British Lower Carboniferous Stratigraphy

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Chapter 3

Northumberland Trough

M.A. Purnell and P.J. Cossey

INTRODUCTION

The Lower Carboniferous rocks of the Northumberland Trough outcrop as an easterly widening wedge between the Southern Uplands to the north and the Alston Block to the south (Figure 3.1). A number of sub-basins are recognized in the Northumberland Trough: the Solway Basin in the west, the Northumberland Basin, and the Tweed Basin to the north of the Cheviot Block (Figure 3.2). Except for excellent coastal sections in the east and west, exposure is limited to streams and a few quarries, with many areas of outcrop bounded by faults. Because of this sporadic pattern of exposure and rapid lateral facies changes, both within and between sub-basins, several areas have Lower Carboniferous successions that are sedimentologically distinctive. Precise correlation between these areas is difficult, and stratigraphical terminology varies, with no standard scheme applicable to all of the sub-basins (Figure 3.3).

History of research

The occurrence of coal and other mineral deposits in northern England has meant the Northumberland Trough area has attracted the attention of geological researchers since the early days of the science. Some of the first accounts of Carboniferous sequences in the area date from the early 19th century (e.g. Forster, 1809; Thompson, 1814; Winch, 1817) and by the middle of the 19th century these successions had been described in some detail. Subsequent classic work on the geology of the Northumberland Trough includes that of Tate (1867), Lebour (1875a), Smith, S. (1910) and Garwood (1913).

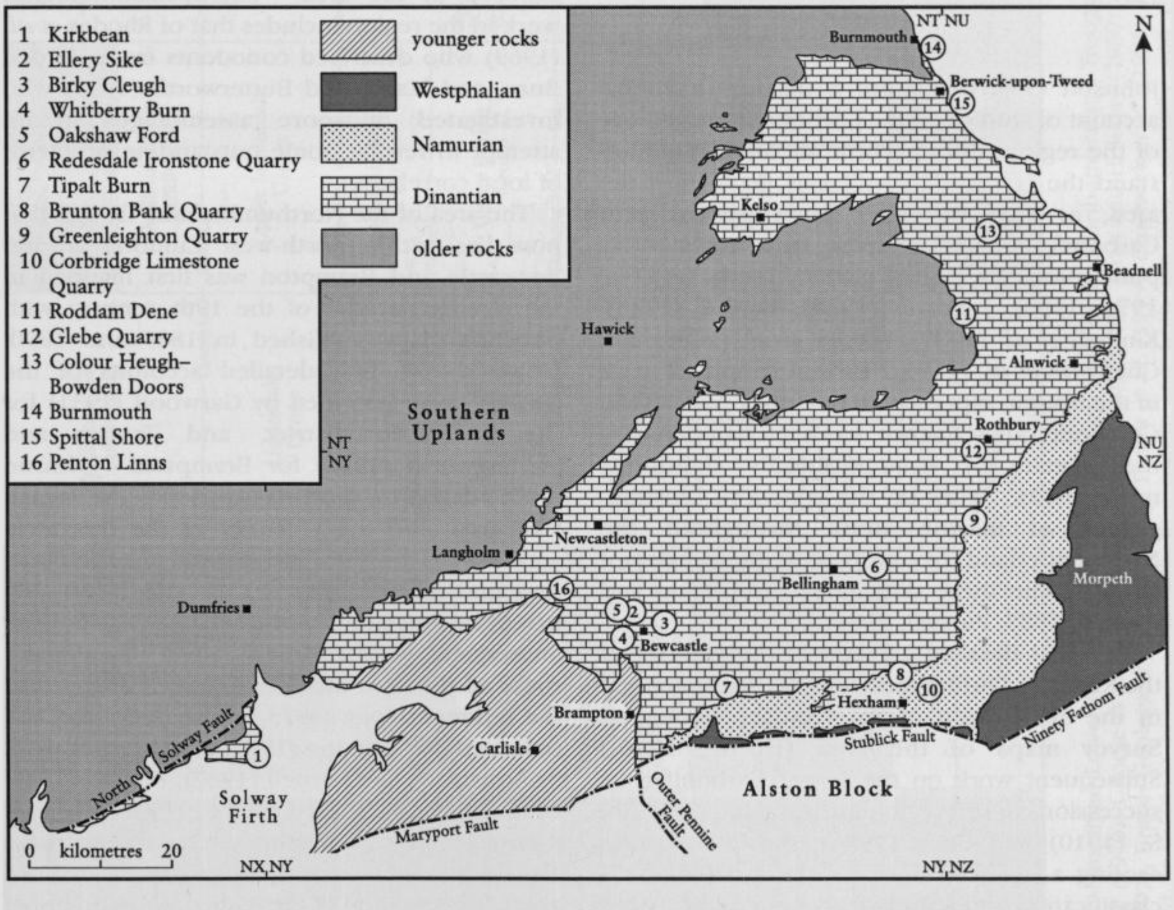


Figure 3.1 Geological map of northern England illustrating the distribution of Carboniferous outcrops in the Northumberland Trough and the locations of GCR sites described in the text. Details of the geology south of the Maryport–Stublick–Ninety Fathom Fault System and in the Southern Uplands area are omitted. After Johnson *et al.* (1995), and including information from Ord *et al.* (1988), Leeder (1992) and Chadwick *et al.* (1993a,b, 1995). Note that the position of the Maryport Fault is extrapolated from the subsurface.

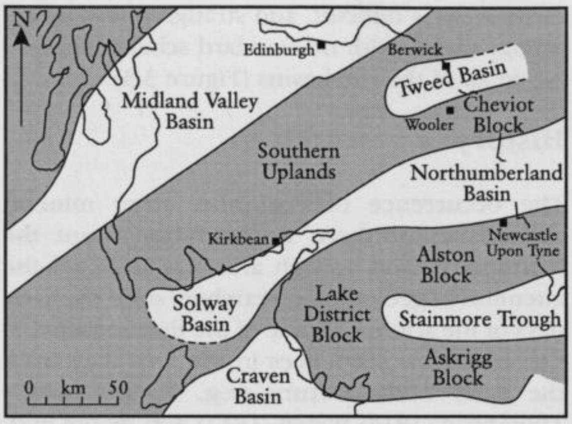


Figure 3.2 Simplified palaeogeography of northern England and southern Scotland illustrating the distribution of Lower Carboniferous sedimentary basins. Note the positions of the Tweed Basin, Northumberland Basin and Solway Basin, which together constitute the Northumberland Trough area. Based on Johnson (1984) and Armstrong and Purnell (1993).

Johnson (1995) includes a detailed historical account of studies on the Carboniferous geology of the region. More recent attempts to understand the Lower Carboniferous geology of the area, as part of wider investigations into Carboniferous stratigraphy, have resulted in publications by Rayner (1953), Leeder (1974a, 1976, 1988), Johnson (1984), Barrett (1988), Kimbell *et al.* (1989), Leeder *et al.* (1989) and Chadwick *et al.* (1995). Biostratigraphical work in the trough, especially in the lower parts of the Carboniferous sequence, has been hampered by the paucity of stratigraphically significant macrofossils. Work on the conodont biostratigraphy of marine strata throughout the Northumberland Trough represents an attempt to overcome these difficulties (Armstrong and Purnell, 1987; Purnell, 1989).

The first detailed account of the geology of the Kirkbean Outlier (Solway Basin) is contained in the explanation of the [British] Geological Survey maps of the area (Horne, 1896). Subsequent work on the Lower Carboniferous successions in this region includes that by Smith, S. (1910) and Craig (1956), the latter representing a major revision of the stratigraphical classification and correlation of the rocks. More recently, Maguire *et al.* (1996) published a detailed analysis of Dinantian depositional environments in the Solway area, and important coastal sections in the Kirkcudbright–Dalbeattie area have been re-surveyed to produce a new British Geological Survey map (British Geological Survey, 1993a) and memoir (Lintern and Floyd, 2000) of the region.

Exposures of Lower Carboniferous strata in the Langholm area were first described by Peach and Horne (1903) as part of their work on the Canonbie Coalfield. Garwood (1931) later provided detailed descriptions of several sections and proposed new stratigraphical subdivisions and correlations with strata exposed in other areas of the Northumberland Trough. [British] Geological Survey activity in the area culminated in the publication of the Langholm memoir (Lumsden *et al.*, 1967). Around the same time, Leeder published a series of papers describing the detailed sedimentology of the siliciclastic facies (Leeder, 1974b) and the carbonate and laminated microbial facies (Leeder, 1975a,b) of the lower part of the Carboniferous sequence exposed in the area. Micropalaeontological work in the region includes that of Rhodes *et al.* (1969) who described conodonts from Harden Burn, and Mahdi and Butterworth (1994) who investigated miospore assemblages in an attempt to resolve some outstanding problems of local correlation.

The area of the Northumberland Trough that now lies within north-west Cumbria around Bewcastle and Brampton was first mapped in the closing decades of the 19th century, with one-inch maps published in 1889 and 1890. However, the first detailed accounts of the geology were provided by Garwood (1931) for the Bewcastle district, and Trotter and Hollingworth (1932) for Brampton. Johnson (1959) described sections exposed in the Roman Wall area, and the re-survey of the Bewcastle area led to the publication of a new one-inch map and memoir (Day, 1970), which included extensive revisions to the lithostratigraphy. Subsequent work on the Lower Carboniferous rocks of the area includes Leeder's analyses of the sedimentology (1973, 1974b, 1975a,b) and sediment deformation (1987b), and recent work by Armstrong and Purnell (1987), Purnell (1989, 1992) and Purnell and von Bitter (1992) on conodont biostratigraphy within the Northumberland Trough focused particularly on the Bewcastle area. Investigation of the hydrocarbon potential of the region resulted in the drilling of the Easton Borehole, which proved thick evaporite sequences not encountered at the surface (Ward in Chadwick *et al.*, 1993a, 1995).

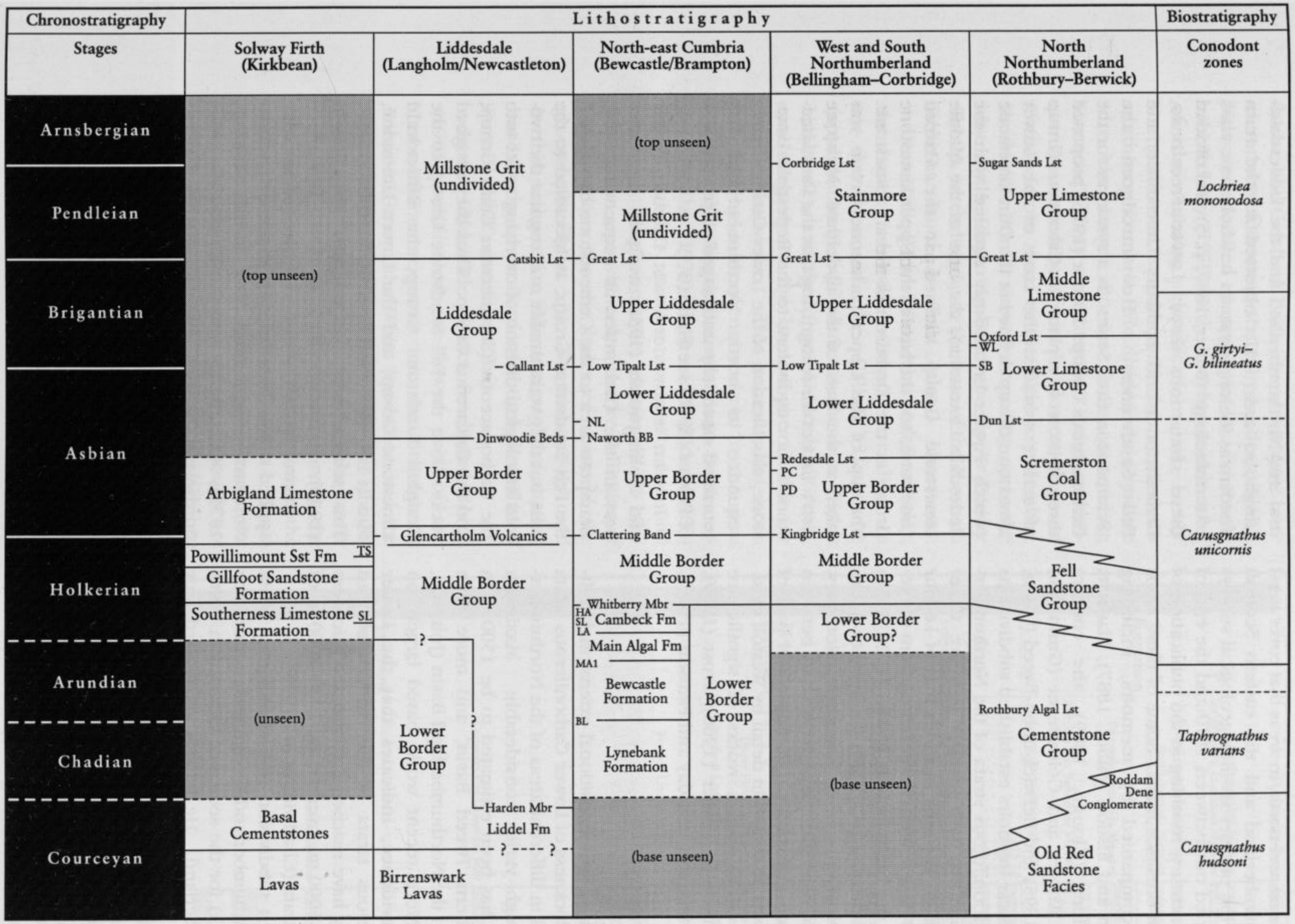


Figure 3.3 Simplified Lower Carboniferous stratigraphical chart of the Northumberland Trough. Compilation based on information from Lumsden *et al.* (1967), Day (1970), George *et al.* (1976), Ramsbottom *et al.* (1978), Frost and Holliday (1980), Armstrong and Purnell (1987), Smith and Holliday (1991), Purnell (1992), British Geological Survey (1993a), Turner *et al.* (1993), Chadwick *et al.* (1995), Johnson *et al.* (1995) and Maguire *et al.* (1996). Note that the implied correlations between the lithostratigraphy and both the biostratigraphy and the chronostratigraphy remains uncertain in many areas. SL – Syringothyris Limestone Member; TS – Thirlstane Sandstone Member; BL – Bogside Limestone Member; MA1 – Main Algal 1 Member; LA – Lower Antiquatonia Member; HA – Hillend Algal Member; Naworth BB – Naworth Bryozoa Band; NL – Naworth Limestone; PD – Plashetts Dun Limestone; PC – Piper's Cross Limestone; SB – Spirifer Band; WL – Watchlaw Limestone; Lst – Limestone; SSt – Sandstone; Mbr – Member; Fm – Formation. Conodont zones from Armstrong and Purnell (1987) and Purnell (1989, 1992). Not to scale.

To the east and north, in areas that cover most of Northumberland and the eastern Scottish Borders, the primary six-inch geological surveys were carried out between 1870 and the end of the 19th century, resulting in the publication of a series of one-inch maps. Some of these maps were accompanied by memoirs, including Otterburn and Elsdon (Miller, 1887), Plashetts and Kielder (Clough, 1889), the country between Wooler and Coldstream (Gunn and Clough, 1895) and Berwick-upon-Tweed (Gunn, 1897). These memoirs established subdivisions of the Carboniferous strata of the Northumberland Trough that have persisted to today. Other early work in the area includes that of Lebour (1873, 1875b,c). Memoirs resulting from the re-survey in the 1920s include Fowler (1926, 1936) and Carruthers *et al.* (1930) for Berwick-upon-Tweed, Norham and Scremerston, Rothbury, Amble and Ashington, and the country between Wooler and Coldstream. A substantial part of the area was discussed in detail by Westoll *et al.* (1955). More recent works of significance include those by Fowler (1966), Frost (1969), Greig (1988), and Holliday and Pattison (1990).

Stratigraphy

As a result of syn-depositional extensional faulting, the thickness of Lower Carboniferous strata deposited in different areas of the Northumberland Trough varies considerably. Maximum thickness has been estimated to be 1500 m in the northern Tweed Basin, and more than 2000 m in the Northumberland Basin (Johnson, 1984). More recent work, based largely on seismic evidence, indicates that the Lower Carboniferous strata in the Northumberland Basin may have reached a compacted thickness of about 5000 m, overlain by 1000–2000 m of Silesian strata (Chadwick *et al.*, 1995).

The first subdivision of Carboniferous strata in the Northumberland Trough was proposed by Tate (1863) for the sequence exposed in north Northumberland. He initially recognized four divisions (Tuedian, Mountain Limestones, Millstone Grit and Coal Measures), later dividing the Mountain Limestones into a lower Carbonaceous Group and an upper Calcareous Group (Tate, 1867). Miller (1887) extended Tate's classification to the south and west into mid-Northumberland and the Liddesdale–Langholm area. He objected to the term Tuedian as 'belonging to an unwholesome class of terminology' (Miller, 1887, p. 5) and divided these strata into three: Lower Freestones, Cementstones and Rothbury Limestones, and Fell Sandstones. He introduced the 'Scremerston Coal Series' as a synonym for the Carbonaceous Group. Fowler (1926) proposed three divisions to replace the Calcareous Group of earlier workers: the base of the Lower Limestone Group defined at the Dun Limestone (which Fowler erroneously equated with the Redesdale Limestone); the base of the Middle Limestone Group defined at the Oxford Limestone; and the base of the Upper Limestone Group at the Dryburn (or Great) Limestone. The top of the Upper Limestone Group was taken at the base of the ill-defined 'Millstone Grit'. Except for recognizing that the Dun Limestone is not equivalent to the Redesdale Limestone, classification of the Lower Carboniferous sequence in north Northumberland has remained essentially unchanged since the work of Fowler (1926; see Figure 3.3).

In what is now north-west Cumbria Trotter and Hollingworth (1932) assigned the lower part of the Carboniferous sequence in the Brampton area to the Cementstone Group and the Fell Sandstone Group, as identified to the east, but they were unable to recognize the two-fold lithological division of overlying rocks into the Carbonaceous (Scremerston Coal) Group, and the Calcareous Group. Thus they assigned rocks above the Fell Sandstone Group to the Craighill Sandstone Group, the Birdoswald Limestone Group, and the Lower Limestone, Middle Limestone and Upper Limestone groups. This scheme was also adopted by Johnson (1959).

Garwood (1931) extended the terminology applied to the Carboniferous sequence in north Northumberland (e.g. Tate, 1863; Lebour, 1875a; Miller, 1887) into the Bewcastle area of north-west Cumbria and the adjacent Scottish Border country. He designated the Bewcastle district as the type area for the Cementstone Group in 'North Cumberland', and in contrast to the practice in other areas, introduced a four-fold subdivision of the Cementstone Group into the Lynebank Beds, Bewcastle Beds, Main Algal

Series, and Cambeck Beds (terms that were later elevated to formation status by Leeder, 1974b). However, detailed mapping in the Bewcastle area led Day (1970) to the conclusion that none of the existing classifications of Lower Carboniferous strata could be applied in north-west Cumbria. He divided the sequence into the Lower Border Group (including Garwood's four Cementstone Group subdivisions), extending from the lowest exposed Carboniferous strata to the Whitberry Member; the Middle Border Group, extending up to the base of the Clattering Band; the Upper Border Group, extending up to the base of the Naworth Bryozoa Band (= Goat Island Limestone; = Dinwoodie Beds of the Archerbeck Borehole); the Lower Liddesdale Group, extending up to the base of the Callant Limestone (approximately equivalent to the Low Tipalt Limestone); and the Upper Liddesdale Group, extending up to the base of the Catsbit (or Great) Limestone. This scheme has been followed by subsequent workers in the area (Figure 3.3). For similar reasons to those outlined by Day (1970), Frost and Holliday (1980) rejected earlier attempts at classification and extended Day's scheme eastwards to the Bellingham area with only minor re-definition of local markers for the bases of some of the groups (see Figure 3.3). The terminology used in this account for lithostratigraphical marker bands in the Lower Border Group follows that of Purnell (1992) (see Figure 3.4).

In the Liddesdale district, Peach and Horne (1903) subdivided the lower part of the Carboniferous sequence into the Birrenswark Volcanic Group, the Whita Sandstone and the Cementstone Group. Garwood (1931) subdivided the Cementstone Group into the Lower Beds and the Main Algal Series, believing the latter to represent a northward extension of the series defined in the Bewcastle area. Strata between the top of the Main Algal Series and the base of the Fell Sandstone Group, although not named, were considered by Garwood (1931) to

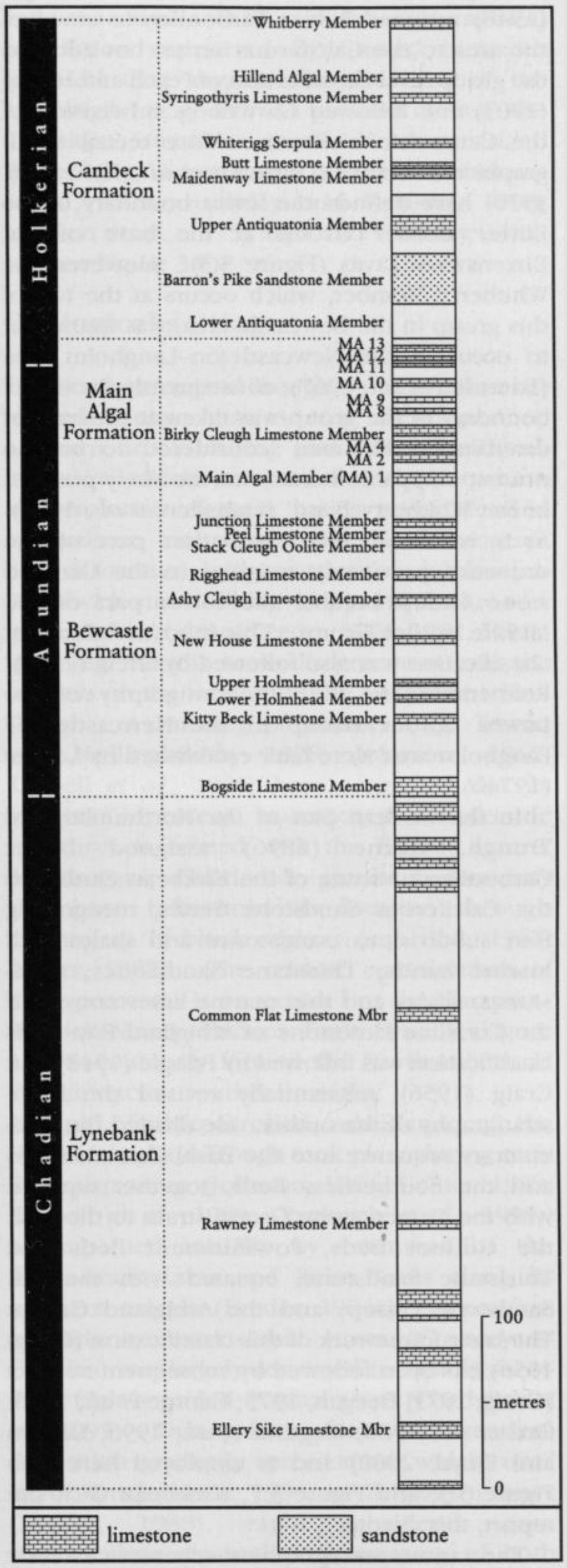


Figure 3.4▸ Lithostratigraphical terminology for the Lower Border Group in the Bewcastle area. The position of MA 14 (Main Algal 14 Member) immediately below the Lower Antiquatonia Member is omitted for clarity. After Purnell (1992).

correspond to the Cambeck Beds. Pringle (1948) assigned Lower Carboniferous strata of the area to the Calciferous Series, but adopted the group level classification of Peach and Horne (1903) and followed Garwood's subdivision of the Cementstone Group. More recent stratigraphical schemes (Lumsden *et al.*, 1967; Day, 1970) have defined the lower boundary of the Lower Border Group at the base of the Birrenswark Lavas (Figure 3.3). However, the Whitberry Member, which occurs at the top of this group in the Bewcastle area, was found not to occur in the Newcastleton–Langholm area (Lumsden *et al.*, 1967); consequently the upper boundary of the group was taken at the base of the Harden Member, 'considered to be the nearest mappable horizon to the likely position of the Whitberry Band' (Lumsden *et al.*, 1967). As a result of this correlation part of the sequence previously assigned to the Cementstone Group became the lower part of the Middle Border Group. This lithostratigraphical classification was also followed by Greig (1971). Refinements to the lithostratigraphy of the Lower Border Group in the Newcastleton–Langholm area were later established by Leeder (1974b).

In the western part of the Northumberland Trough, Horne (1896) assigned Lower Carboniferous strata of the Kirkbean Outlier to the Calciferous Sandstone Series, recognizing four subdivisions: sandstones and shales with marine bands; Thirlstane Sandstones; sandstones, shales and thin marine limestones; and the Coralline Limestone of Arbigland Bay. This classification was followed by Pringle (1948), but Craig (1956) substantially revised the lithostratigraphy of the outlier. He divided the sedimentary sequence into the Basal Cementstones and the Southerness Beds, together equated with the Cementstone Group strata to the east; the Gillfoot Beds, Powillimount Beds and Thirlstane Sandstone, equated with the Fell Sandstone Group; and the Arbigland Group. The basic framework of this classification (Craig, 1956) has been followed by subsequent authors (Greig, 1971; Deegan, 1973; George *et al.*, 1976; Ord *et al.*, 1988; Maguire *et al.*, 1996; Lintern and Floyd, 2000) and is employed here (see Figure 3.3; and Figure 3.7, **Kirkbean** GCR site report, this chapter).

The various stratigraphical schemes currently in use in different areas of the Northumberland Trough are summarized in Figure 3.3. This diagram also shows correlations between the different sections and with Lower Carboniferous chronostratigraphical stages. The history of correlation and mis-correlation in the region is long and complex, and the position of some boundaries and/or time-lines remains uncertain. This is primarily due to rapid lateral facies and thickness variations, and because of the lack of stratigraphically useful macrofossils, especially towards the base of the sequence.

The first attempts at biostratigraphy were made by Garwood (1913), who later (Garwood, 1931) applied a coral–brachiopod zonation to the sequence exposed around Bewcastle, chiefly through correlation with his earlier (1913) zonation of the Lower Carboniferous strata in the Ravenstonedale area to the south. Partly because of Garwood's pioneering work, but also because the sequence exposed around the Bewcastle and Brampton areas of north Cumbria is among the thickest, most complete, and best known in the Northumberland Trough, much of the subsequent stratigraphical work attempted correlation with these strata. Studies of note include Rayner (1953), Westoll *et al.* (1955), Johnson (1959), Johnson *et al.* (1962), Hull (1968), George *et al.* (1976) and Ramsbottom *et al.* (1978). Micropalaeontological studies have helped to resolve some of the long-standing difficulties in correlation in the region (e.g. Neves *et al.*, 1973; Armstrong and Purnell, 1987; Purnell, 1989, 1992; Mahdi and Butterworth, 1994).

The position of the Devonian–Carboniferous boundary in the Northumberland Trough sequence is not known. In some areas, Lower Carboniferous 'cementstones' unconformably overlie Silurian strata, but in the northern part of the area rocks of Old Red Sandstone facies are intercalated with, or conformably overlain by, Cementstone Group rocks (e.g. Leeder, 1973) and in some localities the base of the Carboniferous sequence lies within Old Red Sandstone facies (Leeder, 1974b). In some sections exposed along the northern margins of the Northumberland Trough, the Cementstone Group overlies the Birrenswark Lavas and Kelso Lavas, and the base of the Carboniferous System is traditionally taken at the base of the lavas (Leeder, 1971). Along its southern margin, the base of the sequence is not exposed.

Until quite recently the Lower Border Group and the Cementstone Group were taken to be of Courceyan age (George *et al.*, 1976); however, although biostratigraphical evidence is scant, foraminifera and conodonts from the lower part of the Lower Border Group at Bewcastle indicate a Chadian age (Ramsbottom, 1977a). This has been confirmed by more detailed conodont work (Armstrong and Purnell, 1987; Purnell, 1989), indicating an early Chadian to Holkerian age for the Lower Border Group at Bewcastle. This work also suggests that the Lower Border Group in the Newcastleton area (near Langholm) is of Courceyan age, but miospores indicate that supposed lateral equivalent non-marine rocks exposed just to the south, nearer to Langholm, are of Chadian age. This highlights the problems with lithostratigraphical correlation within the Northumberland Trough and it is unfortunate that correlations between the marine Lower Border Group in the Bewcastle area and Cementstone Group sequences elsewhere rely almost entirely on lithostratigraphical evidence. Thus, although microfossils in particular provide some constraints, the positions of the boundaries between the Courceyan, Chadian, Arundian and Holkerian stages in this region are not known at present (Figure 3.3).

Using foraminifera, the base of the Asbian Stage is correlated with a horizon within the Glencartholm Volcanic Beds in the Archerbeck Borehole (George *et al.*, 1976), which is correlated with the Clattering Band in the Bewcastle sequence (Day, 1970). Correlations into other parts of the basin are lithostratigraphical. Biostratigraphically useful macrofossils become more common higher in the sequence, but many of the stratigraphical problems in the Northumberland Trough have arisen because biostratigraphy and lithostratigraphy have been conflated, with marker beds of supposed or established palaeontological significance being used to correlate between areas (e.g. Frost and Holliday, 1980). Hence the Upper Liddesdale Group corresponds to the D_2 coral–brachiopod zone (Johnson, 1959; Day, 1970) and the Brigantian Stage (George *et al.*, 1976) because the lower boundary of the division was selected to coincide with the incoming of stratigraphically significant fossils. The position of the base of the Brigantian Stage in the Northumberland Trough is based on correlation of the Low Tipalt Limestone with the Peghorn Limestone at the basal Brigantian stratotype (Figure 3.5; and see **Janny Wood** GCR site report, Chapter 5).

Goniatite faunas provide good evidence that the base of the Pendleian Stage lies close to the base of the Great Limestone (Johnson, 1962; and see Figure 3.6). Lithostratigraphical correlation supported by limited biostratigraphical data suggest that the base of the Arnsbergian Stage lies at a position close to the Corbridge Limestone in the Northumberland Trough (e.g. Ramsbottom, 1977a; Ramsbottom *et al.*, 1978; Holliday and Pattison, 1990; Johnson *et al.*, 1995; Mills and Holliday, 1998; and see Figure 3.6).

Geological setting

The Northumberland Trough is one of a number of sedimentary basins that developed in northern Britain during Late Palaeozoic times. It is now widely accepted that the formation and evolution of these basins was controlled by back-arc extension north of an orogenic belt associated with northward subduction (Chadwick and Holliday, 1991) and closure of a 'proto-Tethys' Ocean (Leeder, 1976, 1982, 1988). However, there is some disagreement over the controls on the location of the Northumberland Trough. A number of authors (e.g. Trotter and Hollingworth, 1928; Johnson, 1967; Kimbell *et al.*, 1989) have suggested that its margins represent re-activated Caledonide structures associated with the Iapetus suture. Post-orogenic Caledonide granite bodies may also have influenced its location through buoying-up of block regions (e.g. Bott, 1967; Leeder, 1982). The relative contributions of these processes is uncertain, but the Maryport–Stublick–Ninety Fathom Fault System (Figure 3.1) undoubtedly formed the Northumberland Trough's active southern margin.

Rapid, fault-controlled subsidence of the Northumberland Trough took place during early Dinantian times (Johnson, 1984; Collier, 1989; Kimbell *et al.*, 1989; Chadwick *et al.*, 1995), accompanied initially by extrusion of the Birrenswark Lavas and Kelso Lavas along its northern margin (Leeder, 1974a). Deposition of early syn-extensional strata (Courceyan–Chadian) was largely restricted to rapidly subsiding, fault-bounded, basinal areas (Chadwick *et al.*, 1995). During later phases of extension, deposition gradually spread more widely, until in Asbian (Johnson, 1984) or Brigantian times (Leeder, 1988), rapid subsidence gave way to slow regional down-warping of both the Northumberland Trough and the adjacent bounding block areas.

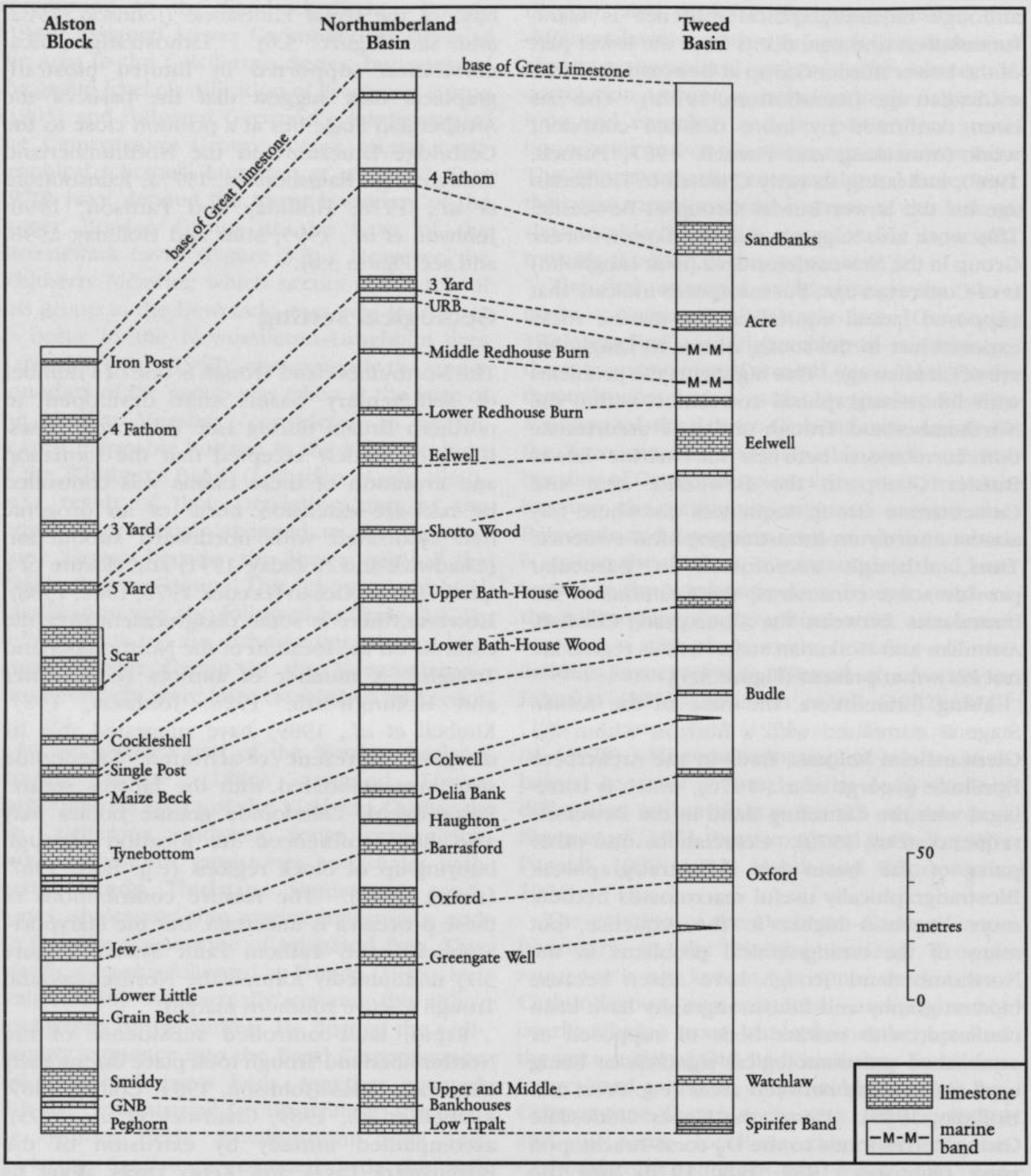


Figure 3.5 Stratigraphy of the Upper Liddesdale Group (Brigantian, D_2) limestones from the Alston Block to the Northumberland Basin and the Tweed Basin. (GNB – Girvanella Nodular Bed; URB – Upper Redhouse Burn.) After Frost and Holliday (1980).

During deposition of Lower Carboniferous strata, sedimentation kept pace with subsidence (Johnson, 1984) and there is little evidence for water depth ever exceeding 50 m (Leeder and McMahon, 1988). For much of Early Carboniferous times, the Northumberland Trough was a narrow gulf-like extension of the open sea, widening to the south-west and with marine influences thus decreasing towards the north and east. Its sedimentary rock successions reflect the interplay of fluvio-deltaic and shallow-marine depositional systems (Leeder, 1974a,b,

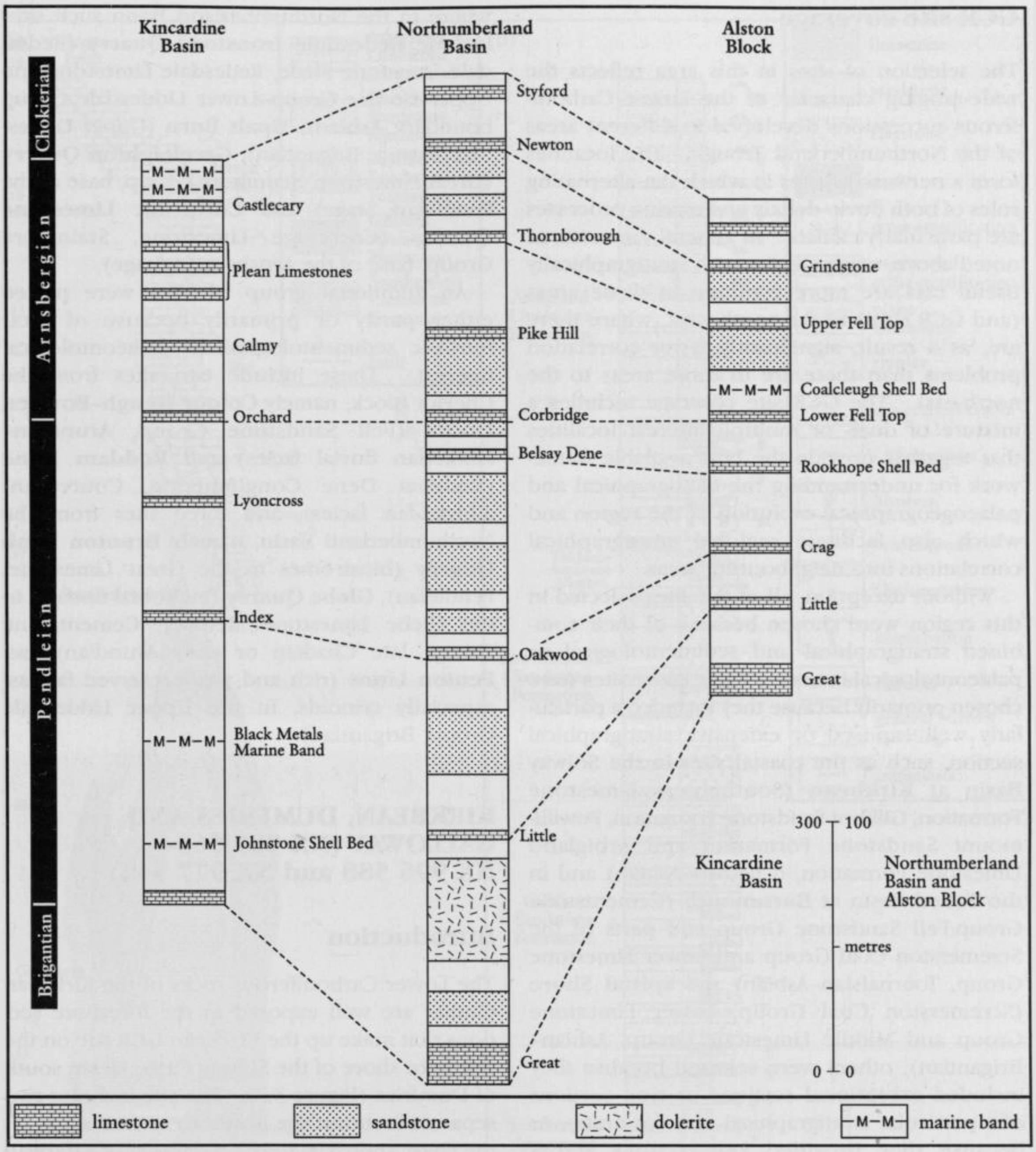


Figure 3.6 Correlation of lower Stainmore Group successions (Pendleian, E_1–Arnsbergian, E_2) between the Kincardine Basin, the Northumberland Basin and the Alston Block. After Ramsbottom *et al.* (1978).

1975a,b; Johnson, 1984; Smith and Holliday, 1991) that were controlled by tectono-sedimentary (Leeder, 1987b; Leeder *et al.*, 1989) and eustatic (Ramsbottom, 1973) influences. The emergent margins of the Northumberland Basin were sources of clastic sediment during the early period of deposition (Leeder, 1974b), but for much of Dinantian times axial drainage systems were dominant, building from the north and east towards a shallow sea in the west (Robson, 1956; Frost, 1969; Leeder, 1974b; Turner *et al.*, 1993, 1997). Marginal clastic deposition persisted in the Solway Basin, adjacent to the active North Solway Fault System (Deegan, 1973; Ord *et al.*, 1988).

GCR site coverage

The selection of sites in this area reflects the wide-ranging character of the Lower Carboniferous successions developed in different areas of the Northumberland Trough. The localities form a network of sites in which the alternating roles of both fluvio-deltaic and marine processes are particularly evident. In general, however, as noted above, marine facies with stratigraphically useful taxa are more common in those areas (and GCR sites) to the south-west, where there are, as a result, significantly fewer correlation problems than there are in those areas to the north-east. The GCR site coverage includes a mixture of dual- or multiple-interest localities that together provide the best available framework for understanding the stratigraphical and palaeogeographical evolution of the region and which also facilitate regional stratigraphical correlations into neighbouring areas.

Without exception, all of the sites selected in this region were chosen because of their combined stratigraphical and sedimentological or palaeontological interest. While some sites were chosen primarily because they included a particularly well exposed or extensive stratigraphical section, such as the coastal sites in the Solway Basin at **Kirkbean** (Southerness Limestone Formation, Gillfoot Sandstone Formation, Powillimount Sandstone Formation and Arbigland Limestone Formation, ?Chadian–Asbian) and in the Tweed Basin at **Burnmouth** (Cementstone Group/Fell Sandstone Group and parts of the Scremerston Coal Group and Lower Limestone Group, Tournaisian–Asbian) and **Spittal Shore** (Scremerston Coal Group, Lower Limestone Group and Middle Limestone Group, Asbian–Brigantian), others were selected because they included exceptional sections or type sections of a particular stratigraphical unit (or units), or because they provided key sections across critical formation or group boundaries. Examples of such sites in the Bewcastle area include **Ellery Sike** (Lynebank Formation, Lower Border Group, Chadian), **Birky Cleugh** (type section of the Main Algal Formation, Lower Border Group, Arundian–Holkerian), **Whitberry Burn** (Holkerian, Cambeck Formation and Lower Border Group–Middle Border Group boundary) and **Oakshaw Ford** (Holkerian–Asbian boundary and type locality for various lithostratigraphical units in the Middle Border Group and Upper Border Group), whereas elsewhere in the Northumberland Basin such sites include **Redesdale Ironstone Quarry** (Redesdale Ironstone Shale, Redesdale Limestone and Upper Border Group–Lower Liddesdale Group boundary, Asbian), **Tipalt Burn** (Upper Liddesdale Group, Brigantian), **Greeleighton Quarry** (Great Limestone, Stainmore Group, base of the Pendleian Stage) and **Corbridge Limestone Quarry** (Corbridge Limestone, Stainmore Group, base of the Arnsbergian Stage).

An additional group of sites were picked either partly or primarily because of their intrinsic sedimentological or palaeontological interest. These include two sites from the Cheviot Block, namely **Colour Heugh–Bowden Doors** (Fell Sandstone Group, Arundian–Holkerian fluvial facies) and **Roddam Dene** (Roddam Dene Conglomerate, Courceyan? alluvial-fan facies), and three sites from the Northumberland Basin, namely **Brunton Bank Quarry** (biostromes in the Great Limestone, Pendleian), **Glebe Quarry** (microbial oncoids in the Glebe Limestone Member, Cementstone Group, late Chadian or early Arundian) and **Penton Linns** (rich and well-preserved faunas, especially crinoids, in the Upper Liddesdale Group, Brigantian).

KIRKBEAN, DUMFRIES AND GALLOWAY (NX 987 563–NX 996 588 and NX 977 543)

Introduction

The Lower Carboniferous rocks of the Kirkbean Outlier are well exposed in the foreshore sections that make up the Kirkbean GCR site on the northern shore of the Solway Firth, 16 km south of Dumfries (Figure 3.7). The site includes two separate sections: the northern section starts on the coast approximately 1.5 km east of Kirkbean (NX 9955 5886) and extends 3 km south (to NX 9867 5624), exposing a section through the Gillfoot Sandstone Formation, the Powillimount Sandstone Formation and the Arbigland Limestone Formation. The second section, just over 1 km to the south (NX 977 543), exposes rocks of the Southerness Limestone Formation and overlying Gillfoot Sandstone Formation. These sequences may span a Chadian to Asbian time interval (Craig, 1956; Deegan, 1973; George *et al.*, 1976; Purnell, 1989, 1992; British Geological Survey, 1993a; Maguire *et al.*, 1996).

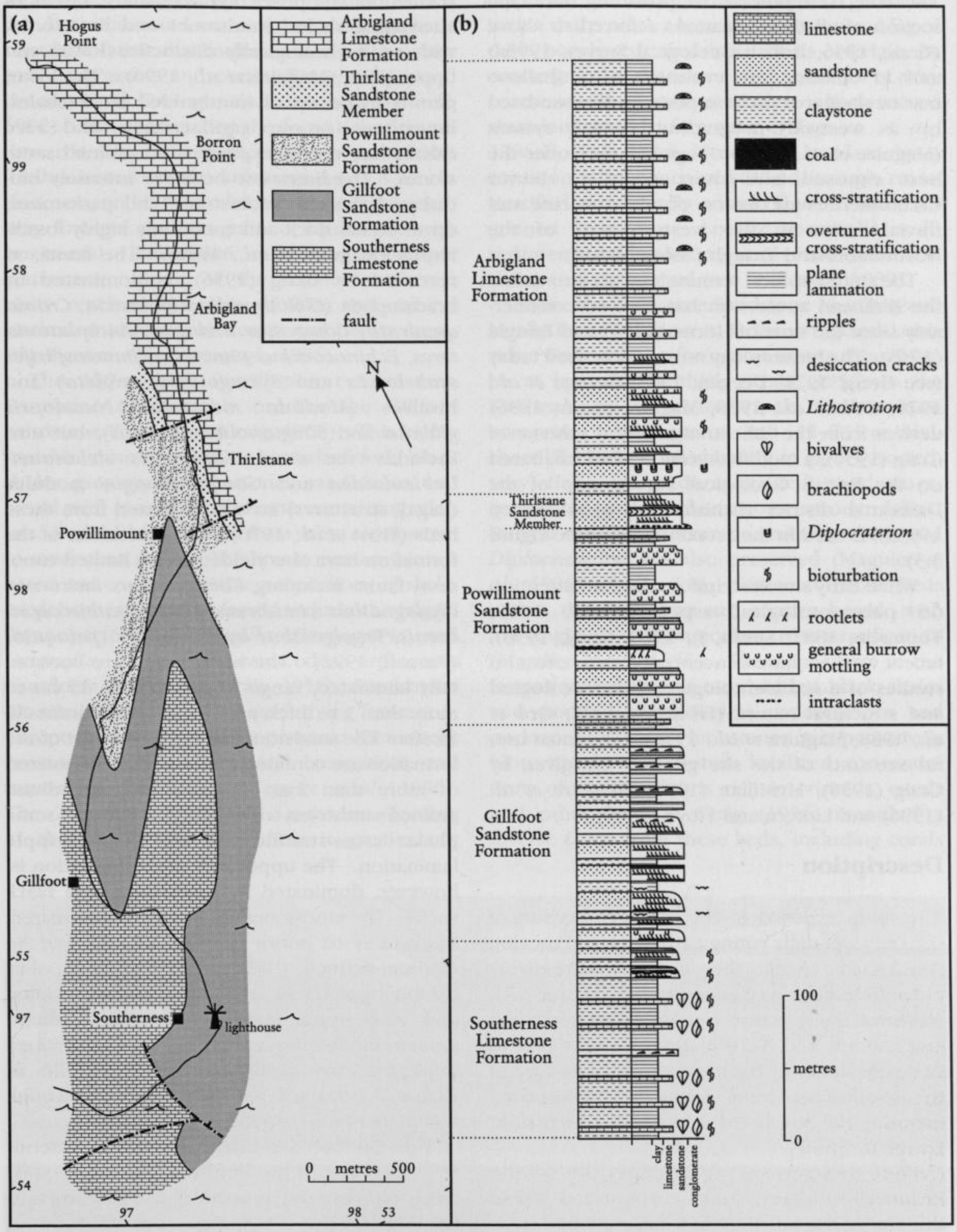


Figure 3.7 (a) Geological map and (b) simplified sedimentary log of the Lower Carboniferous succession at the Kirkbean GCR site, using the lithostratigraphical nomenclature of the British Geological Survey (1993a). (a) After Craig (1956); (b) courtesy of K. Maguire.

The site is important in providing the type section of all the formations referred to above (Craig, 1956; British Geological Survey, 1993a) and in defining the evolution of a shallow-marine shelf area that was periodically inundated by a westward-prograding fluvial system (Maguire *et al.*, 1996). Together they offer the best exposed and most complete Lower Carboniferous succession of mixed marine and fluvial facies in the western part of the Northumberland Trough (Solway Basin).

The stratigraphical terminology used to define the Kirkbean succession has evolved considerably since the time of Horne (1896) and Pringle (1948). The terminology most widely used today (see Greig, 1971; Deegan, 1973; George *et al.*, 1976; Ord *et al.*, 1988; Maguire *et al.*, 1996) derives from the lithostratigraphical scheme of Craig (1956), a modified version of which, based on the British Geological Survey map of the Dalbeattie district (British Geological Survey, 1993a), is used in the account below (see Figure 3.3).

While early site descriptions focused attention on palaeontological aspects (Jolly, 1869; Thomson, 1887; Smith, J., 1910; Craig, 1956), recent workers have concentrated their effort on studies of a sedimentological, palaeoecological and structural nature (Frölicher, 1977; Ord *et al.*, 1988; Maguire *et al.*, 1996). The most useful accounts of the site geology are given by Craig (1956), McMillan (1996), Maguire *et al.* (1996) and Lintern and Floyd (2000).

Description

The strata exposed in the northern section of the site essentially young eastwards, and moving southward along the coast progressively older formations are encountered (Figure 3.7). However, the structure is complicated by folding and faulting, and the dip and strike of the beds vary considerably. The main structural feature of the southern section is the broad anticline exposing the Southerness Limestone Formation on the foreshore.

The Southerness Limestone Formation includes the oldest strata encountered within the site. It has no stratigraphically defined base, the lowermost beds cropping out in the core of the anticline at Southerness Point (NX 971 541) (Craig, 1956). The top is defined by the base of the overlying Gillfoot Sandstone Formation (Craig, 1956). The Southerness Limestone Formation comprises approximately 140 m of alternating shales, sandstones and limestones, with sedimentologically distinctive lower and upper parts (Maguire *et al.*, 1996). The lower part is made up of interbedded black shales, limestones (some argillaceous), and rare calcareous, very fine- to medium-grained sandstones. The limestone beds are intensely bioturbated skeletal wackestones and packstones, up to 60 cm thick and commonly highly fossiliferous (Maguire *et al.*, 1996). The fauna, as recorded by Craig (1956), is dominated by brachiopods (*Cleiothyridina glabistria*, *Crania quadrata*, *Composita ambigua*, *Antiquatonia teres*, *Echinoconchus punctatus*, *Punctospirifer scabricosta* and *Syringothyris exoleta*) and bivalves (*Modiola megaloba*, *Nuculopsis gibbosa* and *Sanguinolites plicatus*), but also includes the coral *Zaphrentis delanouei*. *Orbiculoidea* and '*Somphospongia*' nodules ('algal' structures) are also reported from these beds (Frost *et al.*, 1976). The limestones of the formation have also yielded a very limited conodont fauna including *Cavusgnathus unicornis*, *Clydagnathus windsorensis*, *Patrognathus capricornis*, *Vogelgnathus kyphus* and *V. pesaquidi* (Purnell, 1992). The black shales are horizontally laminated, range from less than 15 cm to more than 1 m thick, and are generally unfossiliferous. The sandstones of the lower part of the formation are confined to one sheet-like horizon of more than 2 m of very fine- to medium-grained sandstone, with horizontal laminae, some planar cross-stratification and current-ripple lamination. The upper part of the formation is, however, dominated by sandstones with black shales. The sandstones are intensely bioturbated, moderately to poorly sorted and very fine- to medium-grained. Where not burrowed, they exhibit ripple cross-lamination, planar bedding and wave-ripple lamination. The medium-grained sandstones tend to be more than 30 cm thick and may amalgamate to form units in excess of 1 m thick, with well-developed trough and planar cross-stratification.

The Gillfoot Sandstone Formation extends from the base of the sandstone with carbonate rods, exposed 460 m north of the lighthouse at Southerness (NX 978 542), to 'a grey calcareous breccia/conglomerate with fragments less than one inch in size' exposed between Southerness and Carsethorne (Craig, 1956). The thickness of the formation has been estimated at 120–180 m. It is dominantly composed of red-purple sandstones, conglomerates and shales. A few thin limestones and some of the sandstone beds contain a fauna that includes bivalves, brachiopods, bryozoans and corals (Craig, 1956), and the conodont *Cavusgnathus unicornis* (Purnell, 1992). The character of the formation changes upwards, with the upper part composed of 50% flat-laminated shale units up to 1.8 m in thickness, and 50% moderately to poorly sorted, very fine- to medium-grained sandstones with horizontal lamination and current-ripple lamination. Some of the coarser sandstone units reach thicknesses of 2 m and exhibit stacked unidirectional trough and planar cross-stratification (Maguire *et al.*, 1996).

The 150 m-thick Powillimount Sandstone Formation conformably overlies the Gillfoot Sandstone Formation (Craig, 1956). This highly variable unit comprises interbedded black shales, grey muddy limestones, sandstones, and a coal with associated seatearth containing rootlets. Bed thicknesses vary from a few centimetres to more than 2.5 m. The limestones are bioturbated and contain variable proportions of skeletal debris; identifiable fossils include the 'algae' (cyanobacteria) *Girvanella*, *Bevocastria* and *Ortonella*, gastropods, ostracodes, orthoconic nautiloids, and corals (Craig, 1956). Sandstones are similar to those of the underlying formation, except that in places they preserve hummocky cross-stratification, horizontal lamination, and wave-ripple lamination (Maguire *et al.*, 1996). The 25 m-thick Thirlstane Sandstone Member at the top of the formation is particularly distinctive. It has a tabular, sheet-like geometry, with a sharp erosive base and disorganized lag of dark purple-red sandstone clasts overlain by coarse-grained sandstone with pockets of very coarse sandstone with mudstone intraclasts and abundant woody fragments (Maguire *et al.*, 1996). This basal interval is overlain by a continuous sequence of stacked, trough cross-stratified, moderately sorted, fine- to medium-grained sandstone. Locally, spectacular soft-sediment deformation, sand volcanoes and slumps are developed (see Ord *et al.*, 1988).

Above the Thirlstane Sandstone Member, and locally faulted against it, is the Arbigland Limestone Formation, a formation that is thought to be at least 300 m thick (Craig, 1956) in the Kirkbean area. In its lower part, the formation comprises black shales and 15–75 cm-thick sheet-like beds of moderately to poorly sorted, very fine- to medium-grained sandstones, commonly with carbonaceous woody debris. Burrow mottling is common and *Chondrites* and *Diplocraterion* are also preserved (Maguire *et al.*, 1996) (Figure 3.8). Some sandstone beds within the formation are erosive based, with low-angle and hummocky cross-stratification (Maguire *et al.*, 1996). The upper part of the formation consists of interbedded black shales and poorly sorted skeletal wackestones and packstones. These limestones are pervasively bioturbated, and contain localized concentrations of skeletal debris rich in crinoids, corals and other fossils. Craig (1956) recorded a diverse fauna from these beds, including corals

Figure 3.8 *Diplocraterion yoyo* from interbedded marine shelf beds (laminated siltstones and bioturbated sandstones) of the Arbigland Limestone Formation at the Kirkbean GCR site. (Photo: P.J. Cossey.)

(*Siphonophyllia benburbensis*, *Carcinophyllum kirsopianum*, *Lithostrotion clavaticum* and *Hapsiphyllum enniskilleni*), brachiopods (*Echinoconchus punctatus*, '*Dielasma hastata*', *Punctospirifer scabricosta*, *Martinia glabra* and gigantoproductids), bryozoans, bivalves and orthoconic nautiloids.

Recently, Veale and Parnell (1996) reported sub-millimetre-sized thoriferous bitumen nodules from the Southerness Limestone and Arbigland Limestone formations.

Interpretation

The rocks described above have been interpreted by Maguire *et al.* (1996) as recording a prolonged period of deposition in a shallow marine setting with periodic inundation by prograding fluvial systems (Figure 3.9). In more detail, the Southerness Limestone Formation was deposited on a tectonically stable, open marine shelf, with the transition from the lower, limestone-dominated part to the sandstone-dominated sequence above reflecting increased clastic input. This culminated in the inundation of the area by the coastal-plain deposits of the Gillfoot Sandstone Formation. These rocks were deposited on a low-relief alluvial plain traversed by entrenched fluvial channels, with the major transport direction towards the west. The rocks of the Powillimount Sandstone Formation mark a return to open marine conditions; the input of clastic material originating from an actively prograding fluvial channel system, and the development of in-situ coal suggesting deposition on a marine shelf next to a swampy coastal plain. The Thirlstane Sandstone Member records a major episode of westwards

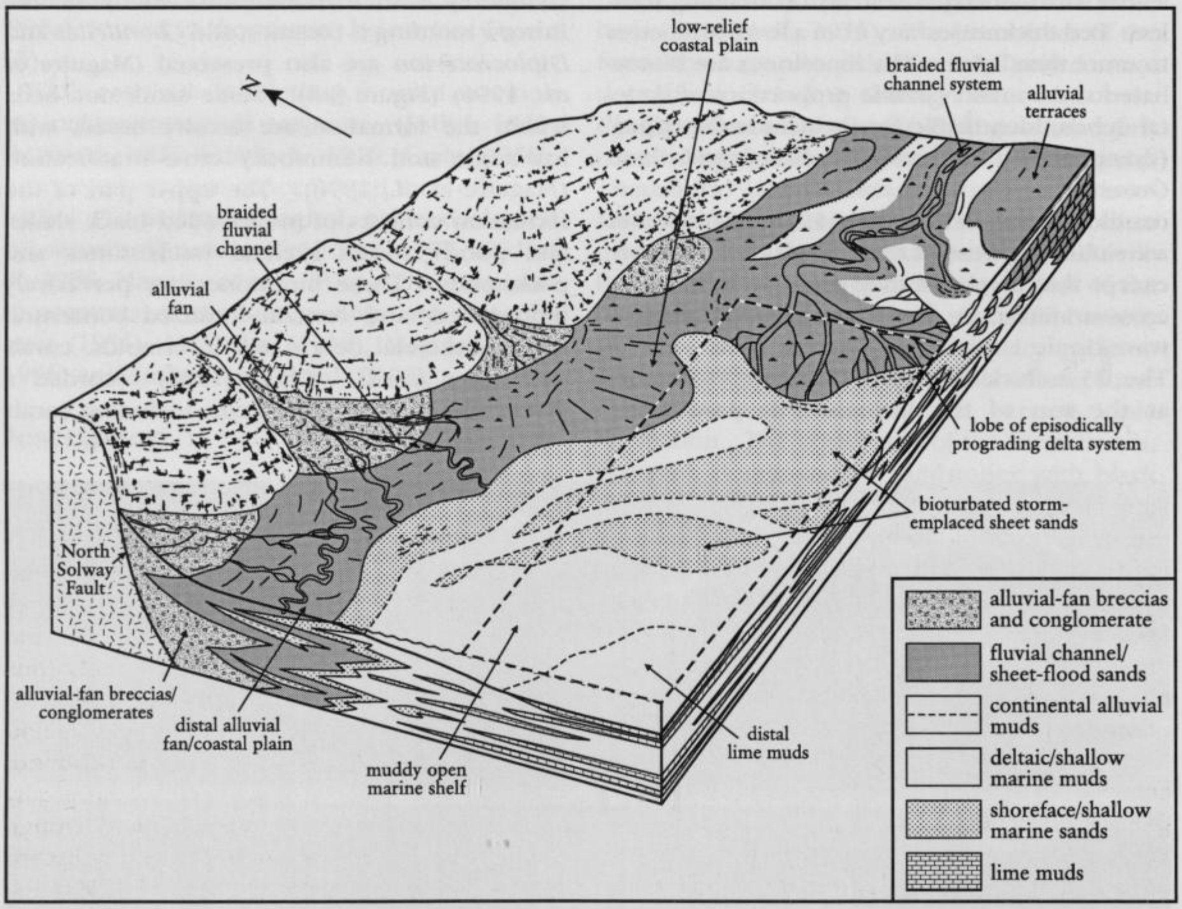


Figure 3.9 Schematic representation of Dinantian depositional environments along the northern margin of the Solway Firth and palaeogeographical setting of the Kirkbean succession (area within rectangular outline, lower right). The length of the east–west section is approximately 40 km. Note that the Kirkbean sequence was deposited in a tectonically stable area away from the North Solway Fault, hence the absence of alluvial-fan breccias at the Kirkbean GCR site. After Maguire *et al.* (1996).

progradation of a braided fluvial system onto the shelf. This was followed by a return to open marine shelf conditions, with the deposition of the Arbigland Limestone Formation. The upward increase in the proportion of limestones in the formation reflects a decrease in the availability of sand as fluvial influences waned.

Correlation of these rocks is poorly constrained, primarily because facies changes between this site and rocks to the east make lithostratigraphical correlation almost impossible, and the faunal content is rather limited for reliable biostratigraphical correlation. Pringle (1948) correlated the Southerness Limestone Formation with the beds in the Newcastleton area now considered to be part of the lower Middle Border Group. Craig (1956) correlated the 'Syringothyris/Derbyia Band' in the lower part of the Southerness Limestone Formation with its lateral equivalent, the Harden Member in the Esk district. He equated the Gillfoot Sandstone Formation and the Powillimount Sandstone Formation with the rocks now considered as belonging to the Middle Border Group, and the Arbigland Limestone Formation with the Upper Border Group. The algal horizons in the Southerness Limestone Formation were believed by Ramsbottom (1973) to represent the regressive beds of Major Cycle 2 and were therefore correlated with the Hillend Algal Member of Bewcastle (see **Whitberry Burn** GCR site report, this chapter). George *et al.* (1976) correlated the Southerness Limestone Formation with the Harden Member and the Cambeck Formation on the basis of their faunal similarity. These authors placed the base of the Chadian Stage in the Kirkbean Outlier at the horizon of the Syringothyris Limestone Member, and followed the correlation of Ramsbottom (1973) in tentatively placing the base of the Arundian Stage at the horizon of algal nodules 28 m above the Syringothyris Limestone Member. They placed the base of the Holkerian Stage at the base of the Arbigland Limestone Formation, and the base of the Asbian Stage at the point of first entry, in the same unit, of a coral–brachiopod fauna comparable with that of the Clattering Band of Bewcastle (see **Oakshaw Ford** GCR site report, this chapter). The limited conodont evidence from the Southerness Limestone Formation and Gillfoot Sandstone Formation indicates a correlation with the Holkerian Cambeck Formation at Bewcastle (Purnell, 1989, 1992). Although the reasons for revision were not given, the recent British Geological Survey map (British Geological Survey, 1993a) proposed rather different correlations, assigning all but the base of the Arbigland Limestone Formation to the Upper Border Group. The basal few metres of the Southerness Limestone Formation were assigned to the Lower Border Group, and the rest of the formation, together with the Gillfoot Sandstone Formation and the Powillimount Sandstone Formation, were assigned to the Middle Border Group. Chronostratigraphically, the base of the Arundian Stage was correlated with a position in the upper part of the Southerness Limestone Formation, the base of the Holkerian Stage with a horizon in the lower part of the Powillimount Sandstone Formation, and the base of the Asbian Stage with a position in the lower part of the Arbigland Limestone Formation. Comparing the fauna reported by Craig (1956) with the ranges of taxa as shown in Riley (1993) does little to help resolve matters. Brachiopods from the Southerness Limestone Formation include taxa that have Chadian, Chadian–Arundian, Arundian, and Asbian ranges, whereas the only reported coral is known only from the Courceyan Stage. The fauna from the Arbigland Limestone Formation (Craig, 1956) includes taxa with Asbian–Brigantian, Arundian and Brigantian, Arundian, and Asbian indicated ranges respectively (Riley, 1993). Further research aimed at resolving the relationship between these strata and those elsewhere in the Northumberland Trough could lead to significant improvements in understanding the evolution of the basin.

Conclusions

The Kirkbean GCR site offers the best mixed marine and fluvial succession of Lower Carboniferous age in the western part of the Northumberland Trough, and the finest sections of the Southerness Limestone, Gillfoot Sandstone, Powillimount Sandstone and Arbigland Limestone formations in southern Scotland. These strata record deposition on a tectonically stable shelf within the Northumberland Trough and provide an exceptional sedimentary record of the changing palaeoenvironments of this shelf area as it evolved through a time interval that may span most of Viséan time. Despite correlation difficulties, the Kirkbean section remains vital to our understanding of the structural and stratigraphical evolution of the Solway Basin.

ELLERY SIKE, CUMBRIA (NY 546 757–NY 543 763 and NY 541 759–NY 545 758)

Introduction

The Ellery Sike GCR site, a composite stream section comprising parts of the River White Lyne (NY 5458 7568–NY 5431 7626) and Ellery Sike (NY 5414 7592–NY 5453 7576), 1.5 km north-west of Bewcastle, offers the finest section of the Lower Border Group, Lynebank Formation (Chadian) and the oldest exposed Carboniferous succession in the Bewcastle area. The site is of considerable importance to the regional correlation of Carboniferous successions throughout northern England and southern Scotland for, unlike the equivalent strata exposed to the east, it contains marine faunas that include stratigraphically significant microfossils. The section also provides a critical insight into the nature of Lower Carboniferous palaeoenvironments in the Northumberland Trough at an early stage in its history.

Garwood (1931) dealt in some detail with the sequence exposed in Ellery Sike, assigning it to his lowest subdivision, the Lynebank Beds, and suggesting that it was close to the local base of the Carboniferous System. In the [British] Geological Survey re-survey of the area (Day, 1970) the term 'Lower Border Group' was introduced to replace the Cementstone Group, but Garwood's subdivisions were only slightly modified. This terminology was followed in all subsequent work, except that the collective term 'beds' of Garwood (1931) and Day (1970), was replaced with 'formation' to accord with modern stratigraphical practice. In the 1970s, detailed sedimentological work by Leeder on the Lower Border Group succession at this site (and elsewhere) led to significant improvements in our understanding of Lower Carboniferous palaeoenvironments, palaeogeography and basin evolution (Leeder, 1974a,b, 1975a,b).

Description

The base of the Lynebank Formation is nowhere exposed (Day, 1970), but the outcrops in the banks and bed of Ellery Sike and the River White Lyne upstream of their confluence have long been recognized as the oldest strata in the area (Garwood, 1931). The Lynebank Formation occupies the core of the NNE–SSW-oriented Bewcastle Anticline. This structure was formed during Variscan inversion of the basin (Chadwick *et al.*, 1995), and the strata of this site form part of the eastern limb of the anticline, dipping at approximately 40°. The exposed sequence (see Figure 3.10) comprises approximately 130 m of alternating limestones, shales and sandstones (Day, 1970; Leeder, 1974b, 1975a). Towards the base of the section, a 6 m-thick limestone unit is exposed, approximately 30 m above which lies the 8.75 m-thick Ellery Sike Limestone Member. These two units comprise well-bedded packstones and wackestones with locally abundant crinoid ossicles, brachiopods, brachiopod fragments and spines, ostracodes, uncommon gastropods and tentaculitoid microconchids (forms previously regarded as vermiform 'gastropods'; see Weedon, 1991). Thinner limestone beds, up to about 75 cm in thickness, occur throughout the sequence. These represent a diverse range of lithofacies, including microconchid boundstones and packstones, oncoid–peloid wackestones, crinoid–ostracode wackestones and lime mudstones (Leeder, 1975a; Purnell, 1989). The siliciclastic part of the sequence is dominated by silty shales and fine sandstones comprising several cycles. These include coarsening-upward sequences, grading from fissile shales with bivalves, through rippled and cross-stratified siltstones with plant fragments, to fine sandstones with cross-stratification, including some small-scale trough cross-stratification, and fining-upward sequences of cross-stratified fine sandstones (Leeder, 1974b).

Fossils occur throughout the sequence (see Ramsbottom in Day, 1970). Bivalves, including *Nuculopsis*, *Sanguinolites*, *Schizodus*, *Myalina* and pectinids occur in the shales, together with ostracodes and rarer orbiculoid brachiopods. Brachiopods, including *Athyris concentrica* and *Pustula interrupta*, are abundant in some of the limestones. A diverse algal flora is also recorded from limestones (Day, 1970) and of particular interest is the development of microconchid boundstones, up to approximately 50 cm thick in the Ellery Sike section (Figure 3.11). Conodonts, including *Cavusgnathus hudsoni*, *Clydagnathus windsorensis*, *Mestognathus praebeckmanni*, *Polygnathus bischoffi* and *Taphrognathus varians*, have also been recovered from limestones at the site (Armstrong and Purnell, 1987; Purnell, 1992).

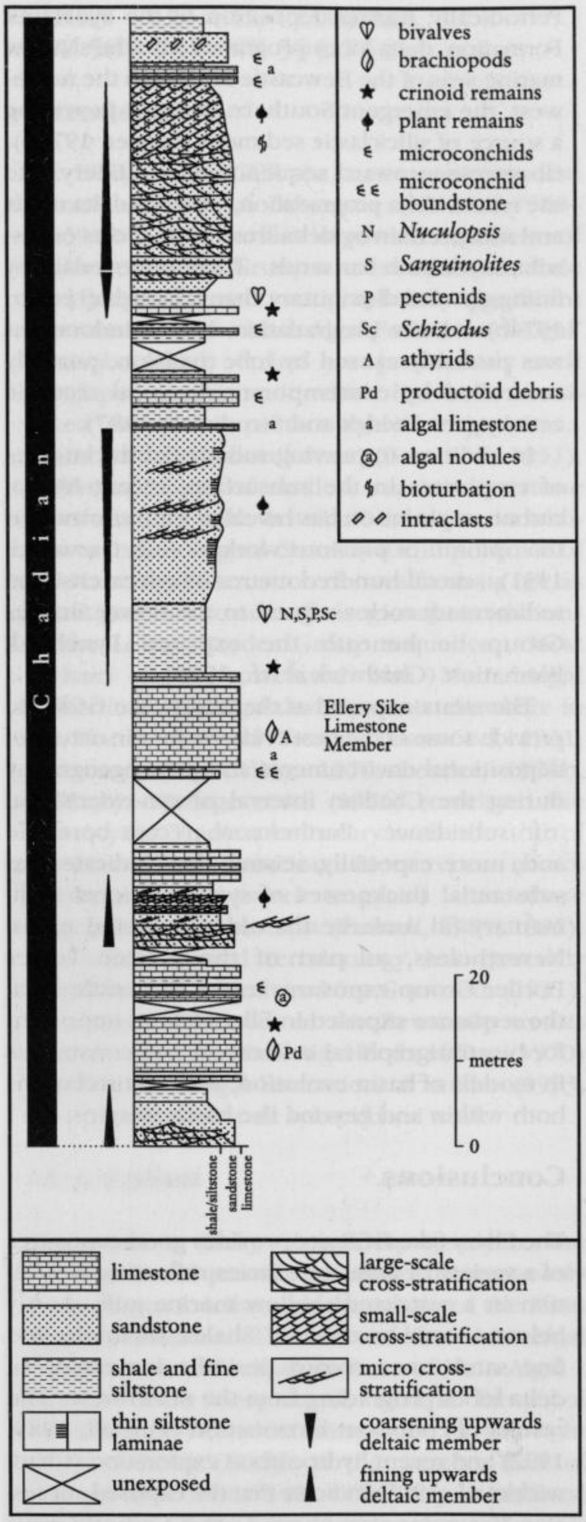


Figure 3.10 Sedimentary log of the Lynebank Formation (Lower Border Group) at Ellery Sike. After Leeder (1974b).

Interpretation

The geological context of the strata in Ellery Sike (i.e. in the core of the Bewcastle Anticline) provides good evidence that they are the oldest beds in the area (Garwood, 1931), but their age and correlation with Lower Carboniferous strata elsewhere, both within the Northumberland Trough and beyond, have been the subject of long debate.

In his earlier work, Garwood (1913) included notes on the preliminary zonal position of the beds in the Northumberland Trough. Later, however, the coral–brachiopod zonation scheme he established for the Lower Carboniferous strata in the Ravenstonedale area to the south (Garwood, 1913) was applied to the Bewcastle sequence (Garwood, 1931). Garwood (1931) did not discuss the position of the Z_2–C_1 boundary, but recorded what he took to be a Z_2 fauna only from the lowermost 100 m of the Lynebank Formation. Subsequent workers essentially followed Garwood's age assignment of the Lynebank Formation (e.g. Rayner, 1953; George, 1958). Ramsbottom (in Day, 1970), however, noted that the zonal position of Lower Border Group strata below the Cambeck Formation

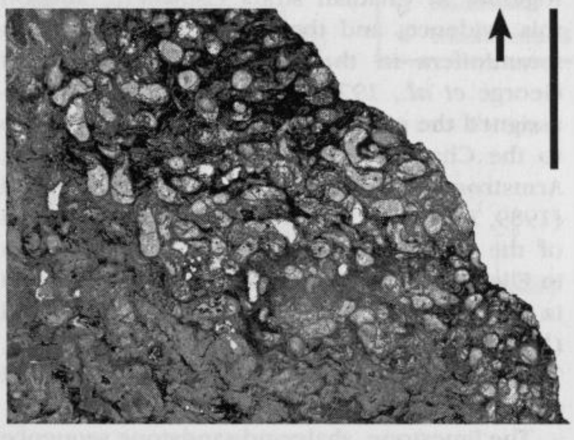


Figure 3.11 Stained acetate peel of tentaculitoid microconchid ('vermetid gastropod' or 'serpulid') boundstone from the lower part of the Lynebank Formation at Ellery Sike. Note the framework of encrusting spar-filled microconchid tubes and the spaces between the organic framework filled with micritic sediment. An arrow symbol indicates the sedimentary 'way up' of the specimen. Sample obtained from the thin limestone immediately below the Ellery Sike Limestone Member illustrated in Figure 3.10. Scale bar = 1 cm. (Photo: M.A. Purnell.)

could not be conclusively demonstrated; he assigned them to the C_1 Zone because the large thickness of rock (730 m) that contains an ostracode fauna 'essentially of Tournaisian type' (Robinson in Day, 1970) lies below beds of demonstrable C_2 age. Leeder (1971, 1974b, 1975a,b) followed the correlations of Day (1970).

Ramsbottom (1973) positioned his cycle boundaries in the sequence on lithological criteria, but in the Northumberland Trough he followed previous authors in his placement of the Tournaisian–Viséan boundary (which he took to lie within the C_1 Zone). George *et al.* (1976) noted the paucity of confirmatory palaeontological evidence for the recognition of cycle boundaries within the Northumberland Trough, but in the absence of other information took cycle boundaries as convenient datum lines for the correlation of Dinantian stages. In addition to ostracode faunas, foraminifera in the lowest limestone of the Lynebank Formation were cited by George *et al.* (1976) as further evidence that these beds were of Courceyan age. Later, Ramsbottom (1977a) reported the discovery of conodonts identified as *Mestognathus beckmanni* and *Polygnathus bischoffi* in the basal limestone of the Lynebank Formation in Ellery Sike. These conodonts are known to occur together in Chadian strata elsewhere, and on this evidence, and the occurrence of Chadian foraminifera in the same limestone (*contra* George *et al.*, 1976), Ramsbottom (1977a) re-assigned the whole of the Lower Border Group to the Chadian Stage (Viséan). Subsequently, Armstrong and Purnell (1987) and Purnell (1989, 1992) conducted a more detailed analysis of the conodonts in the Lynebank Formation in Ellery Sike. The occurrence of *M. beckmanni* in the lowest limestone was not confirmed (Purnell, 1989, 1992, *contra* Ramsbottom, 1977a) but the conodont fauna obtained provided strong evidence of a Chadian age.

The limestone, shale and sandstone sequence of the Lynebank Formation in Ellery Sike reflects the interplay of shallow-marine and deltaic depositional systems. The limestones were deposited in a range of shallow shelf environments including intertidal or shallow subtidal, and moderately to slightly restricted subtidal, below fair-weather wave-base. Brecciated horizons occur within the Lynebank Formation and these are probably collapse breccias, resulting from dissolution of evaporites encountered only in the subsurface (Ward in Chadwick *et al.*, 1993a, 1995). Periodically, during deposition of the Lynebank Formation, delta lobes prograded into the shallow marine seas of the Bewcastle area from the north-west, the emergent Southern Uplands providing a source of siliciclastic sediment (Leeder, 1974b). Coarsening-upward sequences at the Ellery Sike site record delta progradation, with pro-delta muds and silts overlain by delta-front sand-sheets or distributary mouth bar sands. These are overlain by fining-upward distributary channel sands (Leeder, 1974b). Delta progradation and abandonment was probably caused by lobe avulsion, possibly controlled by contemporaneous local tectonic activity (see Leeder and Strudwick, 1987).

In addition to proving substantial thicknesses of evaporites in the subsurface, recent hydrocarbon exploration has revealed that, contrary to the opinion of previous workers (e.g. Garwood, 1931), several hundred metres of syn-extensional sedimentary rock assigned to the Lower Border Group lie beneath the exposed Lynebank Formation (Chadwick *et al.*, 1995).

The strata exposed at the Ellery Sike GCR site provide some of the best evidence for the nature of depositional environments and palaeogeography during the Chadian interval of syn-extensional 'rift' subsidence. Furthermore, recent borehole and, more especially, seismic data indicate that substantial thicknesses of syn-extensional sedimentary fill underlie the oldest exposed rocks. Nevertheless, as part of the marine Lower Border Group exposures in the Bewcastle area, the sequence exposed in Ellery Sike is important for biostratigraphical calibration and constraints in models of basin evolution, and in correlations both within and beyond the basin margins.

Conclusions

The Ellery Sike GCR site provides good exposures of a variety of limestone facies reflecting deposition in a restricted shallow marine gulf, mostly below normal wave-base. Shales, siltstones and fine sandstones record periodic incursions of delta lobes prograding from the north-west. The results of conodont biozonation (Purnell, 1989, 1992) and recent hydrocarbon exploration (Chadwick *et al.*, 1995) indicate that the exposed succession lies some way above Lower Carboniferous base in the Bewcastle area, where it is of considerable importance to regional biostratigraphical and chronostratigraphical correlations, and in reconstructions of the early Carboniferous palaeogeography of the Northumberland Trough.

BIRKY CLEUGH, CUMBRIA (NY 589 754–NY 594 754)

Introduction

The Birky Cleugh GCR site, a stream section less than 2 km east of Bewcastle (NY 5885 7540–NY 5943 7540), provides important exposures of the Lower Border Group succession that include the exceptional and stratigraphically significant type section of the Main Algal Formation. 'Algal' (cyanobacterial) facies are particularly well developed in this unit which has been considered 'the most important algal development ... in the British Carboniferous' (Garwood, 1931). A diverse range of shallow marine limestone facies alternate with deltaic siliciclastics. In addition to its lithological diversity the importance of the Main Algal Formation derives from its use as a stratigraphical marker for regional correlations of the Lower Border Group sequence. Most authors have correlated the Main Algal Formation with algal developments elsewhere in the Northumberland Trough (Garwood, 1931; Anderson, 1950; Day, 1970; Leeder, 1974b, 1975a,b). George *et al.* (1976) correlated the Courceyan–Chadian boundary with the top of the Main Algal Formation. More recent micropalaeontological work suggests that these correlations are incorrect (Purnell, 1989, 1992). Lithostratigraphical terminology has generally followed that introduced by Garwood (1931). His Main Algal Series in the Bewcastle area is equivalent to the Main Algal Beds of Day (1970) and the Main Algal Formation of Leeder (1973, 1974b) and almost all subsequent work.

Description

The strata in Birky Cleugh dip gently to the north-east and provide an almost continuously exposed section through the whole of the Main Algal Formation. The base of the Main Algal Formation is defined at the base of Main Algal 1 Member (the 'Serpula cf. advena Band' of Garwood, 1931) which crops out in the right bank of Birky Cleugh at the western end of the site (NY 5885 7540). The top is defined at the base of the Lower Antiquatonia Member of the overlying Cambeck Formation which rests on the Main Algal 14 Member towards the eastern end of the site (NY 5932 7538) (Figure 3.4). Above this, the Barron's Pike Sandstone Member crops out (NY 5946 7542). Altogether, approximately 30 m of the lower part of the Cambeck Formation are also exposed.

In Birky Cleugh the Main Algal Formation comprises 85 m of alternating sandstone, silty shale and limestone. Within this sequence, Day (1970) recognized 14 algal limestone units ('Main Algal 1' to 'Main Algal 14'), the lowest of which is illustrated in Figure 3.12, but Leeder (1974b, 1975a) divided the sequence into seven carbonate–clastic cycles. The siliciclastic components of Leeder's cycles (1974b, 1975a) vary in thickness up to 4 m. They are dominated by coarsening-upward sequences of silty shales and fine sandstones; some are sharp based with small-scale cross-stratification, others are distinguished by having a marine aspect to the basal shales. Approximately 10% of the Main Algal Formation in Birky Cleugh comprises coarse, erosive-based, cross-stratified, fining-upward

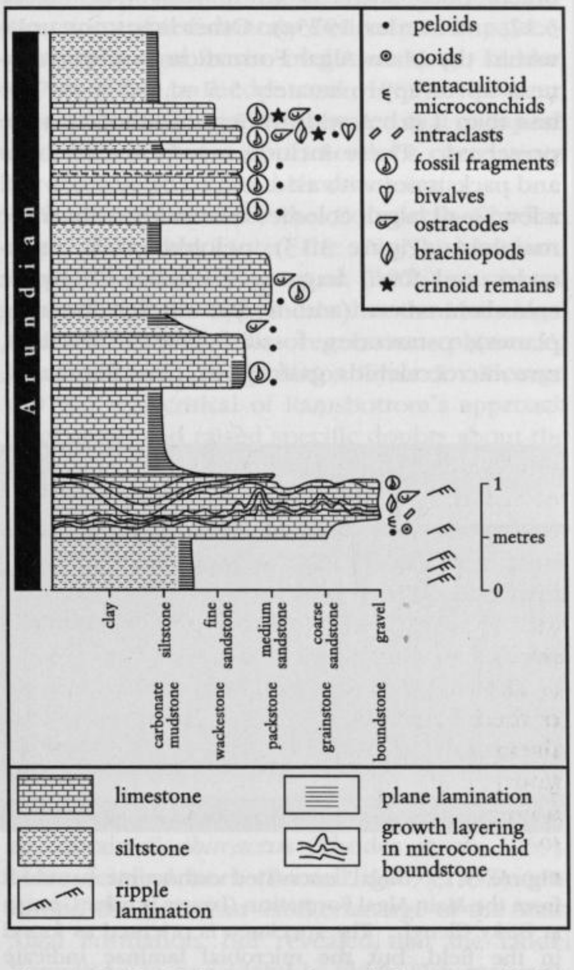


Figure 3.12 Sedimentary log of the Main Algal 1 Member of the Main Algal Formation (Lower Border Group) at Birky Cleugh.

sandstone units (Leeder, 1974b). A few thin shaly coals occur, and plant fragments and rootlets are also common, especially towards the tops of cycles. Other fossils include bivalves and ostracodes.

The limestones are of particular importance because of the diversity of facies represented. The limestone at the base of the Main Algal 1 Member, for example, (see Figure 3.12) grades upwards from a thin faintly ripple cross-laminated grainstone with peloids, ooids and intraclasts into 25–50 cm of boundstone and bafflestone containing abundant tentaculitoid microconchids (formerly vermiform 'gastropods'; see Weedon, 1991). This microconchid bioherm is overlain by a well-bedded, 3.5 m-thick sequence of unfossiliferous shaly lime mudstone, alternating with wackestones and packstones with ostracodes and peloids, undifferentiated fossil fragments and, towards the top, bivalves, brachiopods and crinoid remains (see Figure 3.12; and Leeder, 1975a). Other limestone units within the Main Algal Formation vary in thickness up to approximately 5.5 m, but many are less than 1 m. A wide variety of lithofacies are preserved. These include mostly wackestones and packstones with associations of: oncoids and a few small 'algal' colonies encrusting orthoconic nautiloids (Figure 3.13); peloids, ooids, ostracodes and fossil fragments, often with ripple cross-lamination (and a few rippled bedding planes); ostracodes, fossil fragments, bivalves, rare microconchids, gastropods, plant fragments,

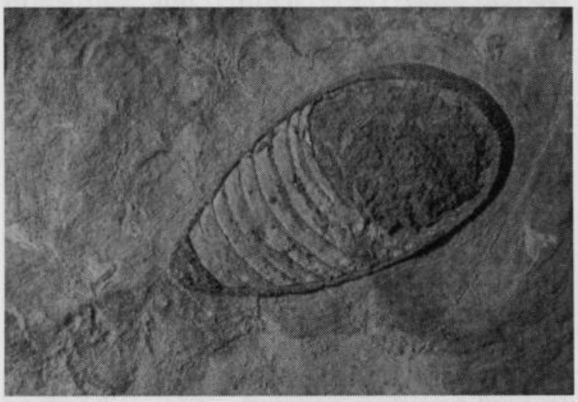


Figure 3.13 'Algal' encrusted orthoconic nautiloid from the Main Algal Formation (Lower Border Group) at Birky Cleugh. The specimen is oriented as found in the field, but the microbial laminae indicate that the orientation of the nautiloid varied during encrustation. The long axis of the section through the nautiloid is 6 cm. (Photo: M.A. Purnell.)

intraclasts and lingulids; crinoid remains, fossil fragments, ostracodes and some bivalves; brachiopod and crinoid remains, commonly with fossil fragments and ostracodes. Carbonate facies are described in more detail by Leeder (1973, 1975a) and Purnell (1989); microconchid bioherms and oncoids from the Main Algal Formation are discussed by Leeder (1973) and Riding (1983) respectively.

The fossil flora of the Main Algal Formation in Birky Cleugh is dominated by 'algae', and Day (1970) lists 13 species from this locality. The fauna, however, is rather limited: brachiopods include *Antiquatonia teres*, *Lingula* cf. *mytilloides*, *Orbiculoidea nitida* and *Ovatia bioni*; bivalves include *Modiolus*, *Phestia attenuata*, *Pteronites latus* and *Sanguinolites striatus*; ostracodes include *Cavellina* cf. *longula*, and new species of *Glyptopleura* and *Knoxiella*; and the nautiloid *Dolorthoceras* is also known (Day, 1970). The limestones yield a low-diversity conodont fauna of *Cavusgnathus unicornis*, *Vogelgnathus kyphus*, *Hindeodus crassidentatus* and *Synclydagnathus* (Purnell, 1992). Birky Cleugh is the type locality for the Birky Cleugh Limestone Member and for *V. kyphus* (Purnell and von Bitter, 1992). The paratypes of the 'algae' *Ortonella kershopensis* and *Girvanella staminea* (forms now regarded as cyanobacteria – R. Riding, pers. comm., 1999) also derive from this locality (Garwood, 1931).

Towards the top of the section the Lower Antiquatonia Member is represented by more than 20 m of silty shales, mostly calcareous and fossiliferous, with thin limestones. The limestones are generally thin packstones less than 5 cm thick with very abundant brachiopods, brachiopod debris (including spines), crinoid debris and ostracodes, together with less common bivalves, rare bryozoans and echinoid spines. The thickness of these packstones varies laterally, with a few reaching 20 cm or more. A couple of wackestone units within the sequence are approximately 1 m thick. The shales contain a similar brachiopod-dominated fauna and the sequence contains a few traces of ripple cross-lamination. The fauna of the Lower Antiquatonia Member is dominated by brachiopods, including *Antiquatonia teres*, '*Camarotoechia*' *fawcettensis*, *Ovatia bioni* and spiriferoids. Some paratype material of *Schuchertella ambigua* Garwood (1931) is also from this unit. Day (1970) includes a more complete faunal listing.

In Birky Cleugh the Barron's Pike Sandstone Member is also exposed. It comprises about 3 m of fine- to medium-grained planar-bedded sandstone with ripple cross-lamination and plant fragments.

Interpretation

The position of the Main Algal Formation in Birky Cleugh within the Lower Carboniferous sequence of the Bewcastle area is well constrained on lithostratigraphical evidence. However, the Main Algal Formation has been pivotal in the development of broader lithostratigraphical schemes within the Northumberland Trough, and in the application of chronostratigraphical subdivisions and biozonations. Because Birky Cleugh is the type section of the Main Algal Formation all correlations of this unit are implicitly correlations of the Birky Cleugh section.

Garwood (1931) included the algal limestones of the Newcastleton area to the north of Bewcastle in his 'Main Algal Series', but correlated algal developments elsewhere in the Northumberland Trough with an algal horizon near the top of the Cambeck Formation (see **Whitberry Burn** GCR site report, this chapter). Anderson (1950), however, correlated the Main Algal Formation of Bewcastle and Newcastleton with the algal horizons developed in the Kershopefoot, Kielder, upper Redesdale and Rothbury areas, thus providing a stratigraphical datum linking the Lower Border Group sections in northern Cumbria with Cementstone Group sections to the north and east. Day (1970) supported and re-inforced this correlation, but noted some faunal differences. For example, Robinson (in Day, 1970) indicated that ostracode assemblages from the Orbiculoidea Shale in Birky Cleugh lacked many of the species found in the Main Algal Formation in the Newcastleton area. Ramsbottom (in Day, 1970) conceded that the zonal position of the beds below the Cambeck Formation could not be determined with any confidence, but concluded that all the Lower Border Group below the Cambeck Formation, including the Main Algal Formation, was of Tournaisian (C_1) age. Later he interpreted the Main Algal Formation and the algal limestones of Rothbury as the regressive phase of his Major Cycle 1, and thus correlated them with other algal and 'regressive facies' in areas as distant as Bristol and Ireland (Ramsbottom, 1973). He equated this level approximately with the Tournaisian–Viséan boundary. Gueinn (in Neves *et al.*, 1972) indicated that samples from the Main Algal Formation in the Bewcastle area contain a Pu Zone miospore assemblage (see Figure 1.4, Chapter 1), but did not state whether the samples were from Birky Cleugh. Neves *et al.* (1972) used this occurrence of Pu Zone assemblages, in strata assigned a C_1 age by Day (1970), to correlate their miospore zones with macrofaunal biozonations.

Leeder (1974a,b, 1975a,b) introduced a more refined lithostratigraphical scheme for outcrops around Langholm and Newcastleton, erecting the Liddel Formation for the algal limestones in the Newcastleton area. Leeder (1974b) also maintained the correlation of these rocks and the overlying Harden Member with the Main Algal Formation and Lower Antiquatonia Member. This correlation provided the stratigraphical underpinning of his detailed reconstructions of sedimentary environments, palaeogeography and basin evolution (e.g. Leeder, 1974b, 1975a,b; Leeder *et al.*, 1989). However, Gueinn (in Leeder, 1974b), noted that miospore evidence did not support Leeder's correlations between Bewcastle and Newcastleton.

The correlation of the Courceyan–Chadian stage boundary into the Northumberland Trough area by George *et al.* (1976) was based primarily on the hypothesis that the Main Algal Formation was the regressive phase of Ramsbottom's (1973) Major Cycle 1. George (1978a) was critical of Ramsbottom's approach in general, and raised specific doubts about the validity of correlating the Main Algal Formation and the Rothbury Limestones to the east 'merely because they are algal' (George, 1978a). Armstrong and Purnell (1987), in their preliminary conodont biozonation of the Northumberland Trough, indicated that the age of the Main Algal Formation in Birky Cleugh was younger than previously thought (Arundian–Holkerian, not Courceyan or Chadian). However, the presence of *Cavusgnathus unicornis* appeared to support correlations with the Liddel Formation, which had been reported to contain *C. charactus* (Rhodes *et al.*, 1969). More detailed work (Purnell, 1989, 1992) confirmed the Arundian–Holkerian age of the Main Algal Formation, but revealed that the Liddel Formation is considerably older (Tournaisian). This has significant implications for models of Northumberland Trough palaeogeography, depositional history and basin evolution which rely on the time equivalence of these two formations.

The siliciclastic facies exposed in Birky Cleugh preserve the deposits of deltas that periodically prograded down the axis of the trough from the east (Leeder, 1974b). Different styles of coarsening-upward cycles represent delta progradation, interdistributary bay fills, back-swamp levees and channel fills. Fining-upward sequences represent channel sand-bodies (Leeder, 1974b). The limestone facies reflect deposition under conditions ranging from inter-tidal or very shallow subtidal high-energy agitated conditions, within fair-weather wave-base (probably less than 4–6 m) through to more open marine, shallow subtidal settings, generally below fair-weather wave-base, but subject to periodic storm agitation. The Lower Antiquatonia Member represents the thickest development of limestones from these more open marine settings, but even in this unit, the relatively impoverished fauna suggests conditions were not fully marine. The Main Algal 1 Member and its overlying clastic sequence in Birky Cleugh has been the subject of especially detailed sedimentological analysis (Leeder, 1974b; Leeder and Strudwick, 1987). A deepening-upward trend in the carbonate unit was used by Leeder and Strudwick (1987) as an example of their tectono-sedimentary model of Yoredale-type cyclicity.

The Main Algal Formation in its type locality in Birky Cleugh provides some of the best evidence of palaeogeography and the diverse depositional environments established in the Northumberland Trough during the Arundian–Holkerian phase of syn-extensional 'rift' subsidence. This is the type locality of several macrofossils and microfossils, and the exposed strata are also important because of their pivotal role in the development of lithostratigraphical and biostratigraphical correlations within the trough area and beyond.

Conclusions

The Birky Cleugh GCR site offers outstanding exposure of a diverse range of shallow marine limestones, including important and unusual algal and microconchid patch reefs. These alternate with a clastic lithofacies deposited by delta lobes which prograded periodically down the axis of the Northumberland Trough from a source to the east. The chief importance of the site derives from its status as the type locality of the Main Algal Formation. The succession has been central to the development of lithological classification as well as to the correlation of Lower Carboniferous rocks across the Northumberland Trough. It also provides an important insight into the changing depositional environments and palaeogeography of northern England during the Arundian and Holkerian ages. Furthermore, the unusual limestone lithofacies include what has been considered to be among the most important British Carboniferous algal developments.

WHITBERRY BURN, CUMBRIA (NY 523 740–NY 519 741)

Introduction

Located approximately 4 km west of Bewcastle, the Whitberry Burn GCR site (NY 5226 7404–NY 5194 7408), provides an outstanding section that extends from the upper part of the Main Algal Formation through the Cambeck Formation and into the lower strata of the overlying Middle Border Group (all within the Holkerian Stage). The site provides the most complete section through the Cambeck Formation, the uppermost formation of the Lower Border Group. It also provides important sections of the Barron's Pike Sandstone Member, Syringothyris Limestone Member, Hillend Algal Member, and Whitberry Member (type locality). These horizons have featured in local and regional correlations of the Lower Border Group and in the application of chronostratigraphical stages to the Bewcastle sequence (Garwood, 1931; Lumsden, 1967a; Day, 1970; Ramsbottom, 1973; George *et al.*, 1976).

Description

The Whitberry Burn succession (see Figure 3.14) lies on the western limb of the Bewcastle Anticline and dips steeply to the WNW (Day, 1970). The oldest bed exposed within the site is the Main Algal 12 Member, which crops out at the eastern boundary. Above this, exposure of the upper part of the Main Algal Formation and the lower part of the Cambeck Formation is poor, with approximately 40 m of section unexposed, including the lower third of the Barron's

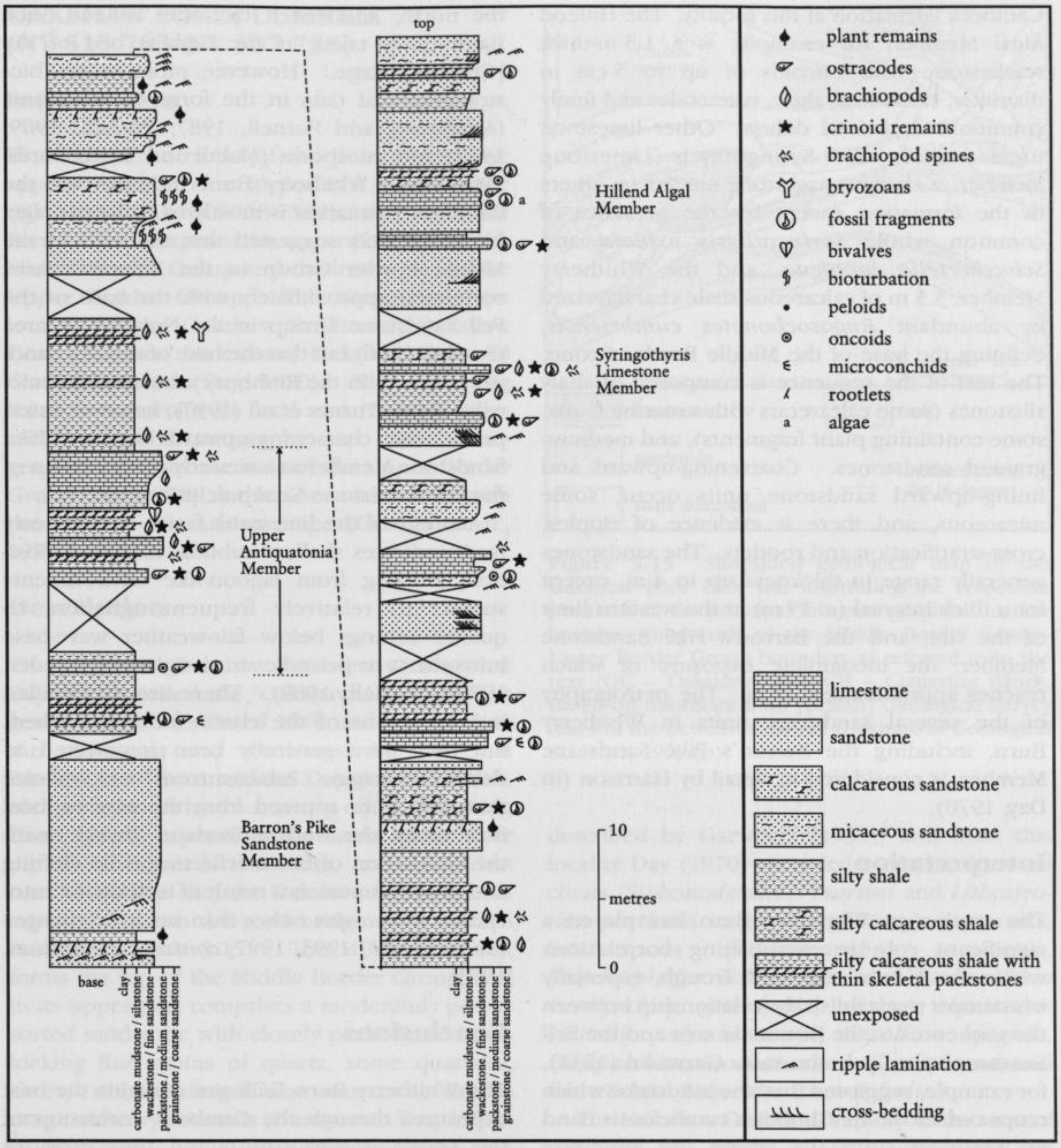


Figure 3.14 Sedimentary log of the Cambeck Formation (Lower Border Group) at Whitberry Burn extending from the Barron's Pike Sandstone Member to the Hillend Algal Member.

Pike Sandstone Member. The remaining 165 m of the Cambeck Formation and 131 m of the Middle Border Group comprise alternations of limestone, sandstone and shaly siltstone (Day, 1970). Limestones are mostly wackestones and packstones with brachiopods, crinoids, fossil fragments and ostracodes in variable proportions. Some of the limestones yield faunas dominated by bivalves (Day, 1970). The Upper Antiquatonia Member is lithologically similar to the underlying Lower Antiquatonia Member (see **Birky Cleugh** GCR site report, this chapter), being composed of alternations of shaly siltstones and limestones, the latter mostly wackestones and packstones dominated by brachiopod and crinoid remains. Individual limestone units within the member are up to 4 m thick. A few algal horizons are also known within the

Cambeck Formation at this locality. The Hillend Algal Member, for example, is a 1.5 m-thick wackestone with oncoids of up to 5 cm in diameter, calcareous algae, ostracodes and finely comminuted skeletal debris. Other limestone units include the Syringothyris Limestone Member, a skeletal packstone similar to others in the formation except for the presence of common whole *Syringothyris exoleta* and *Schuchertella ambigua*, and the Whitberry Member, 3.5 m of calcareous shale characterized by abundant *Rugosochonetes cumbriensis*, defining the base of the Middle Border Group. The rest of the sequence is composed of shaly siltstones (some calcareous with a marine fauna, some containing plant fragments), and medium-grained sandstones. Coarsening-upward and fining-upward sandstone units occur, some micaceous, and there is evidence of ripples, cross-stratification and rootlets. The sandstones generally range in thickness up to 4 m, except for a thick interval (*c.* 35 m) at the western limit of the site, and the Barron's Pike Sandstone Member, the incomplete exposure of which reaches approximately 15 m. The petrography of the several sandstone units in Whitberry Burn, including the Barron's Pike Sandstone Member, is considered in detail by Harrison (in Day, 1970).

Interpretation

The section in Whitberry Burn has played a significant role in establishing correlations within the Northumberland Trough, especially in attempts to establish the relationship between the sequences in the Bewcastle area and the Fell Sandstone Group to the east. Garwood (1931), for example, suggested that 'the sandstone which crops out above the Chonetes cumbriensis Band in Whitberry Burn [i.e. above the Whitberry Member] may represent the Fell Sandstone', and correlated the Hillend Algal Member with algal horizons in the Kershopefoot, Coomsden Burn (Redesdale), Kielder and Rothbury areas. Lumsden *et al.* (1967) correlated the Syringothyris Limestone Member with the Harden Member in the Newcastleton area. Ramsbottom (1973) took the Hillend Algal Member as the top of his Major Cycle 2 regression. Following this, George *et al.* (1976) correlated the Cambeck Formation with the Southerness Limestone Formation to the west (see **Kirkbean** GCR site report, this chapter) and the Harden Member to the north, and stated that the 'Hillend Algal Band ... is taken as the highest bed of the [Chadian] stage.' However, more recent biostratigraphical data in the form of conodonts (Armstrong and Purnell, 1987; Purnell, 1989, 1992) and miospores (Mahdi and Butterworth, 1994) from Whitberry Burn indicate that the Cambeck Formation is mostly of Holkerian age. Purnell (1989) suggested that the base of the Middle Border Group in the Bewcastle area correlated approximately with the base of the Fell Sandstone Group in the North Tyne area (Fowler, 1966) but that the base of the Fell Sandstone Group in the Rothbury area may be somewhat older. Turner *et al.* (1997), however, interpreted the coarsening-upward Barron's Pike Sandstone Member as a westerly progradation of the Fell Sandstone Group delta system.

Analysis of the limestone facies in Whitberry Burn indicates shallow subtidal marine deposition, ranging from lagoon-like environments subject to relatively frequent agitation, to quieter settings below fair-weather wave-base but subject to periodic storm agitation (Leeder, 1975b; Purnell, 1989). There are no detailed interpretations of the clastic facies published, but they have generally been interpreted as deltaic in origin. Palaeocurrent data indicate that they were sourced from the east by axial flow along the Northumberland Trough, with the alternation of facies reflecting delta shifting and abandonment as a result of tectonic or autocyclic mechanisms rather than sea-level changes (Turner *et al.*, 1993, 1997; *contra* Ramsbottom, 1973).

Conclusions

The Whitberry Burn GCR site contains the best exposures through the Cambeck Formation of the Lower Border Group and thus provides important data for lithostratigraphical and biostratigraphical correlation, and for the interpretation of the palaeogeography, depositional environments and evolution of the Northumberland Trough during the Holkerian Age. As the type section of the Whitberry Member, the base of the Middle Border Group is defined in the Whitberry Burn sequence. Furthermore, several other marker horizons crop out that have been of critical importance in the development of lithostratigraphical schemes and sedimentological models within the Northumberland Trough.

OAKSHAW FORD, CUMBRIA (NY 513 763–NY 507 758)

Introduction

Situated on the banks of the River Black Lyne approximately 2.5 km to the west of Bewcastle (NY 5130 7630–NY 5068 7582), the Oakshaw Ford GCR site exposes the uppermost unit of the Middle Border Group and the lower part of the Upper Border Group. The site is the type locality for the Oakshaw Sandstone, Oakshaw Coal, Oakshaw Limestone, Oakshaw Tuff and Clattering Band (Day, 1970). The Clattering Band is important in local and regional lithostratigraphy, biostratigraphy and chronostratigraphy; it defines the base of the Upper Border Group (Day, 1970), and has been correlated with the base of the Asbian Stage (George *et al.*, 1976).

Description

The section at Oakshaw Ford lies within what Day (1970) called the 'Oakshaw Coal Basin', a gentle syncline oriented NNE and bounded to the south-east and south-west by the Goat Island–Lyne Thrust and the Dappleymore Fault, and to the north by the outcrop of the Clattering Band. Strata exposed in the banks of the river dip 5°–10° towards the south, and the oldest unit within the site, the Oakshaw Sandstone, is exposed beneath the road bridge at its eastern end (see Figure 3.15). This 40 m-thick unit forms the top of the Middle Border Group, and in its upper part comprises a moderately poorly sorted sandstone with closely packed and interlocking fine grains of quartz, some quartzite, cherty silica, intergranular muscovite and a range of heavy minerals (Harrison in Day, 1970). Downstream of this sandstone, the river cuts through a thin shale and is successively followed by the Clattering Band (1.7 m), about 6 m of shale with thin shaly limestones and unexposed strata, the Oakshaw Coal (0.6 m) and the Oakshaw Limestone (7 m). The river then cuts back and runs along-strike before once again exposing a section through the Oakshaw Coal, Oakshaw Limestone and Oakshaw Tuff, which is exposed towards the western, downstream limit of the site (see Figure 3.15).

The Clattering Band is made up of approximately 170 cm of fossiliferous calcareous shale and shaly limestone. The fossils were briefly

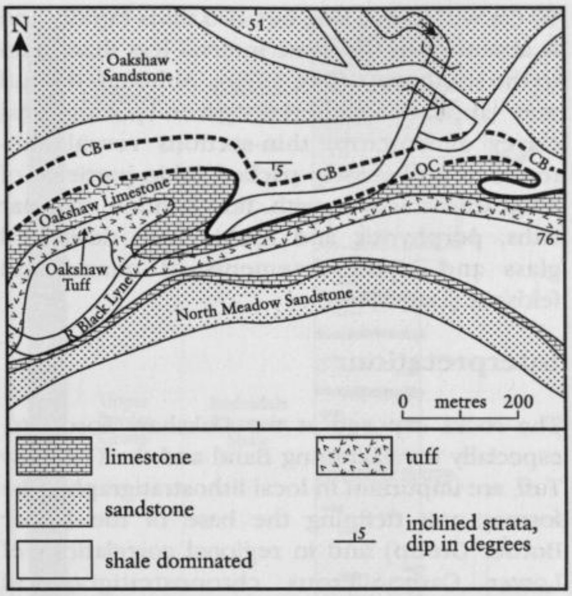


Figure 3.15 Simplified geological map of the Oakshaw Ford GCR site illustrating the respective positions of the principal lithostratigraphical marker horizons either side of the Middle Border Group–Upper Border Group boundary as referred to in the text (OC – Oakshaw Coal; CB – Clattering Band). Based on information on [British] Geological Survey maps of the Bewcastle district (Institute of Geological Sciences, 1969a,b).

described by Garwood (1931), and from this locality Day (1970) recorded a diverse fauna of corals (***Siphonodendron martini*** and ***Lithostrotion portlocki*** in growth position), bryozoans, brachiopods (***Echinoconchus punctatus***, ***Punctospirifer scabricosta*** and ***Stenoscisma isorhyncha***), gastropods, bivalves, ostracodes (***Bairdia submucronata***, ***Cavellina longula***, ***Paraparchites inornatus*** and ***Glyptopleura***) and the trilobite ***Weberides*** (now ***Paladin***).

The Oakshaw Coal thins rapidly to the west of the ford and grades laterally into coaly and carbonaceous fireclay. Although it is of poor quality, with a high ash content, it was worked for household fuel until as recently as 1949 (Day, 1970). Coals of this age in the Northumberland Trough represent the oldest worked thick coals in the European Carboniferous succession.

A thin shale separates the Oakshaw Coal from the overlying Oakshaw Limestone (see Figure 3.15). The latter unit comprises bedded limestone with shaly partings and hard laminated calcareous shales (Day, 1970). These pass upward into the Oakshaw Tuff, which reaches its maximum exposed thickness of approximately

90 cm within this site, but also thins rapidly and is absent from the same interval less than 2 km to the south-west (Day, 1970). Although the tuff may appear weathered, green-looking and clayey at outcrop, thin-sections reveal sub-rounded and closely packed lithic particles of mugearite–trachyte with flow-banded feldspar laths, porphyritic and felsitic lava, devitrified glass and crystal fragments of quartz and feldspar (Day, 1970).

Interpretation

The rocks exposed at the Oakshaw Ford site, especially the Clattering Band and the Oakshaw Tuff, are important in local lithostratigraphy (the former unit defining the base of the Upper Border Group) and in regional correlations of Lower Carboniferous chronostratigraphical stages across the Northumberland Trough. Day (1970) originally established the correlation of the Clattering Band with a horizon within the Glencartholm Volcanic Beds in the Archerbeck Borehole, a view later supported by George *et al.* (1976) who, on the basis of foraminiferal evidence, took this horizon to mark the base of the Asbian Stage. Based on its position in the sequence, Day (1970) interpreted the Oakshaw Tuff as the attenuated lateral equivalent of the Glencartholm Volcanic Beds of the River Esk to the west. The lithic fragments of the tuff do not correspond to any of the local contemporaneous volcanic rocks of the area, but the occurrence of similar fragments in the Glencartholm Volcanic Beds of the Archerbeck Borehole (Day, 1970) appear to support their correlations. Of the macrofossils identified by Day (1970) in the Clattering Band at Oakshaw Ford, *Siphonodendron martini*, *Lithostrotion portlocki* and *Punctospirifer scabricosta* are also consistent with an Asbian age, according to the stratigraphical ranges of taxa indicated by Riley (1993). However, the presence of *Echinoconchus punctatus* and *Stenoscisma isorhyncha* (if identified correctly), conflict with this, as both are (according to Riley, 1993) of Arundian age.

Day (1970) noted a number of difficulties in the lithostratigraphical correlation of Upper Border Group strata over relatively short distances. Although little detailed sedimentological work has been carried out on these beds, Leeder *et al.* (1989) indicated that the Upper Border Group sedimentation in the Bewcastle area was tectonically controlled, and this may account for apparent rapid lateral facies changes and concomitant lithostratigraphical correlation problems noted by Day (1970). Palaeocurrent data show that the dominant flow direction was towards the south-west, with multistorey sand-bodies built by graben-fed, axial fluvial channels, separated by interbedded floodplain, back-swamp and bay facies comprising mudrocks, silt-stones, some coal and discontinuous limestones (Leeder *et al.*, 1989). This interpretation accords well with the sequence exposed at the Oakshaw Ford site.

Conclusions

The Oakshaw Ford GCR site provides the critical reference section for the Clattering Band, the Oakshaw Sandstone, the Oakshaw Coal, the Oakshaw Limestone and the Oakshaw Tuff. The Clattering Band defines the base of the Upper Border Group, the base of which is thus also defined at this site. The Clattering Band and the Oakshaw Tuff are of considerable importance in understanding the lithostratigraphy of the Bewcastle succession and are critical for the correlation of Asbian successions within the Northumberland Trough.

REDESDALE IRONSTONE QUARRY, NORTHUMBERLAND (NY 897 830)

Introduction

Located 6 km east of Bellingham, in the heart of the Northumberland Basin, the Redesdale Ironstone Quarry GCR site (NY 8965 8295) provides an outstanding section through the highly fossiliferous Redesdale Ironstone Shale and the overlying Redesdale Limestone, one of the finest mid-Asbian sections in northern England. The Redesdale Limestone is taken locally as the boundary between the Upper Border Group and overlying Lower Liddesdale Group, and its development marks the onset of Yoredale cyclicity in the North Tyne area. The site has an international reputation for the rich diversity and fine preservation of its fossils, and is of critical importance to the correlation of Asbian successions throughout the Northumberland Basin. Early descriptions of the Redesdale succession are provided by Lebour (1873) and Smith, S. (1910) who added a substantial amount of palaeontological detail. Further information on the Redesdale Limestone is provided by Frost (1969), while a comprehensive account of the Redesdale Ironstone Shale is given by Hemingway (1972). Specific locality details are best described by Frost and Holliday (1980).

Description

The site forms part of a complex of old workings which last saw active service during the 19th century when the Redesdale area was a thriving centre for the extraction of ironstone. Outcrops are confined to the eastern side of the site, with the best sections occurring towards the centre of the quarry face. A summary log of the succession is presented in Figure 3.16.

The Redesdale Ironstone Shale consists of a 9 m-thick sequence of shale with scattered nodules of concretionary ironstone (siderite). The elongate nodules range in size up to 35 cm and weigh up to 23 kg. Laterally, some nodules coalesce to form irregular ironstone layers but the combined thickness of ironstone is less than 10% of the unit. Details of the petrography and petrogenesis of the ironstones are provided by Hemingway (1972). The unit is extremely fossiliferous and celebrated for the fine preservation of its faunas. Common elements of the fauna include brachiopods, bivalves, crinoids and bryozoans, but other groups, including possible algae, foraminifera, sponges, conularids, serpulids, gastropods, nautiloids, goniatites, ostracodes, trilobites, palaeoniscid and bradyodont fish are also represented. Well-preserved wood fragments in carbonaceous bands have also been reported, but corals, phyllocarids and echinoids are rare.

Although fossils occur throughout the unit, they are more commonly found concentrated in thin shell layers. Occasionally they are found in the ironstones. A distinctive ferruginous shelly limestone, typically less than 25 cm thick and known as the 'Shell Band', occurs towards the middle of the sequence. This band, originally used by miners to subdivide the ironstone beds into lower and upper units (Hemingway, 1972), was discarded during mining operations on account of its high lime content and consigned to the spoil tips where it can still be found today. Three other fossiliferous horizons, each no more than 5 cm thick, occur in the 50 cm of shale immediately overlying this band (Hemingway, 1972).

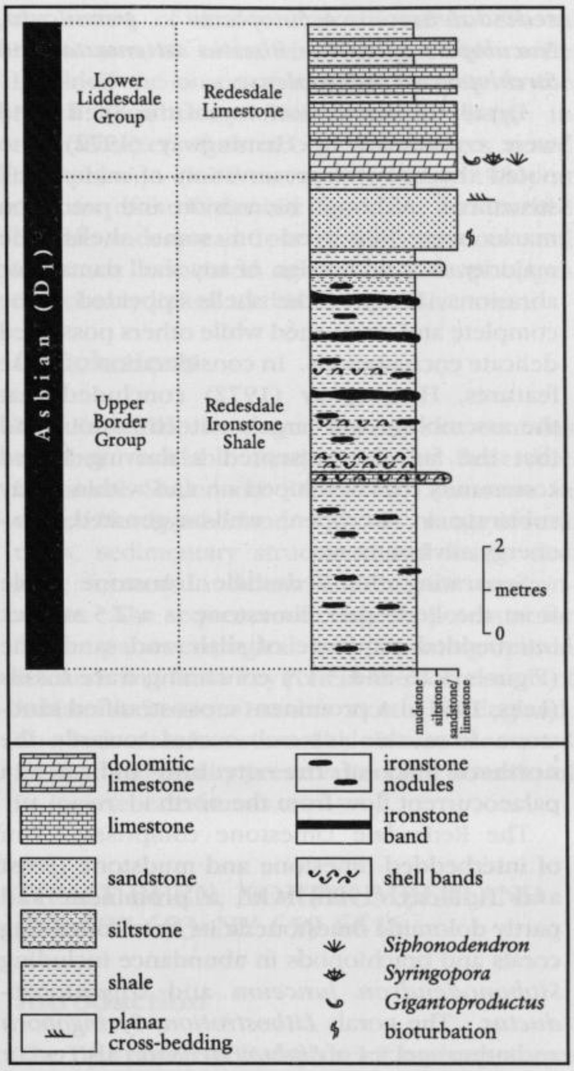


Figure 3.16 Summary log of the succession at Redesdale Ironstone Quarry. Compilation based on information from Hemingway (1972) and Frost and Holliday (1980), and on information supplied by D. Frost (pers. comm., 1979). The lower part of this succession was poorly exposed at the time of writing.

Lebour (1886a) and Smith, S. (1910) recorded close to 100 species from the Redesdale Ironstone Shale and the sequence is a well-known source of type, figured and cited material (Hind, 1896–1905; Lee, 1912; North, 1920; Jackson, 1926; Muir-Wood, 1928; Wright, 1950–1960; Wilson, 1959; Brand, 1972). Frost and Holliday (1980) described the typical bryozoan, brachiopod and bivalve fauna as including *Fenestella* spp., *Stenodiscus redesdalense*, *Composita ambigua*, *Leptagonia caledonica*, *Pugilis scoticus*, *Punctospirifer* *redesdalense*, *Actinopteria persulcata*, *Nuculopsis gibbosa*, *Phestia attenuata* and *Streblopteria*? *redesdalense*.

Details of the taphonomy of the Shell Band were considered by Hemingway (1972) who noted the delicate preservation of many shell structures. Although bioerosion and predation marks were observed on some shells, the majority showed no sign of any shell damage or abrasion. Many of the shells appeared to be complete and uncrushed while others possessed delicate encrustations. In consideration of these features, Hemingway (1972) concluded that the assemblage was largely autochthonous and that the fauna represented a thriving mixed community that developed on and within a clay substrate in an open, well-oxygenated, low-energy environment.

Separating the Redesdale Ironstone Shale from the Redesdale Limestone is a 2.5 m-thick interbedded sequence of shale and sandstone (Figures 3.16 and 3.17) containing trace fossils (Lees, 1991). A prominent cross-stratified sandstone from this interval occurs towards the northern end of the site and indicates a palaeocurrent flow from the north.

The Redesdale Limestone comprises 3.2 m of interbedded limestone and mudstone (Frost and Holliday, 1980) with a prominent and partly dolomitic limestone at its base containing corals and brachiopods in abundance including *Siphonodendron junceum* and *Gigantoproductus*. The corals *Lithostrotion*, *Syringopora* and other species of *Siphonodendron* also occur at this level. Detailed faunal lists prepared by Frost (1969) for this unit included the typical D_1 corals *Palaeosmilia murchisoni*, *S. junceum*, *L. decipiens* and *Dibunophyllum* cf. *bourtonense*. The same author also provided details of the microfaunas (foraminifera and ostracodes) recorded both from the Redesdale Limestone and from the overlying shales.

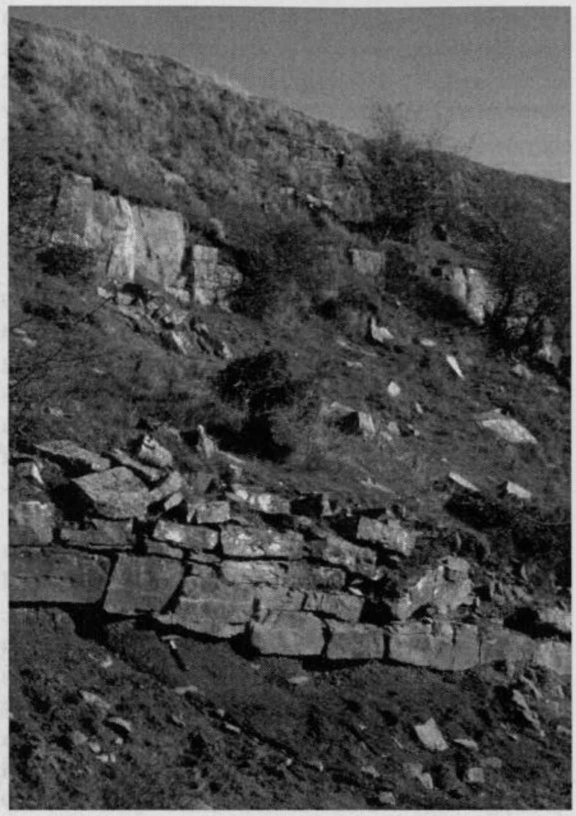


Figure 3.17 The upper part of the succession at Redesdale Ironstone Quarry showing the prominent development of sandstones between the top of the Redesdale Ironstone Shale (bottom) and the overlying Redesdale Limestone (top). (Photo: P.J. Cossey.)

Interpretation

The Redesdale succession occupies a pivotal position at the centre of the Northumberland Basin and has therefore been crucial to the correlation of sequences between the Tweed Basin and Cheviot Block areas to the north and the Solway Basin to the west. However, because of dramatic lateral facies change, discontinuous exposure, structural complexities and poor biostratigraphical control, the correlation of the Redesdale succession with those in neighbouring areas has, over the years, proved to be problematical.

On the basis that it represented the lowest distinctive and mappable marine limestone with Lower *Dibunophyllum* (D_1) Zone faunas, the Redesdale Limestone was taken by early workers to mark the base of the Lower Liddesdale (Lower Limestone) Group in the North Tyne area and the lateral equivalent of the Dun Limestone to the north-east (Miller, 1887; Fowler, 1926, 1936) and the Naworth Limestone to the west (Miller, 1887; Smith, S., 1910; Trotter and Hollingworth, 1932; Frost, 1969). Its correlation to the north-east was questioned by Anderson (in Carruthers, 1929, 1930, 1931) and Fowler (1966) as it became clear that the onset of marine sedimentation at the base of the Lower Limestone Group began much later in north Northumberland than it did in the North Tyne area. The Dun

Limestone was therefore considered to be at a higher stratigraphical level than that of the Redesdale Limestone. In supporting this view, and in recognition of the obvious diachronous nature of the boundary between the Scremerston Coal Group and the Lower Limestone Group, Frost (1969) questioned the validity of using these divisions as chronostratigraphical units, but argued for their retention as useful lithostratigraphical terms.

As a result of the discovery of D_1 faunas in the Piper's Cross Limestone and Plashetts Dun Limestone (Robinson in Westoll *et al.*, 1955), respectively 300 m and 440 m below the level of the Redesdale Limestone in the North Tyne area, the suggested correlation of the Redesdale Limestone and Naworth Limestone has also been called into question (Fowler, 1966; Ramsbottom in discussion of Frost, 1969; Day, 1970). While accepting that this discovery and foraminiferal evidence from the Archerbeck Borehole (George *et al.*, 1976) required the lowering of the base of the D_1 Zone to include the whole of the Upper Border Group, Frost and Holliday (1980) equated the Piper's Cross Limestone with the Redesdale Limestone, and the Naworth Limestone with the Fourlaws Limestone, thus confirming the earlier held view of Frost (1969) that the Redesdale Limestone, if not the exact equivalent of the Naworth Limestone, was 'stratigraphically fairly close' to it (see Figure 3.3). Despite these correlation problems, the Redesdale succession is now widely accepted as being of Asbian (D_1) age. This is confirmed by the occurrence of the typical Asbian faunas referred to above and by the discovery of the B Zone goniatite *Beyrichoceratoides redesdalense* from the Redesdale Ironstone Shale (Delépine, 1940).

The succession at Redesdale provides spectacular evidence of the changing style of sedimentation that is typical of the transition from the higher parts of the Upper Border Group, dominated by coarsening-upward cycles of deltaic origin, into the Yoredale cycles of the Lower Liddesdale Group, where marine influences are more apparent. Although the lower part of the Redesdale Ironstone Shale with its diverse fauna indicates deposition in a fairly shallow marine environment, its development was terminated in the upper part of the sequence by the influx of deltaic sand prograding from the north. The subsequent formation of the Redesdale Limestone marked the return of marine depositional conditions in the area, an event which on the wider scale heralded the onset of Yoredale cyclicity in the North Tyne area. The dramatic change in the character of ostracode assemblages noted by Robinson (in Frost and Holliday, 1980) at the base of the Redesdale Limestone and marked by the widespread loss of carbonaceous and ironstone associated microfaunal assemblages is probably linked to this transgressive event.

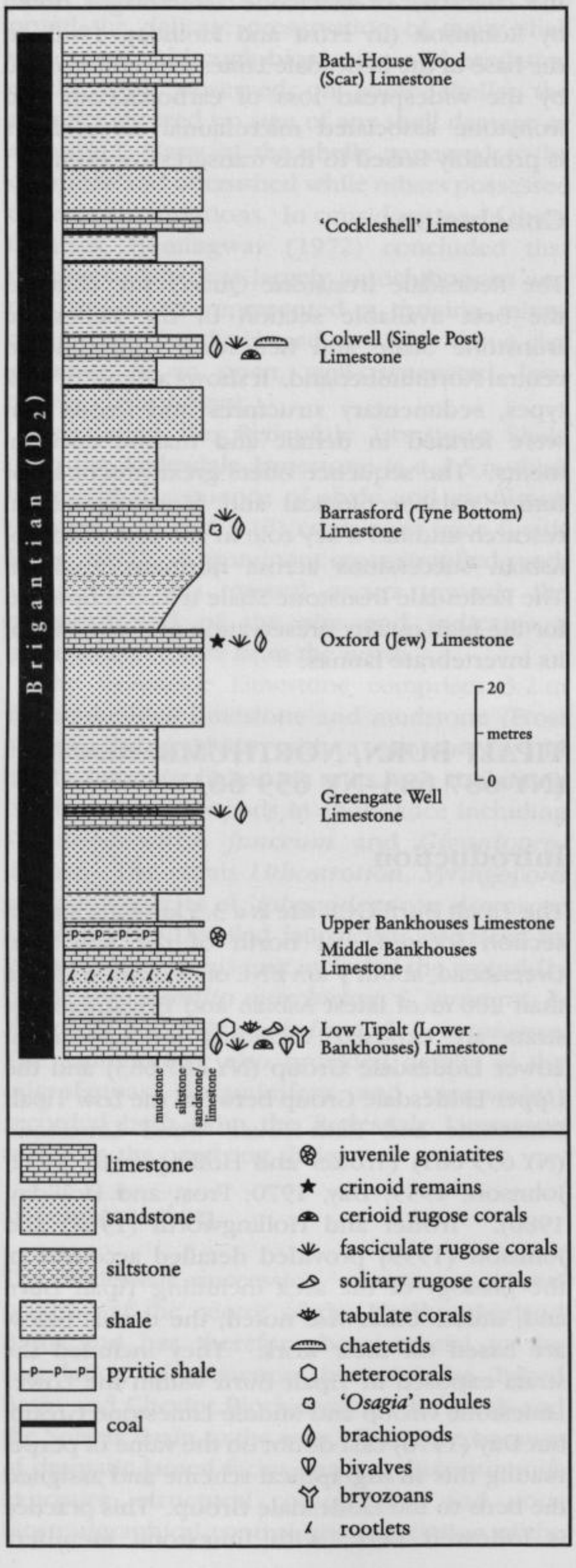
Conclusions

The Redesdale Ironstone Quarry site contains the best available section of the Redesdale Ironstone Shale and Redesdale Limestone in central Northumberland. It shows a range of rock types, sedimentary structures and fossils that were formed in deltaic and marine environments. The sequence offers great potential for future palaeoecological and biostratigraphical research and has a key role in the correlation of Asbian successions across northern England. The Redesdale Ironstone Shale is also renowned for the high-quality preservation and diversity of its invertebrate faunas.

TIPALT BURN, NORTHUMBERLAND (NY 687 683–NY 659 661)

Introduction

The Tipalt Burn GCR site is a 3.5 km-long stream section located just north of the A69 near Greenhead, about 9 km ENE of Brampton. More than 200 m of latest Asbian and Brigantian age strata are exposed, including the uppermost Lower Liddesdale Group (NY 687 683) and the Upper Liddesdale Group between the Low Tipalt Limestone and Bath-House Wood Limestone (NY 659 661) (Trotter and Hollingworth, 1932; Johnson, 1959; Day, 1970; Frost and Holliday, 1980). Trotter and Hollingworth (1932) and Johnson (1959) provided detailed accounts of the geology of the area including Tipalt Burn and, unless otherwise noted, the details below are based on their work. They included the strata exposed in Tipalt Burn within the Lower Limestone Group and Middle Limestone Group, but Day (1970) cast doubt on the value of perpetuating this stratigraphical scheme and assigned the beds to the Liddesdale Group. This practice is followed here, with limestone members identified as shown in Figure 3.18. Spore and trace-fossil assemblages from the section are respectively recorded by Marshall and Williams (1971) and Lees (1991). The Tipalt Burn succession provides several good exposures of the richly fossiliferous Low Tipalt Limestone and an overlying sequence that exhibits one of the finest examples of Yoredale-style, delta–marine cyclicity in the Lower Carboniferous succession of northern England.



◄**Figure 3.18** Section of the Upper Liddesdale Group (Brigantian) succession in Tipalt Burn. After information in Johnson (1959). Limestone names follow the nomenclature used by Day (1970) and Frost and Holliday (1980), while the names in parentheses are those used by Trotter and Hollingworth (1932) and Johnson (1959). See text for discussion of the problems associated with the naming and correlation of these limestone marker beds.

Description

A log of the Tipalt Burn succession is illustrated in Figure 3.18. Across the site the exposed beds dip gently (12°–20°) to the south, with only minor disruption caused by three small faults. At the northern end of the site the uppermost part the Lower Liddesdale Group comprises an alternating and intermittently exposed sequence (35 m) of sandstone, shale and limestone. Day's (1970) record of Asbian gigantoproductids (*Gigantoproductus maximus* group) and the Brigantian coral *Lonsdaleia duplicata* in these beds reflects the transitional nature of this part of the succession which lies close to the level of the Asbian–Brigantian boundary.

Overlying these beds is the fossiliferous Low Tipalt Limestone (16 m), marking the base of the Upper Liddesdale Group (Figure 3.18). The rich fauna reported from this horizon by Johnson (1959) is dominated by rugose and tabulate corals (some in growth position) and brachiopods, but also contains bryozoans, heterocorals, bivalves and rare molluscs. The fauna includes *Diphyphyllum fasciculatum*, *Dibunophyllum*, *Koninckophyllum* spp., *Lithostrotion maccoyanum*, *L. clavaticum*, *Siphonophyllia benburbensis*, *Siphondendron* spp., *Megachonetes* (of the *papillionacea* group), *Cleiothyridina royssii*, *Eomarginifera* spp., *Overtonia fimbriata*, *Phricodothyris paricosta*, *Rhipidomella michelini* and *Schellwienella crenistria* together with numerous other productoids, spiriferoids and gigantoproductids (of the *giganteus* and *latissimus* groups). The most notable Brigantian taxa recorded are *Gigantoproductus* *gigantoides* and *Koninckophyllum* cf. *proprium* (see Johnson, 1959, for more details).

Above the Low Tipalt Limestone, 5 m of sandy shale and alternating flaggy sandstone and sandy shale are overlain by 5 m of flaggy, massive and rootleted sandstone beds (Day, 1970). Petrographical analysis of this sandstone and several others from the Tipalt Burn section has revealed a heavy-mineral suite of tourmaline, zircon, rutile and anatase, and, in some beds, traces of glauconite (Harrison in Day, 1970). The Lower Bankhouses Limestone comprises 75 cm of limestone, 1.2 m of calcareous shale and 1.8 m of limestone (Day, 1970). This is overlain by a thick shale sequence (*c.* 4 m), fossiliferous and marine in its lower part, with a goniatite-bearing pyritic shale towards the middle. Above this sequence lies the thinner Upper Bankhouses Limestone, in turn overlain by 6 m of shale, followed by more than 14 m of erosive-based, massively bedded, medium-grained, brown and yellow sandstone.

The Greengate Well Limestone comprises two 4.5 m limestone beds separated by 1.5 m of calcareous shale. The limestone contains *Siphonodendron junceum* and gigantoproductids. Above this lie shales (not exposed in Tipalt Burn) and sandstones with flaggy partings; the latter were almost certainly used in the construction of Hadrian's Wall.

The Oxford Limestone (5 m) contains crinoid remains and a coral–brachiopod fauna that includes *Lingula*. The overlying calcareous shale is packed with skeletal debris and coarse crinoid debris. This grades upwards into a fossiliferous dark mudstone, which is capped by a ferruginous shale and about 6 m of thin-bedded and flaggy sandstones with numerous trackway markings, possibly made by annelids.

The Barrasford Limestone (6 m) is a dark, skeletal and partly dolomitized limestone with shale partings. A coral–brachiopod fauna dominates this interval, but the unit also contains 'algal' nodules of the form genus *Osagia* and the foraminiferan *Saccaminopsis fusulinaformis*. Above this is a 30 m-thick sequence of shale, sandstones and a 20 cm-thick coal (Figure 3.18). A buff-coloured calcareous sandstone grades upwards into the sandy and dolomitic base of the Colwell Limestone which contains a coral–brachiopod fauna more typical of the Brigantian Stage, including *Actinocyathus floriformis*, *Siphonodendron junceum*, *G. giganteus*, *R. michelini*, *Eomarginifera* cf. *longispina*, as well as the demosponge *Chaetetes*. The overlying shale and sandstone are also well exposed in Tipalt Burn. Trotter and Hollingworth (1932) reported a 20–45 cm coal immediately beneath the Colwell Limestone, but comparison of vertical sections (Trotter and Hollingworth, 1932, fig. 7; Johnson, 1959, fig. 8) suggests that this coal lies beneath the 'Cockleshell' Limestone. The 'Cockleshell' Limestone is a thin (< 2 m), fairly fossiliferous dark-grey skeletal limestone. However, because of its lateral variability and correlation difficulties, this limestone was not formally adopted as a named unit by Frost and Holliday (1980). The overlying siliciclastic sequence includes fine- to medium-grained lenticular sandstones, and, underlying the Bath-House Wood Limestone, a 12–20 cm-thick coal. An adit driven into the thick sandstone beneath the Bath-House Wood Limestone represents an unsuccessful attempt to find galena. The Bath-House Wood Limestone crops out at the southern limit of the site. This limestone is thicker than the 'Cockleshell' Limestone, but is otherwise similar in character. It is overlain by almost a metre of fireclay and a 5 cm-thick coal.

Interpretation

As is the case with other sections in the Northumberland Basin, problems of correlation have provided the focus for most of the work on the Tipalt Burn sequence. Trotter and Hollingworth (1932) correlated the Low Tipalt Limestone and Bankhouses Limestones with the Oxford Limestone to the north and the Smiddy Limestone to the south, but Johnson (1959) concluded that the Low Tipalt Limestone and Bankhouses Limestones must correlate with a lower horizon and suggested a Smiddy–Low Tipalt–Woodend correlation. Frost and Holliday (1980) correlated the Low Tipalt Limestone with the Peghorn Limestone to the south and the 'Spirifer Band' to the north-east (Figures 3.3 and 3.5). They correlated the Bankhouses Limestones with the lower part of the Smiddy Limestone to the south and the Watchlaw Limestone to the north-east (see **Spittal Shore** GCR site report, this chapter). Correlation of the Greengate Well Limestone with the Lower Little Limestone to the south was proposed by Trotter and Hollingworth (1932) and has been followed by subsequent authors

(Johnson, 1959; Frost and Holiday, 1980; Johnson *et al.*, 1995). The Greengate Well Limestone thins northwards (Figure 3.5) and has no lateral equivalent limestone in more northern and eastern parts of the Northumberland Trough (Johnson, 1959; Frost and Holliday, 1980), although Day (1970) proposed its correlation with the Penton Limestone of the Langholm district to the north-west (see **Penton Linns** GCR site report, this chapter). The correlation of the Oxford Limestone of the Northumberland Trough with the Jew Limestone of the Alston Block has been stable since originally proposed by Garwood (1910). The Barrasford Limestone was described as the 'Tyne Bottom Limestone' by Trotter and Hollingworth (1932) and Johnson (1959), and correlated with the Tyne Bottom Limestone to the south. Frost and Holliday (1980), however, correlated the Barrasford Limestone with the upper part of the Jew Limestone to the south (Figure 3.5). To the north and east the Barrasford Limestone has no named lateral equivalent. Johnson (1959) described the Colwell Limestone as the 'Single Post Limestone' and correlated it with a unit of the same name to the south. He was unable to correlate it with a specific horizon to the north or east. Frost and Holiday (1980) correlated the Colwell Limestone with the Tyne Bottom Limestone to the south and the Budle Limestone of north-east Northumberland (Figure 3.5). While Trotter and Hollingworth (1932) and Johnson (1959) regarded the Bath-House Wood Limestone as the correlative of the Scar Limestone, Frost and Holliday (1980) equated it with the Single Post Limestone farther south. No named lateral equivalent has been identified to the north or east. Johnson *et al.* (1995) follow Frost and Holliday's (1980) correlations of the Greengate Well Limestone and Oxford Limestone, but not those proposed for the higher units or for the correlation of the Low Tipalt Limestone with the 'Spirifer Band' in north Northumberland.

As noted by Frost and Holliday (1980), subdivision and correlation of the Carboniferous sequence exposed in Tipalt Burn and the surrounding area has been based on the establishment of marker beds with supposed or established palaeontological significance. Some of the problems of correlation noted above have arisen because of this conflation of biostratigraphy and lithostratigraphy. The Upper Liddesdale Group corresponds to the D_2 coral–brachiopod zone (Johnson, 1959; Day, 1970), or the Brigantian Stage of the current chronostratigraphical scheme (George *et al.*, 1976; see Figure 3.3). The base of the Brigantian Stage is defined at the base of the Peghorn Limestone near Kirkby Stephen to the south (George *et al.*, 1976; see **Janny Wood** GCR site report, Chapter 5) and, consequently, the correlation of this horizon with the Low Tipalt Limestone in Tipalt Burn is important in establishing the Low Tipalt Limestone as the marker horizon for the base of the Brigantian Stage in the Northumberland Trough (Figures 3.3 and 3.5).

The Tipalt Burn succession provides an outstanding example of the interdigitation between marine and deltaic deposits so typical of the Yoredale style of cyclicity found throughout northern England. However, since the site has received little attention from modern researchers, only general comments on its sedimentological significance are outlined in this account. Clastic facies probably represent deposition in river-dominated deltaic settings, with pro-delta mudrocks, mouth-bar coarsening-upward sand-bodies, bay–levee–crevasse sequences, distributary channel sandstones and lacustrine backswamp mudrocks (Leeder *et al.*, 1989). Palaeocurrent data from distributary channel sand-bodies indicate a south-westerly palaeoflow (Leeder *et al.*, 1989). Thin, laterally persistent coals represent periods of delta-lobe abandonment, often followed by subsidence, the re-establishment of marine conditions and the deposition of fossiliferous limestones and shales (Elliott, 1974a, 1975). Johnson (1959) interpreted a dome-like structure in the Low Tipalt Limestone as evidence that knoll reefs were developed at the top of the unit. However, Day (1970) interpreted the doming as a tectonic feature and it seems unlikely that true knoll reefs occur here.

Conclusions

The Tipalt Burn GCR site provides arguably the best section for the examination of upper Viséan Yoredale cyclothems in the southern part of the Northumberland Basin. The exposure extends through several carbonate–clastic depositional cycles formed by alternating marine and fluvio-deltaic processes, resulting in the formation of a number of named lithostratigraphical units (especially limestones) of the Liddesdale Group which are among the finest developments of their kind in the region. The sequence as a whole, and the Low Tipalt Limestone in particular, has great potential in future sedimentological, palaeoecological and palaeontological investigations. The Low Tipalt Limestone has been central in establishing local lithostratigraphical subdivisions and in regional correlations of the Brigantian Stage across the Northumberland Trough and onto the adjoining Alston Block.

BRUNTON BANK QUARRY, NORTHUMBERLAND (NY 928 699)

Introduction

Situated to the north of the B6318 and approximately 1 km to the south-east of Chollerford, Northumberland, the Brunton Bank Quarry GCR site is a disused quarry (NY 928 699), with a unique exposure of the Great Limestone (basal Namurian, Pendleian, E_{1a}) lying close to the southern margin of the Northumberland Basin. Johnson (1958) recorded two prominent organic buildups from the sequence, including the 'Brunton Band', containing the rare alga *Calcifolium*, and a spectacular development referred to as the '*Chaetetes* Band' – the finest Carboniferous example of a sponge biostrome in Britain. Fairbairn (1980) and Frost and Holliday (1980) recorded details of the succession, but the original account by Johnson (1958) remains the most useful site description to date. Further palaeontological detail relating to the *Chaetetes* biostrome is provided by Shiells (1961), Johnson (1979), Brunton and Mundy (1988a) and Cossey and Mundy (1990).

Description

At this site, the Great Limestone succession (*c.* 15 m) is divisible into three parts (Figure 3.19; and see Johnson, 1958): a lower division (*c.* 2 m) of dark-grey, dolomitic limestone, which includes the highly fossiliferous Chaetetes Band; a middle division (*c.* 7 m) of well-bedded, paler-grey limestone, which includes the Brunton Band with its rich microfaunas; and an upper division (*c.* 6 m) of dark-grey limestone with interbedded calcareous shales. These three divisions correspond broadly with the long-established 'Bench Posts', 'Main Posts', and 'Tumbler Beds' units of

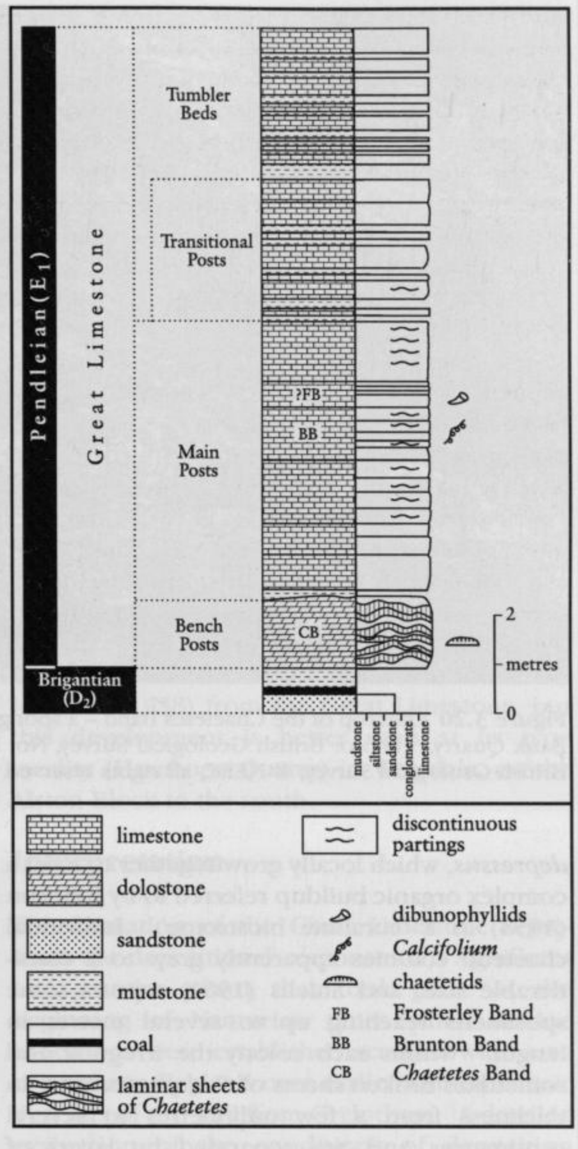


Figure 3.19 Sedimentary log of the Great Limestone (Pendleian) succession in Brunton Bank Quarry illustrating the position of key 'biostromal' developments referred to in the text. Compilation based on information in Johnson (1958), Fairbairn (1980) and Frost and Holliday (1980).

the traditional Great Limestone terminology, although Fairbairn (1980) recognized a fourth subdivision in the quarry, the 'Transitional Posts', which broadly equates to the lower part of the Tumbler Beds.

The Chaetetes Band (Figure 3.20) forms the most prominent limestone 'post' in Johnson's 'lower division' and ranges from 0.5 m to just over 1 m in thickness. The bed is packed with large discoidal and laminar sheets of *Chaetetes*

Figure 3.20 Outcrop of the Chaetetes Band – a sponge bioherm at the base of the Great Limestone in Brunton Bank Quarry. (Photo: British Geological Survey, No. L1551, reproduced with the permission of the Director, British Geological Survey, © NERC, all rights reserved (IPR/19-39C).)

depressus, which locally grow together to form a complex organic buildup referred to by Johnson (1958) as a 'coralline biostrome'. Individual chaetetid colonies apparently grew to a considerable size, and Shiells (1961) reports some specimens reaching up to several metres in length. Within each colony the irregular and sometimes broken sheets of *C. depressus* vary in thickness from a few millimetres to several centimetres and are separated by layers of dolomitized sediment and occasional spar-filled cavities (Figure 3.21). Shiells (1961) also noticed chaetetid 'trials' in the underlying bed and that turbidity and substrate consistency were a major influence on chaetetid development. A variety of carbonate phases are developed in the biostrome including both ferroan and non-ferroan calcites and dolomites, although details concerning their distribution and significance have yet to be fully evaluated.

Johnson (1958) described a rich fauna from the Chaetetes Band characterized by the occurrence of numerous coral and brachiopod taxa, rare echinoids and a remarkable cryptic fauna of adherent bryozoans, annelids and brachiopods attached to the undersurfaces of the chaetetid colonies. Subsequent investigation of this highly specialized cryptic fauna has revealed spectacular examples of the rare cementing aulostegacean brachiopod *Sinuatella johnsoni*, complete with its creeping adherent spines and cementation scars (Johnson, 1979; Brunton and Mundy, 1988a), and the loosely attached foraminifer *Tetrataxis* (Cossey and Mundy, 1990). A similar cryptic community associated with laminar chaetetid colonies has been described by Suchy and West (1988) from the Middle Pennsylvanian Pawnee Limestone of Iowa, USA. The origin of the cryptic cavities beneath the chaetetids most probably resulted from sediment scouring (Suchy and West, 1988; Cossey and Mundy, 1990).

The rich fauna from the Chaetetes Band includes *Tetrataxis*, '*Serpula*', '*Spirorbis*' cf. *laxus*, *C. depressus*, *C. septosus*, *Aulopora*?, *Caninia cornucopiae*, *Cladochonus brevicollis*, *Dibunophyllum bipartitum*, *Diphyphyllum lateseptatum*, *Koninckophyllum echinatum*, *Siphonodendron pauciradiale*, *Actinocyathus floriformis laticlavia*, *Syringopora geniculata*, *Fenestella*, *Polypora*, *Stenopora*, indeterminate stick bryozoans, *Actinoconchus planosulcatus*, *Athyris lamellosa*, *Brachythyris decora*, *Crania quadrata*, *Pugilis pugilis*, *Echinoconchus*

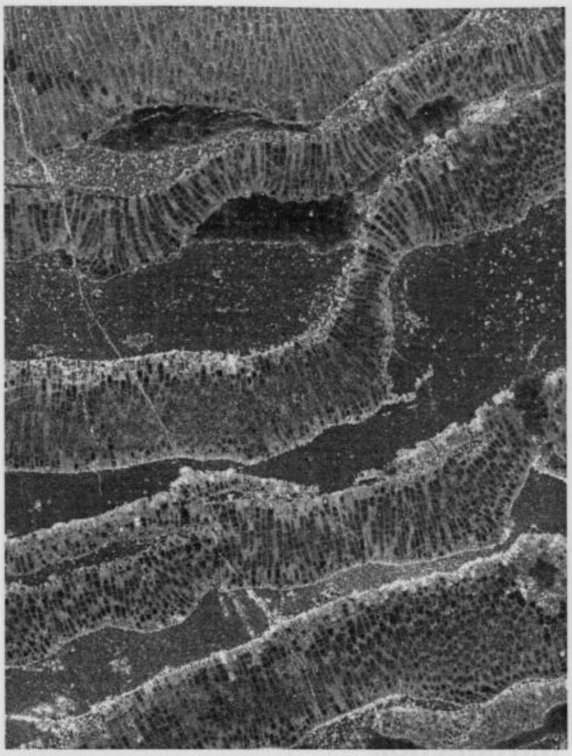


Figure 3.21 Laminar sheets of *C. depressus* separated by irregular bands of dolomitized sediment associated with geopetal fabrics, from the *Chaetetes* biostrome at Brunton Bank Quarry. Negative print of stained acetate peel (× 3.9). (Photo: P.J. Cossey.)

punctatus, *Eomarginifera longispina*, *Leptagonia caledonica*, *Overtonia fimbriata*, *Rhipidomella michelini*, *Schellwienella crenistria*, *S. johnsoni*, *S. sinuata*, *Spirifer*, *Tylothyris* cf. *subconica castletonensis* and *Archaeocidaris urii* (Johnson, 1958; Brand, 1972; Frost and Holliday, 1980; Brunton and Mundy, 1988a; Cossey and Mundy, 1990).

Although Johnson (1958) clearly regarded *C. depressus* as a tabulate coral, comparisons made with Recent sponge taxa (Hartman and Goreau, 1970, 1972, 1975) and the discovery of spicule pseudomorphs in chaetetids in the Ty-nant Limestone at Eglwyseg Mountain (Gray, 1980; and see **Eglwyseg Mountain** GCR site report, Chapter 8) lend support to the more recent view of chaetetids as demosponges (West and Kershaw, 1991).

In the upper part of the 'middle division', Johnson (1958) recorded a 3.5 m-thick algal limestone, the Brunton Band, containing a rich microfauna that included *Calcifolium bruntonense* (a codiacean alga now regarded as the junior synonym of *C. okense*; Holliday *et al.*, 1975; Frost and Holliday, 1980) in abundance, textulariid, ammodiscid, endothyrid, nodosariid and tetrataxiid foraminifera, ostracodes, dasycladacean algae and *Girvanella*. A fragmented macrofauna of coral, crinoid, bryozoan, brachiopod, gastropod and echinoid (*Archaeocidaris*) debris also occurs at this level. Although the '*Calcifolium* Band' (Johnson *et al.*, 1995) was originally described by Johnson (1958) as an algal 'biostrome', Shiells (1961) indicated that algae do not occur in sufficient quantity here to justify use of the term 'biostrome'. Although best developed at this locality, *C. okense* is also known from Pendleian and upper Brigantian Yoredale limestones elsewhere in northern England and in Scotland (Burgess, 1965).

Frost and Holliday (1980) tentatively suggested that scattered specimens of *Dibunophyllum bipartitum* from above the Brunton Band at this site may mark the presence of the Frosterley Band, the third 'biostrome' described by Johnson (1958) from the Great Limestone, but this development is better seen at its type locality (Harehope Quarry) in Weardale, on the Alston Block to the south.

Interpretation

The formation of the Great Limestone represents the depositional response to a significant transgressive event that took place at the beginning of Namurian times when marine conditions were established across a wide area of northern England over earlier-formed deltaic deposits of the 4 Fathom Cyclothem. A detailed evaluation of the conditions of deposition and sedimentary environments of the Great Limestone at this site awaits further sedimentological study, but the presence of a rich coral–brachiopod fauna associated with calcareous demosponges in the Chaetetes Band and the abundance of calcareous algae in the Brunton Band, are indicative of deposition in clear, shallow seas, above wave-base and within the photic zone.

The palaeoecology of the Chaetetes Band was considered by Shiells (1961), who stressed how important it was for the chaetetids to keep their living surfaces above the sediment–water interface. Shiells further suggested that their laminar growth form may have been an adaptive strategy to prevent sinking in soft sediment. He also suggested that the interfingering of sediment layers and chaetetid laminae resulted from periodic influxes of argillaceous material which killed off parts of the organism, followed by a re-establishment phase in which a spread of lateral growth took place from a surviving part of the colony. In addition, Shiells (1961) related the initiation of the *Chaetetes* biostrome to reduced levels of turbidity and a coarsening of the substrate sediment, while its termination was attributed to increased levels of turbidity and a fining of the substrate sediment, although little petrographical evidence was presented in support of these claims.

Studies of chaetetids from North America have indicated that the major factors influencing chaetetid growth form were substrate type, sedimentation rate, turbidity, turbulence and water depth (Kershaw and West, 1991; West and Kershaw, 1991). These authors suggested that although laminar chaetetids occurred in both high- and low-energy facies, they were better adapted to environments of high energy and generally confined to areas of very shallow water, well within wave-base. Considering all available evidence, it is suggested that the *Chaetetes* biostrome most probably developed in a relatively quiet, shallow, subtidal environment in which there was a good oceanic circulation.

The Great Limestone was originally used to define the base of the Upper Limestone Group in the Tweed Basin (Fowler, 1926), and later to mark the base of the Stainmore Group from the Northumberland Basin across the Alston Block and into the Stainmore Basin (Burgess and Holliday, 1979; Frost and Holliday, 1980; Smith and Holliday, 1991). It is the thickest and most prominent of the Yoredale limestones, and as such it forms one of the most useful lithostratigraphical marker horizons in northern England. Fairbairn (1978, 1980) noted the remarkable lateral continuity of individual beds in the Great Limestone and successfully correlated beds from the northern part of the Alston Block across the Ninety Fathom–Stublick Fault System and into the Northumberland Basin. Unsurprisingly, therefore, the sequence at Brunton Bank closely resembles that of the Great Limestone at Greenleighton Quarry, where goniatite evidence was used by Johnson *et al.* (1962) to establish an E_{1a} (basal Pendleian) age for the unit. The discovery of '*Eumorphoceras*' in the Black Pasture 'Sill' (Sandstone) overlying the Great Limestone at Brunton Bank substantiates this view (Johnson, 1986).

Conclusions

The Brunton Bank Quarry GCR site provides the best available exposure of sponge biostromes and algal limestones in the Great Limestone. As the type locality for the Brunton Band, the Chaetetes Band and a number of spectacularly well-preserved fossils, Brunton Bank Quarry is one of the most important palaeontological sites of Lower Carboniferous age in the north of England. The poor understanding of the depositional environments represented by the Great Limestone and the lack of knowledge concerning the ecology and development of sponge biostromes in the Carboniferous Period means that this site has great potential for future research, particularly in the fields of sedimentology and palaeoecology.

GREENLEIGHTON QUARRY, NORTHUMBERLAND (NZ 034 917)

Introduction

Greenleighton Quarry, a restored old quarry (NZ 034 917) 10 km south of Rothbury, exposes one of the finest accessible and fossiliferous sections of the lower Pendleian (E_{1a}) Great Limestone Cyclothem. The discovery of rare goniatites here has provided critical evidence in defining the position of the Brigantian–Pendleian (basal Namurian) stage boundary throughout northern England and proved vital to the dating and correlation of Stainmore Group sequences across the Northumberland Basin. Details of the succession and palaeontological information are recorded by Fowler (1936) and Fairbairn (1980), while the stratigraphy is discussed in depth by Johnson *et al.* (1962) and Hull (1968).

Description

The exposed section (Figure 3.22) includes 12 m of the Great Limestone and is overlain by 7 m of highly fossiliferous shale which contains thin rippled and bioturbated siltstone–sandstone beds. The sequence is capped by a thin sandstone (Figure 3.23). The Great Limestone is divisible into a lower unit (7 m) of thick limestones with thin mudstone partings (the 'Bench Posts' and 'Main Posts' subdivisions of Fairbairn, 1980) and an upper unit (5 m) of thick

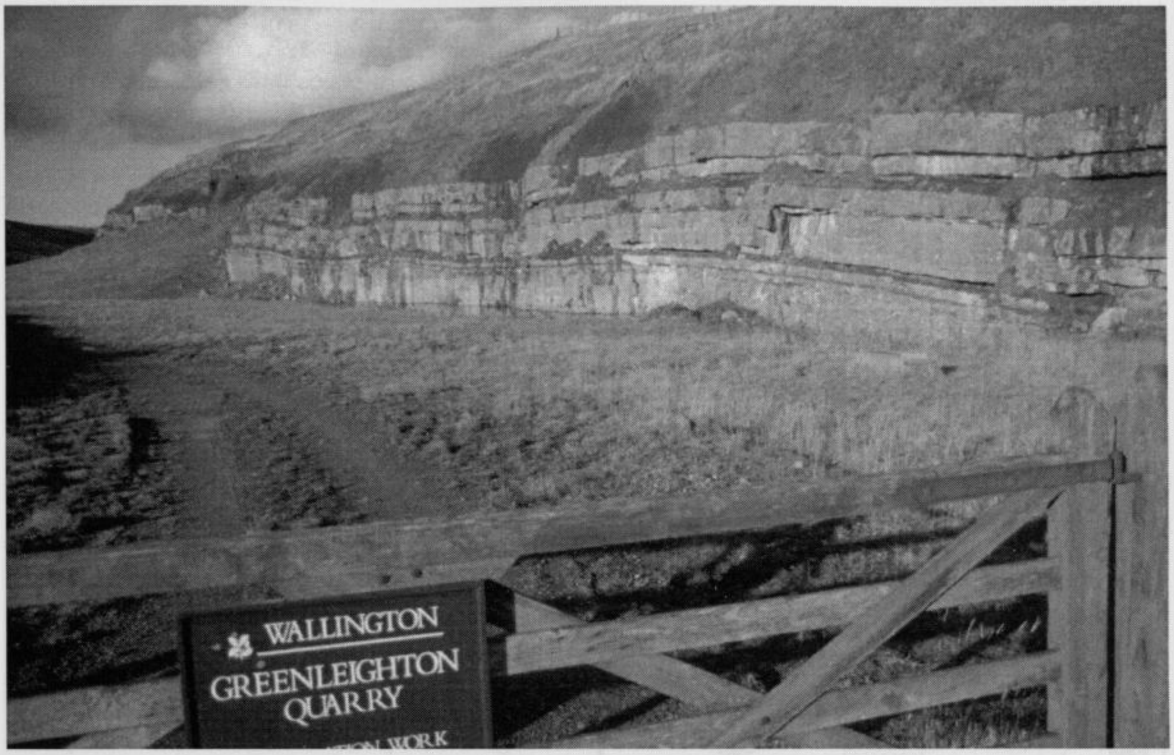
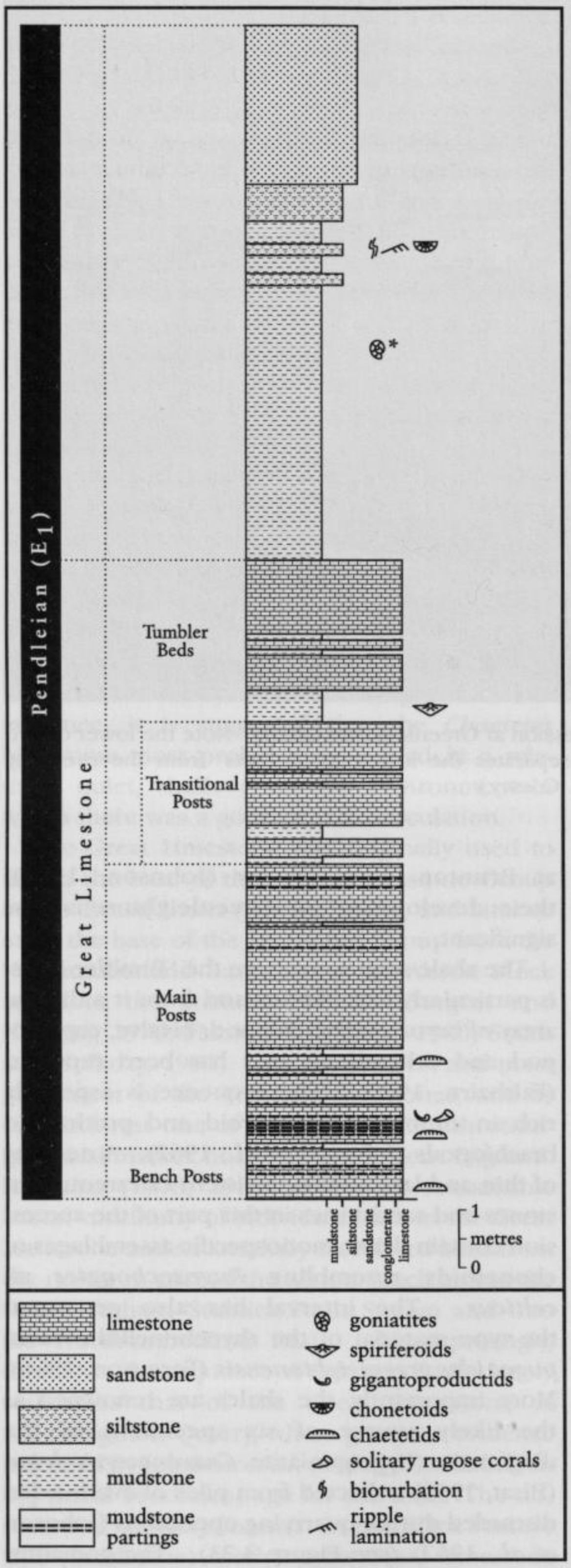


Figure 3.22 General view of the Great Limestone succession at Greenleighton Quarry. Note the lower of two thin mudstones within the limestone sequence that separates the lower 'Main Posts' from the overlying 'Tumbler Beds'. See text for further details. (Photo: P.J. Cossey.)

limestones with prominent mudstone interbeds (the 'Transitional Posts' and 'Tumbler Beds' subdivisions of Fairbairn, 1980). The fauna of the Great Limestone here includes sponges (*Chaetetes depressus*, *C. septosus*), corals (*Dibunophyllum*, *Actinocyathus floriformis laticlavia*), bryozoans (*Tabulipora*), a variety of productoid and spiriferoid brachiopods (e.g. *Latiproductus latissimus* and *Spirifer trigonalis*), nautiloids (*Orthoceras*) and the trace fossil *Zoophycos* (Fowler, 1936; Fairbairn, 1980). Although the distribution of fossils within the sequence is poorly constrained, coral and sponge remains are more common in limestones at the base of the succession while the shelly faunas are more prevalent in the younger mudstones. A list of the fauna from the mudstones of the Tumbler Beds provided by Fairbairn (1980) includes brachiopod taxa in abundance, together with a number of coral, bryozoan, echinoderm, trilobite and bivalve taxa, but it is unclear how many, if any, of these originate from the Greenleighton Quarry site. Although chaetetids occur at the same level as the *Chaetetes* biostrome in the Great Limestone at Brunton Bank Quarry (Johnson, 1958), their development at Greenleighton is less significant.

The shale sequence above the 'Tumbler Beds' is particularly fossiliferous and from it a diverse array of bryozoan, brachiopod, bivalve, cephalopod and echinoderm taxa has been reported (Fairbairn, 1980). The sequence is especially rich in chonetoid, spiriferoid and productoid brachiopods (Johnson *et al.*, 1962). A number of thin and laterally impersistent calcareous siltstones and sandstones in this part of the succession contain dense monospecific assemblages of chonetoids resembling *Rugosochonetes* cf. *celticus*. The interval has also generated the type material of the rhynchonellid *Pleuropugnoides greenleightonensis* (Ferguson, 1966). More importantly, the shales are renowned as the likely source of six specimens of the diagnostic (E_{1a}) goniatite *Cravenoceras leion* (Bisat, 1930) collected from piles of overburden discarded during quarrying operations (Johnson *et al.*, 1962) (see Figure 3.23). The goniatites were found as uncrushed specimens in limestone nodules and are believed to have originated



from a similar band of nodules from the middle of the shale sequence. This remarkable find, in a sequence that was reputedly devoid of useful goniatite markers, enabled Johnson *et al.* (1962) to fix the position of the base of the Pendleian Stage and, for the first time, establish a line of division between Viséan and Namurian age strata in the Northumberland Basin (see discussion below).

Interpretation

Although goniatites are relatively uncommon elements of the Yoredale succession in the Northumberland Basin, significant finds by Johnson *et al.* (1962) and Hull (1968) have facilitated the recognition of a number of Namurian stage boundaries and, in particular, the junction between the Viséan and Namurian series. The latter (formerly also the boundary between the Lower and Upper Carboniferous subsystems) is characterized by an upward change in the goniatite faunas and the replacement of ***Sudeticeras*** and ***Girtyoceras*** by ***Cravenoceras*** and ***Eumorphoceras*** (Bisat, 1950). The discovery of ***Cravenoceras leion*** (E_{1a}) from shale above the Great Limestone at Greenleighton Quarry, and ***Girtyoceras*? *costatum*** (P_{2c}) from 2 m above the Undersett Limestone (= 4 Fathom Limestone) in the Mount Pleasant Borehole near Barnard Castle, together with records of ***?Cravenoceras*** and ***Eumorphoceras pseudobilingue*** from the intervening beds (Hudson, 1941; Black, 1950; Rayner, 1953; Wilson, 1960a), led Johnson *et al.* (1962) and Hull (1968) to establish the Brigantian–Pendleian stage boundary (and the base of the Namurian Series) in sandy facies beds close to, but below, the base of the Great Limestone. This is further supported by the discovery of ***Eumorphoceras*** close above the Great Limestone at Brunton Bank, Chollerford (Johnson, 1986) and

◂**Figure 3.23** Section of the Lower Namurian (Pendleian) Great Limestone succession at Greenleighton Quarry. An asterisk marks the position of a horizon of limestone nodules that Johnson *et al.* (1962) regarded as the most likely source of the basal E_{1a} goniatite marker *Cravenoceras leion* found in the tips nearby. Based on Johnson *et al.* (1962) and Fairbairn (1980).

from the Throckley Borehole, Newcastle (Richardson, 1965; Ramsbottom, 1966). The Great Limestone has since been widely used as a key lithostratigraphical marker at the base of the Namurian Series and in particular for regional stratigraphical correlations across northern England and southern Scotland (Taylor *et al.*, 1971; Ramsbottom *et al.*, 1978; Johnson *et al.*, 1995). Further refinement of the position of the base of the Pendleian Stage in the Northumberland Basin is expected with advances in micropaleontological and palynological research.

The results of detailed sedimentological work have yet to be published, but the general character of the succession reflects the typical Yoredale pattern of fossiliferous marine limestones and shales capped by coarser clastic beds of deltaic origin (Johnson, 1962).

Conclusions

The discovery of the E_{1a} Zone goniatite *Cravenoceras leion* at Greenleighton Quarry has been used to fix the position of the base of both the Pendleian Stage and the Namurian Series close to the base of the Great Limestone. Its occurrence in a richly fossiliferous sequence makes this site one of the most important localities for the dating and correlation of Lower Carboniferous successions in the Northumberland Basin. In addition, the site remains of critical importance to future research, particularly in areas of biostratigraphy, sedimentology and palaeoecology.

CORBRIDGE LIMESTONE QUARRY, NORTHUMBERLAND (NY 996 656)

Introduction

The Corbridge Limestone Quarry GCR site lies close to the A69, about 1 km north of Corbridge, near Hexham. This disused limestone quarry (NY 996 656) also known as 'Deadridge Quarry', provides the finest section of the Corbridge Limestone in the Northumberland Basin. Despite poor biostratigraphical control, the exposed sequence contains a distinctive but rather unusual fauna, which is generally regarded as basal Arnsbergian (E_{2a}) in age. The site is of critical importance to the correlation of Stainmore Group successions across the Northumberland Basin and into the adjoining Alston Block and Midland Valley Basin areas. The geology of the area is documented by Lebour (1885), Hedley and Waite (1929) and Hedley (1931), and significant palaeontological information is given by Smith, S. (1910). However, the most useful accounts of the site geology are provided by Holliday and Pattison (1990) and Mills and Holliday (1998).

Description

Lying approximately 100 m above the Oakwood Limestone and 55 m below the Thornborough Limestone, the Corbridge Limestone is one of a number of prominent units within the cyclothemic Stainmore Group (Upper Limestone Group) sequence, and one that is better developed in the Corbridge district than anywhere else in northern England (Holliday and Pattison, 1990; Mills and Holliday, 1998). Its position within the Stainmore Group succession is illustrated in Figures 3.3 and 3.6.

A boring at Corbridge Pottery works (Hedley and Waite, 1929) revealed a 30 m sequence of interbedded sandstone, shale and fireclay beneath the Corbridge Limestone but failed to intersect the Belsay Dene Limestone thought to lie locally approximately 20 m below the Corbridge Limestone (Holliday and Pattison, 1990). Above the Corbridge Limestone, a thick succession of sandstone is exposed in the A69 road cutting adjacent to the site just a short distance to the south-east.

Exposure of the Corbridge Limestone in the quarry is limited to a 6 m section of fine-grained, bioclastic limestone with interbedded calcareous and dark-grey mudstone partings (see Figure 3.24) which increase to 0.5 m in thickness near the top of the sequence. At the base of the section, a thin (0.2 m) sandstone with rootlets and a 1.5 m-thick fireclay once used by the Corbridge Pottery industry (Hedley and Waite, 1929) lies directly beneath the limestone. An adit excavated into this unit was formerly visible at the northern end of the site (Mills and Holliday, 1998). The Corbridge Limestone fauna is typified by the presence of brachiopods such

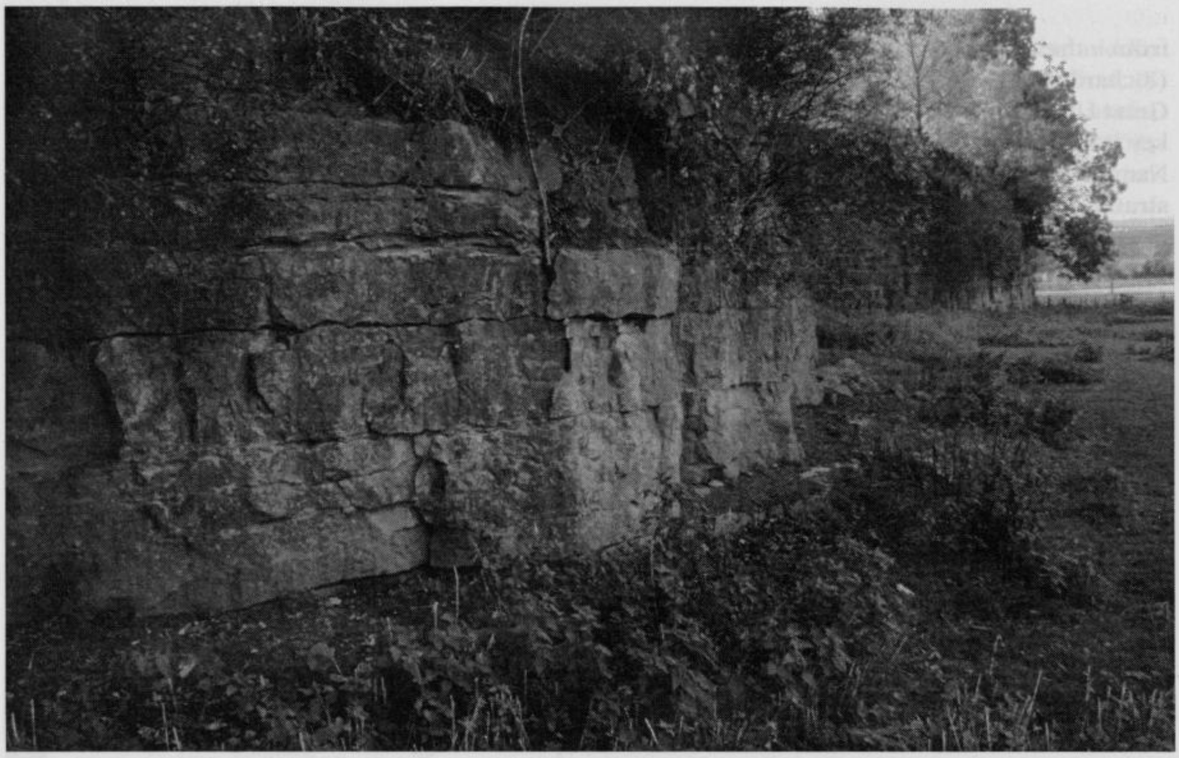


Figure 3.24 Exposure of fine-grained bioclastic limestones close to the base of the Corbridge Limestone at Corbridge Limestone Quarry. (Photo: P.J. Cossey.)

as *Buxtonia* and *Edmondia sulcata* which occur in abundance, by the occurrence of *Chaetetes septosus*, *Fenestella*, *Composita ambigua* and *Latiproductus latissimus*, and by the absence of solitary corals (Smith, S., 1910; Hedley and Waite, 1929; Hedley, 1931; Pattison, 1980; Holliday and Pattison, 1990; Mills and Holliday, 1998). Its faunal character serves to distinguish this limestone from the many other carbonate-rich marker horizons in the Stainmore Group with which, in the past, it has sometimes been confused (Holliday and Pattison, 1990).

Interpretation

To date, the only detailed and published account of the sedimentology of the Stainmore Group in the Northumberland Basin is that provided by Elliot (1976a) who worked exclusively on fluvio-deltaic deposits exposed along the Northumberland coast between Howick Bay and Longhoughton Steel. Comparable studies of similar successions inland and containing significant limestone intervals have yet to be undertaken (Holliday and Pattison, 1990). Despite this, it is generally accepted that the Stainmore Group successions of this region, as elsewhere in northern England, are the product of a delicate interplay between marine and deltaic influences operating in the southern part of the Northumberland Basin during early Namurian times. Seen in this context the chaetetid–brachiopod association of the Corbridge Limestone is a clear indication of deposition under shallow and open marine conditions. Without further investigation, reasons for the absence of corals remain totally speculative; however, the incorporation of significant amounts of fine-grained terrigenous material within the limestone, and thick piles of coarser clastic deltaic deposits above and below it may indicate that, following coastline retreat and the onset of lime deposition, conditions were too turbid for coral growth.

An understanding of the stratigraphy of the Stainmore Group in the Corbridge district has, in the past, been hampered by the scarcity of diagnostic goniatites and by the difficulties experienced in mapping key lithostratigraphical marker horizons across poorly exposed and faulted ground into areas where a previously established but different lithostratigraphical nomenclature already exists (Mills and Holliday, 1998). While advances in palynological and micropalaeontological research are currently providing a clearer understanding of the stratigraphy (Owens, 1972, 1978a,b; Riley, 1982b), outstanding correlation problems remain. Because of this, the age of the Corbridge Limestone remains critical to the correlation of Stainmore Group successions across the Northumberland Basin and into the adjoining areas of the Alston Block and Midland Valley Basin. Recent mapping in the Newcastle area (Mills and Holliday, 1998) has confirmed the long-held view (Ramsbottom, 1977b, Ramsbottom *et al.*, 1978) of the Corbridge Limestone as the lateral equivalent of the Lower Fell Top Limestone of the Alston Block (Figure 3.6). The occurrence of low E_2 Zone spores close to this unit, and its correlation with the Mirkfell Ironstones containing *Cravenoceras cowlingense* farther south (Hudson, 1941; Wilson and Thompson, 1959), led Hull (1968) and subsequent authors (Mills and Hull, 1976) to regard the Lower Fell Top Limestone as basal Arnsbergian (E_{2a}) in age. While a similar age for the Corbridge Limestone is generally accepted (Ramsbottom, 1977b; Ramsbottom *et al.*, 1978; Mills and Holliday, 1998), suggestions of a slightly earlier E_1 age are implied by Holliday and Pattison (1990), who compared the Corbridge Limestone faunas with those of the Index Limestone of the Midland Valley Basin, and Johnson *et al.* (1995), who equated the Corbridge Limestone to a horizon a little below the Lower Fell Top Limestone in the Harton Borehole on the Alston Block.

Conclusions

As the type locality of the Corbridge Limestone, the Corbridge Limestone Quarry GCR site provides a vital section for the definition of the Pendleian–Arnsbergian boundary within the Northumberland Basin, and for the correlations within the Stainmore Group throughout northern England. Uncertainties regarding the precise age and depositional environment of this distinctive marine interval serve to highlight the site's significant research potential, particularly in terms of biostratigraphy and sedimentology.

RODDAM DENE, NORTHUMBERLAND (NU 018 207–NU 025 207)

Introduction

The stream section at the Roddam Dene GCR site (NU 0182 2072–NU 0248 2073) provides the best available section of basin-margin alluvial fanglomerate (the Roddam Dene Conglomerate) in Northumberland. Situated close to Wooler on the eastern side of the Cheviots, the section is critical to the understanding of the early evolution of the Northumberland Trough (Leeder, 1974a; Leeder *et al.*, 1989). Although poor biostratigraphical control prevents accurate dating, the conglomerate, which lies at the base of the Cementstone Group, is widely regarded as 'basal' to the Carboniferous succession in the Cheviot area (Lebour, 1886b; Carruthers *et al.*, 1930, 1932; Hickling, 1931; Westoll *et al.*, 1955; George, 1958; Robson, 1965; Taylor *et al.*, 1971; Johnson, 1980; Johnson *et al.*, 1995; Scrutton, 1995). Sedimentological investigations of the Roddam Dene Conglomerate have concentrated on defining sediment origins, environment of deposition and the relationship of the deposit to the adjacent Cheviot landmass. The account that follows derives mainly from the work of Carruthers *et al.* (1930), Westoll *et al.* (1955), Johnson *et al.* (1995) and Turner and Heard (1995).

Description

The Roddam Dene Conglomerate (Figure 3.25) is one of a number of coarse conglomerates that outcrop on the margins of the Cheviot Massif, a late Caledonian (early Devonian) igneous complex dominated by andesitic lavas arranged around an intrusive granite core.

The formation, formerly regarded as part of the Old Red Sandstone (Winch, 1817), is now generally accepted as part of the Cementstone Group and of basal Carboniferous age (Carruthers *et al.*, 1930, 1932; Westoll *et al.*, 1955; Taylor *et al.*, 1971; Robson, 1980; Johnson *et al.*, 1995) despite the absence of diagnostic fossils. Although the apparent interdigitation of the Roddam Dene Conglomerate and Cementstone Group beds, and certain lithofacies similarities between the two units, would appear to support this view (Carruthers *et al.*, 1930; Robson, 1965), Johnson *et al.* (1995)

Figure 3.25 Interbedded fluvial sandstones (below hammer) and flash-flood conglomerates of the Roddam Dene Conglomerate – an alluvial-fan deposit of possible Courceyan age from the Roddam Dene GCR site near Wooler, Northumberland. (Photo: B. Turner.)

indicated that the reported similarities between the two units were entirely superficial. Furthermore, in consideration of thickness variations in the Cementstone Group, Carruthers *et al.* (1930) remarked that the Roddam Dene Conglomerate might even be slightly younger than 'basal' Carboniferous if considered in the regional context. A possible Courceyan age for the deposit has been suggested by Smith and Holliday (1991).

Although structural complexities (small faults and gentle folds) and discontinuous exposure preclude accurate measurement, the estimated thickness of the Roddam Dene Conglomerate locally is around 170 m and generally beds dip to the east at around 9° (Turner and Heard, 1995). The conglomerate occupies a deeply eroded hollow in Cheviot lavas of Lower Devonian age, but neither its unconformable contact with the underlying igneous complex nor its overlying conformable contact with the Cementstone Group is exposed in the section.

Lithologies in the Roddam Dene Conglomerate include a mix of conglomerate, sandstone, shale, mudstone and marl of various colours, but are dominated by massive reddish-coloured conglomerates (Figure 3.25) with subangular to subrounded clasts ranging from pebble to boulder size (4–256 mm) set in a clay-rich sandstone matrix (Turner and Heard, 1995). The predominant conglomerate clasts are of locally derived Cheviot andesite. Rare pebbles of Silurian shale and greywacke, red sandstone and Cheviot granite, granophyre and granodiorite have also been reported (Carruthers *et al.*, 1930; Westoll *et al.*, 1955; Johnson *et al.*, 1995; Turner and Heard, 1995).

The succession includes three fault-bounded conglomeratic units unconformably overlain by a finer clastic interval. The lower conglomerate is generally poorly stratified and matrix-supported, with rare horizontal stratification, tabular cross-stratification and some imbricate pebble fabrics. Some beds appear to fine upwards. The unit gets progressively more sandy with bar-edge wedges, bar-top drapes and channel fills towards its top. Massive cobble conglomerates occupy the middle unit while the higher conglomerate unit coarsens towards its top and is associated with both trough cross-bedded sandstones and pedogenic horizons. The overlying sandy interval consists of a fining-upward sequence of red sandstones and siltstones with plane bedding, trough cross-bedding and an assortment of asymmetric ripples and interference ripples indicative of a possible lacustrine origin. A sharp erosive contact separates this unit from the conglomerates beneath (Johnson *et al.*, 1995; Turner and Heard, 1995; B. Turner, pers. comm., 1998).

Interpretation

The Roddam Dene Conglomerate is interpreted as the product of ephemeral stream systems that drained the deeply eroded margins of a Cheviot landmass that was exposed to semi-arid weathering conditions in Early Carboniferous times. Dramatic variations in rock fabric, grain size and sorting suggest that stream velocity, flow viscosity and sediment discharge rate fluctuated widely. While some matrix-supported conglomerates are likely to be the product of flash-flood-generated debris flows, other better-sorted intervals are likely to be the product of less-viscous stream flows.

The abundance of water-worn Cheviot andesite pebbles in the conglomerate supports the view of a local source for the sediment which must have been transported by fluvial processes. Despite the very close proximity of Cheviot granite at outcrop, some 2–3 km to the west, the occurrence of rare Cheviot granite clasts in the conglomerate has been taken to indicate a northerly derivation for the material (Taylor *et al.*, 1971), and as proof that the Cheviot granite had been 'unroofed' by early Carboniferous times (Robson, 1965).

Leeder's (1974b) original view that the Roddam Dene Conglomerate represented an alluvial fan was later substantiated by others, including Turner and Heard (1995), who suggested an origin from braided streams on an alluvial fan that issued from an elevated land area to the north, edged possibly by an active basin-margin fault scarp (the Harthope Fault?) that controlled fan development. The overlying sandy lithofacies was interpreted as a product of a separate river system draining the Cheviot Block and flowing across a floodplain in an easterly or south-easterly direction after active faulting ceased (Johnson *et al.*, 1995). Supporting evidence for the suggested palaeocurrent directions is provided by imbrication fabrics in the conglomeratic lithofacies and from the orientation of ripples and trough cross-stratification in the sandy lithofacies (B. Turner, pers. comm., 1998).

Conclusions

The Roddam Dene GCR site is the type locality for the Roddam Dene Conglomerate, the finest example of an early Carboniferous alluvial-fan deposit in north-east Northumberland. Its proximity to the Cheviot Block (Johnson, 1984), separating the Northumberland Basin from the Tweed Basin, make it a critical locality for understanding Lower Carboniferous palaeogeography and basin development in north-east England. Continued uncertainty regarding the precise age of the deposit and a lack of published material on sedimentological aspects highlights the site's potential in future research.

GLEBE QUARRY, NORTHUMBERLAND (NU 052 006)

Introduction

Located in the northern part of the Northumberland Basin, the Glebe Quarry GCR site, a disused limestone quarry (NU 0515 0055) 1 km south-west of Rothbury, provides a key section of the Glebe Limestone Member with arguably the thickest continuous development of 'algal' limestone in the north of England. This unit, lying close to the top of the Cementstone Group, provides the clearest possible evidence of the northern limit of marine sedimentation within the Northumberland Trough during the early part of the Carboniferous Period. Although limited biostratigraphical evidence precludes confident dating, recent micropalaeontological work suggests that the section lies at or close to the Chadian–Arundian boundary (Purnell, 1989, 1992; Armstrong and Purnell, 1993). A brief description of the site geology has been given by Garwood (1931), Fowler (1936) and Westoll *et al.* (1955) but modern, published accounts of the sedimentology are altogether lacking. In conjunction with other Northumberland Trough GCR sites in the Tweed Basin (**Burnmouth**) and in the Bewcastle district (**Whitberry Burn**, **Birky Cleugh** and **Ellery Sike**), the outcrops at Glebe Quarry are critical to the understanding of early Carboniferous palaeogeography in northern England.

Description

Although no formal lithostratigraphy for the Cementstone Group has been established so far, the Glebe Limestone Member recognized by Purnell (1989) forms part of the Rothbury Limestones described by Miller (1887) at the top of the Cementstone Group. The same unit is referred to as the 'Rothbury Algal Limestone' by George *et al.* (1976).

Fowler's (1936) description of the exposed section at Glebe Quarry mentions 6.7 m of well-bedded, grey limestone (Figure 3.26) packed with nodular, concentrically laminated oncoids (Figure 3.27) containing the microscopic calcified sheaths of *Ortonella furcata*, a form once regarded as a filamentous blue-green alga (Riding, 1977) and now assigned to the cyanobacteria. A prominent band of oncoids

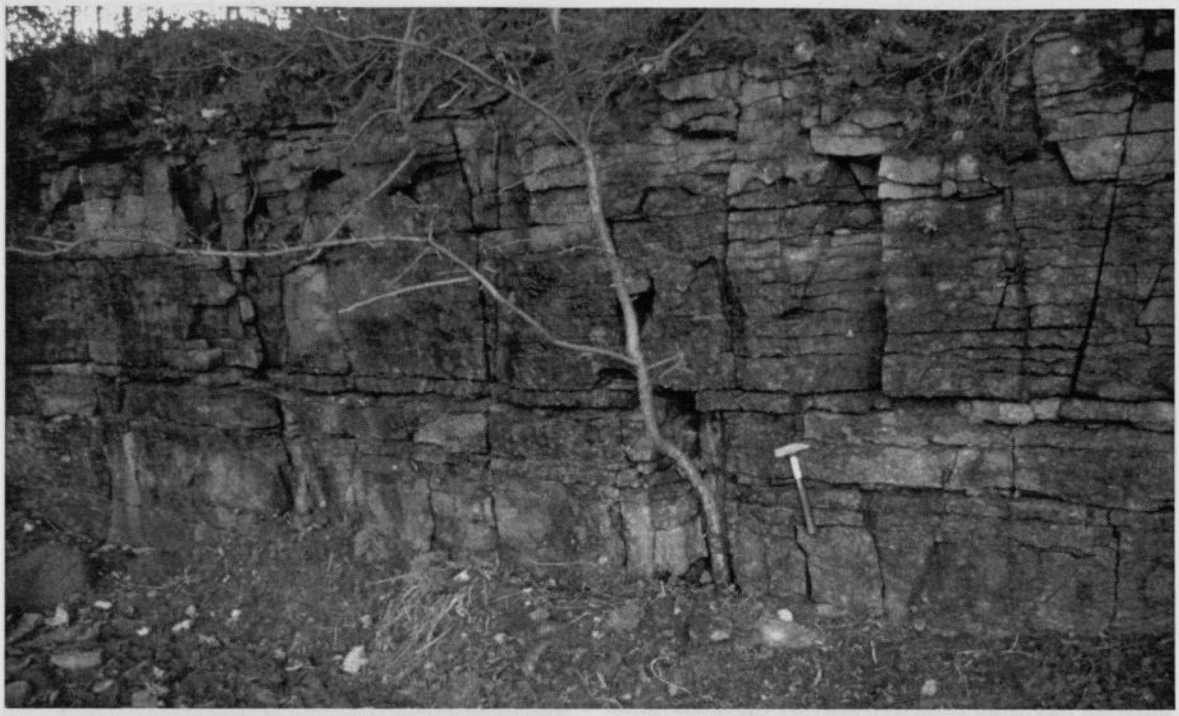


Figure 3.26 Thin-bedded 'algal' (oncoidal) limestones of the Glebe Limestone Member (Cementstone Group) at Glebe Quarry, Rothbury, Northumberland. (Photo: P.J. Cossey.)

nearly a metre thick occurs towards the middle of the sequence. Although widely known from other Lower Carboniferous rocks in northern England and southern Scotland (Anderson, 1950; Leeder, 1975b), the prolific development of *O. furcata* in the Glebe Limestone Member led Garwood (1931) to conclude that the species reached its acme at this horizon. The oncoids range up to 3 cm in diameter and are commonly associated with adnate 'spirorbids', a sparse and possibly restricted fauna of small gastropods, ostracodes, crinoid remains and spongiostromate algal forms (Fowler, 1936). The conodonts *Taphrognathus carinatus* and *T. varians* are also reported from this locality (Purnell, 1992).

Interpretation

Whereas the presence of conodonts and crinoid remains is a clear indication of deposition in a marine environment, their association with oncoids, gastropods and ostracodes, in the absence of open marine forms such as corals and cephalopods, suggests deposition in a restricted but very shallow marginal marine environment that was subject to periodic salinity fluctuations. A peritidal setting for the majority of fossil oncoids has been suggested by Wright (1990a).

The oncoids resemble those described from the Lower Border Group by Leeder (1975b), who made comparisons with Recent material described by Logan *et al.* (1964) and suggested formation in a shallow subtidal setting where there was persistent but gentle substrate agitation. A similar origin is envisaged for the concentrically laminated oncoids (Figure 3.27) in the Glebe Limestone Member which appear to have grown as a result of the accretion of carbonate around mobile grains. A more precise understanding of the mechanism of oncoid development at this site requires further petrographical investigation.

During Early Carboniferous times the Rothbury area formed part of a shallow hypersaline gulf with restricted access to the open ocean. While, to the south-west, both fluvio-deltaic and marine processes appear to have influenced the development of Lower Border Group strata at this time, the role of marine processes is less apparent in the formation of the Cementstone Group (their lateral equivalent in the north-east) which were formed dominantly by fluvio-deltaic and lacustrine processes in an

Figure 3.27 Stained acetate peel illustrating the development of sub-spherical oncoids in the Glebe Limestone Member. Scale bar = 1 cm. (Photo: M.A. Purnell.)

arid alluvial-plain setting (Belt *et al.*, 1967; Smith, 1967; Scott, 1971, 1986; Leeder, 1974b, 1975a, 1992; Johnson, 1984; Chadwick *et al.*, 1995).

Leeder (1974b, 1975a) suggested that the development of gulf carbonate lithofacies interleaved with deltaic deposits in the Lower Border Group was related to periodic phases of delta retreat. In a similar way, the Glebe Limestone Member may have formed as a result of a marine incursion over a subsiding north-easterly derived fluvio-deltaic interval within the Cementstone Group, but further studies are clearly required for the succession to be more fully understood.

Despite early difficulties in the dating and correlation of the algal limestones from Rothbury because of the absence of biostratigraphically useful macrofossils (Johnson *et al.* 1995), correlations with the better known sequences in the Bewcastle district to the south-west have been attempted. Garwood (1931) originally suggested an indirect correlation of the Glebe Limestone Member with the highest algal limestone of the Cambeck Formation, while others (Westoll *et al.*, 1955; Day, 1970; Ramsbottom, 1973) preferred a correlation with the Main Algal Formation, which George *et al.* (1976) regarded as uppermost Courceyan in age (but see **Birky Cleugh** GCR site report, this chapter). Purnell (1989) questioned the validity of these correlations and, on the basis of the occurrence of a *T. varians* conodont biozone fauna, made a tentative correlation of the Glebe Limestone Member with the Bogside Limestone Member at the base of the Bewcastle Formation, a horizon he regarded as basal Arundian in age (Purnell, 1989, 1992; Armstrong and Purnell, 1993). Riley (1993), however, regards the occurrence of both *Taphrognathus carinatus* and *T. varians* as indicative of a late Chadian rather than Arundian age.

Conclusions

The exposed section of Glebe Limestone Member at the Glebe Quarry GCR site contains arguably the most significant occurrence of sub-tidal oncoidal limestone in the Northumberland Basin and is widely regarded as one of the finest developments of 'algal' limestone of the British Carboniferous System (George, 1958). As the most northerly marine interval within the Cementstone Group, the exposures are of considerable importance in understanding the palaeogeography of the Northumberland Basin during its early syn-extensional phase of development. The locality remains an important research site for studies in carbonate sedimentology and palaeontology.

COLOUR HEUGH–BOWDEN DOORS, NORTHUMBERLAND (NU 066 337–NU 070 326)

Introduction

The crags of the Colour Heugh–Bowden Doors GCR site (NU 066 337–NU 070 326), 8 km north-east of Wooler, Northumberland, are among the most impressive and important outcrops of the Fell Sandstone Group in northern England. The group defines an important phase in the evolution of the Northumberland Trough, recording the mid-Viséan (Arundian–Holkerian) activity of a large braided river system which may have been comparable in extent to the braided stretches of the Brahmaputra River in Bangladesh (Monro, 1986; but see Turner *et al.*, 1997). The outcrops at this site preserve excellent sedimentary structures, including unusual overturned cross-stratification and several small, steep-sided channels, and these have featured in several detailed analyses of Fell Sandstone Group sedimentology (e.g. Robson, 1956; Hodgson, 1978; Turner and Monro, 1987). The term 'Fell Sandstone' dates back to Miller (1887) and Fowler (1926), and the lithostratigraphical terminology established in the Northumberland area by these authors has changed little since. The deposit is an important aquifer and source of water for the Berwick-upon-Tweed district. It has also been considered as a potential reservoir for geothermal energy in the Tyneside area (Cradock-Hartopp and Holliday, 1984; Holliday, 1986).

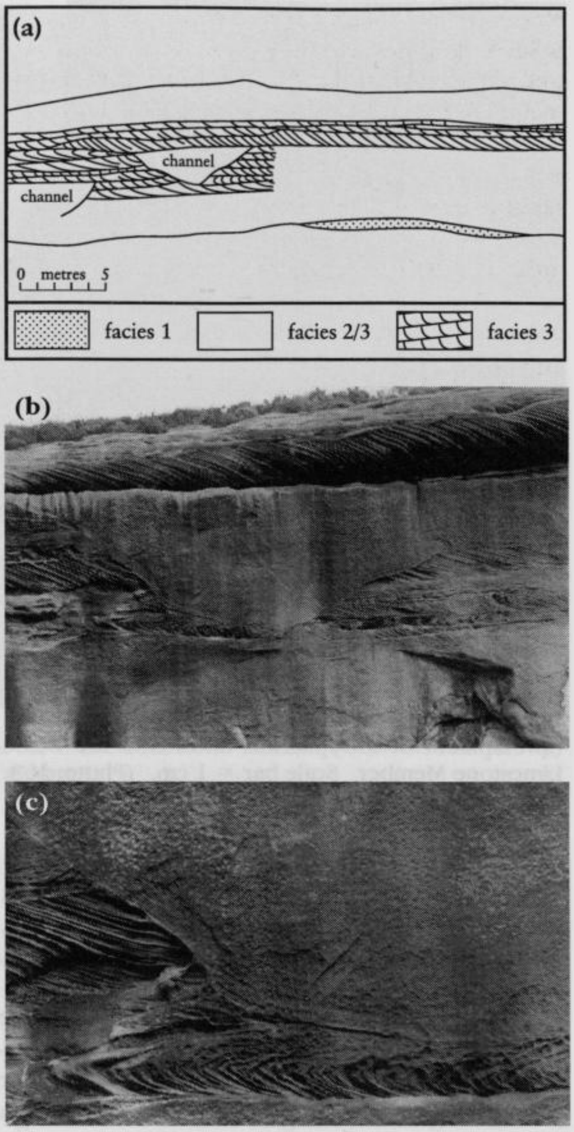


Figure 3.28 (a) Part of the outcrop face at Bowden Doors illustrating the facies distribution within the Fell Sandstone Group and the position of mass-emplaced channel margins. (b) Cross-section of a prominent channel which cuts down 2.5 m through the underlying facies. (c) The channel fill is mostly structureless, but faint diffuse marginal laminations are evident on the left side of the channel. The lower part of the channel intersects with a zone of overturned cross-stratification. After Turner and Monro (1987). (Photos: B. Turner.)

Description

Petrographically, the Fell Sandstone Group consists of moderately to poorly sorted, medium- to coarse-grained, quartz arenites and subarkosic and lithic arenites with subangular to subrounded clasts and a few pebble layers (Monro, 1986). The following description is drawn largely from the work of Turner and Monro (1987). At Colour Heugh and Bowden Doors, several hundred metres of SW-facing crags up to 8 m high expose the upper parts of the Fell Sandstone Group succession, not far below the overlying Scremerston Coal Group (Turner and Monro, 1987; Turner and Heard, 1995). These strata form part of the faulted north-east limb of the Holburn Anticline. Turner and Monro (1987) recognized three facies, the lateral and vertical relationships between which are illustrated in Figure 3.28a. Facies 1, with exposed thicknesses of up to 0.5 m, comprises coarse reddish sandstone with large-scale, but generally poorly defined trough cross-stratification. There is also evidence of scour at the base of this facies. Facies 2 consists of poorly sorted, fine- to medium-grained sandstone. It is generally structureless, but contains undulatory lamination, isolated sets of cross-stratification, some channels and a few water-escape structures. This facies occurs in units of between 3.5 m and 3.75 m thickness. Facies 3 forms units up to 7 m thick, consisting of fine- to medium-grained sandstone with alternating trough and planar cross-stratification (including partially overturned cross-stratified units; see Figure 3.28c) and minor horizontal stratification. These may combine to produce complex patterns of internal structure. Cutting across facies 2 and 3 are nine sharply defined channels (eight at Bowden Doors, one at Colour Heugh). These channels are small, steep-sided, between 1.7 m and 2.5 m deep, and filled with fine- to medium-grained structureless sandstone (Figure 3.28b). At this site, the Fell Sandstone Group is unfossiliferous, although elsewhere, it is known to include wood fragments, bivalves and ostracodes (e.g. Turner *et al.*, 1997).

Interpretation

Although earlier workers considered the Fell Sandstone Group to be at least partly marine in origin (Robson, 1956; Smith, 1967; Hodgson and Scott, 1970) and to include some aeolian beach-dune deposits and littoral beach sands, more recent work has indicated that the Fell Sandstone Group was deposited by a low-sinuosity, perennial, braided river system that flowed westwards into a shallow sea in the Bewcastle area via braid delta complexes (Hodgson, 1978; Monro, 1986; Turner and Monro, 1987; Turner *et al.*, 1993). The areal extent of the river may, however, have been over-estimated, as analysis of the Fell Sandstone Group on a regional scale highlights a number of facies changes that are difficult to explain as a simple consequence of increasing distance from source. These local variations in facies and thickness have been attributed to tectonic control of sand-body development in transfer zones between tilted fault blocks (Turner *et al.*, 1997). Thus, the Fell Sandstone Group river system was probably made up of a number of active braid-plains locally confined by intrabasinal syn-depositional normal faults, and was not a single basin-wide river system (Turner *et al.*, 1993, 1997).

At Bowden Doors and Colour Heugh, facies 1 was deposited in the lower parts of laterally extensive, shallow channels; facies 2 was deposited in channels adjacent to linguoid or transverse bars in which facies 3 was deposited (Turner and Monro, 1987). The channels were formed by sediment-laden mass flows initiated by collapse of the river bank. These flows moved across rather than down the main depositional channel, along scoured, pre-channelized pathways in front of large sandy bedforms. The steep channel banks would have collapsed if unsupported, indicating very rapid cutting and filling of the channel.

The deformation of the cross-stratification at this locality has been attributed to shear resulting from sediment-laden water acting on the top of the original sandy bedform (Turner and Monro, 1987).

Conclusions

The Fell Sandstone Group preserves a sedimentary succession of considerable importance in understanding the Northumberland Trough's depositional systems, palaeogeography and evolution during mid-Viséan times. The Colour Heugh–Bowden Doors GCR site is of considerable regional importance as one of the best inland exposures of the Fell Sandstone Group in Northumberland, and is renowned throughout the north of England for the spectacular preservation of its sedimentary structures.

BURNMOUTH, SCOTTISH BORDERS (NT 971 589–NT 958 615)

Introduction

The Burnmouth GCR site is a foreshore section located adjacent to the village of Burnmouth (NT 9540 6095). It encloses a wave-cut platform that extends some 2.7 km from Burnmouth Bay in the north-west to Lamberton Skerrs in the south-east. This provides near-continuous exposure through more than 600 m of strata that are typical of the Lower Carboniferous deposits of this north-eastern area of the Northumberland Trough (often referred to as the Tweed Basin). The exposed section extends from the upper Old Red Sandstone, through the complete sequence of the Cementstone Group (the best section through this facies anywhere in the Northumberland Trough), into the Fell Sandstone Group. Parts of the Scremerston Coal Group and the Lower Limestone Group are also exposed. This section spans an interval from the Tournaisian through to the Asbian. The site is arguably the most important Tournaisian–Viséan section in the Northumberland Trough, primarily because of the completeness of exposure through Cementstone Group facies which contrast markedly with their more marine equivalents to the west (see **Ellery Sike**, **Birky Cleugh** and **Whitberry Burn** GCR site reports, this chapter) and because of exposure of the contact between the Cementstone Group and the overlying Fell Sandstone Group. Superbly developed sedimentological features demonstrate contrasting styles of fluvial, lacustrine and some deltaic deposition.

Detailed correlation between eastern and western parts of the Northumberland Trough remains problematic and although the stratigraphical terminology applied in the Tweed Basin is somewhat out of step with other areas, the terminology of Fowler (1926) and Greig (1988) is used in this account. Scott (1985), Greig (1988, 1992) and Scrutton and Turner (1995) provide detailed accounts of the geology of this site and much of the description below is based on their reports.

Description

The Lower Carboniferous strata exposed across the foreshore at this site strike northwards more-or-less parallel to the coast and form part of the steep eastward-dipping limb of the northern end of the Berwick Monocline (Figure 3.29). The succession youngs to the east (seawards) and is downthrown by the Boundary Fault (Shiells, 1964) against Silurian or lower Old Red Sandstone strata lying inland to the west. This fault has a slightly sinuous, northward trend and forms a western margin to the Carboniferous outcrop along the full length of this coastal section. Beds adjacent to the fault are often locally overturned; elsewhere the dips in the section vary between vertical and about 70° eastwards.

Another major fault crossing the site is the NE-trending Hilton Bay Fault, which diverges from the Boundary Fault near the centre of Hilton Bay beach. The closure of the Berwick Monocline is exposed near the southern end of the site, in the southern headland of Hilton Bay. The succession is intruded by a number of E–W-trending tholeiite and quartz dolerite dykes up to 12 m in thickness (see Greig, 1988, for more details).

At the northern end of the site, near Burnmouth, the basal 50 m of succession is of Old Red Sandstone facies (Figure 3.29). Up to five erosive-based fining-upward sequences are present, each comprising generally red-coloured erosive-based, coarse-grained, trough cross-stratified sandstone, overlain by fine-grained sandstones, siltstones and silty mudstones containing irregular, calcareous cornstone-like layers. The critical few metres of outcrop covering the junction between these rocks and the overlying Cementstone Group is covered by beach material and is rarely, if ever, exposed, but the contact is interpreted as being conformable (Smith, 1968; Scrutton and Turner, 1995).

The Cementstone Group is completely exposed on the foreshore between Burnmouth Bay and Ross Point, and consists of more than 450 m (Greig, 1988; Scrutton and Turner, 1995) of interbedded sandstones, shales and argillaceous dolomites ('cementstones') (Figure 3.29). Sedimentological investigations of the group have been made by Smith (1967) and subsequently by Scott (1971), who recognized two major facies associations. The first association consists of a repeated fining-upward sequence made up of a basal, cross-stratified, fine-grained sandstone unit containing intraformational clast conglomerates, overlain by an upper unit within which siltstones and mudstones predominate. These fining-upward associations together form almost half of the total thickness of the sequence and they are the major component of the succession in the upper part of the group. The fining-upward sequences are characterized by well-developed, laterally accreted point-bar deposits and fine-grained channel fills. Lag conglomerates occurring in these fluvial sandstones contain intraformational clasts of cementstone, and many such sandstone units cut erosively into underlying cementstone horizons. The second facies association consists of laterally continuous, thinly bedded sandstones (usually < 1 m), silty mudstones and cementstones. These beds are in places mottled and contain modiolid bivalves, ostracodes, burrows (including *Chondrites*) and evidence of bioturbation. This association is particularly evident in the lower part of the group. Cementstone Group sandstones are feldspathic (subarkosic), moderately sorted, often tightly cemented and micaceous. The cementstones are, in the main, argillaceous ferroan dolomites and examples of the various types defined by Belt *et al.* (1967) are readily found within the sequence. In addition, reddened cementstone horizons occur in the upper part of the sequence. Some coarsely crystalline, nodular carbonate horizons have anhydrite inclusions and other mineralogical features indicative of an origin as replacements after nodular anhydrite (Scott, 1986). Scott and Rex (1987) noted the presence of permineralized plant remains (*Lepidodendron calamopsoides* and *Stauropteris berwickense*) in a silty wackestone horizon in the Cementstone Group at this locality.

The Burnmouth site is one of very few localities that expose the contact between the Cementstone Group and the overlying Fell Sandstone Group. This contact is an undulating erosion surface, in places cutting down 2–3 m. The Fell Sandstone Group is exposed across a

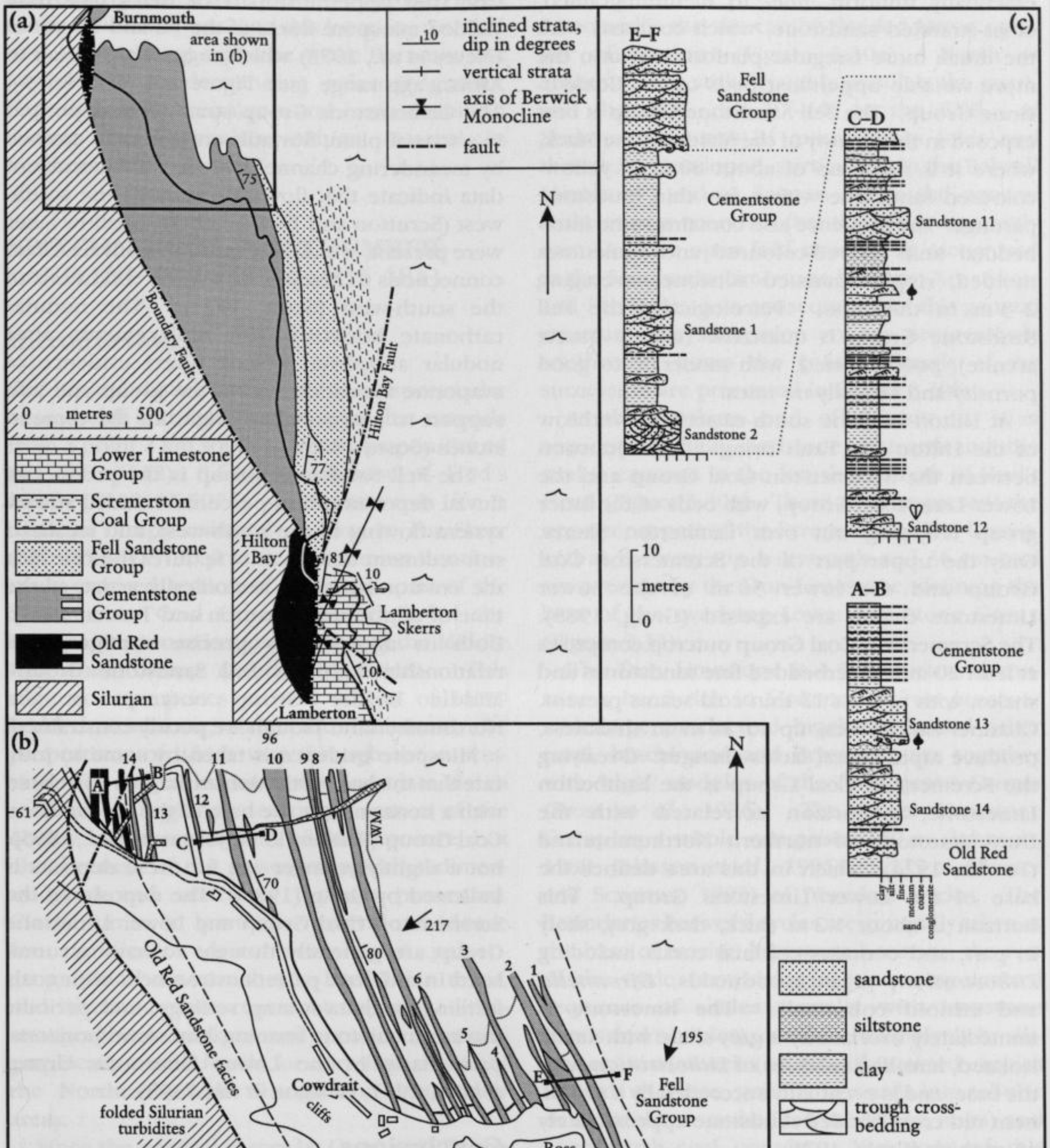


Figure 3.29 The Lower Carboniferous geology of the Burnmouth GCR site. (a) Simplified geological map after Smith (1967). (b) Detailed geological map, and (c) sedimentary log, after Scrutton and Turner (1995).

smooth wave-cut platform scoured out of an essentially uniform, fine- to medium-grained, cross-stratified sandstone, which contrasts with the much more irregular platform cut into the more variable uppermost beds of the Cementstone Group. The Fell Sandstone Group is best exposed in the vicinity of the Maidenstone Stack, where it is made up of about 80 m of yellow-coloured sandstone with a few thin mudstone partings. The sequence also contains some interbedded units of red-coloured and sometimes mottled, ripple-laminated siltstones averaging 2–3 m in thickness. Petrologically, the Fell Sandstone Group is quartzose (mostly quartz arenite), poorly sorted, with moderate to good porosity and virtually no mica.

At Hilton Bay, the south-easterly downthrow of the Hilton Bay Fault brings in the junction between the Scremerston Coal Group and the Lower Limestone Group, with beds of the latter group cropping out over Lamberton Skerrs. Only the upper part of the Scremerston Coal Group and the lower 50 m of the Lower Limestone Group are exposed (Greig, 1988). The Scremerston Coal Group outcrop comprises at least 20 m of interbedded fine sandstones and shales, with at least 12 thin coal seams present. Channel sandstones, up to 14 m in thickness, produce rapid lateral facies changes. Overlying the Scremerston Coal Group is the Lamberton Limestone, a horizon correlated with the Dun Limestone of northern Northumberland (Fowler, 1926), which in this area defines the base of the Lower Limestone Group. This horizon is about 1.2 m thick, dark grey, shaly in part, and contains colonial corals including *Lithostrotion*, gigantoproductids, *Girvanella* and crinoid columnals. The limestone is immediately overlain by a grey shale with small, isolated, lens-like colonies of *Lithostrotion* near the base, and is eventually succeeded by a prominent red cross-bedded sandstone approximately 45 m thick (Greig, 1971).

Interpretation

A Tournaisian age for the Old Red Sandstone at this site is indicated by unpublished spore evidence (Leeder, 1974b). These rocks reflect deposition in a continental alluvial setting with fluvial channel sandstones and fine-grained fluvio-lacustrine deposits containing calcretes.

The lack of diagnostic macrofossils in the Cementstone Group also creates difficulties with age assignment, but laterally equivalent strata from the uppermost part of the group have yielded miospore floras of the Pu and TC zones (Neves *et al.*, 1973) which suggest a Chadian to Asbian age range (see Figure 1.4, Chapter 1). The Cementstone Group strata were deposited in a coastal plain, fluviatile environment crossed by meandering channel systems. Palaeocurrent data indicate that flow was towards the south-west (Scrutton and Turner, 1995). Shallow lakes were present, which may intermittently have had connections to brackish or marine conditions to the south-west (Scott, 1971). The nodular carbonate horizons with replacements after nodular anhydrite provide direct evidence of evaporate formation within the group and add support to a hypersaline origin for the cementstones (Scott, 1986).

The Fell Sandstone Group is the product of fluvial deposition by a perennial braided stream system flowing to the south-west, and localized soft-sediment deformation features indicate that the environment was tectonically active at the time of deposition (Scrutton and Turner, 1995). Both its age and its precise stratigraphical relationship to other Fell Sandstone Group–Middle Border Group outcrops in the Northumberland Trough are poorly constrained.

Miospore evidence is taken by some to indicate that the base of the Asbian Stage is correlated with a horizon near the base of the Scremerston Coal Group (Wilson, 1974; Johnson *et al.*, 1995), but a slightly younger age for these deposits is indicated by Greig (1988). The deposits of the Scremerston Coal Group and Lower Limestone Group are generally thought to have accumulated in a deltaic palaeoenvironment with coals forming in delta-swamp settings, and periodic marine incursions forming limestone horizons, particularly in the Lower Limestone Group (Smith, 1967; Johnson *et al.*, 1995).

Conclusions

The Burnmouth GCR site contains some of the best and most complete sections of the lower part of the Lower Carboniferous sequence in the Northumberland Trough. Exposures of the Cementstone Group seen here are among the finest examples of Lower Carboniferous coastal plain, fluvial and lacustrine facies associations anywhere in Britain. Also exposed are several important stratigraphical boundaries that are rarely seen elsewhere. The site is situated between the Midland Valley Basin to the north and other parts of the Northumberland Trough to the south and west, and this location, coupled with the quality of exposure, make Burnmouth a key site for understanding palaeogeography, depositional environments and basin evolution during the Tournaisian–Asbian interval in northern Britain.

SPITTAL SHORE, NORTHUMBERLAND (NU 009 511–NU 035 481)

Introduction

The Spittal Shore GCR site is a spectacular coastal cliff and foreshore section that extends from a point 2 km south of Berwick-upon-Tweed (NU 0093 5112), 0.6 km north-west of Hud's Head (NU 0135 5076) south-eastwards for a distance of approximately 4.3 km to Far Skerr (NU 035 481). It provides an almost continuously exposed section of the upper part of the Scremerston Coal Group, the whole of the Lower Limestone Group and most of the Middle Limestone Group (Asbian–Brigantian). This sequence comprises around 450 m of interbedded sandstone, shale and limestone, the proportions of which vary through the succession. The site ranks among the finest late Viséan sections in England, not only because of the quality and completeness of the exposure, but also because of the palaeontological, sedimentological and structural features preserved. Clastic units in particular provide evidence for significant environmental and palaeogeographical changes during late Viséan times, and limestone units represent important lithostratigraphical markers and provide biostratigraphically useful fossils for correlations within the Northumberland Trough and into other areas.

Since the original survey by Gunn (1897), the site has been the subject of numerous geological investigations, principally by Fowler (1926), Frost (1969), Breare (1986), Lees (1991), Reynolds (1992), Frank and Tyson (1995) and Turner and Scrutton (1995). The account below, however, focuses particularly on the work of Reynolds (1992) and Turner and Scrutton (1995). The site and its stratigraphical significance are also discussed in overviews of the Carboniferous rocks of the area (e.g. Johnson, 1980; Johnson *et al.*, 1995).

Description

Structurally, the site can be divided into a number of sections (Figure 3.30a). North of Seahouse, the strike roughly parallels the coast, and the rocks dip 30°–60° to the ENE. At Seahouse, a series of minor sharp folds and thrusts are developed, particularly in the Eelwell Limestone, and at Saltpan Rocks the general strike swings round so that the rocks dip gently east. A more open fold structure is recognized in the Sandbanks Limestone between Near Skerr and Far Skerr. As a consequence of this general structure, the succession youngs progressively southwards down the coast. Details of the succession are presented in Figure 3.30b.

At the northern end of the site, a 30 m sequence of shale, sandstone, seatearth and thin coal is exposed in the foreshore north of Hud's Head (Figure 3.30a). These rocks represent the uppermost part of the Scremerston Coal Group, and at the very top a seatearth and 36 cm coal are overlain by the Dun Limestone, defining the base of the overlying Lower Limestone Group (Figure 3.31).

The Dun Limestone is 1.5 m thick and contains a band rich in *Siphonodendron junceum* with large productoid brachiopods and other coral, brachiopod and bryozoan taxa together with 'algal' nodules of the form genus *Osagia* (Frost *et al.*, 1976). The Lower Limestone Group as a whole comprises 150 m (Johnson, 1980; Johnson *et al.*, 1995) to 175 m (Turner and Scrutton, 1995) of 'Yoredale' cycles. The boundaries between cycles are generally taken at the base of marine limestone horizons, the rest of the cycle comprising a coarsening-upward sequence of shales (usually with ironstone bands and nodules), overlain successively by siltstones, sandstones (often with starved ripples towards the base, grading upwards into tabular or lenticular cross-bedded sandstone units) and a seatearth–coal couplet. Variations of this idealized sequence occur throughout the group, but in general, thin and well-spaced coals occur throughout, with thick intervening shales and sandstones, some of which are strongly channelized. The sequence above the Dun Limestone, for example, includes a thick sandstone with intersecting lenticular, fine-grained cross-bedded units near the base, overlain by coarse-grained multistorey sand-bodies with planar cross-stratification developed towards the top. This is overlain in turn by shale, into

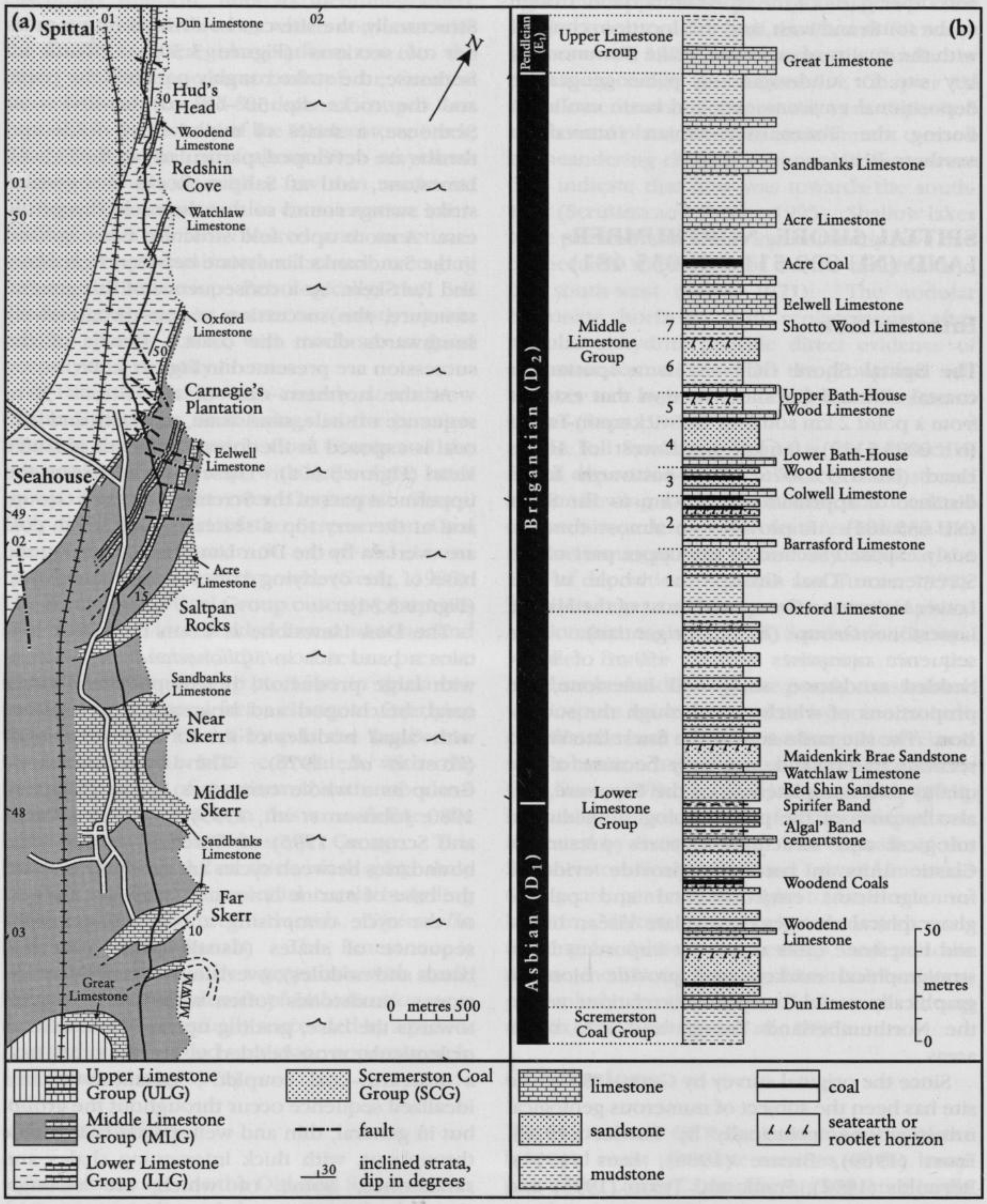


Figure 3.30 (a) Simplified geological map and (b) section of Lower Carboniferous Lower Limestone Group to Middle Limestone Group strata exposed at the Spittal Shore GCR site, Berwick-upon-Tweed (details of the Scremerston Coal Group and Upper Limestone Group omitted). After Turner and Scrutton (1995), with additional section details from Frost (1969) and Reynolds (1992). Numbers in (b) relate to cyclothemic sedimentary cycles identified in the Middle Limestone Group beds by Reynolds (1992).

Figure 3.31 Lateral accretion surfaces (epsilon cross-bedding) in fluvio-deltaic channel sandstones near the top of the Scremerston Coal Group at Hud's Head in the Spittal Shore section (the hammer, for scale, is 30 cm long). Above this, a prominent bed, the Dun Limestone (1.5 m thick), marks the base of the overlying Lower Limestone Group. (Photo: P.J. Cossey.)

which a major sandstone-filled channel is cut containing small- to medium-scale trough cross-bedding. A prominent calcrete is developed below the limestone (Woodend Limestone) at the base of the next cycle.

The Woodend Limestone (2 m) contains a noteworthy coral fauna that is dominated by colonies of *S. junceum* in their growth position, but which also includes *S. martini*, *Lithostrotion maccoyanum*, *Dibunophyllum*, *Caninia* and the calcareous sponge *Chaetetes septosus*. This limestone is overlain by a coarsening-upward cycle ending with the Woodend Coals (Turner and Scrutton, 1995) which probably equate with the Little Howgate Coal of Fowler (1926), shown on the [British] Geological Survey map of the Berwick-upon-Tweed and Norham district (Institute of Geological Sciences, 1977a). About 15 m higher in the sequence, an unfossiliferous limestone described by Scrutton and Turner (1995) as 'cementstone' and a distinctive 'algal' band with *Somphospongia* cf. *multiformis* occur together with a 4.5 m-thick oil shale containing fish debris, ostracodes and plant fragments (Frost *et al.*, 1976). At least part of this sequence is equivalent to the Doupster Oil Shale (Fowler, 1926; Institute of Geological Sciences, 1977a), but above this point the older description of the sequence (Fowler, 1926; Institute of Geological Sciences, 1977a) differs significantly from more recent accounts. For example, Fowler (1926) claimed that there was a pronounced unconformity in this part of the succession that occurred over much of north Northumberland and which accounted for the absence of the Watchlaw Limestone in the Berwick area. Frost (1969), Johnson (1980), Johnson *et al.* (1995) and Turner and Scrutton (1995), however, indicate that the Watchlaw Limestone (2 m) is present in the Berwick section sandwiched between the Red Shin Sandstone and Maidenkirk Brae Sandstone (see Figure 3.30b). A few metres below the Red Shin Sandstone is the distinctive Spirifer Band. Above the Maidenkirk Brae Sandstone, the remaining upper part of the Lower Limestone Group comprises a cyclic siliciclastic succession almost 60 m thick.

The Oxford Limestone (5 m) defines the base of the Middle Limestone Group (250 m). This group is similar to the underlying Lower Limestone Group in that it is made up of a series of 'Yoredale' cycles, but the limestones are thicker and laterally more persistent, and there are some distinctive differences in the siliciclastic facies. Reynolds (1992) discussed the sedimentology of these siliciclastic facies, analysing the seven cycles between the Oxford Limestone and the Eelwell Limestone exposed on Spittal Shore in great detail (Figure 3.30b). These cycles are between 8 m and 36 m thick. They commence with a thin shale and are overlain by a marine limestone (mostly skeletal wackestones and packstones). The limestones pass gradually into a black shale at the base of a coarsening-upward clastic interval in which the degree of bioturbation decreases upwards. These sequences have either wave-ripple lamination or storm-influenced structures, including hummocky cross-stratification. In some cycles the top of the coarsening-upward succession is capped by a palaeosol, and this in turn may be overlain by channel sands or by another coarsening-upward cycle. A palaeosol or a coal, overlain by a marine shale, marks the top of a complete cycle. Reynolds (1992) identified a number of distinctive facies in the Spittal Shore sequence: a cross-bedded facies with a range of features, including bipolar opposed palaeoflows and cross-beds with claystone drapes; a heterolithic facies dominated by rippled sandstone and mudstone; a hummocky cross-stratified and a migrating hummocky cross-stratified facies; a climbing-ripple facies; a wave-ripple facies; a plane-laminated facies; a mudstone-free cross-bedded facies; and a microswale facies. He singled out a prominent distributary channel sandstone of his cycle 2 (the cycle containing the Barrasford Limestone) for particular attention (see Figure 3.32). The basal 1 m of this erosive-based 5 m-thick unit is dominated by rippled sandstone and mudstone of the heterolithic facies, with rippled sandstone commonly passing laterally into medium-scale trough cross-beds. The central portion of the sand-body is characterized by cross-beds up to 50 cm thick that indicate a palaeoflow to the south. The upper part of the unit is characterized by medium-scale cross-beds with evidence of repeated changes of palaeoflow directed to the north-west and to the south and south-east.

Some of the limestone units of the Middle Limestone Group are also quite distinctive, and have been correlated over considerable

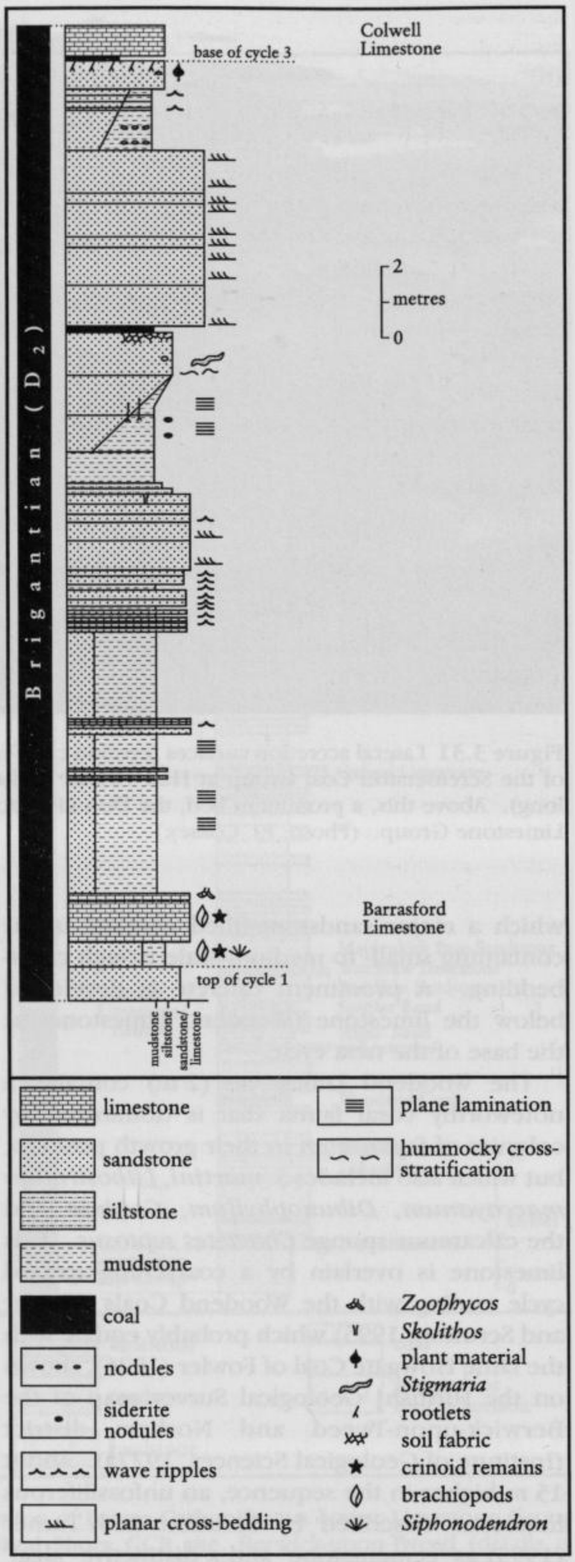


Figure 3.32 Graphic log of Middle Limestone Group (Brigantian) sedimentary cycle 2 at the Spittal Shore section. After Reynolds (1992). See text for further details.

distances. The Oxford Limestone is poorly fossiliferous, but for the occurrence of nodular algal structures with crinoid stem cores coated by red 'haloes' containing *Girvanella* (Frost *et al.*, 1976). The Eelwell Limestone (8 m) is easily distinguished by its prominent fauna of large *Gigantoproductus* and corals including *S. junceum*. A layer of spiriferoid brachiopods occurs near the top of the unit. The limestone is also locally dolomitized, brown weathering and vuggy. Overlying a thin sulphurous coal, the Acre Limestone (4.5 m) is of a similar character, containing a rich coral–brachiopod fauna, crinoid remains and small algal nodules. Towards the top of the sequence, and the southern end of the site, the Sandbanks Limestone is made up of a series of thin limestone beds with shaly partings. In addition to layers with abundant brachiopods, and prominent solitary corals (mainly *Aulophyllum pachyendothecum*, with rarer *Palaeosmilia murchisoni*) excellent examples of the trace fossil *Zoophycos* occur, and the top of the unit contains characteristic dark-brown chert nodules. The sandstones beneath the Sandbanks Limestone also have a well-preserved ichnofauna including *Diplocraterion* and the beaded burrow *Eione moniliforme*. Further details of the distribution of trace-fossil assemblages in this section are presented by Lees (1991).

Interpretation

Like much of the sedimentary fill of the Northumberland Trough, the sequence exposed at Spittal Shore reflects the interplay of fluvio-deltaic and shallow marine depositional systems. The gross changes in the proportions of limestone, sandstone and shale from the Scremerston Coal Group, through the Lower Limestone Group and into the Middle Limestone Group record a gradual increase in marine influence and a decrease in periods of emergence. The coarsening-upward siliciclastic sequences of the Lower Limestone Group reflect delta progradation, with the development of facies characteristic of interdistributary bay, distributary channel and floodplain environments reflecting the 'classic' interpretation of 'Yoredale' cycles in the Carboniferous System of the UK. A somewhat different interpretation was envisaged by Reynolds (1992) for the Middle Limestone Group in which tidal distributary channels developed, and storm and wave processes dominated the delta fronts. In more detail, the thin shale at the base of each cycle records the gradual flooding of the lower delta plain (represented by the underlying palaeosol), and the succeeding limestone represents the withdrawal of clastic supply. The gradual resumption of clastic input is marked by the transition into bioturbated shales, the upward decrease in bioturbation in the siliciclastic phase of the cycle reflecting progressively higher sedimentation rates and lower salinities. The coarsening-upward sequences record the gradual infilling of protected marine embayments where ripples dominated, followed by progradation of storm-dominated shoreline deposits with hummocky cross-stratification (hummocky cross-stratified facies and climbing-ripple facies reflecting storm activity). The wave-ripple facies, plane-laminated facies, mudstone-free cross-bedded facies and micro-swale facies of Reynolds (1992) reflect periods of wave-dominated sedimentation. The channel of cycle 2 described briefly in the preceding section provides important evidence for tide-dominated sedimentation, the upper part of the unit recording the alternating palaeocurrent directions of the ebb and flood tides.

Although the Spittal section contains a rich and varied suite of lithofacies, it is also rather poorly fossiliferous and this has caused problems in correlating the section into neighbouring areas of the Northumberland Trough (Figure 3.5) and Midland Valley Basin. Early workers (Miller, 1887; Fowler, 1926, 1936) regarded the Dun Limestone as the equivalent of the Redesdale Limestone in south Northumberland (see **Redesdale** GCR site report, this chapter) but subsequent [British] Geological Survey mapping and micropalaeontological evidence indicated that the former was likely to be some 150–170 m above the latter (Frost *et al.*, 1976; Frost and Holliday, 1980). In addition, Frost and Holliday (1980) correlated the Spirifer Band with the Low Tipalt Limestone. This established the local base of the Brigantian Stage, as the Low Tipalt Limestone is correlated with the Peghorn Limestone, the base of which defines the base of the stage (George *et al.*, 1976; Frost and Holliday, 1980; see **Tipalt Burn** GCR site report, this chapter, and **Janny Wood** GCR site report, Chapter 5). George *et al.* (1976) and Johnson *et al.* (1995) seem to indicate a Peghorn–Low Tipalt–Watchlaw correlation. The Spittal section is also believed to equate in part with the Upper Liddesdale Group succession exposed at **Penton Linns** (see GCR site report, this chapter; and Figure 3.5.

Structurally, the minor folds and thrusts in the area of Seahouse have recently been interpreted as part of the synclinal member of a monoclinal fold pair, thus establishing the easterly vergence of the 'Berwick Monocline'. This suggests that the formation of the Berwick Monocline was controlled by strength and density contrasts within the Caledonian basement (Roper, 1997).

Conclusions

The Spittal Shore GCR site contains one of the finest late Viséan sections in England. The exposed succession preserves important evidence of changing palaeoenvironments and of secular trends in delta–marine interactions during Asbian and Brigantian times. The site contains good examples of 'Yoredale' cycles, with well-developed sequences reflecting tide-, wave- and storm-influenced deltaic deposition. They provide important reference sections against which other 'Yoredale' cycles may be compared for such influences. Several of the limestones of the Lower Limestone Group and Middle Limestone Group contain well-preserved and diverse faunas, some of which are used as important lithostratigraphical marker horizons of regional significance in correlations across the Northumberland Basin and into the areas beyond.

PENTON LINNS, DUMFRIES AND GALLOWAY–CUMBRIA (NY 431 772–NY 437 774)

Introduction

Situated to the south-east of Langholm on the border between England and Scotland, the gorge at Penton Linns, Liddel Water (NY 431 772–NY 437 774) provides one of the finest inland sections of the Upper Liddesdale Group (Brigantian) in the Northumberland Trough. The section is also renowned for the high quality of the preservation of its crinoid faunas. Peach and Horne (1903) included some information on the site in their account of the structure of the Canonbie Coalfield. The Langholm and Bewcastle memoirs (Lumsden *et al.*, 1967; Day, 1970) include details of the section and Monro (in Stone, 1996) has written an excursion guide to the locality. The site is most accessible from its northern side.

Description

At Penton Linns, the Liddel Water has eroded a course across an asymmetrical anticlinal structure and exposed an excellent, fault-bounded section containing 130 m of strata belonging to the central part of the Upper Liddesdale Group. The succession, which is of 'Yoredale' type, extends from the Penton Limestone at the base, to the sandstones overlying the Harelawhill Limestone at the top. A simplified log of the exposed section, based on information in Lumsden *et al.* (1967) and Day (1970), is presented in Figure 3.33. Extensive faunal records from the section are also recorded by Day (1970). In the core of the anticline the upper parts (6.7 m) of the Penton Limestone are exposed as beds of limestone with calcareous shale partings. The limestone contains patches of *Girvanella*, and near its top, *Zoophycos*, *Gigantoproductus* and large solitary corals (including *Aulophyllum pachyendothecum*, *Clisiophyllum* and *Dibunophyllum bipartitum*) occur. Gastropods, bivalves and colonial corals (*Siphonodendron junceum*, *Diphyphyllum* cf. *lateseptatum*) are also found in this unit. The clastic parts of this cycle (12.8 m) consist of mudstones passing up into siltstones, silty sandstone and a rooty sandstone capped by a thin coal seam (0.07 m).

Above this, 1.5 m of calcareous shale with gigantoproductids and broken shell fragments pass up into the poorly fossiliferous Bridge Limestone (3.7 m), which contains large crinoid stem fragments, corals (*S. pauciradiale*), *Zoophycos* and some brachiopods and bivalves. From the interval between the Penton Limestone and Bridge Limestone, Day (1970) also recorded *Dibunophyllum* cf. *bourtonense*. The calcareous shales overlying the Bridge Limestone (2.0 m) are rich in brachiopods, bryozoans and bivalves. These are overlain by a thick sandstone (9.6 m) which passes up into a rooty seatearth with a thin coal seam (0.05 m) on top. Above this, a calcareous sandstone (1.8 m) with roots and a few fossils has been interpreted as a decalcified limestone. This interpretation is based upon the correlation of strata from the nearby Archerbeck Borehole where a limestone is present at this level (Lumsden *et al.*, 1967). A

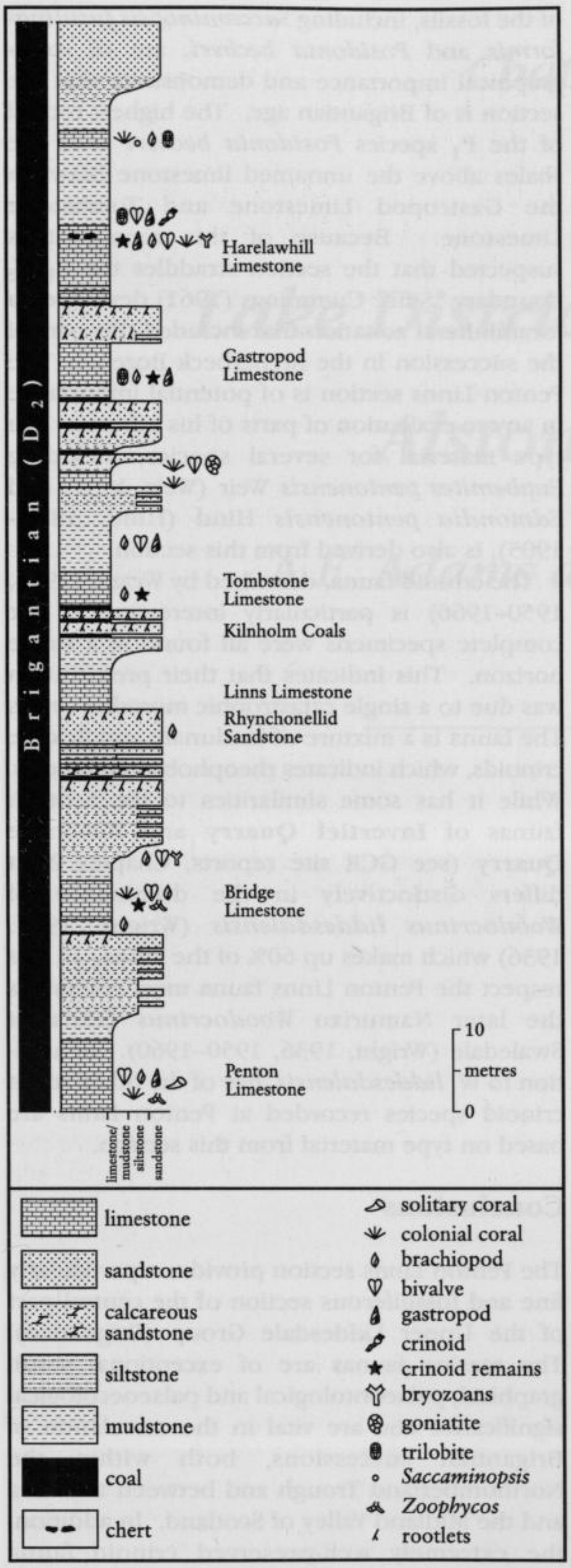


Figure 3.33 Simplified stratigraphical log of the Upper Liddesdale Group (Brigantian) succession at the Penton Linns GCR site, near Langholm. Based on information in Lumsden *et al.* (1967) and Day (1970).

thin (3.0 m) sequence of mudstones and sandstones occurs between this sandstone and the Rhynchonellid Sandstone, another rooty sandstone, containing brachiopod fragments in which the eponymous form is particularly well represented. This is immediately overlain by the crinoidal, dolomitic Linns Limestone (4.3 m), which has a red-stained iron-rich upper surface. The clastic components of this cyclothem are mudstones, sandstones and seatearths (5.8 m) with three thin coal seams (the Kilnholm Coals).

The Tombstone Limestone, which is the marine unit of the next cycle, consists of sparsely crinoidal and bioclastic limestone beds with shale partings. The limestone gets its name from the well-developed jointing pattern which divides the posts up into rectangular slabs. The overlying shales with ironstone nodules (7.0 m) contain a prolific fauna of brachiopods, bivalves and gastropods, and both Lumsden *et al.* (1967) and Day (1970) have drawn attention to the presence here of the stratigraphically useful bivalve *Posidonia becheri*. The mudstones pass up into a sandstone (3.7 m). Above this, a thin (1.2 m), unnamed limestone with a red-stained upper surface contains *S. pauciradiale*. The overlying shales contain an abundant and diverse fauna including *Microcyathus cyclostomus*, *Edmondia pentonensis*, *Posidonia becheri* and *Beyrichoceratoides truncatum*? (Lumsden *et al.*, 1967; Day, 1970). These shales (1.7 m) are overlain by sandstones and siltstones (8.2 m) with three thin coal seams. Resting on these beds are the mudstones (1.4 m) that underlie the Gastropod Limestone.

The Gastropod Limestone (5.1 m) is bedded with calcareous shale partings. It contains a fauna of crinoid columnals, brachiopods, molluscs and trilobites but its most characteristic feature, from which it gets its name, is a bed at the top of the unit which is rich in poorly preserved pleurotomariid gastropods (Lumsden *et al.*, 1967). Sandstones, in places rooty and capped by a thin coal seam (4.6 m), lie between the Gastropod Limestone and the Harelawhill Limestone. This latter limestone is the thickest limestone in the sequence (9.6 m). Faunas from it include gastropods, bivalves and trepostomous bryozoans. It also includes a thick (1.0 m) calcareous shale parting, with productoid and spiriferoid brachiopods, and large crinoid columnals, 1.3 m above the base. Towards the top of the limestone there are several bands of chert nodules. Colonies of *S. junceum* in the limestone are the highest records for this species in the local sequence. The roof shales (1.0 m) of the limestone are rich in productoid and spiriferoid brachiopods, but also contain crinoids, trilobites, bivalves, gastropods and cephalopods (Peach and Horne, 1903; Lumsden *et al.*, 1967). It was in these shales that Wright (1924, 1936) collected a large number of more-or-less complete crinoids and, probably also, the type material of the gastropod *Euphemites pentonensis* (Weir, 1931). The shales pass up into siltstones and silty mudstones with ironstone nodules (17.1 m) which include, about 3 m above their base, a 1.5 m limestone band with patches of *Saccaminopsis fusulinaformis*. Marine fossils are also common in the shales immediately above the limestone. The section is completed by a thick, fine-grained sandstone (7.3 m). Further details of the fauna from beds above the Harelawhill Limestone are reported by Day (1970).

Interpretation

The Penton Linns section provides a vital exposure of a sequence through part of the Upper Liddesdale Group (Brigantian), which is otherwise poorly exposed and best known from the nearby Archerbeck Borehole. Correlations by Day (1970) have equated the Penton Limestone, Bridge Limestone, Linns Limestone, Tombstone Limestone, Gastropod Limestone and Harelawhill Limestone with, respectively, the Greengate Well Limestone, Jew Limestone, Tyne Bottom Limestone, Single Post (= Lower and Upper Bath-House Wood) Limestone, Scar Limestone and 5 Yard Limestone recorded elsewhere. However, some of these correlations appear to be contradicted by work in other areas (see **Tipalt Burn** site report, this chapter, and Figures 3.5, 3.18 and 3.30 for further details). The cyclicity developed in the Upper Liddesdale Group provides evidence of rapid palaeogeographical changes with marine conditions, in which calcareous shales and limestones were deposited, alternating with delta-front and delta-top conditions, in which coarsening-upward terrigenous clastic units were deposited. These are often capped by rooty seatearth or ganister beds and thin coal seams, which represent fossil soils.

The different marine horizons have a variable and sometimes distinctive fossil content. Some of the fossils, including *Saccaminopsis fusulinaformis* and *Posidonia becheri*, are of stratigraphical importance and demonstrate that the section is of Brigantian age. The highest record of the P_1 species *Posidonia becheri* is in the shales above the unnamed limestone between the Gastropod Limestone and Tombstone Limestone. Because of this record it is suspected that the section straddles the P_1–P_2 boundary. Since Cummings (1961) developed a foraminiferal zonation that included this part of the succession in the Archerbeck Borehole, the Penton Linns section is of potential importance in any re-evaluation of parts of his scheme. The type material for several species, including *Euphemites pentonensis* Weir (Weir, 1931) and *Edmondia pentonensis* Hind (Hind, 1896–1905), is also derived from this section.

The crinoid fauna, described by Wright (1924, 1950–1960) is particularly interesting as the complete specimens were all found at a single horizon. This indicates that their preservation was due to a single catastrophic mortality event. The fauna is a mixture of inadunate and flexible crinoids, which indicates rheophobic tendencies. While it has some similarities to the Scottish faunas of **Invertiel Quarry** and **Roscobie Quarry** (see GCR site reports, Chapter 2) it differs distinctively in the dominance of *Woodocrinus liddesdalensis* (Wright, 1924, 1936) which makes up 60% of the fauna. In this respect the Penton Linns fauna most resembles the later Namurian *Woodocrinus* fauna of Swaledale (Wright, 1936, 1950–1960). In addition to *W. liddesdalensis*, five of the other seven crinoid species recorded at Penton Linns are based on type material from this section.

Conclusions

The Penton Linns section provides a particularly fine and fossiliferous section of the central part of the Upper Liddesdale Group (Brigantian). The marine faunas are of exceptional stratigraphical, palaeontological and palaeoecological significance and are vital in the correlation of Brigantian successions, both within the Northumberland Trough and between this area and the Midland Valley of Scotland. In addition, the extremely well-preserved crinoid fauna above the Harelawhill Limestone is an early occurrence of the *Woodocrinus* fauna, and arguably one of the finest examples of its kind in northern England.