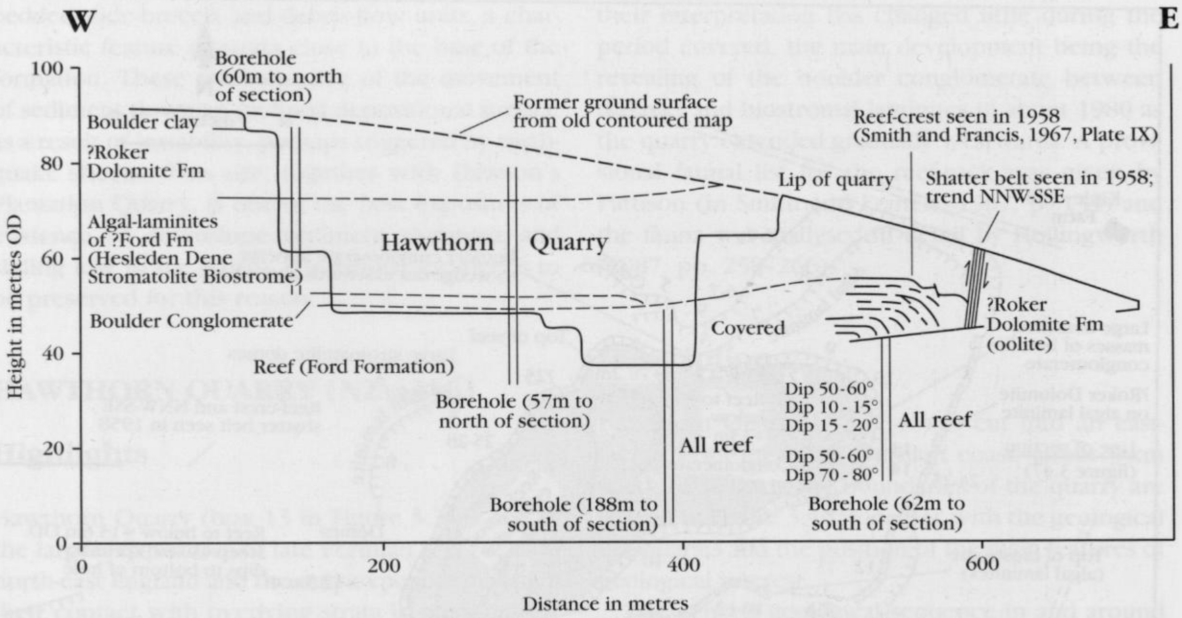


Figure 3.47 Section across Hawthorn Quarry, showing the relationships of the main geological features. The line of section is shown in Figure 3.46.

appeared to decline eastwards in a flight of 1–2 m steps (Figure 3.47).

The erosion surface

This is exposed mainly in the south-west and west of the quarry, but is not well seen because it generally coincides with a quarry bench. In the few places where it is exposed clearly, especially in the middle of the south and west faces of the quarry, the surface is sub-horizontal with an average relief of 0.05–0.10 m. In detail, the surface is diversified by scattered slopes of up to 45° and minor depressions up to 0.15 m deep. Even where well exposed, however, the contact has commonly been blurred by diagenetic changes.

Hesleden Dene Stromatolite Biostrome

This member at Hawthorn Quarry comprises a basal boulder conglomerate up to 4 m thick that is present only in the west and south of the quarry, and a thick (*c.* 22 m) unit of algal-laminated dolomite bindstone which is (or was) recognizable all round the quarry except near the entrance.

The boulder conglomerate at the base of the biostrome is 2–4 m thick in the west and south faces of the quarry, but appears to die out eastwards (or to pass into non-conglomeratic bedded rock) in the inaccessible north face. Generally the conglomerate forms a single bed, but in a number of places boulders are only thinly scattered in the uppermost 1–2 m of the unit which is composed mainly of chaotic, finely laminated dolomite with a wide variety of ?algal growth forms. Below this the conglomerate is clast-supported and is composed of subangular to rounded small boulders (mostly 0.1–0.3 m across, but exceptionally 0.6 m) and subordinate cobbles of dolomite boundstone derived from the underlying reef. Most of the clasts are uncoated and a few bear signs of contemporaneous fracturing and re-cementation. The rock is generally poorly-graded and lacks clear imbrication or cross-bedding; possible crude east-dipping foresets, however, are present where the bed thins out in the north face. Interstices between the cobbles and boulders are filled or partly filled with white to pale cream, unfossiliferous, saccharoidal dolomite or calcite (according to location), and calcite-lined irregular voids are common. The filling comprises an estimated 20–30% of the conglomerate and is mainly faintly finely laminar, the laminae being parallel with the cavity walls; similar material also lines the walls of scattered steeply-inclined cracks, some of which are now more than 1 m deep and may have been contemporaneous.

The algal-laminated dolomite is of cream, pale buff and pale grey, silt- to sand-grade saccharoidal dolomite and calcitic dolomite with abundant calcite-lined, irregular cavities after secondary anhydrite; scattered patches of grey and brown saccharoidal dedolomite occur. Bedding is thin to thick, partly according to the state of diagenesis, but is mainly thin where the rock is least altered. At several levels the beds are disposed in rounded to flat-topped domes up to 20 m across and 3 m high, though most are 3–10 m across and 1–2 m high, and some are quite small (Figure 3.48); dips on the flanks of domes range to almost vertical, and extend down to the basal surface on which the domes lie. In detail the dolomite of the domes, where least diagenetically altered, is finely and slightly unevenly laminated, the laminae featuring widespread delicate crenulation and commonly being domed on a millimetre–centimetre scale. The basal 1.5 m of the algal laminates is generally an almost pure dolomite rock and is composed of distinctively crenulated dolomite (Smith, 1981a, fig. 27) that readily distinguishes it from the remainder of the biostrome; the lamination in this, the informally designated 'Crinkly Bed', is accentuated by slight concentrations of manganese dioxide (Figure 3.49).

Loose fragments of pisoidal dolomite are mixed on the quarry floor with debris from the 'Crinkly Bed' and from the boulder conglomerate, but the pisoidal rock has not been found ***in situ***; similar pisoidal rock at Blackhalls Rocks appears to be an uncommon local variant of the 'Crinkly Bed', filling deep pockets between atypically tall algal domes. The pisoids are up to 18 mm across, flattened, simple or compound, with smooth fine concentric coatings; Kitson (1982, fig. 62) illustrated partly silicified pisoids from this bed at Hawthorn Quarry.

Roker Dolomite Formation

Rocks doubtfully referred to this formation form the upper part of the faces of most of the quarry, including those of the narrow entrance where they have been lowered to present ground level by faulting or foundering (or both); they also underlie most of the surrounding fields, where they are known from small quarries and soil brash.

The base of the formation is taken at a thin, but varied bed of brown clayey dolomite or dolomitic clay which is generally inaccessible, although it is well exposed near the south-west corner of the quarry; here it is 0.15–0.25 m thick and has been partly contorted by plastic flow. The basal

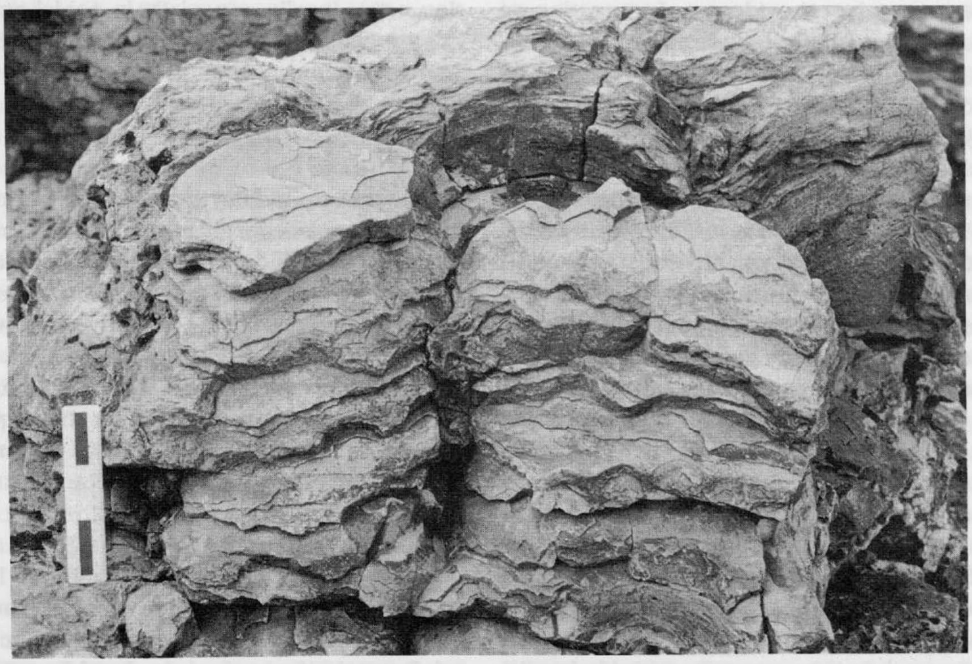


Figure 3.48 Small columnar stromatolites just above the boulder conglomerate of the Hesleden Dene Stromatolite Biostrome near the middle of the south face of Hawthorn Quarry. Bar: 0.32 m. (Photo: D.B. Smith.)

Figure 3.49 Slight concentrations of manganese dioxide coating a bedding plane in the 'Crinkly Bed' near the base of the Hesleden Dene Stromatolite Biostrome near the middle of the south face of Hawthorn Quarry. Note the asymmetry of the ?algal growth-forms, indicating water flow from the right. Coin: 20 mm across. (Photo: D.B. Smith.)

grainstone at this exposure displays slight onlap, perhaps indicative of a depositional hiatus, but there is no unequivocal evidence of truncation or of a hiatus at the top of the underlying biostrome, and no evidence of the former presence of evaporites.

The Roker Dolomite at Hawthorn Quarry comprises pale buff and cream, mainly ooidal dolomite grainstone in which abundant irregular calcite-lined cavities up to 0.10 cm across mark the site of former secondary (replacive) anhydrite. According to Kitson (1982), rock in the basal 2 m of the formation is of relatively pure dolomite, but higher beds have a sparry calcite cement; local dedolomitization (by surface water) has occurred near the base of the drift, where travertine and calcite veins are abundant and the rock has been brecciated in places. Component ooids are of coarse to very coarse sand-grade and have leached centres (Kitson, 1982, fig. 44); most are simple and subspherical, but a few irregular compound grains are present in most hand specimens and compound pisoids up to 5 mm across are locally common. Most of the rock is thin- to medium-bedded, with much of the bedding poorly defined. Preservation of sedimentary structures is similarly generally poor, although traces of ripple lamination, cut-and-fill structures and small-scale planar cross-lamination occur locally, especially in ooidal grainstones exposed near the quarry entrance (NZ 4383 4631).

Interpretation

The exposures at Hawthorn Quarry are of special importance because they furnish a complete sequence from the reef of the Ford Formation well up into the inferred Roker Dolomite Formation. They are unique in being the only place where the contact of the reef with overlying strata may be studied; the record of the former position of the reef crest, now covered, enables the sequence to be precisely located relative to the main late Permian facies belts in the area.

Ford Formation, reef-facies

Hawthorn Quarry contains one of only three remaining substantial exposures of the reef-flat sub-facies of the reef of the Ford Formation, the other being the much smaller Townfield Quarry (NZ 4343 4380) at Easington Colliery and Stony

Cut GCR site. Several small quarries in this facies in the Easington–Hawthorn area have been filled in recent years, but were described by Smith and Francis (1967). The reef-rocks at Hawthorn Quarry (then much smaller than now) and Townfield Quarry were discussed briefly by Smith (in Smith and Francis, 1967) and later by Kitson (1982), Aplin (1985) and Hollingworth (1987); Smith (1981a) gave a general review of the characteristics of rocks of the reef-flat based mainly on the two quarries, and Hollingworth (1987) gave detailed analyses of the fauna from them.

Much of the importance of the exposures of reef-rocks at Hawthorn Quarry stems from their large size, which alone allows a comprehensive overview of the general lithology, faunal distribution and great lateral variability of the reef-flat sub-facies. This sub-facies is shown by a combination of former and present exposures to have been at least 300 m wide, and boreholes in the quarry floor showed that it overlies reef-core and reef slope rocks; for comparison, the reef transect at Ford Quarry, Sunderland, revealed a total reef width there of at least 200 m.

Exposures (NZ 4415 4666) at the foot of present coastal cliffs, about 450 m north-east of the reef crest in Hawthorn Quarry, throw some light on contemporary reef-front relief here; allowing for a dip not exceeding 2°, a contemporary reef-front relief of 40–50 m is suggested. This is comparable with that inferred at the southern end of Tunstall Hill GCR site, but is appreciably less than the inferred relief of at least 80 m at Beacon Hill, about 1 km south of Hawthorn Quarry. The exposures feature a coarse breccia (?talus) of reef-derived boundstone, overlain by up to 1.4 m of bedded cream ?ooidal dolomite that fills hollows in the surface of the breccia and is, in turn, succeeded by the dissolution residue of the Hartlepool Anhydrite. The breccia has yielded shelly reef fossils (Trechmann, 1954) and appears to include rounded masses up to 4 m across of intensely encrusted dolomite similar to that at the summit of Maiden Paps, Tunstall Hills.

The reef as a whole is known to stretch in a somewhat tortuous belt from West Boldon (NZ 3464) southwards to Hartlepool (e.g. Trechmann, 1925; Smith, 1981a), and forms the edge of the Cycle EZ1 carbonate shelf-wedge; it plunges gently southwards so that, in general, lower parts are exposed in the north and higher parts in the south. Smith (1980c, 1981a) recognized and defined several main sub-facies of the reef, and Hollingworth (1987) investigated the faunal distribution and ecology of these. Each of the main sub-facies is exposed in one or other of the several GCR sites in the reef, which include Hylton Castle road cutting, Claxheugh Rock and Ford Cutting and Quarry, Humbledon Hill and Tunstall Hills.

The erosion surface

This is readily accessible only at Hawthorn Quarry, its other known surface exposure being in a gorge (NZ 471370) in Crimdon Dene where the reef is in a different facies; a possible additional exposure at the northern end of Blackhalls Rocks awaits the removal of about 1.5 m of recent colliery waste from the beach there so as to reveal the reef top (suspected from a borehole (NZ 4716 3991)) drilled in 1984 by the University of Durham.

The importance of the erosion surface lies in its bearing on interpretation of the local and regional sedimentary history and on some aspects of the stratigraphy. In particular, it must record an episode of erosion and redeposition of the rocks of the underlying reef-flat, and, by inference, a sea-level fall of at least a few metres. The extent and duration of the sea level bears on the problematical age of the biostrome (Cycle EZ1 or Cycle EZ2?) and the choice of the EZ1/EZ2 boundary.

Hesleden Dene Stromatolite Biostrome

Hawthorn Quarry is one of the three main exposures of this unit, the others being the eponymous type locality (not a GCR site) and Blackhalls Rocks. Most of the features of the main part of the biostrome are common to the three main exposures, except that broad algal domes such as occur here and at Blackhalls Rocks have not been recorded at the type locality. Algal domes of this exceptionally large size (up to 20 m) were first reported from Hawthorn Quarry and Blackhalls Rocks (Smith and Francis, 1967), but have since been recorded by Eriksson (1977) from Precambrian dolomites in South Africa and from Precambrian limestones in north Africa. Nothing comparable has been recorded in rocks of any age in the British Isles or elsewhere in rock of Zechstein age. The striking 'crinkly' algal laminite at the base of the main part of the biostrome is similar in both thickness and lithology at each of the three main exposures and was illustrated by Smith (1981a, fig. 27).

The environmental interpretation of the algal laminites of the biostrome was considered by Smith (1981a, p. 15), who concluded from modern partial analogues that the rocks were formed on the broad reef-flat of the Ford Formation under a few metres of hypersaline water; this view was accepted by Kitson (1982).

The areal extent of the biostrome is poorly documented, with only a few exposures and borehole provings other than those cited. It has not been proved north of Hawthorn Quarry and known surface exposures farther south are restricted to a working quarry (NZ 475345) near Hart and to two small old quarries (NZ 448340) near Whelly Hill Farm (Smith and Francis, 1967, p. 144); in the subsurface, the biostrome was proved above reef dolomite in two boreholes (NZ 465337) at Naisberry Waterworks and, judging from the brief records by Trechmann (1932, p. 170 and 1942, pp. 321–322), possibly also above reef-rocks in boreholes (NZ 507333) at Hartlepools Water Works. It may also have been present in the Mill Hill Borehole (NZ 4122 4248), Easington. With only one exception the biostrome has not been proved east of the main shelf-edge reef and its apparent absence from areas north of Hawthorn Quarry may result from poor exposure and erosion.

The boulder conglomerate at Hawthorn Quarry, like the overlying laminites, is exposed also in Crimdon Dene (NZ 4715 3705) (a downstream continuation of Hesleden Dene) and at Blackhalls Rocks, but is thinner and less diverse at Hawthorn. Here, too, it differs uniquely in having only a partial matrix, the laminar fill in many of the larger interstices having a central void up to several centimetres across. Other, poorer, exposures of the conglomerate are at the base of coastal cliffs between Hive Point (NZ 443458) and Beacon Point (NZ 444454), near Hawthorn, where they appear to form part of the collapse-breccia.

The conglomerate at Hawthorn was first described by Kitson (1982). It is an accumulation of clasts of boundstone derived from the underlying Ford Formation reef; the angularity of many of the clasts shows clearly that they were eroded and transported from an already lithified reef surface, indicating a high-energy environment similar to that of a modern boulder storm beach. The origin of the laminar matrix is problematical, but it much resembles travertine and deposition from marine or partly vadose waters passing through the interstices seems likely; the incompleteness of the filling may indicate early constriction of the 'throats' by fine detritus and contemporaneous cements, but could also have resulted from inadequate time before burial; close proximity to sea level is probably indicated. The period of conglomerate formation was completed by a phase of apparently chaotic ?algal-stromatolite growth before the more uniform subaqueous regime of the succeeding crenulated algal laminites became established.

Roker Dolomite Formation

The Roker Dolomite Formation exposed in the quarry is normal for the region and requires no special comment except on the uncertainty of its attribution; this doubt results from its apparent lack of diagnostic fossils and its unknown relationship with younger strata, but lithologically similar ooid grainstones at Seaham and Blackhalls Rocks are probably of the same age as those at Hawthorn Quarry and are assigned to the Roker Dolomite Formation with reasonable confidence. The formation as a whole is interpreted as the shelf facies of the marginal carbonate wedge of Cycle EZ2 (Smith, 1971a, 1980a, b); its outcrop is restricted to north-east coastal districts from Whitburn southwards (Smith, 1980b, fig. 9), where its main exposures are in coastal cliffs at Whitburn (NZ 4161), Roker (the type locality, NZ 4059) and Seaham (NZ 4250), and in coastal rock platforms at Hartlepool (NZ 5234).

Structure

The geological structure requires no comment except for the narrow reverse shatter-belt formerly seen between the reef and younger ooid grainstones (Roker Dolomite Formation) near the quarry entrance. The shatter-belt is roughly parallel with the strike of the reef crest and also with a normal NNW/SSE trending fault of 5–6 m displacement (downthrow to the east) in the underlying coal workings; it may be a surface expression of this fault, but it could also have resulted from differential compaction between the reef and the grainstones or from subsidence caused by dissolution of the Hartlepool Anhydrite that formerly lay against the steep reef-face. A combination of any of these causes is also possible, but the third suggested mechanism seems more likely than the others because it most readily accounts for the vertical displacement of 30 m+ in the Magnesian Limestone. Further evidence favouring this third mechanism comes from the partial (?collapse) brecciation of the ooid grainstone near the quarry entrance, and from the presence of fragments of red mudstone (from previously overlying strata) in some of the breccias there.

Future research

There are many unresolved geological problems in the rocks of Hawthorn Quarry, and correspondingly good opportunities for future research; some of these are currently being addressed. The ecology and biota of the reef, having been investigated by Hollingworth (1987), is now reasonably well understood, but the precise depositional conditions of the reef, its petrology and the nature and mode of origin of reef encrustations and laminar sheets still require further study. Other problems requiring further research include the nature, extent and origin of the erosion surface and overlying boulder conglomerate, the age, origin and diagenesis of the pisoids and algal laminites of the biostrome, and the age and diagenetic history of the Roker Dolomite Formation.

Conclusions

Hawthorn Quarry is an extremely important GCR site in that firstly, it is the largest exposure of late Permian (Ford Formation) reef-flat rocks in north-east England, and secondly, is the only exposure where their disconformable contact with the overlying Hesleden Dene Stromatolite Biostrome can be seen. The boulder conglomerate at the base of the Biostrome is seen elsewhere only in Crimdon Dene and at Blackhalls Rocks, whilst the contact between the biostrome and the overlying ?Roker Dolomite Formation is well-exposed only here. The site is ideal for further study and research into reef-rock characteristics, the age and diagenetic history of the Hesleden Dene Stromatolite Biostrome and the overlying Roker Dolomite Formation.

HORDEN QUARRY (NZ 435417)

Highlights

This small and very old quarry (box 14 in Figure 3.2) at Horden is now the best of the exposures in north-east England where a one-time crest of the shelf-edge reef of the Ford Formation may be seen and examined. The east side of the quarry also contains indifferent exposures of collapse-breccia (probably mainly of the Roker Dolomite Formation), showing that the Hartlepool Anhydrite, now dissolved, once lay against the steep reef-face here.

Introduction

This excavation, which formerly contained a concrete reservoir, lies near the foot of a steep slope on the west side of Horden township; it should not be confused with Yoden Quarry, which lies on the hill 400 m farther west. The slope into which the quarry is cut roughly marks the position of the seaward margin of the shelf-edge reef of the Ford Formation (Cycle EZ1b).

The quarry reveals two exposures of dolomite boundstone and bindstone at a one-time crest of the Ford Formation reef, and an adjoining collapse-breccia probably composed mainly of fragments of the Roker Dolomite Formation. The locality was probably that mentioned by Trechmann (1925) who reported *Epithyris (Dielasma)* and several bivalve and gastropod genera from his reef-limestone 'C' from a 'knoll behind Horden Colliery', and brief descriptions and illustrations were given by Smith (in Smith and Francis, 1967, p. 139 and Smith, 1973b, 1981a). The petrography of the reef dolomite at this exposure was considered by Aplin (1985) and the fauna of the rock here was used by Hollingworth (1987, fig. 6.18, reproduced in Hollingworth and Tucker, 1986, fig. 7) as the basis for his graphic reconstruction of a reef crest faunal community. There is some confusion regarding the local source of bivalves collected by Logan (1967), for he appears to have believed that they came from the same locality as those recorded by Trechmann (1925). He attributed them to 'Yoden Quarry (Horden Colliery)'.

Description

The location and outlines of the old quarry at Horden are shown in Figure 3.50, which also shows the position of the main points of geological interest. Figure 3.51 shows the section in the main surviving face in the west of the quarry, but similar features are also displayed in the south face.

The main geological interest at Horden is a one-time reef crest of the Ford Formation, exposed in two places on opposite sides of the quarry, and the presence of a collapse-breccia of later strata lying against the ultimate steeply-inclined reef-face in the north of the quarry.

Ford Formation, reef crest

The configuration of the reef crest at the old quarry at Horden, as it was towards the end of reef

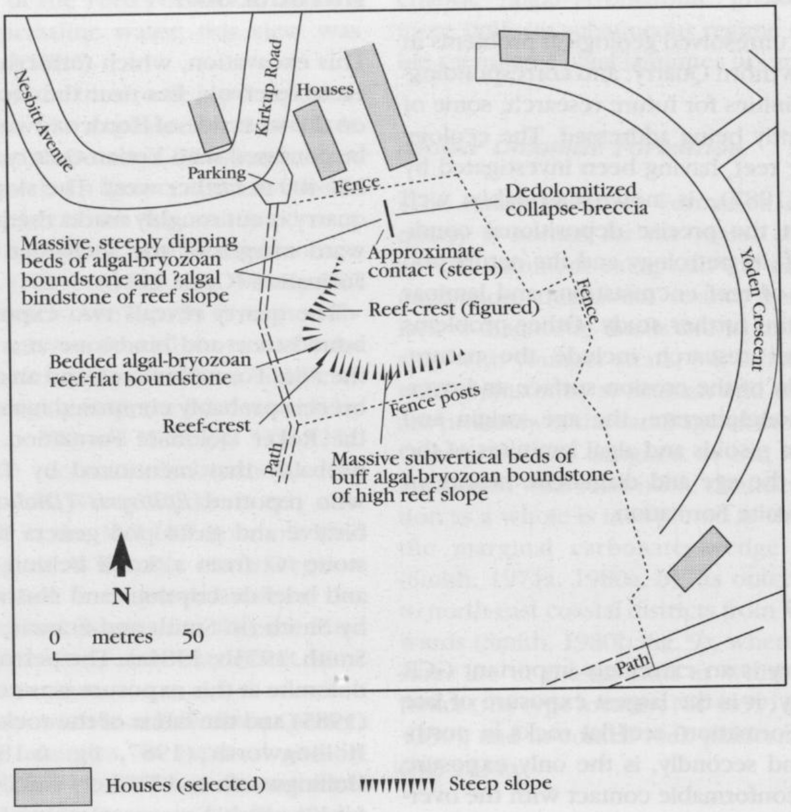


Figure 3.50 Location of Horden Quarry and the main features of geological interest.

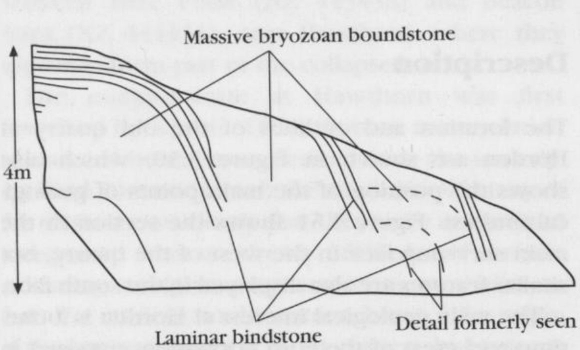


Figure 3.51 Sketch of the north-west face of Horden Quarry as seen in 1954 and later (parts of the face are now covered).

growth, is shown in Figure 3.52. This crest comprises a sharp transition from almost horizontally, fairly thin-bedded, dolomite boundstone of the reef-flat sub-facies to much thicker bedded, steeply dipping boundstone and bindstone of the uppermost reef slope sub-facies. Exposures near the floor of the western and southern part of the quarry show that the primary dip of the reef slope steepens there to 75° to 85°. The bindstone forms sinuous laminar sheets 0.1–0.3 m thick between exceptionally thick (1–3 m) boundstone beds, but appears to die out or become much thinner, at or just below the crest.

The dolomitized reef boundstone at Horden is a buff-coloured rock with an abundant fauna of low diversity. Lists by Trechmann (1925) and Pattison (in Smith and Francis, 1967) included ramose bryozoans (*Acanthocladia anceps*) and a small number of brachiopod, bivalve, gastropod, foraminifera and ostracod genera. These lists are confirmed by more detailed collecting by Hollingworth (1987), who quantified the relative proportions of the genera present; his observations showed that the bryozoans *Acanthocladia* (32%) and *Dyscritella* (18%) together make up half of the faunal elements present and that the remainder was dominated by *Dielasma* (18%), *Bakevellia* (16%) and

Figure 3.52 A reef crest in the north-west face of Horden Quarry (for position see Figures 3.50 and 3.51). Hammer: 0.33 m. (Photo: D.B. Smith.)

Pseudomonotis (12%). In his reconstruction of the reef crest community, Hollingworth also showed that most of the shelly organisms occupied (and presumably lived in) spaces in the tangled masses of *Acanthocladia zoaria*, and that most of the latter were heavily encrusted with ?algal laminae. Hollingworth (1987) found that almost all the *Dielasma* present in his sample died before reaching maturity, but only about 5% of the *Pseudomonotis speluncaria* collected by Logan (1967) were juveniles.

The laminar bindstone sheets between the massive boundstone beds are buff-cream in colour and are composed of finely crystalline, slightly calcitic dolomite. They are mainly lacking in skeletal fossils, but patches of densely crowded *Dielasma* and bivalves, and scattered fragments of bryozoans, occur parallel with the lamination of some of the sheets (Smith, 1981a). Presumably these organisms were all firmly attached to the seaward face of the reef. Bioclasts were also recorded by Aplin (1985, p. 92) in the algal-laminated lining of vertical tension fissures in reef-flat boundstone just landward (i.e. west) of the reef crest here, where fissures were bridged by reef-flat boundstone.

Roker Dolomite Formation, collapse-breccia

Hard grey limestone (dedolomite) collapse-breccia, with some residual cream dolomite, is poorly exposed in the eastern part of a low rock eminence in the north of the quarry. The rock comprises angular fragments, up to a few centimetres across, of finely crystalline limestone in a grey to brown dense calcite matrix; few traces of its original lithology remain. Because of the poor quality of the exposure, the sub-vertical contact with the reef slope is somewhat obscure, but its approximate position and trend are shown in Figure 3.50.

Interpretation

Horden Quarry is of major importance, firstly in being the only good and readily accessible exposure of rocks formed at the crest of the shelf-edge reef of the Ford Formation, and secondly, because it illustrates the juxtaposition of the steep Cycle EZ1 reef slope and the Cycle EZ2 collapse-breccia. The exposures are thus vital links in the chain of evidence leading to present understanding of the reef profile, its communities and the mutual relationships of the reef and the Hartlepool Anhydrite.

Ford Formation, reef crest

The ultimate reef crest (i.e. that formed just before the reef ceased to grow) has been eroded off at the Horden exposure but, by comparison with former exposures at Hawthorn Quarry site (Figure 3.47) and at an old quarry (NZ 436437) at Easington Colliery (Figure 3.53), was probably only a few metres above present ground level. Elsewhere, the ultimate reef crest is exposed inaccessibly high in the north face of the working quarry (NZ 476344) near Hart, and earlier reef crests are indifferently exposed at Ford Quarry SSSI and in the Stony Cut site (NZ 418473), Cold Hesledon. As at Hawthorn Quarry, the relative thickness of the reef-flat and equivalent reef slope rocks at Horden and Easington Colliery show that the reef crest prograded basinward three to six times faster than it grew upward, perhaps because its upward growth was limited by an approach to sea level. There are, indeed, hints at all three quarries that, at times, the reef crest prograded without any corresponding

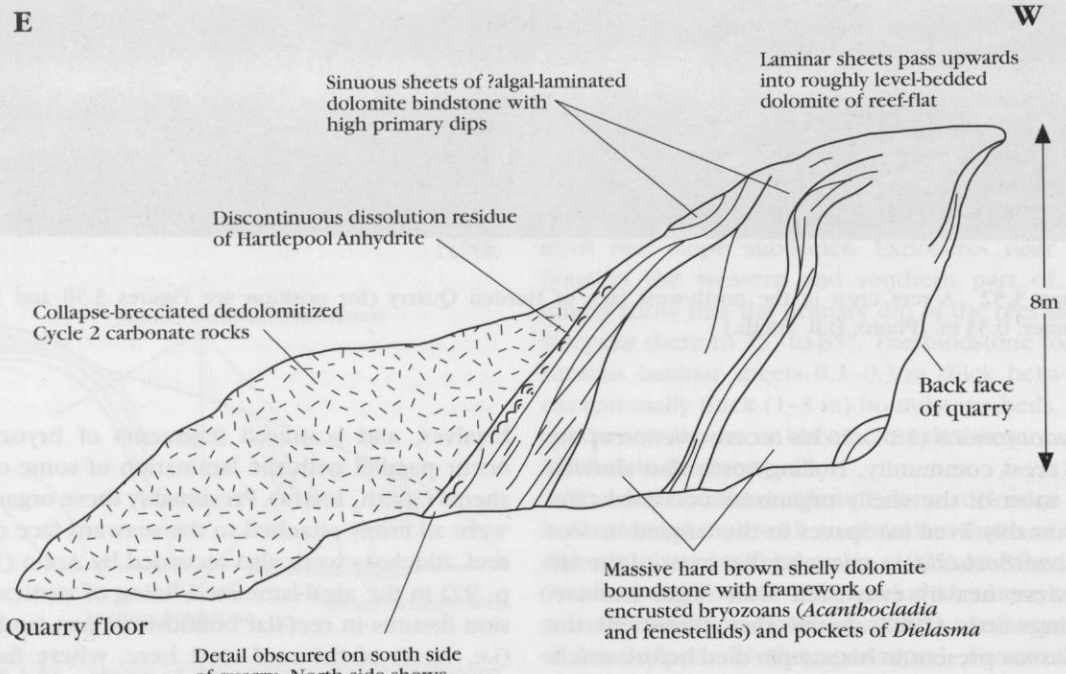


Figure 3.53 South side of old quarry (now filled) on the east side of Townfield Hill, Easington Colliery, showing the crest and stromatolitic seaward face of the shelf-edge reef, and succeeding residue and collapse-breccias. This quarry was recommended for SSSI designation but was filled before action could be taken; it is included here for the purposes of comparison.

build-up of its surface or even with reef-top erosion during phases of slightly lowered sea level.

The exposure of the ultimate reef-face in the old quarry (now filled) at Easington Colliery was uniquely important in that the youngest of the steeply-dipping laminar bindstone sheets was characterized by two short courses of unmistakable columnar stromatolites (Smith, 1981a, fig. 22). This showed that at least the last of the laminar sheets was a reef-face coating, perhaps implying a similar origin for the other steeply-dipping laminar sheets; probable stromatolitic laminite with domes up to 0.3 m across also coats the seaward face of the reef in the quarry at Hart, where the ultimate upper reef slope has a primary dip of 75–85° throughout its exposed height of about 13 m. The presence of a double layer of short columnar stromatolites on the outermost steep reef slope in the quarry at Easington Colliery invites comparison with parts of the Trow Point Bed (Smith, 1986; also this volume), which, in places, similarly comprises two short courses of columnar stromatolites and similarly lies immediately below the dissolution residue of the Hartlepool Anhydrite.

The faunal assemblage of the reef crest is of considerable interest in that it comprises only genera that could withstand high energy conditions and maintain their position on a near-vertical slope. The dominance of sessile flexible and robust bryozoans is predictable and, except for small gastropods, most of the shelly animals were adherent or encrusting forms. The smoothly even curvature of the crest, as compared with the sharply ragged angularity of some modern counterparts, presumably results from the smaller size of the late Permian reef frame builders and the abundance of laminar ?algal sheets.

From the known position of the reef crest and of two former quarries on top of the hill immediately west of the Horden exposure, the shelf-edge reef of the Ford Formation is shown to be at least 400 m wide between Peterlee and Horden. Its clear topographical expression here, at Easington Mill Hill and in Easington Colliery township, implies that a major reef re-entrant may be present between Horden and Easington Colliery, with the reef crest stepping back some 1.2–1.5 km to the west of its main position. It is not known whether the reef was continuous around this inferred re-entrant or whether, as is equally possible, it was discontinuous and present in sub-parallel stretches separated by open sea or large surge-channels. There is similar uncertainty over comparable re-entrants near Seaham and between Blackhalls Rocks and Hartlepool (see Figure 3.1).

?Roker Dolomite Formation, collapse-breccia

The juxtaposition of the reef slope and collapse-brecciated Roker Dolomite at Hawthorn Quarry, Easington Colliery and Horden indicates that here the Hartlepool Anhydrite must, before its dissolution, have lain against the steep reef slope and been at least as thick (?80–110 m) as the height of that slope. Foundering of the Roker Dolomite and higher strata in each place must have been by a similar amount, less a proportion resulting from a lower packing density, and was probably episodic. As at Hawthorn Quarry and in the nearby coastal cliffs, the foundering at Horden probably also involved the Hesleden Dene Stromatolite Biostrome that formerly overlay the reef, and must have affected all strata above the Roker Dolomite Formation. As elsewhere in the area to the south of Ryhope, reaction of the reef dolomite with brines rich in calcium sulphate from the dissolving anhydrite is assumed to have caused the dedolomitization in the collapse-breccia, but very little of the adjoining reef-rock at Horden has been dedolomitized.

Future research

The stratigraphy, palaeontology and petrology of this small but important exposure have all been investigated in considerable detail since 1980, and there is probably little immediate scope for further research on most aspects of the rocks exposed. Possible exceptions to this are a more detailed analysis of differences and similarities of faunal communities behind and in front of the reef crest and further research on the laminar sheets to determine if, like the youngest sheets at the Easington Colliery exposure, they are indeed stromatolitic in origin and at one time draped the seaward face of the reef.

Conclusions

This is the only GCR site where the one-time crest of the shelf-edge reef of the Ford Formation can still be seen in juxtaposition with collapse-breccias of the Roker Dolomite Formation. The reef crest is characterized by a sharp change from gently-dipping, mainly thin-bedded dolomite of the reef-flat to thicker bedded, steeply-dipping dolomite of the uppermost reef slope. The reef contains frame-building bryozoans and shelly fossils, the former encrusted with ?algal laminae.

The breccias comprise angular rock fragments with little evidence of the original lithology. The close juxtaposition of reef slope rocks and the breccias suggest that the Hartlepool Anhydrite must have lain against the reef slope before its dissolution. Both the exposure of the reef crest and the opportunity to relate the position of the reef to the anhydrite to the east, mark this site as being extremely important for the study of the stratigraphy and sedimentology of the late Permian marine rocks in Durham.

BLACKHALLS ROCKS (NZ 4683 3948 – 4763 3826)

Highlights

The coastal cliffs and shore platforms at Blackhalls Rocks (not shown in Figure 3.2) constitute the largest and best exposure of the Hesleden Dene Stromatolite Biostrome. The biostrome is almost entirely of dolomite rock and comprises a thick and highly varied boulder conglomerate overlain by a thicker unit of algal laminites ('stromatolites'). The conglomerate is formed mainly of rolled cobbles and boulders derived by erosion of the underlying (but unexposed) reef-flat rocks of the Ford Formation and the algal laminites include a strikingly complexly finely laminated basal layer and several generations of spectacular domes individually up to 1.5 m high and 18 m across. The sequence is capped by ooidal dolomite of the Roker Dolomite Formation and the overlying Seaham Residue.

Introduction

Blackhalls Rocks is a coastal site that exposes almost the full thickness of the Hesleden Dene Stromatolite Biostrome (?45 m) together with the whole of the overlying Cycle EZ2 Roker Dolomite Formation (?16 m) and much of the Seaham Formation. The sequence is gently anticlinal and a borehole near the core of the anticline is thought to have entered reef dolomite of the Cycle EZ1 Ford Formation almost immediately below the lowest beds currently exposed. The anticline is bounded to the north by the mineralized Blackhall Fault (Smith, 1964), which has a northwards downthrow of perhaps 12 m, and to the south by the steeply-dipping Seaham Residue of the Cycle EZ2 Fordon Evaporites. The age of the biostrome is uncertain, with delicately balanced arguments allowing either EZ1 or EZ2 affinities.

The boulder conglomerate at Blackhalls Rocks was first mentioned and scenically illustrated by Sedgwick (1829) and was termed a 'Shell-Limestone conglomerate' by Howse (1858) in recognition of its faunal similarity to the shelf-edge reef of what is now termed the Ford Formation. The section received little further attention until Trechmann (1913) published a brief summary of strata exposed there, and added a list of 24 invertebrate species from clasts in the conglomerate; later, Trechmann (1914) published chemical analyses of the conglomerate and of a thin 'large-grained pea-oolite' (= pisolite) from the top of it (also illustrated in thin-section), and subsequently (1925) gave an augmented fossil list of 29 species and a further five doubtfully identified forms. Woolacott (1918, 1919a) referred to the conglomerate at Blackhalls Rocks as a fossiliferous breccia composed of blocks that had rolled down the eastern edge of the reef, ie. a 'Vorreef', and illustrated it in 1919(a); Trechmann (1925) similarly referred to the conglomerate as a 'Vor-riff' of reef talus.

Apart from a brief mention by Trechmann (1931), the section at Blackhalls Rocks received no further attention until it was described and illustrated by Smith and Francis (1967). Pattison compiled a faunal list (in Smith, 1970a, repeated in Pattison *et al.*, 1973) comprising 28 species with an additional four doubtful identifications. Logan (1967) cited the locality as a host to seven species of bivalves, two of which were illustrated and designated as hypotypes. Further description by Smith (1981a) was within a proposed new lithostratigraphical framework in which most of the sequence at Blackhalls Rocks was ascribed to the newly-defined stromatolite biostrome. Finally a full investigation of the sedimentology of the whole of the sequence at Blackhalls Rocks was reported by Kitson (1982). The site also features in several field guides, excursion reports and popular articles (e.g. Smith, 1984).

Description

This site lies on the Durham coast about 8 km north-west of Hartlepool and comprises about 1.1 km of cliffs and shore-platforms (Figure 3.54); the cliffs are about 15–32 m high and comprise up to 24 m of southwards-thickening Quaternary (late Devensian) glacial drift deposits overlying up to 10 m of Magnesian Limestone. The drift deposits

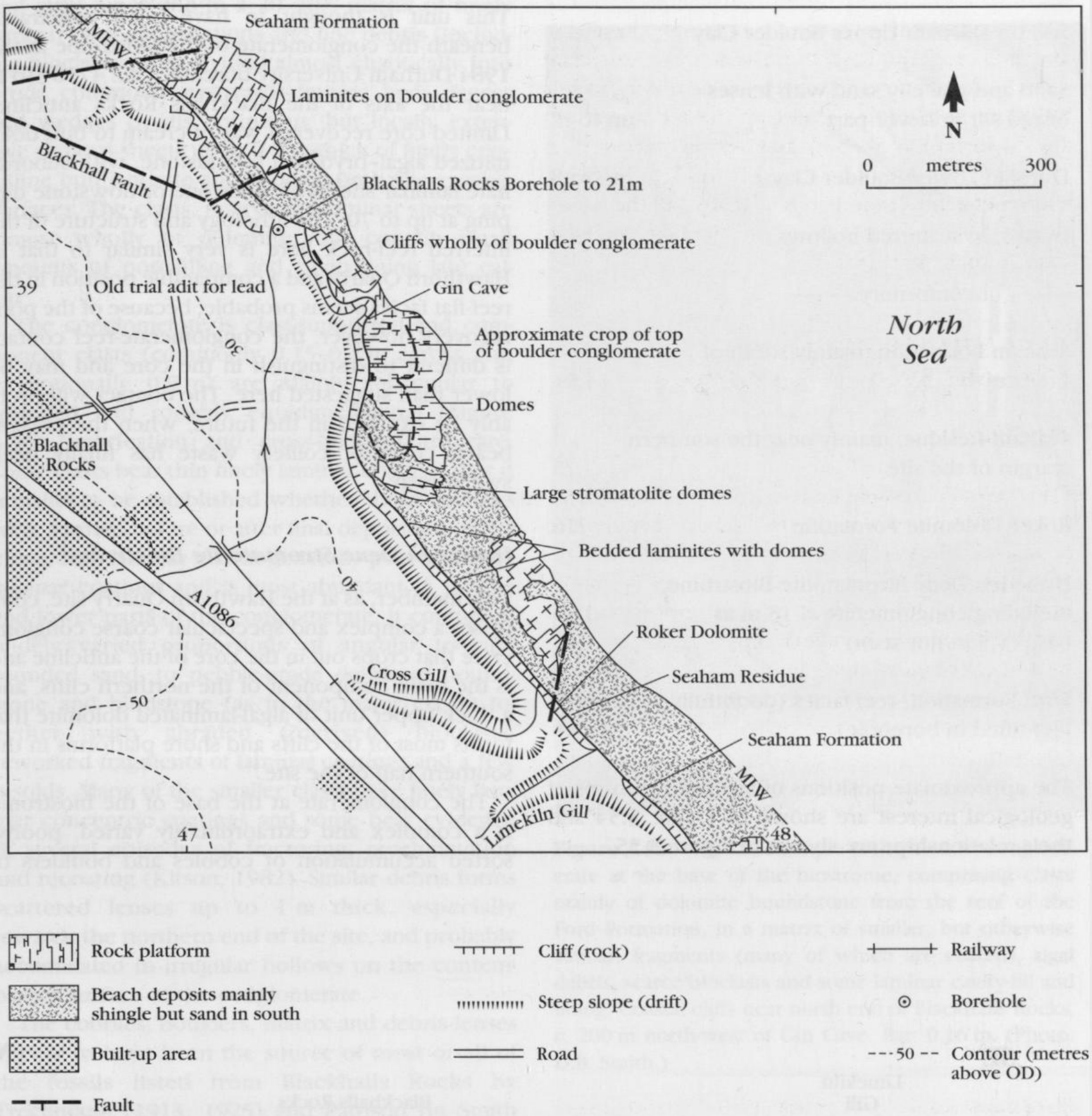


Figure 3.54 Blackhalls Rocks GCR site and its environs, showing the location of the main geological features.

form a layered sequence of two stony clays separated by a sand and gravel layer from which perennial seepages cause instability; this level of the cliffs is well known for its unusual plant communities and part of the cliffs is scheduled as a botanical SSSI. The northern section of the cliffs, extending to Blue House Gill, is managed as a local nature reserve by the Durham Wildlife Trust.

The general geological sequence in and adjoining the designated area is given on p. 116.

	Thickness (m)
Soil on Durham Upper Boulder Clay	up to 8
Sand and gravelly sand with lenses of red silt in lower part	up to ?7
Durham Lower Boulder Clay	up to 8
Gravel, in scattered hollows	up to 4
----- unconformity ------	
Seaham Formation, mainly south of the site	14.5+
Seaham Residue, mainly near the southern margin of the site	?5
Roker Dolomite Formation	?16
Hesleden Dene Stromatolite Biostrome, including conglomerate *c.* 18 m at base (1.5 m not seen)	?45
Ford Formation, reef-facies (doubtfully identified in borehole)	19.5+

The approximate positions of the main features of geological interest are shown in Figure 3.54 and their relationships are shown in Figure 3.55.

Ford Formation reef

This unit is thought to have been penetrated beneath the conglomerate of the biostrome in the 1984 Durham University borehole (NZ 4716 3911) near the axis of the Blackhalls Rocks anticline. Limited core recovered was of cream to buff dolomitized algal–bryozoan boundstone, with subordinate laminar sheets of bindstone or flowstone dipping at up to 70. The lithology and structure of the inferred reef-rock here is very similar to that in Hawthorn Quarry and a comparable position in the reef-flat facies seems probable; because of the poor recovery however, the conglomerate-reef contact is difficult to distinguish in the core and may be lower than suggested here. The contact will probably be exposed in the future, when the present beach cover of colliery waste has finally been swept away.

Hesleden Dene Stromatolite Biostrome

This member, as at the Hawthorn Quarry site, comprises a complex and spectacular coarse conglomerate that crops out in the core of the anticline and is the main component of the northern cliffs, and a thick upper unit of algal-laminated dolomite that forms most of the cliffs and shore platforms in the southern half of the site.

The conglomerate at the base of the biostrome is a complex and extraordinarily varied, poorly-sorted accumulation of cobbles and boulders of

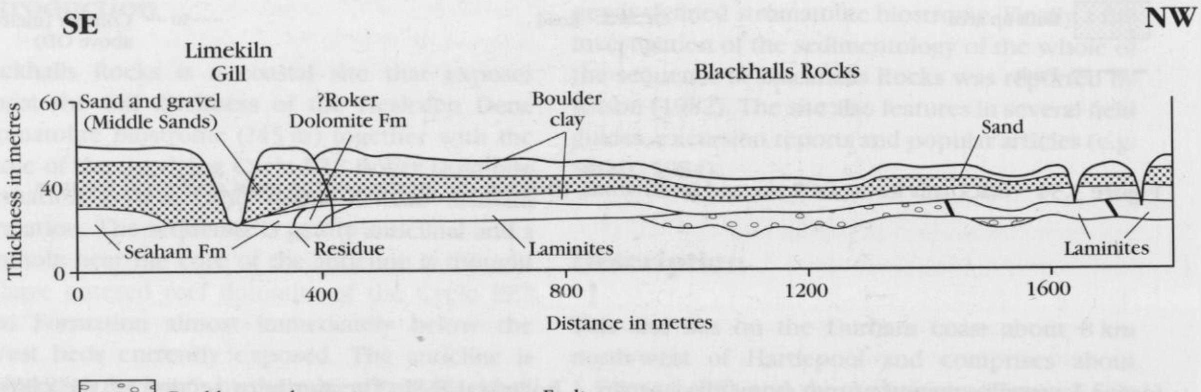


Figure 3.55 Geological strata in the cliffs of the Blackhalls Rocks GCR site (diagrammatic). The laminites and conglomerate together comprise the Hesleden Dene Stromatolite Biostrome. Slightly modified from Smith (1984, p. 24).

buff, algal–bryozoan boundstone (predominant) and algal bindstone in a 20–40% matrix of finely laminar clast-encrustations and fine debris (including bioclasts); it is divided almost chaotically into crude commonly eastwards-dipping beds, lenses and wedges by discontinuous, but locally extensive sinuous sheets up to 0.5 m thick of finely crystalline buff laminite and by local probable erosion surfaces. The clasts, matrix and laminar sheets are almost wholly of dolomite, but contain small amounts of pore-filling and cavity-lining late calcite.

The conglomerate is clast-supported and component clasts (commonly 0.15–0.4 m across, but exceptionally 0.9 m) are mainly subangular to rounded and roughly equidimensional (Figure 3.56); imbrication and cross-bedding are rare. Some clasts bear thin finely laminar coatings, but it remains to be established whether these coatings were formed before or after final deposition of the clasts. Non-laminar matrix generally post-dates any laminar coatings and is most abundant in middle and lower parts of the conglomerate; it comprises widely varied proportions of angular to subrounded sand- to pebble-grade debris of boundstone and bindstone (as in the major clasts) together with abraded (?derived) bioclasts, reworked fragments of laminar coatings and a few pisoids. Many of the smaller clasts have finely laminar concentric coatings and some bear evidence of several episodes of fracturing, recementation and recoating (Kitson, 1982). Similar debris forms scattered lenses up to 1 m thick, especially towards the northern end of the site, and probably accumulated in irregular hollows on the contemporary surface of the conglomerate.

The cobbles, boulders, matrix and debris lenses appear to have been the source of most or all of the fossils listed from Blackhalls Rocks by Trechmann (1913, 1925) and Pattison (in Smith and Francis, 1967, p. 143 and in Smith, 1970a, pp. 85–88). Smith (1981a), however, recorded *Peripetoceras* and Kitson (1982) reported *Bakevellia* and *Permophorus* from laminite sheets in the conglomerate, although it is not clear whether these fossils were part of an indigenous biota or are reworked bioclasts.

The laminar sheets that divide the conglomerate form 30–40% of its bulk in higher parts and generally somewhat less lower down; the thicker sheets are mainly low-dipping (5°–25°), but locally steepen to 50° or more. They divide and reunite grotesquely, and in places appear to surround trapezoidal to rectilinear conglomerate masses (Kitson, 1982) and to line both sides of subvertical fissures up to 1.5 m deep; some sheets are clearly bilateral, with a median void, void-fill or mutual contact. The laminae are fine and relatively even and, in the thicker sheets, are mainly gently undulate and flowing. Most of the thinner laminar sheets, however, clearly coat boulders forming the walls of primary cavities and display a wide range of simple or multistage 20–50 mm diameter botryoidal or laterally-linked hemispherical to columnar stromatolite-like structures with axes disposed at all angles. Kitson (1982, fig. 25b) illustrated probable algal relics in laminar sheets near the site of the 1984

Figure 3.56 Typical example of the boulder conglomerate at the base of the biostrome, comprising clasts mainly of dolomite boundstone from the reef of the Ford Formation, in a matrix of smaller, but otherwise similar, fragments (many of which are coated), algal debris, scarce bioclasts and some laminar cavity-fill and lining. Coastal cliffs near north end of Blackhalls Rocks, *c.* 200 m north-west of Gin Cave. Bar: 0.16 m. (Photo: D.B. Smith.)

borehole. Late-stage partly botryoidal laminites also line cracks penetrating or crossing some of the larger clasts.

The uppermost bed (0.5–0.8 m) of the conglomerate is a highly complex buff laminar bindstone with relatively fewer boulders than most of the remainder. Lamination in this bed is strikingly tortuous and includes both obvious cavity-lining and a wide range of steep-sided stromatolite-like domes individually up to 0.5 m tall and 1.5 m across, but mostly much smaller; scattered inter-dome hollows in this bed contain much multi-coated laminar debris and also rare clusters of subspherical ?oncoids up to 40 mm across and with more than 30 concentric layers.

The algal-laminated unit is at least 28 m thick and comprises unfossiliferous cream to pale buff silt- to fine sand-grade saccharoidal dolomite with abundant empty or calcite-lined small cavities after dissolved secondary anhydrite; interstitial calcite is widespread. Much of the rock has been finely brecciated by diagenetic processes and Liesegang-type colour banding is widespread. The primary lamination is generally faint and in hand specimens is commonly almost invisible; it is, however, generally distinct on weathered surfaces and is particularly clear and spectacularly crinkly in a widespread 1.3–1.8 m bed (the 'Crinkly Bed', Figure 3.57) at the base where laminae average 45 per centimetre (Smith and Francis, 1967; see also Al-Rekabi, 1982, fig. 3.4). In at least one place this unique lowest bed passes into or includes ooid grainstone and it also contains steep-sided pockets up to 1.2 m deep filled with smoothly thinly multi-coated dolomite pisoids individually up to 50 mm across, but mainly 5–15 mm (Figure 3.58). First noted by Trechmann (1913), and later (1914) illustrated and analysed by the same author, these pisoids commonly have an abraded nucleus of fine dolomite laminite and many bear clear evidence of early lithification in the form of fractures, re-cementation and re-coating (Smith, 1981b, fig. 29; Al-Rekabi, 1982, fig. 3.2B; Kitson, 1982, fig. 30b).

Bedding in the algal laminites is generally even and parallel, but is widely diversified by minor domes and gentle undulations with a relief of up to 0.3 m. At several levels, however, continuous layers of large steep-sided rounded to flat-topped domes are present (McKay, in Trechmann, 1913; Smith and Francis, 1967; Kitson, 1982). These domes are formed entirely of crinkly or rippled finely laminated dolomite and exceptionally are up

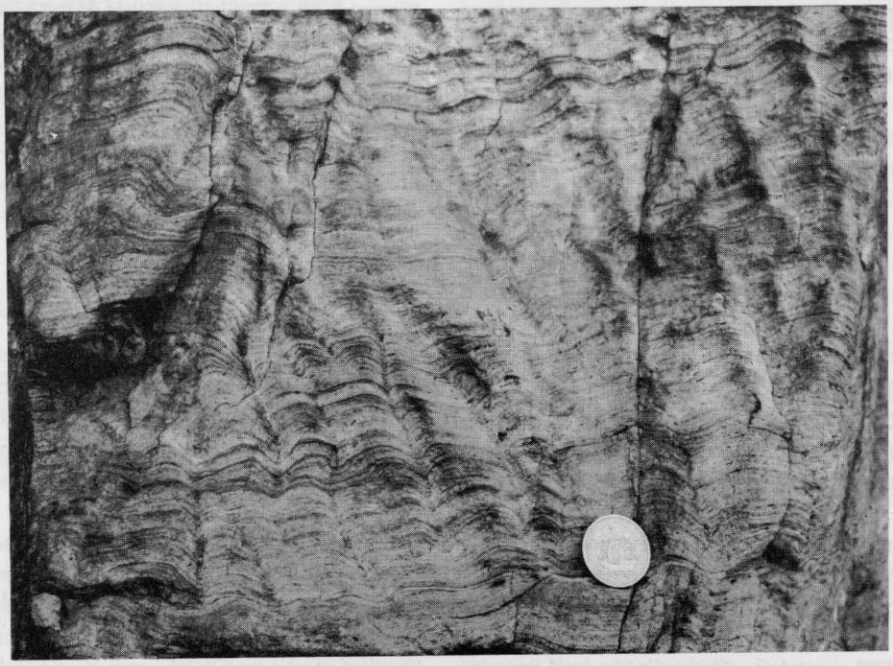


Figure 3.57 Laminar algal bindstone of the 'Crinkly Bed' at the base of the Hesleden Dene Stromatolite Biostrome. Coastal cliffs *c.* 60 m south of Gin Cave (see Figure 3.54). Coin: 26 mm across. (Photo: D.B. Smith.)

Figure 3.58 Thin section of multi-coated pisoids from steep-sided pockets in the upper part of the 'Crinkly Bed' in coastal cliffs near Gin Cave, Blackhalls Rocks. Interstices and the core of some formerly leached pisoids are occupied by equant dolomite microspar, but many of the pisoids are nucleated on to abraded dolomite clasts including portions of earlier fractured pisoids. Bar: 8 mm. (Photo: D. Kitson.)

to 1.5 m tall and 18 m across; they are best seen on the foreshore rock platform (Figure 3.59), but mutual relationships are clearer in the cliffs where the domes are locally seen to be separated by gently onlapping dolomite and limited fine contemporaneous debris.

Roker Dolomite Formation

This eastward-dipping formation forms much of the rock section in the cliff at the southern end of the site, its base rising north-westwards to reach rockhead near Cross Gill; it reappears patchily on the north side of the anticline, north of the Blackhall Fault. The uppermost 5–6 m of the formation comprise a markedly streaky and partly finely brecciated body of white to cream dolomite ooid grainstone and it is possible that this unit should be regarded as part of the Seaham Residue. Most of the formation, however, is of undisturbed cream dolomite ooid grainstone with strong tabular and trough cross-stratification at several levels; Kitson (1982) reported foresets dipping north-west and north-east at 10°–15°. Thin sections show that the ooids have been leached, and that some compound ooids and stromatolite flakes are present; Trechmann (1913, p. 201) reported cores of secondary fluorite in ooids of this formation in the north of the designated area. Trechmann also records *Schizodus* here, the only positive faunal

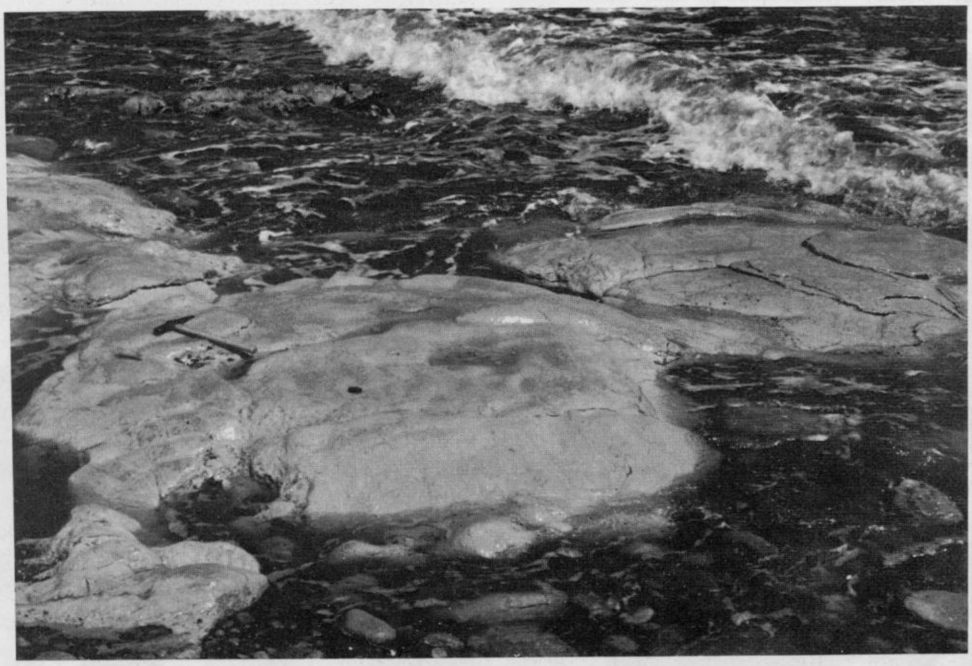


Figure 3.59 Broad dolomite stromatolite domes in about the middle of the Hesleden Dene Stromatolite Biostrome, on the foreshore near Green Stairs, Blackhalls Rocks. Hammer: 0.33 m. (Photo: D.B. Smith.)

identification in this formation at Blackhalls Rocks, though scattered bivalve-shaped cavities are present in the southern exposures.

The base of the Roker Dolomite Formation is generally difficult to distinguish in the cliff sections, where it is widely obscured by surface wash, but it is partly exposed in the lower ravine (NZ 4759 3825) of Cross Gill where it is interbedded with laminites and includes a 1.35 m ooidal dolomite bed that contains many coarse compound grains, pisoids and lumps. An interbedded basal passage was also recorded on the northern limb of the anticline (Smith and Francis, 1967, p. 150).

Seaham Residue

These insoluble clayey remains of the Fordon Evaporites lie in a gully near the southern boundary of the site; they are perhaps 5 m thick (depending on where the base is taken; see Interpretation). They comprise a lower 2.9–4 m layer mainly of cream ooid grainstone, but with many thin streaks, lenses and layers of brown and buff-brown argillaceous dolomite or dolomitic clay, a median 1.2–1.6 m layer of soft off-white dolomite ooid grainstone (partly brecciated) and an upper layer (maximum 1 m) of complexly interlayered multicoloured streaky clay or clayey dolomite. All the units of the residue are locally contorted and brecciated and the formation as a whole dips eastwards at 35°–50°.

Seaham Formation

Carbonate rocks of this formation occupy synclines both north and south of the designated area. They are best exposed in the south where they comprise a foundered and partly collapse-brecciated sequence similar to that at the type locality at the Seaham site; a detailed section here (Smith in Smith and Francis, 1967, pp. 157–160; see also plate XIIIC) shows thinly-layered basal shelly dolomite with *Calcinema* overlain by crystalline limestones patchily rich in spherulitic and globular calcite concretions. Red-stained and ochreous fine-grained carbonate or clay is a feature of the abundant infiltrated fill between disarticulated collapse-breccia fragments here.

Interpretation

The cliffs and rock-platforms at Blackhalls Rocks are doubly important in affording by far the best and most spectacular exposures of the Heselden Dene Stromatolite Biostrome, including most of the boulder conglomerate at its base, and also in furnishing a complete sequence from the reef of the Ford Formation up to (and including) the Seaham Formation. In this latter respect, the section at Blackhalls Rocks parallels and supplements that at the Hawthorn Quarry site, supporting the inferred identification of Roker Dolomite at the top of the sequence there.

The drift at Blackhalls Rocks epitomizes that of much of the Durham coast and requires no special comment; similarly, the Seaham Formation there has much in common with that at its type locality at the Seaham site, and the account (under 'Concretionary Limestone') by Smith and Francis (1967, pp. 157–160) will suffice. The Roker Dolomite Formation and the reef of the Ford Formation are normal for the area and also need no further discussion.

Hesleden Dene Stromatolite Biostrome

Blackhalls Rocks exposes almost the full thickness of this remarkable unit, a feature it shares with Hesleden Dene (and its downstream continuation) and the Hawthorn Quarry site; the boulder conglomerate at its base, however, is much thicker here than at the other localities.

The distribution of the conglomerate at the base of the biostrome is poorly known, but it is more variable in thickness and lithology and much less extensive than the overlying laminites, and in the Hawthorn Quarry site dies out sharply on its basinward side; the nature of its landward margin is unknown, though abutment against a basin-facing cliff notch may be speculated.

The origin of the conglomerate has been the subject of much discussion, but authors from Trechmann (1913) onwards agree that the major clasts were mainly derived from the shelf-edge reef of the Ford Formation. Woolacott (1918, 1919a) regarded it as an offshore (i.e. deep-water) equivalent of the reef and Trechmann (1925) interpreted it as reef talus with the clasts rounded by wave action on the eastern slope of the reef (ie. shallow water). Current research by the writer and Mr D. Kitson suggests that the conglomerate is a storm beach deposit that was formed on the reef-flat when a sea-level fall resulted in erosion of the Ford Formation reef, and that it was subject to phases of exposure, erosion, reworking and burial by conformable sheets of laminar carbonate. The angularity of some of the clasts indicates that the reef-rock was fully lithified before dislodgement and transport.

The origin of the laminar coatings on clasts in the conglomerate at Blackhalls Rocks and of the ramifying laminar sheets remains uncertain and is subject to continuing research. Field relationships and the abundance of laminar debris show that at least some of the laminar coatings and/or sheets must have been formed and lithified whilst the conglomerate was accumulating, and the localized fracturing of the conglomerate itself and of some of its large component clasts indicates that it too was cemented penecontemporaneously. The striking morphological similarity of many structures in the clast coatings and laminar sheets to algal stromatolites previously led the writer to infer deposition through the agency of blue-green (cyanophytic) algae, but the presence of (and lateral passage into) otherwise apparently identical linings of narrow fissures and of sheets of totally inverted laterally-linked hemispherical structures casts doubt on a wholly algal origin and deposition through other microbial or inorganic agencies may have been involved; in this connection the absence of the remains of a browsing fauna may be significant, possibly implying unusual salinity levels (either continental or marine). Final filling of fissures and inter-boulder voids by contemporaneous debris (including much fragmented laminite) distinguishes the Blackhalls Rocks conglomerate from that at Hawthorn Quarry in which much void space remained unfilled.

The general character, distribution and depositional environment of the main (upper) part of the biostrome are discussed in the account of the Hawthorn Quarry site, where it is noted that the biostrome is roughly co-extensive with the shelf-edge reef of the Ford Formation from Hawthorn Quarry southwards, but is not known farther north and only in fragmentary (brecciated) form at one exposure a short distance to the east. The main features of interest and importance in these upper strata at Blackhalls Rocks are exceptionally good exposures of large stromatolite domes on the foreshore rock platforms in the southern part of the designated area; although exposure varies greatly with the movement of sand and shingle, a selection of ripple-topped domes is almost always visible at about mid-tide levels. The basal 'Crinkly Bed' of this upper (stromatolitic) part of the biostrome is superbly exposed in the cliffs near the middle of the site (Figure 3.54), where it closely resembles its equivalent in Hawthorn Quarry site and in Hesleden Dene. This thick bed forms the roof of several of the main caves in the central headlands of the site.

The origin of the pisoids in the 'Crinkly Bed' at the base of the laminates is similarly uncertain. Originally described by Trechmann (1913) as 'peastone', Smith (1981b) reinterpreted them as oncoids (algal pisoids); provisional current thinking is that whilst derived algal debris may indeed form the core of many of these bodies, their smooth cortices have more in common with those of cave pearls and their travertine equivalents and they may, therefore, have formed at least partly inorganically in splash pools or other agitated areas. Other pisoids, especially those in pockets near the top of the conglomerate, have finely mammilar coats and resemble those at the Gilleylaw Plantation Quarry site from which F.W. Anderson (in Smith, 1958) recognized the algal growth-forms *Bevocastria conglobata* Garwood.

The considerable significance of the biostrome and the assumed underlying erosion surface in terms of the local and regional evolution of the Zechstein Sea is discussed in the account of the Hawthorn Quarry site.

Seaham Residue

This formation, where exposed near the southern boundary of the Blackhalls Rocks site, is somewhat thinner than at its type locality at Seaham, but this may be a result of attenuation on the dipping limb of a fold. Strict similarity between the two sections is not to be expected, but a broadly similar tripartite lithological subdivision is recognizable at both exposures, with ooid grainstone separating two more plastic clayey layers; a major difference lies in the apparent lack of dedolomite at the Blackhalls Rocks exposure, possibly indicating that the dissolved Fordon Evaporites here were halite-rich rather than sulphate-rich. The uncertainty regarding the thickness of the residue at Blackhalls Rocks arises from doubts on the determination of its base; a case could be argued for taking this at the top of the median dolomite unit and a less plausible case could be made for taking it 5–6 m below that chosen here, at the base of the brecciated ooid grainstone.

The relatively steep easterly dip of the Seaham Residue and adjacent strata at the southern end of Blackhalls Rocks is atypical of the local Magnesian Limestone sequence and may indicate that it overlies the crest of the shelf-edge reef of the underlying Ford Formation and its associated belt of differential dissolutional foundering (Figure 3.47).

Future research

The complexity of the different rock types and their mutual relationships at Blackhalls Rocks poses many problems, most of which have been addressed but few wholly solved. In particular, the mode and environment of origin of the laminar coatings of clasts in the boulder conglomerate and of related laminar sheets and void-fill needs to be established, and resolution of the doubt regarding the age of the sparse biota (derived or indigenous?) is crucial. Solution of these problems would throw much light on the local and regional depositional history including the key questions of the age of the biostrome and possible major sea-level fluctuations. Higher in the sequence, the uncertainty regarding the nature of the contact between the biostrome and the Roker Dolomite Formation prevents definition and full understanding of the Cycle EZ1–Cycle EZ2 boundary, and, near the top of the sequence, the base of the Seaham Residue needs to be defined satisfactorily.

Conclusions

This coastal site is the largest exposure of the Hesleden Dene Stromatolite Biostrome, including its distinctive coarse basal conglomerate of clasts of boundstone eroded from the Ford Formation reef. At this site, the algal laminates or stromatolites characteristically exhibit spectacular dome structures and a complexly finely-laminated basal bed. Above the biostrome are the Roker Dolomite Formation in the form of cream-coloured oolitic dolomite, and the Seaham Residue (the insoluble remnant of the Fordon Evaporites). The cliffs and shore platforms afford excellent exposures of the above sequence, and detailed evidence of the large variety of depositional and post-depositional structures can be observed along the shoreline. The site requires further study to understand the sedimentological nature and faunal character of the sequence, as well as to define the stratigraphical relationship of its upper part.

TRIMDON GRANGE QUARRY (NZ 361353)

Highlights

Trimdon Grange Quarry (not shown in Figure 3.2) is a secluded place where backreef to lagoonal limestone of the Ford Formation may be studied. Much of the rock has been severely altered by mineralogical changes linked to the dissolution or replacement of gypsum and/or anhydrite that were formerly abundant in it, but enough has escaped such alteration to show that the rock is mainly a cross-bedded, shallow-water ooid grainstone with traces of burrows and a sparse shelly fauna.

Introduction

This quarry, not to be confused with the Grange Quarry (NZ 362345) near Trimdon, lies about 1 km south-west of Trimdon Grange, County Durham; it is part of a nature reserve owned and managed by the Durham Wildlife Trust, mainly for its botanical interest, but with considerable faunal interest also.

The quarry is about 70 m across and 5–9 m deep, and is cut entirely into gently-dipping, shallow-water, backreef or lagoonal carbonate rocks of the Ford Formation (formerly the Middle Magnesian Limestone). Most of these rocks probably were primary ooidal limestone, but they have undergone extensive mineralogical changes and are now a complex mixture of secondary limestone and subordinate dolomite; there is much evidence of replaced gypsum and/or anhydrite. The formation exposed here may also be seen in a number of other quarries in the area, although many nearby quarries have been filled in recent years and others are under threat; details of strata in all these exposures are available in the field-notes files of the British Geological Survey.

Trimdon Grange Quarry was first described by Smith and Francis (1967, p. 129) and further details were given by Smith (1981d). It is a peaceful place, almost cut off from the outside world, and its fascinating geology and botany are best enjoyed in the summer when its abundant wild strawberries are in season.

Description

The position and outlines of the designated area are shown in Figure 3.60, together with the locations of the main features of geological interest. The main rock exposures are in the north-west and south-west faces, where exposures are up to 7 m high; smaller exposures are in the lower south face and behind undergrowth on both sides of the quarry entrance.

The rocks in the faces of Trimdon Grange Quarry are extremely varied, both vertically and laterally, and almost all display evidence of a complex diagenetic history; they dip gently eastwards, roughly parallel with the quarry floor, and about 9 m of strata are exposed. Strata in the north-west face and in some northern and upper parts of the south-west face are mainly of hard, off-white to pale buff-grey, finely saccharoidal secondary limestone, and most of the rock in the south face is of hard, coarsely saccharoidal, brown and grey-brown secondary limestone; rocks in the lower and southern parts of the south-west face are mainly of fairly soft, cream, finely crystalline dolomite which in places is soft and powdery. Traces of hollow ooids and of pisoids up to 4 mm across suggest that much of the rock was formerly an

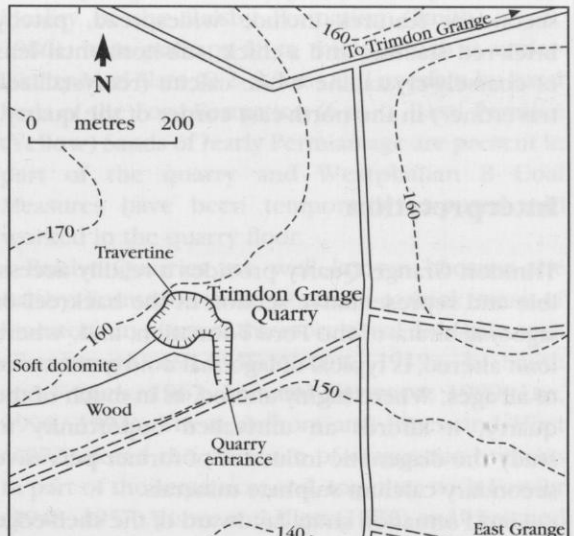


Figure 3.60 Trimdon Grange Quarry and its immediate surroundings, showing the main features of geological interest.

ooidal and pisoidal grainstone, though thin packstones and wackestones were probably also present. Much of the bedding has been blurred or obliterated by diagenetic changes, but enough has survived to suggest a mixture of beds, wedges and gentle lenses generally less than 1 m thick; abundant traces of low-angle, herringbone tabular cross-stratification (in sets up to 0.3 m thick) and hints of minor channels are present locally. Sub-vertical and U-shaped burrows up to 8 mm across are common in some beds and these have preferentially calcitized walls, but possible invertebrate remains are restricted to scattered bivalve-shaped casts.

Secondary features in the rocks of this quarry take the form of scattered, ovoid to irregular calcite-lined cavities up to 0.1 m across, of widespread, 'felted', platy calcite crystals after anhydrite or gypsum and of extremely numerous rectilinear and stellate intercrystalline dissolution voids; judging from the distribution and abundance of these features, the proportion of sulphate may once have ranged from 10 to as much as 90% of the rock. The 'felted' fabric is particularly eye-catching and is commonly associated with a boxwork of thin calcite veins; it was prevalent in cross-stratified ooidal dolomite exposed in a railway cutting (now filled) immediately east of the quarry. Other secondary features include widespread, patchy brick-red staining and a thick, sub-horizontal lens of coarsely-crystalline white calcite (recrystallized travertine?) in the north-east corner of the quarry.

Interpretation

Trimdon Grange Quarry provides a readily accessible and representative section in the backreef or lagoonal strata of the Ford Formation, and, where least altered, is typical of lagoonal ooid grainstones of all ages. Where highly altered, as in much of the quarry, it affords an unrivalled opportunity to study the diagenetic influence of former pervasive secondary calcium sulphate minerals.

Ford Formation strata landward of the shelf-edge reef occupy most of the outcrop of the Magnesian Limestone in County Durham, forming a triangular belt that exceeds 8 km in width in the Trimdon area; they are more than 100 m thick where adjoining the reef, but thin westwards (partly through erosion) and are probably mainly 30–60 m thick around Trimdon. Exposures are uncommon and mainly small in the narrow north of the outcrop, where they are near the reef and generally of shelly ooidal dolomite with scattered patch-reefs (as at Silksworth; see the account of Gilleylaw Plantation Quarry). In the wide outcrop to the south, by contrast, there are many quarries and natural exposures of only sparingly shelly ooidal strata lying several kilometres west of the reef (Smith and Francis, 1967, pp. 123–131) and it is these rocks that are epitomized by the beds exposed at Trimdon Grange Quarry. Ubiquitous low-angle cross-stratification, shallow channels and lenticular bedding all point to free grain movement under agitated (perhaps occasionally intertidal) shallow water, and the scarcity and low diversity of the shelly fauna may indicate slightly enhanced salinity. Lateral salinity gradients are common in many modern tropical lagoons and shallow marine shelves and may account for the westwards-diminishing faunal abundance and diversity in the Ford Formation. The general impression is of a broad, shallow marine shelf that evolved into a lagoon when the shelf-edge reef built up to sea level; near normal salinity probably characterized eastern parts, near the reef, but salinity increased gradually westwards (landwards) where the shelf/lagoon probably shelved imperceptibly into a marginal sabkha plain in which secondary evaporites may have been formed penecontemporaneously.

The predominantly dolomitic character of the rocks in the west face of Trimdon Grange Quarry is typical of the backreef/lagoonal peloid grainstones of the Ford Formation in a broad belt extending westwards to Bishop Middleham (NZ 3331) and northwards to South Hetton (NZ 3845), but most large exposures display some or all of the diagenetic changes noted in the rocks in the remainder of the quarry. In particular the 'felted' fabric is extremely common and dominates some exposures; it results from the volume-for-volume replacement by calcite of sheaths and aggregates of intersecting secondary calcium sulphate crystals (Jones, 1969). In addition, irregular layers and patches of secondary limestone (dedolomite) occur in many exposures, and fractured strata alongside faults are almost invariably of dense crystalline secondary limestone. As an exception, almost the whole of the formation exposed in Witch Hill Quarry (NZ 34439), Old Cassop, has been converted into massive and complex dedolomite. Field and petrographic evidence suggest that the proportion of former secondary sulphate and subsequent dedolomite in the rocks increases westward, perhaps in sympathy with the inferred westward salinity increase in the lagoon; it must be emphasized, though, that there is no evidence of the precipitation of primary evaporites on the lagoon floor.

The dolomitization of the backreef/lagoonal strata of the Ford Formation has been ascribed to refluxing dense brines relatively enriched in magnesium by the precipitation of thick calcium sulphate rocks in the succeeding Edlington Formation (Smith, 1981a, p. 179). Such brines might also have been generated in sabkhas marginal to the Ford Formation lagoon, which have now been eroded off. Harwood (1986) postulated a similar mechanism to account for the equally pervasive dolomitization of equivalent strata in the Yorkshire Province, and Lee and Harwood (1989) invoke a reflux mechanism for the dolomitization of the underlying Raisby Formation in Durham. The calcium sulphate ions that subsequently replaced much of the dolomite presumably were introduced in the brines that effected dolomitization, and much of the dedolomitization was probably accomplished when the anhydrite was hydrated and dissolved during the current cycle of uplift (?Tertiary to present).

Future research

There has been relatively little research into the diagenetic and depositional history of the backreef/lagoonal beds of the Ford Formation and both these aspects deserve attention; Trimdon Grange Quarry would form an excellent starting point.

Conclusions

Trimdon Grange is the only GCR site in which can be observed an accessible section of typical backreef or lagoonal carbonate sediments formed some kilometres west of the shelf-edge reef, the dominant feature of late Permian sedimentation in County Durham. Where unaltered, the oolitic limestones display bedding and channelling characteristic of lagoonal environments. However, in much of the exposure they are highly altered, the original limestone having been replaced by dolomite and this by calcium sulphate. The latter, in turn, was then either dissolved and its place taken by calcite, or replaced by calcite (together with some dolomite), producing a fascinating variety of rock fabrics and textures. The preservation of this site is important to safeguard the section of 'normal' lagoonal sediments, and the profound effects of later diagenetic processes.

RAISBY QUARRIES (NZ 3435)

Highlights

In addition to being the type locality of the Raisby Formation, the whole of which is exposed in the north face, Raisby Quarries (not shown in Figure 3.2) are amongst the largest man-made excavations in northern England. The formation mainly comprises well-bedded sparingly fossiliferous dolomite rock, but here includes an atypically thick and somewhat more fossiliferous limestone in its lower part. The underlying Marl Slate and uppermost part of the Yellow Sands are exposed in the quarry floor, below the Raisby Formation, and the basal beds of the overlying Ford Formation are present at the top of the main face. A varied suite of secondary minerals has been reported from these quarries.

Introduction

The enormous eye-catching north face of Raisby Quarries (formerly known as Raisby Hill Quarry) lies a short distance east of Coxhoe and just north of the Butterknowle Fault. The quarries have been worked for most of this century; they are the type locality of the Raisby Formation (Smith *et al.*, 1986), here perhaps 58 m thick, which is underlain by Marl Slate (0.2–0.9 m) and overlain by basal beds of the Ford Formation (6 m+). Basal Permian (Yellow) Sands of ?early Permian age are present in part of the quarry and Westphalian B Coal Measures have been temporarily exposed and worked in the quarry floor.

Raisby Quarries are well known because the Raisby Formation here contains a thick mass of limestone in place of the more usual dolomite rock (Trechmann, 1914; Woolacott, 1919a, b; Smith and Francis, 1967; Lee and Harwood, 1989; Lee, 1990, 1993). These authors and Jones and Hirst (1972) noted the presence of diagenetic breccias in part of the sequence, and, together with Fowler (1943, 1957), Jones and Hirst (1972) and Hirst and Smith (1974) reported a substantial range of secondary minerals including small amounts of native copper. Rocks from the quarry figure largely in Lee and Harwood's (1989) detailed investigation of the isotopic composition, sedimentology and diagenetic history of the formation.

The quarries are fully operational and permission to enter must be obtained; stout footwear and hard hats are essential and the bases of the higher faces should be avoided.

Description

The position of the site is shown in Figure 3.61, which also shows the location of the main points of geological interest. The principal face is more than 1.5 km long, though only part of this is to be preserved, and is worked in three main (17–29 m) benches with a subordinate basal 4–6 m bench. Beds dip gently north-northeastwards.

The general sequence in Raisby Quarries is given below.

	Thickness (m)
Soil on thin Durham Lower Boulder Clay	0–4
------ unconformity ------	
Ford Formation, at top of highest part of face	0–6
Raisby Formation, forming most of the worked faces	?58
Marl Slate, exposed only in deepest part of quarry	0.2–0.9
Basal Permian (Yellow) Sands, in floor of quarry, forming a gentle WSW–ENE ridge	?0–6.0+
------ unconformity ------	
Coal Measures (Westphalian B), temporarily exposed and worked	8.0+

Basal Permian (Yellow) Sands

Unfossiliferous, almost uncemented, aeolian yellow sand, ranging from parallel-laminated to coarsely trough cross-stratified, forms the lowest unit semi-permanently exposed in the floor of the quarry. It is overlain by a thinner unit of carbonate-cemented, buff-brown, redistributed sandstone in which winnowed *Lingula* are locally present at the top. Both units are medium- to coarse-grained.

Marl Slate

This comprises a basal unit of dark grey, finely-laminated, argillaceous and carbonaceous dolomite mudstone which thins against eminences on the surface of the underlying Basal Permian (Yellow) Sands, and a more uniform upper unit of buff, finely-laminated dolomite mudstone. Both units contain scattered fish scales.

Raisby Formation

Summaries of the Raisby Formation in Raisby Quarries have been given by Woolacott (1919b, p. 167), Smith and Francis (1967, pp. 111–112), Lee and Harwood (1989) and Lee (1990, 1993); they differ in detail on matters of thickness and dolomite/calcite content, but all are agreed that a thick, limestone unit separates a thin, basal dolomite from a thick upper dolomite unit.

The basal dolomite is about 5 m thick and is very finely crystalline; it comprises a brown-buff flaggy sequence overlain by a grey thin-bedded nodular sequence; the contact with the underlying Marl Slate is sharp and planar, without interdigitation.

The median limestone thins westwards (Francis, in Smith and Francis, 1967) and comprises uniformly bedded grey and blue-grey calcite microspar which, according to Lee (in Lee, 1993) is thinly layered in shades of grey in its lower two-thirds, and is of a more uniform dark blue-grey above; the base and top of the limestone is gradational, with limestone nodules in a dolomite matrix. Lee (1990, 1993) and Lee and Harwood (1989) recorded hemispherical concretionary masses averaging 0.1 m across of dolomite-replacive coarsely-crystalline calcite in upper parts of the limestone and Lee and Harwood (1989) investigated the isotopic composition of these masses. Patchy *in situ* brecciation in the transitional nodular beds between the limestone and the overlying dolomite has been recorded by several authors and was investigated in detail by Lee and Harwood (1989).

The thick uppermost unit of the Raisby Formation here is of relatively evenly-bedded cream and buff very finely crystalline dolomite with many calcite-lined irregular cavities (after secondary anhydrite); much of the unit appears to be unfossiliferous. Lee (1990) recorded patchy to pervasive calcite replacement of dolomite in this unit.

Fossils in the Raisby Formation at the type locality are concentrated in the lower beds of the limestone unit, in which a few beds are relatively rich in a varied assemblage of foraminifers, bryozoans, brachiopods, bivalves and ostracods (see list by Pattison in Smith and Francis, 1967, p. 111); amongst forms listed by Pattison and illustrated and further discussed by him in Smith and Francis (1967, plate V1 and p. 181) is an unnamed and previously undescribed cryptostome bryozoan resembling *Penniretopora waltheri*. Some beds low in the sequence bear abundant invertebrate burrows and trails, and complex grazing patterns are present at some levels (Figure 3.62); Trechmann

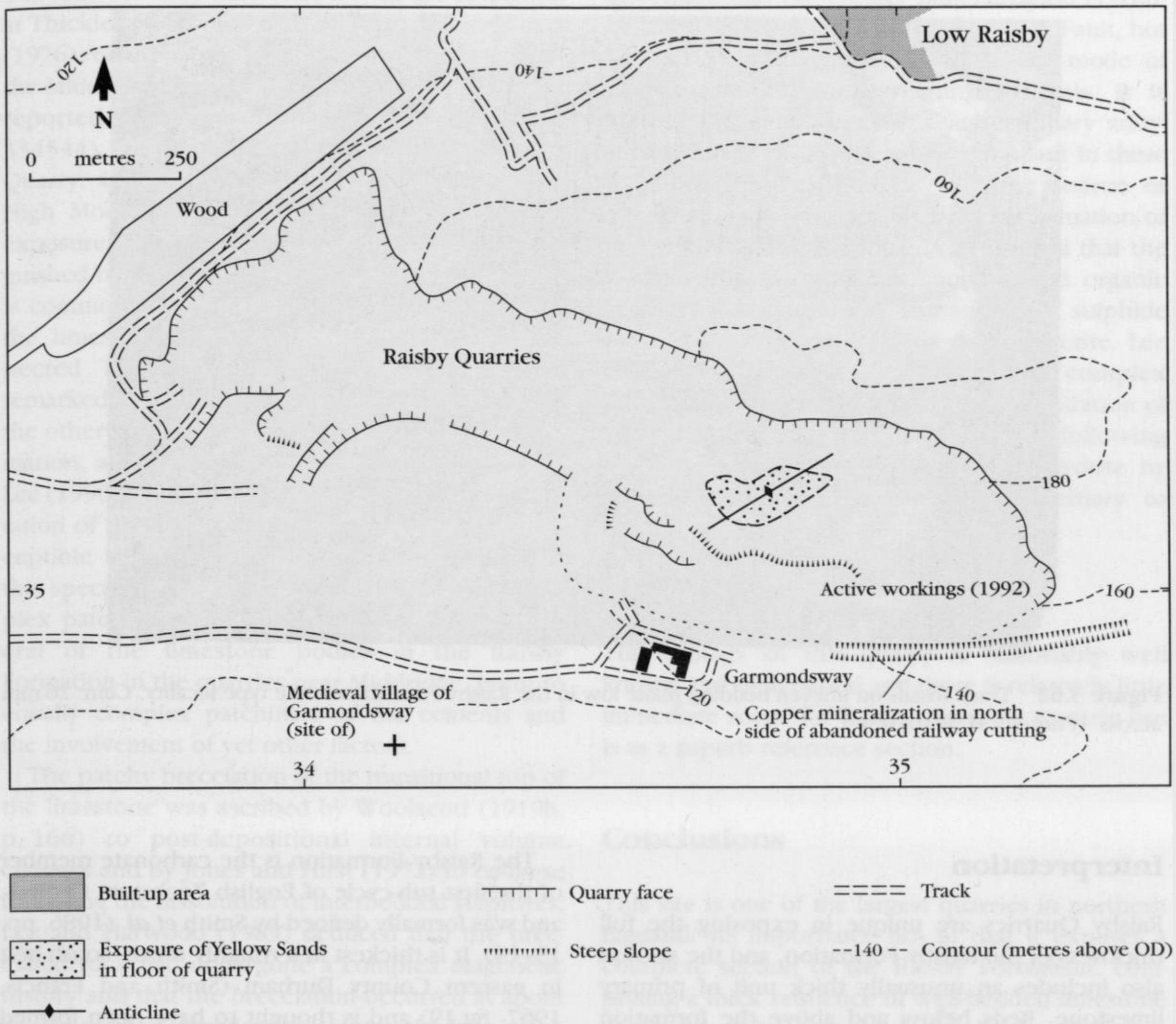


Figure 3.61 Raisby Quarries: the north face in the east is the type locality of the Raisby Formation (Smith *et al.*, 1986).

(1914) also recorded plants from these early Raisby Formation beds. The dolomite in the upper part of the sequence contains only a sparse fauna of poorly-preserved foraminifera and bivalves.

Ford Formation

Rocks of this formation lie at the top of the 26–29 m uppermost bench and are being progressively removed as the face recedes; they comprise up to 6 m of cream and pale-buff, cavernous, ooidal and pisoidal grainstones which, according to Lee (1990), are of calcitized dolomite with leached grain centres. The rocks are evenly bedded with traces of cross-lamination, and the base, though not readily accessible, appears to be conformable.

Secondary Minerals

The quarries have long been known for their suite of secondary minerals which occupy veins, geodes and replacive patches; authors reporting mineralization are listed in the introduction. Minerals recorded from here include azurite, baryte, calcite, chalcocite, fluorite, galena, malachite, selenite, pyrite and sphalerite. Of these, the copper minerals and much of the calcite and some dolomite occupy fractures, and the remainder (including much calcite) occur either in geodes or are replacive.

Figure 3.62 Trace fossils on uneven bedding plane low in the Raisby Formation at the type locality. Coin: 26 mm across. (Photo: T.H. Pettigrew.)

Interpretation

Raisby Quarries are unique in exposing the full thickness of the Raisby Formation, and the section also includes an unusually thick unit of primary limestone. Beds below and above the formation are typical of their respective stratigraphical units.

The thin Basal Permian (Yellow) Sands at Raisby Quarries lie at the north-eastern extremity of the Chilton sand ridge documented by Smith and Francis (1967, fig. 18) and the clear evidence of onlap of the lower part of the Marl Slate against the flanks of the ridge is typical of this formation. Similar relationships, in which the lower (dark grey) carbonaceous part of the Marl Slate is overlapped by the grey, less carbonaceous, upper part which then thins out over the highest ridges have also been seen at Houghton Quarry (NZ 340506), Sherburn Hill Quarry (NZ 345417) and Quarrington Quarry (NZ 327380). The Marl Slate is a principal feature of the fish- and plant-bearing GCR site at Middridge, some 15 km south-west of Raisby Quarries. Lower beds of the Raisby Formation are gently arched over the Yellow Sands ridge, without onlap, but the arch dies out upwards by slight differential thinning of the beds.

The Raisby Formation is the carbonate member of the first sub-cycle of English Zechstein Cycle 1, and was formally defined by Smith *et al.* (1986, pp. 13–14). It is thickest in a roughly north–south belt in eastern County Durham (Smith and Francis, 1967, fig.19) and is thought to have been formed on the outer part of the Zechstein marginal shelf and adjoining slope (Smith, 1989, fig. 6). Evidence of mass downslope sediment movement such as is seen at High Moorsley Quarry and several other localities (Smith, 1970c) has not been recognized at Raisby. Other GCR sites at which the Raisby Formation is present are Claxheugh Rock (NZ 362574) at Sunderland, Trow Point (NZ 3467) and Frenchman's Bay (NZ 389662) at South Shields, and Dawson's Plantation Quarry (NZ 326548) at Penshaw.

Primary Limestone in the Raisby Formation is relatively uncommon and is concentrated in (though not confined to) the lower half of the formation. In addition to Raisby Quarries, it was reported by Woolacott (1919a, b) in the Cotefold ('Cotefield') Close Borehole (NZ 4319 3276) where it was about 30 m thick, and in the Sheraton Borehole (NZ 4338 3466) where it was about 36 m thick; farther south, Trechmann (1914) recorded a

3 m lens of shelly limestone low in the formation at Thickley Quarry (NZ 240257) and Mills and Hull (1976) record patchy limestone at several places in the Middridge area. To the north, Lee (1990, 1993) reported limestone in Penshaw Quarry (NZ 334544), in the nearby Dawson's Plantation Quarry, at Houghton Quarry (NZ 341506) and at High Moorsley Quarry (NZ 334455). In surface exposures the limestone may generally be distinguished by its pale grey colour, but in boreholes it is commonly buff or brown. A primary origin for the limestone at Thickley and Raisby was suspected by Trechmann (1914, p. 259) who remarked that the rocks seemed to have escaped the otherwise ubiquitous dolomitization of the formation, and a similar conclusion was reached by Lee (1990, 1993) who speculated that early cementation of the limestone may have made it less susceptible to penetration by dolomitizing fluids. If this speculation is correct, the spectacularly complex patchiness and near-vertical margins of several of the limestone bodies in the Raisby Formation in the quarries near Middridge, point to equally complex patchiness of the cements and the involvement of yet other factors.

The patchy brecciation of the transitional top of the limestone was ascribed by Woolacott (1919b, p. 166) to post-depositional internal volume changes and by Jones and Hirst (1972) to collapse following the dissolution of interbedded sulphates. Lee and Harwood (1989) deduced that the brecciated rock had undergone a complex diagenetic history and that the brecciation occurred at about the time when abundant replacive anhydrite in the rock was being dissolved; they speculated that this dissolution might have been effected by fluids introduced during Tertiary re-activation of the nearby Butterknowle Fault. Farther east, away from known faults, apparently secondarily brecciated dolomite was reported by Magraw *et al.* (1963) at a comparable stratigraphic level in Elwick No. 1 Borehole (NZ 4531 3117) and Dalton Nook Plantation Borehole (NZ 4811 3144).

The mineralization of the rocks at Raisby Quarries has been considered by a number of authors (see Introduction). There is reasonable agreement that the copper mineralization is related to the proximity of the Butterknowle Fault, but somewhat more diverse views on the mode of emplacement of the remaining minerals. It is generally agreed, however, that secondary anhydrite was once widespread and abundant in these rocks and, on dissolution, was the source of marine sulphate ions involved in the formation of baryte. Jones and Hirst (1972) speculated that the anhydrite, perhaps with a bacterial and organic carbon involvement, was the source of sulphide ions incorporated into galena and sphalerite. Lee and Harwood (1989) envisage a complex sequence of events leading to the precipitation of late-stage anhydrite, baryte and fluorite following the dissolution of early diagenetic anhydrite by meteoric-derived fluids during the Tertiary to present cycle of uplift.

Future research

The geology of this quarry is reasonably well known and understood and there is relatively little immediate scope for further research; its main use is as a superb reference section.

Conclusions

This site is one of the largest quarries in northern England. Its importance lies in that it exposes a complete section of the Raisby Formation, comprising a thick sequence of well-bedded limestone (below) and dolomite, underlain by the Marl Slate and Yellow Sands in the quarry floor. The basal few metres of the overlying Ford Formation are present at the top of the main face. Much of the limestone of the Raisby Formation is original, particularly in the lower part of the formation, but higher beds are mainly of dolomite. This limestone and dolomite contains a well-documented suite of secondary minerals. Fossils are concentrated in the primary limestones in the lower part of the formation. The principal significance of Raisby Quarries is that they provide an excellent type section of the Raisby Formation.