British Lower Carboniferous Stratigraphy

P.J. Cossey
Department of Geology, School of Sciences,
Staffordshire University, College Road, Stoke-on-Trent ST4 2DE

A.E. Adams
Department of Earth Sciences,
University of Manchester, Oxford Road, Manchester M13 9PL

M.A. Purnell
Department of Geology,
University of Leicester, University Road, Leicester LE1 7RH

M.J. Whiteley
Barrisdale Limited, 16 Amberley Gardens, Bedford MK40 3BT

M.A. Whyte
Department of Environmental and Geological Sciences,
University of Sheffield, Dainton Building, Brookhill, Sheffield S3 7HF

V.P. Wright
Department of Earth Sciences,
Cardiff University, PO Box 914, Main Building, Park Place, Cardiff CF10 3YE

with contributions from
P. Gutteridge (Cambridge Carbonates Limited, Nottingham)
N.J. Riley (British Geological Survey, Keyworth)
J. Miller (Department of Continuing Education, Edinburgh) ,
G.M. Walkden (Department of Geology and Petroleum Geology, University of Aberdeen)

GCR Editor: L.P. Thomas

JOINT NATURE CONSERVATION COMMITTEE

Chapter 6

Craven Basin

P.J. Cossey, N.J. Riley, A.E. Adams and J. Miller

INTRODUCTION

The Craven Basin, which here includes the Bowland Basin of Ramsbottom (1974) and Gawthorpe (1986, 1987a) and the Lancaster Fells Basin of Gawthorpe *et al.* (1989), is an asymmetric half-graben embracing a number of depositional 'highs' and 'lows' south of the Askrigg Block and South Lake District High (Figure 6.1). The base of the Dinantian succession is not seen and has not been reached by boreholes, but a maximum of at least 2 km of Dinantian strata is known, and gravity modelling and seismic evidence suggest the thickness could be twice this figure (Gawthorpe *et al.*, 1989; Aitkenhead *et al.*, 1992; Kirby *et al.*, 2000).

To the east of Settle, the boundary between the Askrigg Block and the Craven Basin is largely marked by the Middle Craven Fault. To the west of Settle, although mostly obscured by Upper Carboniferous outcrop, there is geophysical evidence for the existence of a WNW-trending fault boundary as far as Ingleton, where it joins the Dent Fault (Arthurton *et al.*, 1988) and meets the South Lake District High. From here the northern boundary of the basin trends south-westwards to the Carnforth–Lancaster area (Figure 6.1).

The southern margin of the basin is masked by Upper Carboniferous deposits, but thickness and facies variations (Miller and Grayson, 1982; Gawthorpe, 1987a) and geophysical data

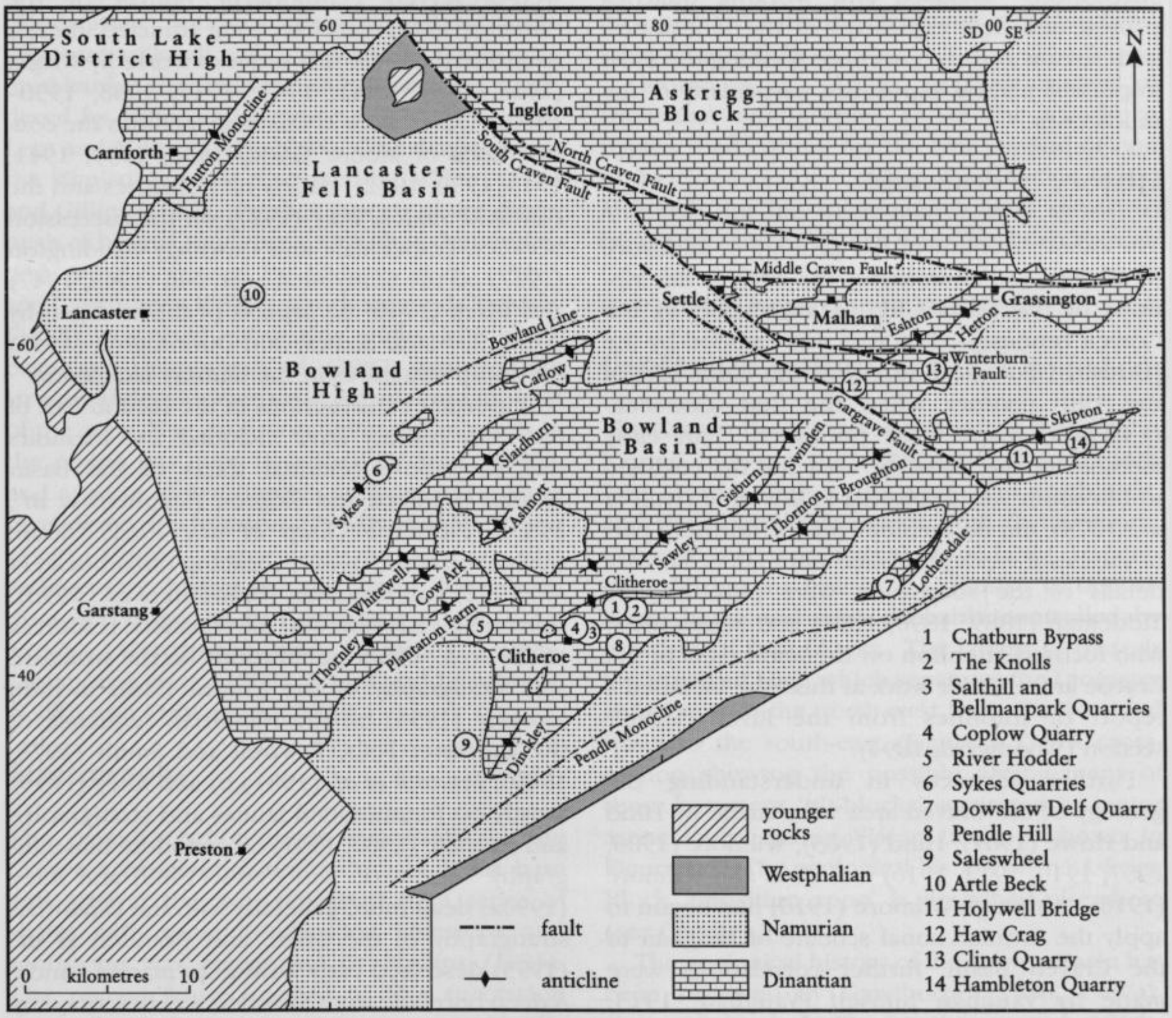


Figure 6.1 Geological map of the Craven Basin illustrating the distribution of Carboniferous outcrops and the locations of GCR sites described in the text. Note that in the Bowland Basin area, the hinge traces of major folds within the Ribblesdale Fold Belt are also shown. The Central Lancashire High lies to the south of the Pendle Monocline beneath the area obscured by the key. Based on Riley (1990a) and Brandon *et al.* (1998).

1 Chatburn Bypass
2 The Knolls
3 Salthill and Bellmanpark Quarries
4 Coplow Quarry
5 River Hodder
6 Sykes Quarries
7 Dowshaw Delf Quarry
8 Pendle Hill
9 Saleswheel
10 Artle Beck
11 Holywell Bridge
12 Haw Crag
13 Clints Quarry
14 Hambleton Quarry

(Arthurton *et al.*, 1988; Lee, 1988a,b; Fraser and Gawthorpe, 1990; Fraser *et al.*, 1990) suggest that the boundary was a fault at depth beneath the Pendle Monocline (Figure 6.1; and see Evans and Kirby, 1999; Kirby *et al.*, 2000). This fault separated the Craven Basin from an area of relatively stable basement with a thin Lower Carboniferous succession, known as the 'Central Lancashire High' (Figure 1.3, Chapter 1; and see Miller and Grayson, 1982).

Outcrop in the area is almost entirely of Carboniferous rocks. Away from the northern margin of the basin, earlier Carboniferous strata are seen mostly in a series of NE–SW-trending anticlines which form part of the Ribblesdale Fold Belt (Figure 6.1). Exposure is generally poor, especially of the fine-grained rocks in the succession. Disused and working quarries provide the best exposures of the limestones, with stream and river sections forming the most important natural exposures, particularly of the mudstones.

History of research

The classic account of the geology of Yorkshire by Phillips (1836) contains the earliest descriptions of the Carboniferous succession in the Craven Pennines. The area was mapped by the [British] Geological Survey in the latter part of the 19th century when the first 'one-inch' (1:63 360) maps were published. An early memoir for the Clitheroe area and the coalfield to the south was published at this time (Hull *et al.*, 1875), but no memoirs for the northern part of the basin were published until later. Further details of the succession were published by Tiddeman (1889, 1890, 1891) and Marr (1899) who focused attention on the knoll reefs of the Cracoe area. Other work at this time included a report of trilobites from the River Hodder section (Woodward, 1894).

Further advances in understanding the geology of the Craven area were made by Hind and Howe (1901), Hind (1903), Wilmore (1906, 1907, 1910, 1912, 1916) and Hind and Wilmore (1918). Although Wilmore (1910) had begun to apply the Avonian zonal scheme of Vaughan to the Craven Basin, further correlations were made by Vaughan himself (Vaughan, 1915, 1916). In the middle years of the 20th century the contributions of four workers stand out. Bisat's work on goniatites led to refinements in the stratigraphy, particularly of the Bowland Shales (Bisat, 1924, 1928, 1933, 1950, 1952). Parkinson (1926, 1935, 1936, 1944, 1950b, 1952a, 1957, 1967, 1968, 1974a) published on the geology of the Clitheroe and Slaidburn areas, with a particular emphasis on the faunas and origin of the Clitheroe knolls. Hudson and various co-workers studied the Carboniferous succession of the Askrigg Block, Craven Basin and the 'transition zone' (see Chapter 5) between these areas. Papers that consider the geology of the Craven area include Booker and Hudson (1926), Hudson (1927, 1933, 1938a,b, 1944b, 1945, 1949), Hudson and Versey (1935), Hudson and Mitchell (1937) and Hudson and Dunnington (1944). It was Hudson (1933) who first introduced the term 'Craven Basin'. The well-preserved echinoderm faunas of the Clitheroe knoll reefs have long attracted interest and were the focus of a series of works by Wright (1928, 1935, 1942, 1943, 1947, 1948, 1950–1960). Other work at this time includes the contributions of Moore (1930, 1936, 1939, 1941, 1946, 1950, 1952), largely on goniatites and the Bowland Shales; Bray (1927) on the succession between Lothersdale and Cowling; Waddington (1927) on the Stonyhurst area; Gill (1940, 1947) and Black (1940) on aspects of the stratigraphy of the Bowland Shales; and Dunnington (1945) on slump structures in the Embsay Limestone.

Important contributions in the second half of the 20th century have included five memoirs that describe substantial tracts of the basin around Bradford and Skipton (Stephens *et al.*, 1953), Clitheroe (Earp *et al.*, 1961), Settle (Arthurton *et al.*, 1988), Garstang (Aitkenhead *et al.*, 1992) and Lancaster (Brandon *et al.*, 1998). Harrison (1982) reviewed the limestone resources of the area. Other publications on the structure and stratigraphy of the Craven Basin include Moseley (1954) on the Namurian sequence of the Lancaster Fells, Fewtrell and Smith (1978, 1980), Fewtrell *et al.* (1981a,b) and Riley (1995) mostly on foraminiferal faunas and stratigraphy, and Metcalfe (1980, 1981) on conodont biostratigraphy. Arthurton and Jones (1980) and Riley (1990a) dealt more generally with the Dinantian stratigraphy of the basin, and Brandon *et al.* (1995) described early Namurian marine bands. A deep borehole from Swinden was described by Charsley (1984). Aspects of the structure of the area have been described by Moseley (1962), Arthurton (1984) and Lee (1988a,b).

Faunas of the area have continued to attract interest and more recent contributions include Westhead (1967, 1979), Donovan and Sevastopulo (1985, 1988), Donovan (1986, 1992) and Donovan and Westhead (1987) on echinoderms; Osmólska (1968) and Miller (1973) on trilobites; Riley (1982a, 1985, 1987, 1996) on trilobites and ammonoids; Mitchell and Somerville (1988) on corals; and Chapman *et al.* (1993) on dendroid graptolites.

Contributions on sedimentology include Trotter (1952) on the Namurian sequence, and Black (1952) and Bathurst (1959, 1982) on the origin of the sparry calcite fabrics ('Stromatactis') in the Clitheroe Limestone Formation. The PhD thesis of Barraclough (1983) covered aspects of the sedimentology of the basin, and the origin and development of 'Waulsortian' buildups (also referred to in the literature as 'knoll reefs', 'reef knolls', 'carbonate mud-banks' and 'mud-mounds') has been considered by Miller and Grayson (1972, 1982) and Lees and Miller (1985, 1995). The diagenesis of the Waulsortian was discussed by Miller (1986) and Gillies (1987). Further aspects of the diagenesis of basinal sequences, including dolomitization, were discussed by Addison *et al.* (1985) and Gawthorpe (1987b). Gawthorpe and Clemmey (1985) described submarine slides within the basin and Lawrence *et al.* (1987) reviewed the structural development and petroleum potential of the area. The evolution of Pendleian sands in the region has been described by Sims (1988), and aspects of Arnsbergian sedimentation were considered by Johnson (1981) and Martinsen (1990, 1993). Aspects of the tectonic and sedimentary history of the basin have been discussed in papers by Gawthorpe (1985, 1986, 1987a), Gawthorpe and Clemmey (1985), Gawthorpe *et al.* (1989), Fraser and Gawthorpe (1990) and Kirby *et al.* (2000).

Stratigraphy

The overall Carboniferous succession in the Craven area, comprising limestones at the base and grits at the top, separated by a series of shales with some interbedded limestone and sandstone was recognized by Phillips (1836). The nomenclature applied to this succession was refined during the early mapping by the [British] Geological Survey when some of the current terms such as 'Bowland Shales' and 'Pendleside Limestone' were introduced. The knoll reefs were named by Wilmore (1907) and correlations to other areas were made by Wilmore (1916) and Vaughan (1915, 1916). The zonation of the Bowland Shales was established by Bisat (1924).

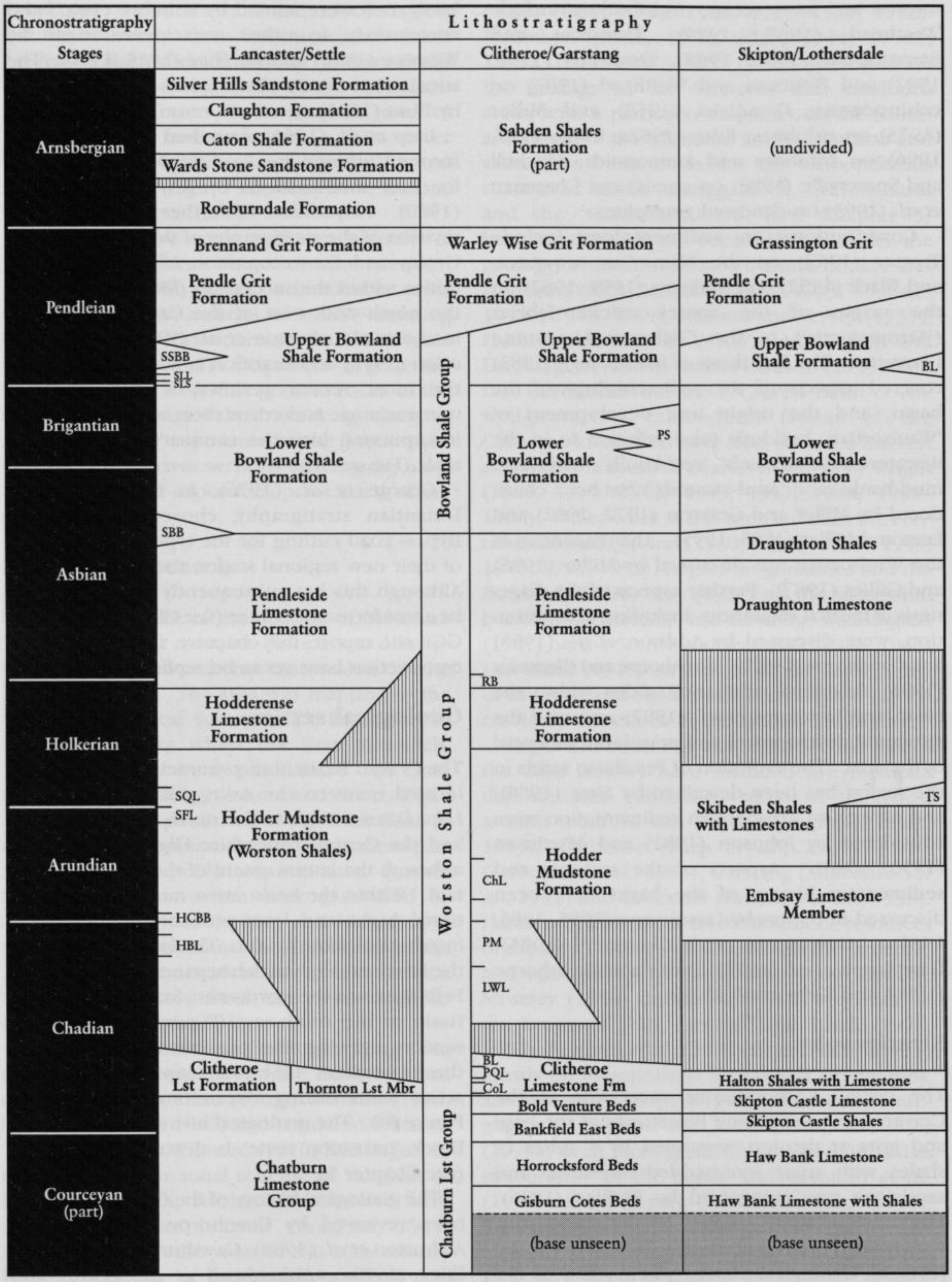
Earp *et al.* (1961) described the stratigraphy for the Clitheroe area and this formed the basis for later modifications by Fewtrell and Smith (1980). Acquisition of further data allowed a revision of the stratigraphy of the Worston Shale Group and the recognition of four unconformities within the succession (Riley, 1990a). For the north and west of the Craven Basin, the memoirs of Arthurton *et al.* (1988), Aitkenhead *et al.* (1992) and Brandon *et al.* (1998) contain the most recent reviews of stratigraphical nomenclature and correlation, and their data is incorporated into the summary stratigraphical table (Figure 6.2).

George *et al.* (1976), in their review of Dinantian stratigraphy, chose the Chatburn Bypass road cutting for the type section of one of their new regional stages, the Chadian Stage. Although this has subsequently been shown to be an unfortunate choice (see **Chatburn Bypass** GCR site report, this chapter), the stage and its type section have yet to be replaced.

Geological setting

The Craven Basin is an asymmetrical half-graben located between the Askrigg Block and South Lake District High to the north and north-west, and the Central Lancashire High to the south, although the lateral extent of the latter is uncertain. Within the basin are a number of depositional highs and lows probably controlled by intrabasinal fault blocks. The largest of these is the Bowland High which separates the Lancaster Fells Basin to the north-west from the Bowland Basin to the south-east (Figure 6.1). A cross-section showing the possible arrangement of these basement 'tilt-blocks' separated by major active faults during Viséan times is shown in Figure 6.3. The geological history of the Askrigg Block 'transition zone' is described elsewhere (see Chapter 5).

The geological history of the Craven Basin has been reviewed by Gawthorpe (1986, 1987a), Arthurton *et al.* (1988), Gawthorpe *et al.* (1989), Riley (1990a), Aitkenhead *et al.* (1992) and Brandon *et al.* (1998). The base of the


Chronostratigraphy
Lithostratigraphy
Stages
Lancaster/Settle
Clitheroe/Garstang
Skipton/Lothersdale
Arnsbergian
Silver Hills Sandstone Formation
Claughton Formation
Caton Shale Formation
Wards Stone Sandstone Formation
Roeburndale Formation
Sabden Shales Formation (part)
(undivided)
Pendleian
Brennand Grit Formation
Warley Wise Grit Formation
Grassington Grit
Pendle Grit Formation
Pendle Grit Formation
Pendle Grit Formation
Upper Bowland Shale Formation
Upper Bowland Shale Formation
Upper Bowland Shale Formation
SSBB
SLL
SLS
BL
Brigantian
PS
Lower Bowland Shale Formation
Lower Bowland Shale Formation
Lower Bowland Shale Formation
Bowland Shale Group
Asbian
SBB
Draughton Shales
Pendleside Limestone Formation
Pendleside Limestone Formation
Draughton Limestone
RB
Holkerian
Hodderense Limestone Formation
Hodderense Limestone Formation
Worston Shale Group
SQL
SFL
Hodder Mudstone Formation (Worston Shales)
Skibeden Shales with Limestones
TS
Arundian
Hodder Mudstone Formation
ChL
Embsay Limestone Member
HCBB
HBL
PM
LWL
Chadian
BL
PQL
CoL
Clitheroe Lst Formation
Thornton Lst Mbr
Clitheroe Limestone Fm
Halton Shales with Limestone
Bold Venture Beds
Skipton Castle Limestone
Bankfield East Beds
Skipton Castle Shales
Courceyan (part)
Chatburn Limestone Group
Chatburn Lst Group
Horrocksford Beds
Haw Bank Limestone
Gisburn Cotes Beds
Haw Bank Limestone with Shales
(base unseen)
(base unseen)

◂**Figure 6.2** Simplified stratigraphical chart for the Lower Carboniferous succession of the Craven Basin. (HBL – Hetton Beck Limestone Member; HCBB – Haw Crag Boulder Bed; SFL – Scaleber Force Limestone Member; SQL – Scaleber Quarry Limestone Member; SBB – Scaleber Boulder Bed; SLS – Sugar Loaf Shales; SLL – Sugar Loaf Limestone; SSBB – School Share Boulder Bed; CoL – Coplow Limestone Member; PQL – Peach Quarry Limestone Member; BL – Bellman Limestone Member; LWL – Limekiln Wood Limestone Member; PM – Phynis Mudstone Member; ChL – Chaigley Limestone Member; RB – Rad Brook Mudstone Member; PS – Pendleside Sandstones Member; TS – Twiston Sandstone Member; BL – Berwick Limestone.) Areas of vertical ruling indicate non-sequences. Not to scale. Compilation based on Hudson and Mitchell (1937), Metcalfe (1981), Arthurton *et al.* (1988), British Geological Survey (1989), Riley (1990a, 1995), Aitkenhead *et al.* (1992), Brandon *et al.* (1995, 1998).

Carboniferous succession is nowhere seen, and geophysical evidence suggests that only half the full thickness of Dinantian strata is seen at the surface (Gawthorpe *et al.*, 1989; Aitkenhead *et al.*, 1992; Kirby *et al.*, 2000). The latter authors suggested that, by analogy with other areas, the concealed succession is likely to be composed of basal terrigenous clastics overlain by tidal-flat deposits, possibly including evaporites. Later Courceyan and early Chadian times are represented by a thick succession (up to 3 km) of fairly uniform dark muddy limestones interbedded with calcareous shales. These were deposited on a southerly dipping ramp (Gawthorpe, 1986). Little variation in thickness or facies is apparent in the exposed part of this succession, suggesting that although subsidence was rapid, it was fairly even across the basin and that sedimentation rates kept pace, maintaining water depths. However, in early Chadian times thickness and facies variations become apparent indicating that differential subsidence had begun. At this time, the Waulsortian buildups (regarded here as carbonate mud-banks) developed on the flanks of fault blocks within the basin (Miller and Grayson, 1982; Lees and Miller, 1985). Probable facies variations on the carbonate ramp at this time are shown in Figure 6.4. A major unconformity at the early–late Chadian (Tournaisian–Viséan) boundary can be traced throughout the basin and is recognizable internationally across Eastern Europe and into Asia.

Differential subsidence continued into Arundian times with the development of a marked sea-floor topography. Minor unconformities developed on local highs, with dominantly fine terrigenous deposits (Worston Shales) accumulating in the lows (Gawthorpe, 1986). Local turbidites and sedimentary slides occurred during this interval (Dunnington, 1945; Gawthorpe and Clemmey, 1985; Gawthorpe, 1986). From late Arundian to early Asbian times there was a gradual increase in carbonate sedimentation, which Gawthorpe (1986) and Gawthorpe *et al.* (1989) related to the gradual establishment of a carbonate shelf margin along the southern side of the Askrigg Block. Much of the basinal area was described as a slope environment by Gawthorpe (1986) and facies variations are shown on Figure 6.4. The late Asbian to Brigantian interval was marked by renewed tectonism. The deep basin was characterized by background mud sedimentation

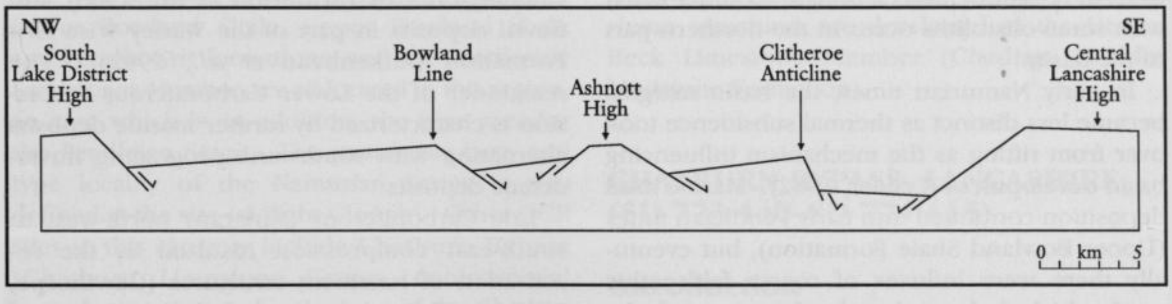


Figure 6.3 Schematic section across the Craven Basin from the South Lake District High to the Central Lancashire High showing the possible basement structure during the Arundian–Brigantian interval. After Riley (1990a).

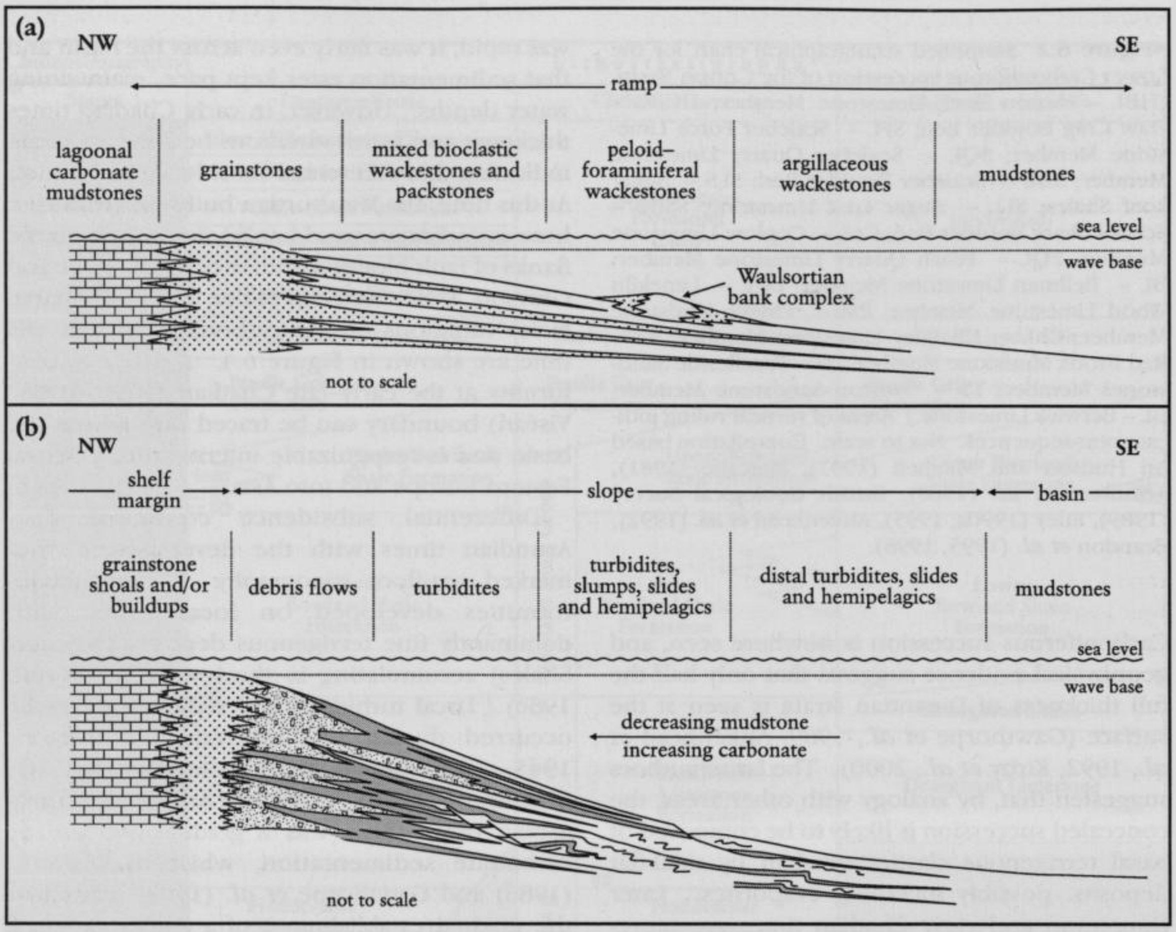


Figure 6.4 (a) Lateral facies variations along the carbonate ramp that characterized the Craven Basin during the Courceyan–Chadian interval. (b) Facies variations down the slope environments of the Craven Basin during the Arundian–Asbian interval. After Gawthorpe (1986).

(Lower Bowland Shale Formation) with some siliciclastic and carbonate turbidites (e.g. Pendleside Sandstones Member), but major units of re-sedimented carbonate (boulder beds) with some olistoliths occur in the northern part of the basin.

In early Namurian times, the basin margins became less distinct as thermal subsidence took over from rifting as the mechanism influencing basin development (Leeder, 1982). Marine mud deposition continued into early Pendleian times (Upper Bowland Shale Formation), but eventually there were influxes of coarse feldspathic sand which led to the development of the Pendle, Warley Wise, Grassington and Brennand grits. Brought in by a major river flowing from the north or north-east, and deriving sediment from eastern Greenland, these sediments were initially deposited in marine conditions (Sims, 1988). However, with the progression of time, deltas prograded southwards such that delta-top sediments are recognized in parts of the Grassington Grit (Arthurton *et al.*, 1988) and fluvial deposits in part of the Warley Wise Grit Formation (Aitkenhead *et al.*, 1992). The remainder of the Lower Carboniferous succession is characterized by further marine deposits alternating with southwards-prograding fluvio-deltaic deposits.

Late Carboniferous (Variscan) north-west to south-east compression resulted in the re-activation of basement structures (Gawthorpe, 1987a). This subsequently led to a period of basin inversion, which caused the development of a series of *en echelon* folds (Ribblesdale Fold Belt), the reversal of throws on normal faults and the development of local thrust faults (Corfield *et al.*, 1996).

GCR site coverage

The choice of GCR sites in the Craven Basin reflects key episodes in the structural, stratigraphical and palaeogeographical evolution of the basin during Lower Carboniferous times. Their location is illustrated on Figure 6.1. The sites can be conveniently subdivided into three groups.

The first of these groups includes sites of outstanding stratigraphical importance, either because they contain the type section of a particular stratigraphical interval (or intervals) or because they contain an especially thick or complete succession. Most of these sites are located away from the basin margin. Two sites stand out as being especially significant on account of the range of stratigraphy that is represented and because of their great size. The first of these, the **River Hodder** GCR site, provides a classic section through arguably the finest and thickest deep-water marine and hemipelagic sequence of Viséan (Chadian–Asbian) age in Britain, and includes the type sections of the Hodder Mudstone Formation, the Limekiln Wood Limestone and Chaigley Limestone members, and the Hodderense Limestone Formation. Key sections of the younger Pendleside Limestone and Lower Bowland Shale formations are also represented at the site. The second, at **Pendle Hill** (a composite GCR site comprising the Little Mearley Clough, Little Mearley–Limekiln and Light Clough GCR sites), offers an extensive section ranging from the Hodder Mudstone Formation through to the Pendle Grit Formation (Holkerian–Pendleian) and is one of the classic sites of late Dinantian and early Namurian ammonoid (goniatite) biostratigraphy. The type sections of the Pendleside Limestone, Lower Bowland Shale, Upper Bowland Shale and Pendle Grit formations, and the Pendleside Sandstones Member, are all located in this region, an area which is, in addition, the type area for the Pendleian Stage. The stratotypic base and type locality of the Namurian Series is also defined at the site (at Light Clough). Other GCR sites in this category include **Chatburn Bypass** (Chatburn Limestone Group, controversial boundary stratotype for the base of the Chadian Stage); **Holywell Bridge** (Haw Bank Limestone–Skipton Castle Limestone, Courceyan–Chadian); and **Saleswheel** (Warley Wise Grit Formation, Sabden Shales Formation, candidate as boundary stratotype for the base of the Arnsbergian Stage).

The second group includes sites located towards the basin margin where relatively thin and/or incomplete successions are developed, and which are commonly punctuated by non-sequences and/or debris beds of regional stratigraphical and tectono-sedimentary significance. These include **Haw Crag** (Chadian–Arundian, unconformity between the Thornton Limestone Member (Clitheroe Limestone Formation) and the Worston Shales (Hodder Mudstone Formation) and the Haw Crag Boulder Bed); **Clints Quarry** (Holkerian–Brigantian, unconformity between the Worston Shales (Hodder Mudstone Formation) and the Pendleside Limestone Formation, limestone conglomerate, coral faunas); **Hambleton Quarry** (?Holkerian–Asbian, Skibeden Shales with Limestones (Hodder Mudstone Formation), the Draughton Limestone with Tiddeman's Breccia and the Draughton Shales (Pendleside Limestone Formation)); **Dowshaw Delf Quarry** (Arundian–Holkerian, unconformity within the Hodder Mudstone Formation between the Embsay Limestone Member and the Twiston Sandstone Member); and **Artle Beck** (Arnsbergian, unconformity between the Roeburndale and Wards Stone Sandstone formations, plus basin-margin thickening of the Eumorphoceras yatesae Marine Band).

A third group comprises sites of particular sedimentological and/or palaeontological interest. Among these are **Coplow Quarry**, **Salthill and Bellmanpark Quarries**, and **The Knolls** GCR site – a complex suite of sites close to Clitheroe which illustrate a range of features associated with the development of 'Waulsortian' mudbank facies in the Chadian Clitheroe Limestone Formation and which contain rich echinoderm faunas. A further site in this category is **Sykes Quarries** where spectacular gravity slide and slump structures are developed in the Hetton Beck Limestone Member (Chadian, Hodder Mudstone Formation).

CHATBURN BYPASS, LANCASHIRE (SD 773 440–SD 774 445)

Introduction

The Chatburn Bypass GCR site lies in a cutting on the A59 trunk road immediately east of Chatburn village and 4 km north-east of Clitheroe (SD 774 445–SD 773 440) (see Figure 6.7, **The Knolls** GCR site report, this chapter). A thick section of the Chatburn Limestone Group is exposed, comprising a substantial part of the Bankfield East Beds and the base of the overlying Bold Venture Beds (Figure 6.2). The site is particularly important since it was said to illustrate the regressive phase of Ramsbottom's (1973) 'Major Cycle 1' and the early part of 'Major Cycle 2', and was chosen by George *et al.* (1976) to be the stratotype for the Chadian Stage, named after St Chad from whom Chatburn also derives its name. The biostratigraphy of the section has been described and discussed by Riley (1993, 1995) and the sedimentology described by Barraclough (1983).

Description

The complete section on both sides of the road cutting totals 186.2 m in thickness and is made up of 163.1 m of Bankfield East Beds, overlain successively by the Four Foot Shale (1.4 m) and 21.7 m of Bold Venture Beds (Riley, 1995). Strata dip southwards on the southern limb of the Clitheroe Anticline. The rocks are mostly pale grey- or brown-weathering fine bioclastic limestones which are dark grey or black when fresh. Individual limestones are typically between 0.2 m and 0.5 m thick; texturally they are packstones and wackestones. They contain significant argillaceous material and pyrite, and emit a sulphurous odour when struck. Mudstones are interbedded with the limestones and both are bioturbated by chondritiform and thallassinoid burrow systems. Mudstones are mostly thin, many of them no more than partings between adjacent limestones, but there are some thicker units, including the Four Foot Shale near the top of the succession. Macrofossils in the limestones are sparse and are mainly crinoid ossicles, solitary corals and chonetoid, spiriferoid and productoid brachiopods with some in-situ colonies of *Syringopora*. Fenestellid bryozoans are common in some of the interbedded mudstones (Riley, 1995). The algal limestones mentioned by Ramsbottom (1973) and George *et al.* (1976) are oncoid-bearing horizons that are found at a number of levels, particularly in the lower part of the succession (Figure 6.5).

Unforunately, there is confusion over the exact siting of the Chadian stratotype. According to George *et al.* (1976), it is exposed on the west side of the cutting, 80 m from its northern end and 'is taken at the first change in lithology below the entry of the eostaffellid foraminiferal

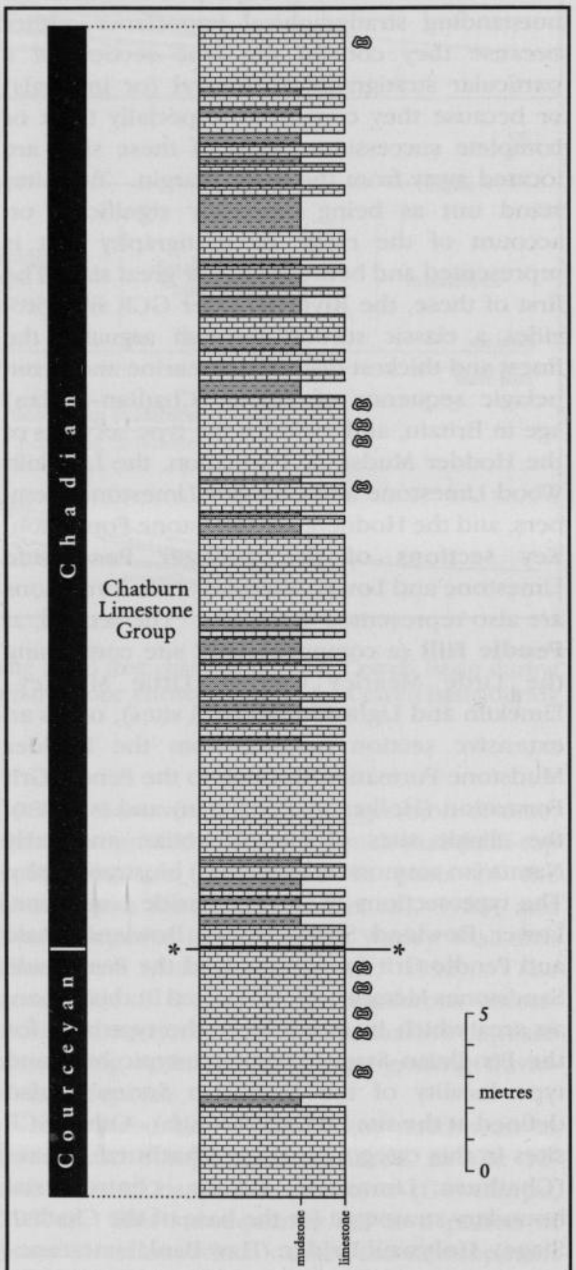


Figure 6.5▸ Sedimentary log of the Chadian stratotype showing the position of Ramsbottom's (1973) 'Major Cycle 1–2 boundary' (defined by asterisks) and the location of the Courceyan–Chadian boundary as envisaged by George *et al.* (1976). Based on Barraclough (1983) and Leeder (1988). See text for further discussion.

genus *Eoparastaffella*'. They also took this to be the junction between the Horrocksford Beds and the Bankfield East Beds. The lithological change they describe is from fine-grained and algal limestone below, to crinoidal limestone interbedded with calcareous mudstones above. However, in a photograph published as part of a field guide (Ramsbottom, 1981), the stratotype is marked on the eastern side of the cutting. Furthermore the boundary is shown at a different level on the accompanying log to that shown on the photograph (Riley, 1995). Since it is the only published illustration of the stratotype, the photograph has been taken as the definitive evidence for the position of the boundary (Riley, 1995). A further illustration of this boundary is shown in Figure 6.6.

The siting of the stratotype is problematical on two counts. Firstly, the lithological change described by George *et al.* (1976) does not exist in the Chatburn Bypass cutting. Their description is based on the distinction between the Horrocksford Beds and the Bankfield East Beds made by Earp *et al.* (1961) elsewhere in the Clitheroe area, but as noted by Barraclough (1983) and Riley (1995), crinoids and oncoids are both present above and below the boundary defined in the Chatburn Bypass section, and there is little change in the proportion of interbedded mudstone (Figure 6.5). Largely for these reasons, Riley (1995) regarded the lower part of the succession in the cutting as being entirely within the Bankfield East Beds. Secondly, the report of *Eoparastaffella* has not been confirmed by subsequent workers (Fewtrell *et al.*, 1981a,b; Riley, 1990a, 1993, 1995). Its first confirmed appearance is some 300 m higher in the succession, in the Hodder Mudstone Formation (Riley, 1990a). A detailed appraisal of the foraminiferal biostratigraphy of the succession has been carried out by Riley (1995). The assemblages, which include three species described for the first time, can be correlated with the late Tournaisian Cf4a1 Subzone (see Figure 1.4, Chapter 1). Riley (1995) stressed that there is no biostratigraphical identity to the stage boundary.

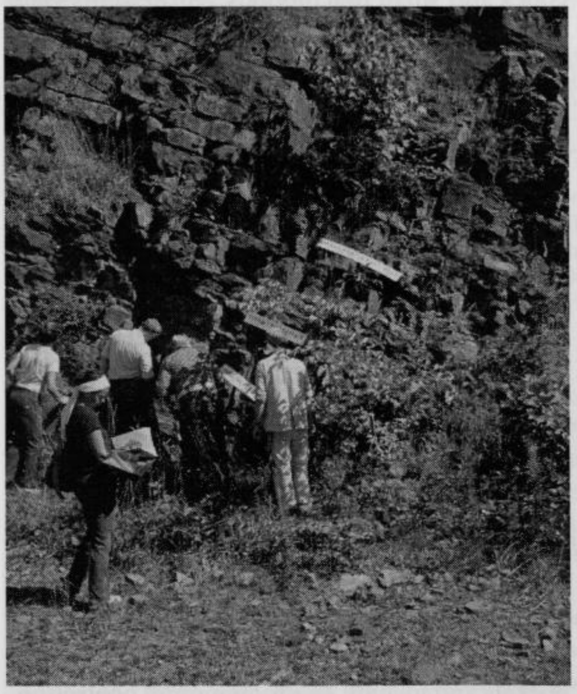


Figure 6.6 The Chadian boundary stratotype at the Chatburn Bypass GCR site, as originally defined by Ramsbottom (1981) at the junction between the Horrocksford Beds (below the middle worker) and the Bankfield East Beds (above the middle worker) (Chatburn Limestone Group). See text for further details. (Photo: JNCC.)

Interpretation

During early Dinantian times, the floor of the Craven Basin was a southerly dipping ramp (Gawthorpe, 1986). The Chatburn Limestone Group at this site represents the deposits of the more distal parts of the ramp, below wave-base, with periodic influxes of mud from river systems draining the Askrigg Block (Barraclough, 1983). Riley (1995) noted very little evidence for variations in water depth and inferred that sediment accumulation kept pace with subsidence. There is no evidence for the shallowing marking the regressive phase at the top of Major Cycle 1, defined by Ramsbottom (1973). The presence of bioturbation suggests an oxygenated sea floor, but the abundance of pyrite suggests that anoxic conditions prevailed in shallow burial environments.

It is clear from the discussion above that this locality is not a suitable choice for a stratotype. As defined, there is no distinction on lithological or biostratigraphical grounds between the late Courceyan and early Chadian successions. Correlations on the basis of the evidence from this section are therefore not possible and, as stated unequivocally by Riley (1995), 'unqualified use of the stage is of little value'. Riley (1995) pointed out that George *et al.* (1976) had intended their stage boundary to be coincident with the appearance of *Eoparastaffella*, which would also mark the base of the Viséan Series. Riley (1990a) used the term 'late Chadian' for the interval between the appearance of *Eoparastaffella* and the first occurrence of primitive archaediscids. Clearly, it would be most appropriate to abandon the Chadian Stage and to propose a new stage for the 'late Chadian' interval, with the possibility of also defining a new stage within the late Tournaisian interval (Riley, 1995).

Conclusions

Despite the serious concerns regarding the suitability of this site as the Chadian stratotype, which may eventually lead to its abandonment, the status of the Chatburn Bypass as a Lower Carboniferous GCR site remains significant. It exposes the best section of the Chatburn Limestone Group outside working quarries and provides an important record of mid- to outer-ramp sedimentation during early Dinantian times of the Craven Basin. The site also provides an invaluable record of late Tournaisian foraminiferal faunas and is the type locality for a number of species.

THE KNOLLS, LANCASHIRE (SD 789 435, SD 779 433, SD 773 434, SD 770 434–SD 767 429)

Introduction

The Craven Basin has long been famed for its 'knolls' of fine-grained carbonate of early Carboniferous (early Chadian) age which have been exhumed by recent weathering to form more-or-less conical hills. The Knolls GCR site, centred 4 km ENE of Clitheroe, embraces a number of these knolls, running from Gerna Hill (SD 789 435) westwards to include Worsaw Hill (SD 779 433) and Warren Hill (SD 773 434) (Figure 6.7). It also includes Crow Hill (SD 768 429) and part of the adjacent road cutting on the A59 (SD 770 434–SD 767 429). The structure, composition and origin of these knolls has been discussed by many workers, especially Parkinson (1926, 1935, 1944), Earp *et al.* (1961) and Miller and Grayson (1972). The knolls and associated limestone facies are now generally accepted as part of a Waulsortian carbonate mud-bank complex (Lees and Miller, 1995) in the Clitheroe Limestone Formation (Figure 6.2).

Description

The best exposures at this site are to be found in the road cutting (Figure 6.8). The northern part of the cutting, north of the junction with the road to Chatburn, is in the Peach Quarry Limestone Member (Figure 6.2) and the southern section, on the Worston side of the junction, bisects the western margin of the Crow Hill knoll. Both exposures are briefly described by Miller and Grayson (1972). The Peach Quarry Limestone Member consists of an alternation of a thickly bedded limestone facies and a thinly bedded shale-rich facies. The thickly bedded facies consists of crinoidal packstones and grainstones with reworked fragments of *Girvanella*, lithoclasts, foraminifera, molluscan fragments and other skeletal debris. Sedimentary structures in this facies include hummocky cross-stratification and small-scale scour features, together with evidence of grading and current reworking. The thinly bedded facies consists of wackestones with an abundant in-situ biota including *Girvanella* mats, dasycladaceans, collapsed *Hyalostelia* sponges, gastropods, ostracodes and small brachiopods. Shale units yield abundant and only partly dissociated crinoid remains (*Amphoracrinus* and platycrinitids being common, together with inadunates) and numerous echinoids. The large productoid *Levitusia humerosa* is common and characteristic of these early Chadian beds. A prominent mudstone near the middle of the section has an interesting fauna of large, complete, smooth-shelled ostracodes, small productoids with spines attached, and euomphalid gastropods.

At the eastern side of the field above the road, the upward transition from the Peach Quarry Limestone Member through crinoidal facies into the Waulsortian bank facies of Crow Hill is seen particularly well (Miller and Grayson, 1972) (Figure 6.8). In the A59 road cutting on the western side of Crow Hill the exposure is entirely in the fine-grained limestones of the Waulsortian bank facies with local patches of crinoidal material and cavities filled with coarse calcite cements clearly visible. Macrofossils are often found in pockets and include *Pleuropugnoides pleurodon*, *Spirifer bisulcatus*, *S. striatus*, *S. coplowensis*, *Pugnax acuminatus*, *Entomoconchus scouleri*, *Conocardium* sp. and *Amplexus coralloides*, together with abundant *Fenestella* and smooth spiriferoids, productoids and athyrids. Two further and unusual finds from this locality

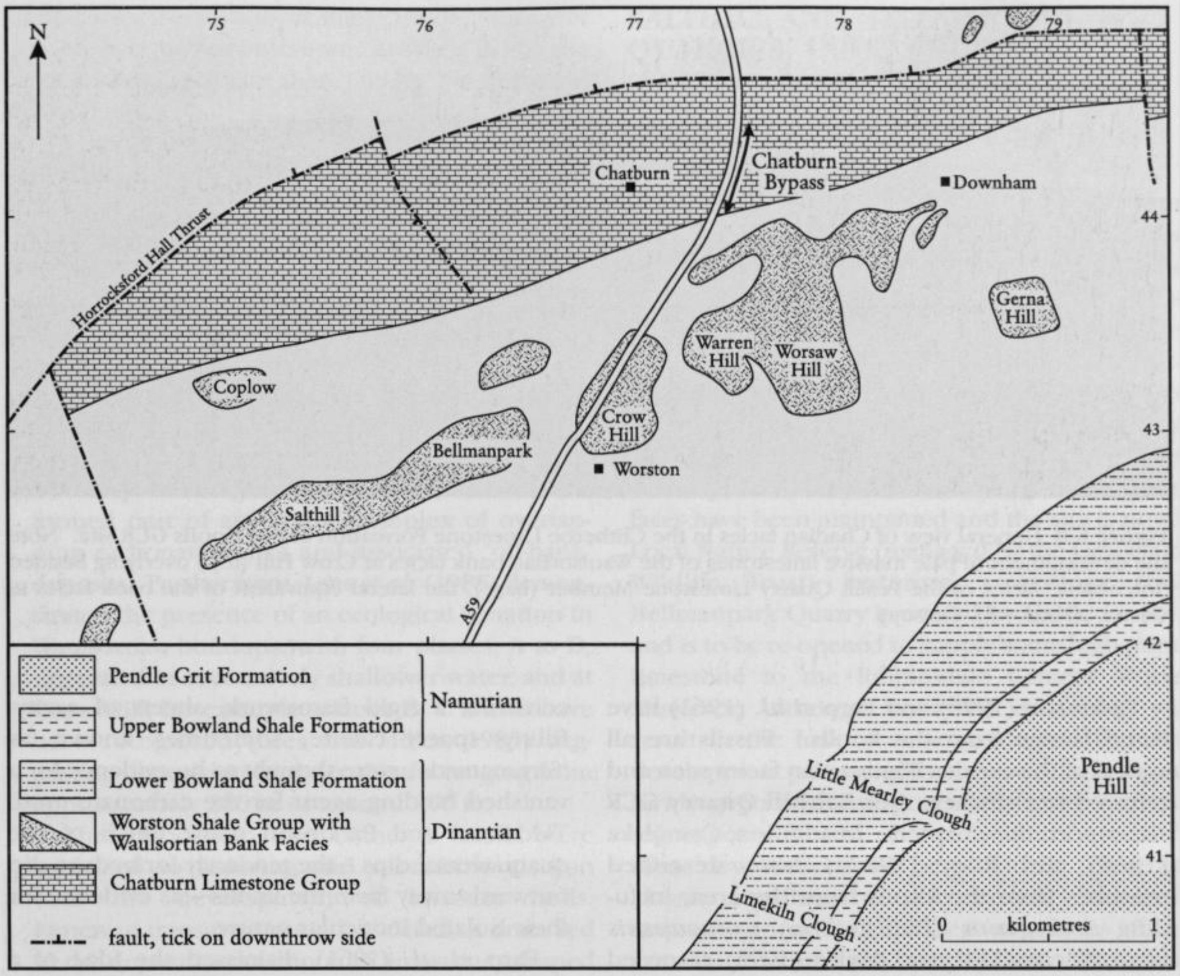


Figure 6.7 Geological map of the area to the east of Clitheroe showing the location of the exposed eroded remnants of the Waulsortian bank facies at The Knolls GCR site (Crow Hill to Gerna Hill) based on a [British] Geological Survey map of the area (Institute of Geological Sciences, 1970). The locations of several other GCR sites in the region (**Chatburn Bypass**, **Salthill and Bellmanpark Quarries**, **Coplow Quarry**, **Pendle Hill**) are also shown.

include the blastoid *Mesoblastus* and a nautiloid comparable to *Epidomatoceras subsulcatum*. A notable feature of this locality is the development of fissures, predominantly vertical, but sometimes turning sideways to open laterally. The fissure-fills include finely laminated micrites, sometimes incorporating marine fossil fragments.

The old quarries and natural exposures of the knolls are mostly highly weathered and lichen-covered. Different facies are present, but the scattered nature of the exposures means that they are difficult to relate to one another. On Gerna Hill there appears to be a single development of the Waulsortian bank facies, whereas to the south-west on Worsaw Hill there is a lower unit, the Coplow Bank Beds (= Coplow Limestone Member of Riley, 1990a) and a higher, thicker development, the Salthill Bank Beds (= Bellmanpark Limestone Member of Riley, 1990a) (Figure 6.2). The oldest beds of Worsaw and Warren hills are seen in Piked Acre Wood where crinoidal facies can be followed westwards, passing laterally into typical Peach Quarry Limestone. Both Worsaw Hill and Gerna Hill display outward ('quaquaversal') dips, but these are often seen in bedded crinoidal limestones, at least some of which post-date bank formation. A boulder–breccia bed, relating to the erosion of Salthill Bank Beds, has been traced from the south-west flank of The Ridge (SD 771 432) to a small quarry at SD 771 433 where it apparently lies directly on the Peach Quarry Limestone Member.

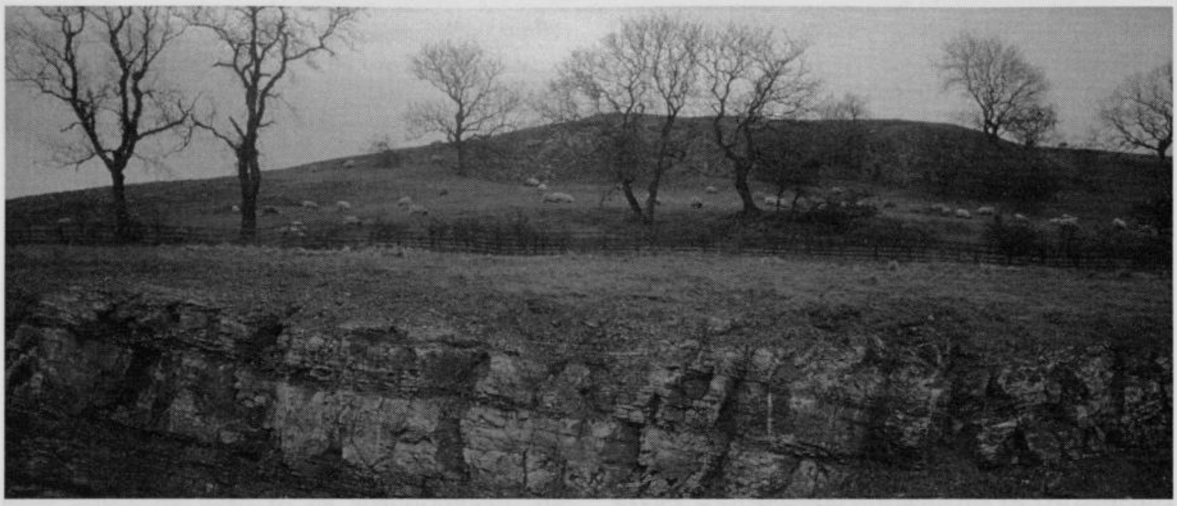


Figure 6.8 General view of Chadian facies in the Clitheroe Limestone Formation at The Knolls GCR site. Note the development of pale massive limestones of the Waulsortian bank facies at Crow Hill (top) overlying bedded 'inter-bank' facies of the Peach Quarry Limestone Member (base), the lateral equivalent of the bank facies at Gerna. (Photo: P.J. Cossey.)

Parkinson (1926) and Earp *et al.* (1961) have listed faunas from the knolls. Fossils are all typical of the various Waulsortian facies seen and referred to elsewhere (see **Salthill Quarry** GCR site report, this chapter). In addition, Osmólska (1968) and Riley (1982a) have described trilobites from the knolls from the area, including *Archegonus* (*Phillibolina*) *worsawensis* from Worsaw Hill, and Miller (1973) recorded two new trilobites, *Carbonocoryphe* (*Wintergia*) *hahnorum* and *Namuropyge decora* from a fissure-fill of the Limekiln Wood Limestone Member (Riley, 1990a), formerly the 'Salthill Cap Beds' of Miller and Grayson (1972), in a now-infilled quarry on the south-west corner of Crow Hill.

Interpretation

The origin of the knolls of the Craven Basin has been debated for many years. The site described here includes knolls originally regarded as Carboniferous reef structures by Tiddeman (1889, 1891). Further work on the composition and relationships between these structures by Parkinson (1926, 1950b, 1957, 1967) re-inforced the idea that each knoll was an isolated lenticular reef surrounded by mudstone. It was argued that the topography of the knolls suggested that the reefs stood high above the contemporary sea floor and, although there was no direct evidence of an organism able to construct a rigid framework, sheets of cavity-filling sparry calcite, sometimes known as 'Stromatactis', were thought to be evidence for a vanished binding agent for the carbonate mud. Tiddeman and Parkinson made much of the quaquaversal dips – the tendency for beds to dip outwards away from the knolls – as evidence for their isolated lenticular nature.

Earp *et al.* (1961) dismissed the idea of a skeletal reef origin and instead compared the knolls to limebanks of a similar age in Ireland and the United States. No algal or bryozoan frame-builders were found, nor any evidence that the knolls were wave-resistant structures. They concluded that knolls formed from limebank deposition and the differential compaction of such banks within an envelope of mudstone, and that the original knolls were subject to strong tectonic deformation, with the resulting knoll topography enhanced by glacial erosion.

Miller and Grayson (1972) were the first to describe in detail the facies that make up the Clitheroe Limestone Formation and their lateral relationships. They recognized that their bank facies (the knoll limestone of previous authors) formed a thick wedge in the Twiston to Worsaw area which projected thinner wedges to the south-west, separated by a wedge of 'interbank facies' (Peach Quarry Limestone). In addition, they demonstrated that the knolls form part of a limestone sheet that was uplifted and eroded before burial. The Worston Shales (= Hodder

Mudstone Formation of Riley, 1990a) were not deposited penecontemporaneously with the banks, but post-date them, burying the eroded remnants.

The Clitheroe knolls are regarded as 'Waulsortian' mud-banks similar to those that occur in Ireland, North America and at Waulsort (the type locality) in Belgium (Lees and Miller, 1985, 1995). They originated as local accumulations of carbonate mud, probably of microbial origin. The original geometry of the structures cannot be ascertained with complete certainty. Most were sheet-like, although some may have formed lenses raised above the sea floor. However, Lees and Miller (1995) suggested that rather than representing isolated lenses, the 'knolls' formed part of an eroded complex of overlapping carbonate banks and associated 'off-bank' deposits. Furthermore, Lees *et al.* (1985) demonstrated the presence of an ecological zonation in Waulsortian buildups, with four phases, A to D, deposited in successively shallower water, and at Crow Hill, for example, phases B, C and D have been recognized (Lees and Miller, 1985) suggesting deposition in water depths ranging from approximately 280 m to around 200 m.

After deposition, the Clitheroe knolls were subjected to fissuring and submarine erosion with the development of boulder beds. Renewed transgression in late Chadian times led to the deposition of crinoidal limestones draped over the eroded bank complex and giving rise to the quaquaversal dips. Further deepening led to the deposition of the Worston Shales which completed the burial of the knolls. Glacial and post-glacial erosion has picked out the knoll topography by selectively removing the soft Worston Shales to produce the spectacular line of conical hills that can be seen today.

Conclusions

This site is of great interest for the spectacular outcrop of an early Chadian Waulsortian mud-bank complex whose origin and diagenesis is the subject of ongoing debate. Furthermore, the road cutting along the A59 provides the best available exposure of the Peach Quarry Limestone Member. Waulsortian bank facies are exposed in the Crow Hill road cutting and other exposures are scattered across the hills of the site. Lateral facies relationships are complex and even small exposures can be vital in helping to piece together the history of these important structures.

SALTHILL AND BELLMANPARK QUARRIES, LANCASHIRE (SD 751 424–SD 763 428)

Introduction

The quarries at Salthill (disused) and Bellmanpark (formerly disused but recently re-opened and extended) which constitute the Salthill and Bellmanpark Quarries GCR site extend from the north-eastern edge of Clitheroe ENE for more than a kilometre towards Worston (SD 751 424 to SD 763 428). The site is split by the Pimlico Link Road, which connects to the A59 Clitheroe Bypass. The floor of Salthill Quarry has been developed as an industrial estate, but the quarry faces have been maintained and the site is now a Local Nature Reserve (managed by the Lancashire Wildlife Trust) featuring a geology trail. Bellmanpark Quarry is owned by Castle Cement and is to be re-opened to supply some high-purity limestone to the Ribblesdale Cement Works. However, although renewed quarrying will result in the loss of some geological features, development plans require the retention of some newly generated and potentially more interesting exposures, and ultimately better access to these new sections will be provided. These are classic localities of the British Dinantian sequence, providing the best exposures of the internal structure and composition of limestone knolls in the Clitheroe Limestone Formation (Figure 6.2) and both quarries are justly famous for their diverse and abundant faunas. The most important contribution on the facies relationships seen here is by Miller and Grayson (1972), and a modern account of the Salthill Geology Trail has been published by Bowden *et al.* (1997). Accounts of faunas from this locality include those of Parkinson (1926), Westhead (1967) and Donovan (1992).

Description

This site includes exposures of the upper part of the late Tournaisian Salthill Bank Beds of Miller and Grayson (1972), a unit now referred to as the Bellman Limestone Member of the Clitheroe Limestone Formation (Riley, 1990a) (Figure 6.2). The Bellman Limestone Member is the upper of the two major developments of the Waulsortian facies in the Clitheroe area. The overlying beds, the Salthill Cap Beds of Miller and Grayson (1972), rest unconformably on eroded

Waulsortian mud-banks and are also well exposed at the site (Figure 6.9). This unit is now included in the Limekiln Wood Limestone Member of the Hodder Mudstone Formation by Riley (1990a) and is of early Viséan age (Figure 6.2). The regional dip is about 25° to the south-east, but this is not always immediately apparent, because of the unbedded nature of Waulsortian bank facies and depositional dips in some of the subsequent beds.

Detailed plans of the Salthill Quarry faces have been provided by Miller and Grayson (1972) and sketches of the faces at localities on the geology trail are provided by Bowden *et al.* (1997). The eroded tops of the mud-banks which constitute the Bellman Limestone Member are seen in Salthill Quarry (Figure 6.9), but a thicker development of this unit is seen in Bellmanpark Quarry where it forms the high easternmost face. Typically, the Bellman Limestone Member consists of poorly bedded, fine-grained limestone with groups of stromatactoid cavities showing multiple fills of sediments and cements.

The erosion that followed the development of the main Waulsortian Complex is most marked along the southern faces of the quarries, where, at intervals, there are boulder beds. Some of the boulders are more than a metre across. The boulders are of different limestone types, including crinoidal limestones not normally associated with the Bellman Limestone Member, and some have their bedding or geopetal fabrics rotated or even inverted. Grey calcareous mudstone may form a matrix to the boulders. Draped over the erosion surface are more than 20 m of crinoidal packstones and grainstones. These are locally well sorted and free of matrix, but may retain partial carbonate mud-fills within the crinoidal lumen. These geopetal infills indicate that the crinoidal facies was deposited on slopes of up to at least 30°. The boulder beds and breccias can be followed north-east into those of the Crow Hill–Twiston area (see **The Knolls** GCR site report, this chapter) and are probably related to tectonic activity along the south-east edge of the Waulsortian Complex, producing submarine

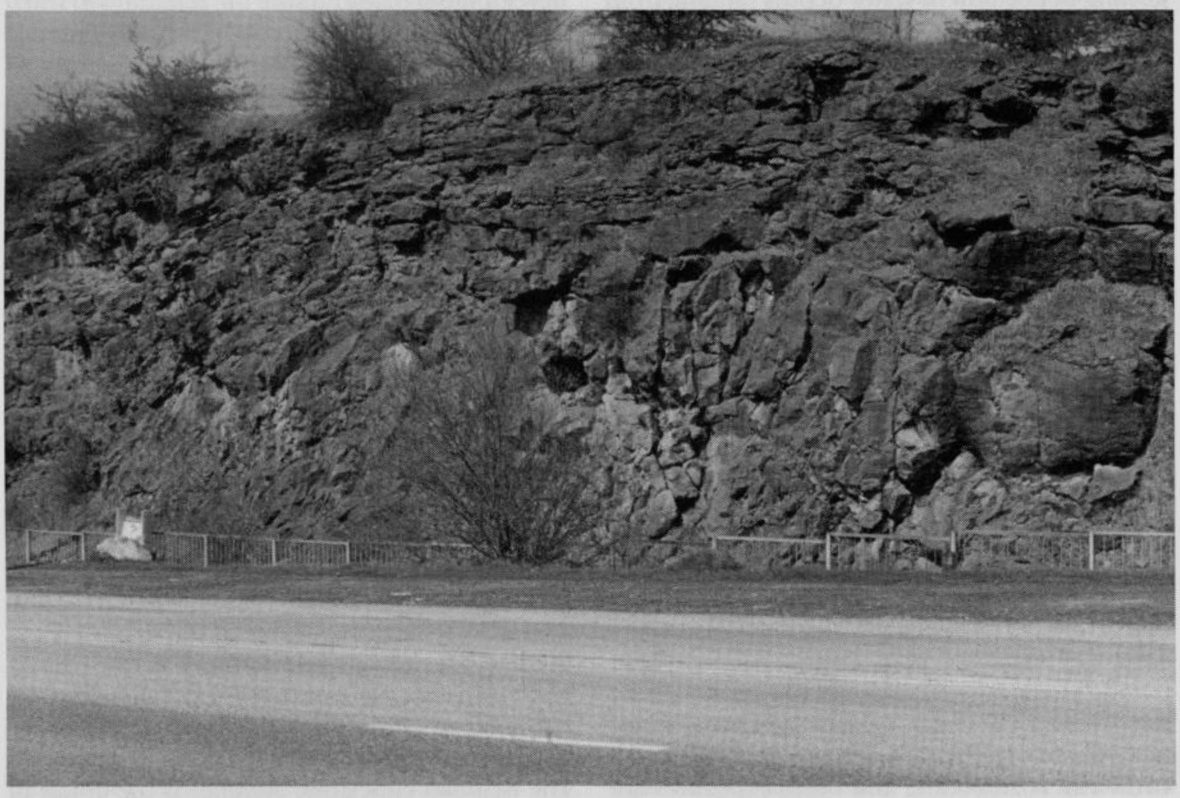


Figure 6.9 Development of the Waulsortian bank facies (Bellman Limestone Member of the Clitheroe Limestone Formation (Chadian) at Salthill Quarry, Clitheroe. An erosion surface above the bank facies is draped by a crinoid debris layer ('boulder bed') of variable thickness and this is in turn unconformably overlain by dark-grey bedded limestones of the Limekiln Wood Limestone Member. (Photo: A.E. Adams.)

collapse and break up of the Waulsortian bank margin. Evidence for this is shown by the sudden increase in depositional dip from the crest of the Salthill–Bellman ridge towards its southern side.

The fauna of the Limekiln Wood Limestone Member is much richer than that of the Bellman Limestone Member and most of the fossils described from this site were obtained from these crinoidal beds. Parkinson (1926) was one of the first to describe the faunas in detail. Among the corals he described were *Clisiophyllum* and *Koninckophyllum clitheroense* (type locality at Salthill). Other corals present include *Michelinia* cf. *megastoma*, *Caninia cylindrica* and *Syringopora*. The only corals commonly found in the Bellman Limestone Member are *Amplexus coralloides* and heterocorals. Parkinson (1926) also recorded many brachiopods, the most typical being athyrids such as '*Dielasma*', '*Girtyella*' and *Leptaena analoga*, productoids including *Pustula nodopustulosa* (type locality at Salthill), smooth brachythyrids, many species of *Spirifer*, and varieties of *Pugnax acuminatus* and *P. mesogonus*. Muir Wood added an appendix to Parkinson's paper, describing for the first time *Spirifer bollandensis* and *Reticularia lobata* with paratypes from this site. Other fossils listed include bryozoans, bivalves and echinoderms. Parkinson (1926) especially mentioned the abundance and diversity of the blastoids, which include the rare *Mesoblastus*. This site is also famous for its crinoids. Westhead (1967) and Donovan (1992) described crinoid faunas from Salthill and Bellmanpark and compared them with the faunas from the older Coplow Limestone Member at **Coplow Quarry** (see GCR site report, this chapter) and with other localities in Bowland and in Scotland. Westhead (1967) commented on the large number of grapnel-like crinoid roots. *Cyathocrinites* and *Poteriocrinites* are the most common inadunate genera, with *Euryocrinus* representing the Flexibilia, and *Amphoracrinus*, *Actinocrinites*, *Platycrinites*, *Pleurocrinus* and *Gilbertsocrinus* the camerates. Further descriptions of crinoids from this locality can be found in Westhead (1979), Donovan and Sevastopulo (1985, 1988), Donovan (1986) and Donovan and Westhead (1987).

According to current directions indicated by crinoid toppling orientations, the Limekiln Wood Limestone Member was deposited over the irregular eroded surface of the Bellman Limestone Member under the influence of north–south currents. Orientated crinoid stems are well seen in the relatively fresh exposures at the south-west end of the site where a footpath comes down to road level by means of a short set of steps (SD 752 424).

Other points of interest around Salthill are described in the trail guide by Bowden *et al.* (1997). Of particular note are the exposures either side of the road between the industrial developments, where the quarry faces are closest to the road (SD 756 426). To the north of the road the quarry face features the dome-shaped geometry and irregular (eroded) top surface of a prominent mud-bank within the Bellman Limestone Member (Figure 6.9). Draped over this is a 'boulder bed' development, which here consists mostly of crinoid debris, followed by the dark-grey, bedded limestones of the Limekiln Wood Limestone Member, which thin over the dome and thicken into the troughs on either side. On the south side of the road, on the corner where the quarry face turns southwards, an unparalleled example of sharp facies intertonguing between dark-grey well-bedded deposits and pale crinoidal limestones of the Limekiln Wood Limestone Member can be seen. At the top of the face is a small tabular development of pale fine-grained limestone with typical mud-bank features. This seems to be a minor development of Waulsortian bank facies of Viséan age within the Limekiln Wood Limestone Member.

Interpretation

Salthill and Bellmanpark lie along the same line of knolls as Crow Hill, Worsaw, Gerna and Twiston, part of which constitute **The Knolls** GCR site (see previous site report, this chapter; and Figure 6.7), the original knolls of Bellmanpark and Salthill having largely been quarried away. Miller and Grayson (1972) provided borehole evidence that the drift-covered interval between Bellmanpark and Crow Hill is underlain by the Waulsortian Complex and thus that the mud-banks originally formed a continuous belt. Later work on the Waulsortian at Bellmanpark (Lees and Miller, 1985) indicated the presence of the component phases B, C and D of Lees *et al.* (1985), indicating original water depths for the accumulation ranging from approximately 280 m to around 150 m. Further discussion about the origin and development of the Waulsortian facies in the Clitheroe area can be found in **The Knolls** GCR site report (this chapter) and is not repeated here.

Miller and Grayson (1972) stressed that there is no evidence at this site for any original outward-dipping slopes in the Bellman Limestone Member. Although there may have been some depositional topography, they regard the whole Waulsortian Complex as essentially a tabular body that was strongly eroded after deposition to form the domes and troughs which are seen today. It is worth contrasting these structures with the younger Dinantian buildups that occur along and to the south of the Craven Faults at the northern margin of the Craven Basin and which are described in Chapter 5. There, interpretations determined the existence of a marginal reef complex dissected by erosion to produce a knoll topography, but to the south of this marginal belt are isolated structures, such as that of Stebden Hill (see **Cracoe Knolls and Swinden Quarry** GCR site report, Chapter 5) which are apparently surrounded by shale and which are thought to have stood up as significant topographical features above the sea floor during growth (Mundy, 1980a).

Conclusions

The quarries of Salthill and Bellmanpark have become a classic British Lower Carboniferous locality. The striking clarity with which the complex early to late Chadian sedimentation history of the Craven Basin is revealed here, has made this an invaluable site for teaching, as well as for research. The prolific faunas, including several species for which this is the type locality, make Salthill and Bellmanpark one of the most valuable palaeontological sites in northern England.

COPLOW QUARRY, LANCASHIRE (SD 751 432)

Introduction

The Coplow Quarry GCR site is a disused quarry lying 1.5 km NNE of Clitheroe town centre at SD 751 432. Exposures at Coplow include part of the earliest phase of 'knoll reef' development in the Clitheroe area, but much of the 'knoll' structure has been quarried away and the centre of the quarry has been filled. Nevertheless, parts of the original Waulsortian bank that made up the knoll (Figure 6.7), and the associated facies, are well exposed in the quarry walls. The quarry is historically important for its rich and well-preserved echinoderm faunas (Figure 6.10). Aspects of the site geology have been described by many workers, including Parkinson (1950b), Earp *et al.* (1961), Miller and Grayson (1972) and Arthurton *et al.* (1982).

Description

The rocks exposed in the quarry walls belong to the lower part of the Clitheroe Limestone Formation. The section includes the type section of the Coplow Limestone Member of Riley (1990a), the base of which is defined at the site (Figure 6.2). The oldest exposed rocks consist of alternating dark calcareous shales and impure limestones, informally assigned to the Lower Coplow Shales by Miller and Grayson (1972). The regional dip in the quarry is to the south-east. On the northern face, the proportion of limestone increases upwards and there is a transition first to cross-stratified crinoidal beds and then into the pale carbonate mudstones of the Waulsortian facies (= Coplow Bank Beds of Miller and Grayson, 1972). This rapid transition was described in detail by Miller (1986). On the west wall of the quarry there are complex intertonguings of Waulsortian bank and crinoidal flank facies, while the same horizon on the east wall is dominated by bank facies.

Coplow Quarry is particularly well known for its extensive faunas which include examples of bryozoans, sponges, tabulate and rugose corals, brachiopods, bivalves, gastropods, echinoderms, nautiloids, goniatites, trilobites and ostracodes (Parkinson, 1926). Of special importance are the abundant, superbly preserved echinoderms, described in a long series of papers by Wright (1928, 1935, 1942, 1943, 1947, 1948, 1950–1960; see Figure 6.10). Useful summaries of the Coplow echinoderm faunas are also provided by Westhead (1967) and Donovan (1992).

Of the 20 genera and 60 crinoid species described by Wright (1950–1960), many have type specimens from Coplow (Figure 6.10A) and some have distinctive local names such as *Taxocrinus coplowensis*, *Pleurocrinus coplowensis*, *Actinocrinites coplowensis*, *Gilbertsocrinus coplowensis* and *Pimlicocrinus clitheroensis*. Whilst *Actinocrinites* is the most common and characteristic genus represented

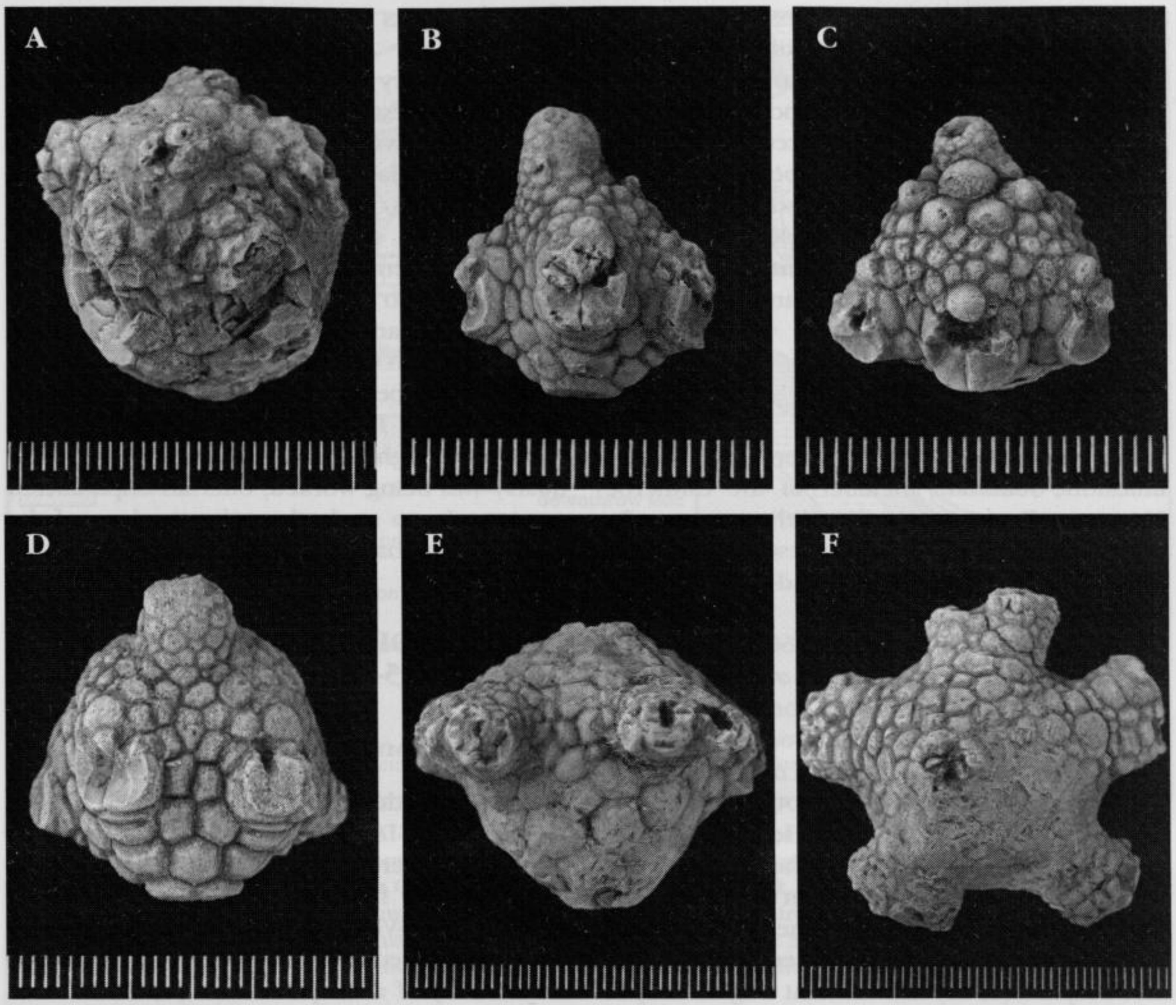


Figure 6.10 Crinoid calices from the Coplow Quarry GCR site. A – *Sampsonocrinus westheadi* (Wright), holotype, lateral view (calyx width is 2.8 cm); B – *Amphoracrinus gilbertsoni* (Phillips), lateral view (calyx width is 1.8 cm); C – *Amphoracrinus gilbertsoni* (Phillips), lateral/oblique view (calyx width is 2.0 cm); D – *Amphoracrinus rotundus* Wright, lateral view (calyx width is 2.6 cm); E – *Actinocrinites parkinsoni* Wright, lateral view (calyx width is 3.7 cm); F – *Actinocrinites parkinsoni* Wright, lateral view (calyx width is 3.9 cm). Scalebars show millimetre graduations. (Photos: courtesy of D. Lewis, S. Donovan and staff in the Photographic Unit of the Natural History Museum (British Museum).) All specimens are from the Stanley Westhead collection (BMNH).

(Wright, 1928; Earp *et al.*, 1961), the flexible crinoid *Euryocrinus rofei* is worthy of note on account of its rarity. Other uncommon elements of the fauna include the blastoids *Orophocrinus pentangularis* and *O. versus* (Wright, 1947, 1948) and the echinoids *Archaeocidaris* spp., *Lovenechinus anglicus*, *Melonechinus etheridgii*, *M. keepingi*, *Palaechinus* spp., *Perischodomus biserialis* and *Pholidocidaris tenuis* (Jackson, 1912; Hawkins in Parkinson, 1926).

Within the mud-bank there is a distinctive fauna characterized by the absence of corals, apart from *Amplexus coralloides* which is locally abundant, and by the occurrence of brachiopods not usually found outside this facies, such as plicated varieties of *Pugnax acuminatus* and *P. sulcatus*, *Brachythyris pinguis* and *Spirifer coplowensis*. The last named is the most common brachiopod in the bank facies, the holotype being originally described from Coplow by Parkinson (1926).

The limestone–shale bedding plane surfaces on the northern face of the quarry offer excellent opportunities for detailed palaeoecological studies of the bedded facies, although much less is visible today than formerly. Complete in-situ cup-shaped fenestellid bryozoans, outstretched or coiled crinoid stems, often with complete or partly dissociated calices are abundant, and mats of well-preserved hyalosteliid sponges with rod bundles over 15 cm long also occur. Articulated athyrid and spiriferoid brachiopods also occur, with an abundance of delicate 'stick' bryozoans. Many limestones contain a rich microbiota including *Girvanella*, foraminifera and palaeoberesellids. *Chondrites* and thalassinoid burrows are also common.

Interpretation

The Coplow Limestone Member is the lowest limestone-dominant member of the Clitheroe Limestone Formation in the Clitheroe area. Its development records the earliest development of the Chadian Waulsortian mud-bank facies in the Craven Basin (Figure 6.2). The section at Coplow begins approximately 60 m above the base of the formation (Earp *et al.*, 1961), with the Waulsortian facies itself originally being more than 100 m thick (Parkinson, 1950b; Earp *et al.*, 1961). Parkinson (1950b) maintained that the depositional slope on the south-east side of his alleged mound was 29.5°. He assumed that all changes in dip and strike of the exposed beds were caused by lateral changes in the facies associated with 'mound' development. However, using the attitudes of geopetal sediments, Miller and Grayson (1972) showed that original slopes were nowhere greater than 10°. The Coplow Waulsortian facies is now generally regarded as an aggregate of gently lensing carbonate mud-banks (cf. Lees and Miller, 1995)

Earlier ideas for the development of the Waulsortian bank facies are discussed in **The Knolls** GCR site report (this chapter). The Coplow accumulation includes the Waulsortian phases B, C and D in common with other buildups of the Clitheroe area, suggesting deposition in water depths ranging from approximately 280 m to around 150 m (Lees and Miller, 1985).

The superb preservation of the faunas in the facies surrounding the Waulsortian mud-bank, with virtually undisturbed bryozoans and crinoids, testifies to the tranquil environments during deposition and perhaps to rapid post-mortem burial. However, the presence of cross-stratified crinoidal limestones elsewhere in the associated beds points to the existence of traction currents at other times.

Conclusions

Coplow Quarry is one of the most important multiple-interest sites of Lower Carboniferous age in the Craven Basin, with a range of stratigraphical, palaeontological and sedimentological features of interest within its boundary. It provides the type section of the Coplow Limestone Member and, in addition, a rare opportunity to examine the transition from Waulsortian bank facies laterally into bedded strata. It is also the type locality for many fossils. Furthermore, bedding planes with exceptionally well-preserved faunas on the north face of the quarry, although not as clearly seen as when the quarry was being worked, offer an unparalleled opportunity to study the palaeoecology of the Chadian mud-bank and associated facies.

RIVER HODDER, LANCASHIRE (SD 646 435–SD 708 389)

Introduction

The River Hodder GCR site is a river section (SD 646 435–SD 708 389) to the north-west and west of Clitheroe, approximately 15 km long (Figure 6.11). It shows the thickest (> 1.5 km) early- to mid-Viséan sequence in the Craven Basin, preserved over the hanging wall (downthrow side) of a deep basement fault that was active during deposition as the crust was stretching (extension). At the end of the Carboniferous Period, this fault was compressed (inverted), through shortening of the crust by earth movements associated with continental collision and mountain building (Variscan Orogeny) in south-west Britain. The Carboniferous rocks were thus intensely folded, as a result of which (and because of river meandering) many intervals are repeated at various points along the section. Cleavage is also developed on the northern flank of this folding, which is centred around Limekiln Wood (SD 6630 4330). The site is the type section for the Hodder Mudstone Formation (Riley, 1990a) and two of its constituent members (Limekiln Wood Limestone and Chaigley Limestone) and for the Hodderense Limestone Formation (see Figure 6.2). The Pendleside Limestone Formation and the basal part of the Lower Bowland Shale Formation are also exposed. It is also the type locality for several trilobite and ammonoid (goniatite)

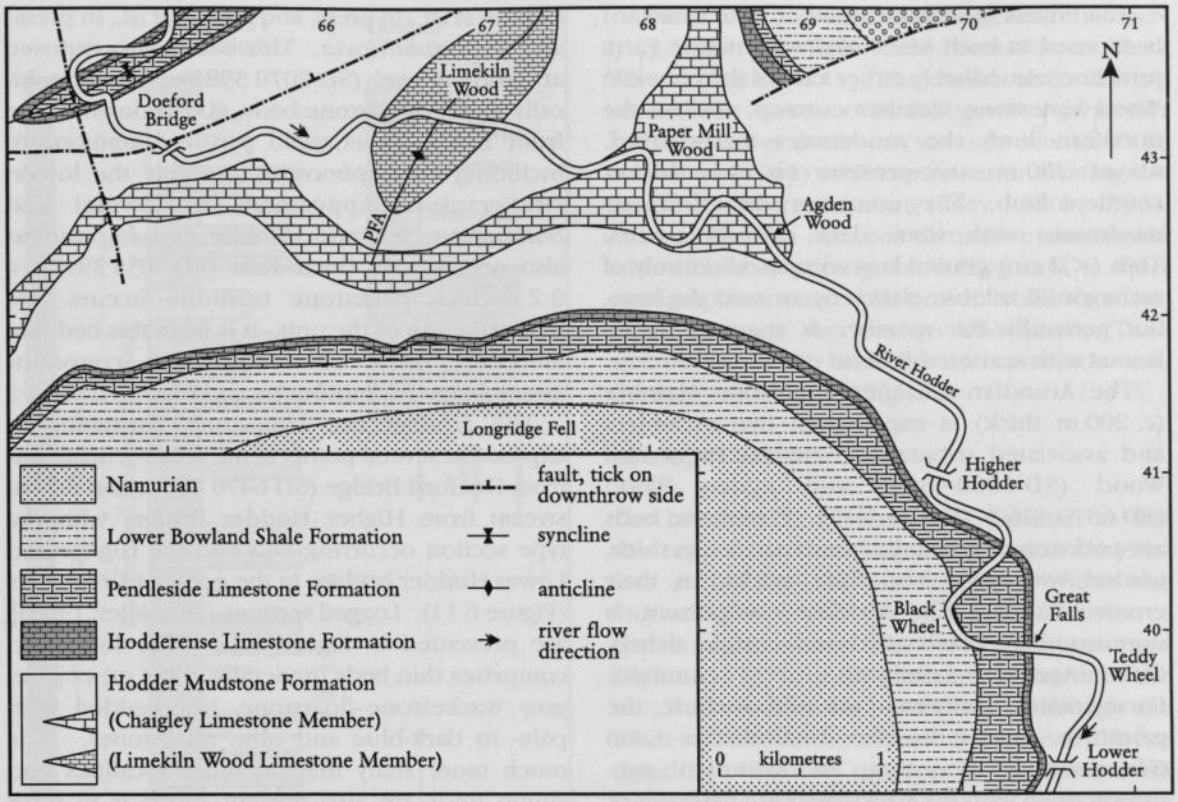


Figure 6.11 Simplified geological map illustrating the distribution of Carboniferous strata at the River Hodder GCR site. Based on information from [British] Geological Survey maps of the area (Institute of Geological Sciences, 1975a; British Geological Survey, 1990). Note that areas depicted here as the Hodder Mudstone Formation, the Lower Bowland Shale Formation and the Namurian include, respectively, the following undifferentiated units: the Phynis Mudstone Member; the Pendleside Sandstones Member; and the Upper Bowland Shale and Pendle Grit formations. (PFA – Plantation Farm Anticline.)

species (see Phillips, 1836). The River Hodder offers the best British section for examining a Viséan deep-water mixed clastic–carbonate succession in an extensional basin setting. Detailed descriptions of the sections are given by Earp *et al.* (1961) and Aitkenhead *et al.* (1992). Riley (1990a) defined the lithostratigraphy and reviewed the depositional history. Ammonoid faunas were also monographed by Riley (1996).

Description

At the base of the succession is the Limekiln Wood Limestone Member (late Chadian), exposed in tightly folded periclines at Limekiln Wood (SD 6630 4330–SD 6715 4330) (see Figure 6.11). Although the base of this unit is not seen, it typically comprises about 120 m of graded crinoidal packstones and grainstones, some with significant packstone lithoclasts derived from the (older) Clitheroe Limestone Formation. Bed thickness is generally less than 0.6 m. Silicification and chert is common, with beekite replacing the surfaces of crinoids. Interbedded dark-grey mudstones are silty and micaceous, similar in character to the overlying Phynis Mudstone Member. The limestones are rich in brachiopod debris and crinoids. Disarticulated trilobites referable to *Brachymetopus maccoyi*, *Phillipsia gemmulifera* and *Phillibole*, and crinoid calices, especially *Actinocrinites* and *Gilbertsocrinus*, occur, together with the coprophagous gastropod *Platyceras*. The foraminifera *Eotextularia* and *Eblanaia* are particularly common. Towards the top of the member, on the northern limb of the Plantation Farm Anticline (Figures 6.1 and 6.11), is a shaly carbonate lithoclast debris bed rich in crinoid calices including, in addition to the above, *Amphoracrinus*, *Bollandocrinus*, *Pimlicocrinus*, *Platycrinites* and *Pleurocrinus*.

The Phynis Mudstone Member (late Chadian) is exposed in both limbs of the Plantation Farm Anticline immediately either side of the Limekiln Wood Limestone Member outcrop, and on the northern limb the mudstones are cleaved. About 200 m are present on the thicker southern limb. They comprise silty calcareous mudstones with some dark calcisiltite beds. Thin (< 2 cm) graded lags composed entirely of archegoniid trilobite debris occur near the base, but generally the member is sparsely fossiliferous with scattered crinoid ossicles occurring.

The Arundian Chaigley Limestone Member (*c.* 200 m thick) is exposed in two meanders and associated tributaries between Paper Mill Wood (SD 6800 4330) and Agden Wood (SD 6870 4260) (Figure 6.11). Limestone beds are packstones, generally more than 0.6 m thick, graded with prod and flute marks on their erosive bases. The bioclast component is dominated by brachiopod and crinoid debris. Cummingellid trilobites are common. Foraminifera are abundant and include the primitive archaediscids *Uralodiscus* and *Glomodiscus*, denoting an Arundian age. Interbedded with the packstones are fissile black shales containing scattered micrite nodules (similar to Namurian 'bullions'), and reworked nodules in the packstones yield the ammonoids *Parahammotocyclus chaigleyensis* (type locality), *Bollandites*, *Bollandoceras* and *Dzhaprakoceras hispanicum*. One shale band contains a coquina of the hemipelagic facies bivalves *Dunbarella* and *Pteronites*, with bryozoans attached to the *Dunbarella* valves. This bed strongly resembles similar occurrences in Silesian marine bands and is called the 'Dunbarella Bed'; it is known from several localities in the basin. Siltstones and rarer fine-grained sandstones also occur, some containing plant debris and siderite nodules. Soft-sediment deformation structures (e.g. convolute ripples and slumps) are also present and gravity slide structures are apparent around Agden Wood.

Overlying the Chaigley Limestone Member, mudstone dominates, with thin calcisiltites and wackestones. Slumps are common. Some 30 m upstream from Higher Hodder Bridge (SD 6975 4115) a debris flow occurs and this contains disarticulated brachiopods, the coral *Rotiphyllum* and numerous trilobites including *Griffithides holwellensis* (Hahn), originally described from the Holkerian succession of the Mendips (at the Holwell Quarry GCR site; see Benton *et al.*, in press, and Simms *et al.*, in press) and *Weberiphillipsia*. This bed is also exposed at Teddy Wheel (SD 7070 3985). Stratigraphically higher mudstone beds, 400 m downstream from Teddy Wheel, yield pyritized ammonoids including *Dimorphoceras* (possibly the lowest stratigraphical appearance worldwide) and *Bollandites*; the rare trilobite *Pseudospatulina* also occurs. At Great Falls (SD 7035 3999), a 0.2 m-thick packstone turbidite occurs just below the top of the unit. It is from this bed that Metcalfe (1981) obtained a rich conodont asssemblage of *Gnathodus* and *Mestognathus*.

The Hodderense Limestone Formation is exposed at several points in the section, upstream from Doeford Bridge (SD 6470 4350) and downstream from Higher Hodder Bridge; with the type section occurring between the Higher and Lower Hodder bridges in the gorge at Great Falls (Figure 6.11). Logged sections (after Riley, 1990a) are presented in Figure 6.12. The formation comprises thin beds (generally < 0.3 m) of pale-grey wackestone–floatstone, interbedded with pale- to dark-blue and olive mudstones. It is much more shaly than at other localities and slump folds are also present. This is in stark contrast to the facies developed at Ashnott, on an intrabasinal palaeohigh, which is much less shaly and reduced in thickness. The section at Great Falls is the thickest measured in the formation, even when the repetition due to slumping is removed. Small dark bluish-grey irregular micrite nodules occur throughout, but are most concentrated in the limestones, where many are probably reworked or concentrated by bioturbation and/or winnowing. It is these nodules that give the limestones their characteristic blotchy appearance. Bed boundaries are commonly uneven. Ammonoids are abundant and include the zonal form *Bollandoceras hodderense* (type locality), *Merocanites applanatus*, *Nomismoceras rotiforme*, and the trilobite *Latibole*.

Immediately overlying the Hodderense Limestone Formation, at Great Falls, is another packstone turbidite, 0.3 m thick, containing numerous *Bollandoceras submicronotum*, *Nomismoceras rotiforme* and the lowest stratigraphical occurrence of *Beyrichoceras* in the Craven Basin. This bed, which marks the base of the Pendleside Limestone Formation, has also yielded a valve of the Holkerian marker brachiopod *Davidsonina carbonaria*. The Pendleside Limestone Formation (Figure 6.11) occupies much of the river gorge upstream to

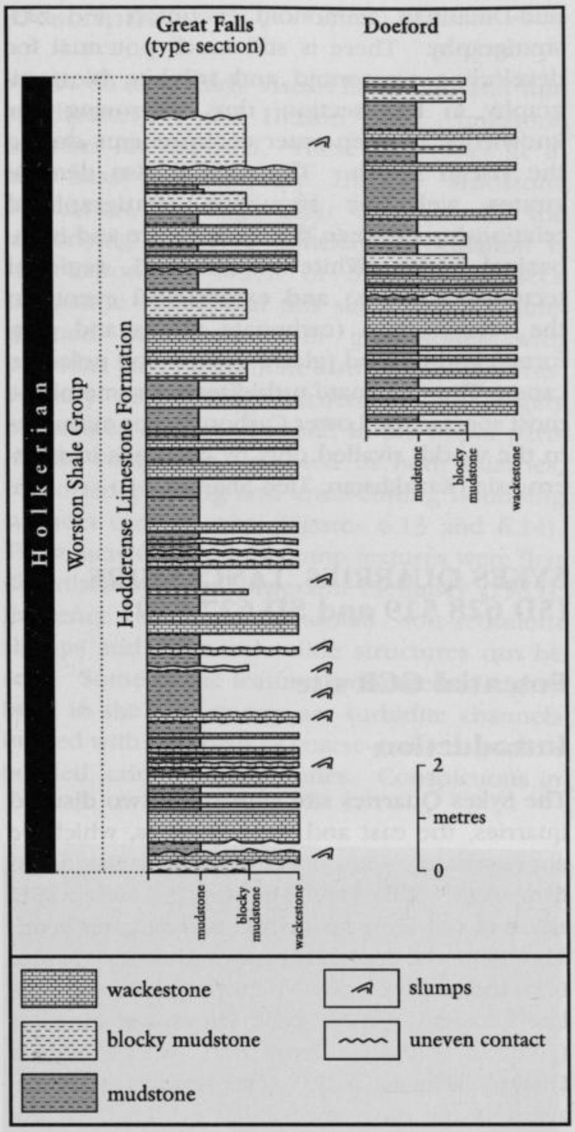


Figure 6.12 Comparative sections of the Holkerian Hodderense Limestone Formation (Worston Shale Group) at the River Hodder GCR site. After Riley (1990a).

Black Wheel (SD 6980 4000). It is about 180 m thick and is much more shaly than the Pendleside Limestone Formation at **Pendle Hill** (see GCR site report, this chapter). It also differs in that soft-sediment deformation is common and slumps are present at several horizons. The sharp-based, graded limestone beds are generally finer-grained here than at Pendle. Within the shales, deep-water trilobites, including *Phillibole polleni* (type locality) and *Vandergrachtia vandergrachtii* (type locality), are common at certain levels.

There is a conformable passage into the overlying Lower Bowland Shale Formation at Black Wheel (Figure 6.11), the basal shale having yielded the ammonoids *Entogonites grimmeri* and *Goniatites hudsoni* (wrongly identified by Earp *et al.* (1961) as *G. crenistria*) indicating the basal B_{2a} ammonoid zone (Riley, 1990b, 1993). *Entogonites* is a rare but distinctive ammonoid with ribbed quadrangular coiling and a short stratigraphical range. Its presence allows correlation between the western USA–Alaska (Titus and Riley, 1997) and Britain eastwards into Germany (Nicolaus, 1963).

Interpretation

The Limekiln Wood Limestone Member at this site represents shedding of carbonate material into an intrabasinal low developed within the footwall of an active basement fault. The source (palaeohigh) was a tilt block (Grayson and Oldham, 1987) running just to the north of the site, from south-west to north-east through the Whitewell and Ashnott areas. During early Viséan (basal late Chadian) times, even the intrabasinal palaeohighs became drowned by deep marine water, intrabasinal carbonate production mainly ceased, and only fine-grained terrigenous material reached the basin centre (Phynis Mudstone Member). Later in Chadian times, shallow-water ramp carbonates began to form, attached to the cratonic areas surrounding the Craven Basin. These ramps prograded southwards (see **Sykes Quarries** GCR site report, this chapter), but it was not until Arundian times, after they had been active for long enough, that these ramps were able to export significant carbonate into the basin. The limestone turbidites of the Chaigley Limestone Member were probably sourced by the carbonate ramp attached to the South Lake District High, with the Arundian highstand marked by the Dunbarella Bed. The coeval Embsay Limestone Member, present in the eastern part of the Craven Basin around Skipton and Lothersdale (e.g. see **Dowshaw Delf Quarry** GCR site report, this chapter), is cleaner with more grainstones and was probably sourced from the Askrigg Block and Central Lancashire High margins. These ramps were switched off at the end of Arundian times by sea-level fall associated with tectonic activity (see **Dowshaw Delf Quarry** GCR site report, this chapter; Davies *et al.*, 1989; Barclay *et al.*, 1994). Once more, during early Holkerian times, terrigenous clastic supply dominated. Holkerian transgression eventually drowned the cratonic areas, largely cutting off clastic supply and providing ample accommodation space for renewed carbonate ramps to form. The basin centre became too distal to receive significant carbonate turbidites from these ramps, resulting in sediment starvation. This gave rise to the deposition of the widespread hemipelagic cephalopod limestones of the Hodderense Limestone Formation, which may be compared with the Sea Mount Member of the Castletown Formation, Isle of Man (Dickson *et al.*, 1987). Towards the end of Holkerian times, rapid and regular alternations of low (lowstand) and high (highstand) sea level began to take effect. These were glacio-eustatic in origin, driven by the waxing and waning of distant Gondwanan polar ice caps (Britain was close to the equator in Early Carboniferous times). During lowstands, the carbonate areas were emergent. During highstands, the platforms were drowned and the resulting accommodation space was soon filled as copious supplies of detrital carbonate were shed into the basin as turbidites in the Pendleside Limestone Formation. Conversely, each lowstand temporarily shut off carbonate supply. The Pendleside Limestone Formation in the Hodder section, with its slumps, finer grain size and high mud content, represents a distal facies equivalent deposited farther away from the source platforms than that at **Pendle Hill** (see GCR site report, this chapter). During late Asbian times, the source platforms surrounding the basin became rimmed with microbial reefs (e.g. at **Settle**, **Malham** and **Cracoe Knolls and Swinden Quarry**, see GCR site reports and Figure 5.2, Chapter 5). The reefs obstructed the export of carbonate and interfered with the exchange of sea water between the basin and the surrounding platforms. Carbonate supply became more localized and black shale deposition, associated with basin anoxia, ensued (Lower Bowland Shale Formation).

Conclusions

The River Hodder section is the best exposed and thickest Viséan marine hemipelagic deep-water sequence in Europe, possibly the world. It is one of only two localities in Britain that have yielded ammonoids of Arundian age (there are less than a dozen worldwide); it also provides an ammonoid record for the Holkerian Stage. It is therefore an essential section for understanding mid-Dinantian ammonoid evolution and biostratigraphy. There is still much potential for developing ammonoid and trilobite biostratigraphy in this section, thus improving our knowledge of deep-water environments during the Viséan Epoch. The section also demonstrates well the sequence stratigraphical relationship between the basin centre and intra-basinal highs (Whitewell–Ashnott), regional tectonics (cratons) and extrabasinal events in the source areas (carbonate ramps and platforms) and beyond (glacio-eustasy and polar ice caps). The carbonate turbidites are some of the most spectacular Lower Carboniferous examples in the world, rivalled only by outcrops in western Asia (Kazakhstan, Tien Shan).

SYKES QUARRIES, LANCASHIRE (SD 628 519 and SD 627 519)

Potential GCR site

Introduction

The Sykes Quarries site consists of two disused quarries, the east and west quarries, which lie approximately 4 km north of Dunsop Bridge on the east (SD 6284 5188) and west (SD 6266 5185) sides of the Dunsop Bridge to Lancaster road. They lie in the core of the Sykes Anticline (Figure 6.1) and expose early Viséan limestones of the late Chadian Hetton Beck Limestone Member (Hodder Mudstone Formation, Worston Shale Group) (Figure 6.2). The section provides arguably the most spectacular evidence for the formation of tectonically induced gravity slide and slump structures in the Craven Basin. These structures developed on a slope at the southern boundary of a large area of carbonate deposition that extended north to the southern Lake District. A deep fault, which controlled the position of this slope, lies beneath the Sykes Anticline. The anticline was formed by compression of this fault (inversion) during late Carboniferous earth movements (Variscan Orogeny). The anticlinal structure is an ideal analogue for oil and gas traps, although here the trap has been breached and has leaked most of its hydrocarbons due to erosion. The limestones still smell of hydrocarbons when freshly broken. Detailed accounts of the site geology can be found in Gawthorpe and Clemmey (1985) and Aitkenhead *et al.* (1992).

Description

About 85 m of early Viséan limestone and thin mudstones of the Hetton Beck Limestone Member are exposed. These limestones lie in the basal part of the Hodder Mudstone Formation, although their contact with the underlying Clitheroe Limestone Formation is not exposed. Much of the Hetton Beck Limestone Member at this site comprises fine-grained packstones and grainstones with peloidal and carbonate lithoclast textures. Primary sedimentary structures are largely obliterated by bioturbation. In the upper parts of the succession, exposed in both quarries, contorted bedding and cross-cutting bounding surfaces can be seen (Figures 6.13 and 6.14). These gravity slide and slump features were first described by Gawthorpe and Clemmey (1985). Evidence of both intrafolial soft-sediment slumps and large-scale slide structures can be seen. Some of the features preserved in higher beds in the east quarry are turbidite channels infilled with thin beds of coarse-grained, graded-bedded, crinoidal packstones. Conspicuous in the west quarry, due to differential weathering, are silicified bands of the tabulate coral *Syringopora*. Other macrofauna include bellerophontid gastropods, solitary caniniid corals (e.g. *Siphonophyllia garwoodi*), spiriferoid, productoid and chonetoid brachiopods and a new undescribed species of the trilobite *Cummingella*. Calcareous microfossils are abundant, and include the cyanobacterium *Girvanella*, the dasycladacean alga *Koninckopora* (both mono- and bilaminar-walled forms), and numerous well-preserved foraminifera of the Cf4a2 Subzone including species of *Eoparastaffella* and *Lysella*, indicating a late Chadian age (not Arundian as correlated by Gawthorpe and Clemmey, 1985). Archaediscid foraminifera, diagnostic of a post-Chadian age, have not been found, despite the examination of over 100 thin-sections by one of the present authors (N. Riley).

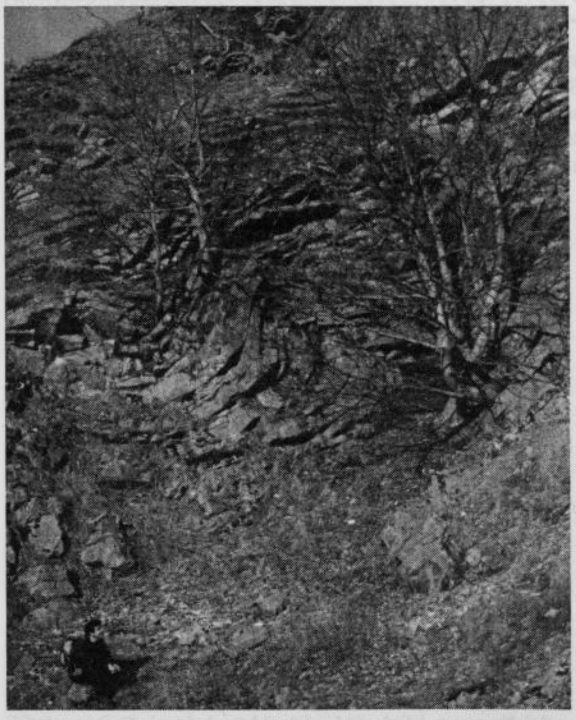


Figure 6.13 Deformational structures (possible slump folds; R. Gawthorpe, pers. comm., 2000) in the late Chadian Hetton Beck Limestone Member (Worston Shale Group) at Sykes Quarry (east), Forest of Bowland. (Photo: P.J. Cossey.)

Interpretation

The Sykes Anticline is a periclinal structure formed by Variscan inversion (with transtensional shear) along a basement fault (Bowland Line; see Figure 6.1); it forms the westernmost pericline (exposing early Viséan rocks) of a series of *en echelon* structures extending eastwards to the Eshton–Hetton area (see **Haw Crag** and **Clints Quarry** GCR site reports, this chapter). The basement fault, which was active during early Viséan extension, bounds the southern margin of a carbonate ramp attached to the South Lake District High; the Hetton Beck Limestone Member seen at this site being the lateral down-ramp facies equivalent of the Martin Limestone (see **Meathop Quarry** GCR site report, Chapter 4) farther north. The gravity slides and slumps demonstrate foundering of the southern margin of the ramp due to movement of the underlying basement fault (interpreted from seismic and gravity data) and the creation of a slope over its footwall. To the south, in the Whitewell and Slaidburn anticlines, coeval turbidites fed from this ramp comprise the Whitemore Limestone Member.

Conclusions

This site demonstrates a variety of effects that deep-seated faults had on sedimentation whilst the Earth's crust was being stretched and extended during Early Carboniferous times.

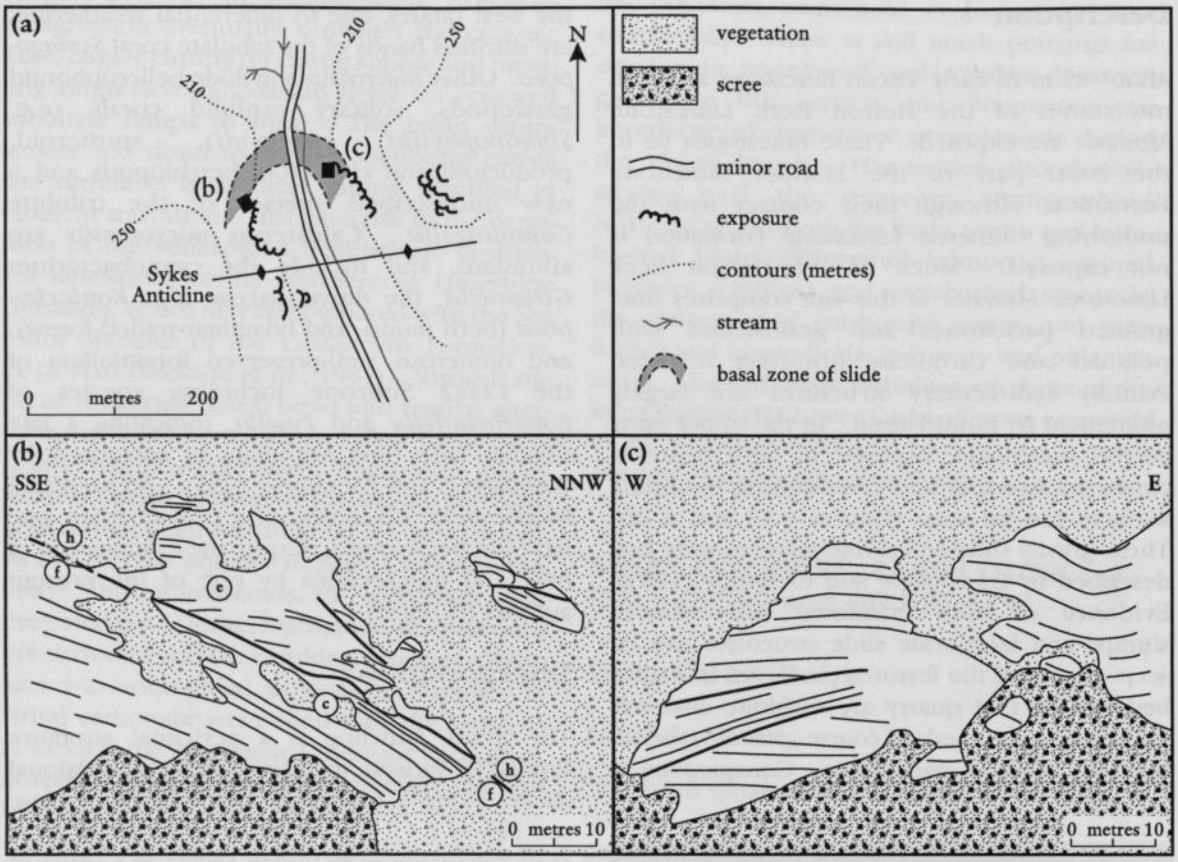


Figure 6.14 Geometry of large-scale gravity slide structures in the late Chadian Hetton Beck Limestone Member at Sykes Quarries. After Gawthorpe and Clemmey (1985). (a) Map illustrating the locations of the sections shown in figures (b) and (c). (b) Sykes Quarry (west) showing deformational bed geometries (e – extensional; c – compressional) associated with the principal slide plane (h – hanging wall; f – footwall). (c) Sykes Quarry (east) showing slide planes at right angles to those seen at Sykes Quarry (west) interpreted as lateral ramps. Bold lines in (b) and (c) are slide planes.

Such effects, in this case, controlled the junction (slope) between a shallow-water carbonate system (ramp) to the north and a deeper-water area to the south in which carbonate turbidites were deposited. Fault movements at depth below this junction also triggered the down-slope movement of partially consolidated masses of gravitationally unstable sediment in the form of slumps and slides.

Toward the end of the Carboniferous Period, the crust was compressed, giving rise to the anticlinal structure in which the site is exposed. The Sykes Anticline and similar structures trending along the Bowland Line to near Skipton, probably held significant hydrocarbons before being breached by erosion, and serve as good models for hydrocarbon traps (gas seeps still occur in the eastern part of the pericline in the adjacent valley of Whitendale to the east).

DOWSHAW DELF QUARRY, NORTH YORKSHIRE (SD 934 448)

Potential GCR site

Introduction

The Dowshaw Delf Quarry site is a disused quarry (SD 934 448) which lies in the west part of the Lothersdale Anticline (Figure 6.1). It exposes a 30 m section of Embsay Limestone Member (Arundian) unconformably overlain by the Twiston Sandstone Member (Holkerian) (Figure 6.15). Both these members lie within the middle part of the Hodder Mudstone Formation; the Embsay Limestone Member being the lowest exposed member of this formation in the Lothersdale area. Without the benefit of micropalaeontological evidence, the Embsay

Figure 6.15 Unconformable contact between the Embsay Limestone Member (Arundian, thick-bedded; lower right) and the Twiston Sandstone Member (Holkerian, thin-bedded; top left) in the Hodder Mudstone Formation (Worston Shale Group) at Dowshaw Delf Quarry, Lothersdale, Lancashire. Note lens cap for scale, left of centre. (Photo: N.J. Riley.)

Limestone Member was erroneously mapped as part of the Chatburn Limestone Group (Tournaisian) by Earp *et al.* (1961). However, later work by Fewtrell and Smith (1978) revealed the presence of middle Viséan foraminiferal assemblages in this unit. Riley (1990a) demonstrated the significance of the unconformity in its regional context. The locality is significant in that it demonstrates the effect of syn-depositional tectonics at the base of the Holkerian Stage and shows the effect of these tectonics and associated sea-level change on sediment supply. It is also an excellent section for the examination of detrital deep-water carbonates derived from shallow-water regions marginal to the Craven Basin, but which are elsewhere concealed under younger rocks.

Description

The section is about 30 m thick, and exposes the upper part of the Embsay Limestone Member. It contains hardly any interbedded mudstones. Most limestone beds are of metre-scale thickness, with sedimentary bed contacts not necessarily coinciding with bedding planes (amalgamated beds). Basal bed contacts are erosive and show sole structures. Graded bedding is also common. Most beds comprise fine- to medium-grained grainstone with ooids, peloids, foraminiferal tests and calcareous algae. Macrofossils, apart from crinoid ossicles, are rare. Fewtrell and Smith (1978) demonstrated that the abundant foraminiferal assemblages were of Viséan age. They contain abundant primitive Cf4d Subzone archaediscid foraminifera (now referable to *Glomodiscus*, *Kasachstanodiscus* and *Uralodiscus*). Shaly intervals comprise calcisiltites with chondritiform and helminthoid burrows. At the top of the south face of the quarry, a 60 cm-thick development of fine-grained, internally structureless sandstone (the Twiston Sandstone Member) rests with sharp (and angular) unconformity on the Embsay Limestone Member (Figure 6.15). In the Skipton Anticline, to the north, this sandstone rests conformably on shales 175 m above the level of the Embsay Limestone Member, suggesting that significant sediment was removed, or not deposited, at Dowshaw Delf Quarry during the hiatus.

Interpretation

The presence of an unconformity or non-sequence is typical of Arundian–Holkerian contacts in Britain (Davies *et al.*, 1989; Riley, 1990a; Barclay *et al.*, 1994) and beyond (Riley *et al.*, 1995; Riley, 1999) in cratonic and peri-cratonic settings of Europe and the USA. Its development demonstrates the effects of a widespread tectonic event and sea-level fall towards the end of Arundian times, followed by an early Holkerian transgression. At Dowshaw Delf, the Embsay Limestone Member represents a carbonate turbidite system fed from carbonate ramps attached to the Askrigg Block and Central Lancashire High. Its thick, proximal character at Lothersdale may result from a more copious local supply from the Central Lancashire High via a transfer ramp within the Pendle Fault (now inverted to form the Pendle Monocline; the deflection of the monocline southwards by interpolation of the Lothersdale Anticline may be a result of a kink in the Pendle Fault where this transfer ramp once lay). Footwall uplift associated with closure of the transfer ramp by the Arundian–Holkerian tectonic event, not only shut off the carbonate supply from the ramp interior but also shed fine-grained clastics (probably by reworking of Devonian and/or Tournaisian clastics in the footwall, such as those penetrated in the Boulsworth Borehole south of Burnley on the Central Lancashire High), resulting in the deposition of the Twiston Sandstone Member across the regraded and eroded top surface of the Embsay Limestone Member. Subsequent sea-level rise in Holkerian times drowned the Askrigg Block and Central Lancashire High deep enough to accommodate renewed ramp formation without significant export of carbonate into the Craven Basin where mudstones and eventually hemipelagic limestones (Hodderense Limestone Formation) occur, reflecting starvation of the sediment supply.

Conclusions

The association of tectonic activity and sea-level change across the entire Laurussian continent (from USA to the Former Soviet Union) suggests that eustasy and tectonics were related processes that produced the base Holkerian sequence boundary, unlike later in the Carboniferous Period when sea-level change associated with the waxing and waning of polar ice sheets was dominant.

PENDLE HILL, LANCASHIRE (SD 781 414–SD 774 409, SD 786 411 and SD 751 377)

Introduction

The Pendle Hill GCR site report is a composite account of the geology at three GCR sites situated on the western flank of the Pendle Monocline (Figure 6.1), namely Little Mearley–Limekiln, Dinantian (SD 781 414–SD 774 409), Little Mearley Clough, Namurian (SD 786 411) and Light Clough, Namurian (SD 751 377). Together, these sites expose deep-water mudstones, limestones and sandstones spanning an interval that extends from the upper part of the Hodder Mudstone Formation through to the Pendle Grit Formation (Figure 6.2). Along with other sections in the area they formed the basis for Phillips' (1836) terms 'Bolland' and 'Craven Shales'. Later, Hind and Howe (1901) recognized the special importance of these sections, which formed the basis for their now-disused 'Pendleside Series', erected to try to accommodate strata transitional between the 'Mountain Limestone' of Phillips (1836) and the Millstone Grit. The Pendle Hill area provides the type sections for the Pendleside Limestone, Lower Bowland Shale, Upper Bowland Shale and Pendle Grit formations as well as the Pendleside Sandstones Member. It includes some of the classic sections from which Bisat (1928, 1930, 1934, 1950, 1952) and Moore (1930, 1936, 1939, 1946) developed late Viséan and early Namurian ammonoid (goniatite) biostratigraphical schemes. It is also the type area for the Pendleian Stage and includes the stratotypic base and type locality (Light Clough) for the base of the Namurian Series, defined at the first entry point of the ammonoid *Cravenoceras leion* (Figure 1.4, Chapter 1). Excellent field descriptions relating to the stream and quarry sections represented by the GCR sites in this area are given in the [British] Geological Survey memoir for the area (Earp *et al.*, 1961).

Description

At the base of the succession the Hodderense Limestone Formation (= '*Bollandoceras hodderense* Beds' of Earp *et al.*, 1961) is a widespread and regionally important pelagic cephalopod limestone–shale interval of Holkerian age (Riley, 1990a). The formation averages about 6 m in thickness and comprises limestone beds, typically wackestones and floatstones, with diagenetic nodules giving a blotchy appearance. Nautiloid shells and ammonoids, including the zonal form *B. hodderense*, are typical macrofossils, and these are commonly corroded on their upper surfaces. Trilobites (*Latibole*), bellerophontid gastropods, smooth spiriferoids and the cool-water coral *Rotiphyllum* also occur. Micro-crinoids, ophiuroids and conodonts are abundant in microfossil preparations in some of the interbedded mudstones.

The overlying Pendleside Limestone Formation (early Asbian) has a shaly lower unit termed the 'Rad Brook Mudstone Member', which can be up to 100 m thick. In the lowest 5 m of this unit a widespread marker band contains the dendroid graptolite *Callograptus carboniferus*. The main limestone-dominated interval that forms the upper part of the Pendleside Limestone Formation is about 200 m thick and comprises limestone turbidites and carbonate gravity-flow units, slumps and channels. Limestones in this unit are composed entirely of carbonate debris (e.g. brachiopod and crinoid debris, peloids, ooids, foraminifera and algal fragments), and 'Bouma-type' sequences are well developed in this part of the succession.

The Lower Bowland Shale Formation (late Asbian–Brigantian) overlies the Pendleside Limestone Formation. The best overall section of the Bowland Shales is at Little Mearley Clough (Figure 6.16). This formation, approximately 85 m thick in the Pendle Hill area, comprises

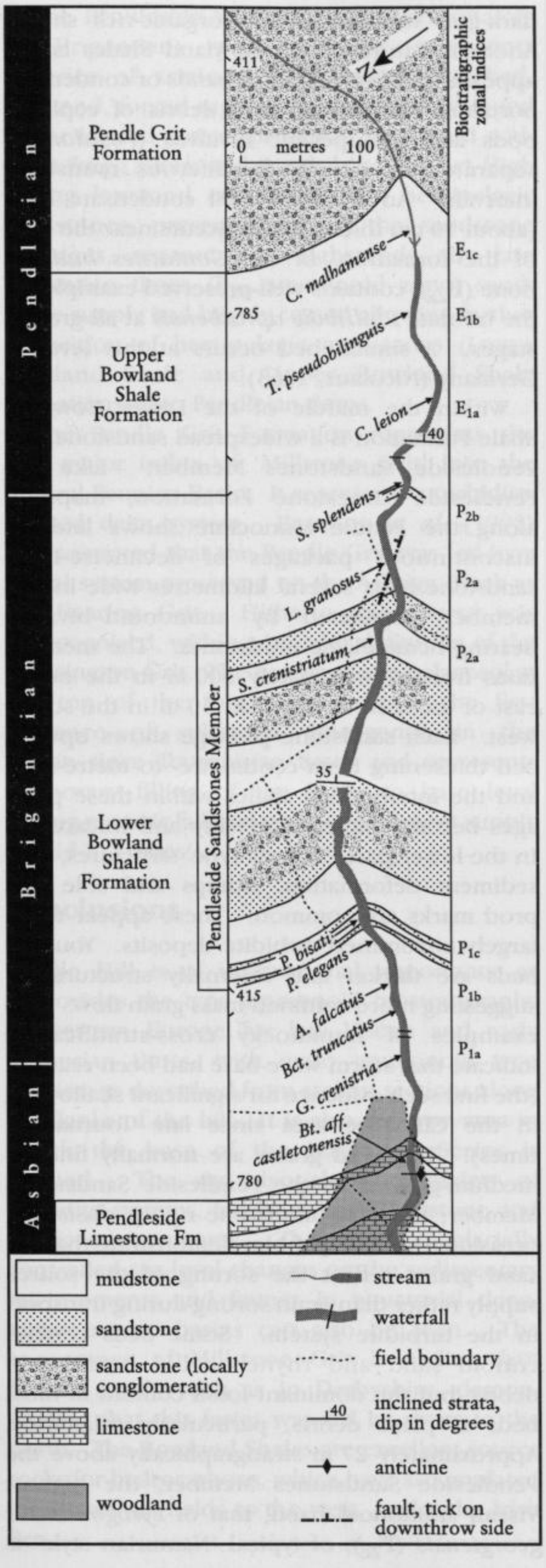


Figure 6.16▸ Geological map and stratigraphy of Lower Carboniferous (Asbian–Pendleian) strata at Little Mearley Clough showing the position of key ammonoid horizons referred to in the text. After Earp *et al.* (1961). *C. – Cravenoceras*; *T. – Tumilites*; *S. – Sudeticeras*; *L. – Lusitanoceras*; *P. – Paragoniatites*; *A. – Arnsbergites*; *Bct. – Beyrichoceratoides*; *G. – Goniatites*; *Bt. – Bollandites*.

dark-grey to black pyritic, organic-rich shales. Another feature of the Bowland Shales is the appearance of several fossil bands or condensate horizons, comprising shell debris of cephalopods and hemipelagic bivalves (*Posidonia*), separated by poorly fossiliferous mudstone intervals. An unusual fossil condensate level (about 10 cm thick), which occurs near the base of the formation, in the *Goniatites hudsoni* Zone (B_{2a}), contains well-preserved examples of the trilobite *Phillibole aprathensis* at all growth stages. A similar bed occurs at this level in Germany (Nicolaus, 1963).

Within the middle of the Lower Bowland Shale Formation is a widespread sandstone, the Pendleside Sandstones Member. Like the Pendleside Limestone Formation, mapping along the Pendle Monocline shows laterally discontinuous packages of decimetre-thick sandstone beds several kilometres wide in this member, separated by ammonoid–bivalve-bearing hemipelagic mudstones. The member thins from approximately 200 m in the north-east of the area to less than 50 m in the south-west. Each sandstone package shows upward bed thickening from centimetre- to metre-scale and the interbedded shales within these packages become increasingly silty and micaceous. In the lower part, 'Bouma-type' structures, soft-sediment deformation, slumps and sole and prod marks are common. These appear to be largely unconfined turbidite deposits. Younger beds are thicker and internally structureless, suggesting more confined mass grain flow. Rare examples of hummocky cross-stratification indicate that storm wave-base had been reached (the first such evidence for significant shallowing in the Clitheroe area since late Tournaisian times). The sand grains are normally fine- to medium-grained in the Pendleside Sandstones Member; however, mudstone rip-up clasts and occasional siderite pebbles demonstrate that the sand grains reflect the sorting of the source supply rather than grain sorting during transport in the turbidite system. Some beds contain crinoid sand and rhynchonellid brachiopod debris, but the dominant fossil content in most beds is plant debris, particularly calamitids. Approximately 27 m stratigraphically above the Pendleside Sandstones Member, the highest Viséan ammonoid band, that of *Lyrogoniatites georgiensis* (P_{2c}), of typical 'Namurian style' is separated from the basal Namurian, Cravenoceras leion Marine Band ($E_{1a}1$) by fissile pyritic mudstones (*c*. 3 m) which lack a marine macrofauna.

The section at Little Mearley Clough (Figure 6.16) shows a virtually continuous and well-exposed section through the lower part of the Pendleian Stage from the Upper Bowland Shale Formation to the Pendle Grit Formation, but a small normal fault cuts out the basal Namurian sequence, hence the basal boundary stratotype for the Namurian Series is defined at Light Clough, the type locality of *C. leion*. This section also extends into the Pendle Grit Formation. The Upper Bowland Shale Formation is more fissile and platy than the Lower Bowland Shale Formation. Several closely spaced ammonoid bands occur through the E_{1a} and E_{1b} ammonoid zones, with the bivalve *Posidonia membranacea* being typically most conspicuous in scree. Only one marine band (*C. malhamense*) is present in the E_{1c} Zone, above which sandstone turbidites of the Pendle Grit Formation resume, starting with centimetre-scale graded beds with 'Bouma-type' internal bedding and basal-bed prod (mainly from plant 'bounces') and scour marks. These beds thicken upwards from centimetre- to metre-scale bed thicknesses at the expense of hemipelagic mudstone. Unlike the Pendleside Sandstones Member, the Pendle Grit Formation becomes increasingly pebbly upwards, with quartz and feldspar pebbles in excess of 1 cm diameter commonly present in scour and channel bases, denoting erosion from a metamorphic–granitic hinterland. This is typical of the Millstone Grit and a feature of many sandstones in the Namurian Series. At the top of the Pendle Grit is a sandstone silcrete palaeosol (ganister), clasts of which, containing rootlets, can be found loose in the brash underlying peat between the head of Little Mearley Clough and Ogden Clough. The highest beds of the Pendle Grit are fluvial in origin.

Interpretation

The Hodderense Limestone Formation formed during Holkerian times when sea levels were high and the Craven Basin was starved of terrigenous sediment (Riley, 1990a). It represents a classic example of a pelagic limestone; a lithofacies well known from Palaeozoic to mid-

Mesozoic deep-water sequences, prior to the evolutionary appearance of calcareous plankton in mid-Jurassic times.

The Pendleside Limestone Formation represents one of the best examples of a deep-water carbonate turbidite system in Britain. Channel and fan morphologies can be recognized at several scales, from kilometre-scale fan systems seen along the Pendle Monocline (as illustrated on [British] Geological Survey maps of the area; Institute of Geological Sciences, 1975a) shaling out from north-east to south-west, to small-scale channels (e.g. at Limekiln Clough). The carbonate debris in these beds is derived from a variety of platform environments developed during late Holkerian and Asbian times at the basin margins (Askrigg Block and Central Lancashire High). The lack of accommodation space on these platforms caused their carbonate production to be exported into the basin. Frequent glacio-eustatic sea-level change was the main cause of the transition from ramps (with ample accommodation space) in Holkerian times, to platforms (with limited accommodation space) in Asbian times.

The onset of the deposition of the Bowland Shales (late Asbian–Pendleian) marked a significant change in marine chemistry, and specifically the change from mainly dysoxic to predominantly anoxic conditions at the sediment surface. Consequently these beds are less bioturbated and more organic rich than the underlying formations (i.e. the Bowland Shales are oil shales). This is in common with some other deep-water sections at this time (e.g. Antler Foreland Basin, Utah, USA; Titus and Riley, 1997). Their development denotes intense stratification of the water column and isolation of the deep basinal water. This was probably a response to climate and ocean circulation change as the Carboniferous glaciation intensified, and was further enhanced in the Craven Basin by the appearance of microbial reefs during Asbian and early Brigantian times, which fringed the surrounding carbonate platforms and restricted the gravitational flow of oxygenated water and carbonate detritus into the basin from the platform interiors. The fossil bands of the Bowland Shales are the forerunners of the marine bands so typical of Namurian rocks and represent marine highstand deposits formed during interglacial periods.

The Pendleside Sandstones Member (mainly mid-Brigantian) most probably represents a series of vertically and laterally stacked, lowstand, forced regression, turbidite lobes fed by fluvial and coastal processes associated with the Askrigg Block and South Lake District High during lowstand emergence; the hemipelagic mudstones, present between the sandstone packages, representing highstand. By late Brigantian times (P_{2b} ammonoid zone) sandstone supply had largely ceased allowing further deposition of hemipelagic mudstones (Lower Bowland Shale and Upper Bowland Shale formations) into Pendleian times.

The Pendle Grit Formation represents the first major influx of 'Millstone Grit' into the Central Pennine Basin. It represents a turbidite-fronted delta system. Brandon *et al.* (1995) demonstrated that the Pendle Grit was fed by a fluvial system preserved on the Askrigg Block as the Bearing Grit. Hitherto this source was unrecognized, within a broader definition of the Grassington Grit. The presence of a palaeosol at the top of the formation provides the first evidence of subaerial emergence in the region since Tournaisian times and represents temporary filling of the basin to base level during eustatic fall and copious sediment supply in mid-E_{1c} times.

Conclusions

Pendle Hill is of international importance as it provides the type ammonoid biostratigraphy of western Europe for late Viséan and early Namurian times, with many ammonoid type specimens described from stream sections along the flanks of the hill. It is also the type area in which the base of the Namurian Series is defined. The site also shows a variety of turbidite systems, fed from both limestone and clastic environments. The effects of glacially controlled sea-level changes on the sedimentary environments and faunas in equatorial deep-water marine basins can also be seen. The appearance of Millstone Grit is earlier than farther south, such as in Derbyshire, demonstrating that this facies was fed by rivers to the north. The Bowland Shales are excellent source rocks for hydrocarbons, which have accumulated in oil and gas fields to the west, under the Irish Sea.

SALESWHEEL, LANCASHIRE (SD 678 360)

Potential GCR site

Introduction

The Saleswheel section (SD 6775 3595) is situated in the River Ribble, about 1.5 km upstream from Ribchester. The outcrop lies within the lower part of the Millstone Grit (Namurian) and straddles the Pendleian–Arnsbergian boundary, for which it may (in due course) be selected as a type reference section, or stratotype. The site occurs at the down-stream end of a deep gorge cut through sandstones and siltstones of the Pendle Grit and Warley Wise Grit formations (Pendleian) and these are overlain by the Sabden Shales Formation (Arnsbergian) (Figure 6.2). The locality compliments and contrasts with the much thicker Arnsbergian section at **Artle Beck** (see GCR site report, this chapter), some 25 km to the NNW, near Lancaster. At Saleswheel, the entire Arnsbergian succession was deposited in deep water, away from the direct influence of rivers and deltas that entered the Pennine Basin to the north (contrast with Artle Beck). This has resulted in the formation of a condensed ('sediment starved') Arnsbergian section, which is dominated by shales and lacking in sandstones, but one which, despite its thinness, is stratigraphically more complete than sections of equivalent age to the north. Although deposited in deep water, the effect of sea-level change driven by glacio-eustatic processes is still evident, with several marine bands present. Evidence of distant ocean arc volcanic activity in the form of an ash fall is also preserved. Saleswheel is the type locality for several ammonoids (goniatites) described by Phillips (1836), Moore (1936, 1939) and Riley (1985), who was the first to publish details of this section. Further details of the section are given by Brandon *et al.* (1995, 1998).

Description

A log of the section is illustrated in Figure 6.17. The base of the section comprises a 7 m-thick massive unit of large-scale, cross-bedded (clinoform), coarse-grained, feldspathic sandstone, which represents the Warley Wise Grit Formation, at the top of the Pendleian Stage. It is underlain by slumped sandstone and siltstone

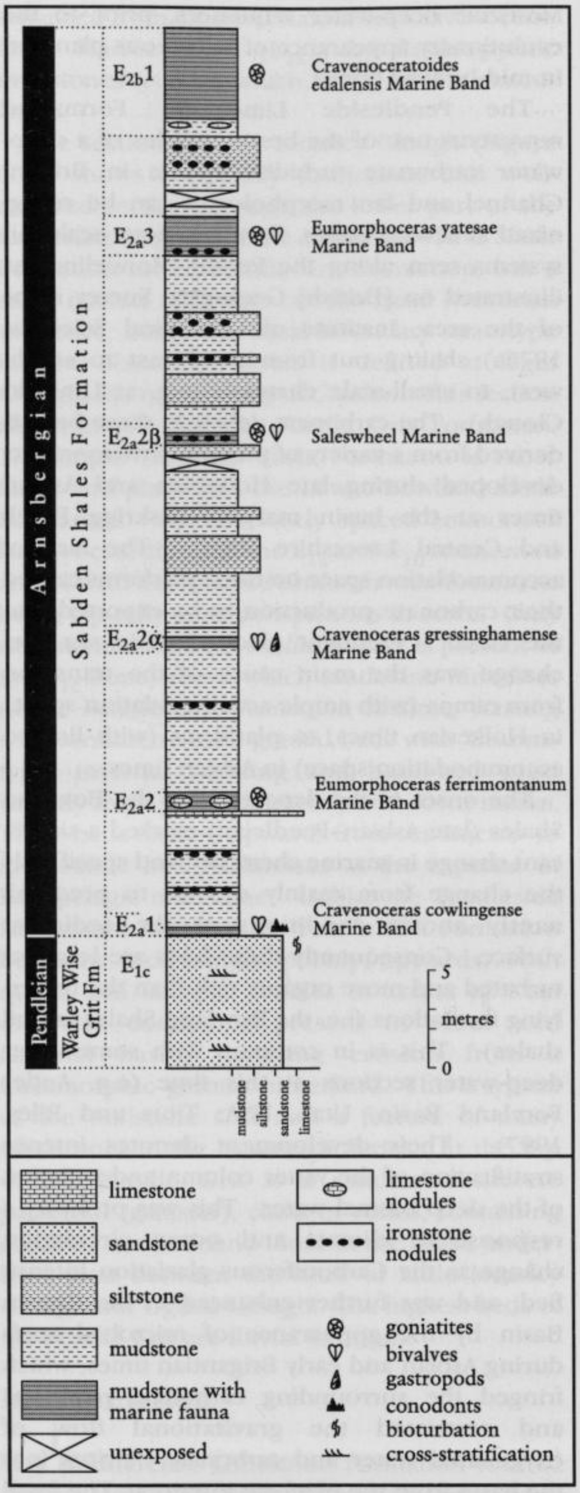


Figure 6.17 Sedimentary log of the upper part of the Warley Wise Grit Formation (Pendleian) and the lower part of the Sabden Shales Formation (Arnsbergian) exposed in the bed of the River Ribble at Saleswheel, illustrating the position of marine bands referred to in the text. Based on Riley (1985) and Brandon *et al.* (1998).

graded beds containing the bivalve *Sanguinolites*, representing the upper part of the Blacko Marine Band ($E_{1c}2$). Its top surface forms the steep dip-slope that dominates the mouth of the gorge. This surface shows evidence of phosphatization and marine bioturbation (mis-interpreted as palaeosol rootlets by Riley, 1985) and is overlain sharply by black shales with marine fossils. Especially abundant are fish fragments, conodonts and the hemipelagic bivalves *Obliquipecten* and *Posidonia corrugata*. No ammonoids have been found, but the relative position to faunal bands above and below denotes that this is the Cravenoceras cowlingense Marine Band ($E_{2a}1$), marking the base of the Arnsbergian Stage (Figure 1.4, Chapter 1). The marine band is about 0.8 m thick, above which the mudstones become much more friable and lack macrofossils. These 'unfossiliferous' beds (for they will have miospores) also contain ironstone nodules and extend for about 6 m until the next marine band is reached, marked by platy calcareous shales and a layer of micrite nodules (bullions) packed with uncrushed ammonoid larvae and conches at various growth stages. Oil bleeds are common in the nodules and along fractures in the enclosing strata. This is the Eumorphoceras ferrimontanum Marine Band ($E_{2a}2$) which contains the zonal ammonoid, plus *E. erinense*, *Cravenoceras* and *Metadimorphoceras saleswheelense*. Large orthoconic nautiloids (*Actinoceras*) and scattered crinoid ossicles also occur, as well as the hemipelagic bivalves *Dunbarella yatesae*, *Obliquipecten* and *Posidonia corrugata*. Conodonts are abundant and exquisitely preserved, with conodont recoveries exceeding 3000 per kilogram of rock (amongst the highest in the UK). Only two genera are present, represented by *Gnathodus bilineatus bollandensis* and several species of *Lochriea*. Shallow-water conodonts are absent. The marine band is about 1.5 m thick, above which fissile friable non-calcareous mudstones return. A 5 mm-thick, soft, pale blue-grey, bentonitic clay occurs within these mudstones, about 6 m above the marine band. Marine shales representing the Cravenoceras gressinghamense Marine Band re-appear 3 m higher in the sequence. This band is about 0.3 m thick and contains a diverse hemipelagic bivalve fauna with *Actinopteria persulcata*, *P. corrugata*, *Obliquipecten* and *Selenimyalina variabilis* (first stratigraphical occurrence), fish and conodonts, but so far ammonoids have not been found. Friable non-marine shales with ironstone nodules are discontinuosly exposed over the next 10 m of section, until 1 m of marine shales representing the Saleswheel Marine Band ($E_{2a}2\beta$) is reached (stratotype) in which only poorly preserved anthracoceratid ammonoids and *P. corrugata* have been found. It should be noted that this same marine 'band' in the area around **Artle Beck** (see GCR site report, this chapter) is over 90 m thick! A further 10 m of discontinuously exposed, friable, ironstone-rich shales intervene up to the Eumorphoceras yatesae Marine Band ($E_{2a}3$). This band is 2 m thick (contrast with 19 m at Artle Beck) and contains the zonal ammonoid, together with *P. corrugata*. Above this, about 4 m of friable shales with ironstones recur. Higher in the sequence are platy, calcareous, marine shales containing large micrite nodules (bullions) crowded with *P. corrugata* and *S. variabilis*. The ammonoids *Asturoceras romanum* (type locality), *Cravenoceras* cf. *subplicatum* and *Metadimorphoceras* occur sparsely. Oil bleeds are common. Large examples of the conodont *G. bilineatus bollandensis* are also present. The overlying 5 m of calcareous, platy mudstones contain, in addition, the zonal ammonoid *Cravenoceratoides edalensis*, plus *Ct. bisati*, characteristic of the Cravenoceratoides edalensis Marine Band ($E_{2b}1$). Although currently unexposed, approximately 5 m further up section is the Eumorphoceras leitrimense Marine Band ($E_{2b}2$), the horizon from which Phillips (1836) obtained the types of *Ct. nitidus*.

Interpretation

Glacio-eustatic lowstand, in latest Pendleian times, is represented by the Warley Wise Grit Formation, in the form of a prograding mouthbar; a formation that most probably was deposited here in an upper delta-slope environment. A major glacio-eustatic transgression, represented by the basal Arnsbergian C. cowlingense Marine Band, drowned the fluvial system that fed the mouthbar, causing its abandonment and forming a marine flooding surface (the big dip-slope). Sea level remained relatively high through the rest of the early Arnsbergian, with only weak lowstands during glacial periods, preventing significant lowstand penetration of fluvial sediments into the basin from the north. This effect was enhanced by extreme subsidence in the Lancaster area to the north which accommodated much of the clastic supply before it could reach the Saleswheel area farther south. The lowstand deposits at Saleswheel are therefore developed entirely in ironstone-rich friable shales. The ironstones originate from acidic freshwater runoff fed by rivers draining from a metamorphic–granitic source entering the basin from the north. These same rivers were responsible for the deposition of fluvial and turbiditic sandstones in the Lancaster and Skipton areas at this time. The lack of marine macrofossils in these lowstand intervals probably results from a combination of factors, including raising of the carbonate compensation depth (due to the acid runoff), more rapid sedimentation (diluting fossil concentrations) and dilution or replacement of marine basinal waters with freshwater. Interglacial periods are represented by marine bands (highstands). Marine highstands intensified sediment starvation and encouraged fossil condensate horizons to form (marine bands). Volcanic ash, sourced from explosive volcanic eruptions (probably associated with island-arc systems formed along destructive continental margins in central and eastern Europe at this time), occasionally reached the area (Spears *et al.*, 1999). The presence of oily hydrocarbons indicates that the Sabden Shales Formation is an excellent source rock.

Conclusions

Saleswheel is a classic Millstone Grit section and was one of the first localities to have been cited for its fossils in British scientific literature (Phillips, 1836; e.g. the ammonoid *Cravenoceratoides nitidus*). The contrast of depositional style with outcrops of a similar age to the north is striking; this being attributed to the lack of any direct fluvial influence in the deposition of the Sabden Shales Formation and to sediment starvation. The marine flooding surface at the base of E_{2b} is particularly significant as it represents one of the last major and widespread Lower Carboniferous highstands that can be traced with confidence from the USA, through Europe into Asia, prior to the lowering of sea level at the end of the Arnsbergian (cf. Upper Carboniferous at the Gill Beck (Stonehead Beck) GCR site; Cleal and Thomas, 1996) and associated unconformity development (e.g. between the Mississippian and Pennsylvanian in the USA). The section also demonstrates the hydrocarbon source-rock quality of the Sabden Shales Formation, a formation that has contributed to the development of commercial oil and gas accumulations in the Irish Sea Basin to the west.

ARTLE BECK, LANCASHIRE (SD 553 624)

Potential GCR site

Introduction

The Artle Beck site consists of a stream gorge section at Artle Beck (SD 5525 6240), close to the village of Crossgill and 7 km to the east of Lancaster. It lies within the lower part of the Millstone Grit and is of early Namurian (Arnsbergian) age. The section extends from the Eumorphoceras yatesae Marine Band ($E_{2a}3$) in the Roeburndale Formation, across an unconformity into the overlying Wards Stone Sandstone Formation (Figures 6.2 and 6.18). The site clearly demonstrates the influence of earth movements on sedimentation at the northern margin of the Pennine Basin during early Namurian times. The locality also preserves the thickest and northernmost known development of the E. yatesae Marine Band. Details of the site geology can be found in the British Geological Survey memoir (Brandon *et al.*, 1998) and on the accompanying geological map (British Geological Survey, 1995a). Aspects of the geology are also described by Moseley (1954).

The Lancaster area has one of the thickest early Namurian sections in the world (over 1.6 km thick), rivalled only by that in the Midland Valley Basin, Scotland (Chapter 2) and in Poland. The Artle Beck section forms part of this thick succession and, although it contains a number of depositional breaks, it provides a stark contrast to the thin but complete, sediment-starved Arnsbergian succession preserved farther south, entirely in mudstones (see **Saleswheel** GCR site report, this chapter).

Description

The succession is approximately 45 m thick, but is stratigraphically complex. This is due to syndepositional folding, faulting and unconformity within the Roeburndale Formation, which occupies most of the section in the valley floor, plus unconformity and overstep across these

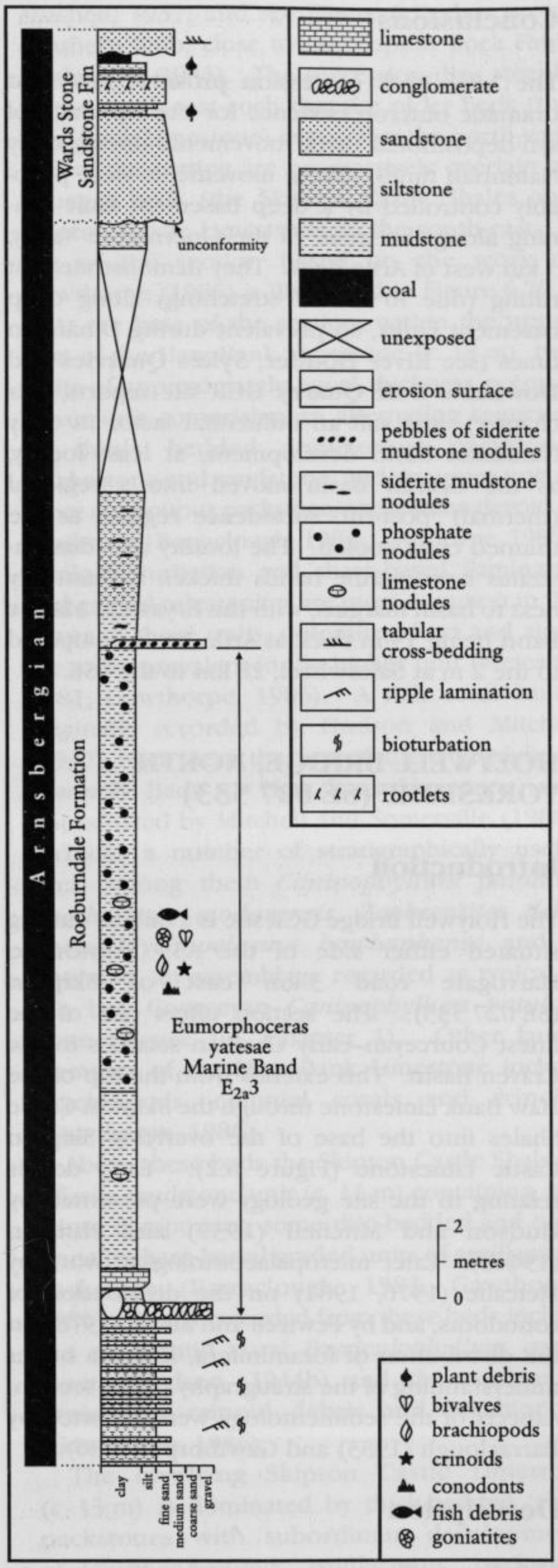


Figure 6.18 Generalized log of Arnsbergian strata (Roeburndale Formation and Wards Stone Sandstone Formation) at Artle Beck, near Caton, Lancashire. After Brandon *et al.* (1998).

structures by the succeeding Wards Stone Sandstone Formation, seen in the valley sides. Figure 6.19 demonstrates these relationships and a log of the succession is presented in Figure 6.18. The basal 5 m lies in thin-bedded siltstones and fine- to medium-grained sandstones in the Roeburndale Formation. These are folded into a broad anticline, truncated by angular unconformity and overlain by black mudstones of the Eumorphoceras yatesae Marine Band ($E_{2a}3$). At the base of this band is a boulder bed made up of reworked siderite and wackestone nodules, some of which show evidence of soft-sediment deformation. The marine band is approximately 19 m thick and grades up into siltstones. Locally these siltstones attain a thickness of approximately 20 m, of which 5 m are exposed. In places this succession is disrupted by faulting. Cutting across these folded and faulted beds with angular unconformity are coarse-grained cross-bedded feldspathic fluvial sandstones belonging to the Wards Stone Sandstone Formation. This overstep is regional and can be mapped over an area of more than 150 km^2. The faults and folds within the Roeburndale Formation at Artle Beck do not pass up through the unconformity. The fluvial sandstones of the Wards Stone Sandstone Formation fine upwards

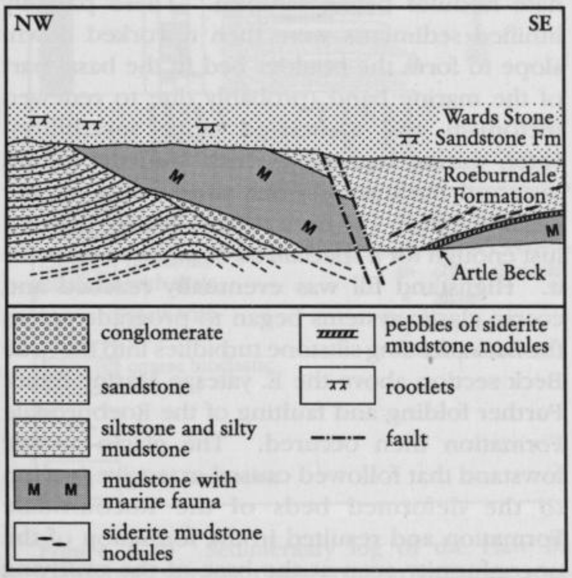


Figure 6.19 Schematic section of strata at Artle Beck illustrating possible relationships between units of the upper part of the Roeburndale Formation and lower part of the Wards Stone Sandstone Formation. After Brandon *et al.* (1998). Note that although this section is not to scale, its length is approximately 400 m.

and are overlain by a palaeosol and a thin coal, which is succeeded by further fluvial sandstones in erosive contact with the coal.

The fauna of the E. yatesae Marine Band is unusual in that it has both hemipelagic elements, such as the ammonoids *Eumorphoceras yatesae* (the zonal form restricted to this horizon) and *Cravenoceras* cf. *gairense*, the bivalves *Posidonia corrugata*, *P. lamellosa* (highest known occurrence), *Selenimyalina variabilis*, together with benthic forms, such as smooth spiriferoid brachiopods and inadunate crinoids, some of which are exquisitely preserved with complete arms and pinnules.

Interpretation

The siltstones and sandstones beneath the E. yatesae Marine Band are delta-slope turbidite equivalents of the more proximal delta-top Sapling Clough Sandstone, 10 km to the south-east. Prior to deposition of the E. yatesae Marine Band these turbidites were folded. Glacio-eustatic transgression then caused sea-level rise, drowning the Sapling Clough Sandstone delta system, cutting off the sand supply. This transgression eroded the underlying delta-slope area and formed an omission surface. The slope was then draped in marine muds within which carbonate nodules began to form. These partially lithified sediments were then reworked downslope to form the boulder bed in the basal part of the marine band (probably due to renewed tectonism and associated slope instability). Later, during highstand, thick mud deposition occurred (indicating a rich supply close to the basin margin). The mud surface was oxygenated just enough for a specialized benthos to colonize it. Highstand fill was eventually reached and coarse clastic systems began to prograde across the basin, feeding siltstone turbidites into the Artle Beck section above the E. yatesae Marine Band. Further folding and faulting of the Roeburndale Formation then occured. The glacio-eustatic lowstand that followed caused extensive erosion to the deformed beds of the Roeburndale Formation and resulted in the formation of the unconformity seen at the base of the overlying Wards Stone Sandstone Formation. Base level then rose, either because of glacio-eustasy or because of regional thermal subsidence, to facilitate the deposition of this fluvial deposit.

Conclusions

The Artle Beck succession provides the most dramatic outcrop evidence for the existence of syn-depositional earth movements during early Namurian times. These movements were probably controlled by a deep basement fault running along the trend of the Quernmore Valley, 5 km west of Artle Beck. They demonstrate that rifting (due to crustal stretching) along deep basement faults, so prevalent during Dinantian times (see **River Hodder**, **Sykes Quarries** and **Dowshaw Delf Quarry** GCR site reports, this chapter), was still an influential factor in early Namurian basin development, at least locally, as the Craven Basin moved into a regional (thermal) 'post-rift' subsidence regime, as the thinned crust cooled. The locality also demonstrates how marine bands thicken dramatically next to basin margins, with the E. yatesae Marine Band being 19 m thick at Artle Beck, compared to the 2 m at Saleswheel, 28 km to the SSE.

HOLYWELL BRIDGE, NORTH YORKSHIRE (SE 027 533)

Introduction

The Holywell Bridge GCR site is a railway cutting situated either side of the A59 Skipton to Harrogate road 3 km east of Skipton (SE 027 533). The section offers one of the finest Courceyan–early Chadian sections in the Craven Basin. This extends from the top of the Haw Bank Limestone through the Skipton Castle Shales into the base of the overlying Skipton Castle Limestone (Figure 6.2). Early details relating to the site geology were presented by Hudson and Mitchell (1937) and Hudson (1944b). Later micropalaeontological work by Metcalfe (1976, 1981) on the distribution of conodonts, and by Fewtrell and Smith (1978) on the distribution of foraminifera, led to a better understanding of the stratigraphy of the section. Aspects of the sedimentology were reported by Barraclough (1983) and Gawthorpe (1986).

Description

This Lower Carboniferous section lies close to the core of the Skipton Anticline (Hudson and

Mitchell, 1937; and see Figure 6.1), but on its southern limb, close to the Skipton Rock Fault (Arthurton, 1983). The succession dips steeply to the south-east such that the older beds (the Haw Bank Limestone) exposed at the north-west end of the cutting are progressively overlain by younger beds (the Skipton Castle Shales and Skipton Castle Limestone) to the south-east. A log of the section based on the work of Gawthorpe (1986) is illustrated in Figure 6.20.

At the base of the section, within the upper part of the Haw Bank Limestone (*c.* 18 m), two units of approximately equal thickness occur: a lower unit comprising an alternating sequence of thinly bedded argillaceous packstone/wackestone and mudstone; and an upper unit of more continuous packstone/wackestone devoid of mudstone (Barraclough, 1983; Gawthorpe, 1986). While bioturbation and sharp-based, laminated and graded calcarenites are more common in the lower of these units, dolomite, chert and algae are more prevalent in the higher unit (Metcalfe, 1981; Gawthorpe, 1986). A rich coral fauna, originally recorded by Hudson and Mitchell (1937) from near the top of their '*Zaphrentis konincki* Beds' (= Haw Bank Limestone) and re-evaluated by Mitchell and Somerville (1988), includes a number of stratigraphically useful taxa, among them *Caninophyllum patulum*, *Cyathoclisia modavensis*, *Zaphrentites delanouei*, *Sychnoelasma hawbankense* and *S. konincki*, an assemblage regarded as typical of the late Courceyan *Caninophyllum patulum* Zone (Figure 1.4, Chapter 1). Other faunal elements of the Haw Bank Limestone include brachiopods, colonial corals and crinoids (Gawthorpe, 1986).

Above these beds the Skipton Castle Shales is a fissile mudstone unit (*c.* 11 m) containing, as a minor component, some thin-bedded and occasionally sharp-based graded units of argillaceous packstone (Barraclough, 1983; Gawthorpe, 1986). Fossils recorded from these beds include the zaphrentid coral *Fasciculophyllum ambiguum* (Hudson, 1944b) and the remains of bryozoans, crinoid debris and brachiopods (Gawthorpe, 1986).

The overlying Skipton Castle Limestone (*c.* 13 m) is dominated by thick-bedded 'algal' packstones with subordinate developments of thinner-bedded argillaceous packstone (Barraclough, 1983; Gawthorpe, 1986). A

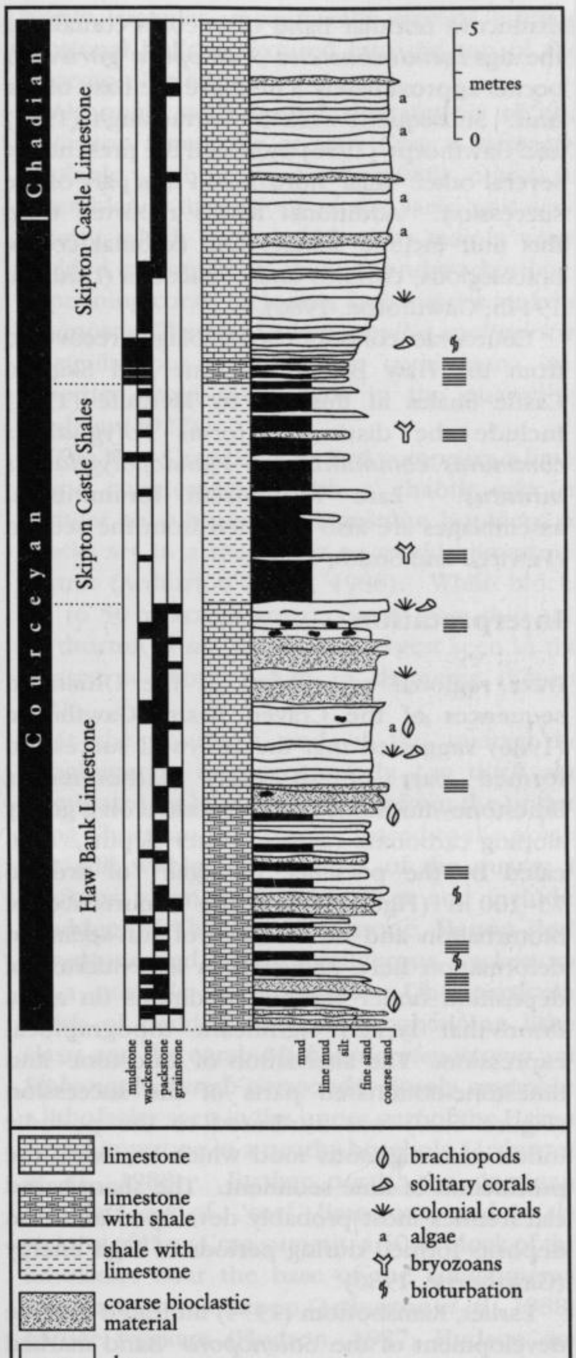


Figure 6.20 Sedimentary log of the Haw Bank Limestone–Skipton Castle Limestone ramp succession (Courceyan–Arundian) at the Holywell Bridge GCR site. After Gawthorpe (1986). The stratigraphical terminology used here follows that of Metcalfe (1981).

distinctive nodular band of oncoids containing the alga *Pseudochaetetes* '*Solenopora*' *garwoodi* occurs approximately 5 m above the base of the unit. Subsequent work by Barraclough (1983) and Gawthorpe (1986) indicated the presence of several other 'algal' horizons in this part of the succession. Additional fossils reported from this unit include solitary and colonial corals, brachiopods, crinoids and ostracodes (Hudson, 1944b; Gawthorpe, 1986).

Courceyan conodont assemblages recovered from the Haw Bank Limestone and Skipton Castle Shales at this site by Metcalfe (1981) include the distinctive forms *Polygnathus communis communis* and *Pseudopolygnathus minutus*. Late Tournaisian foraminiferal assemblages are also reported from the section (Fewtrell and Smith, 1978).

Interpretation

In a regional assessment of the Dinantian sequences of the Craven Basin, Gawthorpe (1986) suggested that the Holywell succession formed part of an early Carboniferous limestone–mudstone facies deposited on a gently sloping carbonate ramp in water depths, 'indicated by the presence of algae', of around 75–100 m (Figure 6.4a); the occurrence of bioturbation and the absence of soft-sediment deformation here being taken as evidence of deposition under aerobic conditions on a sea floor that lacked significant topographical expression. The alternation of mudstone- and limestone-dominated parts of the succession (Figure 6.20) was attributed to the periodic influx of terrigenous mud which inhibited the production of lime sediment. The sharp-based calcarenites most probably developed as storm deposits formed during periods of high energy (Gawthorpe, 1986).

Earlier, Ramsbottom (1974) indicated that the development of the '*Solenopora*' Band marked the terminal regressive (shallowing) phase at the top of the first eustatically controlled 'Major Cycle' he recognized in the Lower Carboniferous successions of the north-eastern part of the Craven Basin. The same band was subsequently used to define the top of the Courceyan Stage in the Skipton area (George *et al*., 1976).

A Courceyan–early Chadian age for the Holywell section is supported on the combined evidence of macrofossil and microfossil distributions (Hudson and Mitchell, 1937; Hudson, 1944b; Fewtrell and Smith, 1978; Metcalfe, 1981; Mitchell and Somerville, 1988), and Metcalfe (1981) assigned the entire section to his *Pseudopolygnathus minutus* conodont zone; the lateral equivalent of the *Scaliognathus anchoralis–Polygnathus bischoffi* Subzone of Varker and Sevastopulo's (1985) conflated conodont zonal scheme for the British and Irish Dinantian Series, which spans the Courceyan–Chadian boundary (Riley, 1993; see Figure 1.4, Chapter 1).

Regional studies generally equate the Holywell succession to the upper part of the Chatburn Limestone Group (= Chatburn Limestone Formation of Fewtrell and Smith, 1980) of the Clitheroe district (Earp *et al*., 1961), though precise correlations between the two areas remain uncertain (Figure 6.2). The prominent '*Solenopora*' Band in the Skipton Castle Limestone was equated by Ramsbottom (1974), George *et al*. (1976) and Metcalfe (1981) with a similar band in the Chatburn Limestone Group between the Horrocksford Beds and the Bankfield East Beds in the Clitheroe area (see **Chatburn Bypass** GCR site report, this chapter). However, the equivalence of the Holywell succession with units stratigraphically higher in the Chatburn Limestone appears to be indicated by Fewtrell and Smith (1980). This view was later supported by Riley (1995) who equated the base of the Skipton Castle Limestone with the base of the Bold Venture Beds at Clitheroe; a view which effectively lowered the Courceyan–Chadian boundary to a position within the Haw Bank Limestone (Figure 6.2).

Conclusions

This classic mixed-interest site offers an outstanding Courceyan–early Chadian section of the Haw Bank Limestone, Skipton Castle Shales and Skipton Castle Limestone, a relatively deep-water (75–100 m) marine sequence deposited on a gently inclined sea floor in the north-eastern part of the Craven Basin during early Carboniferous times. A prominent marker bed containing 'algal' structures near the base of the Skipton Castle Limestone marks the position of the stratigraphically significant Courceyan–Chadian boundary. The site is important for the regional, national and international correlation of early Dinantian successions and vital to reconstructions of early Carboniferous palaeogeography within the Craven Basin.

HAW CRAG, NORTH YORKSHIRE (SD 913 564)

Introduction

The Haw Crag GCR site lies close to Bell Busk and some 9 km to the north-west of Skipton. This locality provides an outstanding section of the Haw Crag Boulder Bed (Arundian), resting unconformably on the underlying Thornton Limestone Member (early Chadian) (Figure 6.2). The development of these features provides spectacular evidence of a late Chadian–early Arundian episode of tectonic and sediment instability that is widely recognized in Lower Carboniferous successions throughout the Craven Basin and across much of central England. The site includes both the partially overgrown exposures seen at Haw Crag Quarry (SD 9135 5640) and the natural outcrops in the vicinity of Haw Crag summit (SD 9134 5648). Important early works relating to the site geology are by Wilmore (1910), Hudson (1927) and Hudson and Dunnington (1944). More recent sedimentological work by Barraclough (1983) and Gawthorpe (1987a) and regional mapping by Arthurton *et al.* (1988) has led to significant improvements in our understanding of the locality. The description below derives mainly from the work of these later authors and follows the lithostratigraphical terminology of Arthurton *et al.* (1988).

Description

The exposures at Haw Crag occur on the south-eastern limb of the NE–SW-trending Eshton–Hetton Anticline, close to its southern end, and just 0.5 km to the north of the Gargrave Fault – a SE-trending splinter of the South Craven Fault System to the north-west. At the base of the succession are beds belonging to the Thornton Limestone. These are unconformably overlain by the Haw Crag Boulder Bed which forms the local base to what Arthurton *et al.* (1988) referred to as their 'median limestone-rich subdivision' of the Worston Shales (= Hodder Mudstone Formation of Riley, 1990a; and see Figure 6.2). Missing from the sequence at this unconformity is the lower part of the Worston Shales, including the Hetton Beck Limestone Member (late Chadian) and the topmost beds of the Thornton Limestone (early Chadian). In the quarry, the Haw Crag Boulder Bed overlies this highly irregular unconformity surface infilling erosional hollows scoured into the top of the Thornton Limestone.

Although no detailed description of the Thornton Limestone at Haw Crag is currently available, Arthurton *et al.* (1988) noted its resemblance to sections of the same unit seen nearby, which they described as mainly wavy-bedded calcarenite packstones and wackestones containing corals including *Syringopora* and the diagnostic Chadian *Siphonophyllia cyclindrica*. A similar but more diverse coral fauna was recorded from these beds in the quarry by Hudson (1927).

The Haw Crag Boulder Bed comprises a limestone conglomerate with a chaotic mix of angular to subrounded limestone boulders or blocks set in a mudstone or muddy limestone matrix (Arthurton *et al.*, 1988). While blocks up to 50 m across are reported from this unit (Arthurton *et al.*, 1988), the largest seen in the quarry is about 4–5 m in diameter (Figure 6.21).

At the southern end of the quarry the conglomerate is approximately 2 m thick and dominated by boulders derived from the underlying Thornton Limestone. Traced to the north, but still within the confines of the quarry, it thickens to an 'estimated' 20 m and includes boulders of Thornton Limestone, Hetton Beck Limestone and a pale fossiliferous wackestone of a possible 'reef' origin. One particular block of bedded limestone, containing lithoclasts and the corals *Michelinia megastoma* and *Siphonophyllia* cf. *garwoodi*, closely resembles a lithofacies seen in the upper part of the Hetton Beck Limestone in a nearby borehole (Arthurton *et al.*, 1988). Farther north, the dominant boulders are of 'reef' limestone, and in the vicinity of Haw Crag summit, a 50 m block of this lithofacies near the base of the conglomerate forms an entire outcrop (Arthurton *et al.*, 1988). Earlier workers (Hudson, 1927; Hudson and Dunnington, 1944) regarded these outcrops as part of a more extensive and autochthonous development of 'reef' limestone below the unconformity surface. However, later workers recognized that at least some of these supposed 'reef' limestones are blocks of Waulsortian facies (Lees and Miller, 1985), and unpublished geopetal evidence indicates that a number of these, including the 50 m block referred to above, are stratigraphically inverted (J. Miller, pers. comm., 2001).

Figure 6.21 Exposure of the Arundian debris-flow deposit (the Haw Crag Boulder Bed) in the Hodder Mudstone Formation at Haw Crag Quarry, Bell Busk. Note that the prominent block at the foot of the crag (a boulder of the Hetton Beck Limestone Member) is approximately 5 m in diameter. (Photo: P.J. Cossey.)

Above the conglomerate, the remaining part of the Worston Shales succession (approximately 10 m thick) comprises an interbedded sequence of mudstones, siltstones and laminated muddy limestones containing graded limestone beds, slump structures and further boulders of Thornton Limestone (Barraclough, 1983; Arthurton *et al.*, 1988). Barraclough (1983) considered these boulders as part of a conglomerate sheet that thickened to the east.

Additional macrofossil records from the quarry indicate the presence of solitary rugose corals and productoid brachiopods in abundance, together with gastropods, cephalopods and trilobite remains (Wilmore, 1910). However, because this fauna was obtained from an unspecified level (or levels), its significance remains uncertain. Similar uncertainties concern the precise level(s) of foraminiferal assemblages recovered from the site by Fewtrell and Smith (1978).

Interpretation

In his revised lithostratigraphical scheme for the Worston Shale Group, Riley (1990a) considered the Worston Shales succession above the Haw Crag unconformity as Arundian in age and part of the Embsay Limestone Member, one of several newly defined members in his Hodder Mudstone Formation (= Worston Shales of Arthurton *et al.*, 1988). Similarly, beds below the unconformity are now assigned to the Thornton Limestone Member, the lowest of four new members in Riley's (1990a) re-defined Clitheroe Limestone Formation which is of early Chadian age (Figure 6.2).

Following detailed work by Gawthorpe (1986, 1987a) and Arthurton *et al.* (1988), Riley (1990a) regarded the early Chadian Thornton Limestone as a relatively shallow-water deposit that formed across the northern and central parts of the Craven Basin on a gently inclined but southward-dipping carbonate ramp. Later, crustal extension during late Chadian–early Arundian times caused this ramp to fragment, transforming what was a sea floor of low relief into one of considerable topographical expression (Gawthorpe, 1987a). Regional uplift and widespread erosion in the northern part of the basin led to the development of the Haw Crag unconformity at this time. Riley (1990a) suggested that the formation of this unconformity may be linked to the progressive erosion of a retreating submarine fault scarp moving away from the ramp's southern edge during latest Chadian times. Erosion on the unconformity surface has evidently stripped the entire thickness of the upper Chadian Hetton Beck Limestone and part of the Thornton Limestone from the sequence – the erosional remnants of these units appearing as boulders in the overlying Haw Crag Boulder Bed.

The Worston Shales sequence above the unconformity surface includes hemipelagic muds (Riley, 1990a) and a heterogeneous suite of debris flows (Haw Crag Boulder Bed), gravity slides, slumps and turbidity flows (Barraclough, 1983). The sediment gravity flows were triggered from sea-floor slopes that were progressively steepening as fault blocks in the underlying basement rotated during a continuing phase of crustal extension in Arundian times (Gawthorpe, 1987a). Barraclough (1983) recognized that the steeper parts of the Haw Crag unconformity profile represented the margins of a submarine channel within which the lower of the Haw Crag debris flows was confined. Similar evidence of confinement at the base of the conglomerate sheet higher in the sequence (the younger of the Haw Crag debris flows) has not been recognized (Barraclough, 1983). The composition and size of the boulders in both flows points to their local origin. Arthurton *et al.* (1988) linked the occurrence of 'reef' limestone blocks in the Haw Crag Boulder Bed to the former existence of 'knoll reefs' in the axial zone of the Eshton–Hetton Anticline, although no trace of an in-situ 'reef' development in this area can currently be identified. However, the Waulsortian character of some of the blocks has led to speculation that they may be a remnant of a previously unrecognized autochthonous Waulsortian development, and a northerly extension of the Waulsortian mud-bank complex in the Clitheroe district (J. Miller, pers. comm., 2001; and see **The Knolls**, **Coplow Quarry** and **Salthill and Bellmanpark Quarries** GCR site reports, this chapter).

Conclusions

The development of the Haw Crag unconformity marks a signicant late Chadian–early Arundian phase in the history of the Craven Basin during which the early Carboniferous sea floor was transformed from a gently inclined carbonate ramp into an area of intrabasinal highs and lows separated by steeper sea-floor slopes that facilitated the passage of gravity flows into basinal regions (see **Sykes Quarries** GCR site report, this chapter). The Haw Crag Boulder Bed represents a particularly good example of a debris flow that developed in this way during early Arundian times, and is, arguably, the finest of its type in the Craven Basin.

CLINTS QUARRY, NORTH YORKSHIRE (SD 967 575)

Introduction

The Clints Quarry GCR site is a disused quarry located close to the Grassington–Skipton railway line a kilometre south of Rylstone (SD 967 575). This site offers a stratigraphically important and fossiliferous Holkerian–Brigantian section that extends from the top of the Worston Shales (= the Hodder Mudstone Formation of Riley, 1990a; and see Figure 6.2) to a prominent limestone conglomerate, variously assigned to the Pendleside Limestone Formation by Arthurton *et al.* (1988) and to the Lower Bowland Shales by Riley (1990a). This conglomerate was formed by erosion at the northern margin of the Craven Basin during a significant period of late Asbian–early Brigantian earth movements. Important site descriptions are provided by Wilmore (1910) and Booker and Hudson (1926).

Description

Clints Quarry, also known as 'Rylstone Railway Quarry' (Wilmore, 1910; Hudson and Mitchell, 1937) and 'Clint Rock Quarry' (Arthurton *et al.*, 1988), lies on south-eastern limb of the NE–SW-trending Eshton–Hetton Anticline, approximately 1 km south of the Winterburn Fault (an easterly trending splinter of the South Craven Fault System to the west; see Figure 6.1). The succession dips gently to the south-east (Figure 6.22).

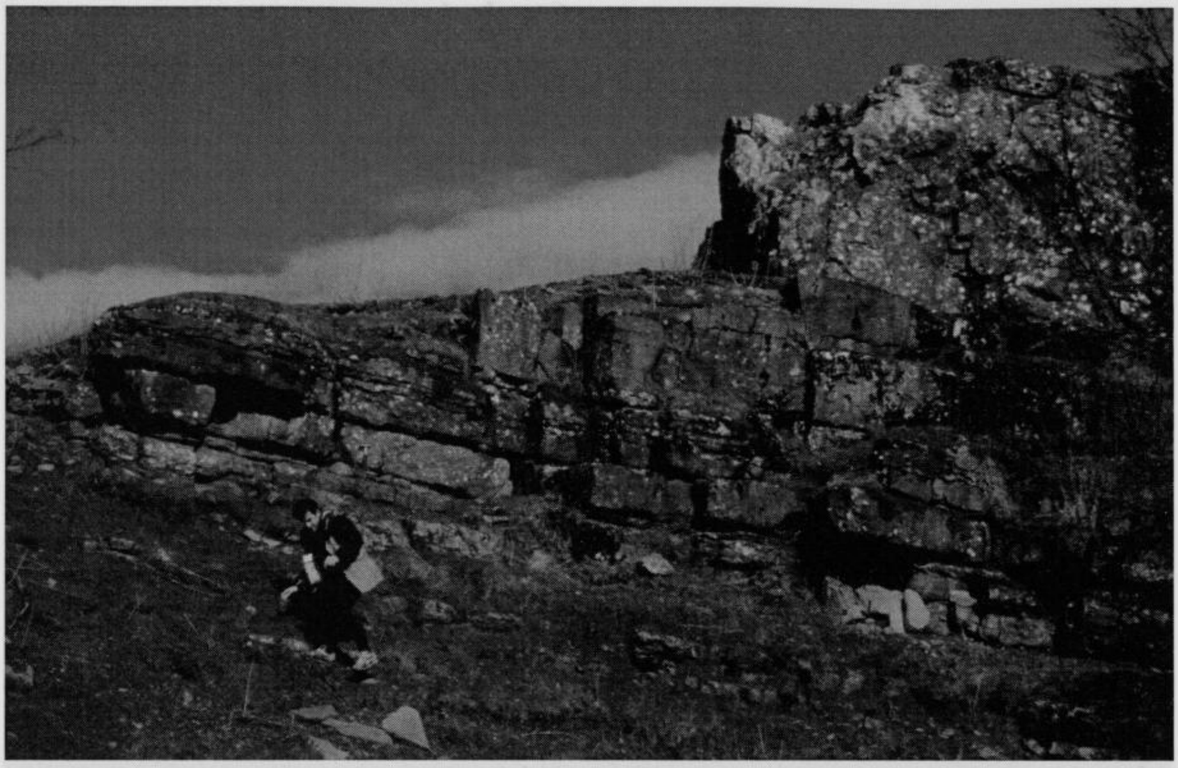


Figure 6.22 Sequence of strata at the Clints Quarry GCR site, Rylstone, illustrating the Hodder Mudstone Formation (lower left) unconformably overlain by thickly bedded limestones (centre and right) at the local base of the Lower Bowland Shales (Riley, 1990a). Note that the thickly bedded limestones seen here were mapped as part of the Pendleside Limestone Formation by Arthurton *et al.* (1988). The most prominent limestone bed is the massive limestone conglomerate (debris bed) referred to in the text. (Photo: P.J. Cossey.)

At its base, the Worston Shales comprise approximately 4 m of calcareous mudstone with thin argillaceous limestone interbeds. These beds, containing *Pustula* cf. *pyxidiformis* (Arthurton *et al.*, 1988) and *Merocanites* (Rose *et al.*, 1973), were referred to as part of the 'upper mudstone-rich subdivision' of the Worston Shales by Arthurton *et al.* (1988), and as part of the Rylstone Limestones by Booker and Hudson (1926). A sharp but planar unconformity surface separates this unit from the overlying beds which Arthurton *et al.* (1988) regarded as part of the Pendleside Limestone Formation (= Skelterton Limestone of Booker and Hudson, 1926) and which Riley (1990a) considered as part of the Lower Bowland Shales (see Aitkenhead *et al.*, 1992). Missing from the succession at this unconformity is the Hodderense Limestone Formation and, if Riley is correct, the Pendleside Limestone Formation (Riley, 1990a).

Above the Worston Shales an 8.4 m succession, ascribed to the Pendleside Limestone Formation by Arthurton *et al.* (1988) and to the Lower Bowland Shales by Riley (1990a) crops out, which can be subdivided into two unequal parts. The lower part (= the 'well bedded limestone subdivision' of Arthurton *et al.* (1988) and the 'Zaphrentid Bed' of Booker and Hudson, 1926) comprises well-bedded grey crinoidal packstones (*c.* 3 m) with possible chlorite mottlings near the base and limestone lithoclasts at its top. A rich fauna dominated by zaphrentid corals and brachiopods is reported from these beds including *Amplexizaphrentis enniskilleni*, cf. *Fasciculophyllum densum*, *F.* cf. *junctoseptatum*, *Rotiphyllum rushianum*, *Zaphrentites parallela*, *Rylstonia benecompacta*, *R.* cf. *dentata*, *Dictyoclostus multispiniferus*, *Krotovia spinulosa*, and 'an indeterminate goniatite' (Arthurton *et al.*, 1988). The higher part (= the 'limestone conglomerate subdivision' of Arthurton *et al.* (1988) and the 'Lithostrotion arachnoideum Beds' of Booker and Hudson, 1926) is a massive (3.4 m) conglomerate (= 'Tiddeman's Breccia' – see Hudson and

Mitchell, 1937; and Arthurton *et al.*, 1988) with granule- to pebble-sized limestone lithoclasts up to 15 cm in diameter set in a bioclastic limestone matrix (Figure 6.22). Lithoclasts in the conglomerate are subrounded to subangular (Arthurton *et al.*, 1988) and include pebbles of the Hodderense Limestone Formation (Riley, 1990a). Arthurton *et al.* (1988) recorded a mixed coral–brachiopod assemblage of Holkerian or Asbian age from this unit including *Axophyllum vaughani*, *Siphonodendron martini*, *S. sociale*, *Avonia youngiana* and *Plicatifera plicatilis*. Above this, the succession is represented by well-bedded to lenticular packstones (*c.* 2 m) containing a coral–brachiopod assemblage of early Brigantian age including *Diphyphyllum furcatum*, *D. lateseptatum* and *Striatifera striata* (Arthurton *et al.*, 1988), *Sutherlandia 'Emmonsia' parasitica* and *Michelinia tenuisepta* (Booker and Hudson, 1926) but which also includes the late Asbian (P_{1a}) goniatite index *Goniatites crenistria* (Rose *et al.*, 1973).

Interpretation

The Worston Shales (Hodder Mudstone Formation) deposits at this site represent hemipelagic muds (Riley, 1990a) and thin storm-generated limestone interbeds which formed on the upper part of a carbonate slope (Gawthorpe, 1986, 1987a) towards the northern margin of the Craven Basin during Holkerian times (Figure 6.4b).

By contrast, the massive limestone conglomerate, with its mixed and partially derived Holkerian–Asbian faunas near the base of the overlying unit (Lower Bowland Shales), most probably formed as a debris-flow deposit during a period of late Asbian–early Brigantian crustal instability; this causing uplift and widespread erosion of the basin margin and triggering gravity flows down the basin flanks. The unconformity below the conglomerate also developed at this time. Erosion on this unconformity surface evidently removed the Hodderense Limestone Formation (and, possibly, the Pendleside Limestone Formation – if deposited), from the Lower Carboniferous successions of the Eshton–Hetton area, its erosional remnants appearing as pebbles in the overlying limestone debris bed (Riley, 1990a). The associated packstones both above and below the conglomerate (but still within the Lower Bowland Shale sequence) most probably represent either similar but smaller-scale debris deposits or storm-generated beds.

The development of these features (debris bed and unconformity) together mark a significant late Asbian–early Brigantian phase in the evolution of the Craven Basin as early Carboniferous rifting gave way to thermally driven subsidence and regional basin sag (Gawthorpe, 1987a; Fraser and Gawthorpe, 1990).

Conclusions

This site provides one of the finest sections across the Worston Shales–Bowland Shales boundary in the Craven District. The sedimentological and palaeontological characteristics of the sequence (reworked faunas, derived pebbles and sediment gravity flows) provide evidence for the existence of a significant unconformity at the base of the Lower Bowland Shales which developed during a late Asbian–early Brigantian period of tectonic instability that is widely recognized within the Craven Basin.

HAMBLETON QUARRY, NORTH YORKSHIRE (SE 058 533)

Introduction

The Hambleton Quarry GCR site is a disused quarry (SE 058 533) which lies adjacent to the Embsay and Bolton Abbey Steam Railway, 300 m west of Bolton Abbey Station and 6 km east of Skipton. The section includes arguably the finest section of the Asbian Draughton Limestone (= Pendleside Limestone Formation of Riley, 1990a) and Draughton Shales in the Craven Basin (Figure 6.2); here displayed in a spectacular series of minor fold structures (Figure 6.23) on the south-eastern flank of the Skipton Anticline (Figure 6.1). Exposures of the slightly older Skibeden Shales with Limestones (= topmost part of the Worston Shale Group of Riley, 1990a) also occur at the site. The succession incorporates a variety of relatively deep-water sedimentary features including turbidites and storm deposits which bear testament to a period of crustal instability towards the end of Dinantian times. It also includes a varied suite of largely derived macrofossils and microfossils.

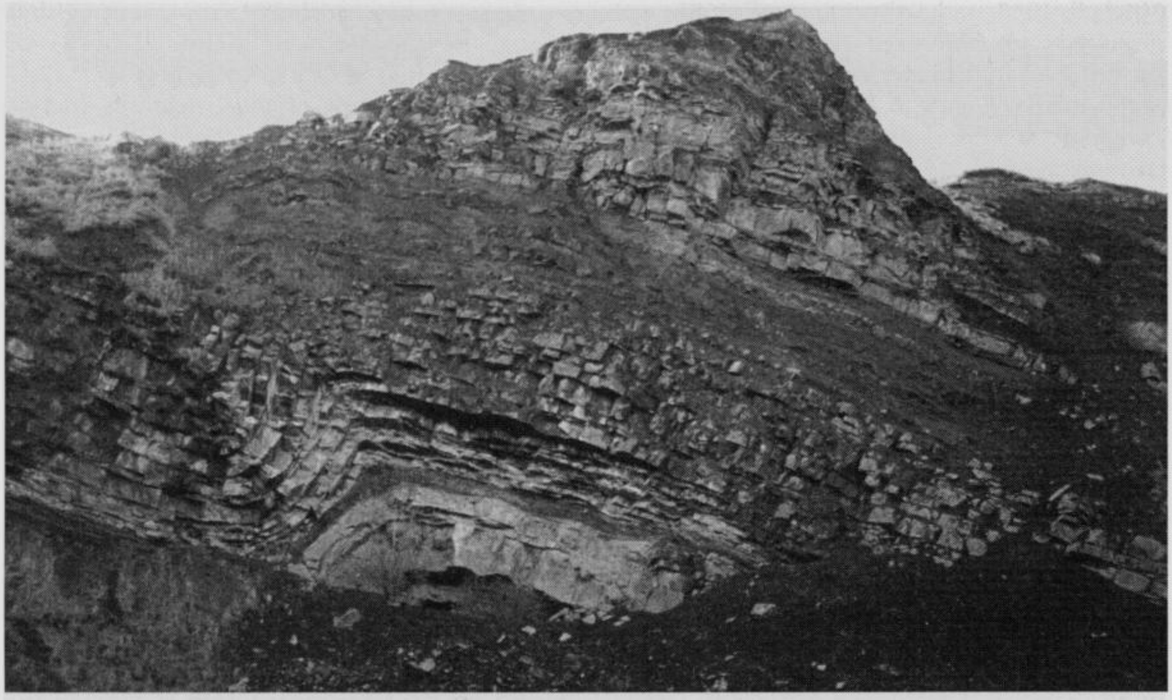


Figure 6.23 Fold structures in the turbiditic Draughton Limestone (centre) at the Hambleton Quarry GCR site. The top of the Lower Draughton Limestone is located at the top of the thick (*c.* 2 m) limestone bed (Tiddeman's Breccia) at the base of the quarry face. Above, and to the right of the Draughton Limestone, are the darker beds of the Draughton Shales. (Photo: P.J. Cossey.)

Details of the stratigraphy and macrofossil distributions were first published by Hudson and Mitchell (1937). Later work focused attention on the distribution of two microfossil groups, namely conodonts (Metcalfe, 1976, 1981) and foraminifera (Fewtrell and Smith, 1978), and on sedimentological aspects (Barraclough, 1983). Because of structural complexities on the northern side of the quarry, the description below considers only those outcrops seen on the south side of the quarry where the stratigraphy is more easily recognized.

Description

The Skibeden Shales with Limestones outcrop in a series of discontinuous exposures towards the eastern end of the quarry. A fault separates these outcrops from those of the Draughton Limestone and Draughton Shales seen to the west. The Skibeden Shales with Limestones comprises a sequence (< 10 m) of thick dolomitic mudstones with subordinate silty limestones, the latter containing occasional chlorite 'patches' but few obvious macrofossils (Hudson and Mitchell, 1937).

By contrast, the Draughton Limestone (*c.* 25 m) is a well-bedded turbiditic and conglomeratic limestone unit with minor shale interbeds (Ramsbottom, 1974; Fewtrell and Smith, 1978). Its lower part (*c.* 13 m), referred to by Hudson and Mitchell (1937) as the 'Lower Draughton Limestone' (Figure 6.24) or 'Breccia Beds', is dominated by thickly bedded limestones and contains a derived coral–brachiopod fauna. Taxa recorded from this interval by Hudson and Mitchell (1937) include *Siphonodendron* cf. *martini*, *Palaeosmilia murchisoni*, *Rylstonia*, *Sutherlandia 'Emmonsia' parasitica*, *Krotovia spinulosa* and *K. aculeata*. The succession includes two distinctive limestone breccia beds containing angular to subrounded clasts of bioclastic limestone up to 30 cm in size (but generally smaller) set in a partially dolomitized limestone matrix (Hudson and Mitchell, 1937). The more prominent of these units (*c.* 2 m thick) at the top of the Lower Draughton Limestone is widely recognized throughout the Craven District as a useful lithostratigraphical marker bed (Figure 6.24). This bed was formally referred to as 'Tiddeman's Breccia' by Hudson and Mitchell (1937) in honour of R.H. Tiddeman

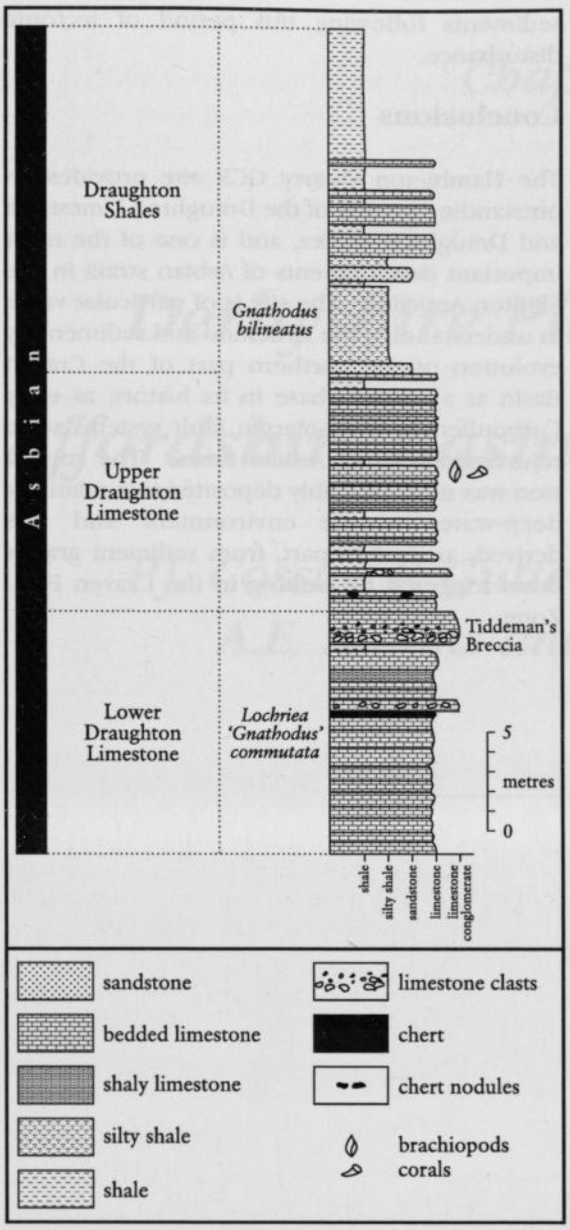


Figure 6.24 Sedimentary log of the topmost beds of the Draughton Limestone and lower part of the Draughton Shales at the Hambleton Quarry GCR site near Skipton, Yorkshire. After Metcalfe (1981).

who first recorded it and in recognition of his pioneering work in the area (see Tiddeman, 1889, 1891). The higher part of the unit (*c.* 12 m), referred to as the 'Upper Draughton Limestone' (Figure 6.24) or 'Emmonsia Beds' by Hudson and Mitchell (1937), consists of darker, thinner-bedded bioclastic and lithoclastic limestone with minor developments of shale and a 'Zaphrentid phase' fauna.

Above this, the Draughton Shales (*c.* 18 m) comprise a sequence of dark shales with occasional thin limestone interbeds and phosphate nodules. A thin flaggy sandstone capped by approximately 5 m of sandy shale occurs at the base of the unit. Although identifiable macrofossils are rare in these beds, locally they are known to contain bryozoans, goniatites, brachiopods and crinoids (Hudson and Mitchell, 1937).

Despite the dearth of identifiable shelly macrofossils, rich microfaunas are recorded from both the Draughton Limestone and the Draughton Shales at Hambleton by Fewtrell and Smith (1978) and Metcalfe (1981). Rare dendroid graptolites (*Dictyononema kittyae* and *Pseudodictyonema*) from either the 'Skibeden Shales' or the Draughton Limestone also occur at the site (Chapman *et al.*, 1993).

Interpretation

The Skibeden Shales with Limestones were included as part of the Worston Shale Formation by Fewtrell and Smith (1980) – a formation generally regarded as the lateral facies and time equivalent (in part) of Riley's (1990a) newly defined Hodder Mudstone Formation and Worston Shale Group (see Figure 6.2). Similarly, the Draughton Limestone is now generally equated with the Pendleside Limestone Formation (Ramsbottom, 1974; Arthurton *et al.*, 1988; Riley, 1990a). Following the work of previous authors (Hudson and Mitchell, 1937; Ramsbottom, 1974; George *et al.*, 1976; Fewtrell and Smith, 1980), the Draughton Shales are considered as a separate unit below the Lower Bowland Shales and, in this account, they are grouped with the Draughton Limestone as part of the Pendleside Limestone Formation (see Figure 6.2). Metcalfe (1981), however, regarded them as part of the Lower Bowland Shales.

Despite the presence of derived faunal elements in the Draughton Limestone, the Hambleton succession is considered to be of D_1 (Asbian) age (Hudson and Mitchell, 1937; George *et al.*, 1976). This view was later confirmed by the discovery of suspected upper Viséan foraminifera (Fewtrell and Smith, 1978) and Asbian conodonts (Metcalfe, 1981). The base of the *Gnathodus bilineatus* conodont zone (Metcalfe, 1981) lies in the Draughton Limestone at the top of Tiddeman's Breccia (I. Metcalfe, pers. comm., 1978) (see Figure 6.24).

The Hambleton succession is interpreted as a relatively deep-water sequence deposited on a southward-dipping carbonate slope during a period of tectonic instability that persisted from Asbian to early Brigantian times. Although the Skibeden Shales with Limestones are thought to represent storm deposits (Barraclough, 1983) that formed immediately prior to this period of instability, the Draughton Limestone most probably developed as a series of turbidite and debris-flow deposits as a direct response to it, these having been triggered by earth movements to the north that simultaneously caused the break up of the Asbian reef limestone complex along the northern margin of the basin (Gawthorpe, 1986, 1987a). The presence of fossils derived from the Cracoe Reef-Belt indicates a northerly derivation for this unit (Ramsbottom, 1974). The Draughton Shales were most probably deposited as hemipelagic sediments following this period of tectonic disturbance.

Conclusions

The Hambleton Quarry GCR site provides an outstanding section of the Draughton Limestone and Draughton Shales, and is one of the most important developments of Asbian strata in the Skipton Anticline. The site is of particular value in understanding the structural and sedimentary evolution of the northern part of the Craven Basin at a critical phase in its history, as early Carboniferous basin-margin fault systems were rejuvenated during Asbian times. The succession was most probably deposited in a relatively deep-water marine environment and was derived, at least in part, from sediment gravity flows triggered by faulting in the Craven Fault Zone.