British Lower Carboniferous Stratigraphy

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Chapter 7

Derbyshire Platform, North Staffordshire Basin and Hathern Shelf

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INTRODUCTION

In this chapter, GCR sites in Derbyshire, north Staffordshire and north Leicestershire are described. Their location with respect to the limits of Dinantian and Namurian outcrop is illustrated in Figure 7.1. This area of outcrop includes the shelf on the northern flanks of the Wales–Brabant Massif in the East Midlands (Hathern Shelf), the North Staffordshire Basin, the Widmerpool Gulf and the Derbyshire Platform. The structural and palaeogeographical setting of these areas is illustrated in Figure 7.2, and Figure 7.4 – see 'Geological setting'.

The Edale Fault, identified on gravity and seismic data, defines the northern margin of the Derbyshire carbonate platform (Lee, 1988a; Gutteridge, 1991a) which is divided into a number of tilt-blocks separated by basement fault structures, the most significant of which is the Cronkston–Bonsall Fault Zone (Gutteridge, 1987; Gawthorpe *et al*., 1989; and see Figure 7.2). To the south, the boundary between the platform and the Widmerpool Gulf is probably marked by the Cinderhill Fault (Frost and Smart, 1979; Whitcombe and Maguire, 1981). In the west, there is no obvious fault-controlled margin, the basement sloping gradually down into the North Staffordshire Basin–Widmerpool Gulf (Maroof, 1976; Whitcombe and Maguire, 1981; Bridges, 1984; Gawthorpe *et al*., 1989). The Derbyshire Platform passes eastwards into the subsurface, merging into the extensive East Midlands Shelf (e.g. Strank, 1987; and see Figure 7.2a).

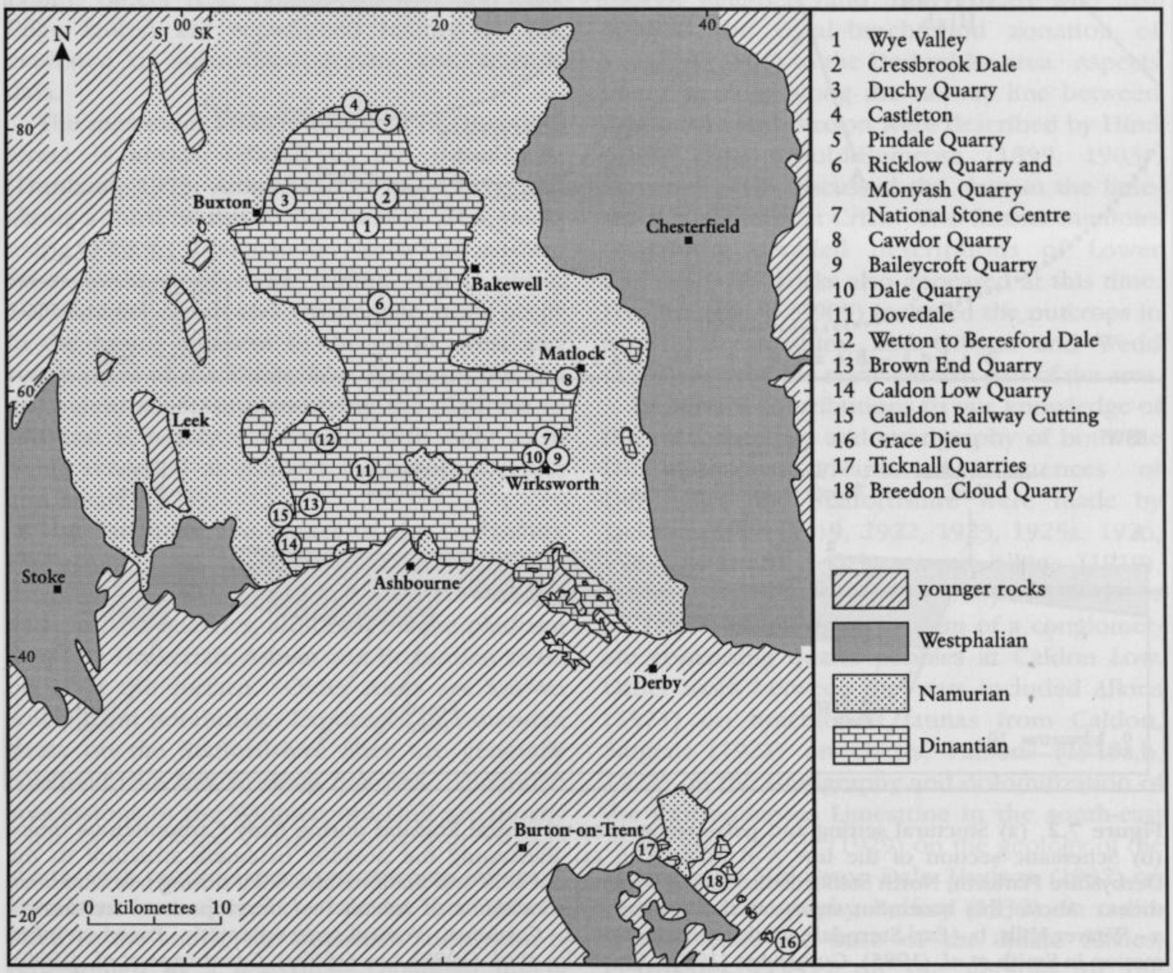


Figure 7.1 Geological map illustrating the distribution of Carboniferous rocks in Derbyshire, north Staffordshire and north-west Leicestershire, and the locations of GCR sites described in the text. Based on information from [British] Geological Survey memoirs (Aitkenhead *et al*., 1985; Chisholm *et al*., 1988) and maps of the area (Institute of Geological Sciences, 1976a, 1978, 1979b, 1983).

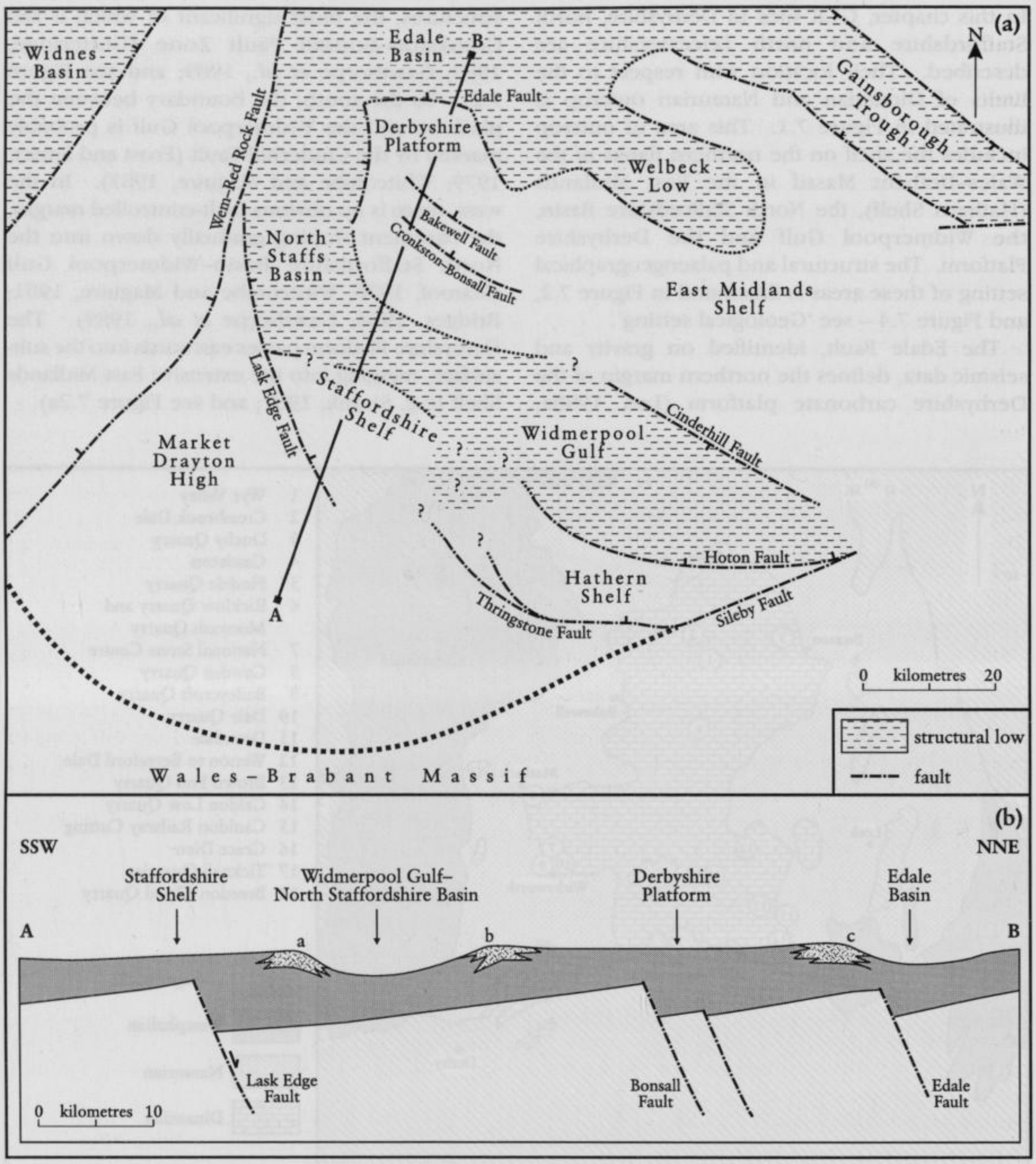


Figure 7.2 (a) Stuctural setting and palaeogeography of central England during Early Carboniferous times. (b) Schematic section of the line A–B marked in (a) illustrating the possible basement structure to the Derbyshire Platform, North Staffordshire Basin–Widmerpool Gulf and Staffordshire Shelf during late Dinantian times. Above this basement structure the approximate locations of Asbian reef developments are shown: a – Weaver Hills; b – Earl Sterndale–Wirksworth margin; c – Castleton. Vertical scale schematic. Based on information in Smith *et al.* (1985), Gutteridge (1987), Chisholm *et al.* (1988), Lee (1988a), Gawthorpe *et al.* (1989), Ebdon *et al.* (1990), Fraser and Gawthorpe (1990), Corfield (1991), Corfield *et al.* (1996) and Rees and Wilson (1998).

The North Staffordshire Basin west and southwest of the Derbyshire Platform is a narrow gulf whose western margin is controlled by the Lask Edge Fault (Lee, 1988a). The easterly extension of the North Staffordshire Basin, the Widmerpool Gulf, is probably bounded on the south side by a suite of NNW–SSE-trending faults of which the Hoton and Thringstone fault systems are a part (Gawthorpe *et al.*, 1989). The shelf area between this and the Wales–Brabant Massif is variously referred to as either the West Midlands Shelf (Strank, 1987) or the Staffordshire Shelf (Chisholm *et al.*, 1988) in the west, and the Hathern Shelf in the east (Ebdon *et al.*, 1990).

Whereas the existence of some of those faults illustrated in Figure 7.2 has been confirmed by surface mapping (e.g. Cronkston–Bonsall Fault Zone), others (e.g. Edale, Bakewell and Lask Edge faults) are recognized mainly on the evidence of subsurface gravity and seismic data.

The maximum known thickness of Dinantian strata is about 1900 m in the Eyam area (Dunham, 1973; Aitkenhead *et al.*, 1985), and about a third of this in the Buxton area, thickening to about 1000 m in the North Staffordshire Basin (Aitkenhead *et al.*, 1985). Up to about 500 m of Pendleian and Arnsbergian strata occur in the basins adjacent to the north, west and south sides of the Derbyshire Platform, but the equivalent succession overlying the platform to the east is highly condensed, with only 27 m being recorded at Ashover for example (Frost and Smart, 1979).

The Dinantian limestones of the Derbyshire Platform and North Staffordshire Basin are well exposed in dale sides and in numerous working and disused quarries, although on the platform only late Holkerian, Asbian and Brigantian strata occur at the surface. Older rocks are known solely from boreholes. Exposures of Dinantian strata on the Staffordshire Shelf are generally confined to a few working quarries. Dinantian successions in the Widmerpool Gulf are mostly covered by Upper Carboniferous and Triassic strata, with outcrop restricted to some inliers of Dinantian basinal rocks; while on the Hathern Shelf to the south, the Dinantian succession is represented by a few small Dinantian inliers (Figure 7.1). Pendleian and Arnsbergian successions are dominated by shales and are best known from railway cuttings and stream sections at the surface, and from boreholes.

History of research

The earliest observations on the geology of Derbyshire are to be found in the publications of Whitehurst (1778), Mawe (1802), Farey (1811) and Watson (1811). Although these authors went some way to establishing the broad succession, it was the work of the [British] Geological Survey in the mid-19th century, leading to the publication of the first one-inch maps and accompanying memoirs (Hull and Green, 1866; Green *et al.*, 1869, 1887), that first dealt in any detail with Lower Carboniferous stratigraphy. Other work from the late 19th and early 20th centuries includes Barnes and Holroyd (1897) on shell beds in the Castleton area; Hind and Howe (1901) who drew a comparison between the faunas of the Castleton area and those of the Craven Reef-Belt; and Sibly (1908) who first applied the coral–brachiopod zonation of Vaughan (1905) to the Derbyshire area. Aspects of the geology along the railway line between Ashbourne and Buxton were described by Hind (1897) and Arnold-Bemrose (1899, 1903). Sargent (1912) discussed the clays in the limestone succession at Crich. Two further memoirs containing detailed descriptions of Lower Carboniferous rocks also appeared at this time: Fox-Strangways (1905) included the outcrops in north Leicestershire, and Gibson and Wedd (1913) covered the north-eastern part of the area.

Important contributions to our knowledge of the palaeontology and stratigraphy of both the Dinantian and Namurian sequences of Derbyshire and Staffordshire were made by Jackson (1908, 1919, 1922, 1923, 1925a, 1926, 1927, 1941a,b). Jackson and Alkins (1919), Jackson and Charlesworth (1920) and Barke *et al.* (1920) discussed the origin of a conglomerate containing quartz pebbles at Caldon Low. Other work between the wars included Alkins (1921) on brachiopod faunas from Caldon, Sargent (1921) on cherts, Parsons (1918a,b, 1922) on the stratigraphy and dolomitization of the Carboniferous Limestone in the south-east of the area, Morris (1929) on the geology of the area around Middleton Dale, Hudson (1932) on the knoll topography, Pulfrey (1932) on radiolarians from the base of the Edale Shales, Fearnsides (1932) on the geology of the Derwent Valley, and Fearnsides and Templeman (1932) on a borehole at Hope. Aspects of the stratigraphy of the Carboniferous Limestone in the Buxton area and in north Derbyshire were reported by Cope (1933, 1936, 1937, 1939, 1949, 1972, 1973).

Studies published during and in the years immediately after the Second World War include Ludford (1940, 1951) on the geology of the Weaver Hills, Shirley and Horsfield (1940, 1945) on the outcrop at the northern edge of the Derbyshire Platform, Shirley (1959) on the Monyash to Wirksworth area, Mitchell and Stubblefield (1941) on the inlier of Lower Carboniferous strata at Breedon Cloud, north Leicestershire, Hudson and Cotton (1943, 1945a,b) on the Lower Carboniferous rocks of the Alport Borehole and the Namurian of the Alport and Edale areas, Parkinson (1943, 1947, 1950a, 1953, 1964, 1965) on the 'reef' limestones and their contained fauna both from north Derbyshire and Dovedale, Sweeting (1946) and Sweeting and Himus (1946) on the Ashover Anticline, Prentice (1951, 1952) on the geology of the Manifold Valley, Ford (1952, 1965) on aspects of the Castleton Reef-Belt, including goniatite faunas, Bisat (1957) on goniatites from the Manifold Valley, Wolfenden (1958, 1959) on the palaeoecology and sponge faunas of limestones in the Castleton area, and Robinson (1959) on ostracode faunas from shales near Matlock.

With the expansion in scientific research since 1960, the Lower Carboniferous successions in this area have perhaps received more attention than those of any other region. This is probably partly because of the quality of exposure, but also because of the central location and easy access. Five [British] Geological Survey memoirs cover the Derbyshire and Staffordshire area: Smith *et al.* (1967) on the eastern area around Chesterfield and Matlock; Stevenson and Gaunt (1971) on the northern part of the area; Frost and Smart (1979) on the south-eastern area; Aitkenhead *et al.* (1985) on the area around Buxton, Leek and Bakewell; and Chisholm *et al.* (1988) on the southern part of the area, including Dovedale, Caldon and the Weaver Hills. Important contributions on palaeontology and/or biostratigraphy from Mitchell, Mundy, Ramsbottom, Reynolds, Riley and Strank are included in these memoirs. Useful bibliographies of the geology of the Peak District have been compiled by Ford and Mason (1967) and Ford (1972, 1999).

Ramsbottom *et al.* (1962) described sections from boreholes in the Ashover area, and Holdsworth (1963a,b, 1966), Holdsworth and Trewin (1968), Trewin (1968) and Trewin and Holdsworth (1972, 1973) considered aspects of Namurian stratigraphy and sedimentation in the North Staffordshire Basin. Eden *et al.* (1964) reported a detailed study of the northern margin of the Dinantian outcrop around Pin Dale; sedimentological studies of limestones from near Sparrowpit, Castleton and the Hartington area were reported by Sadler (1964a,b, 1966, 1969, 1970) and Sadler and Wyatt (1966); while the PhD thesis of Thach (1964) dealt with limestones of the south-western part of the area. Parkinson and Ludford (1964, 1973), Ludford (1970) and Ludford *et al.* (1973) discussed the geology of the south-western Dinantian outcrops; Morris (1967a,b, 1969, 1970a,b) described stratigraphy and faunas from the Dinantian and Namurian outcrops of south-west Derbyshire and Staffordshire; and Llewellyn *et al.* (1969) and Llewellyn and Stabbins (1970) described the Hathern Anhydrite Series. Two PhD theses of this period were by Biggins (1969) who described a Carboniferous knoll reef at High Tor, Matlock, and Coffey (1969) who discussed the geology of the Mixon and Ecton area, north Staffordshire.

Aspects of sedimentology, stratigraphy and faunas of the Castleton Reef-Belt have been described by Broadhurst and Simpson (1967, 1973), Simpson and Broadhurst (1969), Shaw (1970), Timms (1973, 1978), Parkinson (1974b), Tilsley (1977), Brunton and Tilsley (1991), Cossey (1997) and Wyse Jackson *et al.* (1999). Other 'reef' or carbonate buildups and their associated facies and faunas have also continued to attract the interest of palaeontologists and sedimentologists, and contributions include those of Orme (1970), Brunton and Champion (1974), Morgan (1980), Chapman (1984), Bridges and Chapman (1988), and Gutteridge (1990a, 1991b, 1995). Other largely sedimentological studies on the Lower Carboniferous rocks include those of Walkden (1970, 1972a,b, 1974, 1977, 1982) on volcanic, erosive and early diagenetic events in the limestone succession of the platform and on the geology of the area around Wirksworth; Butcher and Ford (1973) on the Monsal Dale area; Brown (1973) on the eastern Derbyshire outcrops; Bolton (1978) on part of the Namurian succession in the North Staffordshire Basin; Adams and Cossey (1978) on a slumped unit in the Monsal Dale Limestones; Bridges (1982) on cyclicity in the Crich outcrop; Pazdzierski (1982) on the Monsal Dale Limestones; Schofield (1982) and Schofield and Adams (1985) on the Woo Dale Limestones; Gutteridge (1983, 1987, 1989a, 1990b, 1991a,b) on Brigantian sedimentation; Oakman (1984) on the Asbian and Brigantian limestones of the south-eastern part of the platform; Gawthorpe and Gutteridge (1990) on carbonate shoals at the northern margin of the platform; and Vanstone (1996) on late Dinantian climates.

Further contributions to our understanding of the palaeontology and stratigraphy of the Lower Carboniferous rocks of the area include those of Mortimer *et al.* (1970) on miospores from Breedon Cloud, Dunham (1973) on the Eyam Borehole, Chisholm and Butcher (1981) on a borehole near Matlock, Strank (1981, 1982b, 1985, 1986, 1987) who described foraminiferal faunas from key sections and boreholes in the area and also discussed the structure and stratigraphy of the Dinantian succession in the concealed area of the East Midlands Shelf to the east of the Peak District, Aitkenhead and Chisholm (1982) who standardized the nomenclature for the Dinantian formations of the area, Chisholm *et al.* (1983) on revisions to the stratigraphy in the area west of Matlock, Welsh and Owens (1983) on miospores from the Caldon Low Borehole, Cossey (1983, 1997) on corals (especially heterocorals), Tilsley (1988) on trilobites, and Cossey *et al.* (1995) on **Brown End Quarry**, Staffordshire.

A number of studies in recent years have focused on the diagenesis of the limestone succession. These include Orme and Brown (1963) on diagenetic fabrics, Orme and Ford (1970) and Orme (1973) on aspects of chert formation, Adams (1980) on calcretes, Munn and Jackson (1980) on de-dolomitization in the Wirksworth area, Berry (1984) and Walkden and Berry (1984) on cementation, Schofield and Adams (1986) on the origin of the Woo Dale Dolomite, Walkden (1987) on diagenesis and depositional cyclicity, Fowles (1989) on dolomitization, and Currie (1988) on the relationship between diagenesis in the Monsal Dale Limestones and the occurrence of igneous rocks. Williams (1988), Walkden and Williams (1991), Bingham (1992), Hollis (1995) and Hollis and Walkden (1996) all deal with aspects of the diagenetic history of the succession on a regional scale.

Large-scale structural and stratigraphical studies that embrace the area include those of Maroof (1976), Whitcombe and Maguire (1981), Smith *et al.* (1985), Gutteridge (1987), Lee (1988a), Gawthorpe *et al.* (1989), Ebdon *et al.* (1990), Fraser and Gawthorpe (1990) and Rogers and Stuart (1991). Reviews of the limestone resources have been compiled by Cox and Bridge (1977), Cox and Harrison (1980), Bridge and Gozzard (1981), Harrison (1981), Gatliff (1982), Bridge and Kneebone (1983) and summarized for the whole of the Peak District by Harrison and Adlam (1985).

Stratigraphy

Early accounts of the stratigraphy refer to the 'Carboniferous Limestone' or 'Mountain Limestone', together with various igneous rocks, overlain by shales termed 'Yoredale Beds' and the sandstones of the 'Millstone Grit', although the term 'Yoredale Beds' was soon dropped in this area. Barnes and Holroyd (1897) recognized that in north Derbyshire later strata are unconformable on the Carboniferous Limestone.

During the latter part of the 19th and most of the 20th century a plethora of lithostratigraphical names was introduced, ranging from names for major units, recognizable over a wide area, to local marker beds often named after a characteristic fossil. According to Aitkenhead and Chisholm (1982), at least 60 different lithostratigraphical names for parts of the Carboniferous Limestone of the Peak District had appeared in the literature during the previous 30 years. Accordingly, Aitkenhead and Chisholm (1982) provided a standard nomenclature for the Derbyshire and Staffordshire outcrops, dividing the region into four areas. Their scheme appears in Figure 7.3, together with the nomenclature of the succession seen on the Hathern Shelf, adapted from Ambrose and Carney (1997, 1999). The nomenclature of the Namurian Series is based on that of the relevant memoir.

Geological setting

On the Derbyshire Platform, the earliest exposed rocks are of late Holkerian age. Earlier Dinantian strata and basement rocks are only certainly known from two boreholes, at Woo Dale (Cope, 1949, 1973, 1979; Strank, 1986) and Eyam (Dunham, 1973; Strank, 1985). Pre-Holkerian marginal marine evaporites and shallow-marine carbonates onlapped an irregular Charnian and Lower Palaeozoic basement surface, which in the northern part of the area was broadly a south-easterly dipping tilt-block (Gutteridge, 1987; Gawthorpe *et al.*, 1989). By late Arundian or

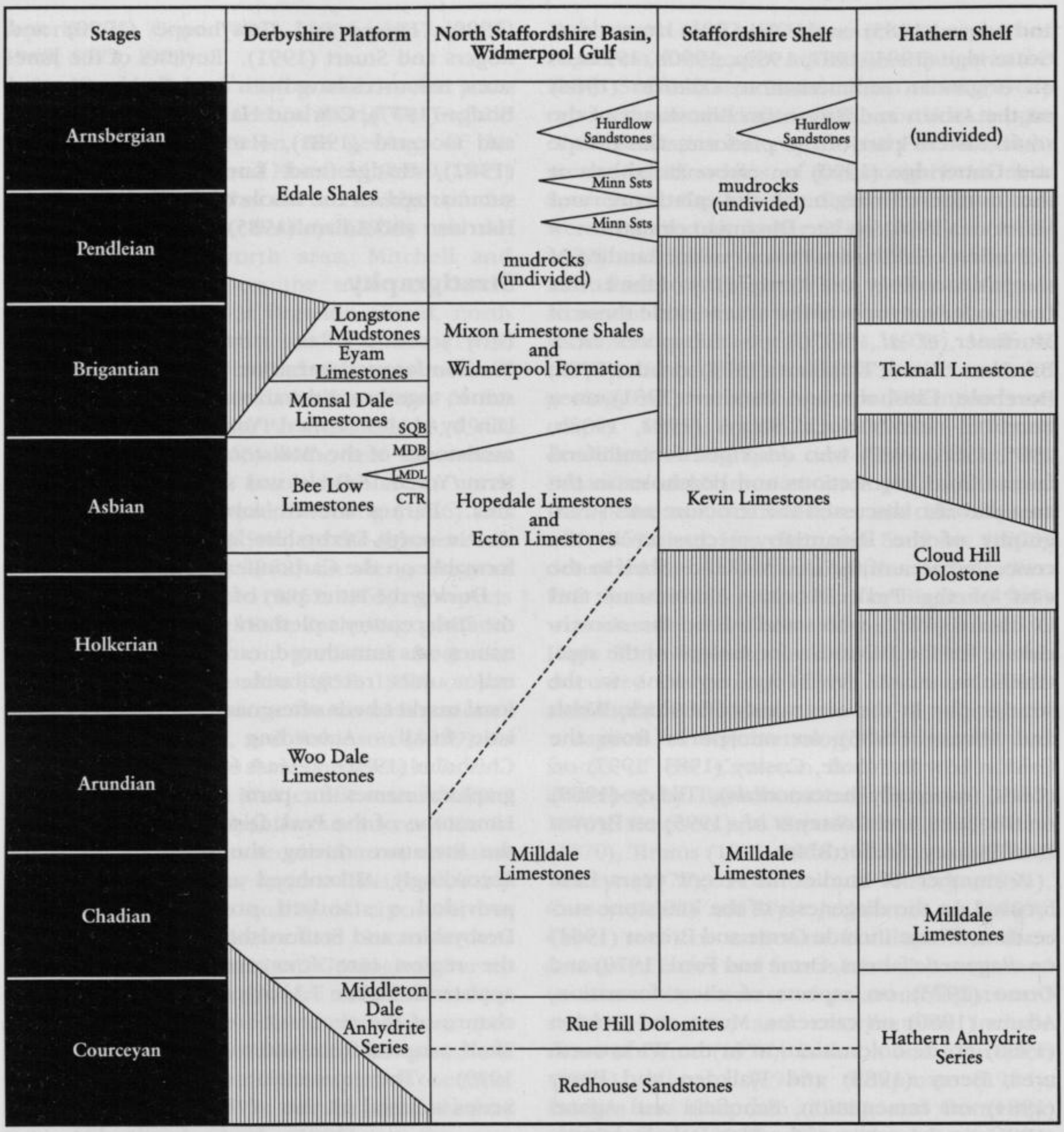


Figure 7.3 Simplified stratigraphical chart for the Lower Carboniferous succession of Derbyshire, north Staffordshire and north-west Leicestershire. CTR – Chee Tor Rock; LMDL – Lower Millers Dale Lava; MDB – Millers Dale Beds; SQB – Station Quarry Beds. Areas of vertical ruling indicate non-sequences. Not to scale. Note that, unless otherwise stated, all major lithostratigraphical units shown on this chart are recognized as formations. Compilation based on information from Aitkenhead and Chisholm (1982) with additional details from Smith *et al.* (1967), Aitkenhead *et al.* (1985), Chisholm *et al.* (1988), Ambrose and Carney (1997, 1999) and Ambrose (1999).

Holkerian times, a shallow carbonate platform had been established over the whole area. Uplift at the end of Holkerian times led to Asbian limestones resting unconformably on Holkerian strata in the central and southern parts of the platform. During Asbian times a rimmed shelf margin characterized by apron reefs developed around the north, west and south of the platform while cyclic shelf limestones separated by episodes of subaerial exposure and karstification developed in the interior (Figure 7.4a). Occasional footwall uplift along the Edale Fault led to local

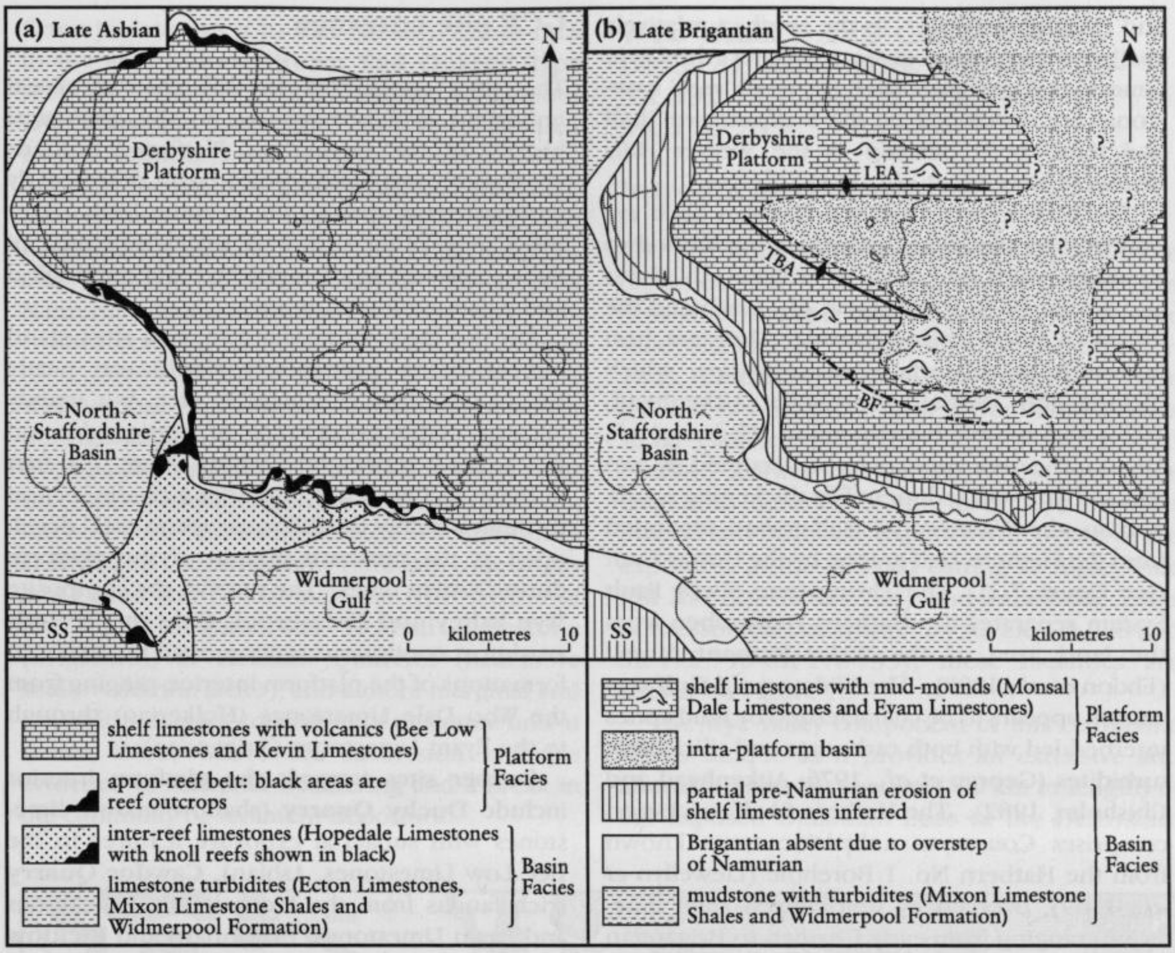


Figure 7.4 Palaeogeographies of the Derbyshire and north Staffordshire areas for (a) late Asbian times and (b) late Brigantian times. A faint dotted line marks the position of the Dinantian–Namurian boundary. SS – Staffordshire Shelf; LEA – Longstone Edge Anticline; TBA – Taddington–Bakewell Anticline; BF – Bonsall Fault. After Aitkenhead and Chisholm (1982), with additional information from Gutteridge (1987, 1995).

unconformities along its northern margin. At the beginning of Brigantian times, the platform margin became dominated by crinoidal grainstone shoals (Walkden, 1982; Gawthorpe *et al.*, 1989; Gawthorpe and Gutteridge, 1990). An intra-platform basin also developed at this time as a result of re-activation of basement faults (Gutteridge, 1987, 1989a) (Figure 7.4b). Towards the close of the Brigantian Age, an eastwards-dipping carbonate ramp developed on the central part of the platform (Gutteridge, 1984, 1987, 1995) (Figure 7.4b).

The North Staffordshire Basin occurs to the west and south-west of the Derbyshire Platform (Figure 7.4a). During the early to mid part of Dinantian times there was probably a W- or SW-dipping carbonate ramp (Bridges, 1984) between the two areas rather than a distinct shelf margin, although by Asbian times a reef-rimmed margin separated platform from basin. The Caldon Low Borehole records late Devonian–early Dinantian fluvial terrigenous clastics of the Redhouse Sandstones, overlain by interbedded dolomitized shaly limestones and brecciated dolomites (Rue Hill Dolomites) of Courceyan age, interpreted as marginal marine deposits (Chisholm *et al.*, 1988). For the remainder of Dinantian times the area was one of deep-water, largely turbidite deposition. On the ramp, carbonate buildups of Chadian age are found in the Milldale Limestones (although some authors prefer to describe these structures as carbonate 'mud-banks' (see Chapter 6) the term 'mud-mound' is preferred here in keeping with current usage). Local non-sequences and unconformities are also recorded from within the Milldale Limestones (Aitkenhead and Chisholm, 1982). To the south, a relatively shallow-water Asbian carbonate facies (the Kevin Limestones) and associated marginal 'reef' limestones are developed on the Staffordshire Shelf and these beds outcrop in the Weaver Hills district (Chisholm *et al.*, 1988).

The Widmerpool Gulf and Hathern Shelf are poorly represented at outcrop, being limited to localities south and west of Wirksworth (Frost and Smart, 1979; Chisholm *et al.*, 1988) and the inliers in north Leicestershire. They are best known from subsurface investigations, which include the Duffield Borehole (Aitkenhead, 1977) and seismic interpretation (Ebdon *et al.*, 1990). The area appears to be occupied by two half-graben, with sediment fills thickening southwards – the Widmerpool Half-graben separated from the Hathern Half-graben by the Hoton Fault (see Figure 7.2). The Thringstone–Sileby Fault System separates the Hathern Half-graben from the land area of the Wales–Brabant Massif (Ebdon *et al.*, 1990). The Widmerpool Gulf succession appears to be characterized by mudstones interbedded with both carbonate and siliciclastic turbidites (George *et al.*, 1976; Aitkenhead and Chisholm, 1982). The Hathern Shelf succession comprises Courceyan anhydritic strata known from the Hathern No. 1 Borehole (Llewellyn *et al.*, 1969), overlain by dolomitized shelf limestones ranging from early Chadian to Brigantian age (Ambrose and Carney, 1997, 1999).

Carbonate sedimentation ceased during mid-Brigantian times. Late Brigantian and early Namurian strata are mostly marine shales with turbiditic sandstones. In the basinal areas these rest conformably on the Dinantian strata, but where they overlie Dinantian shelf or shelf-margin facies, the relationship is unconformable, with some or all of the Brigantian carbonates missing and an incomplete or condensed early Namurian succession is present (Aitkenhead *et al.*, 1985; Chisholm *et al.*, 1988).

Locally, and especially during later Dinantian times, the continuity of carbonate sedimentation across the Derbyshire Platform was interrupted by episodes of volcanic activity, the most common by-product of which was the formation of basaltic lavas and tuffs. These and other igneous rocks in the area are described in detail by Aitkenhead *et al.* (1985) and Chisholm *et al.* (1988); the more important igneous exposures in the area are described in a companion GCR volume, *Carboniferous and Permian Igneous Rocks of Great Britain*, by Stephenson *et al.* (2003).

GCR site coverage

The sites considered in this chapter reveal important evidence relating to the geological history of the Derbyshire Platform, Hathern Shelf and North Staffordshire Basin during early Carboniferous times. In keeping with other areas, most of the sites were selected because of their combined stratigraphical, sedimentological and palaeontological interest.

On the Derbyshire Platform, two sites stand out as being particularly significant, partly because of their considerable size, but mainly because of the great range of stratigraphy and facies that is represented within them. The first of these, at **Castleton**, provides a classic section through a highly fossiliferous 'apron reef' developed at the northern margin of the platform during Asbian times. The second, the composite **Wye Valley and Cressbrook Dale** site, records an almost continuous section of all the exposed formations of the platform interior, ranging from the Woo Dale Limestones (Holkerian) through to the Eyam Limestones (Brigantian).

Further sites towards the platform interior include **Duchy Quarry** (shallow marine limestones with subaerial exposure features in the Bee Low Limestones, Asbian), **Cawdor Quarry** (rich faunas from the Monsal Dale Limestones and Eyam Limestones, Brigantian) and **Ricklow Quarry and Monyash Quarry** (Monsal Dale Limestones and Eyam Limestones, Brigantian – including faunas and carbonate mud-mounds). Other sites either close to or at the platform margin include **Pindale Quarry** (carbonate sand shoal, Bee Low Limestones, Asbian), both **Dale Quarry** and **Baileycroft Quarry** (shelf and slope deposits including slumps, slides and re-sedimented beds, Bee Low Limestones–Eyam Limestones, Asbian–Brigantian) and the **National Stone Centre** (carbonate mud-mounds, Monsal Dale Limestones and Eyam Limestones, Brigantian).

In the North Staffordshire Basin, two large sites are of particular importance. The first of these, at **Dovedale**, offers spectacular sections through the largest and best exposed deep-water carbonate mud-mound complex of Early Carboniferous age in Britain (Milldale Limestones, Chadian). The second, the **Wetton to Beresford Dale** site, includes similar facies together with a younger (Asbian) reef complex developed across the basin margin in the Hopedale Limestones and Bee Low Limestones, and the turbiditic

Ecton Limestones (Chadian–Asbian). Other sites in the area include **Brown End Quarry** (type sections, in part, of both the Milldale Limestones and Hopedale Limestones and re-sedimented beds), **Caldon Low Quarry** (unconformity between the Milldale Limestones and Hopedale Limestones at the basin margin and the ?Holkerian or Asbian Caldon Low Conglomerate) and **Cauldon Railway Cutting** (fossiliferous Namurian shales, Pendleian).

Sites from the Hathern Shelf illustrate a range of sedimentary facies developed between the Widmerpool Gulf and the Wales–Brabant Massif during Dinantian times. These include the extensive Chadian–Asbian sections of dolomitized ramp successions containing storm deposits, carbonate mud-mounds and stratigraphical discontinuities at **Breedon Cloud Quarry** (Milldale Limestones and Cloud Hill Dolostone), the type section of the highly fossiliferous Ticknall Limestone (Brigantian) at **Ticknall Quarries** (nearshore shallow marine facies), and a more marginal and dolomitized facies equivalent of this same unit at **Grace Dieu**, where the succession contains evidence of subaerial weathering and a break in the continuity of sediment deposition.

WYE VALLEY AND CRESSBROOK DALE, DERBYSHIRE (SK 100 724–SK 192 713 and SK 172 740–SK 178 755)

Introduction

The Wye Valley and Cressbrook Dale GCR site report considers the geology at two GCR sites in central Derbyshire, the Midland Railway to Wye Valley site and the Cressbrook Dale site, together. Thus, it includes details of the extended section (SK 100 724–SK 192 713) of Lower Carboniferous strata exposed along the line of the disused Midland Railway cutting and in the valley-side crags and quarries of the River Wye between Buxton and Bakewell, together with details of the exposures in the A6 road cutting at Topley Pike (SK 108 724–SK 114 724) and valley-side crags of Cressbrook Dale (SK 172 730–SK 173 728 and SK 172 740–SK 178 755); these localities are shown on Figure 7.5.

The Wye Valley component of this composite site is unique as it provides an extensive and almost continuous section (> 9 km in length) of the exposed Dinantian beds of the Derbyshire

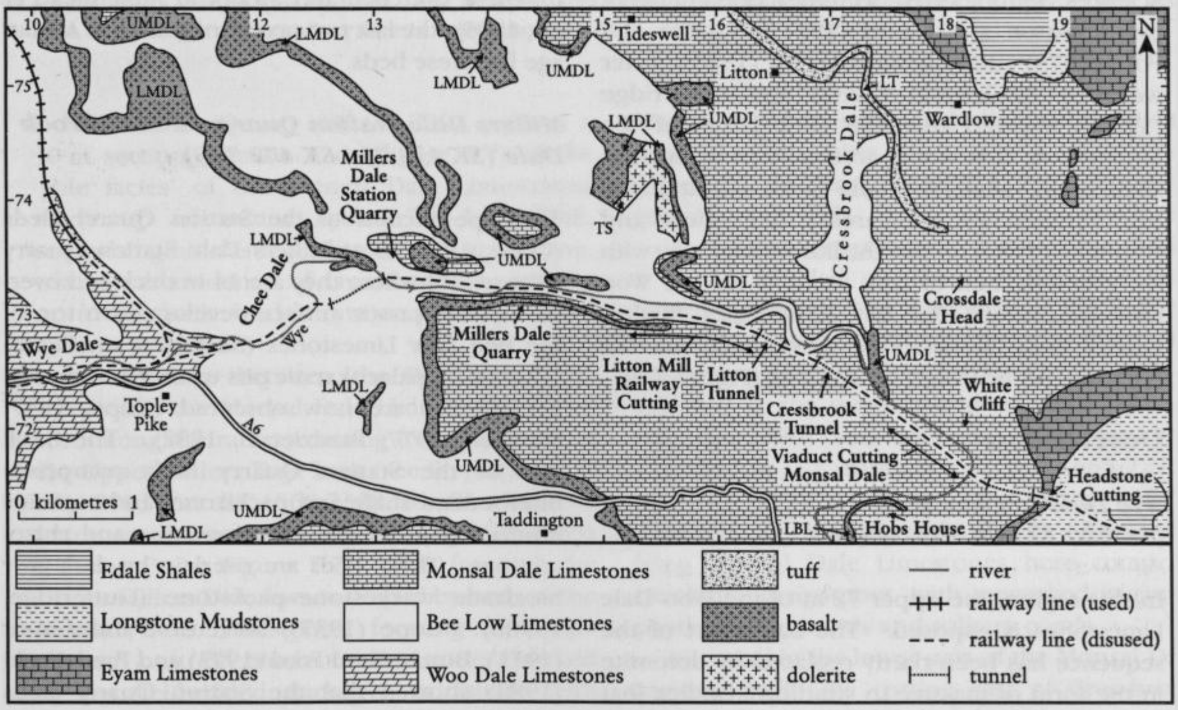


Figure 7.5 Simplified geological map of Wye Valley and Cressbrook Dale area illustrating the position of localities referred to in the text. LMDL – Lower Millers Dale Lava; TS – Tideswell Sill; UMDL – Upper Millers Dale Lava; LBL – Lees Bottom Lava; LT – Litton Tuff. Based on the [British] Geological Survey maps of the Chapel en le Frith and Buxton districts (Institute of Geological Sciences, 1975b, 1978).

carbonate platform ranging from the Woo Dale Limestones (Holkerian) through to the Eyam Limestones (Brigantian) (Figure 7.3). The succession demonstrates many features, including dolomitization, changing depositional environments, the response of carbonate sedimentation to sea-level changes, contemporaneous volcanism, the influence of syndepositional uplift and subsidence, the development of an intra-platform basin and the final abandonment of carbonate sedimentation on the Derbyshire Platform in late Brigantian–early Namurian times.

The basic lithostratigraphy and biostratigraphy of the central part of the platform was first established by Sibly (1908) and Cope (1933, 1937) in this area. The latter author also recognized the complex stratigraphical relationships around the Asbian–Brigantian boundary in the Millers Dale area, which was further elaborated by Butcher and Ford (1973), Walkden (1977), Pazdzierski (1982), Aitkenhead *et al.* (1985) and Gutteridge (1989a, 1990b).

The Monsal Dale Limestones were divided into a 'dark' and 'pale facies' by Cope (1933). These facies, recorded on [British] Geological Survey maps of the area (Institute of Geological Sciences, 1976b, 1978), were described in detail by Stevenson and Gaunt (1971), Butcher and Ford (1973) and Aitkenhead *et al.* (1985). Later work by Pazdzierski (1982) and Gutteridge (1989a) showed that the dark facies of the Monsal Dale Limestones accumulated in an intra-shelf basin, while the pale facies accumulated over surrounding shelf areas. Aitkenhead and Chisholm (1982) refined the lithostratigraphy with the establishment of type sections for the Woo Dale Limestones, Bee Low Limestones, Station Quarry Beds, Monsal Dale Limestones and the Longstone Mudstones in this area (Figure 7.3).

Description

Wye Dale to Chee Dale (SK 100 724–SK 123 734)

In this region, the upper 72 m of the Woo Dale Limestones is exposed. The basal part of the sequence has been partly replaced by dolomite in the form of massive to stratiform bodies that locally cross-cut bedding (Aitkenhead *et al.*, 1985; Schofield and Adams, 1986). The Woo Dale Limestones comprise lenticular-bedded wackestone–packstone beds 0.5–1.0 m thick with fenestrae, gastropods, bivalves and *Daviesiella* valves (see Cope, 1940). Sharp, erosively based, beds of fine-grained bioclastic grainstone are also present. Some unusually thick (1–2 cm) bituminous stylolite residues that resemble thin coal seams are also present (Schofield, 1982). A Holkerian age for this formation is indicated by the presence of *Davidsonina carbonaria*, *Composita* cf. *ficoides* and foraminifera listed by Strank (1986).

The contact between the Woo Dale Limestones and the Bee Low Limestones is marked by a transition from medium-grey lenticular-bedded limestones to thick and planar-bedded pale-grey limestones. The whole of the Bee Low Limestones (130–150 m), including the Lower Millers Dale Lava, is exposed between Blackwell Cottages (SK 1135 7265) and Millers Dale (Aitkenhead *et al.*, 1985). The formation consists of thickly bedded, pale bioclastic peloidal packstone–grainstone with minor wackestone and calcrete features associated with palaeokarstic surfaces. Scattered coral–brachiopod bands typically contain *Daviesiella*, *Linoprotonia hemisphaerica*, *Davidsonina septosa* and *Dibunophyllum bourtonenese* (Mitchell and Strank in Aitkenhead *et al.*, 1985), the last two taxa confirming an Asbian age for these beds.

Millers Dale Station Quarry to Cressbrook Dale (SK 132 734–SK 172 729)

The type section of the Station Quarry Beds (Cope, 1937) is at Millers Dale Station Quarry (Figure 7.6) where they are 14 m thick and overlie a palaeokarstic surface developed on top of the Bee Low Limestones (Section 1 on Figure 7.7). Some palaeokarstic pits up to 3 m deep are present but are now obscured (Cope, 1937; Walkden, 1977; Pazdzierski, 1982). The basal 1 m of the Station Quarry Beds comprises interbedded shale and packstone, and contains *Koninckopora*, intraclasts, fenestrae and rhizocretions. These beds are overlain by dark-grey bioclastic wackestone–packstone (Gutteridge, 1990b). Cope (1937), Stevenson and Gaunt (1971), Butcher and Ford (1973) and Pazdzierski (1982) showed that the Station Quarry Beds pinch out to the south and north against the Taddington–Bakewell Anticline and the Longstone Edge Anticline respectively.

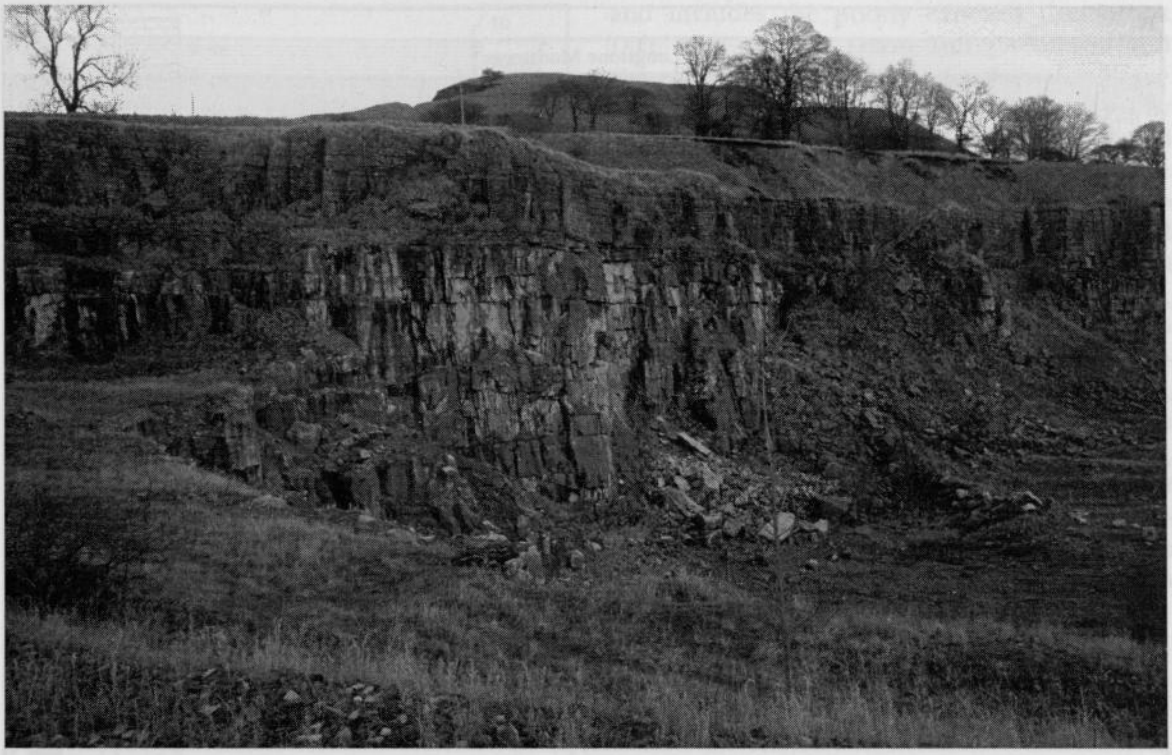


Figure 7.6 The contact between the Bee Low Limestones (Asbian) and the Station Quarry Beds (Brigantian) at Millers Dale Station Quarry. The contact, which is marked by a significant palaeokarst, occurs towards the top of the quarry where thicker-bedded Bee Low Limestones are overlain by thinner-bedded, darker-coloured limestones of the Station Quarry Beds. The elevated area behind the quarry is formed by the Upper Millers Dale Lava. The height of the quarry face is approximately 20 m. (Photo: P.J. Cossey.)

Millers Dale Quarry (SK 141 730) exposes a 30 m section (Section 2 on Figure 7.7) of the 'pale facies' of the Monsal Dale Limestones, made up of minor cycles 0.5–3 m thick, comprising bioclastic packstone and grainstone, with some evidence of cross-bedding, passing up to bioclastic wackestone or packstone with calcrete textures.

Relationships between the Bee Low Limestones and the Monsal Dale Limestones can be seen along the railway cutting from the front of the Upper Millers Dale Lava (see Stephenson *et al.*, 2003) at SK 1560 7300 to the western entrance of Cressbrook Tunnel (SK 1675 7255) (Section 3 on Figure 7.7). The front of the Upper Millers Dale Lava is draped by beds of the Monsal Dale Limestones, forming a wedge-shaped unit of bioclastic limestone overlain by parallel-bedded dark-grey calcisiltite with tabular chert. The latter contain a sparse fauna of thin-shelled bivalves and *Chondrites* burrows. A lateral facies change to wackestone with a diverse bioclast suite including large in-situ colonial corals takes place over a distance of 250 m to the east. Cope (1937) recorded gigantoproductids, numerous lithostrotionid corals and *Saccaminopsis* from these beds. A thickly bedded sequence of the Bee Low Limestones topped by a prominent palaeokarst with deep-brown to bluish-grey clay-filled pits containing pebbles of the Station Quarry Beds is exposed at the western end of Litton Tunnel (SK 1620 7280) and between the Litton and Cressbrook tunnels (SK 1665 7270–SK 1675 7255) (Butcher and Ford, 1973; Walkden, 1977; Pazdzierski, 1982). The overlying Monsal Dale Limestones here comprise bioclastic grainstones with reworked gigantoproductids, crinoids and solitary corals.

A section in the lower part of the Monsal Dale Limestones in the cutting east of Cressbrook Tunnel (SK 1725 7255) (Section 4 on Figure 7.7) comprises some 8 m of cherty calcisiltite with two slumped units of recumbently folded

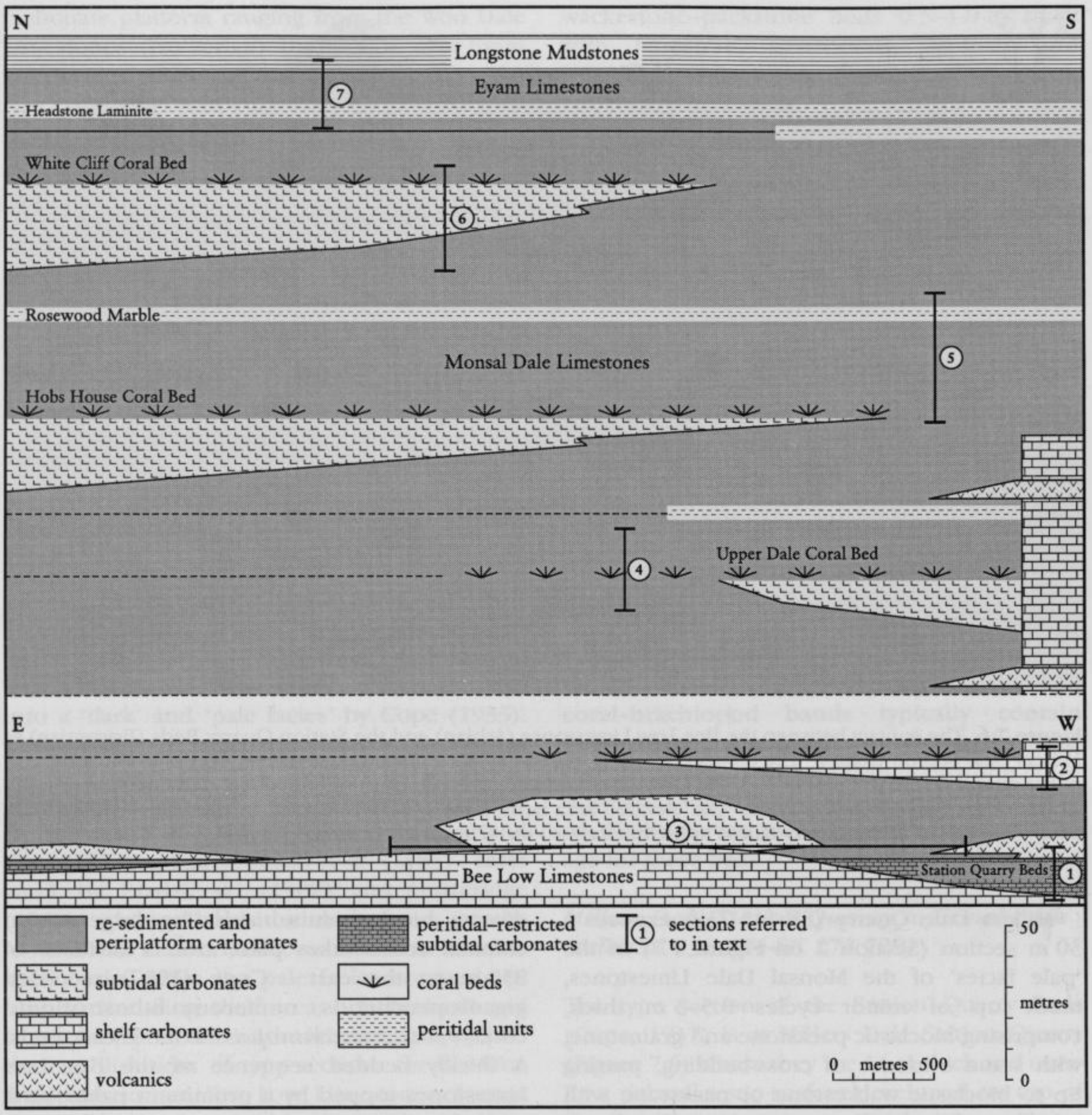


Figure 7.7 Summary of the late Asbian–Brigantian stratigraphy of the Millers Dale–Monsal Dale area. Note that the section is split in two: the lower part represents an east–west section through the Litton Mill–Millers Dale area; the upper part represents a north–south section across the Monsal Dale area. The sections described in the text are as follows: 1 – Millers Dale Station Quarry; 2 – Millers Dale Quarry; 3 – Litton Mill Railway Cutting; 4 – Cressbrook Tunnel; 5 – Monsal Dale Viaduct Cutting; 6 – White Cliff; 7 – Headstone Cutting. After Butcher and Ford (1973) and Gutteridge (1989a).

bioclastic packstone–wackestone. Some thin graded beds of grainstone–packstone with reworked bioclasts also occur here. Butcher and Ford (1973) record the Upper Dale Coral Bed (1 m) halfway up this section; the corals include *Siphonodendron junceum* with *S. martini* and *Diphyphyllum lateseptatum* (Butcher and Ford, 1973; Aitkenhead *et al.*, 1985) and some show evidence of having been reworked (toppled and inverted colony fragments and re-orientated growth forms, etc).

An excellent section of the 'pale facies' of the Monsal Dale Limestones, incorporating numerous lithostratigraphical marker bands, is developed in north Cressbrook Dale. The section here (Figure 7.8) extends from the top of

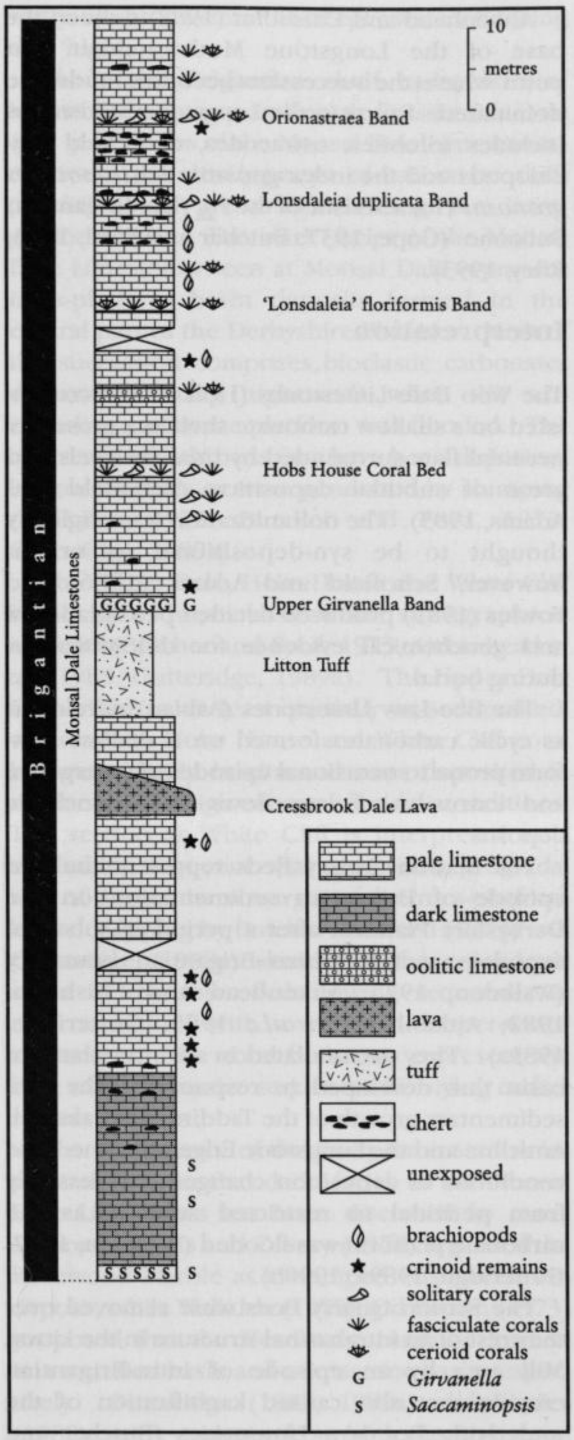


Figure 7.8 Simplified sedimentary log of the Monsal Dale Limestones (Brigantian) at Cressbrook Dale. After Stevenson and Gaunt, 1971.

the Bee Low Limestones, through the entire thickness of the Monsal Dale Limestones (*c.* 155 m), to the base of the Eyam Limestones and includes the poorly exposed Cressbrook Dale Lava and the Litton Tuff (Stevenson and Gaunt, 1971). A notable development, some 15 m above the Litton Tuff, is that recognized by Shirley and Horsfield (1945), Taylor (1957) and Stevenson and Gaunt (1971) as the Hobs House Coral Bed, and which Cossey (1983) referred to as the 'Cressbrook Dale Coral Band'. A typical Brigantian coral assemblage from this band includes *Aulophyllum pachyendothecum*, *Dibunophyllum bipartitum*, *Slimoniphyllum slimonianum*, *Siphonodendron* spp., *Diphyphyllum lateseptatum*, *Palastraea regia*, *Lithostrotion maccoyanum* and *Actinocyathus floriformis* (Taylor, 1957; Stevenson and Gaunt, 1971; Cossey, 1983). Its structure, development and significance at the top of a shallowing-upward (regressive) cycle capped by a calcrete and a minor angular discordance has been described by Cossey (1983).

Monsal Dale to Headstone Cutting (SK 172 724–SK 190 713)

A 44 m section in the middle part of the Monsal Dale Limestones extending from the Hobs House Coral Bed (0.5 m) to just above the 'Rosewood Marble' (1.6 m) is exposed in Monsal Dale Viaduct Cutting between Monsal Dale Station and Monsal Head Viaduct (Section 5 on Figure 7.7). The Hobs House Coral Bed is best exposed at Hobs House (SK 1760 7122) where it is up to 5 m thick and contains spectacular examples of both solitary corals and large in-situ colonial corals including *D. bipartitum*, *Koninckophyllum magnificum*, *Slimoniphyllum slimonianum*, *Clisiophyllum keyserlingi*, *Siphonodendron* spp., *Diphyphyllum* spp., *Lithostrotion decipiens* and *Nemistium edmondsi* (Cossey, 1983). This fauna, together with other coral assemblages in the Monsal Dale Limestones (see below), confirms the Brigantian age assigned to this formation by Aitkenhead and Chisholm (1982). The Hobs House Coral Bed also occurs at Crossdale Head (SK 1825 7310).

The majority of the section in Monsal Dale consists of thickly bedded, fine-grained, dark packstone with comminuted bioclasts and *Chondrites* and *Zoophycos* burrows. These are interbedded with thin shale beds and some K-bentonite beds. Both the extensional and compressional parts of slump sheets overlain erosively by metre-thick graded beds of coarse bioclastic grainstone are also exposed. The

Rosewood Marble consists of millimetre- to centimetre-scale laminations of carbonate mudstone and dolomite replacing fine grainstone layers. The laminations show slumping and are cut by burrows infilled by dark calcisiltite. This unit is described in more detail by Adams and Cossey (1978).

A 19 m section in the Monsal Dale Limestones between the Rosewood Marble and the White Cliff Coral Bed is exposed at White Cliff (SK 1825 7200) (Section 6 on Figure 7.7). This records an upward transition from fine-grained cherty calcisiltite through bioturbated open marine bioclastic wackestone to bioclastic grainstone with reworked gigantoproductids and crinoids. The White Cliff Coral Bed, at the top of the section, contains *Lonsdaleia duplicata*, *Actinocyathus floriformis*, *Palastraea regia*, *Diphyphyllum lateseptatum* and *Orionastraea placenta* (Butcher and Ford, 1973; Aitkenhead *et al.*, 1985). The White Cliff Coral Bed and underlying bioclastic limestones are also exposed around Monsal Head (SK 1845 7150).

Headstone Cutting (Section 7 on Figure 7.7) provides a complete section through the Eyam Limestones (19.5 m) and the overlying Longstone Mudstones (3.5 m). The base of the Eyam Limestones is taken at the base of a 7.5 m-thick sequence of laminated and dolomitized limestones (Aitkenhead and Chisholm, 1982). These consist of dolomitized grainstone and carbonate mudstone layers interlaminated at a millimetre-scale. Grainstone laminae contain ostracodes, possible green algae and calcareous encrusting organisms. Carbonate mudstone laminae contain early diagenetic evaporite pseudomorphs, desiccation curls, fenestrae, plant fragments and calcrete features (Gutteridge, 1983, 1989a). A millimetre-thick coal seam with associated seatearth is present 10.6 m above the base of the bed. At least three slump sheets are present below the coal; these slumps are erosively overlain by thickly bedded (up to 1 m) graded intraclast packstone. Intraclasts are derived from the laminated dolomitized limestones. The laminated dolomitized limestones are overlain by a 0.2 m-thick bioclastic packstone dominated by *Spirifer trigonalis* with minor *Martinia glabra* and *Productus productus* (Butcher and Ford, 1973). Above this are 12 m of interbedded bioclastic calcisiltite and shale. Limestone beds in this part of the sequence contain sparse reworked bioclasts.

Aitkenhead and Chisholm (1982) defined the base of the Longstone Mudstones at that point where the succession becomes mudstone dominated. Fauna in the Longstone Mudstones includes trilobites, ostracodes, chonetoid brachiopods and the index goniatite *Lusitanoceras granosus* characteristic of the P_{2a} (late Brigantian) Subzone (Cope, 1937; Butcher and Ford, 1973; Riley, 1993).

Interpretation

The Woo Dale Limestones (Holkerian) accumulated on a shallow carbonate shelf as a mosaic of peritidal flats surrounded by tidal channels and areas of subtidal deposition (Schofield and Adams, 1985). The dolomitization was originally thought to be syn-depositional in origin; however, Schofield and Adams (1986) and Fowles (1989) produced detailed petrographical and geochemical evidence for dolomitization during burial.

The Bee Low Limestones (Asbian) developed as cyclic carbonates formed on a shallow platform prone to occasional episodes of emergence and extrusion of lava flows and pyroclastic deposits.

The Station Quarry Beds represent the first episode of Brigantian sedimentation on the Derbyshire Platform after a period of subaerial exposure at the Asbian–Brigantian boundary (Walkden, 1977; Aitkenhead and Chisholm, 1982; Aitkenhead *et al.*, 1985; Gutteridge, 1989a). They accumulated in an intra-platform basin that developed in response to the syn-sedimentary growth of the Taddington–Bakewell Anticline and the Longstone Edge Anticline. The conditions of deposition changed progressively from peritidal to restricted subtidal as the carbonate platform was flooded (Walkden, 1977; Gutteridge, 1989a, 1990b).

The Station Quarry Beds were removed over the crest of an intrabasinal structure in the Litton Mill area by an episode of intra-Brigantian erosion that also caused karstification of the underlying Bee Low Limestones (Butcher and Ford, 1973; Walkden, 1977; Pazdzierski, 1982). The intrabasinal high continued to influence sedimentation during early Brigantian times, with oxygenated, high-energy conditions over its crest passing down-dip into low-energy near-anoxic conditions down its flanks. The slumps seen in the cutting east of Cressbrook Tunnel represent the down-slope transport of shallow-water limestones into the deeper waters flanking this 'high'.

The cyclic Brigantian shelf carbonates of Millers Dale Quarry and north Cressbrook Dale (the 'pale' facies of the Monsal Dale Limestones) represent the development of carbonate shelf conditions in areas surrounding the intra-platform basin. The 'dark' facies of the Monsal Dale Limestones seen at Monsal Dale represent intra-platform basin deposits formed in the central part of the Derbyshire Platform. Most of the succession comprises bioclastic carbonates deposited during highstands when the surrounding carbonate platform was flooded. The coarser bioclastic beds may have been deposited by storm events or were generated by slumping (Walkden, 1970; Butcher and Ford, 1973; Gutteridge, 1989a).

The Upper Dale, Hobs House and White Cliff coral beds form basin-wide stratigraphical markers (Butcher and Ford, 1973; Aitkenhead *et al.*, 1985; Gutteridge, 1989a). The Upper Dale Coral Bed is at least partially re-sedimented, whereas the Hobs House and White Cliff coral beds are largely *in situ* and were deposited in moderate- to high-energy subtidal conditions. The section at White Cliff is interpreted as a shallowing sequence that represents progradation of the northern margin of the intra-platform basin. Mapping by Butcher and Ford (1973) and Gutteridge (1989a) show that the coral beds occur at the top of shallowing sequences at the transition with overlying deeper-water carbonates. The coral beds may represent the base of transgressive sequences overlying earlier regressive units.

The significance of the finely laminated dolomitized units in the 'dark' facies of the Monsal Dale Limestones has been discussed by many authors. Adams and Cossey (1978) regarded the Rosewood Marble as a slumped offshore storm deposit, while Walkden (1970) and Brown (1973) proposed that the Headstone Laminite formed in a stratified basin and a lacustrine basin respectively. Gutteridge (1983, 1989a) and Fowles (1989), using evidence from both the Rosewood Marble and the Headstone Laminite interpreted them as slumped tidal-flat deposits that formed when the intra-platform basin was almost completely drained during sea-level lowstands. The Headstone Laminite at the Monsal Dale Limestones–Eyam Limestones boundary represents peritidal carbonates formed during a lowstand when surrounding parts of the Derbyshire Platform were exposed above sea level (Aitkenhead *et al.*, 1985; Gutteridge, 1989a). The Longstone Mudstones were deposited in deep-water subtidal conditions below wave-base; the diverse benthic fauna suggests that bottom conditions were oxygenated.

Conclusions

The sections at these extensive and important localities collectively provide a continuous record of the sedimentary evolution of the central part of the Derbyshire Platform from Holkerian through to Brigantian times when carbonate sedimentation was abandoned. Deposition during Holkerian and Asbian times took place on a flat-topped carbonate shelf, with the development of minor shallowing-up cycles becoming apparent during the Asbian Age. An episode of differential subsidence at the Asbian–Brigantian boundary caused the development of an intra-platform basin. Brigantian sedimentation took place by deposition of bioclastic carbonates reworked from surrounding shelf areas with minor carbonate production over an intrabasinal high within the intra-platform basin. The intra-platform basin responded to sea-level changes by the development of peritidal facies during high-magnitude lowstands and progradational episodes of the basin margin during low-magnitude lowstands. The coral beds formed during transgressions after progradation. The conformable transition from the Eyam Limestones to the overlying Longstone Mudstones represents the abandonment of carbonate sedimentation during mid-Brigantian times.

DUCHY QUARRY, DERBYSHIRE (SK 094 768)

Introduction

The Duchy Quarry GCR site is a disused quarry (SK 094 768) near Peak Dale, 5 km to the north-east of Buxton. It offers an outstanding section of the Chee Tor Rock; part of the Bee Low Limestones (see Aitkenhead and Chisholm, 1982). The existence of subaerial weathering phenomena (palaeokarsts and palaeosols) in this otherwise shallow marine sequence make it a key site for monitoring sea-level and environment changes across the Derbyshire Platform during Asbian times. The section also includes a number of fossiliferous lithostratigraphical marker bands important for the correlation of successions across the platform area. Logs of the succession are provided by Stevenson and Gaunt (1971) and Berry (1984).

Description

This site was originally selected as one of the type sections of the Bee Low Limestones by Aitkenhead and Chisholm (1982). The section is ascribed to the upper part of the Chee Tor Rock (Green *et al.*, 1869; Cope, 1933), that part of the Bee Low Limestones sequence immediately below the level of the Lower Millers Dale Lava (Stevenson and Gaunt, 1971). It comprises 33.5 m of pale, massive and rather homogeneous, fine-grained limestones (principally calcarenites) and is characterized by closely spaced vertical joints (Figure 7.9). Typical lithologies include bioclastic and peloidal grainstones with a few packstone layers. Besides the ubiquitous crinoid debris, comminuted brachiopod and coral fragments also occur at various levels in the sequence.

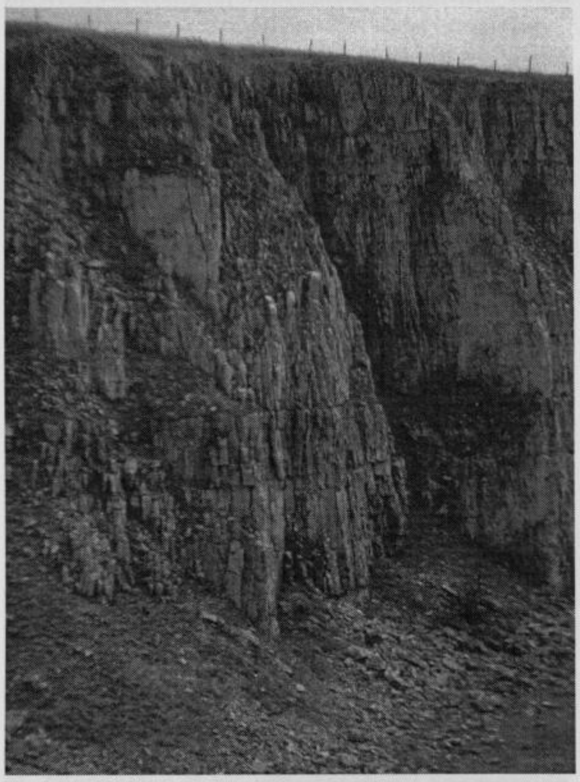


Figure 7.9 General view of the thick-bedded and strongly jointed Asbian grainstone facies in the Chee Tor Rock (Bee Low Limestones) at Duchy Quarry. The height of the quarry face is approximately 30 m. (Photo: P.J. Cossey.)

At the base of the section, a spectacular pot-holed surface or 'palaeokarst' (see Walkden, 1972b, 1974) with solution pits up to 20 cm deep, and once visible across much of the quarry floor, is now partly obscured by infill. A similar surface occurs 13 m higher in the sequence. Clay wayboards up to 0.6 m thick above these surfaces most probably represent palaeosols derived from the weathering of pyroclastic deposits (volcanic ash) deposited over the sub-aerially exposed limestone surfaces during periods of platform emergence (Walkden, 1972a, 1984). K-bentonite residues of a volcanic origin (Walkden, 1972a) are also recorded from a prominent stylolite 7.5 m above the quarry floor.

Three prominent lithostratigraphical marker bands occur 3.5 m, 15.2 m and 26 m above the base of the section. From the base to the top these are respectively the Duchy Quarry Algal Band, the Lower Davidsonina septosa Band and the Upper Davidsonina septosa Band, and each of these has proved useful in the correlation of Asbian successions across the Derbyshire Platform (Stevenson and Gaunt, 1971). *D. septosa* does however occur, both in association with and without 'algae', at several other levels in the section (Stevenson and Gaunt, 1971).

The Duchy Quarry Algal Band (0.3 m) contains microbial oncoids up to 7 cm in diameter with micrite laminae enclosing the calcified tubes of the cyanobacterium *Girvanella* concentrically arranged around a nucleus of either crinoid or brachiopod shell fragments (e.g. *D. septosa*). Encrustations of the demosponge *Chaetetes depressus* occur between the micrite laminae of some oncoids. The associated fauna includes fragments of solitary and colonial corals, foraminifera and an abundance of the dasycladacean alga *Koninckopora*.

A faunal assemblage typical of the Asbian Stage is reported from the Lower D. septosa Band (0.25 m) including *D. septosa*, *Delepinea comoides*, *Gigantoproductus* sp. *edelburgensis* group, *Linoprotonia*, *Megachonetes* sp. *papilionaceus* group, *C. depressus*, *Dibunophyllum bourtense*, *Siphonodendron* cf. *sociale*, *S. martini*, *Palaeosmilia murchisoni*, *Syringopora*, gastropods, foraminifera and *Koninckopora* (Mitchell in Stevenson and Gaunt, 1971). A somewhat similar brachiopod fauna is reported by the same author in the Upper D. septosa Band (*c.* 0.5 m) (= '*Cyrtina septosa* Band' of Cope, 1936, 1939).

Interpretation

The succession at Duchy Quarry is typical of the upper part of the Bee Low Limestones across much of the Derbyshire Platform. It represents part of a laterally extensive carbonate sand-sheet formed in the warm, clear and subtidal waters of a shallow shelf sea. A predominantly subtidal setting is confirmed by the presence of microbial oncoids and *Koninckopora* at several levels in the sequence. The uniformity of sediment texture, high level of bioclast fragmentation and absence of sedimentary structures is attributed to the combined effects of extensive wave and current action and bioturbation (Sadler, 1964a; Aitkenhead *et al.*, 1985; Gutteridge, 1987). Prolonged episodes of platform emergence and subaerial weathering are indicated by the presence of palaeokarsts and palaeosols (Walkden, 1972a, 1974). These features most probably form the tops to minor shallowing-upward sedimentary cycles which are as yet imprecisely defined within the sequence (Walkden, 1984, 1987).

Conclusions

The section at Duchy Quarry offers one of the best and most easily accessed sections of the Chee Tor Rock in central Derbyshire. The alternation of shallow marine strata with subaerial exposure features (palaeokarsts and palaeosols) reveals important information on the nature of sea-level fluctuations across the Derbyshire Platform during Asbian times. The site has considerable potential as an educational resource for demonstrating aspects of carbonate sedimentology and as a research site.

CASTLETON, DERBYSHIRE (SK 132 832–SK 149 824 and SK 126 830)

Introduction

The Castleton GCR site is a classic Lower Carboniferous site in north Derbyshire. It provides a unique opportunity for the examination of highly fossiliferous apron-reef limestones formed at the northern margin of the Derbyshire Platform during late Dinantian (Asbian) times; arguably the finest and most intensively studied apron-reef complex of Early Carboniferous age in Britain. Important accounts of the stratigraphy of the area are by Shirley and Horsfield (1940), Ford (1952) and Parkinson (1943, 1947, 1953, 1965) and Stevenson and Gaunt (1971). The anatomy, development and palaeoecology of the reef complex has been described by Wolfenden (1958), Broadhurst and Simpson (1973) and Timms (1978). Aspects of the limestone diagenesis are detailed by Bingham (1992). An excellent overview of the site geology has recently been presented by Ford (1996).

Additional features of interest that make this one of the most popular destinations for educational field parties and tourists include the spectacular development of Pleistocene cave systems, some unusual mineral deposits, both disused and fully operational mineral workings (the latter most notably for the extraction of 'blue john' – a variety of the mineral fluorite) and the famous Mam Tor Landslip (Ford, 1996).

Description

The site, which occupies a 2.5 km strip of land west of Castleton village, extends from Cave Dale (SK 149 824) in the east, via Long Cliff (SK 140 825), Winnats Pass (SK 135 826), Treak Cliff (SK 135 830) and the Blue John Mine (SK 132 832) to Windy Knoll Quarry (SK 126 830) in the west (Figure 7.10). Enclosed within it are a range of sedimentary facies that illustrate the shelf–apron-reef–basin transition across the northern margin of the Derbyshire Platform during Asbian times.

Occupying the higher ground around Cave Dale and Winnats Pass, and forming an integral part of the Deryshire Platform as far south as Hartington, are the massive and generally flat-lying beds of the Bee Low Limestones (shelf facies). This formation is of D_1 age (Stevenson and Gaunt, 1971). To the north-east, an apron-reef complex of B_2 age defines the position of the shelf margin separating the Derbyshire Platform from the Edale Basin (Stevenson and Gaunt, 1971; Gutteridge, 1991a, 1996). Although Shirley and Horsfield (1940) originally regarded the B_2 reef limestones as post-dating the D_1 shelf facies, and separated from them by an unconformity, later workers demonstrated the lateral continuity and equivalence of these two facies (Parkinson, 1943, 1947, 1953, 1965; Ford, 1952). Similarly, the relatively steep outward dip (up to 35°) to beds of the reef complex,

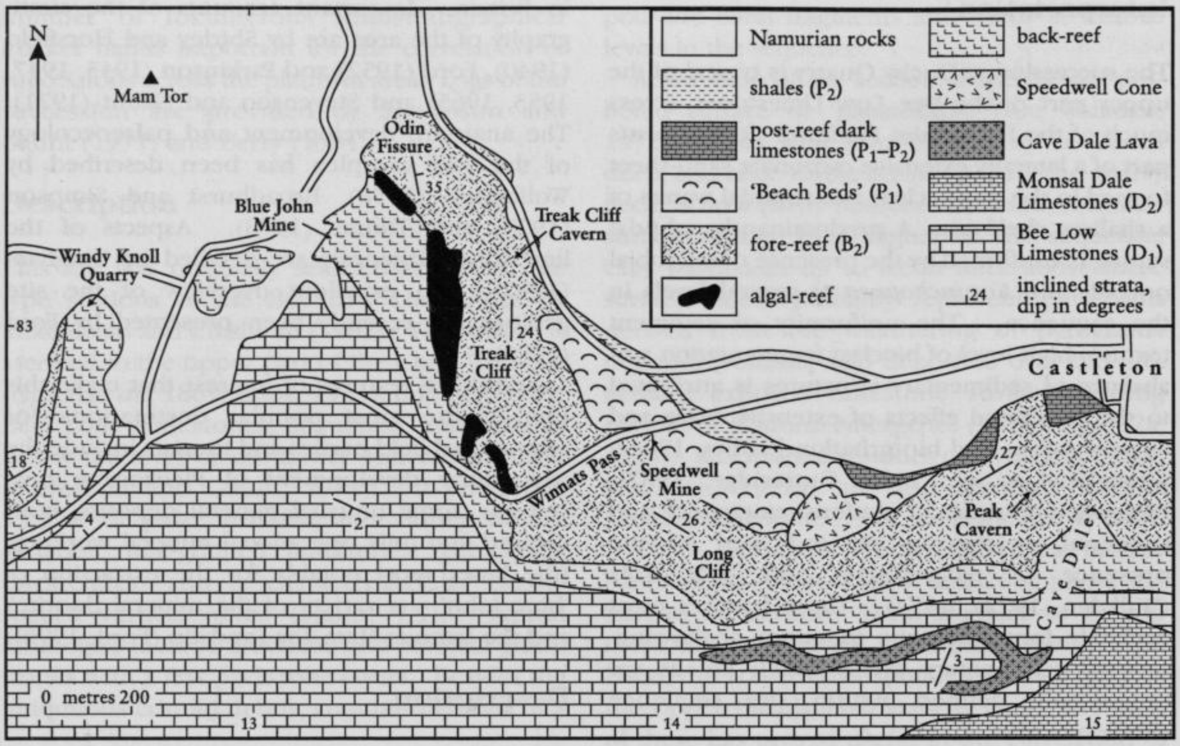


Figure 7.10 Geological map of the Castleton Reef-Belt (Asbian). After Stevenson and Gaunt (1971).

once thought to be tectonic in origin (Green *et al.*, 1887; Fearnsides and Templeman, 1932), is now considered to be a depositional feature and the manifestation of an original reef palaeoslope at the platform margin flanking the Edale Basin to the north (Wolfenden, 1958; Broadhurst and Simpson, 1967). Remarkably, the original form of this Lower Carboniferous palaeoslope has been exhumed by recent erosion and is beautifully preserved in the hillside slopes of Treak Cliff and Long Cliff, which border the high ground shelf area between Mam Tor and Castleton village (Figure 7.11).

The shelf facies (Bee Low Limestones) is characterized mainly by thickly bedded, pale-coloured, crinoidal grainstones, some with superficial ooids, marine cements and hydrocarbon residues, while others contain *Koninckopora*, locally in abundance. In Cave Dale, a prominent (7.5 m thick) olivine basalt (the Cave Dale Lava) occurs in the sequence. Macrofossils, mainly corals and thick-shelled brachiopods, are generally sparse with concentrations of fossils occurring in discrete bands. Two notable developments include, the Upper Davidsonina septosa Band recorded by Wolfenden (1958) from the Winnats Pass area approximately 50 m below the Cave Dale Lava, and the Lithostrotion aff. maccoyanum Band of Shirley and Horsfield (1940), identified with some uncertainty by Stevenson and Gaunt (1971) in Cave Dale approximately 12 m above the Cave Dale Lava.

The terminology used here to describe the various apron-reef facies (i.e. back-reef, algal-reef and fore-reef) derives mainly from the work of Wolfenden (1958), with minor modifications by Stevenson and Gaunt (1971). The distribution of these facies and their three-dimensional relationship to each other are illustrated in Figures 7.10 and 7.12.

The back-reef deposits comprise a variable facies with characteristics intermediate between those of the shelf and those of the algal-reef. A notable feature in this respect is the association of both thick-shelled brachiopods (typical of the shelf) and thin-shelled brachiopods (typical of the reef). Generally, the macrofossils here appear to be more common, larger and less fragmented than they are on the shelf. The occurrence of foraminifera, cyanobacteria and algae (*Koninckopora*) in abundance indicates formation in shallow water (Ford, 1996). The back-reef beds are gently inclined towards the shelf area.

Figure 7.11 General view across the Castleton Reef-Belt at the northern margin of the Derbyshire Platform. The steeply sloping ground of the fore-reef is clearly seen to the right of Castleton village (left), separating the high plateau shelf area (right) from the basin (lower left). (Photo: P.J. Cossey.)

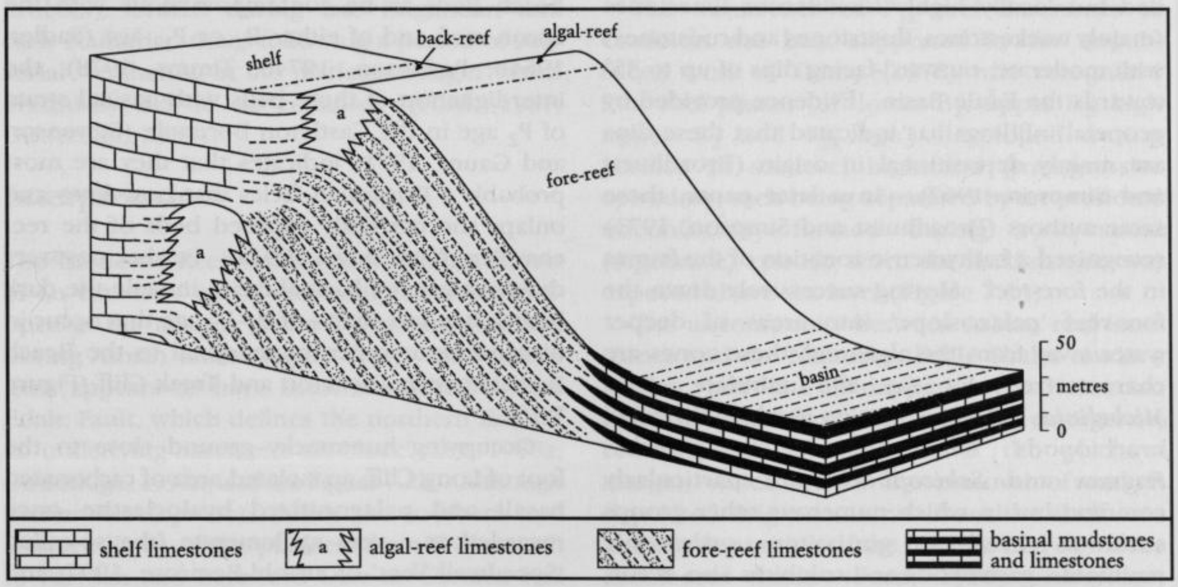


Figure 7.12 Block diagram illustrating the distribution of sedimentary facies in the Castleton Reef-Belt. Based on Wolfenden (1958), Timms (1973) and Ford (1996).

The algal-reef comprises two discontinuous wall-like masses of pale micritic limestone with an organic framework composed of microbial stromatolites (of the '*Collenia-Cryptozoon*' type) with associations of *Girvanella*, *Ortonella* and *Aphrylasia* (Wolfenden, 1958). Additional elements of framework include the encrusting bryozoans *Fistulipora* and *Tabulipora* and the lithistid sponges *Haplistion* '*Radiatospongia*' *carbonaria* and *Scheiia* '*Microspongia*' *castletonense* (Wolfenden, 1959; Mundy, 1994; Rigby and Mundy, 2000). Also present are large but isolated colonies of the lithostrotionid corals *Siphonodendron martini* and *S. pauciradiale* (Stevenson and Gaunt, 1971), the heterocorals *Hexaphyllia marginata* and *Heterophyllia ornata* (Cossey, 1997) and scattered concentrations of brachiopods, bivalves, gastropods and ostracodes. The abundance of *Girvanella* and microbial structures (Wolfenden, 1958) supports the view of this being the shallowest facies of the reef-belt and of deposition in the upper levels of the photic zone. The algal-reefs effectively separated the shallow-water shelf and back-reef areas to the west and south from the more open and deeper-water areas of the fore-reef and basin to the north-east. The facies is particularly well exposed in the prominent ridge at the top of the fore-reef slope above Treak Cliff Cavern (Figure 7.10).

The fore-reef constitutes a zone of poorly bedded but locally highly fossiliferous limestones (mainly wackestones, floatstones and rudstones) with moderate, outward-facing dips of up to 35° towards the Edale Basin. Evidence provided by geopetal infillings has indicated that these dips are mainly depositional in origin (Broadhurst and Simpson, 1967). In a later paper, these same authors (Broadhurst and Simpson, 1973) recognized a bathymetric zonation of the faunas in the fore-reef. Moving successively down the fore-reef 'palaeoslope' into areas of deeper water away from the algal-reef, these zones are characterized by (a) the tabulate coral *Michelinia*; (b) an association in which the small brachiopods '*Dielasma*', *Pleuropugnoides*, *Pugnax* and *Schizophoria* are particularly common but in which numerous other groups such as bivalves, goniatites, orthoconic nautiloids, gastropods and trilobites also occur; and (c) bivalves (especially Streblochondria = '*Pseudamussium*' of Shaw, 1970) and bryozoans. Palaeoslope depths of around 122 m for the reefs at Castleton have been suggested by Wolfenden (1958).

Extensive faunal lists from the various reef facies are provided by Wolfenden (1958) and Mitchell (in Stevenson and Gaunt, 1971). Additional palaeontological works on foraminifera (Cossey and Mundy, 1990), bryozoans (Owen, 1966; Wyse Jackson *et al.*, 1999), heterocorals (Cossey, 1983, 1997), brachiopods (Parkinson, 1952b, 1954a,b,c, 1960, 1961, 1969; Timms, 1973, 1978; Brunton and Tilsley, 1991), bivalves (Shaw, 1970), trilobites (Tilsley, 1977, 1988) and goniatites (Ford, 1965) bear witness to the rich diversity of the faunas in the apron reef.

Marginal to the apron reef and occupying low-flanking ground either side of Winnats Pass are the Beach Beds – a coarsely bioclastic grainstone unit containing large mechanically worn and bioeroded brachiopod shell fragments of shelf aspect set in a finer-grained matrix of brachiopod and crinoid debris (Sadler, 1964b, 1970). Formerly regarded as the littoral deposits of an ancient shoreline (Barnes and Holroyd, 1897; Shirley and Horsfield, 1940), the Beach Beds are now regarded as re-sedimented beds (see Sadler 1964b; Gutteridge, 1991a) derived from earlier formed deposits at the platform margin (e.g. grainstone shoals, seen at **Pindale Quarry**) that were subsequently washed down the reef slope (Sadler, 1964b; Ford, 1987, 1996; Gutteridge, 1991a, 1996). Although many considered the Beach Beds to be contemporaneous with the apron reef, and of either B_2 or P_{1a} age (Sadler, 1964b; Parkinson, 1974b; Timms, 1978), the interdigitation of these beds with basinal strata of P_2 age in the Castleton Borehole (Stevenson and Gaunt, 1971) indicates that they are most probably a Brigantian facies that post-dates and onlaps the currently exposed beds of the reef complex (Gutteridge, 1991a). Further post-reef developments of basinal facies include the dark limestones and shales of P_1–P_2 age that occur in discontinuous outcrops marginal to the Beach Beds between Castleton and Treak Cliff (Figure 7.10).

Occupying hummocky ground close to the foot of Long Cliff, an isolated area of carbonated basalt and palagonitized hyaloclastite once regarded as a vent agglomerate (the so-called 'Speedwell Vent' of Arnold-Bemrose, 1907; and see Wilkinson in Neves and Downie, 1967) has also been considered as a subaqueous littoral cone, formed by the rapid chilling and brecciation of a lava tongue extension of the Cave Dale Lava as it flowed subaerially over the exposed top to the apron reef into shallow seas lapping against the fore-reef during a period of sea-level lowstand (Broadhurst and Simpson, 1973; Cheshire and Bell, 1977).

An angular unconformity separates the late Viséan (Asbian) apron reef from the overlying Namurian (Pendleian–Kinderscoutian) Edale Shales (Barnes and Holroyd, 1897; Jackson, 1925a, 1927). The latter comprise a succession of dark pyritic shales with marine bands containing pelagic goniatites and bivalves. Outcrops are confined to a few small exposures at the northern end of the site (north of Odin Fissure) and at the foot of Treak Cliff. Locally developed at the base of the formation and overlying a fissured palaeokarst surface in the underlying apron reef is a prominent boulder bed consisting of limestone blocks up to several metres in diameter set in a calcareous or shale matrix (Simpson and Broadhurst, 1969). The boulder bed is seen particularly well at Treak Cliff Cavern in association with fluorite ('blue john') deposits (Ford, 1969) and at Windy Knoll Quarry infilling deep palaeokarstic pits in limestones of the back-reef facies as 'Neptunean dykes' where they are associated with some rare hydrocarbon deposits (Ford, 1996). It also occurs near Odin Fissure and at Winnats Pass. Although the age of the boulder bed remains uncertain, it most probably formed during late Brigantian and early Namurian times following a period of subaerial weathering at the platform margin which eventually led to its collapse (Ford, 1987; Gutteridge, 1996).

Interpretation

The Castleton Reef-Belt forms a significant part of an extensive apron-reef complex that developed at the margin of the Derbyshire Platform during Asbian times (Figure 7.4a). Its location here appears to have been controlled by the Edale Fault, which defines the northern limit of an underlying basement 'tilt-block' (Lee, 1988a; Gutteridge, 1991a; and see Figure 7.2b). Although similar developments define the southern and western limits of the platform from Wirksworth to Parwich and Beresford Dale to Chrome Hill respectively (see **Wetton to Beresford Dale** GCR site report, this chapter), these are generally either less well exposed or less accessible.

Although various episodes of reef development have been recognized, the stratigraphy of the apron reef is complex and a clear understanding of its development has been hampered by uncertainties relating to the distribution of stratigraphically useful goniatites and the relationships between certain critical lithostratigraphical units. A lower B_2 (B_{2a}) and upper B_2 (B_{2b}) phase of reef development was recognized by Wolfenden (1958), but Parkinson (1947, 1965) and Timms (1978) also recognized the presence of reef limestones of P_{1a} age (Figure 7.13). Records of goniatites including *Bollandites castletonensis*, *B. umbilicatum*, *Bollandoceras micronotum*, *Beyrichoceras delicatum*, *B. rectangularum*, *B. vesiculiferum*, *Dimorphoceras gilbertsoni*, *Nomismoceras vittiger*, *Prolecanites discoides*, *Goniatites 'maximus'* (= *G. globostriatus*), *G.* cf. *hudsoni* (Bisat, 1934; Shirley and Horsfield, 1940; Parkinson, 1947, 1965; Ford, 1952, 1965; Brunton and Tilsley, 1991) confirm the B_2 age assigned to the apron reef by most authors (e.g. Stevenson and Gaunt, 1971), as well as its placement largely in the B_{2b} Subzone of Riley (1990b). However, although goniatites diagnostic of the B_{2a} Subzone appear to be absent from the reef complex, the occurrence of forms resembling *Goniatites crenistria* and *Beyrichoceratoides truncatum* from the northern slopes of Treak Cliff indicates that a P_{1a} phase of reef development is most probably also present (Parkinson, 1947, 1953).

The occurrence of P_{1a} reef limestones at Castleton was later supported by the unpublished work of Timms (1978) who recognized four reef phases (of 'lower B_2, upper B_2, high upper B_2 and P_{1a} age') developed during periods of sea-level highstand (transgressive episodes), each being separated by an erosional unconformity formed during a lowstand (regressive) episode when the shelf margin was exposed above sea level (Figure 7.13).

The unconformity between Asbian reef limestones and the Namurian Edale Shales marks a further but late Dinantian–early Namurian regressive episode which resulted in emergence, erosion and karstification of the platform margin, which led to the removal of earlier-deposited Brigantian strata from the shelf area and the deposition of the boulder bed down the apron-reef flanks (Ford, 1996; Gutteridge, 1996). A similar process is envisaged for the formation of the Beach Beds formed earlier in Brigantian times (Gutteridge, 1991a, 1996).

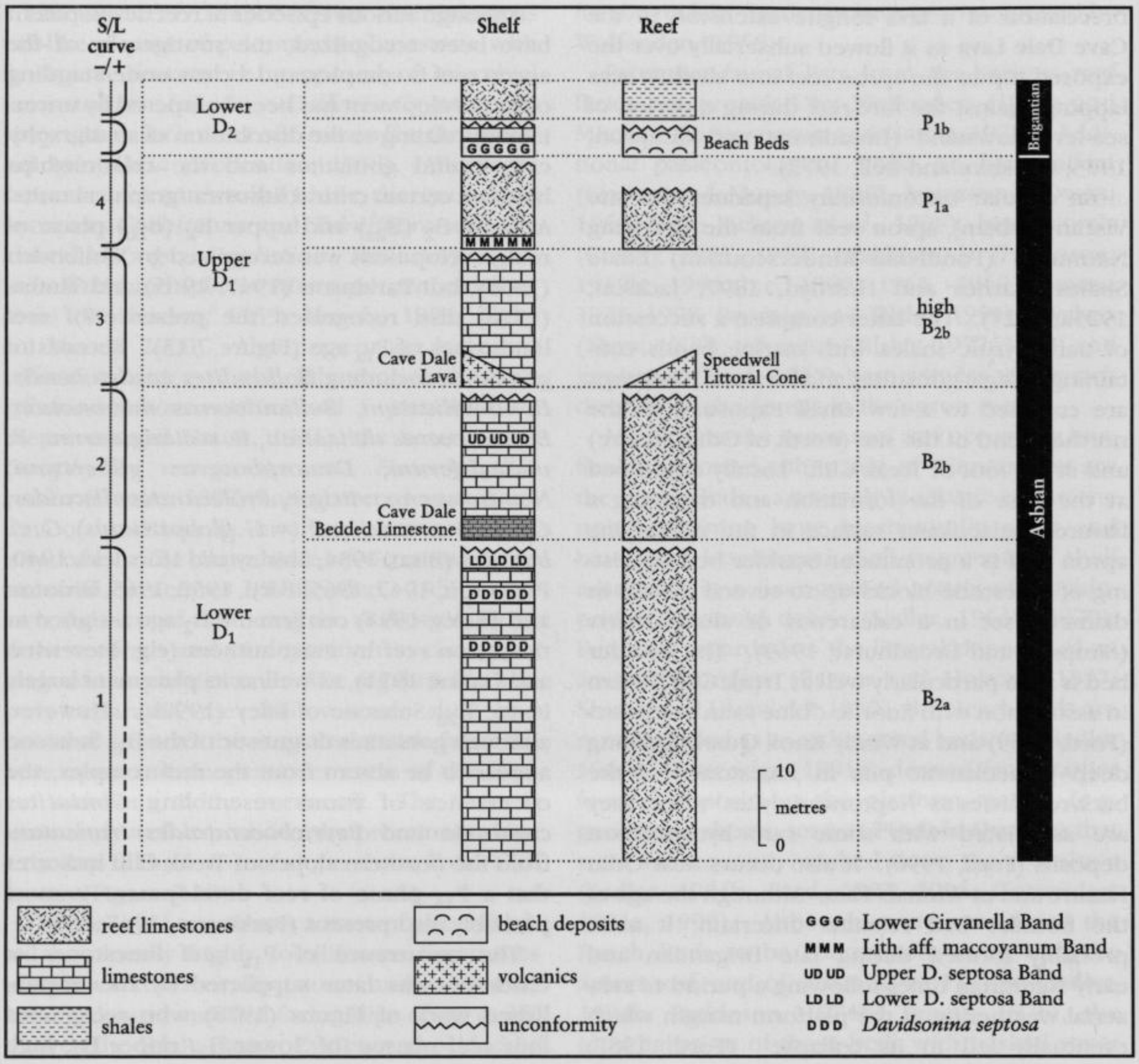


Figure 7.13 Interpretation of the stratigraphy at the Castleton GCR site showing the four principal transgressive–regressive cycles responsible for reef development. Whereas transgressive episodes influenced periods of reef growth as the platform margin was flooded, erosion took place during regressive episodes when parts of the reef complex became subaerially exposed. Although Timms (1978) regarded the Beach Beds as a P_{1a} erosional by-product of a high B_{2b} reef which is no longer preserved, their placement at a higher stratigraphical level here (P_{1b}) is based on evidence provided by Gutteridge (1991a, 1996); see text for further details. After Timms (1978).

Conclusions

This site offers visitors a spectacular insight into the nature and origin of arguably the finest and best preserved Lower Carboniferous apron reef in England. With its rich macrofossil assemblages and its diverse suite of sedimentary rocks, the site is vital in the reconstruction of ancient reef environments and in understanding the progressive evolution of the margin of the Derbyshire Platform during late Dinantian times. The site is particularly important for illustrating the relationship between strata of shelf, shelf-margin and basin facies and for establishing correlations between the coral–brachiopod zonal scheme of the shelf area and the goniatite–bivalve scheme of the basin. Considered together, these features combine to make this one of the most important educational sites in Britain.

PINDALE QUARRY, DERBYSHIRE (SK 159 823)

Introduction

The Pindale Quarry GCR site (SK 159 823) is a disused quarry 1 km to the east of Castleton (Figure 7.14a). The exposed section straddles the boundary between the Bee Low Limestones (Asbian) and the Monsal Dale Limestones (Brigantian). It provides an almost perpendicular section through the northern margin of the Derbyshire Platform. Its historical importance lies in the relationships displayed between shelf and shelf-margin limestones which provided critical evidence in reconciling the macrofaunal biostratigraphical schemes of basin and platform carbonate successions. The succession includes numerous erosional surfaces and macrofaunal bands in which solitary and colonial corals are common. An exceptional example of the geometry and internal structure of a large-scale sedimentary structure is also exposed. The succession was first described as part of a stratigraphical study of the Castleton area by Shirley and Horsfield (1940). Eden *et al.* (1964) and Stevenson and Gaunt (1971) determined the stratigraphical relationships between the limestones in shelf and slope settings by fine-scale mapping and correlation that was supported by a detailed biostratigraphical study. More recent work at the site includes the detailed sedimentological work by Gawthorpe and Gutteridge (1990) and the micropalaeontological investigations conducted by White (1992).

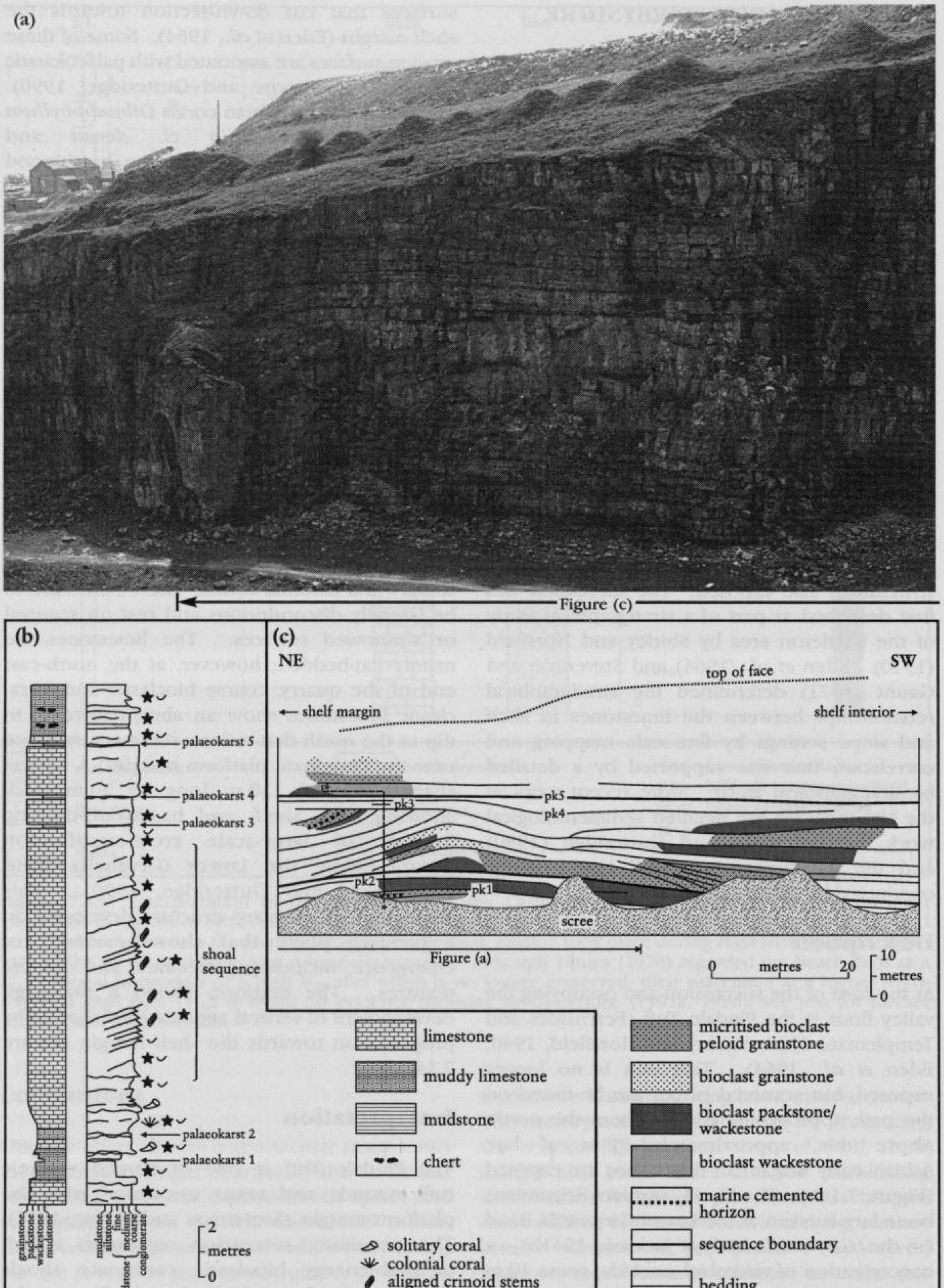
Description

At the base of the succession and occupying the valley floor is the Pindale Tuff (Fearnsides and Templeman, 1932; Shirley and Horsfield, 1940; Eden *et al.*, 1964). This unit is no longer exposed, but scattered pieces can be found on the path approaching the site from the north. Above this, approximately 22 m of late Asbian–early Brigantian limestones are exposed (Figure 7.14b). The D_1–D_2 (Asbian–Brigantian) boundary is taken at the Lower Girvanella Band (= the '*Girvanella*-bed' of Jackson, 1941b) – a concentration of microbial oncoids, some 10 m below the top of quarry face, which is truncated by one of a number of low-angle erosion surfaces that cut down-section towards the shelf margin (Eden *et al.*, 1964). Some of these erosion surfaces are associated with palaeokarstic features (Gawthorpe and Gutteridge, 1990). The characteristic Asbian corals *Dibunophyllum bourtonenese*, *Caninia* cf. *densa* and *Palaeosmilia murchisoni* and the brachiopod *Davidsonina septosa* have been found in limestones below the Lower Girvanella Band. Typical Brigantian fossils including *Dibunophyllum bipartitum* and *Diphyphyllum* cf. *lateseptatum* occur immediately below the Upper Girvanella Band (Eden *et al.*, 1964). Comprehensive lists of the fossils recorded from this section are provided by Eden *et al.* (1964) and Stevenson and Gaunt (1971).

The succession consists mainly of grainstone and packstone with subordinate wackestone; the limestones are dominated by highly abraded and disarticulated bioclasts, comprising mainly crinoids and brachiopods. Several macrofaunal beds occur containing rolled and abraded brachiopods, microbial oncoids, solitary and colonial corals. These beds tend to be laterally discontinuous and rest on scoured or winnowed surfaces. The limestones are mainly flat-bedded; however, at the north-east end of the quarry, coarse bioclastic and intraclastic limestones show an abrupt increase in dip to the north that reflects sedimentary drape over the carbonate platform margin. A wedge-shaped interval 130 m long by 20 m thick showing both shelf- and basinward-dipping foresets of large-scale cross-stratification occurs below the Lower Girvanella Band (Gawthorpe and Gutteridge, 1990). This large-scale sedimentary structure developed on a bedding plane that shows evidence of emergence, including palaeokarst and calcrete textures. The bedform shows a two-stage development of vertical aggradation followed by progradation towards the shelf margin (Figure 7.14c).

Interpretation

The Pindale Tuff is one of several volcanic tuff mounds and vents associated with the platform margin (Stevenson and Gaunt, 1971). The remaining succession represents a belt of high-energy bioclastic carbonate shoals deposited in the turbulent conditions at the shelf margin. Shallow-water conditions were


(a)
Figure (c)
(b)
palaeokarst 5
palaeokarst 4
palaeokarst 3
shoal sequence
palaeokarst 2
palaeokarst 1
2
metres
0
(c)
NE
SW
top of face
shelf margin
shelf interior
pk5
pk4
pk3
pk2
pk1
scree
Figure (a)
0 metres 20
10
metres
0
limestone
muddy limestone
mudstone
chert
solitary coral
colonial coral
aligned crinoid stems
crinoid remains
shell fragments
micritised bioclast peloid grainstone
bioclast grainstone
bioclast packstone/ wackestone
bioclast wackestone
marine cemented horizon
sequence boundary
bedding
pk1–5 palaeokarst surfaces

punctuated by periods of subaerial exposure during sea-level lowstands. A large-scale sedimentary bedform developed as the shelf margin was flooded. Initially this feature developed by vertical accretion but subsequently it prograded laterally until it spilled over the shelf margin. The macrofaunal developments and beds with microbial oncoids appear to rest on scoured or winnowed surfaces in the troughs of these large-scale bedforms. This suggests that not all of the macrofaunal bands and erosion surfaces are of regional stratigraphical significance as previously suggested by Shirley and Horsfield (1940), Eden *et al.* (1964) and Stevenson and Gaunt (1971); the majority may only be of local sedimentological significance.

Conclusions

The succession at Pindale Quarry demonstrates the nature of the northern margin of the Derbyshire carbonate platform during late Asbian to early Brigantian times. In contrast with the Asbian margin seen in Cave Dale and around Winnats Pass (see **Castleton** GCR site report, this chapter), the shelf margin at this site was characterized by the development of a bioclastic carbonate shoal complex deposited in high-energy conditions close to the platform edge. Carbonate sediment was largely transported off shelf and a drape over the shelf break can be seen at the north-eastern end of the quarry.

◄**Figure 7.14** (a) General view of the large-scale carbonate sand-body (lower centre) in the Bee Low Limestones (Asbian) at the Pindale Quarry GCR site, near Castleton. The dip of the overlying thinly bedded Monsal Dale Limestones (Brigantian) at the top of the face increases to the north-east (left) as they drape the platform margin. The height of the face is approximately 25 m. (Photo: P.J. Cossey.) (b) Sedimentary log of the Pindale succession. The shoal sequence refers to the large-scale carbonate sand-body illustrated in (a). The Asbian–Brigantian boundary is taken at the second palaeokarstic surface overlying the carbonate sand-body (see Eden *et al.*, 1964). (c) Detailed sketch section of the lower part of Pindale illustrating the geometry of beds and limestone microfacies associated with the large-scale bedform in the Bee Low Limestones (Asbian). Note that blank areas of the section are those from which no microfacies data are currently available. The dashed line between asterisks marks the line of the logged section illustrated in (b). After Gawthorpe and Gutteridge (1990).

RICKLOW QUARRY AND MONYASH QUARRY, DERBYSHIRE (SK 165 662 and SK 149 677)

Introduction

The disused Ricklow Quarry is situated 1.5 km ESE of the village of Monyash, where Ricklow Dale joins Lathkill Dale (SK 165 662). The site also includes exposures on either side of Ricklow Dale, to the north of the quarry, and on the northern side of Lathkill Dale (SK 169 660). Monyash Quarry (also disused and sometimes known as 'Bricks Quarry') lies to the east side of the Monyash to Taddington road 1.2 km north of Monyash (SK 149 677). Together, these sites offer the best exposures of late Brigantian facies in the interior of the Derbyshire Platform, including two developments of carbonate mud-mound facies, coarse crinoidal limestones and dark-coloured bedded limestones. The sites are described by Adams (1980) and Gutteridge (1983, 1990a, 1991b, 1995).

Description

Ricklow Quarry

The strata exposed at this site include the top of the Monsal Dale Limestones and the lower part of the Eyam Limestones as re-defined by Gutteridge (1991b). Adams (1980) described the succession at Ricklow Quarry and in the surrounding dale sides in terms of three main facies: a buildup-core facies, a flank facies and a basin-fill facies. The buildup-core and flank facies together form the 'reef facies' of previous workers and are shown on [British] Geological Survey maps of the area (Institute of Geological Sciences, 1977b, 1978). Subdivisions of these facies are possible and have been mapped in detail by Gutteridge (1983).

The buildup-core facies consists of lenticular bodies of massive, pale-coloured, fine-grained limestone. These are now described as mud-mounds (e.g. Gutteridge, 1995). Although carbonate mud is the dominant component, there are abundant spar-filled cavities and a distinctive fauna similar to that described from other late Dinantian carbonate mud buildups, such as those at Wirksworth (Timms, 1978; and see **National Stone Centre** GCR site report, this chapter) and in the Craven Reef-Belt (Mundy, 1980a; see Chapter 5). Brachiopods are the dominant element of the macrofauna and occur in 'pockets' up to 0.5 m across and 0.3 m high (Gutteridge, 1983, 1990a). Large brachiopods such as dictyoclostoids and echinoconchoids are preserved in life position at the base of pockets and are succeeded by smaller types such as *Avonia*, *Aliteria* and the most common species throughout the buildups, *Balanoconcha 'Girtyella' saccula* (Gutteridge, 1983, 1990a). Other important elements of the fauna are fenestrate bryozoans and fragmented crinoids. The significance of the macrofauna has been discussed by Gutteridge (1990a). The buildup-core facies is best seen in the crags on the east side of Ricklow Dale immediately north of the quarry and in the crags on the north side of Lathkill Dale (SK 1685 6600) (Figure 7.15).

The flank beds consist of coarsely crinoidal limestones banked up against the buildup-core facies and show depositional dips away from the core. The inter-buildup flank facies shows evidence of subaerial exposure in the form of a discontinuous laminar calcrete at its contact with the succeeding basin-fill facies, and the presence of rhizocretions and alveolar texture in its top 0.3 m (Adams, 1980). The buildup-core also shows cement and other textures indicative of subaerial exposure and vadose meteoric diagenesis (Gutteridge, 1983).

The basin-fill facies post-dating the buildup facies consists of dark-coloured, sometimes cherty, well-bedded wackestones and packstones. Initially, in the depressions between the buildup-core facies, there are wackestones with an impoverished fauna of molluscs and calcareous algae and some fenestral fabrics. These give way to more laterally extensive bioclastic wackestones and packstones with a diverse fauna including *Gigantoproductus*.

Monyash Quarry

Monyash Quarry provides exposures entirely in the Eyam Limestones as defined by Gutteridge (1991b). A succession about 22 m thick is exposed on two levels with a break between. The lower part of the quarry shows bedded dark-coloured limestones consisting of a lower molluscan wackestone facies and an upper gigantoproductid packstone. These are thought to correlate with the basin-fill facies at Ricklow Quarry (Gutteridge, 1983). After a poorly exposed interval, the upper part of the quarry shows a transition from dark-coloured

Figure 7.15 Development of late Dinantian (Brigantian) carbonate mud-mound at the top of the Monsal Dale Limestones in upper Lathkill Dale (Ricklow Quarry GCR site). The mud-mound forms a prominent crag (*c.* 8 m high) at the top of the valley side where the lateral transition from the mainly unbedded buildup-core facies (right) into flank facies (left) can be clearly seen. (Photo: P. Gutteridge.)

packstones to pale-coloured cross-stratified crinoidal grainstones. Gutteridge (1989b) recorded damage to gigantoproductid brachiopods from this locality, which he attributed to shark predation. A tabular and lens-shaped carbonate mud-mound up to 1.5 m thick occurs within the crinoidal limestones. Details of the succession at this site are summarized in Figure 7.16.

Interpretation

The succession at Ricklow Quarry was originally regarded as belonging entirely to the Eyam Limestones (e.g. Aitkenhead *et al.*, 1985). However, the recognition of a stratigraphical break between the buildup facies and the basin-fill facies (Adams, 1980; Gutteridge, 1983), which can be traced down to the top of the Monsal Dale Limestones, led Gutteridge (1991b) to propose that the buildup facies more properly belong to the Monsal Dale Limestones. The origin and development of Brigantian mud-mounds on the Derbyshire Platform has been discussed by Gutteridge (1995). The mud-mound at Ricklow falls into the category of Gutteridge's 'Group 1 mounds' occurring at the contact between the Monsal Dale Limestones and Eyam Limestones. It developed in shallow water in the interior of the platform and largely grew by lateral accretion. The tabular mound at Monyash Quarry represents one of Gutteridge's 'Group 2 mounds' and this developed wholly within the Eyam Limestones on the shallow part of an intra-platform ramp (Gutteridge, 1995).

Carbonate mud was produced *in situ* probably by microbial processes as with other Dinantian mud-dominated buildups. Crinoids colonized the surfaces of the buildups and accumulated as a flank facies banked up against the buildup cores. In the case of the mud-mound at Ricklow, soon after deposition a relative drop in sea level led to subaerial exposure and meteoric diagenesis. This resulted in the calcretization of flank deposits and the precipitation of a complex series of cements (Gutteridge, 1983). This shallowing event can be recognized elsewhere in Derbyshire at the Monsal Dale Limestones–Eyam Limestones boundary (Gutteridge, 1991b).

As sea level rose again, firstly a restricted tidal-flat and lagoonal facies was deposited around the still-exposed tops to the buildups. When they were finally submerged, subtidal limestones containing *Gigantoproductus* spread across the area.

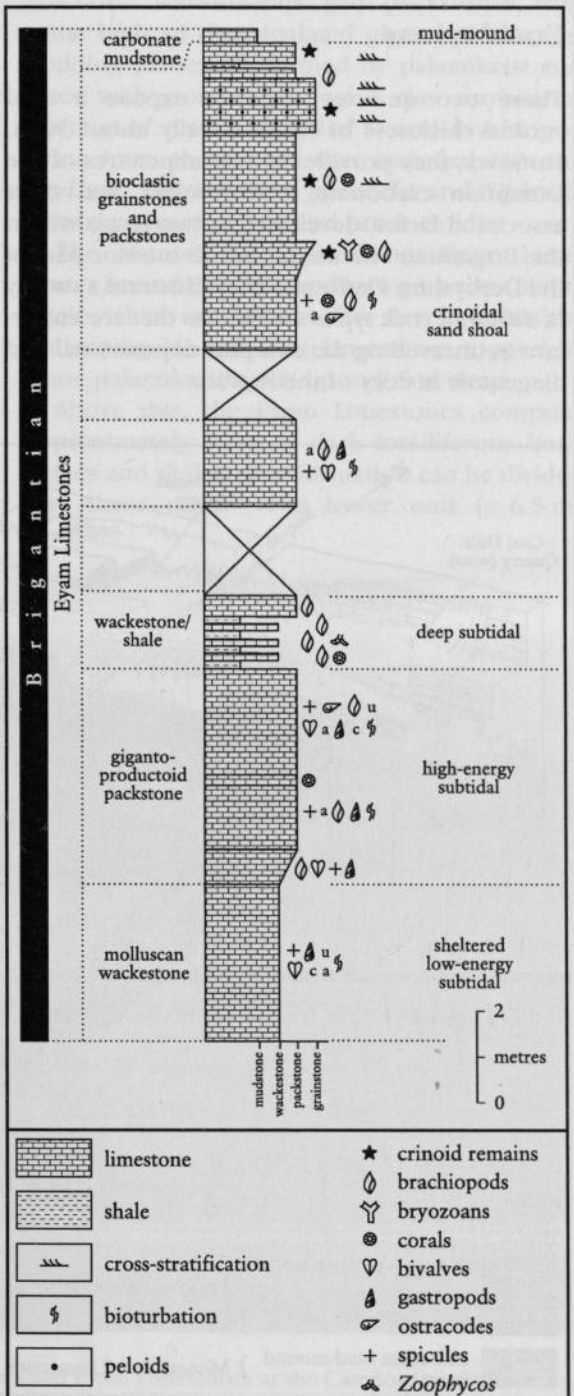


Figure 7.16▸ Sedimentary log of the Eyam Limestones succession exposed at Monyash (Bricks) Quarry. After Gutteridge (1983).

Bioclastic, mainly crinoidal, sand shoals subsequently became established in the area, marking a change to higher energy conditions at the head of a shallow intra-platform ramp. At Monyash, small tabular mud-mounds developed in this facies.

Conclusions

These two quarries together expose a total vertical thickness of strata of only about 30 m. However, they provide the best exposures of late Dinantian carbonate mud-mounds and their associated facies, developed at two levels within the Brigantian succession in the interior part of the Derbyshire Platform. They illustrate a variety of different rock types and faunas that are important in unravelling the complex depositional and diagenetic history of the region.

NATIONAL STONE CENTRE, DERBYSHIRE (SK 288 553)

Introduction

The complex of disused quarries at the National Stone Centre (SK 288 553), north of Wirksworth (Figure 7.17) provides a spectacular three-dimensional view of the stratigraphical evolution and sedimentology of limestones deposited at the edge of the Derbyshire Platform during Brigantian times. The exposed succession, which includes parts of both the Monsal Dale Limestones and the Eyam Limestones, also reveals important sections through some late Brigantian carbonate mud-mounds. The locality, also known as the 'Steeplehouse Quarries Complex' (the original GCR site name) or the 'Coal Hills Quarry Complex' (Walkden, 1982), has

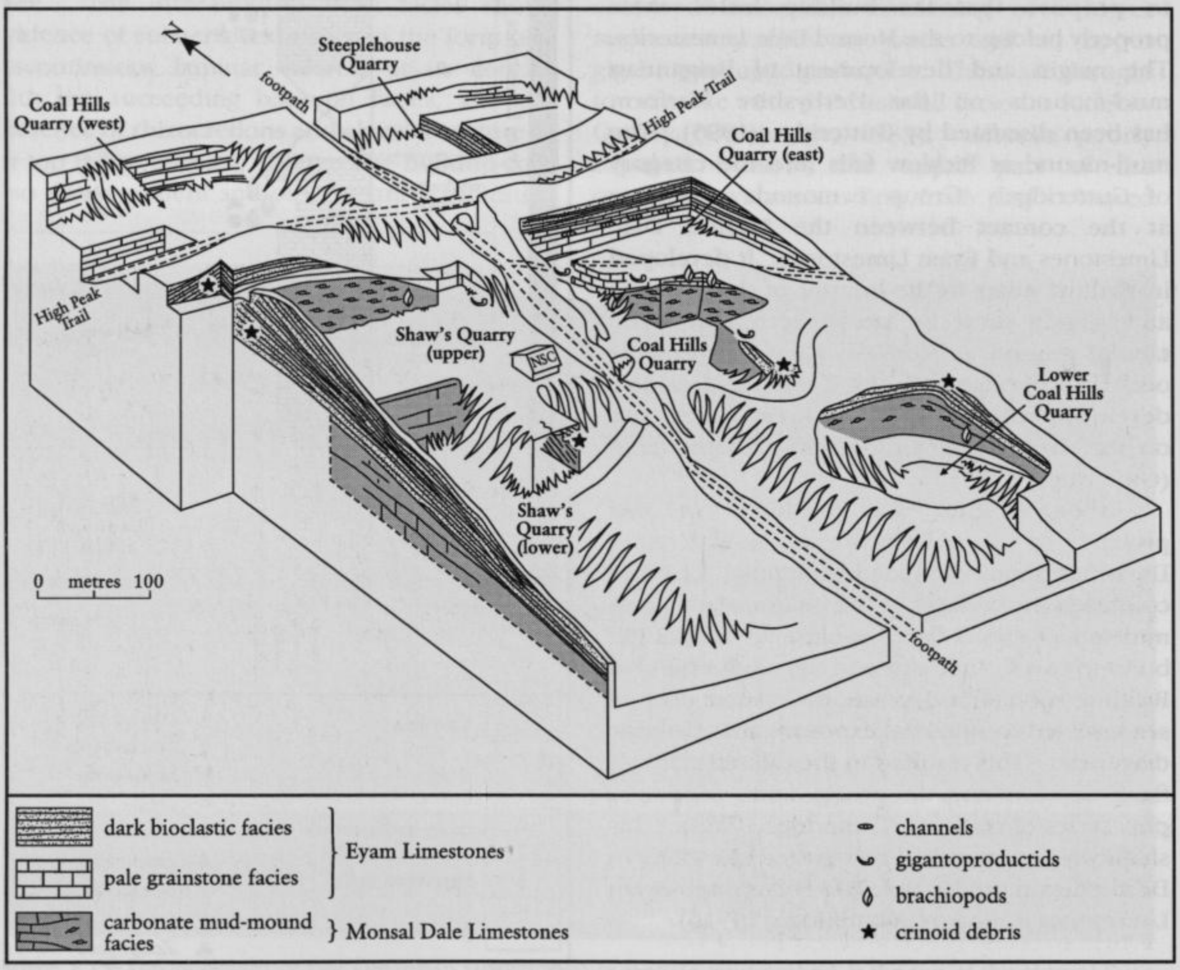


Figure 7.17 Block diagram illustrating the relative distribution of quarries at the National Stone Centre, Wirksworth. Note that in this figure an element of an east–west shortening is illustrated in the vicinity of the footbridge. NSC indicates the approximate position of the National Stone Centre building. After Walkden (1982).

been an important focus of geological research for many years. Significant early accounts of the site stratigraphy were provided by Shirley (1959) and Smith *et al.* (1967). Later sedimentological and palaeontological work by Walkden (1970, 1982), Timms (1978), Weaver and Jeffcoat (1978), Gutteridge (1983, 1989a, 1995) and Oakman (1984) focused attention primarily on the character of the carbonate mud-mounds and their relationship to surrounding strata. Fossilized shark remains recorded by Ford (1964) from the Eyam Limestones at a part of this site (Steeplehouse Quarry, SK 2875 5535) are re-evaluated in an earlier GCR volume, *Fossil Fishes of Great Britain* (Dineley and Metcalf, 1999).

Description

Approximately 27 m of the topmost beds of the Monsal Dale Limestones (= Matlock Limestones of Frost and Smart, 1979) occur at this site. These are best exposed in Lower Coal Hills Quarry (SK 2880 5505), Shaw's Quarry (SK 286 552) and Coal Hills Quarry (SK 2875 5515) (Figure 7.17). These consist mainly of crinoidal grainstone and packstone with some evidence of cross-stratification. They are overlain by an undulatory erosion surface that appears to cut down-section to the south. At least two carbonate mud-mounds are developed at the top of the formation (Figure 7.18). The mud-mounds comprise largely unbedded accumulations of fine-grained carbonate mud with irregular depositional cavities lined by marine cement and pocket-like accumulations of a mixture of in-situ and reworked brachiopods and bivalves (Gutteridge, 1983, 1995). The flanks of the mud-mounds comprise thick beds of coarse crinoidal grainstone that dip away from the mud-mound cores. The mud-mounds contain a diverse brachiopod fauna including *Antiquatonia*, *Buxtonia*, *Eomarginifera*, *Schizophoria* and *Spirifer* together with bivalves, fenestrate bryozoans crinoids, goniatites and nautiloids. A list of the macrofauna from the mud-mound facies is given by Timms (1978).

The carbonate mud-mounds contain brown vadose calcite cements that form an asymmetrical lining of depositional cavities, as well as speleothem-like deposits in fissures that are locally overlain by crinoidal material. An impersistent calcrete is also present at the top of the mud-mounds (Gutteridge, 1983). In the south-east corner of Coal Hills Quarry, a large cave-like cavity in the mud-mound facies is lined

Figure 7.18 Carbonate mud-mound at Coal Hills Quarry (National Stone Centre) at the top of the Monsal Dale Limestones. Note that the massive mud-mound core facies (middle), seen here draped by bedded crinoidal grainstones of the Eyam Limestones (left), is now largely quarried away. (Photo: P.J. Cossey.)

by brown calcite flowstone. The flowstone is cut by stylolites and contains traces of fluorite and hydrocarbon residue. Some light-brownish clay is also present in the cave. The boundary between the Monsal Dale Limestones and the Eyam Limestones is located at the top of the mud-mounds and represents an exposure surface (Gutteridge, 1989a).

Above this, the lowest beds of the Eyam Limestones (*c.* 23 m thick) drape the topography of the mud-mounds in the underlying Monsal Dale Limestones. The Eyam Limestones (= Cawdor Limestone of Frost and Smart, 1979) comprise a bioclastic grainstone–packstone facies dominated by crinoid debris, gigantoproductids and reworked corals; the limestones become increasingly cherty towards the top of the succession. Some beds with layers of intraclasts and very coarse, well-rounded bioclasts are also present. Evidence of large-scale cross-stratification is visible in the face of Coal Hills East Quarry (SK 2875 5525), Shaw's Quarry, and in a small quarry (SK 2855 5520) north of Shaw's Quarry. The crinoidal limestones appear to thin and become darker towards the south. Intervals of dark, thinly bedded biomicritic limestone with abundant whole but disarticulated *Gigantoproductus* valves preserved in a convex-down position, are also present. Taxa recorded from these beds are detailed by Smith *et al.* (1967).

The quarries to the north of the High Peak Trail at Coal Hills West Quarry (SK 2850 5530) and Steeplehouse Quarry expose an 11 m sequence comprising bioclastic grainstones with reworked brachiopods and crinoids, well-sorted thickly bedded crinoidal grainstone, some beds of whole gigantoproductids, and scattered developments of nodular and tabular chert.

A notable bed at Steeplehouse Quarry contains scattered fish debris, including the dermal denticles of the primitive shark *Petrodus* (Ford, 1964; Dineley and Metcalf, 1999). This bed lies at least 10 m above the top of the mud-mound in Coal Hills East Quarry but to the west it lies within 3 m of the top of the Shaws Quarry mud-mound core.

Interpretation

Both the Monsal Dale Limestones and the Eyam Limestones are Brigantian age. The Monsal Dale Limestones were deposited in a high-energy, subtidal setting mainly above normal wave-base. Scattered carbonate mud-mounds were present in this setting. These mud-mounds are thought to have originated by the production of carbonate mud within an algal-bacterial mat that bound the surface of the mud-mound structures (Gutteridge, 1983, 1995). The Eyam Limestones rest with a stratigraphical break on the Monsal Dale Limestones – a stratigraphical break that probably also relates to the development of lowstand wedge deposits (the Pendleside Sandstones Member) in the Craven Basin (see **Pendle Hill** GCR site report, Chapter 6). The presence of mineralization and other features that formed during post-Dinantian burial (Gutteridge, 1983) show that both the flowstone and the cave are Dinantian age. The precipitation of vadose cements in cavities and fissures, calcrete development and cave formation all indicate a period of subaerial exposure at the Monsal Dale Limestones–Eyam Limestones boundary. This boundary may represent a period when the whole of the Derbyshire carbonate platform was emergent (Gutteridge, 1989a). Crinoidal material within fissures in the core facies of carbonate mud-mounds was deposited during the initial transgression of the Eyam Limestones. The brown clay in the cave is interpreted as a later, probably Pleistocene, infill. The Eyam Limestones were deposited as a high-energy bioclastic carbonate sand-body with some large-scale sedimentary bedforms and channels. The general facies relationships, thickness changes and palaeocurrents in the Eyam Limestones suggest that the main transport direction of carbonate sediment was off shelf to the south.

Conclusions

These quarries expose a complex of crinoidal grainstone carbonate sand-bodies with large-scale sedimentary structures and scattered carbonate mud-mounds that formed the upper part of the southern margin of the Derbyshire Platform during Brigantian times. A wide variety of rarely preserved features, including ancient cave deposits and speleothem cements formed during a late Dinantian period of subaerial exposure, are also present. Together with other disused quarries in the Wirksworth area (e.g. **Baileycroft Quarry** and **Dale Quarry**), the National Stone Centre offers one of the finest three-dimensional views of the facies relationships and stratigraphical evolution of a late Dinantian platform margin in England.

CAWDOR QUARRY, DERBYSHIRE (SK 286 606)

Introduction

The Cawdor Quarry GCR site is a disused quarry (SK 286 606) extending for over 1 km due west of the station at Matlock Bridge. It exposes the upper part of the Monsal Dale (Matlock) Limestones and the lower part of the overlying Eyam (Cawdor) Limestones (for which it is the type locality as defined by Shirley, 1959). Cawdor Quarry was a key locality in determining the Brigantian lithostratigraphy and biostratigraphy of the southern part of the Dinantian outcrop in Derbyshire. The Eyam Limestones are particularly well known for their diverse conodont (Higgins, 1975), ostracode (Robinson, 1959) and zaphrentid coral (Hudson, 1943) faunas. The most comprehensive accounts of the geology at this site are by Shirley (1959) and Smith *et al.* (1967).

Description

Most of the main face (Figure 7.19) is made up of the topmost 21.3 m of the Monsal Dale Limestones (Cox and Harrison, 1980). These comprise uniform, massively bedded, grey bioclastic wackestones and packstones with some beds of disarticulated gigantoproductids. Bedding planes are formed by palaeokarst surfaces with poorly developed clay wayboards. Smith *et al.* (1967) recorded a coral–brachiopod fauna from these beds that included *Dibunophyllum*, *Lithostrotion portlocki* and *Siphonodendron pauciradiale* and productoids.

The Monsal Dale Limestones–Eyam Limestones boundary is marked by a grey clay (30 cm thick), which overlies a surface developed on the underlying Monsal Dale Limestones topped by some palaeokarstic pits up to 0.5 m deep.

Above this, the Eyam Limestones comprise approximately 23 m of dark fossiliferous limestones and shales. The formation can be divided into three units. The lower unit (*c.* 6.5 m)

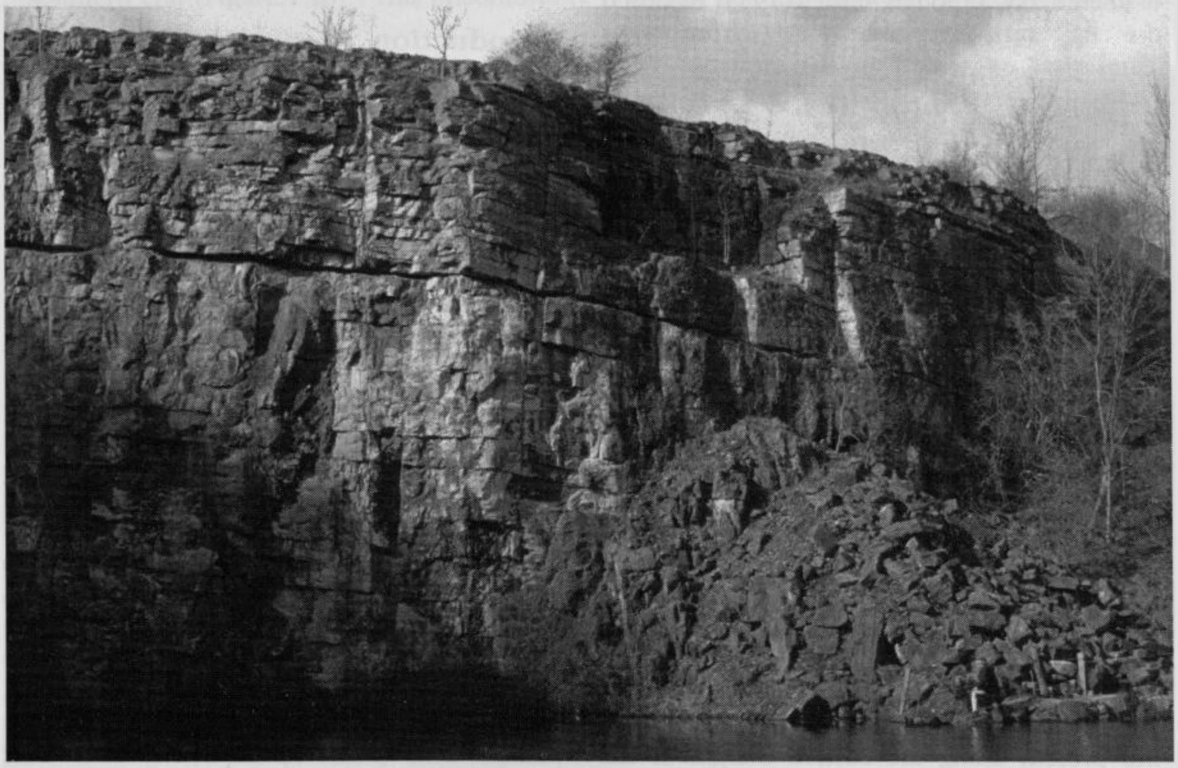


Figure 7.19 General view of the Monsal Dale Limestones and Eyam Limestones at the Cawdor Quarry GCR site, Matlock. The Monsal Dale Limestones comprise pale, thickly bedded limestones that form the lower two-thirds of the face. The top of the formation is marked by a palaeokarstic surface overlain disconformably by thinly bedded and darker units of the Eyam Limestones. The height of the face is approximately 15 m. (Photo: P. Gutteridge.)

consists of thinly bedded dark cherty biomicrites with minor shale partings and a relatively sparse fauna. It is capped by an angular discordance that represents an intra-Brigantian unconformity. This in turn is overlain by a middle unit (*c.* 7.5 m) composed mainly of shales with minor developments of limestone in its middle and top sections. This unit has proved to be particularly fossiliferous, yielding ostracodes in abundance (Robinson, 1959) and rich zaphrentid coral assemblages (Hudson, 1943; Smith *et al.*, 1967), together with trilobites (*Paladin*), brachiopods (including *Lingula*, *Orbiculoidea* and *Productus concinnus*), gastropods and scattered bivalves. The upper unit (*c.* 9 m) comprises dark fossiliferous shales with a prominent muddy limestone bed (1 m) near its top. Trilobite–brachiopod assemblages recorded from this unit resemble those of the underlying middle unit; however, the upper unit does contain some distinctive P_2 bivalve–goniatite taxa including *Posidonia membranacea*, *Sudeticeras stolbergi* (P_{2b}) and *Lyrogoniatites* aff. *georgiensis* (P_{2c}) (Smith *et al.*, 1967; Riley, 1993).

Regrettably, although Shirley (1959) recorded the P_{2a} subzonal indicator *Lusitanoceras* '*Goniatites*' *granosus* from this sequence, there remains uncertainty as to whether this record was from beds below or above the unconformity. However, it is assumed to have originated from either the lower or middle unit of the Eyam Limestones as described in this account (see Smith *et al.*, 1967).

Interpretation

The Monsal Dale Limestones were deposited on a shallow carbonate shelf prone to occasional periods of emergence. The palaeokarst that defines the Monsal Dale Limestones–Eyam Limestones boundary most probably developed during a period of exposure when the whole of the Derbyshire Platform became emergent (Gutteridge, 1989a). This was followed by the establishment of a sheltered, low-energy depositional setting in which the Eyam Limestones accumulated. The intra-Brigantian unconformity is one of several local unconformities present along the eastern margin of the Derbyshire Platform that may have formed during an episode of intra-Brigantian inversion (Gutteridge, 1989a). The progressive upward change to a shale-dominated succession reflects the progressive shut-down of carbonate production on the platform. Fossils indicate a Brigantian and late Brigantian age for the Monsal Dale Limestones and Eyam Limestones respectively.

Conclusions

Cawdor Quarry demonstrates the sedimentological and faunal evolution of the south-eastern part of the Derbyshire Platform during Brigantian times. The Monsal Dale Limestones were formed on a shallow carbonate shelf subject to periods of subaerial exposure, while the Eyam Limestones, represented by the 'dark facies' (traditionally regarded as 'quasi-basinal' deposits and formed at an uncertain water depth) most probably developed on the margins of an intra-platform basin or sheltered shelf setting (Walkden, 1970; Gutteridge, 1987, 1989a).

BAILEYCROFT QUARRY, DERBYSHIRE (SK 286 542)

Introduction

The Baileycroft Quarry GCR site (SK 2865 5420) is a disused quarry either side of the B5036 a few hundred metres north of Wirksworth town centre. The main part of the quarry is behind a petrol station to the west of the road; part of the quarry is on the opposite side of the road and is now used as a salt stockpile (SK 2875 5415). These exposures provide a dramatic demonstration of the stratigraphical relationships between the Bee Low Limestones–Monsal Dale Limestones (Asbian–Brigantian) deposited on a shallow-water carbonate shelf, and the unconformably overlying slope and re-sedimented beds of the Eyam Limestones (Brigantian). The unconformity developed on the Bee Low (Hoptonwood) Limestones and Monsal Dale (Matlock) Limestones was first identified by Shirley (1959) who considered it to be a product of an erosional episode prior to the deposition of the Eyam (Cawdor) Limestones; an episode which, by implication, was responsible for the removal of the entire Monsal Dale (Matlock) Limestones from the south-east end of the quarry. This view was supported by the stratigraphical and sedimentological investigations of Smith *et al.* (1967), Walkden (1970) and Frost and Smart (1979).

Description

At this site, approximately 11 m of Bee Low Limestones are exposed, comprising thickly bedded grainstones and packstones with a few discontinuous layers and lenses of disarticulated brachiopods. A typical Asbian fauna is present, including *Axophyllum* '*Carcinophyllum*' *vaughani*, *Dibunophyllum bourtonenese*, *Palaeosimilia murchisoni* and *Davidsonina septosa* (Frost and Smart, 1979). The prominent bedding planes are overlain by clay wayboards and represent palaeokarstic surfaces. The top of the Asbian Stage is marked by an irregular karstic surface with a prominent shale. Overlying this are a few metres of the Brigantian succession (Monsal Dale Limestones) comprising dark wackestone passing upwards into massive, well-sorted, crinoidal packstone–grainstone. Above this is an unconformity that progressively cuts down through the Monsal Dale Limestones into the Bee Low Limestones as the unconformity surface is traced from the top of the quarry face at its northern end to the base of the face at its southern end (Figure 7.20). This unconformity is irregular and, in the main part of the quarry to the west of the road, it is overlain by dark, thinly bedded limestones with argillaceous partings; the bedding in these limestones is highly irregular with abrupt thickness changes. These beds have been dated palaeontologically as P_2 (Smith *et al.*, 1967) and are thus of late Brigantian (Eyam Limestones) age.

Some 10 m of section is exposed in the salt stockpile area, and at the south end of this face a prominent, highly undulatory discontinuity is present, overlain by thinly bedded dark limestones that drape the disconformity surface (Figure 7.21). Shirley (1959), Walkden (1970) and Frost and Smart (1979) suggested that this is a continuation of the unconformity seen in the main part of Baileycroft Quarry, although the possibility that this surface represents a slumped contact within the Brigantian succession cannot be completed dismissed. This disconformity is developed on pale, thickly bedded limestones in which macofossils, including reworked solitary corals and gigantoproductid brachiopods, are common. These pale limestones comprise thickly bedded, graded, bioclastic grainstones

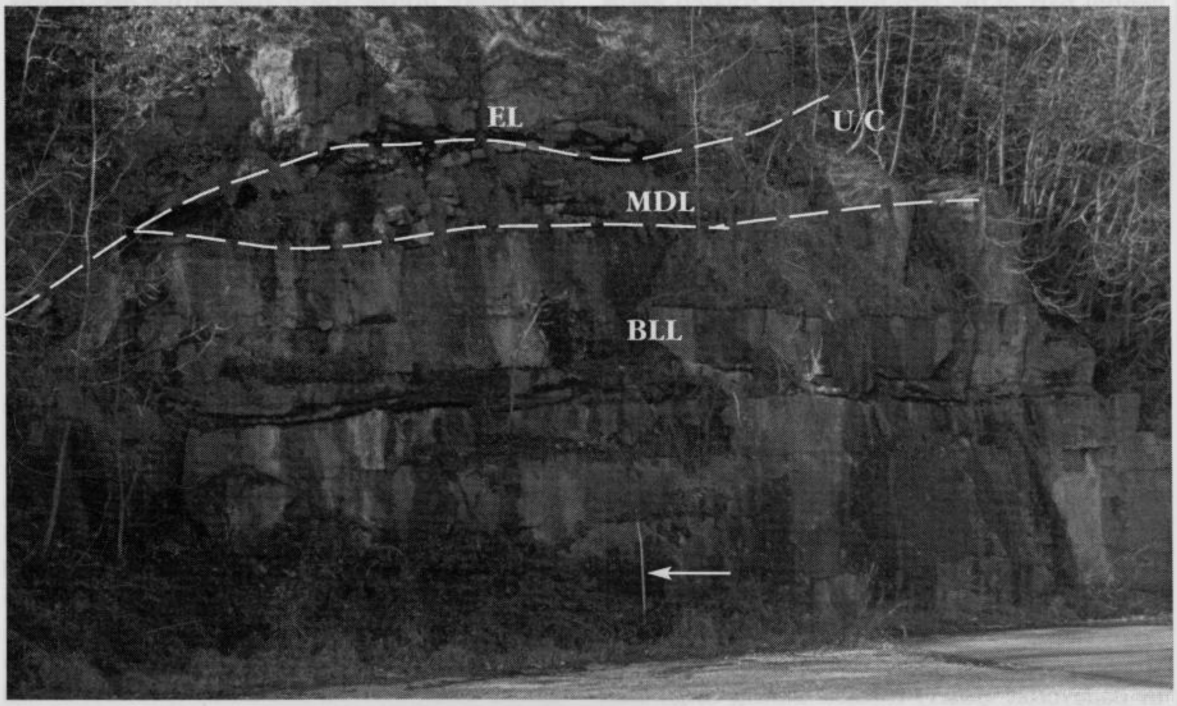


Figure 7.20 The intra-Brigantian angular unconformity at Baileycroft Quarry showing irregular bedded Eyam Limestones (EL) above the unconformity surface (U/C) cutting down into the thinner, darker beds of the Monsal Dale Limestones (MDL) and the underlying thicker, paler beds of the Bee Low Limestones (BLL). The tape measure (see arrow, bottom centre) is 1.3 m long. (Photo: P. Gutteridge.)

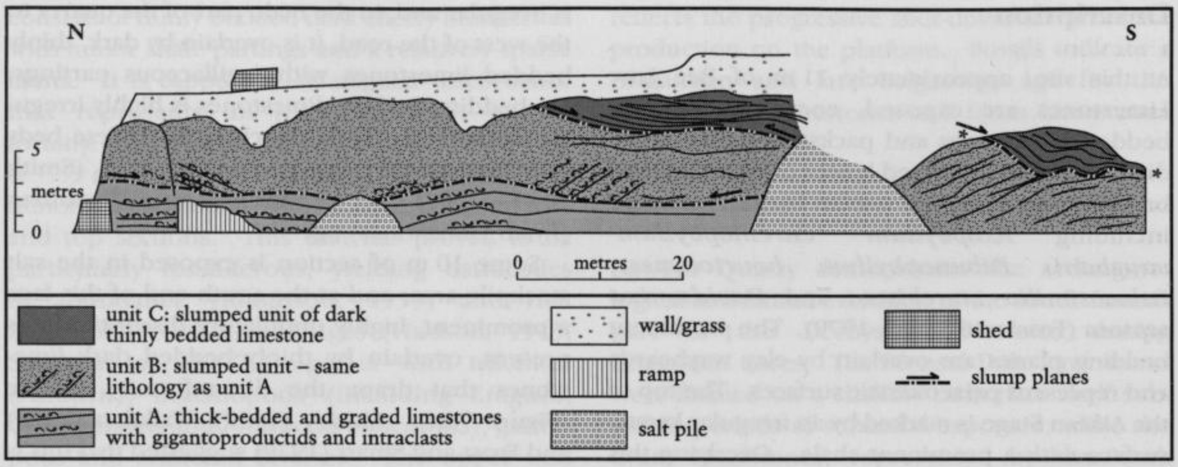


Figure 7.21 Sketch section of the slumped and re-sedimented Brigantian beds in the salt stockpile area at Baileycroft Quarry. Half-arrows indicate slump planes (probable movement is into the plane of the section). The asterisked slump plane marks the contact previously interpreted as the sub-Brigantian (P_2–D_1) unconformity (see text for further details).

with highly scoured undulatory bases. Some beds contain highly abraded solitary corals, gigantoproductid brachiopods and rounded granule- to cobble-sized intraclasts. The bedding in this unit is chaotic; some beds in the central part of the face have been rotated up to 45° to the horizontal (Figure 7.21). Thinly bedded dark argillaceous limestones form the top of the section. These show highly contorted beds that drape the discontinuity at the southern end of the exposure.

Interpretation

The Bee Low Limestones were deposited on a flat-topped carbonate shelf in a few tens of metres water depth. Occasional sea-level lowstands resulted in the accumulation of volcanic-derived soils on palaeokarstic surfaces over the emergent carbonate platform during this period. The shelf carbonates were deposited within a few hundred metres of the Asbian shelf margin, located beneath Wirksworth at this time. This was followed by an episode of exposure and karstification at the Asbian–Brigantian boundary with carbonate sedimentation resuming in a shelf-top environment. The unconformity seen in Baileycroft Quarry formed during Brigantian times and locally removed all of the underlying Brigantian succession (Shirley, 1959; Walkden, 1970; Frost and Smart, 1979). This unconformity is thought to be below the level of the section exposed in the salt stockpile area. The pale limestones in this exposure are interpreted as bioclastic carbonates deposited by submarine debris flows and slumps derived from the Brigantian shelf. At least one major slumped unit is present in the pale bioclastic limestones that make up the lower part of the succession. The discontinuity seen at the south end of the salt stockpile is re-interpreted as a slump plane that emplaced thinly bedded argillaceous limestones on top of the thinly bedded, pale, coarsely bioclastic limestones. The contorted bedding was probably accentuated by compaction. The presence of gigantoproductids in the pale limestones at the base of the exposure suggests that they are of Brigantian age (Pattison, 1981).

Conclusions

The unconformity seen at Baileycroft Quarry may represent part of a deep channel-like incision that formed perpendicular to the platform margin during Asbian times. This channel probably originated during a lowstand in Brigantian times when the shelf margin was deeply karsted removing much of the Brigantian shelf and slope deposits. This feature subsequently formed a submarine channel down which shelf-derived bioclastic sediment was transported by debris flows and slumps. Further work is needed to determine the date of the lower bioclastic interval at the salt stockpile and the age of the overlying dark thinly bedded limestones.

DALE QUARRY, DERBYSHIRE (SK 283 542)

Introduction

The Dale Quarry GCR site (SK 283 542) is a disused, partly infilled quarry located immediately to the west of Wirksworth. The exposed succession includes the upper part of the Bee Low (Hoptonwood) Limestones and a complete section through the Monsal Dale (Matlock) Limestones and lower part of the Eyam (Cawdor) Limestones. Together with the other quarries in the Wirksworth area, Dale Quarry provides an unparalleled three-dimensional view of the evolution and lateral variation within the progradational carbonate platform margin that fringed the northern margin of the Widmerpool Gulf during late Dinantian times. The exposed section reveals limestones that were deposited on the platform margin slope and includes some spectacular examples of large-scale soft-sediment deformation. Aspects of the site geology were considered in regional stratigraphical studies by Shirley (1959) and Smith *et al*. (1967), but the most informative accounts are provided by Walkden (1982) and Gutteridge (2003). In the latter account, Gutteridge (2003) makes the case for re-exposing parts of the section recently obscured by infill.

Description

The Bee Low Limestones (25 m) comprise thickly bedded bioclastic peloidal grainstones and packstones with bedding planes marked by palaeokarstic surfaces overlain by thin volcanic-derived soils (Walkden, 1982). A typical late Asbian fauna including ***Dibunophyllum bourtonenese*, *Siphonodendron pauciradiale*** and ***Palaeosmilia murchisoni*** is present in these beds (Walkden, 1982).

The Asbian–Brigantian boundary is marked by a karstic surface probably with a few metres of Asbian strata missing. The Monsal Dale Limestones (30 m) and Eyam Limestones (3 m) consist of thinly bedded fine-grained bioclastic wackestones with shale partings (Figure 7.22). A few bioclastic packstones and grainstones (0.1–0.2 m thick) are also present; these have scoured bases and some show grading. Isolated lenses of coarse crinoidal grainstone up to 5 m thick and several tens of metres long also occur. These display large-scale southerly directed

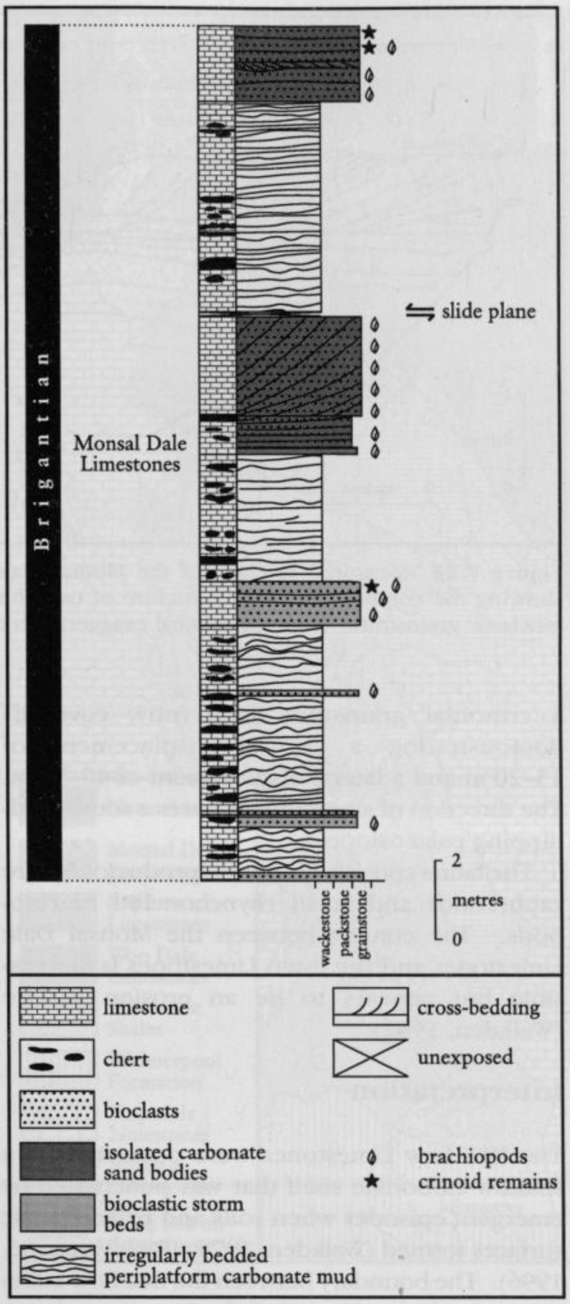


Figure 7.22 Sedimentary log of the section in the Monsal Dale Limestones (Brigantian) formerly seen at the Dale Quarry GCR site, Wirksworth. Parts of the section are now obscured by infill (see Gutteridge, 2003).

cross-stratification and are buried by the thinly bedded fine-grained bioclastic limestones. Soft-sediment deformation at various scales is common, including recumbent folds, small-scale flexures, imbricated thrusts and extensional slide planes (Figure 7.23). One of the latter cuts

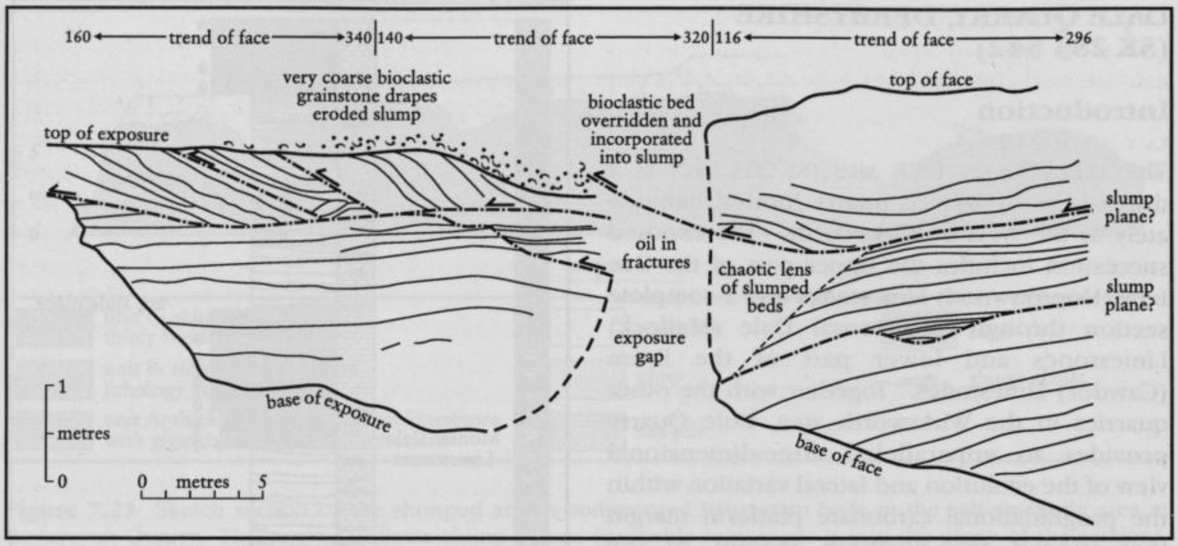


Figure 7.23 Measured sections of the Monsal Dale Limestones along the lower entrance to Dale Quarry showing the complex imbricate structure of two slump sheets. The slump is overlain erosively by a coarse bioclastic grainstone. Note the vertical exaggeration of the scale (×4). After Gutteridge (2003).

a crinoidal grainstone lens (now covered) demonstrating a vertical displacement of 15–20 m and a lateral displacement of 40–50 m. The direction of slumping indicates a southward-dipping palaeoslope.

The fauna consists of spinose productoids, rare zaphrentids and small rhynchonellid brachiopods. The contact between the Monsal Dale Limestones and the Eyam Limestones is inaccessible but appears to be an erosion surface (Walkden, 1982).

Interpretation

The Bee Low Limestones were deposited on a shallow carbonate shelf that was punctuated by emergent episodes when soils and palaeokarstic surfaces formed (Walkden, 1974, 1982; Vanstone, 1996). The boundary between the Bee Low Limestones and the Monsal Dale Limestones may represent a period of subaerial erosion; Shirley (1959) and Walkden (1982) recorded an unconformity at this level, and Walkden (1977) suggested that this surface marked an episode of subaerial erosion that is evident elsewhere on the carbonate platform at the Asbian–Brigantian boundary.

Shirley (1959), Smith *et al*. (1967) and Walkden (1970) recognized a major facies change in the Brigantian limestones, from cyclic limestones (with palaeokarstic surfaces) deposited in shallow shelf seas to the north, to a much thinner succession of thinly bedded argillaceous limestones (with no palaeokarstic surfaces) with a deeper-water fauna in the south. Walkden (1970, 1982), Oakman (1984) and Gutteridge (in unpublished work) interpreted this change as the depositional record of the shelf-to-slope transition across the southern margin of the Derbyshire carbonate platform.

The Brigantian succession represents the unstable marginal slope of the carbonate platform. This is dominated by fine-grained carbonate sediment that was winnowed and transported off the shelf by storm and tidal currents and deposited below wave-base. The thin bioclastic beds represent occasional storm-deposited influxes of coarser material derived from higher-energy environments up the platform margin. Some storm beds were mixed with the surrounding fine-grained slope carbonates by bioturbation. Isolated mega-ripples of crinoidal grainstone migrated down the slope until they were starved of coarse bioclastic sediment and were buried by fine-grained slope carbonates. The platform margin slope was unstable and was affected by down-slope creep and major slumping. It is possible that some of the major slumps cut down to the level of the lithified Asbian platform carbonates. The nature of the contact between the Monsal Dale Limestones and the Eyam Limestones in Dale Quarry is not known but is also thought to be a subaerial erosion surface.

Conclusions

Dale Quarry is a key site for demonstrating the changing nature of the southern margin of the Derbyshire Platform during late Dinantian times. Asbian strata record a flat-topped carbonate shelf with shallowing-upwards cycles capped by emergence surfaces passing laterally into a narrow high-angle margin probably underlying Wirksworth. The transition from shelf carbonates to marginal slope carbonates stepped back some 1–2 km shelfward at the end of Asbian times such that the transitional area became broader and less steep. Subsequently, during Brigantian times, the platform margin built out progressively southwards into the Widmerpool Gulf by the off-shelf transport of shelf-derived carbonates and slumping.

DOVEDALE, DERBYSHIRE–STAFFORDSHIRE (SK 131 584–SK 152 510)

Introduction

Situated on the Derbyshire–Staffordshire border between Thorpe and Hartington, the Dovedale GCR site offers an outstanding array of natural cliff sections through the Milldale Limestones (mainly Chadian) and includes the best exposed deep-water 'knoll reef' (carbonate mud-mound) complex in the North Staffordshire Basin – the largest exposed development of its kind in England. In addition, the site reveals important evidence of the lateral facies passage from the topmost beds of the Milldale Limestones (basin facies) into the Holkerian Woo Dale Limestones (shelf facies). Shelf facies strata of the overlying Bee Low Limestones (Asbian) also occur at this locality. The site extends for some 10 km between Wolfscote Dale (SK 131 584–SK 142 570) and Biggin Dale (SK 150 587–SK 142 570) in the north, to Thorpe Cloud (SK 152 510) and Bunster Hill (SK 143 514) in the south (Figure 7.24). It includes the subsidiary valley sections at Sharplow Dale (SK 148 522), Hall Dale (SK 135 537), Nabs Dale (SK 145 535) and east of Coldeaton Bridge

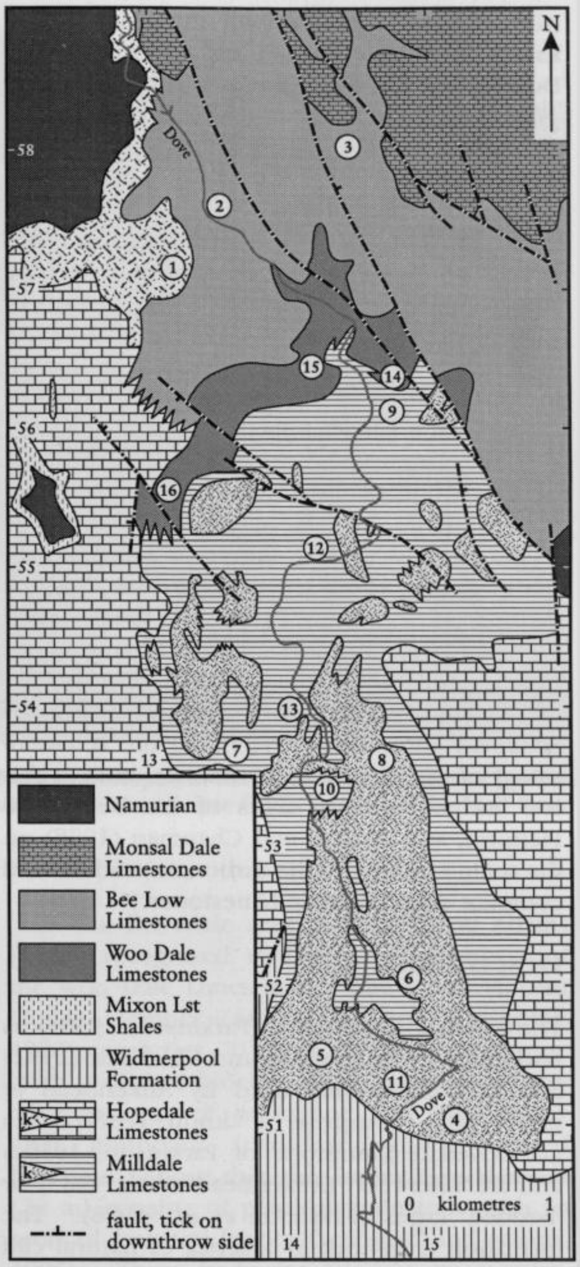


Figure 7.24 Simplified geological map of the Dovedale region illustrating the distribution of 'knoll reef' (carbonate mud-mound) facies (k) in the Milldale Limestones and the positions of localities referred to in the text: 1 – Gratton Hill; 2 – Wolfscote Dale; 3 – Biggin Dale; 4 – Thorpe Cloud; 5 – Bunster Hill; 6 – Sharplow Dale; 7 – Hall Dale; 8 – Nabs Dale; 9 – Coldeaton Bridge; 10 – Dove Holes; 11 – Dovedale Castle; 12 – Milldale; 13 – Ravens Tor; 14 – Iron Tors; 15 – Gypsy Bank; 16 – Alstonefield. Compilation based on [British] Geological Survey maps of the area (Institute of Geological Sciences, 1978, 1983).

(SK 146 561), together with the many recent karstic landforms (pillars and caves) between Dove Holes (SK 142 535) and Dovedale Castle (SK 148 514) south of Milldale (SK 139 548).

The first significant account of the site geology was by Parkinson (1950a) who produced an informative map of the area. Later work by Parkinson and Ludford (1964) and Ludford (1970) contributed further important details. However, the most comprehensive accounts of Dovedale geology are by Aitkenhead *et al.* (1985) and Chisholm *et al.* (1988); the former, in consideration of the area between Wolfscote Dale and Milldale (the northern half of the site), and the latter, in consideration of the area between Milldale and Thorpe Cloud (the southern part of the site). More specific works on the palaeontology and sedimentology of Lower Carboniferous rocks exposed here are those by Jackson (1919, 1941a), Parkinson (1964), Thach (1964), Chapman (1984), Schofield and Adams (1985) and Bridges and Chapman (1988). Two of the more significant of these were by Schofield and Adams (1985), on the sedimentology of the Woo Dale Limestones, both at this site and in adjacent areas of the Derbyshire Platform, and Bridges and Chapman (1988) on the sedimentology of the carbonate mud-mound complex in the Milldale Limestones.

Description

The Milldale Limestones (Parkinson, 1950a) as re-defined by Aitkenhead and Chisholm (1982) and as subsequently used by Aitkenhead *et al.*, (1985) comprise a 'knoll reef' facies (= Dovedale Limestone of Parkinson, 1950a) and an 'inter-reef' (Aitkenhead *et al.*, 1985) or 'bedded' facies (Chisholm *et al.*, 1988). The formation crops out in a series of natural cliff sections either side of the River Dove in the core of the N–S-trending Dovedale Anticline. Detailed work by Bridges and Chapman (1988) has demonstrated that the Dovedale 'reefs' represent deep-water carbonate mud-mounds rather than true 'ecologic reefs' (Dunham, 1970) and this view is adopted in the account below.

Although isolated carbonate mud-mounds occur to the south-west and east of Milldale, the principal outcrop (a composite development hereafter referred to as the 'mud-mound complex') occurs to the south of Milldale between Ravens Tor (SK 1412 5385) and Thorpe Cloud, occupying an area of approximately 6 km^2 (Figure 7.24). Outcrops of the 'bedded facies' are best exposed around Milldale and between Milldale and Iron Tors (SK 146 563) to the north.

Chisholm *et al.* (1988) estimated that the Milldale Limestones are around 320 m thick in the Dovedale area, with maximum mud-mound thicknesses ranging from 180 m to 300 m. The mud-mounds comprise irregular bodies of massive (largely unbedded) pale-coloured micritic limestone. Typically these contain a variety of cavity and cavity-fill structures including the problematical 'stromatactis', and a macrofauna consisting of crinoids, brachiopods, fenestrate bryozoans, ostracodes, gastropods together with a few bivalves, corals, trilobites, goniatites and nautiloids. A Chadian age for the mud-mound facies is indicated by the presence of ***Levitusia humerosa*, *Spirifer bollandensis*, *Fascipericyclus*, *Ammonellipsites*, *Dzhaprakoceras*, *Merocanites*, *Polaricyclus* '*Pericyclus*' *minimus*, *Eonomismoceras*, *Cummingella raniceps*, *Phillipsia gemmulifera*** and ***Phillibolina worsawensis*** (Jackson, 1919, 1941a; Chisholm *et al.*, 1988; Tilsley, 1988; Riley, 1991). A rich brachiopod fauna from the mud-mound complex at Thorpe Cloud is reported by Brunton and Tilsley (1991).

Bridges and Chapman (1988) recognized a distinctive facies suite in the mud-mound complex that included a mound-core facies, mound-flank facies (coarse and fine) and an intermound facies (coarse and fine). The mound-core facies consists of massive wackestones with, in addition to those fossil groups mentioned above, a diverse array of skeletal fragments set in a peloidal and clotted micrite matrix. The most common skeletal fragments are of assorted sponges (hyalosteliids, moravamminids and aoujgaliids), but foraminifera, calcispheres and echinoid remains also occur. Cryptalgal laminites, graded laminites, small-scale slump structures, fissures and fissure-fill breccias are also found in this facies.

The associated flank and intermound facies comprise a varied mix of 'bedded' carbonate lithologies ranging from crinoidal packstones and algal-encrusted intraclast floatstones in the mound-flank (coarse) facies to grainstones and rudstones in the intermound (coarse) facies and a packstone–wackestone association in both the mound-flank (fine) facies and intermound (fine) facies (Bridges and Chapman, 1988). The lateral facies transition from mound-core to intermound facies is beautifully exposed at Ravens Tor (Figure 7.25).

Figure 7.25 General view of the carbonate mud-mound facies developed in the Milldale Limestones at Ravens Tor, Dovedale. Note the lateral transition from the massive mud-mound core facies (centre) to bedded flank and intermound facies (right). (Photo: P.J. Cossey.)

Away from the mud-mound complex, the typical 'bedded' facies of the Milldale Limestones is poorly fossiliferous. It comprises grey bioclastic grainstones with subordinate developments of a dark cherty micritic limestone (Aitkenhead and Chisholm, 1982). On the [British] Geological Survey maps of the Buxton and Ashbourne districts (Institute of Geological Sciences, 1978, 1983) the latter are mapped separately as the 'dark facies' of the Milldale Limestones. Although a Chadian age is indicated for the majority of these beds (Aikenhead and Chisholm, 1982), microfossil evidence indicates the upper part of the 'bedded' facies of the Milldale Limestones may be of Asbian age (Chisholm *et al.*, 1988). This accords with the best available field evidence from near Gypsy Bank (SK 142 565) and south of Alstonefield (Institute of Geological Sciences, 1978) where the topmost beds of the Milldale Limestones appear to pass laterally into the Woo Dale Limestones (= Iron Tors Limestone of Parkinson, 1950a) (Figure 7.24); a formation which at outcrop is generally regarded as Holkerian–early Asbian age (Aikenhead and Chisholm, 1982; Aitkenhead *et al.*, 1985).

In the Dovedale area, Schofield and Adams (1985) recognized two separate members of the Woo Dale Limestones. The lower Vincent House Member (Aitkenhead and Chisholm, 1982) comprises 70 m of bioclastic grainstone 'with a diverse bioclast suite' and subordinate developments of packstone and wackestone with abundant intraclasts and scattered fenestrae. Above this, the Topley Pike Member (20 m) consists of peloidal grainstone with an array of fenestral fabrics (Schofield and Adams, 1985). These beds are overlain by massive-bedded pale-grey calcarenites of the Bee Low Limestones (Asbian). A thickness of around 190 m is recorded for this formation in the Wolfscote Hill area (Aitkenhead *et al.*, 1985), but at this site only parts of the succession are exposed, these occurring in discontinuous outcrops along the valley sides of Wolfscote Dale and Biggin Dale (Figure 7.24). This shallow-shelf facies, which passes laterally into Asbian 'knoll reef' and 'apron-reef' limestones in the Beresford Dale–Gratton Hill area, is described in the **Wetton to Beresford Dale** GCR site report (this chapter).

Interpretation

The mud-mounds ('knoll reefs') of the Milldale Limestones represent deep-water 'Waulsortian' carbonate mud-mounds; buildups that are of a similar character to those recorded in successions of broadly equivalent age in other parts of Europe and in North America (Lees, 1964, 1982; Lees *et al.*, 1977, 1985; Miller and Grayson, 1982; Lees and Miller, 1985). The generally accepted view favours a microbial origin both for the lime mud that formed main structure of the buildups and for at least some of the cavity-filling cements within them. The formation of the cavities themselves remains contentious, although the circulation of phreatic marine pore-water beneath the organically coated mud-mound surfaces may have been influential in their development (Bridges and Chapman, 1988).

Cyanobacteria are thought to have been particularly influential in the formation of the mud-mounds (Bridges and Chapman, 1988). These may have contributed to the deposition of lime sediment in various ways – most notably by the photosynthetically induced precipitation of fine-grained calcium carbonate within and around the bacterial elements, by the breakdown of bacteria-released ammonia in conditons of high pH, or by the binding and trapping of lime mud in adhesive bacterial films at the sediment–water interface. Other less significant factors include the addition of skeletal remains derived from organisms that lived on or above the mud-mound surfaces and the deposition of fine-grained sediment 'imported' by deep-water drift (Bridges and Chapman, 1988).

The role of deep-sea currents as nutrient suppliers to growing deep-sea mud-mounds is well documented (Wright and Faulker, 1990; Wright, 1991; Bridges *et al.*, 1995). In this context it is interesting to note that the geometry and orientation of the Dovedale mud-mound complex is thought to have been shaped or moulded under the influence of a south-easterly flowing deep-sea current (Bridges and Chapman, 1988). The same current may also have been responsible for the formation of some of the mound's internal sedimentary features (e.g. graded laminites and inclined bedding surfaces).

Careful observation of the relationship between the mound-core and mound-flank facies enabled Bridges and Chapman (1988) to determine that the Dovedale complex was a composite buildup that grew to an elevation of some 50–80 m above the local sea floor with palaeoslopes along its flanks of up to 25° or 30°. The same authors regarded the occurrence of slump structures and fissures in the mound-core facies as evidence of the gravitational instability of the mud-mound palaeoslopes and, following earlier microfacies work by Lees *et al.* (1985) and Lees and Miller (1985), they also established that original water depths over the complex ranged from 220 m to 280 m.

Regional sequence thickness and facies variations coupled with geophysical evidence indicate that the Milldale Limestones were formed as a relatively deep-water facies in the North Staffordshire Basin–Widmerpool Gulf areas, and upon a S- to SW-dipping carbonate ramp that developed over a similarly inclined tilt-block in the underlying basement (Maroof, 1976; Smith *et al.*, 1985; Gutteridge, 1987; Chisholm *et al.*, 1988; Gawthorpe *et al.*, 1989). Although the greater part of this formation, including the mud-mound facies, is of Chadian age, the topmost parts of the formation may be as young as the Holkerian or early Asbian (Chisholm *et al.*, 1988). This, together with field evidence from the northern part of the site, strongly supports the idea of the Milldale Limestones being, at least in part, the lateral and basinal equivalent of the Woo Dale Limestones (shallow-water shelf facies) developed over the Derbyshire Platform to the north-east (Parkinson and Ludford, 1964; Aitkenhead *et al.*, 1985; Bridges and Chapman, 1988).

In consideration of the depositional environment of the Woo Dale Limestones, Schofield and Adams (1985) argued that, over much of the Derbyshire Platform, the Vincent House Member represented an open shelf facies, while the Topley Pike Member developed principally as a tidal-flat facies – although a higher energy beach facies was suggested for beds of this member in the Alstonefield area. Although difficulties arise in the interpretation of the succession around Alstonefield, the upward transition from the Vincent House Member to the Topley Pike Member was most probably the result of shoaling caused by the southward migration of a prograding tidal-flat complex (Schofield and Adams, 1985).

Conclusions

The 'knoll reefs' in the Milldale Limestones at this site form part of the largest and best exposed deep-water 'Waulsortian' carbonate mud-mound complex in Britain, which is one of the finest composite carbonate buildups of Early Carboniferous age in Europe. The complex developed in the North Staffordshire Basin towards the foot of a south-westerly sloping carbonate ramp in water depths of around 220–280 m. The site is a particularly valuable educational resource and is widely used both in the teaching of carbonate sedimentology and for research into the origin of carbonate mud-mound structures and Dinantian sedimentary basins.

WETTON TO BERESFORD DALE, STAFFORDSHIRE–DERBYSHIRE (SK 095 549–SK 095 561–SK 131 584–SK 127 592)

Introduction

The complex Wetton to Beresford Dale GCR site on the north Staffordshire–Derbyshire border offers a unique opportunity to examine the relationships between Lower Carboniferous rock formations deposited in a wide range of sedimentary environments both within the North Staffordshire Basin and in close proximity to its north-eastern margin. It includes both a deep-water 'knoll reef' (carbonate mud-mound) facies and an 'inter-reef' ('bedded') facies in the Milldale Limestones (Chadian), a deep-water 'turbidite' facies in the Ecton Limestones (mainly post-Chadian) and a shallow-water 'knoll reef' facies of the Hopedale Limestones which extends into an 'apron-reef' facies of the Bee Low Limestones (both Asbian), the post-Chadian turbidite facies and reef facies developing respectively some distance from and close to the margin of the North Staffordshire Basin as the Derbyshire shelf area became established to the north-east of the basin in later Dinantian times.

The site (formerly referred to as the 'Wetton–Gratton' GCR site) extends for approximately 6 km from the cliffs and caves of the Manifold Valley (SK 095 549–SK 095 561) near Wetton in the south-west, to the valley-side crags of Beresford Dale (SK 127 592–SK 131 584) in the Dove Valley and Pennilow (SK 1289 5950), near Hartington, in the north-east (Figure 7.26). It also includes the scattered hillside exposures that extend eastwards from Wetton Hill, recognized here as two separate hill features, namely Wetton Hill East (SK 1130 5658) and Wetton Hill West (SK 1049 5627) following the terminology of Aitkenhead *et al*. (1979), to Gratton Hill (SK 1320 5715) and the outlying outcrops at Swainsley (SK 0937 5763), Ecton Bridge (SK 0950 5818–SK 0910 5794) and Apes Tor (SK 0999 5868).

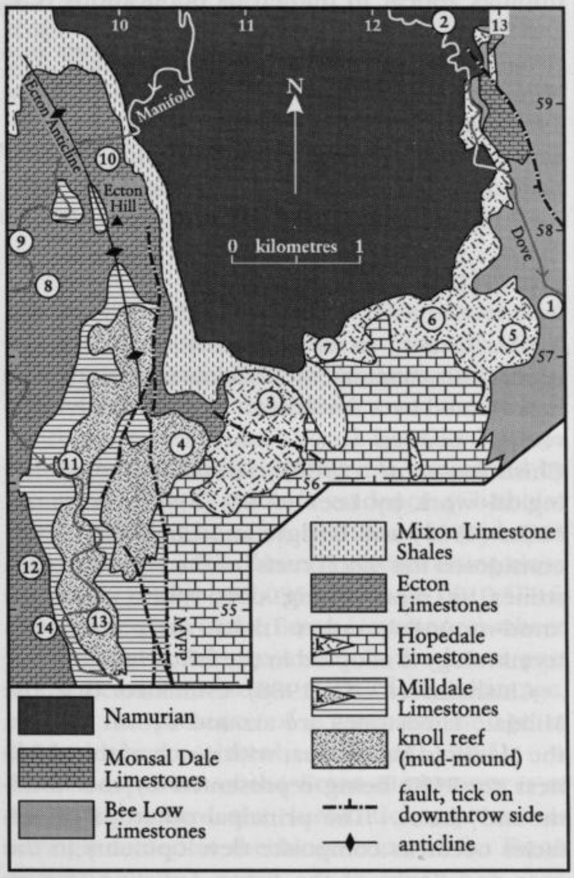


Figure 7.26 Simplified geological map of the Wetton to Beresford Dale GCR site, showing the distribution of 'knoll reef' facies (k) both in the Milldale Limestones (carbonate mud-mound facies) and in the Hopedale Limestones. Also shown are the positions of localities referred to in the text: 1 – Wolfscote Dale; 2 – Beresford Dale; 3 – Wetton Hill East; 4 – Wetton Hill West; 5 – Gratton Hill; 6 – Narrowdale Hill; 7 – Gateham Hill; 8 – Swainsley; 9 – Ecton Bridge; 10 – Apes Tor; 11 – Wettonmill; 12 – Ossoms Hill; 13 – Thors Cave; 14 – Ladyside Wood; MVFP – Manifold Valley Fault Plexus. After the [British] Geological Survey map of the Buxton district (Institute of Geological Sciences, 1978).

Although significant contributions to our understanding of the site geology were made by Parkinson (1950a), Prentice (1951) and Parkinson and Ludford (1964), these works have largely been superseded by the more comprehensive and modern accounts of Aitkenhead *et al.* (1985) and Chisholm *et al.* (1988) in the Buxton and Ashbourne [British] Geological Survey memoirs. In addition, areas of the site, and in particular the Chadian–Asbian 'knoll reef' limestones, have proved a rich hunting ground for palaeontologists, and records of their findings appear in numerous publications (e.g. Davidson, 1851–1886; Carrington, 1865; Brunton and Champion, 1974; Brunton and Mundy, 1986, 1988a, 1993, 1994, 1997; Tilsley, 1988; Riley, 1991). A further work of significance is the detailed sedimentological and palaeoecological study of the Chadian 'knoll reef' facies by Morgan (1980).

Description

At this locality, as at **Dovedale** (see GCR site report, this chapter), the Milldale Limestones are represented by a 'knoll reef' facies and an 'inter-reef' or 'bedded' facies (Aitkenhead *et al.*, 1985; Chisholm *et al.*, 1988). Detailed sedimentological work by Lees *et al.* (1985), Lees and Miller (1985) and Bridges and Chapman (1988) considered the 'knoll reefs' of the Milldale Limestones as representing deep-water carbonate 'mud-mounds' rather than reefs and this terminology is adopted in the following account.

Chisholm *et al.* (1988) estimated that the Milldale Limestones are around 218 m thick in the Manifold Valley area, with much of this thickness (*c.* 75%) being represented by the 'mud-mound' facies. The principal outcrops of this facies occur as composite developments in the core and flanks of the Ecton Anticline (Figure 7.26). The larger of these developments to the west, extends from the southern slopes of Ecton Hill in the north, via Sugar Loaf (SK 0980 5680), Wettonmill (SK 0957 5611) and the eastern slopes of Ossoms Hill to Thors Cave (SK 0982 5496) and Ladyside Wood (SK 0950 5496) in the south. A smaller and slightly younger complex to the east encompassing Wetton Hill West (Aitkenhead *et al.*, 1979, 1985) is partly disrupted by faults that form part of the Manifold Valley Fault plexus (Chisholm *et al.*, 1988). The discovery of a late-Chadian macrofauna from an isolated outcrop on Wetton Hill East by Tilsley (1988) and Riley (1991) indicates that the Chadian mud-mound facies extends farther to the east than is indicated on [British] Geological Survey maps of the area (Institute of Geological Sciences, 1978).

The mud-mound facies comprises massive and poorly bedded micrites with stromatactoid cavities and a macrofauna of brachiopods, fenestrate bryozoans, crinoids, trilobites and ammonoids together with a few corals and nautiloids. Typically these occur either scattered throughout the mud-mound structures or concentrated in isolated pockets within their fabric. Sponge remains, foraminifera and ostracodes also occur in this facies (Ludford, 1970; Bridges and Chapman, 1988).

A Chadian age for the bulk of the mud-mound facies is indicated by the presence of trilobite and ammonoid assemblages that include *Namuropyge decora*, *N. glaphra*, *Bollandia columba*, *Phillibole* cf. *nitidus*, *Phillibolina worsawensis*, *Reediella reedi*, *Weania feltrimensis*, *Winterbergia hahnorum*, *Dzhaprakoceras*, *Rotopericyclus*, *Ammonellipsites* and *Helicocyclus* (Tilsley, 1988; Riley, 1991). Courceyan conodonts and Arundian corals are also reported from this facies (Aitkenhead *et al.*, 1985) but later work by Chisholm *et al.* (1988) has cast doubt on the significance of some of this conodont evidence.

The 'bedded' facies of the Milldale Limestones comprise crinoidal calcarenites and calcisiltites with shaly interbeds and minor developments of dark cherty micritic limestone (Aitkenhead and Chisholm, 1982). This facies is particularly well developed in the core of the Ecton Anticline east of Wettonmill (SK 0984 5607) and either side of the mud-mound at Thors Cave – i.e. both below it, in the bed of the Manifold River, and above it in the cutting of the disused railway line at Ladyside Wood (Prentice, 1951; Chisholm *et al.*, 1988) (Figure 7.27). Although macrofossil and microfossil evidence indicates a Chadian age for the 'bedded' facies at this site, elsewhere the facies is reported to range up into the Asbian (Aitkenhead *et al.*, 1985; Chisholm *et al.*, 1988). The occurrence of *Lamdarina manifoldensis* in a rare and silicified brachiopod assemblage found locally (Brunton and Champion, 1974) confirms the Chadian age suggested for parts of this facies.

Formations lying stratigraphically above the Milldale Limestones include the Ecton Limestones to the north and west, and the

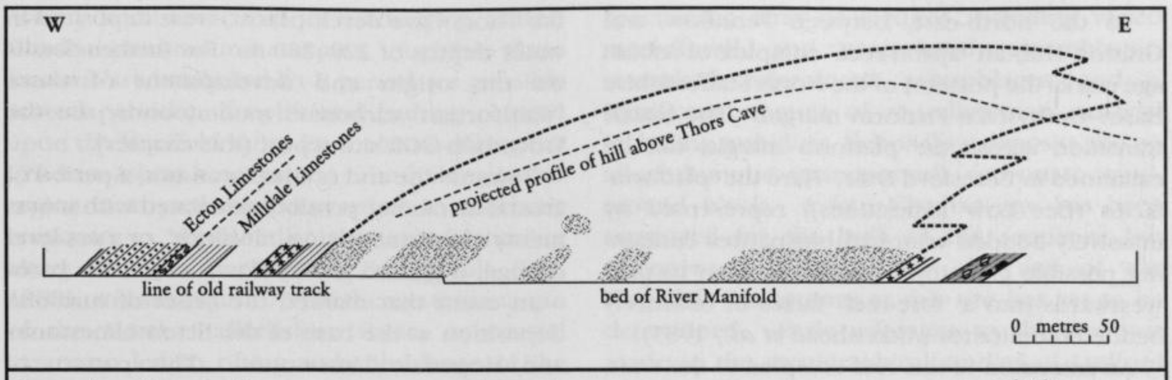


Figure 7.27 Sketch cross-section through the Thors Cave carbonate mud-mound from Ladyside Wood (SK 0947 5487) to the bed of the River Manifold (SK 0988 5509). After Chisholm *et al.* (1988).

Hopedale Limestones to the south and east. Although across much of their outcrop area these younger formations appear to be of Asbian age, faunas as old as the Chadian (some possibly reworked) have been recorded from both of them (Chisholm *et al.*, 1988), and their precise stratigraphical relationship to the underlying Milldale Limestones remains uncertain. Whereas an unconformity between the Milldale Limestones and these younger formations is either present or suspected in certain areas, the boundary between the Milldale Limestones and the Ecton Limestones is at least partly diachronous (Chisholm *et al.*, 1988).

The Ecton Limestones (*c.* 225 m thick) comprise a turbiditic sequence of sharp-based, graded and locally conglomeratic, peloidal bioclastic limestones (some cherty) with sparse developments of dark, laminated and locally bioturbated micritic limestones with shaly interbeds. At Swainsley, a 45 m section near the middle of the formation showing both these lithofacies includes, in the lower and coarser part of the succession, both an Arundian microfauna and a detached limestone block approximately 4 m across containing attached productoids, pseudomonotids and large cavity-dwelling myodocopid ostracodes – an assemblage typical of the shallow-water microbial framework facies of Asbian reefs (Mundy in Aitkenhead *et al.*, 1985; and see Chapter 5). The contact between the Milldale Limestones and Ecton Limestones is exposed at Ladyside Wood where a prominent (1.75 m) and erosively based graded bioclastic limestone occurs at the base of the formation (Figure 7.27). A late Chadian age for the Ecton Limestones here is supported by foraminiferal and trilobite evidence (Chisholm *et al.*, 1988). The same formation boundary is also exposed in the disused railway cutting close to Ecton Bridge (SK 0950 5818–SK 0910 5794; the type section of the Ecton Limestones) where foraminiferal evidence indicates the lower part of the Ecton Limestones to be of Arundian age, despite the presence of a coral assemblage of Asbian aspect (Aitkenhead *et al.*, 1985). A further exposure of the Ecton Limestones is at Apes Tor where the turbiditic sequence is strongly folded in the hinge zone of the Ecton Anticline.

The Hopedale Limestones (the lateral facies equivalent of the Ecton Limestones) comprise a well-bedded, coarsely crinoidal and peloidal calcarenite sequence with some sharp-based limestone conglomerate units. The only significant section is in a disused quarry (SK 1070 5568) 250 m north-west of Wetton; one of four 'type sections' designated for the Hopedale Limestones by Aitkenhead and Chisholm (1982). The sequence here contains an Asbian–early Brigantian coral fauna and is approximately 11 m thick (Aitkenhead *et al.*, 1985).

To the north-east, between Pennilow and Gratton Hill, an 'apron-reef' complex of Asbian age marks the position of the North Staffordshire Basin–Derbyshire Platform margin. The lateral transition across the platform margin can be examined in Beresford Dale. Here the 'platform' facies (Bee Low Limestones), represented by massively bedded crinoidal biosparites containing possible gigantoproductids, is seen to pass westwards into a 'fore-reef' facies of obscurely bedded biomicrites (Aitkenhead *et al.*, 1985).

An extension of this reef complex to the west, away from the platform margin, is represented by a 'knoll reef' facies in the Hopedale Limestones at Gratton Hill, Narrowdale Hill (SK 1233 5723), Gateham Hill (SK 1152 5704) and parts of Wetton Hill East. A rich macrofauna reported from this facies is dominated by brachiopods (Prentice, 1951; Brunton and Mundy, 1986, 1988a, 1993, 1994, 1997) but also include trilobites (Tilsley, 1988), bivalves, corals, bryozoans, ostracodes and sparse goniatites (Prentice, 1951; Aitkenhead *et al.*, 1985). An upper B_2 or late Asbian age for the bulk of this facies is supported by the presence of beyrichoceratid goniatites, *Bollandoceras* cf. *micronotum* and the trilobites *Bollandia obseleta*, *Piltonia humilis* and *Reediella granifera* (Bisat, 1934; Aitkenhead *et al.*, 1985; Tilsley, 1988).

The occurrence of both Chadian and Asbian faunas at Wetton Hill East together with field evidence provided on [British] Geological Survey maps of the area (Institute of Geological Sciences, 1978) indicates the presence of an unconformity between the Chadian mud-mound facies and the Asbian 'knoll reef' facies, and that the younger 'knolls' may have been rooted (at least in part) on the upstanding remnants of the older Chadian mud-mounds.

Interpretation

Regional stratigraphical and geophysical studies suggest that the Milldale Limestones (mainly Chadian) of the North Staffordshire Basin and Widmerpool Gulf areas were deposited on a gently sloping carbonate ramp above a basement 'tilt-block' that dipped to the south or south-west (Smith *et al.*, 1985; Chisholm *et al.*, 1988). Detailed sedimentological work by Lees and Miller (1985) indicated that the deep-water carbonate mud-mounds formed principally as a result of microbial activity and that the 'buildups' of the Manifold Valley area, including the Thors Cave development, were deposited in water depths of 220–280 m. For further details on the origin and development of these 'Waulsortian' carbonate mud-mounds, see the **Dovedale** GCR site report (this chapter).

Towards the end of Chadian times, a period of crustal instability, possibly associated with movements of the underlying 'tilt-block', or a sea-level change, triggered gravity flows within the basin – an event that marked the onset of turbidite deposition at the base of the Ecton Limestones and Hopedale Limestones. This pattern of sedimentation continued into Asbian times (Chisholm *et al.*, 1988). By this time, the North Staffordshire Basin had become clearly differentiated from the Staffordshire Shelf and Derbyshire Platform areas, the margins of which are defined by the development of an apron-reef facies seen to the south-west in the Weaver Hills district (bordering the Staffordshire Shelf) and to the north-east (at this site) in Beresford Dale (bordering the Derbyshire Platform). The latter forms part of a discontinuous apron-reef development that extends around the western and northern margins of the Derbyshire Platform. The significance of this facies is discussed more fully in connection with **Castleton** (see GCR site report, this chapter) where it is better developed.

The Asbian 'knoll reef' extension to the Beresford Dale apron reef developed in an area of mixed water depth where the narrow seaway separating the Derbyshire Platform and Staffordshire Shelf is at its narrowest. In the current-swept 'channels' between the knoll reefs, the Hopedale Limestones were deposited as an 'inter-reef' facies (Aitkenhead *et al.*, 1985) possibly by occasional storm-generated gravity flows. In deeper-water areas to the west, the turbiditic Ecton Limestones continued to be deposited. Sequence thickness trends in the Manifold Valley area and the presence of a detached block of ?Asbian reef limestone in the Ecton Limestones at Swainsley are cited by Chisholm *et al.* (1988) as possible evidence of syn-sedimentary growth faulting along the line of the N–S-orientated 'Manifold Valley Fault plexus'. In this context it is perhaps significant that the line of this fault plexus appears to separate the entire outcrop area of the deep-water Ecton Limestones in the west, from that of the relatively shallow-water Hopedale Limestones and Asbian 'knoll reefs' developed to the east, and where an unconformity exists between the

Asbian 'knoll reefs' and the underlying (older) Chadian mud-mound complex. Together these features are attributed to a period (or possibly several periods) of uplift and faulting centred upon the Manifold Valley Fault plexus during the Chadian–Asbian time interval. The faulting in this region most probably occurred as an antithetic response to similar displacements occurring along the line of the Lask Edge Fault (Lee, 1988a; and see Figure 7.2) at the western margin of the North Staffordshire Basin, as crustal extension led to rifting and subsidence of the basin at this time.

Conclusions

This large and complex site offers a remarkable and unique transect through Lower Carboniferous strata formed in a variety of sedimentary environments close to and across the North Staffordshire Basin–Derbyshire Platform margin during the Chadian to Asbian time period. The vertical transition from deep-water carbonate mud-mound facies (Milldale Limestones) into shelf, apron-reef, knoll reef and inter-reef facies (Bee Low Limestones–Hopedale Limestones) and deep-water basinal facies (Ecton Limestones) marks a significant change in depositional setting from gently inclined ramp to rimmed shelf as the Derbyshire shelf area became clearly differentiated from the North Staffordshire Basin and Widmerpool Gulf during Asbian times. The site includes a fascinating mix of many different sedimentary rock types (some extremely fossiliferous) in an area of considerable structural complexity and where the age of certain parts of the succession remains contentious. For these reasons the site will remain invaluable to future biostratigraphical and sedimentological research work for many years.

BROWN END QUARRY, STAFFORDSHIRE (SK 090 502)

Introduction

This disused quarry (SK 0902 5024) at Waterhouses, 10 km south-east of Leek, shows an outstanding section of the marine Milldale Limestones and Hopedale Limestones, formed towards the foot of a gently sloping carbonate ramp in the North Staffordshire Basin in early Carboniferous times. The succession includes a spectacular array of features including varied macrofossil and trace-fossil assemblages, reworked microfossil assemblages and a significant amount of re-sedimented material including turbidites, debris-flow deposits and an allochthonous (transported) carbonate mud-mound block. A late Chadian age has been suggested for the bulk of the sequence but unequivocal evidence for the age of the Hopedale Limestones at this site has yet to be determined. Early reference to the site was made in the stratigraphical studies of Ludford (1951), Prentice (1951) and Parkinson and Ludford (1964). More detailed accounts of the site geology are presented by Chisholm *et al.* (1988) and Cossey *et al.* (1995). Aspects of the palaeontology are detailed by Morris (1970a,b, 1994). Pioneering conservation work by the North Staffordshire Group of the Geologists' Association in collaboration with the Staffordshire Wildlife Trust resulted in the development of this quarry as Staffordshire's first geological nature reserve in the late 1980s (Cossey *et al.*, 1995).

Description

At this site, the Milldale Limestones comprise a steeply dipping sequence (88 m) of mainly dark, thinly bedded and fine-grained crinoidal wackestones and packstones with some coarser crinoidal rudstone and floatstone beds. A log of the succession is shown in Figure 7.28. Besides the ubiquitous crinoid remains (represented by rare calices, stem ossicles and current-orientated stem lengths), the macrofauna from these beds includes corals, brachiopods, gastropods, bryozoans, the occasional goniatite, trilobite and echinoid (Beasley, 1969) and a possible holothurian (Morris, 1970a, but see Cossey *et al.*, 1995). Rich microfaunas including Chadian foraminifera and Tournaisian conodonts (Chisholm *et al.*, 1988), and a trace-fossil assemblage with *Zoophycos*, *Anconichnus horizontalis*, *Scalarituba missouriensis* and *Planolites* are also reported from this part of the sequence (Cossey *et al.*, 1995).

Prominent at the base of the section are two 'Waulsortian' carbonate mud-mounds (Figure 7.29). Geopetal cavity fills in the younger of these structures has indicated that it is, most probably, a detached and inverted allochthonous block derived from the principal area of Waulsortian outcrop in the Manifold Valley–

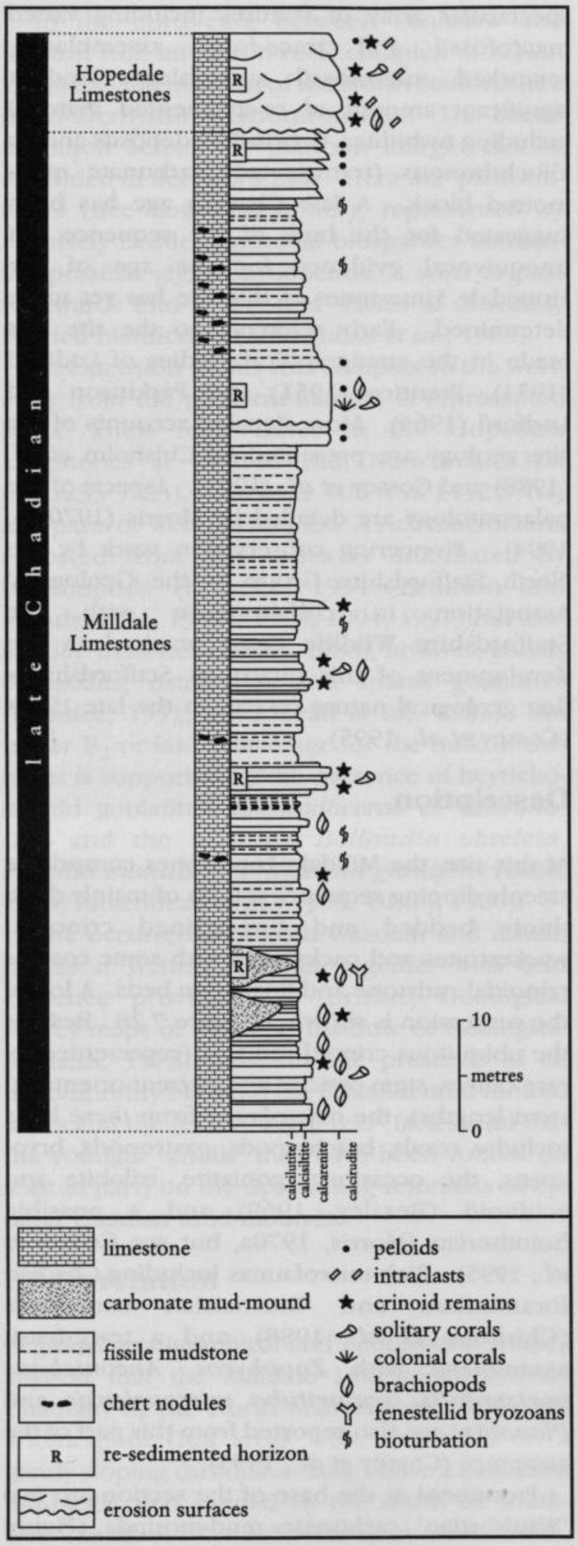


Figure 7.28 Sedimentary log of the late Chadian Milldale Limestones and the Hopedale Limestones succession at Brown End Quarry, Waterhouses. Based on Chishom *et al.* (1988) and Cossey *et al.* (1995).

Dovedale area to the north-east (Cossey *et al.*, 1995; and see **Wetton to Berseford Dale** and **Dovedale** GCR site reports, this chapter). Higher in the sequence an erosion surface at the base of a massive (4.6 m), poorly sorted, fossiliferous crinoidal grainstone–rudstone unit (possibly a gravity-flow deposit) cuts into the underlying laminated peloidal grainstone unit with minor angular discordance. The upper part of the formation comprises laminated and sharp-based graded limestone beds (turbidites) with rare flute casts on their under surfaces. These beds are overlain in turn by the Hopedale Limestones. This formation is represented by another massive (8 m) and composite, intraclast-bearing crinoidal rudstone unit (debris-flow deposit) characterized internally by ill-defined erosion surfaces separating a number of vertically stacked and graded channel-fill beds, each up to 3 m in thickness (Cossey *et al.*, 1995).

Interpretation

The Milldale Limestones (Aitkenhead and Chisholm, 1982) at this site were originally referred to as part of the Weaver Beds by Ludford (1951) and as part of the Cementstones Series by Prentice (1951). A C_1 (Chadian) age was ascribed to them by Prentice (1951), but other authors (Ludford, 1951; Parkinson and Ludford, 1964) referred them to the C_2 Zone (Chadian–Arundian). The original suggestion that part of the formation might be of Courceyan age (George *et al.*, 1976; Aitkenhead *et al.*, 1979) was based on the discovery of the Tournaisian conodont *Scaliognathus anchoralis* in the middle part of the sequence (Morris, 1970b). This view was rejected by Riley (in Chisholm *et al.*, 1988) because the beds containing *S. anchoralis* occur stratigraphically above those in which a younger Chadian microfauna (*Koninckopora inflata*, *Eoparastaffella* cf. *simplex*) occurs. These same authors attributed this anomolous microfossil distribution to the reworking of the older conodont elements (Chisholm *et al.*, 1988), a view that is consistent with the recognition of several re-sedimented beds in the sequence (Cossey *et al.*, 1995). The currently accepted view, based on foraminiferal evidence (see above) and macrofaunal evidence (*Clisiophyllum ingletonense*, *Siphonophyllia* sp. *cylindrica* group, *Lamdarina manifoldensis*, *Eomarginifera derbiensisis* and *Weania*

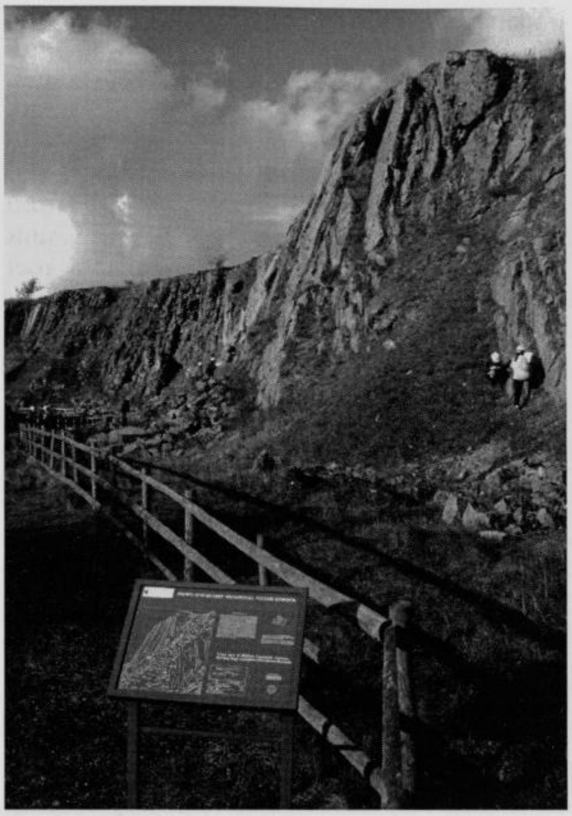


Figure 7.29 General view of the steeply dipping Milldale Limestones at the Brown End Quarry GCR site showing the position of the inverted mud-mound block (top right) referred to in the text. (Photo: P.J. Cossey.)

'Gitarra' colei), is that these beds are of Chadian (Chisholm *et al.*, 1988; Cossey *et al.*, 1995) or, more specifically, late Chadian age (N. Riley, pers. comm., 2002).

Age determinations for the Hopedale Limestones (= Waterhouses Limestone of Ludford, 1951) at the site are equally problematic because of conflicting macrofaunal and microfaunal evidence (Chisholm *et al.*, 1988). Early suggestions of a D_1 or Asbian age for these beds (Ludford, 1951; Parkinson and Ludford, 1964; Aitkenhead *et al.*, 1979) appear to have been based, at least partly, on the presence of corals such as *Palaeosmilia murchisoni* and *Clisiophyllum* cf. *rigidum* – taxa formerly regarded as typical of the late Viséan and whose stratigraphical ranges are now known to extend down to the Chadian (for *P. murchisoni*) and to the Chadian or Holkerian (for *C.* cf. *rigidum*) (Mitchell, 1989; Riley, 1993). The association of these taxa with a foraminiferal assemblage that includes *Pseudolituobella multicamerata* appears to support the 'probable Chadian age' assigned to these beds by Chisholm *et al.*, (1988). Since the Hopedale Limestones overlie the Milldale Limestones with 'apparent conformity' (Chisholm *et al.*, 1988), the slight angular discordance noted between these two formations in the Waterhouses area, by Prentice (1951) and by Parkinson and Ludford (1964), cannot be regarded as stratigraphically significant. This feature most probably represents a minor erosion surface associated with the deposition of gravity-flow deposits (coarse rudstones) at the base of the overlying Hopedale Limestones.

Regional geological investigations in the north Staffordshire area (Maroof, 1976; Bridges, 1984; Smith *et al.*, 1985; Gutteridge, 1987; Chisholm *et al.*, 1988; Gawthorpe *et al.*, 1989; Fraser and Gawthorpe, 1990) indicate that the Milldale Limestones were deposited towards the foot of a W- or SW-sloping carbonate ramp (Ahr, 1973) and above a similarly orientated 'tilt-block' in the underlying basement. The occurrence (at this site) of the classic 'Waulsortian' subfacies (= phase A of Lees and Miller, 1985) from a detached carbonate mud-mound block at the base of the Milldale Limestones indicates that this part of the sequence may have accumulated at water depths in excess of 280 m (Cossey *et al.*, 1995). Furthermore, trace-fossil assemblages typical of either the *Nereites* or *Zoophycos* ichnofacies reported by Cossey *et al.* (1995) indicate that conditions on the ramp may have been dysaerobic and that deposition most probably took place below storm wave-base.

Evidence of re-sedimentation in the form of gravity-flow deposits and reworked microfossil assemblages, lends support to the view that sedimentation during early Dinantian times (and especially during Chadian times) was strongly influenced by the activity of as yet imprecisely defined growth faults at the margins of the North Staffordshire Basin and smaller, possibly antithetic fault systems such as the Manifold Valley Fault plexus (Chisholm *et al.*, 1988; Cossey *et al.*, 1995; and see **Wetton to Beresford Dale** GCR site report, this chapter). Although the source of the re-sedimented material has yet to be securely established, Cossey *et al.* (1995) suggested it may have been derived from the developing Staffordshire Shelf to the south-west, or, as in the case of the detached Waulsortian mud-mound block, from the proximal up-slope parts of a carbonate ramp to the north-east. A further suggestion by these same authors is that the upward transition from thinly bedded turbidites at the top of the Milldale Limestones to thickly bedded debris-flow deposits at the base of the Hopedale Limestones forms part of a coarsening-upward sequence and part of a prograding fan system that spread across a sea floor of irregular topography, infilling depressions between contemporaneous 'knoll reefs' and older carbonate mud-mound structures (Aitkenhead and Chisholm, 1982; Chisholm *et al.*, 1988).

Conclusions

As the type locality (in part) for both the Milldale Limestones and the Hopedale Limestones (Aitkenhead and Chisholm, 1982), Brown End Quarry is one of the most important geological sites in north Staffordshire. The site is critical to the understanding of the tectono-sedimentary evolution and palaeogeography of the North Staffordshire Basin–Widmerpool Gulf area during early Dinantian times. The marine succession formed in the relatively deep waters of the North Staffordshire Basin at water depths of around 300 m. Although the precise age of parts of the sequence remains uncertain, a late Chadian age for the bulk of the section is now generally accepted. The contentious nature of the stratigraphy and the diverse array of rock features make this a promising site for biostratigraphical and sedimentological research work in the future.

CALDON LOW QUARRY, STAFFORDSHIRE (SK 077 491)

Introduction

The Caldon Low Quarry GCR site is a working quarry (SK 0770 4915) close to Waterhouses. It offers a particularly important section of the Caldon Low Conglomerate, locally the basal member of the Hopedale Limestones (Chisholm *et al.*, 1988). Although the precise age and origin of this deposit remains uncertain, its development above an unconformity separating the Hopedale Limestones from the underlying Milldale Limestones (early Chadian) is critical in understanding the palaeogeographical evolution of the North Staffordshire Basin and Staffordshire Shelf during Early Carboniferous times. Early descriptions of the deposit are by Jackson and Alkins (1919), Barke *et al.* (1920) (who regarded it as post-Carboniferous in age), Jackson and Charlesworth (1920) and Ludford (1951). However, the account presented here is based on the more recent work of Chisholm *et al.* (1988).

Although parts of the section originally described by Jackson and Alkins (1919), including the lowest beds of the Caldon Low Conglomerate and the basal unconformity, are now buried by infill, an informative and at least partly comparable section showing features of relevance to the Caldon Low Quarry GCR site occurs at neighbouring Cauldon Quarry 0.4 km to the east. A description of these features is included in the site report below for cross-reference.

Description

A strike section of well-bedded and pale-coloured calcarenite (*c.* 6 m thick) close to the base of the Hopedale Limestones is exposed in a small south-facing cliff, close to the currently disused railway line at the northern end of the quarry (Figure 7.30). The lower part of this succession (the Caldon Low Conglomerate) comprises 3 m of conglomeratic limestone with scattered pebbles of quartz, quartzite, altered green lava and limestone set in a carbonate matrix containing a significant amount of coarse quartz sand. A coral–brachiopod fauna from this locality, including *Siphonodendron martini*, *Acanthoplecta mesoloba*, *Avonia youngiana*, *Linoprotonia* cf. *hemisphaerica* and *Megachonetes* cf. *papilionaceus*, is thought not to be age diagnostic, but is, perhaps, more typical of the Asbian Stage than earlier stage intervals (Chisholm *et al.*, 1988), although it may include some reworked elements.

To the east, in Cauldon Quarry, an erosion surface and angular unconformity separates the Hopedale Limestones from the underlying Milldale Limestones (Figure 7.31). Here, the lower beds of the Hopedale Limestones comprise a varied lithofacies mix of limestone breccia (= the Caldon Low Conglomerate), dark, thin-bedded limestone and pale-coloured, well-bedded or massive calcarenite. The sequence is punctuated by a number of irregular erosion surfaces. Associated undulations in the

Figure 7.30 General view of the Caldon Low Conglomerate (lower half of cliff face) in the Hopedale Limestones at Caldon Low Quarry. The height of the cliff is approximately 6 m. (Photo: P.J. Cossey.)

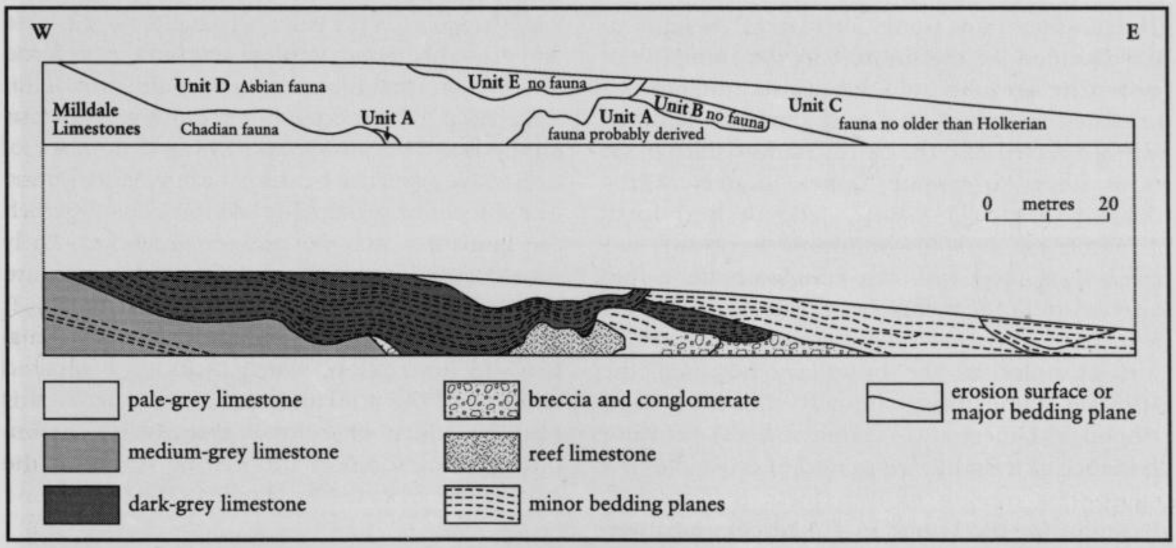


Figure 7.31 Section of strata at Cauldon Quarry, illustrating the distribution of lithofacies (units A–E) at the base of the Hopedale Limestones. Note the development of a prominent conglomeratic unit (unit A), the presumed equivalent of the Caldon Low Conglomerate seen at the Caldon Low Quarry GCR site to the west, overlying a prominent erosion surface (unconformity) cut into the underlying Milldale Limestones. After Chisholm *et al.* (1988).

bedding are generally concordant with the irregular profiles of the erosion surfaces that lie beneath them. At this site (Cauldon Quarry), the Caldon Low Conglomerate contains a large (18 m) detached block of 'reef' limestone (see Parkinson and Ludford, 1964) and a Courceyan–Arundian faunal assemblage (*Zaphrentites delanouei*, *Cyathaxonia rushiana*, *Caninia cornucopiae*, *Koninckophyllum* cf. *praecursor*, *Linoprotonia* cf. *hemisphaerica*, and both tournayellid and endothyrid foraminifera), which is thought to be derived (Chisholm *et al.*, 1988). A significant amount of carbonate mud is present in the matrix of the conglomerate. Beds above the Caldon Low Conglomerate containing scattered quartz grains and pebbles also contain derived faunal elements including Chadian–Holkerian conodonts and foraminifera. The presence of *Lithostrotion araneum*, archaediscid foraminifera (at the *angulatus* stage) and *Gigasbia gigas* at different stratigraphical levels indicates a possible age range for these beds stretching from the Holkerian to the Asbian (Chisholm *et al.*, 1988); however, a more recent assessment by N. Riley (pers. comm., 2002) suggests that these beds are, most probably, of Asbian age.

Interpretation

The Caldon Low Conglomerate is thought to have formed, at least in part, by the slumping of carbonate and siliceous lithoclasts into unconsolidated sediment, this re-sedimented material being directed into the North Staffordshire Basin from steep submarine slopes located nearby (Chisholm *et al.*, 1988). The derived fossil assemblages and discontinuity (erosion) surfaces associated with the conglomerate would appear to support this view. Furthermore, the association of this conglomerate with a major unconformity at the boundary between the Milldale Limestones (locally Chadian) and Hopedale Limestones (mainly Asbian) provides evidence of a significant period of erosion at the south-west margin of the North Staffordshire Basin during the Arundian–Holkerian time interval (Chisholm *et al.*, 1988). It was during this period that the Staffordshire Shelf became established to the south of the area; an area that extended south towards the northern shore of the Wales–Brabant Massif. These events are most probably the result of contemporary fault movements at the margin of a 'tilt-block' in the underlying basement; events which resulted in the clear differentiation of the Staffordshire Shelf from the North Staffordshire Basin during late Dinantian times.

Conclusions

The Caldon Low Conglomerate provides important evidence of the palaeogeographical changes taking place at the south-west margin of the North Staffordshire Basin during Dinantian times. Although the age of this deposit remains uncertain, it probably formed during late Holkerian or Asbian times as a result of uplift and the erosion of sediment from the developing edge of the Staffordshire Shelf margin. Uncertainties regarding the provenance of this sedimentary material make this an important site for sedimentological research in the future.

CAULDON RAILWAY CUTTING, STAFFORDSHIRE (SK 076 496–SK 078 498)

Introduction

The Cauldon Railway Cutting GCR site is a disused railway cutting (SK 076 496–SK 078 498) lying some 250 m north of Cauldon village, near Waterhouses. It provides a particularly valuable and arguably near-complete section through the Lower Namurian (Pendleian) *Cravenoceras leion* Zone (E_{1a}). The succession includes fossiliferous mudstones and shales containing a number of distinctive goniatite-bearing marine bands; some in the form of prominent bullion beds in which the goniatites may be preserved whole. Early records of fauna collected from this site are detailed by Wain and Stobbs (1907), Hester (1932) and Moore (1946). However, the most informative site description, which includes a detailed account of the goniatite sequence, is by Morris (1967b). Rich microfossil assemblages (conodonts) from some of the marine bands in the cutting are reported by Higgins (1961, 1975).

Description

The section extends for approximately 400 m between two footbridges leading into Cauldon village. The NE–SW-orientated cutting runs oblique to the trend of a series of asymmetric fold structures and is locally disrupted by faulting such that parts of the sequence are repeated along the section and the succession becomes difficult to follow. The account presented here is based mainly on the work of Morris (1967b) who made the first serious attempt to unravel the complexities of the section. However, it should be noted that most of the localities described by Morris (1967b) from the northern side of the cutting, especially at its north-east end, are no longer in existence (Prosser, 1989).

The succession (Figure 7.32) comprises approximately 20 m of mudstone, shale, calcareous shale with some thin beds of limestone, volcanic ash (Ludford, 1951) and limestone bullions (Figure 7.33). The dominant lithology is of medium- to dark-grey shales in which bivalves are particularly abundant and structures resembling burrows also occur. Morris (1967b) identified seven goniatite horizons in the sequence, including five bullion bands containing assemblages largely typical of the *Cravenoceras leion* (E_{1a}) Zone (Chisholm *et al.*, 1988). The goniatite succession defined by Morris (1967b) is as follows:

7. *Eumorphoceras* sp., *Dimorphoceras* sp.
6. *Eu.* sp. form A of Moore, *D.* (*Metadimorphoceras*) *wiswellense*
5. *Eu. stubblefieldi*, *Eu.* sp. cf. *Eu. involutum*
4. *Eu.* sp.
3. *Eu.* medusa, *Eu.* sp. (position uncertain)
2. *Cravenoceras* cf. *leion*, *D. wiswellense*
1. *C.* cf. *leion*

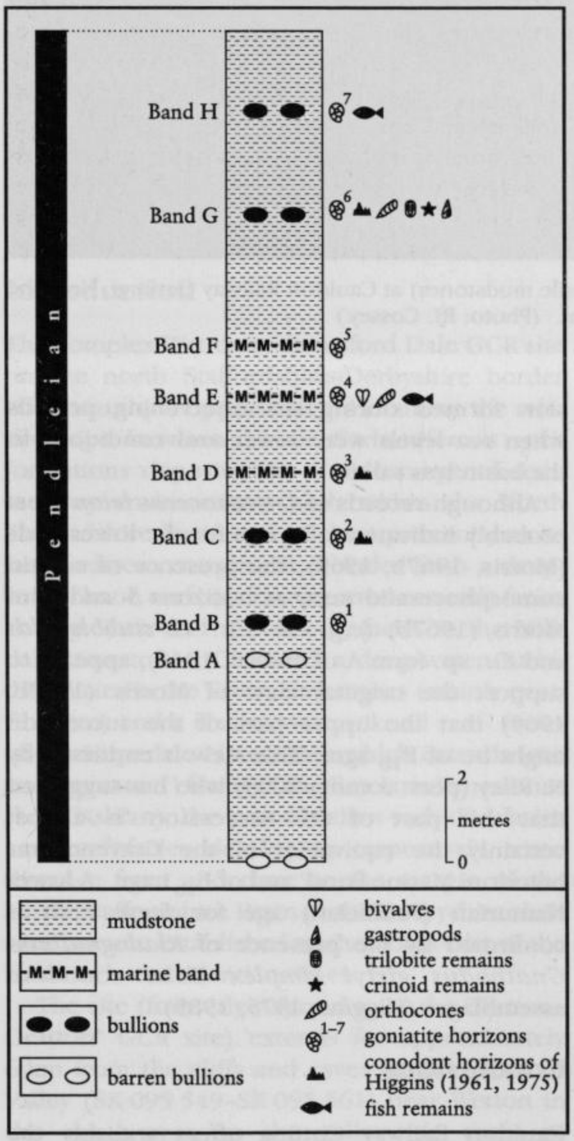


Figure 7.32 Schematic log section of the lower Namurian succession at Cauldon Railway Cutting. After Morris (1967b).

Note that the eumorphoceratid taxa identified by Morris (1967b) listed above are now generally assigned to the genus *Edmooroceras* (N. Riley, pers. comm., 2000) and that the early record of the E_{1b} zonal indicator '*Eumorphoceras* aff. *pseudobilingue*' by Bisat (in Hester, 1932) is most probably either *Edmooroceras* '*Eu*' cf. *medusa* or *Ed.* '*Eu*' cf. *stubblefieldi* (Ramsbottom in Morris, 1967b). Additional records from this section include *Stroboceras*, the bivalves *Posidonia corrugata* and *P. membranacea*, orthoconic nautiloids, gastropods, crinoid ossicles, trilobite pygidia, ostracodes, fish teeth and spines (Higgins, 1961; Morris, 1967b). Rich conodont faunas from horizons 2, 3 and 6 of Morris (1967b) including *Gnathodus girtyi*, *G. bilineatus*, *Idioprioniodus conjunctus*, *Lochriea nodosa*, *L. mononodosa*, *L. commutata*, *Mestognathus bipluti* and *Çavusgnathus naviculus* are also reported from the sequence (Higgins, 1961, 1975).

Interpretation

Although no formal lithostratigraphical name has been applied to the Namurian succession in the Cauldon area, the exposed beds are the lateral equivalent, at least in part, of the Lask Edge Shales recognized in the Macclesfield and Stoke-on-Trent areas to the west (Evans *et al.*, 1968; Rees and Wilson, 1998), and the Edale Shales and the Upper Bowland Shales in basins

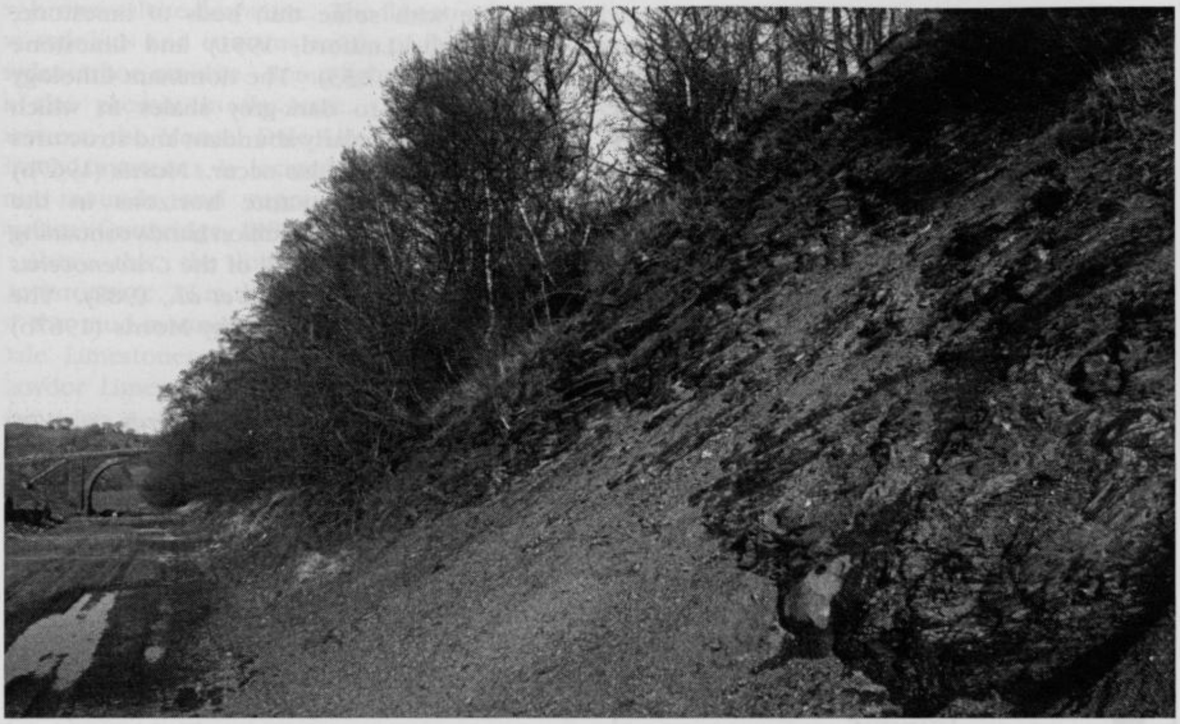


Figure 7.33 General view of Pendleian strata (mainly fissile mudstones) at Cauldon Railway Cutting. Note the prominent bullion beneath the lens-cap scale, lower right. (Photo: P.J. Cossey.)

to the north. The section forms part of a condensed Pendleian sequence deposited towards the southern margin of the North Staffordshire Basin (Trewin and Holdsworth, 1973) over an upstanding mass of Dinantian carbonates at the margin of the Staffordshire Shelf (Chisholm *et al.*, 1988). Evidence presented by Fraser and Gawthorpe (1990) and Ebdon *et al.* (1990) suggests that the rift systems that controlled the basin's development at an earlier stage in its history (during Dinantian times) became progressively inactive during this period as the basin entered a post-rift thermal subsidence phase at this time.

The serial repetition of goniatitic marine bands most probably reflects the development of small-scale, eustatically controlled sedimentary cycles (Holdsworth and Collinson, 1988), the definition, anatomy and significance of which, in terms of lithology, faunal content and palaeosalinity, has yet to be fully evaluated. Studies of broadly comparable but thicker sequences of a similar age in the Craven Basin to the north (Brandon *et al.*, 1995, 1998) indicate that these bands may have been formed during periods of sea-level highstand and full marine salinity, while the remaining parts of the succession formed during the intervening periods when sea levels were lower and conditions in the basin less saline.

Although records of *Cravenoceras leion* most probably indicate an E_{1a} age for the lower beds (Morris, 1967b, 1969), the presence of certain eumorphoceratid taxa, at horizons 5 and 6 of Morris (1967b) (e.g. *Ed. 'Eu.'* cf. *stubblefieldi* and *Eu.* sp. form A of Moore, 1946), appears to support the original view of Morris (1967b, 1969) that the upper part of the succession might be of E_{1b} age. This view is endorsed by N. Riley (pers. comm., 2003) who has suggested that this part of the succession 'is almost certainly the equivalent of the Cravenoceras brandoni Marine Band' and of $E_{1b}1$ age. A lower Namurian (Pendleian) age for these beds is confirmed by the presence of ***Kladognathus–Gnathodus girtyi simplex*** Zone conodont assemblages (Higgins, 1975, 1985).

Conclusions

Cauldon Railway Cutting offers arguably the finest section of basal Namurian (Pendleian) strata in north Staffordshire. Traditionally the section has been regarded as providing an almost complete section through the *Cravenoceras leion* Zone (E_{1a}). However, refinements in Pendleian ammonoid biostratigraphy suggest that the upper part of the sequence may lie within the overlying E_{1b} goniatite zone. Notwithstanding these stratigraphical uncertainties, the section remains an important reference section for regional intrabasinal and interbasinal correlations of Pendleian strata throughout western Europe. Rich goniatite and conodont faunas make this a promising site for further stratigraphical and palaeoecological research.

GRACE DIEU, LEICESTERSHIRE (SK 433 182)

Introduction

Lying within woodland less than 1 km north-east of Thringstone in north-west Leicestershire, the disused quarry workings at Grace Dieu (SK 433 182) expose a unique sequence of shallow-marine, dolomitic limestones; part of the Ticknall Limestone (Brigantian). The lower boundary of this sequence is unexposed, but is probably an unconformable contact with Precambrian basement. At its upper boundary the sequence is truncated by a Triassic unconformity. The rocks of this site have a long but intermittent history of research, being mentioned or featured in work by Hull (1860), Fox-Strangways (1905), Parsons (1918a), Mitchell and Stubblefield (1941), Spink (1965), Kent (1968), Monteleone (1973) and more recently by Carney (1995). The significance of the site derives from its unique palaeogeographical position, being the southernmost Lower Carboniferous section on the Hathern Shelf, in close proximity to the eroding basement that formed the contemporary northern shoreline of the Wales–Brabant Massif.

Description

The strata exposed are close to horizontal. A thick section described in detail by Kent (1968) records almost 17 m of Carboniferous strata below the Triassic unconformity. At the base of the section, Kent (1968) recorded a 1.2 m-thick massive brown sugary oolite capped by a 'deeply pocketed erosion surface' or palaeokarst (Figure 7.34). This erosion surface probably corresponds to the marl-filled pockets and cavities noted here by Fox-Strangways (1905) and Parsons (1918a). Above this, the same author

Figure 7.34 Dissolution surface in the Ticknall Limestone (Brigantian) at the Grace Dieu GCR site. Note that part of this section is currently obscured. (Photo: P.J. Cossey.)

recorded 2.7 m of bedded dolomitic limestone with *Gigantoproductus* and crinoids, 2.4 m of dolomitic and brecciated limestone, 1.2 m of limestone conglomerate containing angular to rounded clasts set in a purplish marly matrix, and more than 9 m of well-bedded and locally dolomitized limestone. The most recent account of the site (Carney, 1995), however, recorded less than 5 m of exposure. Carney (1995) noted undulating bounding surfaces to beds, discontinuous internal partings, lenticular bodies of laminated skeletal wackestones and packstones, and lateral transitions between bedded strata and cemented limestone breccias. Most of the fossils in the Grace Dieu section are fragmentary or dolomitized, but brachiopods (including *Spirifer* and *Gigantoproductus*), crinoid debris, and corals have all been recognized (Parsons, 1918a; Kent, 1968; Monteleone, 1973).

Interpretation

The proximity of the flat-lying and apparently undisturbed dolomitic limestones of the Grace Dieu section to the Neoproterozoic rocks exposed less than 100 m away in Grace Dieu Brook suggests that the Lower Carboniferous sequence in this area most probably rests directly on Charnian basement (e.g. Kent, 1968; Carney, 1995). Unfortunately, the contact is not exposed, and although faulting along the southern margin of the inlier cannot be ruled out entirely (Carney, 1995), there is no evidence for this. Carney (1995) invoked uplift along the Thringstone Fault during the Caledonian orogeny to explain the stratigraphical overstep of the Carboniferous limestone onto the Neoproterozoic basement in this area.

Although many primary lithological characteristics have been obscured by dolomitization, the fauna clearly indicates deposition in a marine setting. The bioclastic nature of at least some of the limestones (Carney, 1995) together with the presence of oolites (Kent, 1968) suggests high-energy, probably shallow-water conditions – depositional conditions that are consistent with the palaeogeographical setting of the site, close to the shoreline along the northern edge of the Charnwood Massif (Kent, 1968), part of the Wales–Brabant Massif to the south. These interpretations are also supported by the occurrence of pebbles of Charnian basement in some beds. The limestone breccias have been variously interpreted as the result of contemporaneous brecciation in a shallow-water environment (Mitchell and Stubblefield, 1941), pseudo-breccias resulting from pre-Triassic diapiric uplift (Spink, 1965), or as products of karstic dissolution processes operating along fault and joint systems before or during deposition of the overlying Triassic strata (Carney, 1995). The more recent of these interpretations is probably the most reliable, and cavities and erosion surfaces in the lower part of the section (Fox-Strangways, 1905; Parsons, 1918a; Kent, 1968) may also be the result of subaerial (karstic) weathering processes (Carney, 1995; cf. Monteleone, 1973).

Stratigraphically, Monteleone (1973) assigned the strata exposed at Grace Dieu to the Ticknall Limestone (see Figure 7.3). This was based on the gross lithological and faunal similarities between the strata at Grace Dieu and the Ticknall Limestone at its type locality (see **Ticknall Quarries** GCR site report, this chapter). The evidence for the age of the beds at Grace Dieu is scant, but the presence of *Gigantoproductus* (Kent, 1968) is consistent with a Brigantian age.

The site provides significant evidence for the development of nearshore shallow marine facies on the southernmost shore of the Hathern Shelf during late Dinantian times. Although the rather complex interplay of lithofacies, diagenesis, dolomitization, post-depositional brecciation and subsurface karstification is still rather poorly understood, the application of modern analytical approaches would probably reveal much more of the geological history of this intriguing and regionally significant site. Micropalaeontological investigation has the potential to provide significant new data to constrain regional correlations and determine the age of the sequence.

Conclusions

The sequence exposed at Grace Dieu provides rare evidence for the development of late Dinantian shallow marine environments along the northern shoreline of the upstanding and eroding Precambrian basement of the Charnian Massif. The locality also has significant potential as a source of new sedimentological and palaeontological data that may shed new light on the geological history of this rather poorly known area within the British Lower Carboniferous sequence.

TICKNALL QUARRIES, DERBYSHIRE (SK 360 238)

Introduction

The Ticknall Quarries GCR site is located 12 km south of the centre of the Derby, just east of the village of Ticknall (SK 360 238). A series of somewhat overgrown and partially flooded abandoned lime quarries expose 10–11 m of flat-lying Brigantian limestones, shales and dolostones of the Ticknall Limestone (type locality). This section offers the best sequence of latest Dinantian strata in the region, providing important evidence for the development of nearshore shallow marine environments on the Hathern Shelf, north of the Wales–Brabant Massif. The site is also significant because of its historically important and diverse shelly faunas. Hull (1860) and Fox-Strangways (1905, 1907) mentioned the Ticknall quarries, and Parsons (1918a), Mitchell and Stubblefield (1941), and Monteleone (1973) provided more detailed accounts, including extensive faunal lists. Recent publications of significance arising from the British Geological Survey re-survey of the area are by Ambrose and Carney (1999) and Ambrose (1999).

Description

Parsons (1918a) and Mitchell and Stubblefield (1941) discussed the nature and stratigraphical subdivision of the succession, but the stratigraphical terminology and thicknesses given here follow the work of Monteleone (1973) as modified by Ambrose and Carney (1999). Within the Ticknall Limestone, two informal units are recognized. The lower unit, equivalent to the 'limestone and shale member' of Monteleone (1973), comprises up to 6 m of interbedded limestone and fissile mudstone (Figure 7.35). The limestones are grey, muddy and finely crystalline; bedding planes are undulatory and thin beds appear nodular – a feature probably enhanced by pressure-solution during diagenesis. The mudstone interbeds are between 10 cm and 30 cm thick and are highly

Figure 7.35 Interbedded limestones and fissile mudstones in the lower unit of the Ticknall Limestone (Brigantian) at the Ticknall Quarries GCR site. The hammer towards the centre of the photograph indicates scale. (Photo: M.A. Purnell.)

fossiliferous. Fossils, including brachiopods, solitary and colonial corals, and crinoids are common throughout the lower unit. Lithologically, most of this unit corresponds to 'facies 2' of Ambrose and Carney (1999), characterized by fine-grained muddy limestones and coarser skeletal wackestones and packstones. The lowest parts of the Ticknall Limestone, previously observed in caves associated with the quarrying (e.g. Parsons, 1918a), are no longer exposed.

The upper unit, equivalent to Monteleone's (1973) 'thinly-bedded limestone and dolomite member', is dominated by dolostones. These are buff-grey in colour but are commonly stained red, yellow or purple. They are finely crystalline and massively bedded, with a few clay partings. The siliciclastic content of the beds varies, some being fine- to very fine-grained dolomitic sandstones. The dolostones are locally fossiliferous, with some beds dominated by brachiopods, especially in the lower 3 m (Monteleone, 1973). Lithologically most of this unit can be assigned to 'facies 1' of Ambrose and Carney (1999).

The macrofauna of the Ticknall Limestone is well known, and extensive lists of taxa are given by Parsons (1918a), Mitchell and Stubblefield (1941) and Monteleone (1973). In addition, micropalaeontological preparations of the limestones have revealed foraminifera, ostracodes and conodonts, while shale beds are rich in foraminifera, ostracodes, conodonts, fish teeth, sponge spicules, crinoid calices, echinoid plates and scolecodonts (Monteleone, 1973). Wilson (1880) listed a diverse fish fauna from mudstones in the formation.

The base of the formation is not exposed at this site but the Ticknall Borehole reveals that the lower boundary is unconformable with, or possibly faulted against, the underlying Cloud Hill Dolostone (Ambrose and Carney, 1999). Most reports indicate that the Ticknall Limestone is unconformably overlain by red and green marls of probable Triassic age, and strata exhibiting this stratigraphical relationship are exposed in the north-eastern part of the quarry complex, beyond the northern limit of the Ticknall Quarries GCR site (e.g. Monteleone, 1973). However, a section in the south-west part of the site reveals the top of the Ticknall Limestone overlain by Millstone Grit (Ambrose and Carney, 1999).

Interpretation

Historically, few age-diagnostic macrofossils have been recovered from the Ticknall Limestone at this site, but all workers have agreed on a D_2 (Brigantian) age for these beds (e.g. Fox-Strangways 1905, 1907; Parsons, 1918a; Mitchell and Stubblefield, 1941; Monteleone, 1973). This age is based on the occurrence of taxa such as *Gigantoproductus*, *Productus productus*, *Pugilis pugilis*, *Dibunophyllum bipartum*, *Siphonophyllia junceum* and *Nemistium edmondi*, but, except for the last named, all these taxa are now known to have an Asbian to Brigantian range (Riley, 1993). The conodonts listed in Monteleone (1973), especially *Gnathodus girtyi collinsoni*, indicate a Brigantian age, and more recently this has been confirmed by foraminiferal evidence (Riley, 1997).

As noted above, the contact between the Ticknall Limestone and the underlying Cloud Hill Dolostone is not conformable. Foraminifera indicate that the top of the Cloud Hill Dolostone at this locality is of early Asbian age (Riley, 1997), indicating that strata of late Asbian age are missing from the sequence (Ambrose and Carney, 1999).

In terms of depositional environments, Ambrose and Carney (1999) interpreted rocks of their facies 2 as being deposited in shallow-marine, high-energy, wave- or current-dominated environments, with periods during which lower-energy shallow-shelf conditions prevailed. The skeletal grainstones of facies 1 were thought also to have been deposited in high-energy, nearshore, shallow marine settings, although most lithological details were destroyed during dolomitization.

The rocks exposed at this site are crucial in understanding the late Dinantian depositional history and evolution of palaeoenvironments close to the northern shoreline of the Wales–Brabant Massif, and the spatial and temporal relationships of these deposits to Brigantian sequences elsewhere. The site is also significant as the type locality for the Ticknall Limestone, preserving the finest section of shallow marine Brigantian strata in the Midlands. Although recent British Geological Survey work (Riley, 1997; Ambrose and Carney, 1999) has gone a long way towards bringing interpretations of the sequence exposed at this site into a modern geological framework, there is still considerable scope for significantly improving the understanding these deposits through the application of modern palaeontological and sedimentological methods.

Conclusions

The sequence exposed at Ticknall Quarries represents the best evidence for late Dinantian nearshore marine environments in the Midlands, and provides evidence that is central to understanding the geological history and evolution of the Hathern Shelf and Widmerpool Gulf during this time period. The site is also significant as the type section for the Ticknall Limestone, and because of the diverse shelly faunas collected from here over the last 100 years. Furthermore, the site has great potential for studies using modern palaeontological and sedimentological techniques.

BREEDON CLOUD QUARRY, LEICESTERSHIRE (SK 413 214)

Introduction

The Breedon Cloud Quarry GCR site is a working quarry (also referred to as 'Cloud Hill Quarry') (SK 413 214) located south of Breedon-on-the Hill in north-west Leicestershire. The site exposes several hundred metres of steeply dipping Lower Carboniferous limestones and dolostones. The early Chadian Milldale Limestones comprise a sequence dominated by bedded dolostones with some chert and dolomitic sandstones. The overlying late Holkerian to Asbian Cloud Hill Dolostone, is made up of bedded dolostones and dolomitized mud-mounds. Most of the sequence was deposited in a nearshore shallow marine shelf setting on the Hathern Shelf, with evidence of storm events and shallowing-upwards. A regionally significant unconformity, the 'Main Breedon Discontinuity', separates the two formations. The importance of the site derives from the quality and thickness of outcrop and the exposure of conformable and unconformable contacts between the various formations and members represented; it is also the type locality for a number of locally significant lithostratigraphical units and for the stratigraphically useful brachiopod *Levitusia humerosa*. Key references to the strata exposed here include Fox-Strangways (1905, 1907), Parsons (1918a), Mitchell and Stubblefield (1941), Mortimer *et al.* (1970) and Monteleone (1973). Recently, Ambrose and Carney (1997) have compiled a detailed report on this site, and much of what follows here, including stratigraphical terminology, is based on their work.

Description

Approximately 300 m of Lower Carboniferous strata are exposed at this site. The beds mostly dip towards the west, the dip increasing from 40° to 50° on the west side of the quarry to 60° to 90° on the eastern side. The lowest exposed beds are assigned to the Milldale Limestones. This unit, more than 200 m thick in the quarry, comprises grey to buff, bedded, crystalline dolostones with undulating bedding surfaces, commonly with clay or shaly partings up to 10 cm thick. Chert nodules in parts of the sequence show evidence of in-situ brecciation. A limestone interval with a significant siliciclastic component (the Holly Bush Member) recognized towards the middle of this sequence at the southern end of the quarry is approximately 45 m thick. This contains beds of fine- to medium-grained dolomitic sandstone, sandy dolostone and beds with well-rounded pebbles up to 5 cm in diameter. The pebbly beds contain a variety of clast types, including some of volcanic origin which may be derived from the Charnian basement. An interval of non-dolomitic or only partly dolomitized grey, fine- to coarse-grained, bedded, skeletal, oolitic and peloidal grainstones lies above the Holly Bush Member. The uppermost part of the formation is entirely dolostone.

The fauna of the Milldale Limestones is quite diverse. Brachiopods, including *Levitusia humerosa* and chonetoids (see Figure 7.36), are the most common fossils, but crinoid debris, solitary and colonial corals, gastropods and the echinoid *Archaeocidaris* are also known. Mitchell and Stubblefield (1941) include a more complete listing; Monteleone (1973) also recorded bivalves, conodonts, fish remains, ostracodes and scolecodonts.

The top of the Milldale Limestones is truncated and eroded by the 'Main Breedon Discontinuity'. This is one of three sharp discontinuities recognized in the quarry (Ambrose and Carney, 1997) which dip

Figure 7.36 Fallen dolostone block from the Milldale Limestones containing numerous internal molds of large brachiopods including *Levitusia humerosa*. The large *L. humerosa* in the foreground is 6 cm wide. (Photo: M.A. Purnell.)

westwards with the adjacent strata. The Lower Breedon Discontinuity occurs within the Milldale Limestones and the Upper Breedon Discontinuity occurs within the Cloud Hill Dolostone. The Main Breedon Discontinuity defines the base of the Cloud Hill Dolostone for which the quarry represents the type locality. In the northern part of the quarry the Cloud Wood Member (up to 36 m thick) is recognized within the lower part of the formation. The member comprises a lower mudstone-dominated unit, and an upper unit of bedded or massive crystalline dolostones, with evidence of syn-depositional slumping.

In most of the quarry the 125 m-thick Cloud Hill Dolostone is not subdivided into formally defined stratigraphical units, but distinctive 'bedded dolostone' and 'mud-mound' facies are recognized (Ambrose and Carney, 1997). The bedded dolostones are crystalline with undulatory bedding planes, many with mudstone or clay partings. Crinoid remains are abundant in some beds, and brachiopods and corals also occur. Evidence of small-scale cross-stratification is also present; originally the bedded dolostones were probably skeletal grainstones. The mud-mound facies that makes-up the bulk of the formation is equivalent to Monteleone's (1973) Bioherm Member, and the upper four of five subdivisions recognized by Mitchell and Stubblefield (1941) above the level of the Main Breedon Discontinuity (see Ambrose and Carney, 1997, table 2). Buff to grey, massive, crystalline dolostones represent the dominant lithology. They are generally fossiliferous, containing a diverse brachiopod fauna, crinoids, corals, bivalves, gastropods, nautiloids and ammonoids, although most of the fossils have been destroyed by dolomitization (for a more complete faunal listing, see Mitchell and Stubblefield, 1941).

In the upper part of the face in the south-west corner of the quarry, bedded, nodular and crystalline dolostones of the Ticknall Limestone are exposed. The base of the formation is taken at the first palaeosol in a sequence of thinly bedded, fossiliferous dolostones.

Interpretation

Early attempts at correlation of the Breedon Cloud sequence hinged on comparisons with the outcrops to the north at Breedon-on-the-Hill: Fox-Strangways (1905, 1907) assigned these beds to the D Zone (Asbian to Brigantian) while Parsons (1918a) assigned them more specifically to the D2 Subzone (Brigantian). With the exception of a mid-Tournaisian determination based on spores (Mortimer *et al.*, 1970), subsequent correlations of the lower part of the sequence were based on correlation of the beds containing *Levitusia humerosa* within the Milldale Limestones. These beds have been assigned a C_2 (Alexander, 1934; Mitchell and Stubblefield, 1941) or C_2S_1 (Monteleone, 1973) age (i.e. Chadian to Arundian). More recently, they have been assigned an early Chadian age (Riley in Ambrose and Carney, 1997).

The beds above the Main Breedon Discontinuity generally have been taken to be of Asbian age (Mitchell and Stubblefield, 1941; Monteleone, 1973). Palynological analysis indicates that the Cloud Wood Member was deposited some time during Holkerian–Asbian times (Turner, 1996) and the presence of the ammonoid *Goniatites* in the mud-mound facies higher in the formation indicates a late Asbian age for this unit (Ambrose and Carney, 1997; Ambrose and Filmer, 1999).

The Main Breedon Discontinuity was described as a fault by Parsons (1918a) and Monteleone (1973), but Mitchell and Stubblefield (1941) regarded it as an unconformity. Ambrose and Carney (1997) interpreted the feature as an angular unconformity representing an interval of erosion and/or non-deposition spanning the early Chadian to late Holkerian time interval. According to Ambrose and Carney (1997) this is an unconformity of regional significance, corresponding to an episode of non-deposition or erosion also seen in the Widmerpool Gulf and on the Staffordshire Shelf (see **Caldon Low Quarry** GCR site report, this chapter). Changes in dip adjacent to the unconformity in Breedon Cloud Quarry indicate tectonic disruption along the surface, and the slumping evident in the Cloud Wood Member may also be related to activity along this discontinuity (Ambrose and Carney, 1997). The other Breedon discontinuities are less significant. The Lower Breedon Discontinuity is interpreted as a slight angular unconformity (Ambrose and Carney, 1997); the nature of the Upper Breedon Discontinuity is less clear, but it seems to be an unconformity associated with post-depositional steepening of bedding, possibly related to movement along the Main Breedon Discontinuity (Ambrose and Carney, 1997).

The locally high siliciclastic content of the rocks, the abundance of fragmentary skeletal remains, and evidence of grading and minor cyclicity indicate that the Milldale Limestones were deposited during storm events in a shallow proximal ramp setting (Ambrose and Carney, 1997). The strata of the Cloud Wood Member, exposed at the northern end of the quarry, reflect mud-dominated deposition in a quiet, relatively deep-water setting, with the interbedded carbonates interpreted as storm deposits (Ambrose and Carney, 1997). The internal structure and composition of the overlying mud-mound facies has been destroyed by dolomitization, but the thickness of the buildup indicates a water depth of at least 40 m. The undifferentiated dolostones of the Cloud Hill Dolostone at the southern end of the quarry are interpreted as storm-generated platform carbonate deposits similar to those of the underlying Milldale Limestones. They preserve evidence of gradual shallowing-up towards emergence and palaeosol development in the overlying Ticknall Limestone (Ambrose and Carney, 1997).

Of all the Lower Carboniferous inliers of the Hathern Shelf, this site preserves the thickest sequence, spans the longest time interval and contains the most diverse suite of sedimentary rocks; in terms of stratigraphy, structure, palaeogeography and depositional environments it is among the most informative Dinantian section in the Midlands. The site is also significant as the type locality for the Cloud Wood Member, the Cloud Hill Dolostone, the Holly Bush Member of the Milldale Limestones, and for the diagnostic Chadian brachiopod *Levitusia humerosa* which is widely known across Europe and from the Russian Platform. The regional significance of the site notwithstanding, dating and correlation of much of the sequence is still rather poorly constrained. Detailed micropalaeontological analysis focusing on groups resistant to destruction by dolomitization (such as conodonts) may lead to a better understanding of the geological history of the strata exposed at the quarry and of the early Carboniferous geological history of the Midlands.

Conclusions

Breedon Cloud Quarry is significant as the site where several locally important lithostratigraphical units (e.g. Cloud Hill Dolostone, Cloud Wood Member, Holly Bush Member) are defined. Furthermore, because of the rich diversity of its sedimentological, palaeogeographical, stratigraphical and structural features, this site has regional significance as one of the most geologically informative Lower Carboniferous sections in the English Midlands.