British Silurian Stratigraphy

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Chapter 4

The Wenlock Series

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INTRODUCTION

The second series of the Silurian System, the Wenlock Series, takes its name from the Wenlock area in Shropshire, which includes the small town of Much Wenlock and Wenlock Edge. Bassett *et al*. (1975) undertook the important stratigraphical revision of this ground that provided the basis for its formal acceptance as the type area. The historical background concerning the decisions by the Silurian Subcommission of the International Commission on Stratigraphy, which concluded with the international ratification of the Wenlock as the second series (Martinsson *et al*., 1981), has been fully documented by Holland (1989).

Murchison (1833) was the first to use the term 'Wenlock' in a stratigraphical context, when he referred to the Wenlock Limestone occurring in the region of Wenlock and Wenlock Edge. A year later (1834) he introduced the term 'Wenlock Shale'. Shortly afterwards he employed both these terms again, firstly when he (1835) presented in outline his Silurian System, and then in his (1839) *magnum opus* on the rocks and fossils of this period. Since the publication of *The Silurian System*, the name 'Wenlock' has been virtually universally used to refer to strata of this interval of time in Earth history. The Salopian of Lapworth (1880a), a stratigraphical term introduced for strata of Wenlock and lower Ludlow age, has long been abandoned (see Cocks *et al*., 1971). Further comment on the historical usage of the term 'Wenlock' can be found in Whittard (1961), Bassett (1974a, 1989a), Bassett *et al*. (1975), and D.A. Bassett (1991).

The Wenlock Series contains two stages, the Sheinwoodian and the Homerian. The basal boundary stratotype for the series, which is also coincident with that of the Sheinwoodian Stage, occurs at Leasows, which forms part of the Hughley Brook GCR site. The stratotype for the base of the Homerian Stage occurs at Whitwell Coppice, also a GCR site. The type area also takes in numerous sections which effectively act as body stratotypes for the series and which, too, are all GCR sites, for example Eaton Track and the Longville–Stanway Road Section.

OCCURRENCE

Wenlock Series strata crop out in the UK in the West Midlands of England, the Welsh Borderland, Wales, the Lake District, the western flank of the Pennines and the Southern Uplands and Midland Valley of Scotland (Cocks *et al*., 1971, 1992). Subsurface records of rocks of this age are also known from East Anglia and Hertfordshire (Woodcock and Pharaoh, 1993). In the West Midlands (Walsall–Dudley district) and throughout much of the central Welsh Borderland, these two areas comprising the main outcrop (e.g. Wenlock Edge) and inliers (e.g. Malverns, Woolhope, May Hill), many Wenlock age sequences are uninterrupted and are assumed to be reasonably complete, though full biozonal control is rare. In some of the areas within this region, for instance the Mendips and Cardiff, the upper and/or lower part of the Wenlock is missing or remains unproven. To the south-west, in Pembrokeshire, there is uncertainty as to where the Wenlock–Ludlow boundary should be drawn within the local succession. Much of central and north Wales has thick sequences of Wenlock rocks, with the Denbigh–Conway district having the most biostratigraphically refined sequence.

Wenlock sequences in the main Lake District (Coniston to Ashgill, and Windermere areas) and the Howgill Fells immediately to the east are largely complete, but the Horton-in-Ribblesdale and particularly the Cross Fell (Pennines) inliers have breaks in the succession, with Cross Fell, additionally, lacking deposits of Homerian age.

The Southern Uplands as a whole has a fairly full Wenlock succession, with only the youngest, post *lundgreni* Biozone horizons being unrepresented. Of the many Silurian inliers present in the Midland Valley of Scotland, those of Lesmahagow, the Hagshaw Hills, Carmichael, and the Pentlands all contain presumed Wenlock strata, though the age constraint on many of these sequences is often found wanting due to their essentially non-marine nature. The Girvan district includes provable Wenlock (Cocks and Toghill, 1973; Dorning, 1982) and, also, does the Stonehaven area (Marshall, 1991), the Silurian deposits of the latter being regarded until recently as Přídolí in age.

PALAEOENVIRONMENTAL SETTING

The Wenlock deposits of the UK were laid down in several major sedimentary basins and associated platform areas (Chapter 1, Figure 4.1 herein; Bassett, 1974a; Hurst *et al*., 1978; Siveter *et al*., 1989; Holland, 1992). The West Midlands

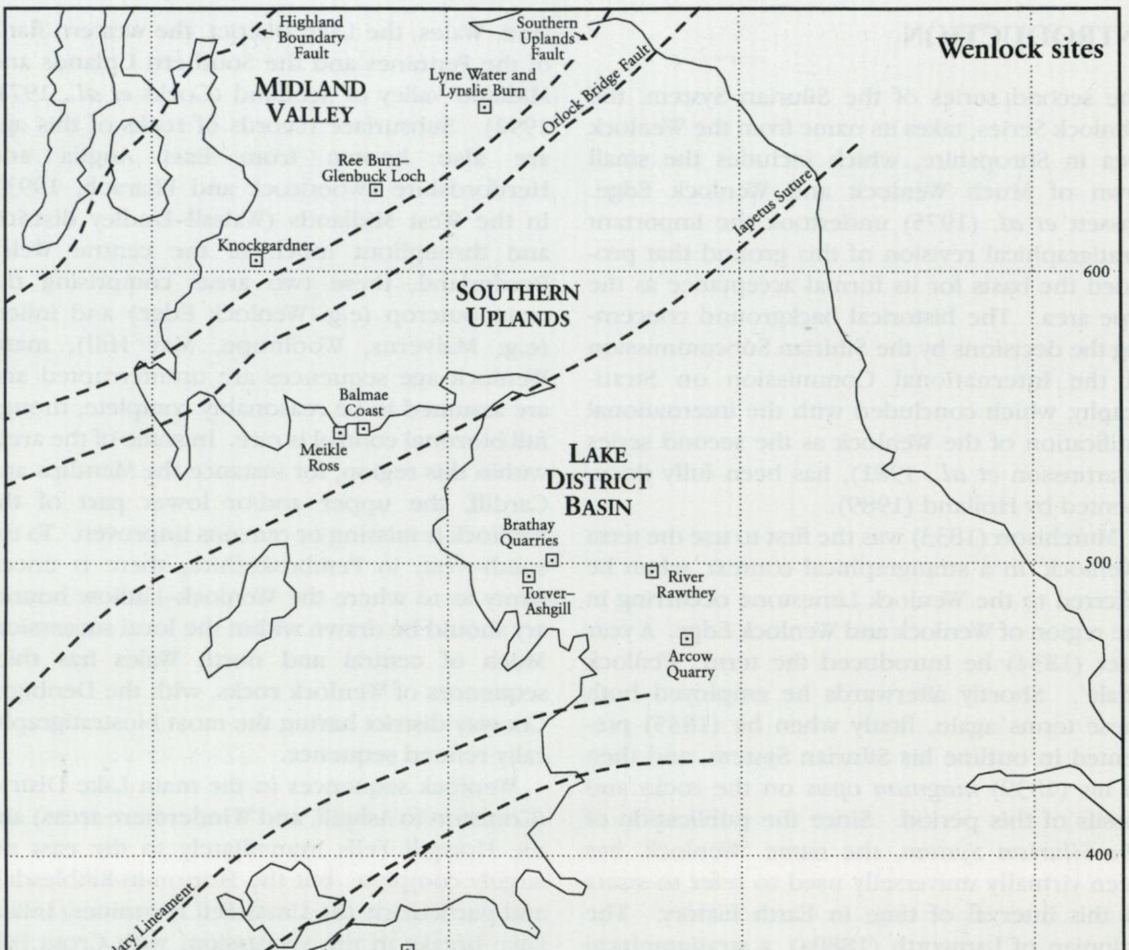


Figure 4.1 Distribution of the Geological Conservation Review sites for the Wenlock Series, set against the palaeogeographical elements of Silurian Britain.

and Welsh Borderland inliers, together with the Wenlock and Ludlow districts and the southern Wales (Cardiff) and Pembrokeshire areas, were all variously situated during this time on some part of the shelf associated with the Midland Platform or on the shoreline area of the Welsh Basin. Central Wales was the site of the deeper part of this basin, which was dominated during this period by the Montgomery and Denbigh troughs. The deposits of the Anglian Basin on the north-east side of the Midland Platform have been related to those of similar age in the Ardennes and Brabant massifs in Belgium (Pharaoh *et al.*, 1987). The Lake District Basin occupied an offshore area to the north-west of the Midland Platform. The Welsh, Anglian, and Lake District basins are all associated with eastern Avalonia, whereas Wenlock rocks of the Southern Uplands of Scotland were deposited to the north of the Iapetus Suture. The sediments of the Midland Valley of Scotland are, in the main, indicative of non-marine environments, though shallow marine conditions persisted into the early Wenlock in the Girvan area.

The Wenlock Epoch saw the development of a wide range of clastic and carbonate facies. In the Anglo-Welsh region limestones predominated during the early and, in particular, the late Wenlock in the shelf areas to the west and south-west of the Midland Platform, that is the West Midlands and the Welsh Borderland areas. Carbonate mud deposition prevailed during mid-Wenlock times in the same areas, which were mostly characterized by shelly faunas. Siltstones and sandstones are typically present adjacent to the south and south-west margin of the Welsh Basin, as evidenced by sites in Tortworth, Cardiff, and Pembrokeshire. In the deeper, central parts of the Welsh Basin, turbidites and hemipelagites were deposited, and associated there with the planktonic graptolites. Some areas on the upper slope region, around Builth and the Long Mountain for example, show a more mixed facies and fauna: muds and graptolites together with carbonates and shells. Algal limestones developed on offshore topographical highs of Precambrian rocks in Radnorshire. Mudstones and to a lesser degree turbiditic sands characterize the Lake District Wenlock, whilst in the Southern Uplands deep marine turbidites are preponderant. The early onset of non-marine conditions in the Midland Valley at this time produced red beds – conglomerates, sandstones and siltstones – which are notable for their early fish fauna. Red beds of possible uppermost Wenlock age are also found in Pembrokeshire. Volcanic rocks are poorly developed with the exception of the Mendips area and, elsewhere in the British Isles, in the Dingle Peninsula, south-west Ireland.

In the Welsh and Lake District basins at least, in terms of sea-level change the Wenlock represents a transitional period between the flooding that occurred during the Llandovery transgression (this rise is manifest in the Southern Uplands and Midland Valley sequences of this age too), and the regressive and final silting-up phase of these basins through the Ludlow and into the Přídolí. This basin filling and the formation of red beds generally are associated with the closure of the Iapetus Ocean.

BIOSTRATIGRAPHY

Wenlock strata in the UK are in general very fossiliferous. Historically the biozonal scheme for subdividing the Wenlock was established on the basis of graptolites from the Welsh Borderland, mainly those from the Builth and Long Mountain districts (Elles, 1900; Wood, 1900); this has since been refined (see Rickards, 1976, 1989b; Bassett *et al.*, 1975; Bassett, 1989a; Chapter 1 herein), and remains that most widely applied for strata of this age both here and abroad. Other groups, particularly of microfossils, have proved useful in adding to the biostratigraphical framework at certain levels or in particular sedimentary facies. For example, the conodont, ostracod, foraminiferan, chitinozoan, and acritarch distribution across the Llandovery–Wenlock boundary interval of the type section has been determined (Mabillard and Aldridge, 1982, 1985), and the biostratigraphy of non-palaeocope ostracods of the type Wenlock area has been documented (Lundin *et al.*, 1991), as has that of certain ostracods through the British Wenlock in general (Siveter, 1978). Discussion of all fossil groups that have biostratigraphical use in the type Wenlock area has been provided by Bassett (1989a). Palynomorphs are particularly useful in dating red bed sequences, and sometimes they can also be put into a biozonal context, such as in the study of sporomorphs from the Silurian inliers of the Midland Valley of Scotland (Wellman and Richardson, 1993), which microflora also shows remarkable similarity with the one from the early Wenlock of the type area (Burgess and Richardson, 1991). Thus correlation of Wenlock strata can sometimes be direct, or is sometimes achieved by a chain of correlation using several fossil groups by way of geographically intermediate sequences.

SITE SELECTION

Most of the GCR sites described here were listed over several decades through the work of the former Nature Conservancy Council as part of the Geological Conservation Review that it instigated. During assessment for this volume, a few of the original GCR sites have been found wanting and omitted, whilst a small number of others have been proposed. Inevitably, some of the sites of Wenlock age encompass Llandovery and/or Ludlow rocks and, occasionally, Přídolí strata as well. The rocks of these other series may form the basis for independent site listing and description in this volume, such as the Ludlow of the Sawdde Gorge section. Where a Wenlock section is continued into deposits of a different series which are less significant, often brief mention is given of the latter in the Wenlock site description, for the sake of completeness.

Several criteria have determined site selection (see Chapter 1), and sometimes sites have been found worthy of inclusion for more than one criterion. The primary reason for selection has been to cover, through the GCR network system, all of the main palaeoenvironments and palaeogeographical and stratigraphical aspects of Wenlock strata that crop out in the UK. Shoreline and platform to basin centre sites are covered for the Welsh Basin. The sites in the Lake District provide adequate facies and stratigraphical coverage, as do those for the Southern Uplands and the Midland Valley. Network coverage has taken into account the international importance of sites in the Wenlock Edge area to Wenlock stratigraphy. Sites significant for historical reasons include, for example, that at Buildwas, which traditionally acted as the unofficial type section for the Llandovery–Wenlock boundary. Palaeontological sites of importance include several in the Builth area, which were used in the establishment of the Wenlock graptolite succession, and Dudley (Wren's Nest) in the West Midlands, which has a worldwide reputation for yielding numerous and various invertebrates of outstanding preservation. Lastly, a small number of sites have been included in the GCR to complete the network coverage that have no particularly unique features, but are necessary complementary sites, so as, usually, to have fully representative palaeogeographical coverage.

HAY HEAD QUARRIES (SP 048 985)

Introduction

The Wenlock rocks of the Silurian inlier of the Walsall area comprise the Coalbrookdale and the Much Wenlock Limestone formations (Bassett, 1974a). Within the lower part of the Coalbrookdale Formation of the Great Barr district to the east of the town there is a discrete carbonate development, the Barr Limestone, which is unique to the inlier. This limestone unit forms the basis of the present site, being formerly mined opencast in the NE–SW line of workings known as Hay Head Quarries. These are mainly located just to the north of the B4151 road from Walsall to Sutton, in which patch of ground the site is contained, but the excavations also continue to the south of this road, towards Daisy Bank (SP 040 977).

F. Jukes (1829), with Sowerby, appears to have been the first to describe fossils from Hay Head, drawing attention to the 'Barr trilobite' and the large orthoconic nautiloids. Murchison (1839) discussed the limestone at Hay Head and formally established the 'Barr trilobite' as *Bumastus barriensis*. J.B. Jukes (1853, 1859) described the limestone and listed the fossils in his surveys of the South Staffordshire Coalfield. The best account available of the geology, fossils and exposures of the Barr Limestone is that of Cantrill (1919). The limestone was also commented on by Lapworth (1889a), Eastwood *et al.* (1925), Whitehead and Eastwood (1927), Butler (1937) and Bassett (1974a, 1977), the last author giving it formal member status within the Coalbrookdale Formation.

Description

The lower Wenlock Barr Limestone Member has a maximum thickness of 9–10 m in the Walsall district (Cantrill, 1919; Butler, 1937), of which only the top 4–5 m are now available (Bassett, 1974a). The best exposures at present in this series of very low quarries are in the north of the outcrop, about 350 m SSE of Aldridge Lodge in the area called 'The Dingle' (SP 052 991), and take the form of small bank and streamside sections. Lithologically, the unit consists of grey and olive, calcareous, blocky and flaggy-bedded shales and siltstones with intercalating layers of limestone nodules. The carbonate bands are 7–25 cm thick and individual nodules have blue-grey centres weathering to buff-coloured. Within that part of the member presently exposed there are three bentonite horizons, the lower two being 2.5 cm thick and the upper one 15 cm (Bassett, 1974a). In the borehole sunk through Silurian strata in Walsall town, four bentonites were recorded from the Barr Limestone (Butler, 1937), but these cannot be matched with the Hay Head examples due to differences in their thicknesses and also those of the intervening shales.

North of the B4151 road to Sutton, the Barr Limestone dips gently at 10° or so to the north-west. South of this road, on the eastern side of 'The Spinney' (SP 045 980), it has been recorded by Cantrill (1919) as dipping ESE. In the gully that continues the line of workings from The Spinney to the south-west, Cantrill also noted calcareous mudstones of the Coalbrookdale Formation overlying the Barr Limestone and dipping to the north-west at 8–10°, whilst farther to the south-east in the gully these beds flatten out and then turn over the axis of a gentle anticline to dip south-east at 8°. It is difficult now to find evidence of these exposures.

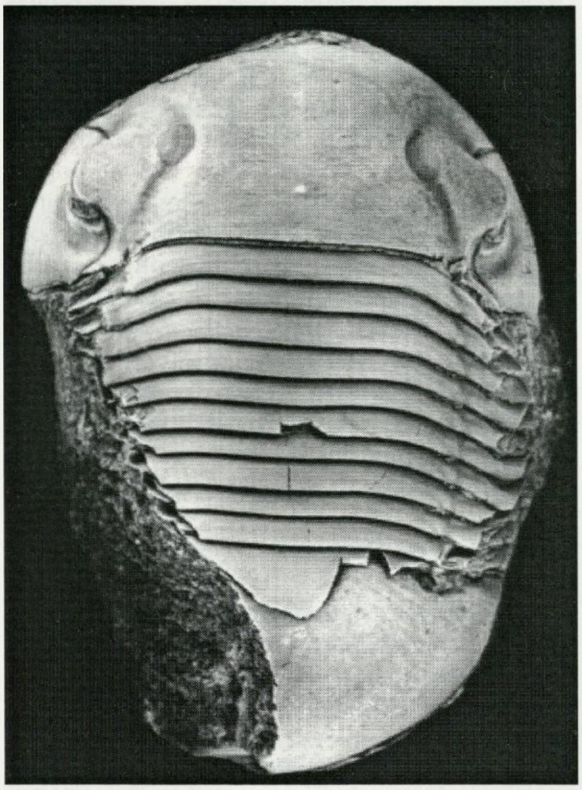


Figure 4.2 The 'Barr Trilobite', *Bumastus barriensis* Murchison, 1839, from the Barr Limestone Member, Coalbrookdale Formation, Wenlock Series, Hay Head Quarries, Walsall area, West Midlands. Lectotype, British Geological Survey specimen (GSM 54421); dorsal view, × 0.8; figured by Jukes (1829), Salter (1849, 1867) and Lane and Thomas in Thomas (1978). (Photo: P.D. Lane.)

The faunal list from the Barr Limestone given by Cantrill (1919) includes brachiopods, corals, orthocones and trilobites. Bassett (1974a) noted the presence of *Dicoelosia biloba* and *Leangella segmentum* from Hay Head, the locality, additionally, being listed (Bassett, 1970a) as one of those providing material for his monographic studies (1970–1977). Of the trilobites from here, in relatively recent times Lane and Thomas (1978) have fully revised *Bumastus barriensis* (see Figure 4.2), Thomas (1978) has established *Proetus* (*Lacunoporaspis*) *oppidanus*, and Siveter (1996) has figured material of *Calymene neotuberculata ludicra*. The limestone provides an abundant conodont fauna, Aldridge (in Bassett 1974a, 1985) recording the following species from Hay Head: *Kockelella walliseri*, *Ozarkodina excavata*, *Panderodus unicostatus* and *Oulodus* sp.. Other microfossils include ostracods, both palaeocope and non-palaeocope, the locality producing specimens for the studies of Siveter (1978, 1980) and Lundin *et al.* (1991), including type material.

Interpretation

In the older literature (e.g. Cantrill, 1919; Eastwood *et al.*, 1925) the Barr Limestone Member was regarded as more or less equivalent to and coeval with the basal Wenlock Woolhope Limestone Formation of the Welsh Borderland Silurian inliers of Woolhope, Malvern and May Hill to the south-west. Bassett (1974a) subsequently refined the age of the Barr Limestone based on the graptolite faunas from the Walsall borehole identified by Elles (in Butler, 1937). He suggested that the occurrence of *murchisoni* Biozone faunas in the mudstones of the Coalbrookdale Formation some 9.5 m below the limestone indicated that the limestone itself was specifically of *riccartonensis* Biozone age and thus not basal Wenlock. The *centrifugus* Biozone was not proven in the borehole, but

Bassett considered it to be probably represented by the 13 m of core that lie between the *murchisoni* Biozone strata and the purple sediments he (and Ziegler *et al.*, 1968b) regarded as Llandovery in age. In the correlation chart of Cocks *et al.* (1992) the Barr Limestone Member is given as coinciding with the top of the *murchisoni* and the bottom of the *riccartonensis* biozones, and slightly overlapping in age with the topmost part of the Woolhope Limestone Formation.

The Barr Limestone formed on the western margin of the land area presumed to exist at this time, the Midland Platform. On the facies/palaeogeographical reconstruction for the early Wenlock of Bassett (1974a), the Walsall area is given as one of offshore calcareous (lower Coalbrookdale Formation) muds at the time of deposition of the Woolhope Limestone Formation, thus reflecting his conclusion on the slight age difference between this unit and the Barr Limestone. Hurst *et al.* (1978) suggested that the Barr Limestone area of carbonate deposition may have been in contact with those of the southern inliers (Woolhope Limestone Formation) and the Dolyhir area (Dolyhir and Nash Scar Limestone Formation) to the south-west during *murchisoni* Biozone times. Holland (1992) also appeared to indicate some contemporaneity of limestone deposition between the Walsall area (Barr Limestone), the southern inliers and the Dolyhir area in *riccartonensis* Biozone times, but lateral continuity of deposition during this time only between the first two of these.

The Hay Head site, stratigraphically, prefaces the nearby Daw End site in the Walsall Silurian inlier, which exposes the upper part of the Coalbookdale Formation and the basal part of the Much Wenlock Limestone Formation. In terms of sites of approximately coeval carbonate facies and palaeogeographically related sites, the Barr Limestone Member of Hay Head Quarries can be broadly compared in particular to the Woolhope Limestone Formation of the Scutterdine Quarry site in the Woolhope Inlier, and to a much lesser extent to the Dolyhir and Nash Scar Limestone Formation of the Dolyhir Quarries site in the Old Radnor area.

Conclusions

Hay Head Quarries are important in displaying a significant carbonate development, the Barr Limestone Member of the Coalbrookdale Formation, which is found only in the Silurian inlier of the Walsall area. Together with the adjacent Daw End site, this site provides a fairly complete facies and stratigraphical coverage through the Walsall Silurian inlier. Fossils from here have been used since the early to mid-19th century for systematic and dating purposes and it forms the type locality for various taxa. It is used for research purposes on a national basis.

DAW END RAILWAY CUTTING (SK 036 003)

Introduction

Daw End Railway Cutting is located within the Silurian inlier of the Walsall district, which is surrounded by or faulted against Carboniferous strata. In this inlier, the Silurian rocks generally dip at about 10° or less into the north-west quadrant. Knowledge of the Wenlock rocks in the Daw End area has been gained through three main types of activity. A great number of quarries, pits and shafts were opened up to work the upper Wenlock Much Wenlock (Dudley) Limestone Formation, such operations probably dating even from Roman times, and mining of the Coal Measures also sometimes tapped into Silurian sediments (Cantrill, 1919). The construction in the mid-19th century of the nearby Rushall Canal made available at that time very fossiliferous sections through the Coalbrookdale Formation and the younger Much Wenlock Limestone Formation. Lastly, construction in 1877 of a branch of the Midland Railway exposed these two units in the Daw End cutting, the older formation to, probably, an unrivalled extent.

Murchison (1839) described the Walsall Silurian and referred to limestone workings at Daw End. Shortly afterwards Jukes (1853, 1859) described the Silurian geology of this district and a list of fossils was provided therein by Salter. Oliver (1877) was the first to describe the cutting itself, whilst Cantrill (1919) provided detailed data on the section and surrounding workings. The latter account, together with that of Butler (1939), are the best descriptions available of the exposure, though it is also discussed in Crossfield and Johnston (1914), Whitehead and Eastwood (1927), Hill *et al.* (1936) and Bassett (1974a). Most recently, Ratcliffe (1988) has investigated the sedimentology of the Much

Wenlock Limestone Formation of the Walsall (and Dudley) area.

Description

The railway section is about 1 km long and approximately coincides with an ENE–WSW trending fault that downthrows to the north and has shifted the strata on the southern side of the cutting to the west (Cantrill, 1919). Butler (1939) provided the following description for the section on the north bank of the track, east of the Rushall aqueduct (Figure 4.3):

Lower Quarried Limestone, Much Wenlock Limestone Formation	4+ m. Dark grey, medium-grained limestone, weathering brown, beds 10–30 cm thick with thin grey shale partings. Few fossils.
Basement Beds, Much Wenlock Limestone Formation	3.2 m. Thin (2.5 cm) beds of mainly fine-grained blue–grey limestones separated by grey shale beds of similar thickness at the base, but thinner towards the top. Contains ballstones. Very fossiliferous.
Coalbrookdale Formation	63+ m. Grey fossiliferous mudstones with bands of calcareous nodules and occasional thin, laterally impersistent beds of fine-grained limestone.

The strata of the Coalbrookdale Formation, which are extensively exposed, represent the upper part of this unit in the area. A deep boring put down in Walsall town encountered, also, some 237 m of it (Butler, 1937; Bassett, 1974a). Within the formation, both the soft grey mudstones and the occasional, very thin, discontinuous limestone bands are very fossiliferous, the fossils often being washed out whole from the steep banks. Corals, cornulitids, brachiopods, gastropods and trilobites from this horizon of the cutting are noted in the faunal list of Cantrill (1919). This list as a whole needs revision, though many of the brachiopods, which in terms of specimens and species are the most abundant part of the macrofauna, have received modern treatment by Bassett (1970a, 1972, 1974b, 1977), who has recorded from the Coalbrookdale Formation of the cutting the following taxa, some examples of which he figured: *Skenidioides lewisii*, *Resserella canalis*, *Dicoelosia biloba*, *Dalejina hybrida*, *Eoplectodonta duvalii*, *Coolinia pecten*, *Pentlandia lewisii*, *Leptaena depressa*, *Leptaena depressa restricta*, *Brachyprion* sp., *Strophonella* (*Strophonella*) *euglypha*, *Leptostrophia* (*Leptostrophia*) *filosa*, *Amphistrophia* (*Amphistrophia*) *funiculata* and *Protochonetes minimus*. In addition, the present author has collected species of *Meristina*, *Gypidula*, *Cyrtia* and *Atrypa*, and Hill *et al.* (1936) recorded the bivalve *Ctenodonta* and the gastropod *Holopella*, together with the corals *Omphyma*, *Spongophylloides* and *Tryplasma*. Conodonts belonging to *Ozarkodina sagitta sagitta* and the earliest specimens of *Ozarkodina confluens* occur (Aldridge, 1975, 1985), as do well preserved acritarchs (K.J. Dorning, pers. comm.).

Just east of where the aqueduct of the Rushall Canal crosses the cutting, three bioherms ('ballstones' or 'crog-balls') interrupt the stratified, thinly bedded limestone and shale units of the Basement Beds. The westernmost of these is the largest, being about 14 m across and 5.5 m high; it extends upwards into the Lower Quarried Limestone and its base sags into the thinly bedded limestones beneath. The central bioherm measures about 4.5 m by 2.5 m, the most easterly one being smaller still. They are composed in large part of the colonial corals *Heliolites*, *Favosites* and *Halysites*, together with other reef-associated organisms such as bryozoans and calcareous algae.

The 4+ m of Lower Quarried Limestone recorded by Butler (1939) on the north side of the track above the bioherms is currently largely covered by vegetation, as are the reported outcrops of this unit elsewhere along the northern bank of the cutting, for example 70 m east of the Bosty Lane road bridge (Cantrill, 1919; Whithead and Eastwood, 1927). The Lower Quarried Limestone was worked along its outcrop, or by shallow shafts and mined underground along dip to the north-west, or even by pits descending through the Coal Measures. The 19th century workings known as Linley Caverns (see Oliver, 1877; Cantrill, 1919), which are indicated on Ordnance Survey maps as an area of disturbed ground immediately north of the cutting and just north-east of Bosty Lane road bridge, and which are included within the boundary of the present site, were opened to mine the Lower Quarried Limestone. Cantrill

Figure 4.3 Daw End Railway Cutting, Walsall area, West Midlands. Section on north side of the track, immediately east of Rushall Canal bridge, showing three small bioherms (in the distance and the centre of the photo) in the Basement Beds of the Much Wenlock Limestone Formation, beneath which is the uppermost part of the Coalbrookdale Formation. (Photo: Derek J. Siveter.)

(1919) recorded a total of 29 species from this unit, adjacent to the Rushall aqueduct, comprising corals, brachiopods, gastropods, bryozoa, trilobites and an orthoconic nautiloid. In modern terms Bassett (1972, 1977) has recorded *R. canalis* and *Scamnomena rugata*.

The Nodular Beds of the Much Wenlock Limestone Formation, which succeed the Lower Quarried Limestone in the area and which were also reported from the northern bank of the cutting, for example west of the Rushall aqueduct and again west of Bosty Lane road bridge, are also effectively unavailable. They were also exposed, originally at least, in the Linley workings by way of 'sinks' or 'crownings-in' – structures produced by collapse of the roof of the (mined) Lower Limestone. Cantrill (1919) records a fauna of corals and brachiopods from the Nodular Beds.

Outcrops of the succeeding Upper (thin) Quarried Limestone were formerly present in 19th century workings at, in particular, the Radleys just to the north of Daw End (Cantrill, 1919; Whitehead and Eastwood, 1927).

Since at least the early 19th century, the Walsall Silurian in general has provided a wealth of fossils. For instance, it provided many middle to upper Wenlock specimens used by Davidson (1847, 1866–1871, 1882–1883) in his classic brachiopod studies, including type and figured material, such as (Bassett, 1974b, 1977) the specimens of *Eoplectodonta duvalii* (Davidson, 1847) and *Megastrophia (Protomegastrophia) semiglobosa* (Davidson, 1871). As exemplified above, most of the exposures in the district that produced such material are now overgrown, filled with water, or built on. Daw End railway cutting is still a prolific source of fossils in its own right, but it might thus also act as a proxy in the area for type localities in the Wenlock from which it is now impossible to collect (e.g. that of *Hypanthocrinites granulatus* Lewis, 1847, from the 'Wenlock Shale' of the Rushall Canal cut), or which were imprecisely localized originally (e.g. 'Wenlock Shale' of Walsall).

Interpretation

Palaeogeographically, the Walsall area lies on the western margin of a presumed land area, the Midland Platform (Bassett, 1974a; Ratcliffe, 1988; Holland, 1992; Ratcliffe and Thomas, 1999). The muds of the Coalbrookdale Formation were deposited under low energy conditions in moderately deep water, with the Much Wenlock Limestone biohermal carbonates being an expression of the distinct, final shallowing phase to the Wenlock Epoch.

Other similar Silurian inliers within the South Staffordshire Coalfield to that of the Walsall district are those of Wren's Nest, Castle Hill and Hurst Hill, all in the Dudley area some 10 km to the south-west. The Daw End site forms part of a group of three sites of Wenlock age in this coalfield. Stratigraphically, it follows on from the nearby Hay Head site which exposes the lower Wenlock Barr Limestone Member of the Coalbrookdale Formation; it precedes, with slight overlap, the Wren's Nest site where less than a metre of Coalbrookdale Formation is exposed together with the full sequence of the Much Wenlock (Dudley) Limestone Formation, the lithological members of which are the same there as in the Daw End–Walsall area.

Conclusions

This railway cutting displays the best exposure of Wenlock rocks in the Silurian inlier of the Walsall district. It provides a superb, 1 km long section through 63 m of the upper part of the Coalbrookdale Formation and the bottom 7 m of the Much Wenlock Limestone Formation. The extent here of the outcrop of the Coalbrookdale Formation is, arguably, unparalleled anywhere, even in the type Wenlock area. In the latter region the thick, facies-equivalent Apedale Member of this formation typically forms low, easily eroded ground with small, stream-course exposures, the Eaton Track site being the exception, though even this is not as extensive nor exposes such a thickness of strata. The Daw End Wenlock rocks are richly fossiliferous, with the Coalbrookdale Formation yielding especially well-preserved brachiopods that have been used in systematic studies since the mid-19th century.

WREN'S NEST (SO 937 920)

Introduction

Within the South Staffordshire Coalfield, Silurian rocks crop out in the Walsall and the Dudley districts. In the latter area they make up, from NNW to SSE, the en-echelon periclines of Hurst Hill, Wren's Nest Hill and Dudley Castle Hill. These three small inliers have Wenlock strata at their centres, their flanks being formed of Ludlow and sometimes Přídolí age rocks which in turn lie unconformably beneath, and are (Wren's Nest and Hurst hills) in part faulted against, Carboniferous deposits. The upper Ludlow and Přídolí sediments only occasionally appear from beneath the cover of Coal Measures.

The geology of the Wren's Nest area has been described since at least the time of Murchison (1839, 1854; Figure 4.4) and Jukes (1859). Later accounts have included those of Lapworth (1889a), Whitehead and Eastwood (1927), Butler (1939), Whitehead and Pocock (1947), Hamblin *et al.* (1978), and Cutler *et al.* (1990). Discussion on the stratigraphy and age of the strata here occurs in Bassett (1974a, 1976), Hurst (1975b), Hurst *et al.* (1978), Dorning (1983), Cocks *et al.* (1971, 1992) and Corfield *et al.* (1992). The Wren's Nest has, historically, figured in field meeting reports, for example those of Lapworth (1889b) and Hill *et al.* (1936). Aspects of the sedimentology of the site have been tackled by Oliver (1981), Ratcliffe (1988) and Ratcliffe and Thomas (1999).

Butler's (1939) study of the Wren's Nest remains the most comprehensive, it having been subject to only relatively modest revision subsequently. The Silurian succession of the inlier as described by him includes the uppermost part of the 'Wenlock Shale', the whole of the 'Wenlock Limestone' and the basal part of the 'Lower Ludlow Shales'. He divided the 'Wenlock limestone' into Basement Beds, Lower Quarried Limestone, Nodular Beds, Upper Quarried Limestone and Passage Beds. Later formalization of lithostratigraphical terms has seen the introduction of the Coalbrookdale, Much Wenlock Limestone, and Lower Elton formations for the major units; the minor divisions of the Much Wenlock Limestone Formation are now regarded as members, with the Basement Beds and Passage Beds being subsumed into the Lower and Upper Quarried Limestone members respectively (see Bassett *et al.*, 1975; Bassett, 1977; Dorning, 1983; Lawson and White, 1989; Cutler *et al.*, 1990).

Hurst (1975b) established the Birmingham Siltstone Formation for the lowest 10 m of shales above the Much Wenlock Limestone Formation at Wren's Nest, the type locality, and also for the equivalent 10 m of shales at Wenlock Edge and the lowest 3 m of these shales at Ludlow. He considered this formation to be of Wenlock age.

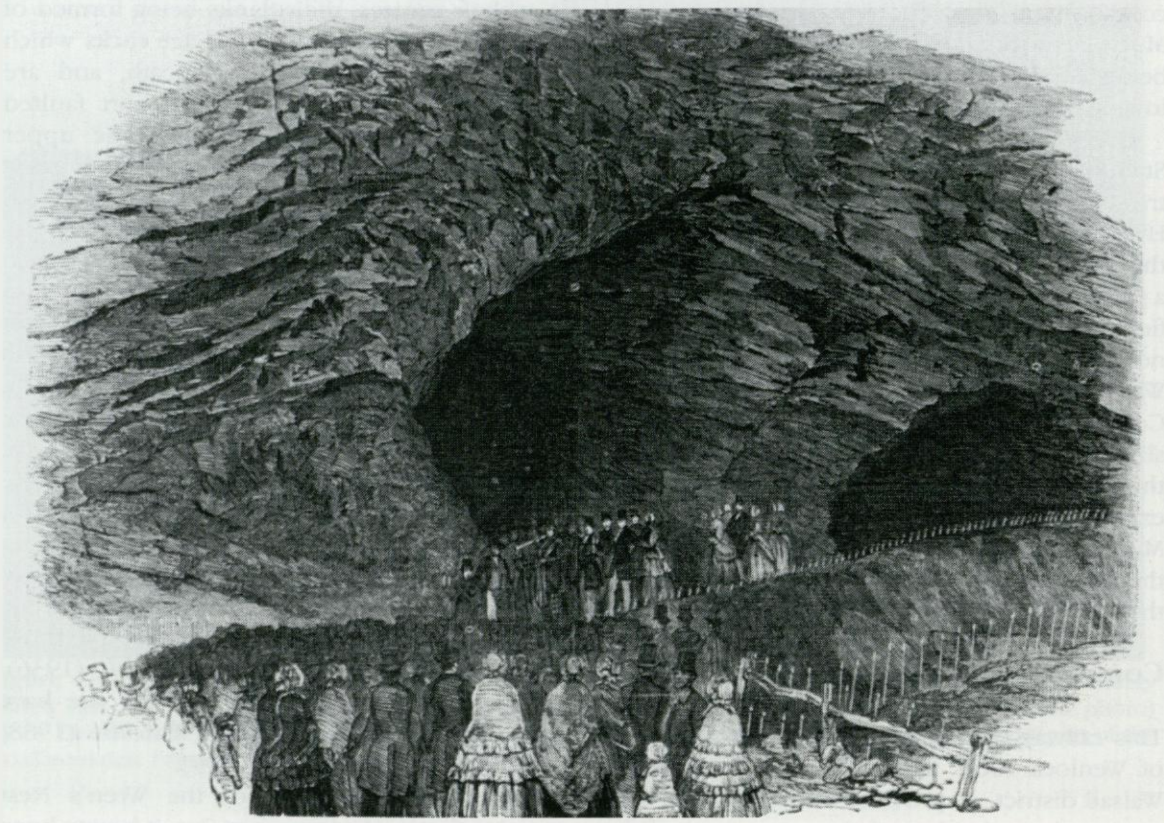


Figure 4.4 A lecture by Sir Roderick Murchison in the 'Dudley Cavern', West Midlands. From *The Illustrated London News*, September 22nd, 1849.

However, the introduction of this unit, the nature of its demarcation, and the notion that it is entirely Wenlock in age are all points that have been questioned by subsequent authors, almost all of whom have recognized only the Lower Elton Formation above the Wenlock Limestone (see Bassett, 1976; Dorning, 1983). The one exception is the relatively recent correlation chart of Cocks *et al.* (1992), in which the Birmingham Siltstone Formation was again used, but only for the Dudley–Walsall column and there only doubtfully shown as partly Wenlock.

The geology and palaeontology of the Wren's Nest are inextricably linked to limestone mining, which began in the Dudley area at least as early as the 17th century, firstly for agricultural and then for industrial purposes (Hamblin *et al.*, 1978). Extraction developed from open-cast quarrying to subterranean workings, the limestone at depth being transported away via underground canals. All these activities provided the collectors and authors of the day, both in this country and abroad, with a great abundance and variety of wonderfully preserved fossils. This is reflected in the myriad of publications in which specimens from here have been described, figured, and used to establish new taxa.

The names of Dudley and the Wren's Nest in particular have, then, become synonymous globally with exquisite fossil material from the Silurian (Wenlock Series). This reputation is perhaps based especially on the trilobites (Figure 4.5) and crinoids from here. All major British museums boast superb collections from the site, and numerous foreign national repositories house 'Dudley' specimens too. The importance of the Wren's Nest was formally recognized in 1956 when it was declared a National Nature Reserve, the first such for geology in the UK. The site also has regional stratigraphical significance for rocks of late Wenlock to earliest Ludlow age.

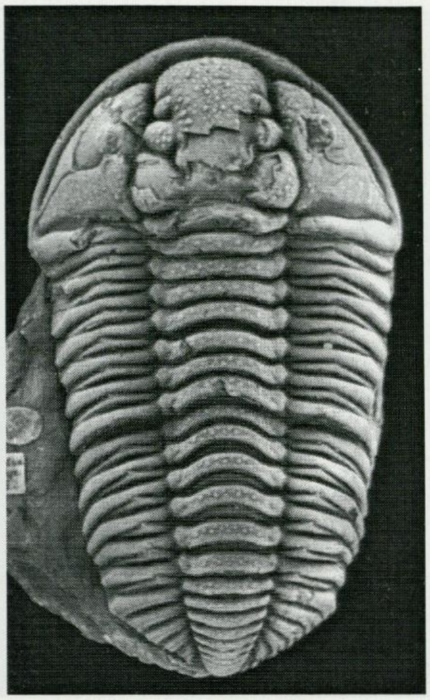


Figure 4.5 The 'Dudley Bug': *Calymene blumenbachii* Brongniart, 1817, Much Wenlock Limestone Formation, Wenlock Series, Dudley, West Midlands. Sedgwick Museum Cambridge specimen (SM A3225); dorsal view, × 1; figured Shirley (1936) and Siveter (1996). (Photo: Derek J. Siveter.)

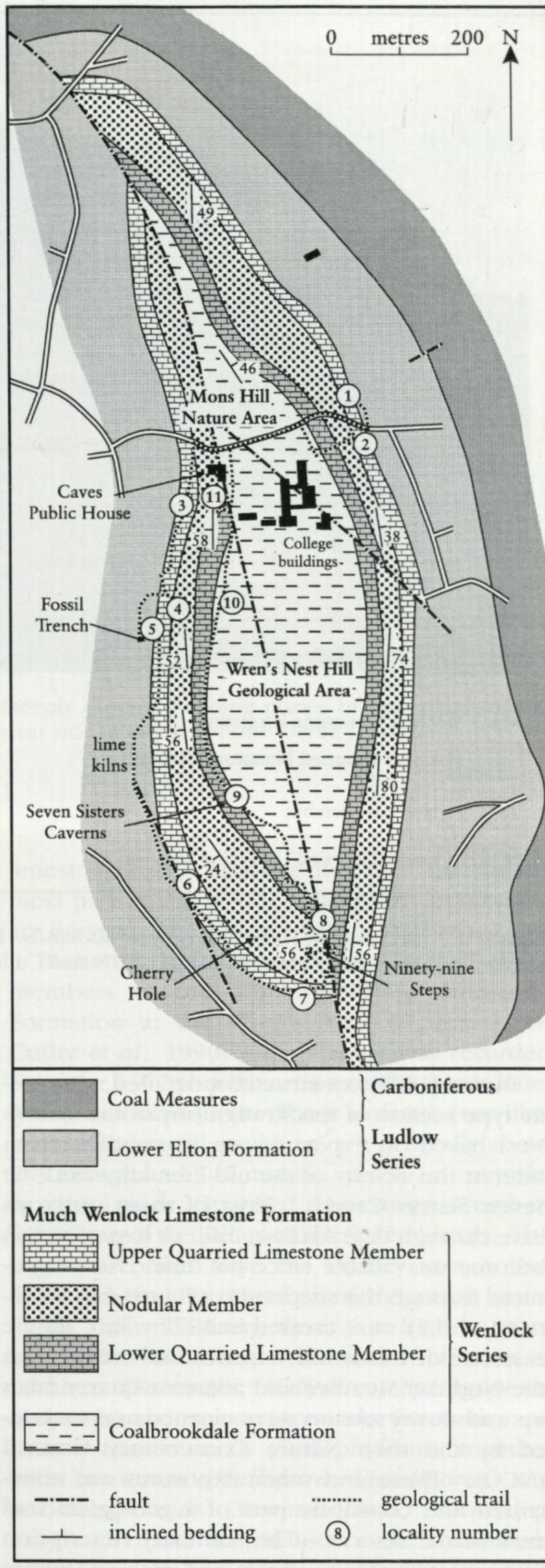


Figure 4.6 Geology of Wren's Nest Hill, Dudley, West Midlands (after Cutler *et al.*, 1990).

Description

Wren's Nest Hill takes the form of a hog's-back ridge about 1.5 km long. It comprises a central, fairly tightly folded core of Coalbrookdale Formation, the succeeding Much Wenlock Limestone Formation dipping away from this at moderate (in general about 45–60°) to steep (about 80°) angles (Figures 4.6, 4.7). End-Carboniferous (Hercynian) movements gave rise to this folding, and also to faulting. A main fault runs north–south and downthrows to the west; it has a NW–SE trending offshoot across the centre of the pericline, offsetting strata on the eastern flank. A reverse fault, sub-parallel to the main one, affects the Upper Quarried Limestone Member and the Lower Elton Formation on the south-west side of the site. The former quarrying operations mirror the structure of the inlier: a series of concentric, deep cuttings that correlate with the Lower and Upper Quarried Limestone members, these being separated by an intervening ridge formed by the more impure Nodular Member (Figure 4.8).

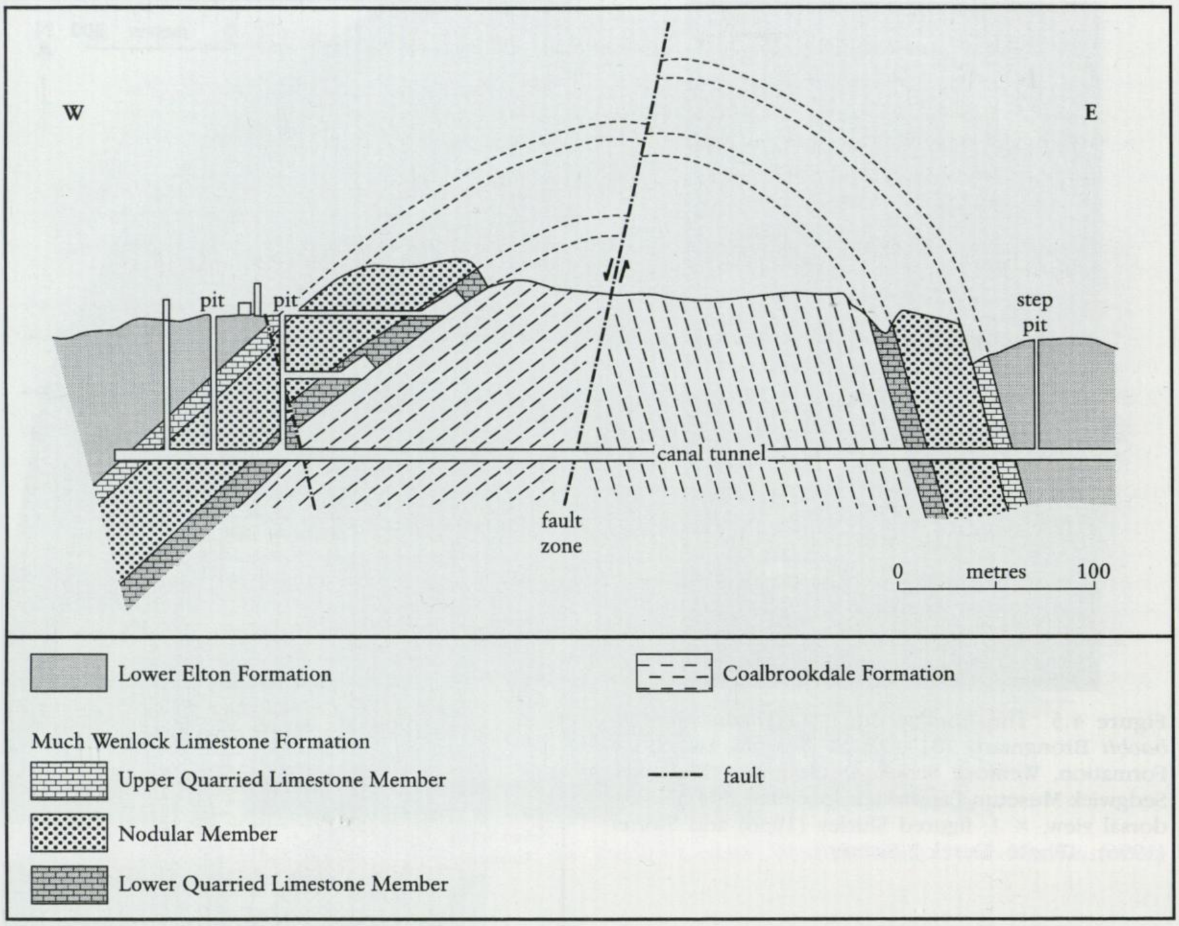


Figure 4.7 Wren's Nest Hill, Dudley, West Midlands. East–west cross section taken at about 400 m south of the college buildings (after Hamblin *et al.*, 1978 and Cutler *et al.*, 1990).

Butler (1939) constructed a detailed, composite type section of the stratigraphy of the Wren's Nest based on exposures on its south-western side, in the vicinity of the old lime kilns and the Seven Sisters Cavern. Most of these outcrops have through degradation, infill or loss of access become unavailable since his time. New exposures through the succession (Figure 4.6, localities 1 and 2) were created in 1977 when, on the eastern side of the hill, a trench was cut through the Nodular Member and adjacent quarry faces up and down section were cleaned and extended by the then Nature Conservancy Council (NCC). These and other exposures are maintained and constitute part of a geological trail around the reserve. The summary description that follows is largely of this NCC section (Figure 4.9; see Hamblin *et al.*, 1978; Cutler *et al.*, 1990). The thickness, composition and palaeontology of the various lithological units may vary slightly in other parts of the site.

The Coalbrookdale Formation is probably represented here by the basal 0.17 m of pale greenish-grey mudstone. An 8 cm limestone band marks the base of the Lower Quarried Limestone Member, which is about 16.2 m thick and generally made up of bedded limestones, with shale partings occurring particularly near its base and in its upper part. The brachiopods *Antirhynchonella*, *Atrypa*, *Eospirifer*, *Gypidula*, *Howellella* and *Strophonella*, and the corals *Paleofavosites*, *Stelliporella* and *Ketophyllum* were recorded from the lower limestone horizons (formerly the upper part of the Basement Beds) of this member. In its upper 1.5 m stromatoporoid colonies are abundant, and its top is marked by a 26 cm thick limestone bed.

The Nodular Member is some 31 m thick and

Figure 4.8 Wren's Nest Hill, Dudley, West Midlands. Steeply dipping bedding planes of upper part of the Nodular Member, Much Wenlock Limestone Formation, west side of inlier. (Photo: Derek J. Siveter.)

consists of nodules, limestone lenses, and silty shales. Up sequence the nodules become less coarsely crystalline, less pure and more laterally continuous. Bentonites occur at about 6 m and 9.7 m above the base of the member. Fossils are more common in its upper two-thirds. Corals, including *Favosites*, the brachiopods *Amphistrophia*, *Atrypa*, *Coolinia*, *Eospirifer*, *Gypidula*, *Meristina* and *Strophonella*, and fragments of the trilobites *Calymene* and *Dalmanites* have been collected.

The Upper Limestone Member has a thickness of 8.6 m. Its lower and upper parts have shale layers up to 10 cm thick, with more massive, coarsely crystalline limestone beds occupying the middle part. Fossils are uncommon, though *Atrypa*, *Strophonella*, *Calymene* and the coral *Acervularia* occur, and there is a stromatoporoid-rich level immediately above these more massive beds. The uppermost part of the member (formerly the Passage Beds) consists of 1.3 m of pale grey silty shale with thin limestone bands and nodules.

The 13 m available of the Lower Elton Formation (localities 1 and 6) also comprise grey, silty shales, though these contain fewer limestone bands and nodules than the uppermost part of the Upper Limestone. Bentonites are present at 2.12 m and 3.82 m above the base.

Bioherms have been noted from all three members of the Much Wenlock Limestone Formation at the Wren's Nest (Butler, 1939; Cutler *et al.*, 1990) though none was recorded from the 1977 trench section or the immediately adjacent exposures. These isolated, lens-like, unstratified reefal structures are generally about 2–3 m high and 3–5 m wide. Such an example, in the Lower Quarried Limestone Member, forms one of the pillars of the Seven Sisters. The largest recorded from the Dudley area is that from the Nodular Member of the canal basin, Castle Hill, measuring about 6 m high by 40 m wide. The bioherms are formed of colonies of tabulate (*Favosites*, *Heliolites*, *Syringopora*, *Halysites*) and rugose (*Acervularia*) corals, and solitary rugose corals (*Dokophyllum*), together with bryozoans (*Hallopora*, *Fistulipora*), and stromatoporoids (*Stromatopora*, *Actinostroma*). Of these framebuilders the main ones were the tabulate corals, especially *Favosites* and *Heliolites*. Framebinding organisms include encrusting calcareous algae (*Girvanella*,

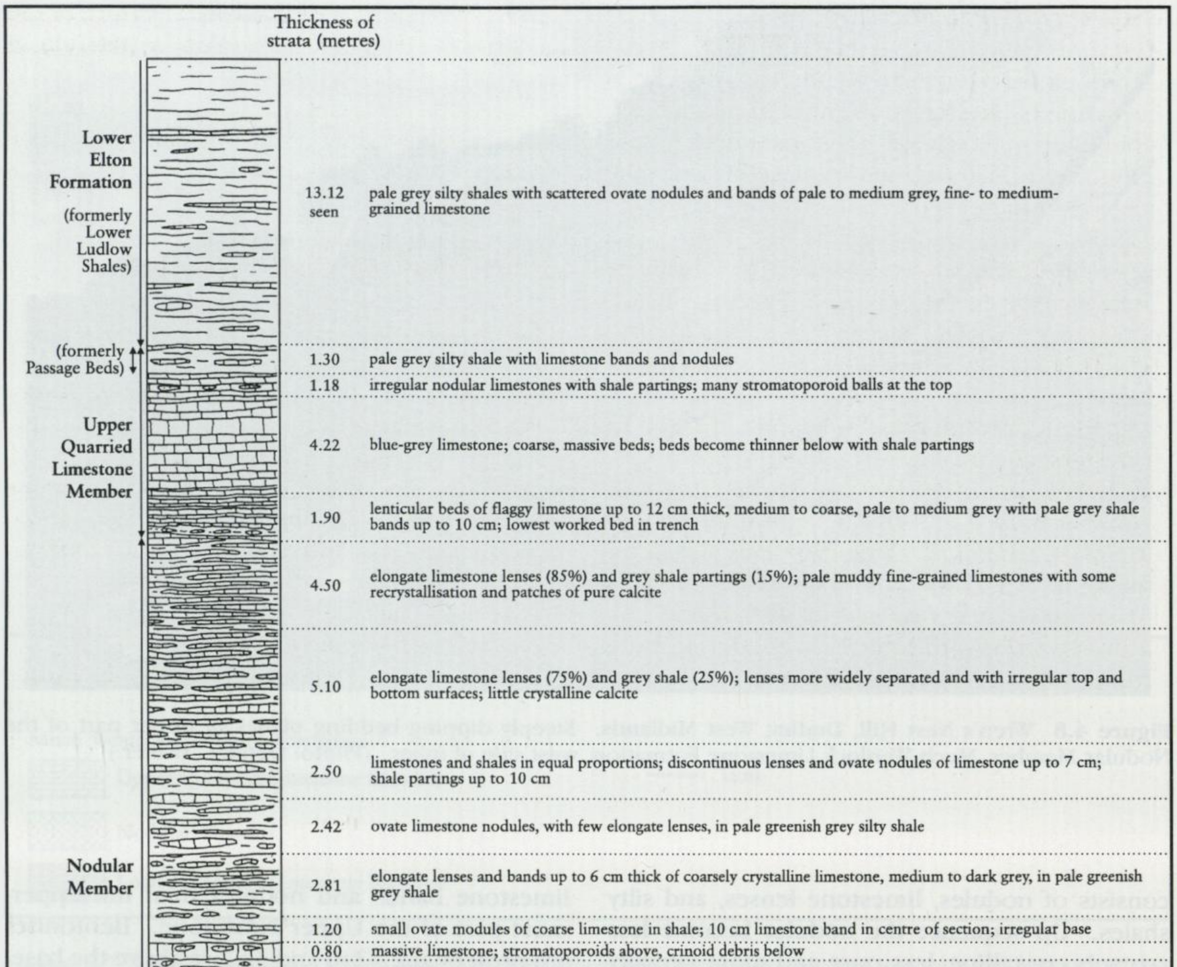


Figure 4.9 Wren's Nest Hill, Dudley, West Midlands. Succession in the 1977 NCC cutting and adjacent exposures (after Hamblin *et al.*, 1978 and Cutler *et al.*, 1990).

Wetheredella, *Rothpletzella*), tabulate corals (*Alveolites*, *Thecia*), stromatoporoids (*Labechia*) and 'net' bryozoans (*Fenestella*). Arching of the bedded limestones above a bioherm and, depending on its size, sagging of the beds below it, are typical, as are thin argillaceous partings (some bentonitic) separating growth phases.

The interstices of the organic framework are variously infilled with coarsely crystalline limestone, which is composed mainly of crinoid fragments, together with micrite. Organisms unassociated with framebuilding or framebinding occur here, and in the bedded, inter-reef limestones too. Brachiopods are sometimes found in clusters, and include *Strophonella*, *Eospirifer*, *Gypidula* and *Leptaena*. Species of the *Sphaerirhynchia wilsoni* Community (Hurst 1975a, 1975b), a nearshore carbonate level bottom assemblage, are typical. Molluscs such as the gastropods *Acroculia* and *Poleumita*, the bivalves *Goniophora* and *Pteronitella*, and the orthocone *Dawsonoceras* are also characteristic, if less common, faunal elements.

Over 30 trilobite genera are known from the Much Wenlock Limestone Formation of 'Dudley', this location often being that cited in 19th century texts and acting as a proxy for 'Wren's Nest'. Of these genera, species of *Calymene*, *Dalmanites*, *Encrinurus*, *Acaste* and *Proetus* are amongst the most common. The site has yielded a rich echinoderm fauna, many of the taxa being specific to it within the UK. There are over 60 species of crinoids belonging to such genera as *Clematocrinus*, *Periechocrinus* and *Gissocrinus,* the material including scores of articulated specimens. Asterozoans, cystoids and carpoids also occur. Conulariids, tentaculitids and cornulitids are present, as are machaeridians. Very rare graptolites assigned to *Monograptus flemingii* are known from largely unspecified levels within the Much Wenlock Limestone Formation, though one of them is known to come from 2.4 m above its base (Butler, 1939; Bassett, 1974a, 1976). An abundant and diverse microfauna and microflora of ostracods, conodonts, chitinozoans and acritarchs has been recovered. Trace fossils (burrows, trails) are present through much of the sequence.

In total, over 600 species have been described, figured or cited from the Wren's Nest–Dudley area, and approaching 200 of these have it as their type locality (Cutler *et al.*, 1990). The following list gives merely an indication of the taxonomic range and historical nature of the publications that have made use of material from here.

- General palaeontology – Murchison (1839), M'Coy (1851c), Salter (1873), Etheridge (1888)
- Brachiopods – Davidson (1869), Bassett (1970a, 1972, 1974b, 1977), Hurst (1975a), Cocks (1978)
- Stromatoporoids – Nicholson (1889)
- Bryozoans – Owen (1969)
- Corals – Edwards and Haime (1854), Sutton (1964)
- Conulariids – Slater (1907)
- Crinoids – Miller (1821), Bather (1890, 1891a, 1891b, 1892), Ramsbottom (1950, 1951, 1952), Watkins and Hurst (1977), Donovan and Sevastopulo (1989)
- Cystoids – Paul (1967)
- Asterozoans – Spencer (1918, 1922)
- Trilobites – Mortimer (1750), Brünnich (1781), Brongniart (1822), Salter (1865), Lane (1971), Owens (1973), Thomas (1978, 1981), Siveter (1980, 1985, 1996), Morris (1988)
- Gastropods – Donald (1905)
- Graptolites – Elles and Wood (1913), Butler (1939), Strachan (1971), Bassett (1976)
- Ostracods – Siveter (1978, 1980)
- Polychaete worms – Thomas and Smith (1998)
- Conodonts – Aldridge (1985)
- Microflora and chitinozoans – Eisenack (1977, 1978), Dorning (1983), Dorning and Bell (1987)
- General micropalaeontology – Aldridge *et al.* (1981)

Sedimentological features that variously occur in different members of the Much Wenlock Limestone include oncoids, ripple marks, cross-bedding and sun-cracks (Ratcliffe, 1988; Cutler *et al.*, 1990).

Fossils from the Lower Elton Formation of Dudley include the graptolites *Saetograptus* cf. *varians*, *S. colonus*, *S. chimaera chimaera* and *Monograptus uncinatus*, all of which were recovered from unknown levels within it (Bassett, 1976). The same formation yielded to Hurst (1975b) brachiopods of his *S. wilsoni* Community. Also, Hurst (1975b) assigned brachiopods from a level or levels purported by him to be at least 10 m above the base of the formation, from a locality 1.6 km north of Wren's Nest

(Whitehead and Pocock, 1947), to the *Dicoelosia* clastic community. Brachiopods from the Lower Elton Formation exposed during the 1977 excavations (Hamblin *et al.*, 1978) belonged to *Amphistrophia*, *Atrypa*, *Eospirifer*, *Leptaena*, *Leptostrophia*, *Meristina*, *Protochonetes*, and *Strophonella*.

Interpretation

The base of the Much Wenlock Limestone Formation at Dudley is, on the basis of the *M. flemingii* record from 2.4 m above this level, no younger than *lundgreni* Biozone age (Bassett, 1974a, 1976). However the age of the upper part of this formation here is equivocal. Bassett (1976) thought it most likely that it belongs to the *ludensis* Biozone, and that, probably, some part of the overlying shales of the Lower Elton Formation does also. Hurst (1975b) also suggested that at Dudley the *ludensis* Biozone extended upwards into these shales, specifically to a level about 10 m above the limestone where he said a transgression occurred. Hurst believed this deepening event could be recognized on the basis of a switch from the *S. wilsoni* to the offshore *Dicoelosia* clastic community, and that it was present and synchronous throughout the Welsh Borderland area. Further evidence on the age of the Much Wenlock Limestone at Dudley was given by Corfield *et al.* (1992), who suggested on the basis of carbon isotope analysis that the *G. nassa* Biozone might be represented there, by the lower part of the Nodular Member.

The base of the Much Wenlock Limestone Formation at Ludlow and Wenlock Edge is known to lie in the *ludensis* Biozone (Holland *et al.*, 1969; Bassett *et al.*, 1975; Bassett, 1989a) and it is thus diachronous between these two areas and Dudley. Evidently, in late Wenlock times, limestone and patch reef development began slightly earlier in the Dudley area than in the Wenlock and Ludlow districts to the west (Bassett, 1976). The graptolites from the Lower Elton Formation of Dudley suggest a *nilssoni* to *scanicus* Biozone age for these sediments (Bassett, 1976). In the Wenlock and Ludlow areas this formation belongs to the *nilssoni* Biozone (Bassett, 1976; Lawson and White, 1989).

In late Wenlock times the Dudley area was located on the (inner) carbonate platform area (Bassett, 1974a; Hurst *et al.*, 1978; Ratcliffe, 1988; Holland, 1992; Ratcliffe and Thomas, 1999). Throughout this area the sea was becoming shallower during deposition of the upper part of the Coalbrookdale Formation, was shallow when the Much Wenlock Limestone formed, and deepened again when sediments of the Lower Elton Formation were laid down (see e.g. Bassett, 1976; Siveter *et al.*, 1989). The Wren's Nest bioherms, and also those formed elsewhere on the platform such as the ones on Wenlock Edge, are analogous to the Recent patch reefs of the tropics and subtropics (Scoffin, 1971; Cutler *et al.*, 1990). The water energy conditions present during the growth of these Silurian reefs varied between quiet to strongly agitated, with occasional evidence of sub-aerial exposure. Influx of bentonitic or terrigenous sediment sometimes led to reef death.

Related network sites include Daw End in the nearby Walsall area; Easthope–Harley Hill, Longville–Stanway and Lincoln Hill in the type Wenlock region; Burrington in the Ludlow district; and Little Hill, Linton Quarry, Hobbs Quarry, Cilwrgi Quarry and Cwm-Ton in the various Silurian inliers of the southern Welsh Borderland. All these localities have exposures of the Much Wenlock Limestone Formation, or a local limestone correlative of it.

Conclusions

Wren's Nest Hill exposes an upper Wenlock sequence from the top part of the Coalbrookdale to the top of the Much Wenlock Limestone formations. During the late Wenlock, the Dudley area was part of the inner carbonate platform. In early Ludlow times the Lower Elton Formation, comprising slightly deeper water sediments, was deposited in the region.

The site is of outstanding palaeontological importance for rocks of Wenlock age in Britain and as such is one of the country's most notable geological localities. It has a worldwide reputation for the exceptional preservation, abundance and diversity of the invertebrates it has yielded, both macro- and microfossil, from at least the mid-18th century. Fossils from the Wren's Nest have been figured and discussed in countless publications, nigh on 200 species having it as their type locality. It is used as a teaching laboratory from school to undergraduate levels. The site falls within the highest rank for conservation purposes.

SCUTTERDINE QUARRY (SO 577 368)

Introduction

Scutterdine Quarry lies within the Woolhope district, which is situated some 10 km west of the southern part of the Malvern Hills, between Ledbury, Hereford and Ross-on-Wye. This district comprises a link in the chain of Silurian inliers that run from the West Midlands in the north to the Cardiff and Mendips areas in the south. The Woolhope Inlier is periclinal in form, the main axis trending NW–SE and the western limb being the steeper (Figure 4.10). Llandovery strata are present in the core, these being successively enveloped by Wenlock, Ludlow and Přídolí age sediments. Numerous dip faults offset all the Silurian rocks throughout the pericline.

The quarry is located in the north-west part of the inlier and exposes the Woolhope Limestone, a name first coined by Murchison (1839) for this essentially calcareous unit which here forms the base of the Wenlock Series. Murchison's lithostratigraphical term was endorsed, slightly later, by Phillips (1848) and used subsequently by all students of the Woolhope Silurian, for example Richardson (1907), Gardiner (1927), Pocock (1930) and Squirrell and Tucker (1960), the last of these providing the now standard account of the inlier. Most lately, Bassett (1977) has given the unit formation status.

The Woolhope Limestone Formation was deposited over a wider area of the central-southern part of the Welsh Borderland than just the Woolhope district. As such, this site is regionally representative for this early Wenlock time in

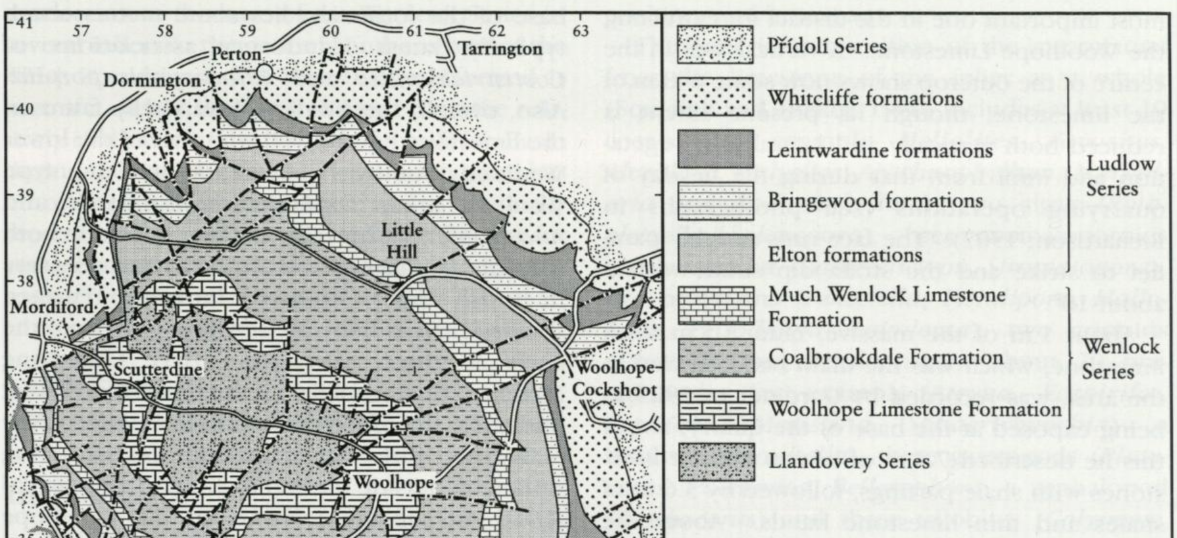


Figure 4.10 Location of Scutterdine Quarry and Little Hill quarries, and geology of the Woolhope Inlier, southern Welsh Borderland (after Squirrell and Tucker, 1960; and Earp and Hains, 1971).

terms of lithofacies, fossils and thus palaeoenvironment.

Description

In the inlier as a whole, the Woolhope Limestone Formation is 36 m thick and consists of nodular argillaceous limestones and fine-grained, rubbly siltstones. The limestones vary in colour from olive-grey to greenish-grey and the siltstones are commonly light olive-grey. The base of the formation generally shows a sharp lithological change from the siltstones, fine sandstones and impure and crinoidal limestone bands of the uppermost Llandovery Haugh Wood Beds below, the latter containing the well-known Petalocrinus Limestone horizon. The top of the formation, in contrast, shows a more gradual transition into the overlying Coalbrookdale Formation. Within the Woolhope area, the Woolhope Limestone contains four bentonites.

The quarry at Scutterdine was formerly the most important one in the district for extracting the Woolhope Limestone. A vertical face in the centre of the outcrop shows now some 6–8 m of the limestone, though its present extent is reduced both vertically and laterally by vegetation and infill from that during the heyday of quarrying operations (see photographs in Richardson, 1907). The face runs roughly parallel to strike and the strata dip south-west at about 10°.

About 1 m of the massive, blue, 1.5 m thick limestone, which was the main bed quarried in the area, was recorded by Gardiner in 1927 as being exposed at the base of the quarry; above this he described 7.3 m of brown impure limestones with shale partings, followed by 3.6 m of shales and thin limestone bands. About the same time Pocock (1930) also noted that the main blue limestone occurred at the base of the old quarries at Scutterdine, and that overlying it there was a 0.6 m thick ('creamy, yellow, soapy clay') bentonite, which was divided by a 10 cm band of ferruginous, cuboidally jointed limestone. Squirrell and Tucker (1960) remarked on the utility of this particular bentonite in local correlation, having traced it around the central topographical dome of the inlier.

The macrofauna of the Woolhope Limestone consists mainly of brachiopods, with corals and trilobites also occurring (Squirrell and Tucker, 1960). Hurst (1975a) assigned the brachiopods from the Woolhope Limestone of the inlier to his *Eoplectodonta duvalii* Community. From Scutterdine Quarry in particular, Gardiner (1927) listed 10 brachiopod species, a coral and an orthoconic nautiloid. Figured specimens from this quarry, some of them types, include those of the brachiopod *Leptaena oligistis* Bassett (1974b), the trilobites *Bumastus barriensis* Murchison, 1839 (Lane and Thomas, 1978) and *Warburgella* (*Warburgella*) *scutterdinensis* Owens (1973), and the alga *Girvanella pusilla* Johnson (1966).

Interpretation

Because graptolite evidence is lacking from the Woolhope Limestone Formation there has previously been uncertainty as to its precise age (Bassett, 1974a). All authors, however, now regard it as basal Wenlock. Some Llandovery elements such as *Costistricklandia lirata lirata* and *Eocoelia sulcata* continue through into the limestone from the upper Llandovery, but the base of the formation lies some metres above typically latest Llandovery associations of *Costistricklandia* and *Palaeocyclus porpita*. Also, overall, the lithology and shelly fauna of the limestone equate well with that of the lower Wenlock Buildwas Formation of the type Wenlock area; *Eoplectodonta duvalii* and *Anastrophia deflexa*, for example, occur in both formations, these species being at best very rare in British upper Llandovery horizons. Further, *B. barriensis* is known elsewhere only from the early Wenlock, carbonate, Barr Limestone Member (Coalbrookdale Formation) of the West Midlands and the Woolhope Limestone of the Malverns, with the genus *Bumastus* being unknown outside the Wenlock. The presence of *Resserella sabrine sabrinae* in the Woolhope Limestone of the type area suggested to Hurst *et al.* (1978) an age between the *centrifugus* and *riccartonensis* biozones for this unit.

In early Wenlock times the Woolhope Limestone Formation of the Woolhope district formed part of the carbonate belt that occupied the central area between Pretannia in the south and the Midland Platform in central England, on the south-east margin of the Welsh Basin (Bassett, 1974a; Hurst *et al.*, 1978; Holland, 1992). Deposition of this formation extended, also, to the May Hill, Malverns and Abberley districts.

Another site that displays evidence of this carbonate belt during the early Wenlock is Hay

Head in the West Midlands, where the penecontemporaneous Barr Limestone occurs. Dolyhir Quarries in the Radnor area also expose lower Wenlock carbonates, but here they are dominantly algal in nature, formed on topographic highs farther offshore, and may or may not have been in depositional continuity with the coeval Woolhope carbonates (Hurst *et al.*, 1978; Holland, 1992). The Buildwas River and Hughley Brook sites, in the type Wenlock area, also show lime-rich deposition during this time, in the form of the Buildwas Formation. The lower Wenlock clastic sediments of the Brinkmarsh Quarry site in the Tortworth Inlier to the south reflect its closer position, compared with Woolhope, to the shoreline of Pretannia.

Conclusions

Scutterdine Quarry has probably the best exposure of the Woolhope Limestone Formation in its type area. This is a notable sedimentary unit that occurs at the base of the Wenlock Series in several inliers in the central-southern part of the Welsh Borderland. The limestone was formed as part of a carbonate belt that existed on the relatively shallow eastern margin of the Welsh Basin during the early Wenlock. The site therefore has lithostratigraphical importance and is regionally representative, and it is also the type locality for some macroinvertebrates. It is used mainly for research purposes.

LITTLE HILL (SO 603 387–SO 613 381)

Introduction

This site is located in the Silurian inlier of Woolhope in the central-southern part of the Welsh Borderland (Figure 4.10). The inlier takes the form of a pericline, Llandovery sediments occurring centrally and these being successively flanked by Wenlock, Ludlow and then Přídolí strata. Murchison (1839) first described the Woolhope Silurian, Phillips (1848) following him shortly afterwards with an account in his classic memoir on the Malvern Hills and adjoining areas. In the 20th century, combined stratigraphical, palaeontological and structural analysis of the inlier was provided by Gardiner (1927) and then Squirrell and Tucker (1960), Little Hill being cited in both studies.

The site exposes both bedded and reefal components of the uppermost Wenlock-age Much Wenlock Limestone Formation.

Description

Little Hill contains a line of quarries in the north-east part of the inlier; they run for about 1 km in a NW–SE direction, parallel with the local strike of the Much Wenlock Limestone which has an estimated thickness in the Woolhope district of 45–52 m. This formation comprises irregularly bedded, greyish-olive, impure limestones and purer, blue limestone bands that are interbedded with buff-olive calcareous muddy siltstones. Nodules are common in the basal and uppermost beds. At Little Hill these bedded units occur together with small biohermal structures. The latter are a few metres in height and diameter and comprise unstratified masses of pale yellowish-green porcellanous limestone with corals and stromatoporoids, some of these in growth position, and bryozoans.

The generic composition of the macrofauna from the limestone of the inlier as a whole (Squirrell and Tucker, 1960) includes at least 10 corals (for example *Heliolites*, *Favosites*, *Alveolites*, *Halysites*, *Arachnophyllum*, *Acervularia* and *Kodonophyllum*), two algae (*Rothpletzella*, *Solenopora*), three stromatoporoids (*Actinostroma*, *Clathrodictyon*, *Stromatopora*), five bryozoans (*Fenestella*, *Fistulipora*, *Hallopora*, *Ptilodictya*, *Leiodema*), two crinoids (*Crotalocrinus*, *Petalocrinus*), about 20 brachiopods (for example *Atrypa*, *Eospirifer*, *Leptaena*, *Meristina*, *Sphaerirhynchia*), a bivalve (*Pteronitella*), three gastropods (*Platyceras*, *Poleumita*, *Bellerophon*), a cephalopod (*Trochoceras*) and three trilobites (*Calymene*, *Illaenus*, *Proetus*). Additionally, and more specifically with respect to provenance within the Woolhope district, beyrichiacean ostracods used in taxonomic studies (Siveter, 1980) and brachiopods of the shallow water *Sphaerirhynchia wilsoni* Community used in palaeoecological work (Hurst, 1975a, 1975b) have been recovered from Little Hill.

Interpretation

The Much Wenlock Limestone Formation, with its biohermal mounds being analogous with present day patch reefs, was formed in clear, warm, shallow seas within or about the subtropics (Scoffin, 1971). The bioherms of Little Hill do not reach the size of those in the same formation on Wenlock Edge, the latter averaging 12 m in width and 4.5 m in thickness. Nevertheless, the presence of the Much Wenlock Limestone in the Woolhope district indicates that the carbonate platform which covered much of the English Midlands in latest Wenlock time extended also to this part of the Welsh Borderland (Bassett, 1974a; Hurst *et al.*, 1978; Holland, 1992). In the late Wenlock low sea level was not confined to the Anglo-Welsh area; it has been recognized globally in rocks of this age (Johnson *et al.*, 1991), although the widespread carbonate deposition has also been attributed to climatic factors (Jeppsson *et al.*, 1995).

Little Hill is thus most closely networked to other sites that provide evidence of the Midlands–Welsh Borderland carbonate platform, such as Hobbs Quarry in the May Hill Inlier, Linton Quarry in the Woolhope area, the Wren's Nest and Daw End Cutting in the West Midlands, and Easthope–Harley Hill on Wenlock Edge.

Conclusions

Little Hill stands as the representative section in the Woolhope Inlier of the Much Wenlock Limestone Formation. It is thus a complementary site to those in the Much Wenlock area exposing the type development of this formation. This limestone is significant for palaeoenvironmental and palaeogeographical interpretation of the late Wenlock. Its presence shows that at this time the Woolhope area was a part of the carbonate shelf centred on central England, and its biofacies, comprising in part small bioherms, indicates that it was formed in warm climates at low latitudes.

LINTON QUARRY (SO 677 257)

Introduction

Linton Quarry is the southernmost of a group of old quarry workings in the Silurian of the Gorsley area (Figure 4.11), which is situated between the May Hill and Woolhope Silurian inliers (Lawson, 1955; Squirrell and Tucker, 1960) in the southern Welsh Borderland. Murchison (1839), Phillips (1848) and Symonds (1872) were early commentators on the Silurian geology of the Gorsley area, but it was Lawson (1954) who first described in detail and put in modern terms the Silurian succession here, including that of Linton Quarry, which locally provides the best section.

In Linton Quarry the Gorsley Limestone is exposed below Ludlow and Přídolí strata. Historically there has been debate (Lawson, 1954) as to whether this lithostratigraphical unit is the lateral equivalent of the (Much) Wenlock Limestone (Formation) of late Wenlock age or of the Aymestry Limestone (= Upper Bringewood Formation) of mid-Ludlow (high Gorstian) age. Murchison (1939), Symonds (1872) and, seemingly, Pocock (1950) all regarded the limestone to be a correlative of, or the same as, the Aymestry Limestone; Phillips (1848) considered both the Wenlock and the Aymestry limestones

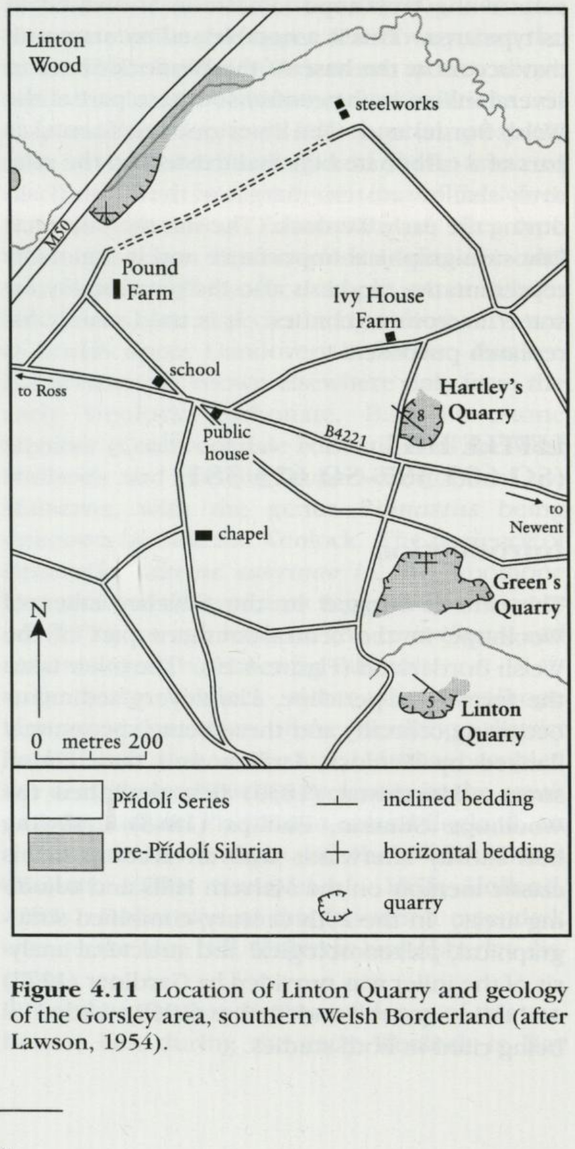


Figure 4.11 Location of Linton Quarry and geology of the Gorsley area, southern Welsh Borderland (after Lawson, 1954).

to be exposed in the Gorsley area; Lawson (1954), supported by Bassett (1974a), equated the limestone with the Much Wenlock Limestone; Hurst *et al.* (1978) thought that whilst it was not equivalent to the Aymestry Limestone, a correlation with the Much Wenlock Limestone was uncertain and that it could be anything from late Wenlock to mid-Ludlow in age.

Description

Wenlock age rocks form the lowest part of the exposure in Linton Quarry, where the Silurian strata (Figures 4.12, 5.46) dip at 5° to the south-west. The Gorsley Limestone here is hard, massive, light bluish-grey in colour, with irregular seams and pockets of silt, and is up to 3.6 m thick though its base is not exposed (Lawson, 1954). It contains a macrofauna mostly of brachiopods, for example species of *Leptaena, Strophonella, Atrypa, Meristina, Sphaerirhynchia, Brachyprion, Fardenia, Delthyris, Gypidula* and *Camarotoechia*, and corals including *Favosites* and solitary forms, plus a species of the gastropod *Platyceras*, together with indeterminate crinoid ossicles and bryozoans. The thelodont *Thelodus parvidens* has also been recorded from the Gorsley Limestone of Linton Quarry (Turner, 1973), and scolecodonts occur (R.J. Aldridge, pers. comm.).

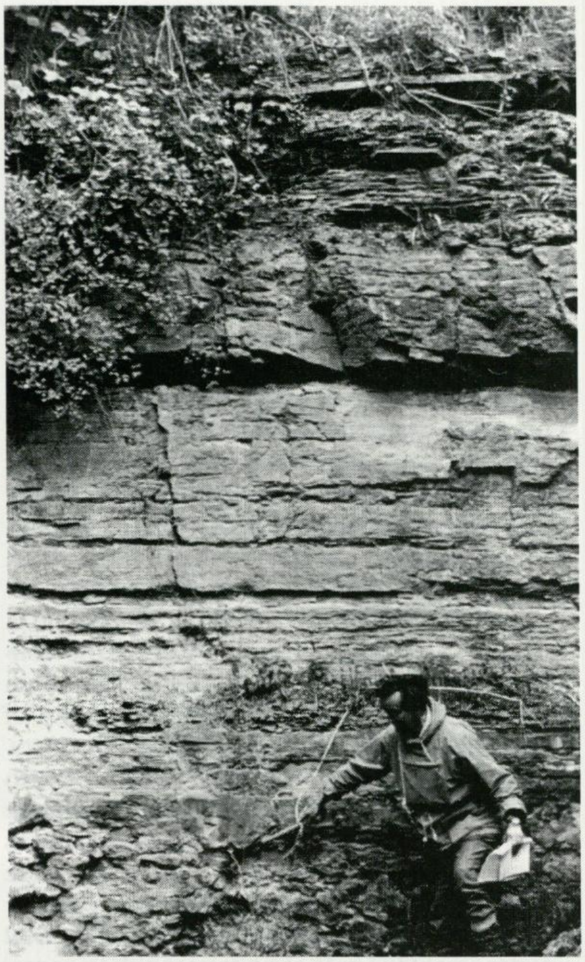


Figure 4.12 Linton Quarry, Gorsley area, southern Wales Borderland. Dr Jim Lawson indicating the Wenlock–Ludlow series boundary: the Gorsley Limestone of Wenlock age lies below the hammer head and the Lower Siltstones of Ludlow age above it. The middle part of the quarry face comprises a much condensed Ludlow sequence, with the Přídolí age Clifford Mesne Sandstone forming the top. (Photo: Derek J. Siveter.)

Interpretation

Lawson (1954) based his correlation of the Gorsley Limestone with the Wenlock Limestone on lithological, stratigraphical and palaeontological grounds. He contended that the Gorsley Limestone was harder, purer and more crinoidal than typical Aymestry Limestone and especially more so than that of the nearest Aymestry outcrop just 5 km to the north in the Woolhope Inlier; moreover that the lithology of the Gorsley Limestone is essentially inseparable from that of the undoubted Much Wenlock Limestone of Ledbury Quarry (= Gurney's Quarry, this volume, Ludlow sites) 13 km to the NNE on the south-western flank of the Malvern Hills.

Stratigraphically, Lawson argued that in both the Woolhope and May Hill inliers – just a few kilometres to the north and south of the Gorsley area respectively, the Aymestry Limestone thins towards this area and is cut out.

Palaeontologically, Lawson maintained in particular that the fairly common occurrence of *Meristina obtusa* at Gorsley, especially in a limestone facies, should be taken as an almost certain indication of a Wenlock age. This followed on from Alexander's (1936) contention that this brachiopod had not been found in the Aymestry Limestone, a view upheld by the work of Bassett (1974a) who regarded *M. obtusa* as a clear indicator of an age within the upper half of the Wenlock and who corroborated Lawson's age assessment of the Gorsley Limestone. Lawson further maintained that several fossils that occur in the Aymestry Limestone, for example *Isorthis* *orbicularis*, *Michelinoceras bullatum* and *Pristiograptus tumescens*, are not found in the Gorsley Limestone. Whilst commenting that this was somewhat negative evidence, and that in addition many species typical of the Wenlock elsewhere were also absent from the Gorsley Limestone, Lawson noted that this latter absence applies equally to the Much Wenlock Limestone of Ledbury (= Gurney's) Quarry, where both the composition and preservation of the fauna closely resembles that of the limestone in Linton Quarry.

Hurst *et al.* (1978), in contrast to Lawson (1954) and to Bassett (1974a), declared the presence of *M. obtusa* to have no bearing on the age of the Gorsley Limestone, this species having been recorded (by R. Watkins, pers. comm.) from the middle Ludlow Bringewood beds in the Abberley Hills (Woodbury Quarry; this volume, Chapter 5). The current consensus (e.g. Cocks *et al.*, 1992), however, follows the conclusion of Lawson. The true Ludlow age strata of Linton Quarry are described in Chapter 5 of this volume.

Linton Quarry is most closely networked to Little Hill and Hobbs Quarry in the Woolhope and May Hill inliers, respectively, and it also links to Cilwrgi Quarry in the Usk Inlier. All these southern Welsh Borderland sites expose the Much Wenlock Limestone Formation or a local correlative of it.

Conclusions

The basal sedimentary unit of the Silurian of the Gorsley area, the Gorsley Limestone, is best exposed in Linton Quarry. This limestone has been variously regarded since the time of Murchison in the mid-19th century as either Wenlock or Ludlow in age. Most authors of the present day consider it to be a correlative of the Much Wenlock Limestone Formation.

HOBBS QUARRY (SO 695 193)

Introduction

The Silurian inlier of May Hill lies between those of Woolhope to the north-west and Tortworth to the south. In structural terms it forms part of a pericline which on its south-eastern side disappears beneath the Permo-Triassic cover of the Severn vale, and on its western side passes into Old Red Sandstone facies. The centre of the inlier is formed of Llandovery strata, these being succeeded by sediments of Wenlock, Ludlow and Přídolí age.

In the 19th century the Silurian geology of May Hill was described in two classic works: Murchison's (1839) *Silurian System* and shortly afterwards Phillips' (1848) memoir on the Malvern Hills and adjacent areas. In the 20th century, Gardiner (1920), then Lawson (1955), re-investigated May Hill, the latter revision forming the standard work on the geology of the district. Minor comment on the inlier has appeared in several other works, for example those of Gardiner (1927, 1934).

Hobbs Quarry takes its name from Hobbs Ridge, a feature referred to by Murchison (1839) and formed of the resistant Much Wenlock Limestone Formation. The quarry stands as the representative exposure within the inlier for this unit.

Description

The site is located on the western flank of the May Hill pericline, 1 km east of Longhope. Here the Silurian strata strike NNW–SSE and dip WSW at 20–25°. Either side of the ridge of Much Wenlock Limestone are carbonate muds of the Wenlock Coalbrookdale Formation and calcareous siltstones of the Ludlow Series, both of which form lower ground.

The Much Wenlock Limestone Formation in May Hill varies between 30–100 m in thickness and can be divided into lower and upper limestone horizons separated by nodular beds (Lawson, 1955). The upper limestone shows variable lithology and near Longhope is notable for being ferruginous and sometimes oolitic in nature, this facies weathering from a fresh, greyish-olive colour to a rusty yellowish-orange. In the south of the inlier, near Flaxley, the formation is at its thinnest and this upper division has not been recognized. The middle, nodular limestones are thinly bedded and contain seams of calcareous shale. The lower limestone is the purest, and provided a focus for former quarrying operations, including those at Hobbs Quarry. Some of the beds of this lower division are pisolitic, and small biohermal structures (the 'ballstones' of older literature) also occur.

The quarries along Hobbs Ridge have yielded abundant fossils belonging to a variety of groups, most particularly brachiopods, with tabulate corals and stromatoporoids being the most common types in the bioherms. Brachiopods from here were used by Davidson in his classic monographs (e.g. 1867), and more lately in taxonomic and community studies by Bassett (1970a) and Hurst (1975a), respectively; the algae were reported on by Wethered (1893) and Johnson (1966); certain corals have been commented on by Ryder (1926), Lang and Smith (1927) and Smith and Tremberth (1929); and more recently the trilobites have been collected by Thomas (1978) and the ostracods investigated by Siveter (1978, 1980). Gardiner (1920) listed about 90 species from the Much Wenlock Limestone Formation of May Hill, many of these records probably being based on Hobbs Ridge material. Some of the specimens from Hobbs have type status (Figure 4.13).

Interpretation

The Much Wenlock Limestone Formation, rich in corals and algae, was formed in low latitudes in a warm, shallow water environment. The bioherms, which occur in other areas as well as May Hill, have been compared to the small patch reefs of the subtropics (Scoffin, 1971). The formation as a whole represents a carbonate shelf extending from the eastern fringe of the Welsh Basin, throughout the Welsh Borderland, to and including most of central England (Bassett, 1974a; Hurst *et al.*, 1978; Holland, 1992). The

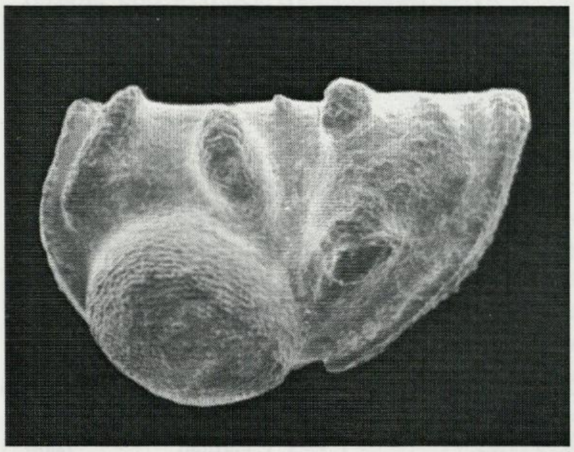


Figure 4.13 *Sleia procincta* Siveter, 1980, a beyrichiacean ostracod from the Much Wenlock Limestone Formation, Hobbs Ridge, May Hill Inlier, southern Welsh Borderland. Holotype, British Museum of Natural History specimen (BM OS6413); female, left valve, lateral view, × 45; figured Siveter (1980). (Photo: David J. Siveter.)

low sea level at this time followed on from the deeper conditions under which the carbonate muds of the Coalbrookdale Formation were deposited, and was succeeded by the transgressive pulse responsible for deposition of the lower Gorstian siltstones. This late Wenlock lowstand in the Anglo-Welsh area reflects here the eustatic sea-level fall that has been recognized on several continental blocks (Johnson *et al.*, 1991).

Hobbs Quarry forms part of a group of sites which indicate the nature and extent of the late Wenlock carbonate platform. This feature is in evidence in the nearby Woolhope and Gorsley inliers at Little Hill and Linton quarries respectively, in the West Midlands it can be demonstrated at the Wren's Nest and Daw End localities, and its more distal part is represented by the Easthope–Harley Hill site at Wenlock Edge.

Conclusions

Hobbs Quarry provides the best representative exposure in the May Hill Inlier of the Much Wenlock Limestone Formation. As such it is a useful complementary site to those on Wenlock Edge, which expose the type development of this lithostratigraphical unit. The Much Wenlock Limestone Formation has palaeoenvironmental and palaeogeographical significance. The occurrence of this formation in May Hill demonstrates the extension here of the carbonate platform that occupied central England in the late Wenlock, and the presence in it of bioherms implies a subtropical environment and position. The site also has some palaeontological significance: since the 19th century various invertebrate species have been described on the basis of material from here.

CWM-TON AREA (SO 3322 0184 AND SO 3335 0149)

R. J. Aldridge

Introduction

The Usk Inlier is a pericline with a N–S trending axis, and exposes Silurian strata deposited on the south-eastern shelf of the Welsh Basin. The disused quarries south of Ton Farm in the inlier (Figure 4.14) display the upper part of the 'Usk Limestone Formation'. There has been some debate regarding the precise stratigraphical posi-

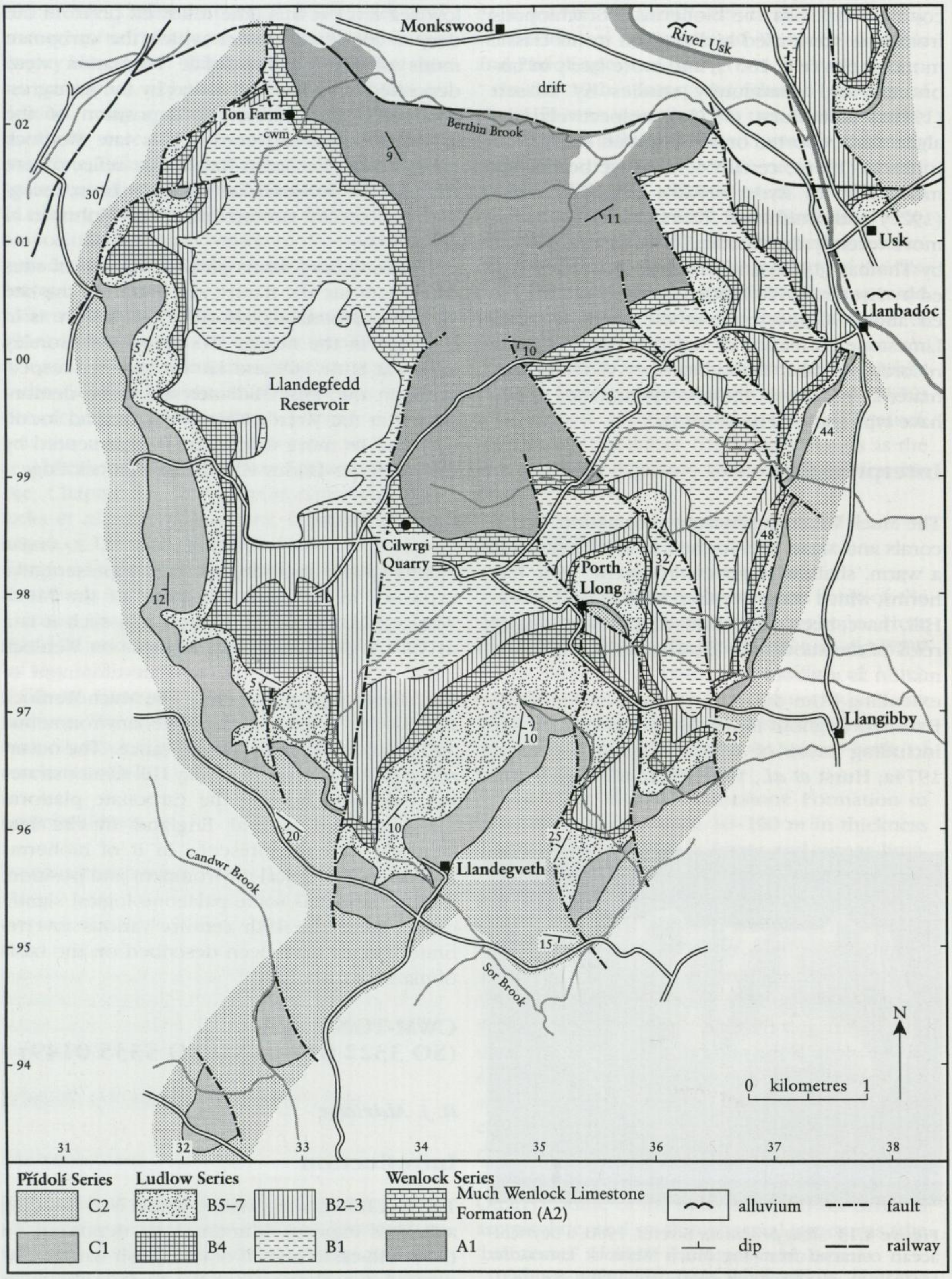


Figure 4.14 Location of Cwm-Ton area and Cilwrgi Quarry, and geology of the central and southern parts of the Usk Inlier, southern Wales (after Walmsley, 1959).

tion of this unit, even though the limestone is clearly a local lithological correlative of the Much Wenlock Limestone Formation of Shropshire. This equivalence was first recognized by Murchison (1839), although he referred the sandy beds below the limestone to the Caradoc Sandstone; Phillips (1848) later correctly identified these lower strata as a sandy facies of the Wenlock Shale. In his mapping and revision of the Usk area, Walmsley (1959) used the term 'Wenlock Limestone' for the limestone formation, and noted that there is a considerable variation in thickness across the area, with a maximum of 13.5 m in the west reducing to less than 1 m in the east. In the thicker developments he recognized a lower, massive division and an upper, nodular division, succeeded by 1–2 m of buff decalcified sandy mudstones that on faunal grounds he also included in the Wenlock Limestone. Squirrel and Downing (1969), in the third edition of the Newport Memoir, also referred to the limestone as the Wenlock Limestone, but mapped the overlying decalcified mudstones as basal Elton Beds, thus referable to the Ludlow Series. Bassett (1974a), however, in his review of the stratigraphy of the Wenlock Series in the Welsh Borderland and southern Wales, noted that these beds contain a typically Wenlock fauna.

The discussion was further complicated by the contention published by Hurst (1975b), on the basis of a study of brachiopod ecology, that the limestone at Usk post-dated a widely recognizable end-Wenlock transgressive event recognizable throughout the Welsh Borderland. Hurst (1975b), therefore, considered that the entire limestone unit represented an early Ludlow carbonate deposit unrelated to the Wenlock Limestone of the Wenlock type area. He proposed that the name 'Usk Limestone' should be used for this formation. This suggestion was severely criticized by Bassett (1976), who considered that all the sedimentological, faunal and palaeogeographical data indicated that the limestone at Usk is contiguous with the Much Wenlock Limestone of other areas in the Welsh Borderland. This equivalence has been generally accepted by subsequent workers (e.g. Cocks *et al.*, 1992). Barclay (1989), in the third edition of the Abergavenny Memoir, retained the name Usk Limestone Formation, but correlated it directly with the Much Wenlock Limestone Formation of the type area; he also introduced the name 'Ton Siltstone Formation' for the sandy beds underlying the limestone.

The Cwm sections provide good exposures of the limestone and there are nearby exposures of the overlying silts; they are thus important in illustrating the stratigraphical and faunal relationships in this controversial part of the succession.

Description

These old quarries display both the lower and upper lithological divisions of the Much Wenlock Limestone Formation as developed in the Usk area (Walmsley 1959, 1967). The lower division comprises massive bioclastic limestone, in which galleries have been opened by pillar and stall mining. The overlying division consists of nodular limestones and interbedded calcareous mudstones. These are very fossiliferous, with brachiopods, especially *Atrypa reticularis* and *Leptaena depressa*, dominant, and corals, crinoids and the trilobite *Dalmanites* common. Barclay (1989) measured the following section in one of the quarries, extending below and above ground:

Lithology	Thickness (m)
Nodular limestone, deeply weathered	0.75
Nodular limestone, well-bedded, with green calcareous silty mudstone interbeds with *A. reticularis*	4.05
Crinoidal limestone, nodular at top	0.55
Coarse-grained, crinoidal, bioclastic limestone, lenticular bedded with green clay partings seen to	3.25

Interpretation

The late Wenlock limestone of the Usk Inlier was deposited close to the southern limit of limestone deposition across the Welsh Borderland at this time (see Bassett, 1974a; Hurst *et al.*, 1978; Holland, 1992). The beds contain a characteristic late Wenlock fauna, and there is no biostratigraphical evidence to support the proposal made by Hurst (1975b) that they are of early Ludlow age.

Strata of the same local formation are also exposed at the related GCR site of Cilwrgi Quarry, where Wenlock conodonts have been recovered. Slightly farther afield, this site is also linked to others in the southern Welsh

Borderland that show evidence of the late Wenlock carbonate platform, for example Hobbs Quarry in the May Hill Inlier and Little Hill quarries in the Woolhope area.

Conclusions

The old quarries around Ton Farm in the Usk Inlier provide typical exposures of the nature of late Wenlock limestone deposition in the southernmost part of the Welsh Borderland. Historically, the age of the limestone has been the subject of some debate, but the lithological and faunal evidence indicates that it correlates with the Much Wenlock Limestone Formation of the type Wenlock area.

CILWRGI QUARRY (ST 3394 9836)

R. J. Aldridge

Introduction

This old quarry (Figure 4.14), also known in the literature as the Borstal Institute Quarry, exposes a typical section within the Much Wenlock Limestone Formation of the Usk Inlier (see Walmsley, 1959). There has been some controversy regarding the precise stratigraphical position of this limestone, with Hurst (1975b) regarding it as a local carbonate development of early Ludlow age and giving it a separate name, the 'Usk Limestone'. Other authors, particularly Bassett (1976), have rejected Hurst's argument that the limestone post-dates a postulated synchronous end-Wenlock transgressive event, and have equated it faunally and chronologically with other late Wenlock limestones of the Welsh Borderland (see discussion of the GCR sites in the Cwm Ton area). Barclay (1989) continued to use the name Usk Limestone Formation, but considered it contiguous with the Much Wenlock Limestone Formation of the Wenlock area; other recent authors (e.g. Cocks *et al.*, 1992) have used the latter name in the Usk Inlier.

Description

The lower 2.5 m of limestone in the quarry belong to the lower, massive division of the Much Wenlock Limestone Formation recognized by Walmsley (1959). This unit comprises hard bioclastic, crystalline limestones in which a biohermal build-up approximately 2.5 m wide and 1.25 m thick is developed (Squirrell and Downing, 1969). Above this, 1.25 m of nodular limestones interbedded with buff silty mudstones represent the upper, nodular division of Walmsley (1959). Squirrel and Downing (1969) recorded a diverse macrofauna from the quarry, including the corals *Favosites gothlandicus, Halysites catenularius, Microplasma lovenianum, Syringopora fascicularia*, and *Thecia bisingeri*. Brachiopods are numerous and varied, including *Amphistrophia funiculata, Atrypa reticularis, Dolerorthis rustica, Leptaena* spp., *Leptostrophia filosa, Resserella* cf. *elegantula*, and *Sphaerirhynchia davidsoni*. Gastropods, bivalves, tentaculitids, crinoid columnals and the trilobites *Acaste downingiae, Dalmanites caudatus*, and *D.* cf. *myops* also occur, and bryozoan material, which includes species of *Fenestella*, is particularly abundant. Dissolution of samples of limestone from both divisions has yielded to the present author a small number of conodont elements, including representatives of the species *Ozarkodina bohemica* and *Ozarkodina excavata*.

Interpretation

The limestones in the Usk Inlier represent the southernmost extension of carbonate deposition on the ESE margin of the Welsh Basin (see Bassett, 1974a; Hurst *et al.*, 1978; Holland, 1992). The exposures at Cilwrgi Quarry contain a typical late Wenlock invertebrate and conodont fauna, and there is no biostratigraphical evidence to suggest that they should be regarded as part of a localized early Ludlow carbonate development (cf. Hurst, 1975b). The depositional environment was in shallow water with little detrital input, allowing the establishment of small bioherms.

This site is most closely networked to the nearby Cwm-Ton, Usk site which, too, displays strata of the same local formation. It is also closely linked to other sites in the southern Welsh Borderland that demonstrate the nature of the late Wenlock carbonate platform, such as Hobbs and Little Hill quarries in the May Hill and Woolhope inliers, respectively.

Conclusions

Together with the exposures in the Cwm-Ton area, Cilwrgi Quarry provides a representative example of late Wenlock carbonate environments in the southernmost part of the eastern shelf of the Welsh Basin. In particular, it exemplifies the development of small bioherms in this area, and the limestones in the quarry are especially fossiliferous, with a diverse invertebrate and conodont fauna recorded. Historically, there has been some controversy regarding the precise age of the Usk Limestone, but the known fauna is consistent with a late Wenlock age, contiguous with the Much Wenlock Limestone Formation throughout the Welsh Borderland.

BRINKMARSH QUARRY (ST 674 913)

Introduction

This site is situated in the Lower Palaeozoic inlier of the Tortworth district (Figure 3.14), about 10 km north of Bristol and 8 km east of the Severn estuary. Ordovician (Tremadoc Series) and Silurian rocks are present beneath Devonian, Carboniferous, then Triassic and Jurassic sediments. The Silurian consists largely of Llandovery and Wenlock rocks that occur in the main part of the inlier, but there is a thin strip of Ludlow present in the north of the area, with the Přídolí and the Devonian comprising the Lower and the Upper Old Red Sandstone, respectively. The Llandovery and Wenlock strata form part of the Bristol Coalfield Syncline. On the north-west limb of this structure there is a complementary, southerly plunging anticline. Brinkmarsh Quarry lies on the nose of this anticline, just west of its axis (Figure 4.15).

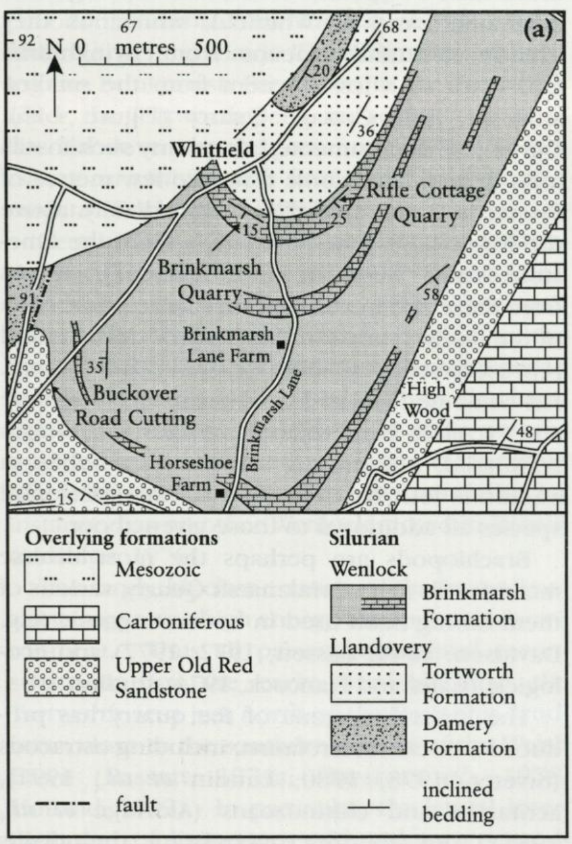


Figure 4.15 Location of Brinkmarsh Quarry and Buckover Road Cutting, and geology of this southern part of the Tortworth Inlier (after Curtis, 1972).

Silurian rocks in the inlier have been commented on by various authors for over 150 years, Murchison (1839) and Phillips (1848) being amongst the earliest of them, with Weaver (1824) providing very early, comprehensive observations, including a description of the section at Brinkmarsh Quarry. Indeed, Weaver's contribution was 'the first detailed study to be made of any area of Lower Palaeozoic rocks in the British Isles' according to one student of the Tortworth region (Curtis, 1955a). After these assessments the following works, in the main, dealt with the Silurian geology and fossils of the area: Morgan and Reynolds, 1901; Reed and Reynolds, 1908a, b; Reynolds, 1924; Smith, 1934; Whittard and Smith, 1944; Curtis, 1955b, 1956, 1958, 1972; Curtis and Cave, 1964; Cave and White, 1971; Bassett, 1974a and Cave, 1977. The stratigraphical accounts of Reed and Reynolds (1908b), Curtis (1972) and Cave (1977) are those most pertinent to the present site.

Fossiliferous beds at the base of the Wenlock Series are exposed in Brinkmarsh Quarry. These have been utilized for local stratigraphy, but more importantly they have wider palaeontological and palaeogeographical significance.

Description

The Wenlock succession of the Tortworth area consists of shales, mudstones, siltstones, calcareous sandstones and some limestones. All these various clastic horizons belong to the Brinkmarsh Formation (Curtis, 1972; Bassett, 1977), which is some 244 m thick and considered to range in time from the base of the *centrifugus* Biozone to the *lundgreni* or the *ludensis* Biozone (Bassett, 1974a; Cocks *et al*., 1992). Certain layers are rich in fossils; also some horizons show sedimentary structures, particularly the fine-grained sandstones that exhibit ripple marks, current bedding and drag marks. Three prominent, discontinuous bands of impure limestone, best exposed just south of Whitfield in the Brinkmarsh area, occur in the lowest, middle and upper parts of the formation. The oldest of them has a maximum thickness of about 30 m and passes laterally into calcareous sandstones. The upper part of this lowest limestone together with overlying mudstones are present in Brinkmarsh Quarry.

The quarry itself, the working of it long discontinued, is no more than a very shallow excavation with exposures now being confined essentially to low banks at the southern to north-west boundary of the field it occupied. The beds dip south-west at 15–20°. Reed and Reynolds (1908b) gave a log of the southern side of the quarry, this area having been opened up during the time they were working, the original section of Weaver (1824) having become overgrown. In modern times Curtis (1972) and Cave (1977) have described the exposures still available, the latter account largely forming the basis for the following description.

At the north-west extremity of the quarry, some 3.7 m of limestone are present. It is fine- to medium-grained, mainly greyish-green in colour but in places red, with calcite veining and slickensiding. Thin lenticular beds of greyish-green, micaceous, cross-bedded sandstone also occur, as do lenticles of fossil remains, mainly crinoid ossicles, brachiopods and bryozoa. Brachiopods from here include *Amphistrophia* (*Amphistrophia*) *euglyphoides*, '*Camarotoechia*' sp. and *Resserella whitfieldensis*.

The centre of the south face of the quarry (ST 6740 9125) shows the following section:

Lithology	**Thickness (m)**
Soft, greyish-green mudstone	1.22
Calcareous, greyish-green, crinoidal sandstone	0.51
Soft, green, shaly mudstone	0.20
Hard, olive-green, ?chloritic, calcareous sandstone	0.36
Massive reddish limestone	0.91

The veins of celestine from this face noted by Reed and Reynolds (1908b) were not seen by Cave (1977).

At the eastern end of the south face more of the mudstone above the limestone is present at the top of the face, and the top part of the limestone is not so arenaceous as that at the centre of the face. The section here comprises 0.30 m of mudstone with some nodular limestone overlying 1.52 m of mudstone, which in turn lies above 0.46 m of rubbly limestone. Fossils from the limestone here include the brachiopods *Brachyprion waltonii*, *Sphaerirhynchia davidsoni*, '*Camarotoechia*' *diodonta*, *Howellella* sp., and *Whitfieldella* sp., the alga *Rothpletzella gotlandica*, the coral *Favosites hisingeri* and bryozoans.

The mudstones immediately above the limestone are fossiliferous. This is the horizon of Reed and Reynolds (1908b) with the coral *Hallia mitrata*, the same level referred to as the Pycnactis Band by Curtis (1972), who recorded from it at the southern face *Pycnactis mitratus*, *Coenites juniperus*, *Resserella* cf. *basalis*, *Sphaerirhynchia davidsoni*, *Microsphaeridiorhynchus* cf. *nucula* and *Whitfieldella* cf. *canalis*.

Reed and Reynolds (1908a, 1908b) estimated the total thickness of massive limestone in Brinkmarsh Quarry to be over 8 m. They listed more than 60 species of fossils from the lower limestone band at Whitfield, which, as they noted, essentially means from Brinkmarsh Quarry or to a lesser extent from the smaller, adjacent, Rifle Cottage Quarry (Figure 4.15). Curtis (1972) commented that many such fossils may, in fact, have come from the few metres of Pycnactis Band mudstones immediately above the lower limestone rather than from the limestone itself, but that nevertheless specimens from these two horizons form a large proportion of the fossils from Tortworth Wenlock rocks and represent nearly all those described and figured. His combined faunal list for the lower limestone and Pycnactis Band totals 23 species, including a conulariid, a coral, an 'annelid', a trilobite, a nautiloid, four brachiopod and three gastropod species all additional to those given above.

Brachiopods are perhaps the most diverse macrofossils from Brinkmarsh Quarry, various of them having been used in both taxonomic (e.g. Davidson, 1848; Bassett, 1972, 1977) and ecological (Calef and Hancock, 1974) studies.

The lower limestone of the quarry has produced a diverse microfauna, including ostracods (Siveter, 1978, 1980; Lundin *et al.*, 1991), acritarchs and chitinozoans (Aldridge *et al.*, 1981), and the microvertebrate thelodonts (Siveter and Turner, 1982) and conodonts (Aldridge, 1975, 1976, 1985; Aldridge and Mabillard, 1981).

Taxa of both macro- and microfossils have been based on material from the quarry, for example *R. whitfieldensis* Bassett, 1972, the ostracod *Nudista cariticuspis* Siveter, 1980, the nautiloid *Armenoceras nummularium* (J. de C. Sowerby in Murchison, 1839) and the coral *Phaulactis glevensis* (Ryder, 1926).

Interpretation

A Wenlock age for the Brinkmarsh Formation as a whole is based on the general aspect of its shelly fauna and microfauna, as it lacks graptolites. Moreover, there has been uncertainty over the precise age of the lower limestone, which contains a number of brachiopod species such as *Leptostrophia compressa* that are more typical of the Llandovery (Bassett, 1974a). These, however, are considered faunal leftovers and the lower limestone has been assigned to the basal Wenlock, making it a correlative of the lower part of the Woolhope Limestone Formation as present at Woolhope, May Hill and the Malverns; this age is corroborated by the presence of the conodont *Ozarkodina sagitta rhenana* (R.J. Aldridge, pers. comm.). The sediments underlying the Brinkmarsh Formation in the Tortworth Inlier, the Tortworth Beds, are securely dated as late Llandovery by the presence of *Eocoelia sulcata*, *Costistricklandia lirata* and *Palaeocyclus porpita* (Cocks *et al.*, 1992).

Certain faunal elements and species associations of the lower limestone and Pycnactis Band are, within Britain, peculiar to the Tortworth Inlier, this perhaps especially applying to the microfossils. The conodont, beyrichiacean ostracod and thelodont faunas from the basal Brinkmarsh Formation have, in their various ways, all been described as unique (Aldridge *et al.*, 1981); the conodont genus *Icriodella*, for instance, has no other Wenlock record in Britain (Aldridge, 1976).

The sandy, bioclastic nature of the lower limestone suggests a high energy, shallow water environment. Thus all palaeogeographical reconstructions for the early Wenlock have the Tortworth area just north of the Pretannia landmass, close to the southern margin of the Welsh Basin (Bassett, 1974a; Hurst *et al.*, 1978; Holland, 1992). In particular, the lateral interdigitation of limestones with calcareous sandstones at Tortworth has been taken to indicate a position at the boundary between an inshore arenaceous facies belt and a slightly more distal, carbonate belt (Bassett, 1974a). The Pycnactis Band mudstones, with their *Resserella* Association (Calef and Hancock, 1974), represent slightly deeper conditions after deposition of the lower limestone.

Other Welsh Borderland sites that contain rocks approximately coeval with those in Brinkmarsh Quarry are those of Scutterdine Quarry in the Woolhope area, which exposes the Woolhope Limestone Formation, and the Hughley Brook and Buildwas sites near Much Wenlock, where the lime-rich Buildwas Formation crops out. The strata at all these other sites lack the markedly arenaceous fingerprint of the lower limestone. However Rumney Quarry in the Cardiff district shows the Rhymney Grit, which is thought to indicate an even more inshore (sub-tidal) position on the basin margin than the lower limestone, but this grit is of late Wenlock age. In the Tortworth Inlier, the Buckover Road section complements the Brinkmarsh Quarry site by exposing upper Wenlock strata, while those sites at Damery Bridge and Cullimore's Quarry have Llandovery significance. Just to the north, on the Severn estuary, is Tites Point, a site important for Ludlow age rocks.

Conclusions

This important site forms part of the Tortworth Silurian inlier and exposes the lower limestone and the Pycnactis Band mudstones of the Brinkmarsh Formation, which belong to the lowest part of the Wenlock Series. The quarry has been a rich source of fossils since the early part of the 19th century and it represents the type locality for various macro- and microfossils. Some of the fauna is distinctive and known only from here. The nature of the limestone facies here is also distinct and indicates a relatively nearshore situation; consequently it is of great utility for palaeogeographical reconstruction of this part of the Anglo-Welsh area for early Wenlock times.

BUCKOVER ROAD CUTTING (ST 667 908)

Introduction

This is the second site of Wenlock age from the Tortworth Inlier in this volume, the other being

Brinkmarsh Quarry (Figures 3.14 and 4.15). Under the report on that quarry, a synthesis is given of the geology of the area together with references to the more important works concerning Silurian rocks and fossils in the inlier. The studies of Reed and Reynolds (1908b), Curtis (1972), and Cave (1977) are the most significant for the general geology of the Silurian hereabouts, and the last two of these plus Curtis and Cave (1964), for data on the present site in particular.

Unlike Brinkmarsh Quarry, which has figured in geological literature for over 170 years, Buckover Road Cutting has only been available since 1963. It exposes beds in the upper part of the Wenlock and amongst other things helps provide a fully representative sequence for this series in the Tortworth Inlier. Wenlock sediments are unconformably overlain in the cutting by the Devonian Upper Old Red Sandstone, and the Triassic is also represented.

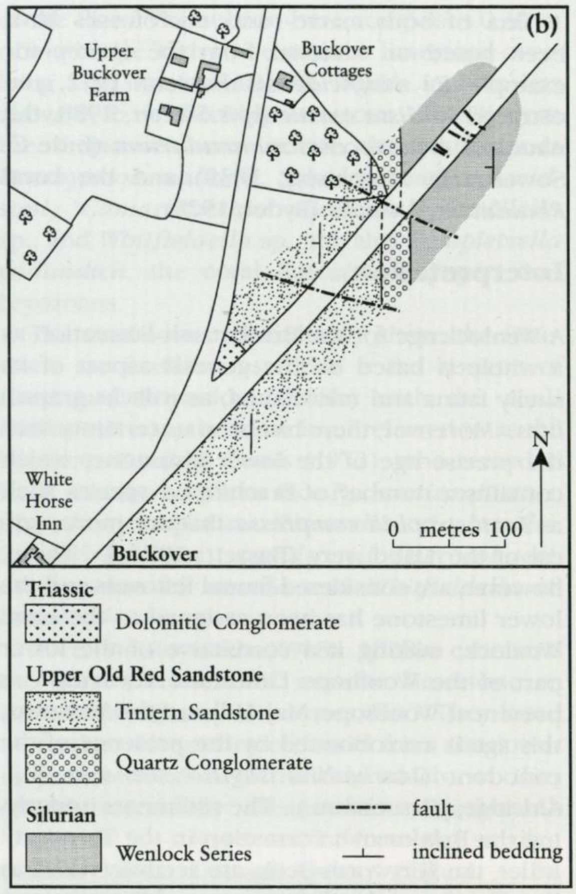


Figure 4.16 Buckover Road Cutting, Tortworth Inlier. General geology (after Curtis and Cave, 1964).

Description

The road cutting is situated on the eastern limb of a southerly-plunging syncline that is composed of Silurian–Devonian rocks, the axis of the syncline running through Buckover and Milbury Heath. This fold is complementary to the southerly-plunging anticline that has its axis passing through Whitfield (very close to Brinkmarsh Quarry) and Horseshoe Farm (Figure 4.15).

There are some 244 m of strata in the Wenlock of the Tortworth Inlier, all belonging to the Brinkmarsh Formation, with three laterally discontinuous bands of bioclastic limestone occurring at the base, near the middle, and towards the top of the succession. The upper 55 m (22%) of these strata are dissected by the cutting, which trends NE–SW (Figures 4.16 and 4.17). The dip of the rocks here is to the west and steepest (37°) in the north-east part of the section, where the oldest strata occur. Towards the south-west, approaching the synclinal axis, dips gradually decrease so that the highest Wenlock beds are at an angle of about 34° and the basal and highest units of the Upper Old Red Sandstone are at about 33° and 20°, respectively. There is no clear angular discordance between the Wenlock and Old Red Sandstone strata, both of which occur either side of the cutting. The bottom bed of the 'Old Red', a sandstone, has in places small (< 1 cm) pebbles at its base. The Trias is confined to a very small patch on the north-west side of the section at its south-western end.

Minor faults are present which trend between west and north-west. The two largest both have a generally southerly downthrow; one involves only the Old Red Sandstone and displaces strata by a minimum of 9–12 m, the other has a throw of about 5 m and affects both Wenlock and Old Red Sandstone rocks at the unconformity. In the north-east of the section, several other smaller faults displace Wenlock strata by a metre or so.

The Wenlock sediments in the section are mainly mudstones and siltstones, with some fine sandstones occurring in its upper part. A full log (Curtis and Cave, 1964) is shown in Table 4.1, bed 6 being the upper limestone referred to above.

Fossils (see Curtis and Cave, 1964; Curtis, 1972) are lacking in the lower part of the sec-

Table 4.1 Lithological log of the Brinkmarsh Formation at Buckover Road Cutting, Tortworth Inlier (after Curtis and Cave, 1964).

Bed no.	Lithology	Thickness (m)
(18)	Hard yellow current-bedded, fine-grained calcareous sandstone, weathering to a brown laminated rottenstone; contains abundant crinoid ossicles.	0.45
(17)	Silty mudstone with some silty sandstone bands; mainly green below and red and green above.	1.21
(16)	Purplish-red shaley mudstone, with occasional bands of hard, green, fine-grained sandstone and a thin layer of green clay at the base.	1.87
(15)	Banded green and purplish-red silty mudstone, with some hard sandy siltstone bands.	2.59
(14)	Banded green and purplish-red silty mudstone, with occasional bands of hard, fine-grained sandstone, and a few pale green clay partings.	1.67
(13)	Green siltstone, with some sandier bands showing fine current bedding and containing rounded masses with curved bedding.	1.21
(12)	Brown sandy siltstone with some curved bedding; abundant fossils.	0.91
(11)	Banded green and purplish-brown silty mudstone.	0.60
(10)	Yellowish-green siltstone, with bands of harder siltstone. Bands of yellowish-brown, fine-grained calcareous siltstone up to 30 cm thick, sometimes highly fossiliferous, most abundant in middle and upper part. Some reddish-brown and purplish streaks towards base and top.	5.48
(9)	Purplish-red mudstone and silty mudstone, with layers of slightly harder siltstone and two 10 cm bands of fine-grained sandstone.	3.04
(8)	Banded purplish-red and drab green mudstone and sandy mudstone with a band of green argillaceous sandstone, 17 cm thick at base.	1.37
(7)	Purplish-red mudstone, with green streaks, and occasional bands of green mudstone and sandy mudstone up to 30 cm thick. Abundant fossils in bed of purple mudstone apparently about 1.8 m above base.	10.05
(6)	Hard, purple and purplish-grey argillaceous and silty limestone, occurring in lumpy, irregular beds with clay partings. The highest 60 cm is most massive and regularly bedded. Drusy cavities, up to 5 cm across, contain small crystals of white and pink celestine. About 60 cm above base is band of purplish-blue clayey mudstone 23 cm thick.	3.66
(5)	Purple and purplish-red mudstone with occasional calcareous nodules; in the lower part a few seams of nodular, lumpy limestone up to 23 cm thick.	2.74
(4)	Purplish-red mudstone, slightly calcareous towards the base, with green limestone and mudstone band, 7 cm thick, at base.	3.95
(3)	Purplish-red mudstone with occasional thin green and purplish-blue bands. Nodular lumps of purple limestone, up to about 10 cm thick, in lower part.	2.42
(2)	Purplish-red mudstone with an occasional calcareous nodule in upper part, and with occasional thin green and purplish-blue bands and streaks.	7.91
(1)	Soft purplish-red mudstone with occasional very thin green partings.	4.50

tion, that is the part of the succession that regionally lies between the middle and upper limestones, but the lower mudstones of bed 7 immediately overlying the latter have yielded a rich fauna, including: *Favosites gothlandicus forbesi*, *Meristina obtusa*, *Trigonirhynchia stricklandi*, *Amphistrophia funiculata*, *Leptaena depressa* and *Cordatomyonia edgelliana*. The siltstones and sandstones of beds 10–18, which form the upper 16 m of the Wenlock here, especially bed 10, have produced a large fauna that includes *Craniops implicatus*, *Salopina*

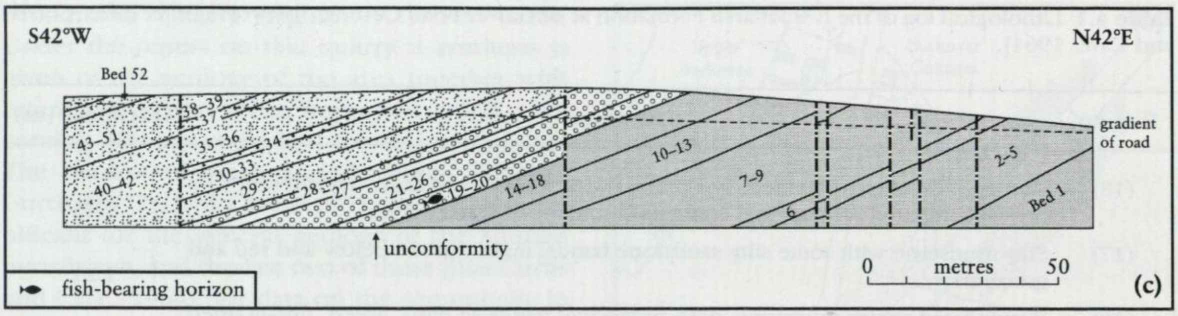


Figure 4.17 Buckover Road Cutting, Tortworth Inlier. Geological section. Beds 1–18 belong to the Brinkmarsh Formation, Wenlock Series; beds 19–52, above the unconformity, belong to the Upper Old Red Sandstone (Devonian). (After Curtis and Cave, 1964.)

conservatrix, *A. funiculata*, *Coolinia pecten*, *Coolinia applanata*, *Protochonetes* cf. *ceratoides*, *Howellella* cf. *angustiplicata*, *M. obtusa*, *Actinopteria* cf. *pleuroptera*, *Cornellites* sp., *Acaste downingiae*, *Dalmanites caudatus*, and *Trimerus* sp..

Interpretation

Prior to the studies of Curtis and Cave (1964) and Curtis (1972), there had been much uncertainty as to whether the highest Silurian beds in the inlier, previously exposed near the Buckover Road Cutting in the lane by Horseshoe Farm, were Wenlock or Ludlow in age. Murchison (1839) and Phillips (1848), for instance, considered these beds to be Ludlow, whereas Reed and Reynolds (1908a, 1908b) thought on balance a Wenlock assignment better. The brachiopods from the cutting from beds that are at the same horizon as the beds in the lane (above the upper limestone) confirm a Wenlock age. Specifically, they indicate correlation with the upper part of the Coalbrookdale Formation or possibly with the Much Wenlock Limestone Formation (Curtis, 1972; Bassett, 1974a; Cocks *et al.*, 1992).

The presence of sandstones in the upper part of the Buckover section, some with ripple marks and current bedding, has been taken to indicate a nearshore situation. Also there is a relative abundance of bivalves – generally shallow water indicators – above the upper limestone. Thus in palaeogeographical reconstructions of the Anglo-Welsh area for late Wenlock times, the Tortworth region is positioned just north of the Pretannia landmass, close to the boundary between clastic and carbonate belts (Bassett, 1974a; Hurst *et al.*, 1978; Holland, 1992).

Strata exposed in the Buckover Road Cutting link stratigraphically with those in the Brinkmarsh Quarry site nearby, where the lowest beds of the Brinkmarsh Formation of earliest Wenlock age crop out, including the lower limestone. The Rhymney Grit of the Rumney Quarry site in the Cardiff Inlier is broadly coeval with the Buckover section and it, too, suggests the proximity of a landmass to the south, but this grit is considered subtidal, which implies an even more proximal position. Other sites in this volume from the main Tortworth Inlier are those of Damery Bridge and Cullimore's Quarry, both of Llandovery age. Also, on the Severn estuary to the north of the main outcrop is that of Tites Point, a Ludlow Series GCR site.

Conclusions

Fossils from this cutting enable a late Wenlock age to be assigned to the upper part of the Silurian succession of the main Tortworth Inlier, there having been longstanding debate as to whether these strata were Wenlock or Ludlow in age. The upper Wenlock strata and fossils of the cutting combine with the lower Wenlock rocks of the Brinkmarsh Quarry site to provide coverage of all the main facies and faunas of Wenlock age in the inlier. Interpretation of the facies and faunas from the cutting enables the Tortworth area to be positioned close to the southern margin of the Welsh Basin in late Wenlock times. The usefulness of this road section is reinforced by the unavailability now of other localities of the same age in the inlier.

MOONS HILL QUARRY (ST 665 460)

Introduction

The most southerly exposures of Silurian rocks in Britain are to be found in the east Mendips, where they comprise an inlier in the form of an E–W trending asymmetrical anticline flanked by Devonian and Carboniferous rocks. Moons Hill Quarry is situated just north of the axial region of the anticline, about 0.5 km south of Stoke Lane. It contains Wenlock age volcanic rocks and also, around its southern margins, Wenlock sediments.

Moore (1867) was the first to discover the igneous rocks of the east Mendips, which were later the subject of a short report by Geikie and Strahan (1899). For most of the present century the most detailed work on the inlier was done by Reynolds (1907, 1912a, 1912b) and by Woodward *et al.* (1909), who assessed its structure, stratigraphy, fauna and volcanics. Subsequently, brief notes on the Silurian here were given by Green (1962) and Green and Welch (1965) and the igneous rocks received specific treatment by Van de Kamp (1969) with further comment from Ponsford (1970). Bassett (1974a) gave a summary of the Wenlock strata in the inlier, but his stratigraphical scheme was based on the structure of the area as understood by earlier authors, which is now believed to be incorrect.

In 1982 Hancock re-investigated the inlier and produced a revised stratigraphy and structural model for it together with a new map of the area. He recognized for the first time that the 'Wenlock Shale' (Coalbrookdale Formation) near the southern margin of the inlier, which was formerly thought to be the youngest unit, is in fact part of an inverted, northern, limb to the anticline and forms the lowest part of the Silurian succession, which here youngs to the north. This means that the tuffs which lie above these shales are Wenlock (Ziegler *et al.*, 1968b; Bassett, 1974a), not Llandovery (Reynolds, 1907, 1912b; Green, 1962), in age. The southern margin of the inlier is marked by a Hercynian thrust fault, which carries gently southerly dipping Old Red Sandstone from the south to the north to lie over both the inverted and normal limbs of the anticline (Figure 4.18).

The Silurian of the Moons Hill site is con-

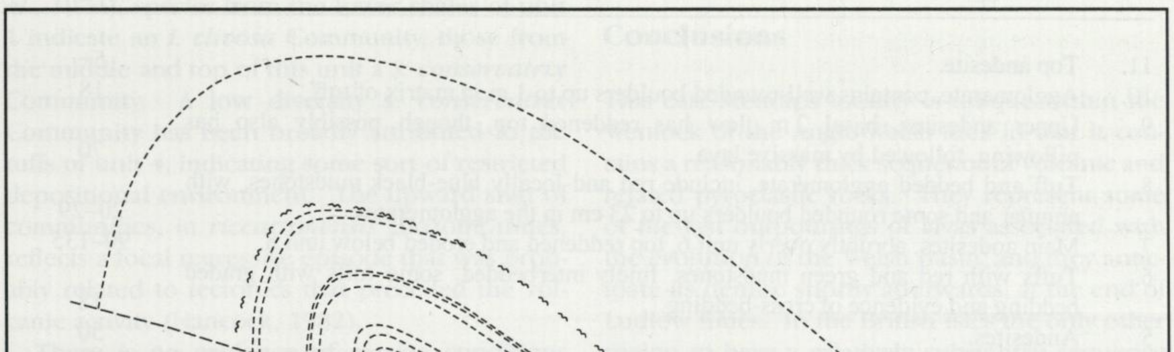


Figure 4.18 Diagrammatic cross-section across the East Mendips (Silurian) Inlier, running southwards from Stoke Lane (after Hancock, 1982).

tained entirely in the overturned (to vertical), northwardly younging, northern limb of the East Mendips Anticline. The site is very distinct in having substantial volcanics of Wenlock age and its southernmost position in terms of Silurian rocks lends it palaeogeographical importance.

Description

Hancock (1982) identified 12 stratigraphical units in the Silurian of the East Mendips Inlier. Units 4–12 are specifically noted by him as occurring within Moons Hill Quarry; at that time units 1–3 lay outside the limits of the main quarry, but are included within the GCR site boundary, which was extended in particular to the south of this quarry so as to include the fossiliferous Wenlock shales and siltstones (unit 1) at the base of the succession.

Unit 12, a vent agglomerate, exhibits a cross-cutting relationship to all the other Silurian beds in the inlier. The agglomerate consists of blocks of various lavas and tuffs up to 30 cm, mostly well rounded, together with quartz–siltstone pebbles, in a matrix of tuff. The rest of the sequence, in descending stratigraphical order, is shown in Table 4.2.

The occurrence of *E. angelini* in the upper part of unit 1 places an age limit on this part of the sequence as this species is the latest member of the *Eocoelia* lineage and on Gotland is known only from the *riccartonensis* Biozone (Ziegler, 1966; Bassett and Cocks, 1974). Grading in several tuffs of unit 4 indicates that the sequence youngs northwards. The position in the sequence of these tuffs thus indicates a Wenlock, not Llandovery, age for them. The whole shale–volcanic Silurian sequence of the East Mendips Inlier has recently been given as spanning the *centrifugus* to *lundgreni* biozones (Cocks *et al.*, 1992), but the precise age of both the bottom and top of the succession is still open to some uncertainty.

The presence of cross-bedding in one tuff of unit 6 suggests the existence of currents and a water-lain origin, though the interbedded mud-

Table 4.2 Stratigraphy of the East Mendips Inlier (after Hancock, 1982).

Unit	Lithology/fossils	Thickness (m)
11.	Top andesite.	5+
10.	Agglomerate, contains well-rounded boulders up to 1 m in matrix of tuff.	18
9.	Upper andesites, basal 2 m flow has reddened top, though possibly also has pillowing, followed by massive lava.	70
8.	Tuff and bedded agglomerate, include red and locally blue-black mudstones, with angular and some rounded boulders up to 23 cm in the agglomerates.	20–29
7.	Main andesites, abruptly overly unit 6, top reddened and eroded below unit 8.	90–135
6.	Tuffs with red and green mudstones, finely interbedded, some tuffs with graded bedding and evidence of cross-bedding.	18
5.	Andesites.	50
4.	Tuffs and sandy tuffs, with fragments up to 2.5 cm, showing graded bedding, together with red and green mudstones, locally fossiliferous. Shelly fauna comprises mainly brachiopods, e.g. *Craniops* sp., *Salopina conservatrix*, '*Camarotoechia*' *tripartita*, '*Camarotoechia*' aff. *llandoveriana*, *Rhynchotreta cuneata* and *Sphaerirhynchia davidsoni*. Also remains of trilobites, bivalves, gastropods and ostracods (see also Reynolds, 1907; Woodward *et al.*, 1909).	105–135
3.	Andesites, no surface exposure, possibly absent in eastern part of inlier.	30
2.	Tuffs, fine-grained, no surface exposure, possibly absent in eastern part of inlier.	34–60
1.	Shales and siltstones, with brachiopod-dominated shelly fauna, including *Salopina conservatrix*, '*Camarotoechia*' *tripartita*, '*Camarotoechia*' *llandoveriana*, *Eocoelia angelini*, *Eoplectodonta duvalii*, *Coolinia applanata*, *Resserella canalis*, *Atrypa reticularis*, ?*Isorthis clivosa*, *Eospirifer radiatus* and *Protochonetes* sp.. Trilobite, ostracod, bivalve, coral and *Tentaculites* remains also occur in these Wenlock Shale sediments (see also Reynolds, 1907; Bassett, 1974a).	95+

stones of this unit are unfossiliferous. The andesites of unit 7 are the main rocks worked in the quarry and four flows were recognized by Van de Kamp (1969). The boundary between unit 8 (tuff and agglomerate) and unit 12 (vent agglomerate) is uncertain as rounded boulders characterize both. A reddened top to unit 9 suggests subaerial conditions, yet if pillowing really is present in the bottom of this unit, this would indicate eruption into water. The top of unit 9 is cut out in most places, with slight angular unconformity, by the base of the overlying Old Red Sandstone. Units 10 (agglomerate) and 11 (top andesite) are limited in extent, both having been largely removed by pre-Old Red Sandstone erosion. The vent agglomerate (unit 12) is the 'Coarse Ashy Conglomerate' of Reynolds (1907), who interpreted this lithology as that of a volcanic neck. The rounded nature of many of the fragments in this unit has been explained by their erosion by gas-fluidized tuff and agglomerate.

Interpretation

In terms of the depth related brachiopod communities established for the Wenlock Series (Calef and Hancock, 1974; see also Hancock *et al.*, 1974), species from the lower shales of unit 1 indicate an *I. clivosa* Community, those from the middle and top of this unit a *S. conservatrix* Community. A low diversity *S. conservatrix* Community has been broadly attributed to the tuffs of unit 4, indicating some sort of restricted depositional environment. The upward shift of communities, in *riccartonensis* Biozone times, reflects a local regressive episode that was probably related to tectonics that preceded the volcanic activity (Hancock, 1982).

There is no evidence of marine conditions after unit 4 was laid down and the overlying lavas and pyroclastics were probably deposited onto a continental landscape of short-lived pools or flowing streams (Hancock, 1982).

The igneous rocks here represent an extremely rare occurrence in the Wenlock Series of the British Isles of true volcanic rocks; moreover they comprise a moderately thick pile. The Dingle Peninsula in Co. Kerry is the only other area in these islands to have a notable Wenlock volcanic–volcaniclastic sequence (e.g. Sloan and Bennett, 1990). Wenlock volcanic activity elsewhere in the Anglo-Welsh area may have been present in the Bishop's Castle district, where three small igneous intrusions have been identified as possible volcanic feeders, but here they are not accompanied by lava flows. In the same district, tuffs have been identified from the borehole sunk at Eaton Farm (Hains, 1962; Cocks and Rickards, 1969; Sanderson and Cave, 1980). Also, an acid tuff of possible late Wenlock, *ludensis* Biozone age has been reported from near Welshpool (Sanderson and Cave, 1980). Apart from these examples, Wenlock age volcanic activity is recognized in Wales and the Welsh Borderland only by the presence of bentonites (e.g. Teale and Spears, 1986). The east Mendips volcanic centre may have been involved in sourcing some of these bentonites.

Overall, the nature of the faunas, volcanics and volcaniclastics of the Moons Hill site suggest that this east Mendips area was variously located near or on the south-east margin of the Welsh Basin throughout mid-Wenlock times (Bassett, 1974a; Hurst *et al.*, 1978; Holland, 1992). In the Tortworth Inlier 50 km to the north, the Brinkmarsh Quarry and Buckover Road Cutting GCR sites indicate marine, nearshore conditions there in the early and late Wenlock respectively, but that area was positioned slightly more distally with respect to the shoreline than the east Mendips.

Conclusions

This east Mendips locality is unique within the Wenlock of the Anglo-Welsh area in that it contains a reasonably thick sequence of volcanic and related pyroclastic rocks. They represent some of the last outpourings of lavas associated with the evolution of the Welsh Basin, and they anticipate its demise shortly afterwards, at the end of Ludlow times. In the British Isles the only other region to have a relatively substantial sequence of Wenlock volcanics is the Dingle Peninsula in south-west Ireland.

The Moons Hill site is also important in providing data useful for palaeogeographical reconstruction of the mid-Wenlock, allowing the east Mendips area to be positioned on or very close to the south-east margin of the Welsh Basin throughout this time.

PENYLAN QUARRY (ST 198 787)

Introduction

The Wenlock rocks of the Cardiff district form

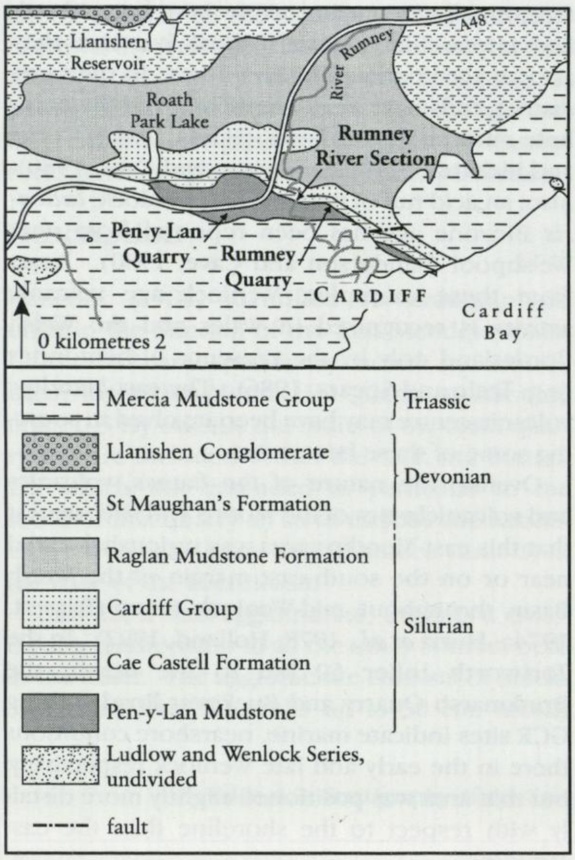


Figure 4.19 Location of Penylan Quarry, Rumney Quarry and Rumney River section, and geology of the Cardiff district (after the British Geological Survey, 1986).

part of an inlier of Wenlock and Ludlow strata around which is Old Red Sandstone of Přídolí and Lower Devonian age together with Triassic sediments (Figure 4.19). The inlier forms an end member of the chain of Silurian inliers trending SSW to the south Wales and Mendips areas from Walsall and Dudley in the West Midlands. Penylan Quarry is situated near the centre of the inlier, and exposes some of the oldest Wenlock rocks in the district.

Silurian strata were first recognized in the Cardiff district in 1861 by Glass, who sent fossils from Penylan Quarry to be identified by Murchison. After Murchison, and also Salter, had examined them, the former declared them to be *'par excellence'* of Wenlock age. At the same time Bevan (1861) suggested that the beds in the quarry 'appear to be Wenlock Shale'. The slightly later study of Sollas (1879) includes description of the strata at Penylan and represents the first detailed, comprehensive account of the Cardiff Silurian, it remaining so for over 100 years. The Geological Survey memoir from the turn of the century that took in the Cardiff Silurian (Strahan and Cantrill, 1902, 1912) drew heavily on the findings of Sollas. Further information was, about then and subsequently, added on these rocks through more limited investigations (e.g. Storrie, 1879, 1908; North, 1915a, 1915b; Anderson and Blundell, 1965).

In relatively recent years Bassett (1969) has dispelled the notion that Llandovery age rocks are present in the inlier and (1974a) has summarized the stratigraphy of the Wenlock rocks here. Lately, the Cardiff Silurian has been reinvestigated by the British Geological Survey (1986; Waters and Lawrence, 1987), who established in large part a new lithostratigraphy for it and also refined aspects of its chronostratigraphy, for example the position in the sequence of the Wenlock–Ludlow boundary (Figure 4.20). This account, which included the strata at Penylan and details from a new borehole (Figure 4.21; Waters and White, 1980), is now by far the best. It also resulted, from re-examination of previous borehole material (Anderson, 1968, 1974), in the discovery of two further small, Silurian inliers in the district.

Description

Wenlock rocks in the main (Rumney and Penylan) Cardiff Inlier emerge from beneath the Triassic cover to the south in the form of an anticline, the E–W trending axis of which lies just a few metres to the south of Penylan Quarry (Sollas, 1879; Strahan and Cantrill, 1902). The northern part of the inlier is composed largely of Ludlow strata and these in turn give way to the north to the Přídolí age Old Red Sandstone facies of the Raglan Mudstone Formation. Wenlock strata comprise the Pen-y-Lan Mudstone, which has a possible maximum thickness of 255 m, and the succeeding 70–80 m thick Cae Castell Formation. The Pen-y-Lan Mudstone passes upwards into the Rhymney Grit, the basal unit of the Cae Castell Formation, but the base of the mudstone has not been proved.

Some of the oldest beds of the Pen-y-Lan Mudstone, which occur as part of the E–W strip of this unit between Penylan and Rumney, are exposed in Penylan Quarry. Overall, the unit comprises very fossiliferous mudstones (80–90%

Sollas (1879)	Strahan and Cantrill (1902)		Waters and Lawrence (1987)		Series
Lower Old Red Sandstone (*pars*)	Red Marls (*pars*)		Raglan Mudstone Formation (*pars*)		Přídolí
alternating mudstones, sandstones and shales	Ludlow Beds		Roath Park Lake Member	Llanedeyrn Formation	Ludlow
			Chapel Wood Member		
			Eastern Avenue Member		
Wenlock Limestone	Wenlock Limestone		Ty Mawr Ironstone	Hill Gardens Formation	
alternating mudstones and sandstones		Wenlock Beds	Newport Road Member	Cae Castell Formation	Wenlock
Rhymney Grit	Rhymney Grit		Rhymney Grit		
mudstones and sandstones			Pen-y-Lan Mudstone		

Figure 4.20 Silurian stratigraphy of the Cardiff district (fom Waters and Lawrence, 1987).

of the total thickness), with thin sandstone and impure limestone horizons (Waters and Lawrence, 1987). When fresh the mudstones are grey, but they weather to grey-green, olive-green and buff. Their mica, calcium carbonate and silt content is variable and in places they grade into siltstone. Two main types of mudstone (though with all gradations between them) have been identified: the most common consists of massive, often blocky beds 0.1–0.45 m thick, which are strongly bioturbated (mainly *Chondrites*) and have shelly fossils, commonly broken, scattered throughout; the scarcer type is in the form of blocky beds only 2–7 cm thick, which are generally less fossiliferous, have little bioturbation and can normally be split parallel to bedding.

Sandstones within the Pen-y-Lan Mudstone are usually between 2–20 cm thick, though exceptionally they can reach 0.6 m. They are grey to greenish-grey when fresh, weathering to buff-coloured; they have flat bases and flat to gradational or ripple-marked upper surfaces and can grade into siltstones. Comminuted shells often occur in the basal centimetre of a bed; burrows may be present. Irregular, ball-like masses of bioclastic limestone (averaging 10 cm in diameter) composed of crinoid and shell debris are scattered within the bioturbated mudstones. Bentonites up to 0.85 m thick have been recorded.

The Pen-y-Lan Mudstone in general is richly fossiliferous, containing, at least, brachiopods, trilobites, corals, gastropods, bivalves, cephalopods and graptolites.

In terms of extent, Penylan Quarry itself is much diminished now compared with its former size, the construction of Eastern Avenue in the early 1970s having removed most of it. However this road did provide at that time fairly continuous additional sections through the Pen-y-Lan Mudstone that were logged (by M.G. Bassett), and a part of the north side of this cutting very near to the quarry (ST 1906 7875–ST 1923 7876) is the designated type locality for this unit (Waters and Lawrence, 1987). In what remains of the quarry, the beds dip north-east at about

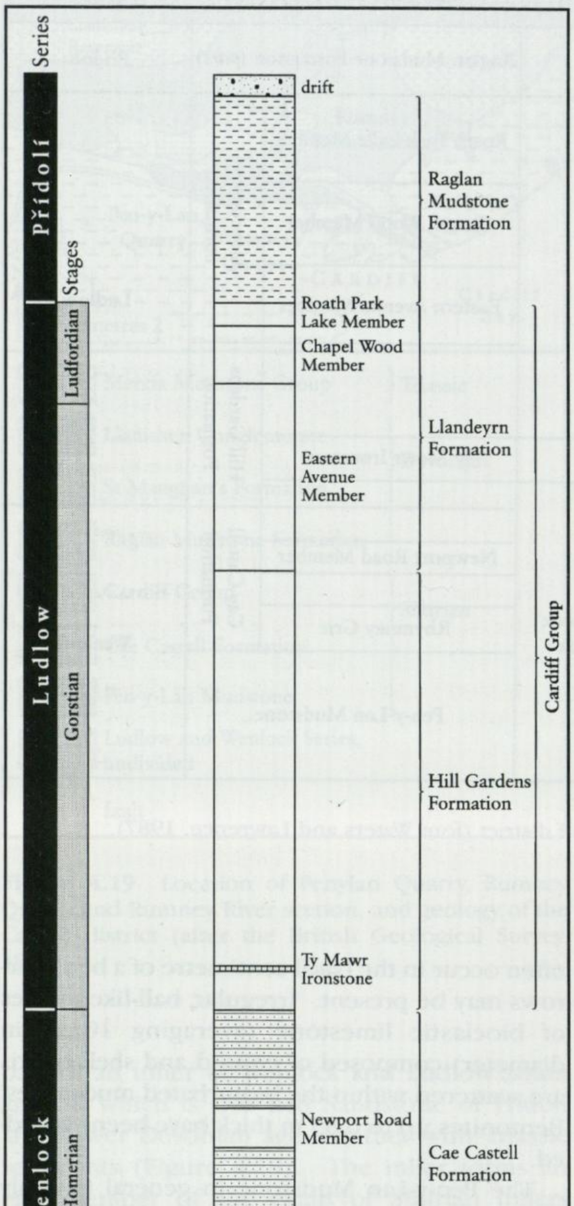


Figure 4.21 Silurian stratigraphy of the Rumney Borehole, Cardiff District (after Waters and Lawrence, 1987).

14° (British Geological Survey, 1986) and cover a stratigraphical interval of some 10 m. They comprise shelly calcareous silty mudstones which occur in blocky bedded units 0.1–0.2 m thick, with subordinate impure silty bioclastic limestones and a few fine-grained sandstones.

The faunal lists from Penylan Quarry (Sollas, 1879; Strahan and Cantrill, 1902, 1912; Waters and Lawrence, 1987) are extensive and the most recent of these includes small rugose corals; the brachiopods *Amphistrophia funiculata*, *Anastrophia deflexa*, *Atrypa reticularis*, *Coolinia pecten*, *Cyrtia exporrecta*, *Dalejina hybrida*, *Dicoelosia biloba*, *Eoplectodonta duvalii*, *Eospirifer radiatus*, *Gypidula galeata*, *Howellella* sp., *Isorthis clivosa*, *Lepidoleptaena poulseni*, *Leptaena depressa*, *Lingula* sp., *Megastrophia* (*Protomegastrophia*) *semiglobosa*, *Meristina obtusa*, *Nucleospira pisum*, *Pentlandina lewisii plakodis*, *Plectatrypa imbricata*, *Resserella canalis*, ?*Salopina conservatrix*, *Sphaerirhynchia wilsoni*, *Spirigerina marginalis*, *Streptis grayii*, *Striispirifer plicatellus* and *Strophonella euglypha*; the gastropod *Loxonema* sp.; the bivalves *Cypricardinia subplanulata*, *Modiolopsis* sp., *Nuculites* sp., and *Ptychopteria* sp.; the cephalopod *Dawsonoceras annulatum*; the trilobites *Acanthopyge* cf. *hirsuta*, *Acastocephala macrops*, *Bumastus*? *xestos*, *Dicranopeltis salteri*, *Encrinurus tuberculatus*, ?*Harpidella* (*H.*) *aitholix*, *Hemiarges scutalis*?, *Leonaspis coronata* and *Platylichas grayii*; and the graptolite *Monograptus flemingii*.

Many specimens from this quarry have been used in systematic palaeontological studies and it represents the type locality for some taxa, examples of the latter being *P. lewisii plakodis* and *L. depressa restricta* (both Bassett, 1974b), the gastropod *Cyclonema tumida* and the bivalve *Ambonychia*? *tumida* (both Sollas, 1879), and the trilobite *Bumastos*? *xestos* (of Lane and Thomas, 1978).

Interpretation

The age of the Pen-y-Lan Mudstone was for many years in debate. Sollas concluded, like Murchison (in Glass, 1861), that the fossils from Penylan proved the beds there to be of Wenlock age, though he placed them near the base of this series and noted also that they were 'very much of a Llandovery facies'. Further, he also recorded from these beds certain brachiopods that are typical Llandovery species, for instance *Pentamerus oblongus* and '*Strophomena*' *compressa* (= *Leptostrophia compressa*), and he claimed that *P. oblongus* together with '*Stricklandinia*' *lirata* (= *Costistricklandia lirata*), another typical Llandovery species, occurred in younger Wenlock beds in the nearby River Rumney section. This record of *P. oblongus* led certain authors (Pringle and George, 1937, 1948; Anderson and Owen, 1968) to indicate the presence of Llandovery strata in the Cardiff Silurian inlier. Bassett (1969) addressed these apparent contradictions and, whilst the specimens used by Sollas may all have been lost, he determined that material in old collections from the Silurian of the Cardiff area labelled *P. oblongus* should be assigned either to *Meristina obtusa* or to *Gypidula galeata*, both Wenlock species. Bassett reassigned other specimens labelled *S. compressa* to *C. pecten,* also a Wenlock form. Even more compelling evidence for the Wenlock age of the Pen-y-Lan Mudstone came from his (1969, 1974a) recognition of *Monograptus flemingii* from this horizon in Penylan Quarry, a species confined to the *rigidus* to *lundgreni* biozones of the Wenlock Series. The Pen-y-Lan Mudstone is now generally considered to be of mid- to late Wenlock age. Cocks *et al.* (1992), for example, gave it a tentative upper age limit coincident with the boundary between the *ellesae* and *lundgreni* biozones, though they showed its lower age limit as being very uncertain. Burgess and Richardson (1995), however, on the basis of sporomorphs recovered from the uppermost part of the Pen-y-Lan Mudstone of the Rumney Borehole, and comparison of these with those from the type Wenlock area (Burgess and Richardson, 1991), suggested that this part of the unit is no older than the *nassa* Biozone.

Palaeogeographically, during mid-Wenlock times the Cardiff district lay fairly close to the landmass of Pretannia (Cope and Bassett, 1987), the northern shore of which stretched in an E–W direction across the Bristol Channel to skirt the present-day southern coastline of Wales (Bassett, 1974a, Hurst *et al.*, 1978; Siveter *et al.*, 1989; Holland, 1992). By late Wenlock times, the shoreline had moved slightly north, running more or less through the Cardiff area.

Palaeoenvironmentally, the silty mudstones formed on the mid-shelf area in water depths that were moderately shallow, but below normal wave base. The accompanying sandstones represent sublittoral sheet sands, probably deposited under the influence of storm-waves plus tidal or storm-surge ebb conditions which took sand from nearshore to the shelf. The limestone beds are analogous 'event deposits', possibly being formed under similar storm conditons, by transport and reworking of autochthonous bioclastic debris. The transition of the Pen-y-Lan Mudstone into the overlying Rhymney Grit, marked by an increased sandstone content and a decrease in faunal diversity in its highest part, reflects the change to a more restricted, inner shelf environment. Brachiopods from the Pen-y-Lan Mudstone have been interpreted (Hurst *et al.*, 1978) as representing a probable *Isorthis clivosa* or *Dicoelosia biloba* Community, the presumed palaeoslope position of these broadly agreeing with that deduced from the sedimentological evidence.

The Penylan Quarry site links stratigraphically with the nearby Rumney Quarry GCR site that exposes the Cae Castell Formation, in particular the Rhymney Grit. The latter formation and succeeding sediments of Ludlow age are encompassed within the geographically intermediate Rumney River site.

Conclusions

Penylan Quarry has for over a century provided a wealth of mainly shelly fossils for systematic, and latterly also ecological, studies. It represents the type locality for various invertebrate species and has also provided graptolite specimens that were critical in determining the Wenlock age of the Pen-y-Lan Mudstone, the oldest stratigraphical unit of the Cardiff Silurian inlier. Together with the Rumney Quarry and Rumney River GCR sites it helps provide complete coverage of all the main lithostratigraphical units of Wenlock age in this part of south Wales. The Pen-y-Lan Mudstone, which has its best exposure here, has been widely used in mid-Wenlock facies interpretations and palaeogeographical reconstructions of this region.

RUMNEY QUARRY (ST 215 788)

Introduction

Rumney Quarry is situated in the Silurian inlier of the Cardiff district, the general geology and stratigraphy of which are depicted in Figures 4.19, 4.20 and 4.21 and brief comment on which is included under the description of the Penylan Quarry site.

In some of the literature, especially the older papers, Rumney Quarry is referred to as Ty-mawr Quarry. Most relevant references for the site are the same as those for Penylan Quarry: Sollas (1879), which was the most comprehensive work on the Cardiff Silurian until recently; Strahan and Cantrill (1902, 1912), in which the Silurian succession of this area was detailed and which leaned to a large extent on the results of Sollas; Bassett (1969), wherein it was proved that rocks in the inlier were no older than Wenlock, and Bassett (1974a), which contained a summary stratigraphy for this series in the area; lastly, but most importantly, Waters and Lawrence (1987), in which the lithostratigraphy, biostratigraphy and facies interpretations of the Cardiff Silurian were revised in modern terms.

All the above works include specific description of the strata in Rumney Quarry, which exposes mainly the Rhymney Grit of the Cae Castell Formation, a distinctive, laterally persistent member within the upper Wenlock strata of the inlier.

Description

In the Cardiff area, the Cae Castell Formation as a whole consists of 70–80 m of sandstones and siltstones, with subordinate mudstones, thin sandy and conglomeratic limestones, a thin ironstone and a bentonite (Waters and Lawrence, 1987). The Rhymney Grit varies in thickness in the inlier between 6 m in the Rumney Borehole (Waters and White, 1980) and probably almost 20 m in the west of the area at Roath Park Lake (Storrie, 1908). The strata comprising this grit are, overall, grey, buff-weathering, variably calcareous, cross-bedded and variably laminated medium-, sometimes fine- or coarse-grained to pebbly sandstones; it also contains scattered mudstone partings.

Rumney Quarry itself (Figure 4.22) was developed in the 19th century for extraction of roadstone. The Rhymney Grit and slightly younger beds of the Cae Castell Formation made available by the quarry dip north-east at about 30° and represent part of the northern limb of an anticline, the approximately E–W trending axis of which runs just to the south (see site report

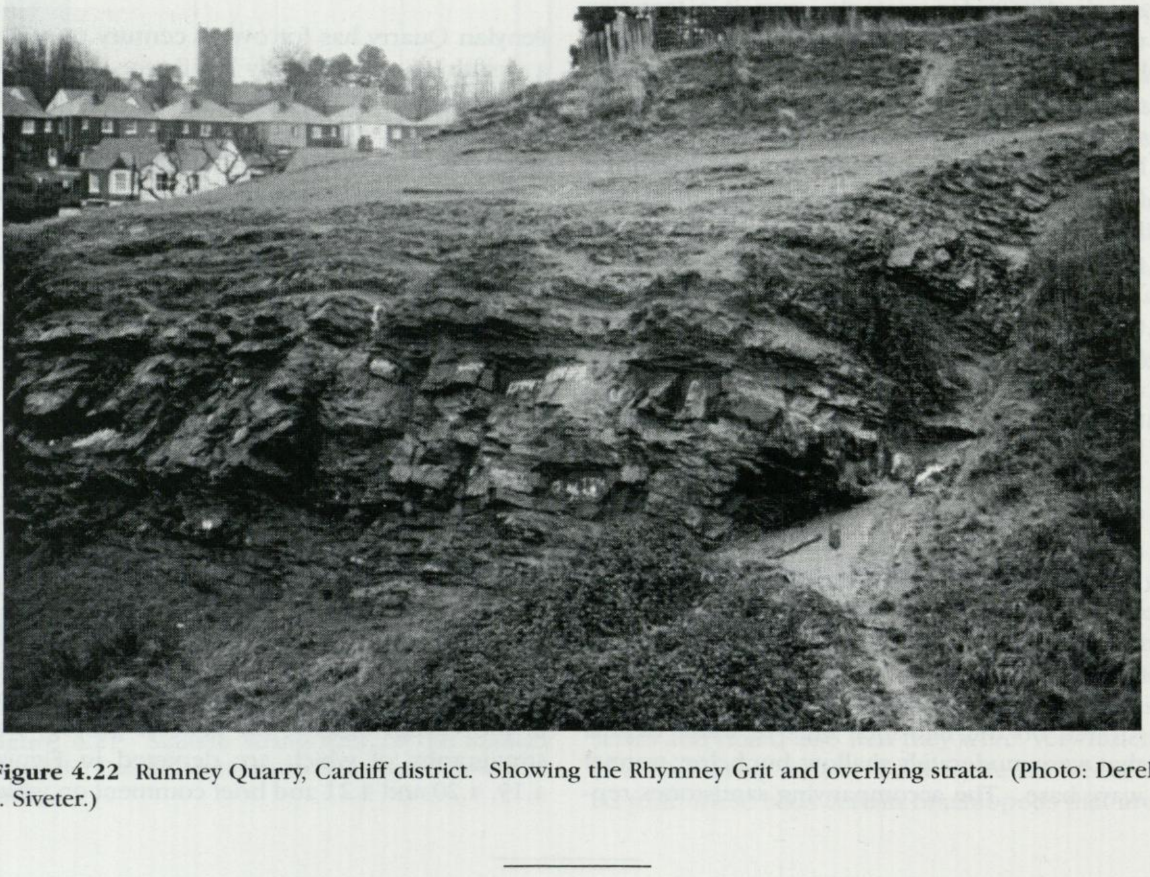


Figure 4.22 Rumney Quarry, Cardiff district. Showing the Rhymney Grit and overlying strata. (Photo: Derek J. Siveter.)

for Penylan Quarry). The following is a recent log (Waters and Lawrence, 1987) of the section.

Beds/lithology/fauna	Thickness (m)
Sandstone; green-grey, fine-grained, in wave-rippled units up to 0.5 m thick, and as thin beds and laminae with scattered thin mudstone beds and partings; scattered *Orbiculoidea* sp. and cf. *Microsphaeridiorhynchus nucula*; moderately burrowed.	5.5
Mudstone; grey, silty with scattered streaks and very thin beds of sandstone; at the base is a 10 mm coarse sandstone with scattered quartz granules, mudflakes and phosphate nodules; scattered burrows; fauna includes *Lingula* sp., *Orbiculoidea* sp., cf. *M. nucula*, gastropod and bivalve fragments, *Pachytheca* sp. and other probable algal fragments.	0.5
Sandstone; yellow, fine-grained, homogenized by burrowing; top 0.14 m is the 'Ctenodonta Bed' of Sollas (1879) and contains '*Ctenodonta subaequalis*', cf. *M. nucula*, horny brachiopod fragments, a bellerophontid, ?*Loxonema gracile*, ?*L. hydropica* and ?*Murchisonia elegans*, with homalonotid and probable algal fragments; wave-rippled and flaser-bedded packet in the middle.	1.67
Sandstone; buff, fine-grained, forming thin beds in subordinate silt- and sand-streaked mudstones; burrowed.	1.6
Mudstone; grey, scattered very thin sandstone beds and streaks.	0.3
Sandstone; buff, fine-grained, wave-rippled in part, a few mudstone partings; *Orbiculoidea* sp., ?*Modiolopsis*, ?*Nuculites* and algal fragments.	0.52
Rhymney Grit; sandstone; grey to buff, fine to medium-grained, trough cross-bedded, scattered lenticular units of wavy- to flaser-bedded sandstone with mudstone partings.	4.33

Sollas (1879) noted some further 7 m of Rhymney Grit below this section, describing it as massive sandstone, locally flaggy and rippled, in places a fine-grained conglomerate (Waters and Lawrence, 1987). The only complete section of the Rhymney Grit is that of the core from the Rumney Borehole (Waters and White, 1980; Waters and Lawrence, 1987; Figure 4.21). Excavations in February, 2000 in the quarry have exposed strata below the faces previously displayed (J. Davies, pers. comm.) but the precise nature of these and how they relate to the Rhymney Grit have yet to be determined.

Individual sets of cross-bedding within the Rhymney Grit are often graded, their bases having intraformational lags and locally showing irregular load casts, passing up into micaceous 'plant'-rich shaly partings; the lenticular units are up to 0.17 m thick. The top of the grit is somewhat gradational (as it is in the Rumney Borehole, with the base of the member in the borehole being sharply defined). Plant-like debris is common in the grit here and scattered crinoid columnals, bryozoans and indeterminate shell fragments are also present.

The fauna of the sandstones, siltstones and mudstones above the Rhymney Grit in the quarry is a low diversity one of inarticulate and articulate brachiopods (the latter represented more or less exclusively by the rhynchonellid cf. *M. nucula*), bivalves and gastropods. Four species of gastropod (*Holopella hydropica*, *H. gracilis*, *H. minuta* and *Murchisonia elegans*), together with one species of bivalve (*Modiolopsis acutipora*) were established by Sollas (1879) on the basis of material from the Ctenodonta Bed here, from which he listed 19 species of invertebrates and plants/algae.

Specific descriptions of the plant/algal material from Rumney Quarry, for example of *Prototaxites storriei* and specimens of *Pachytheca*, have been made by Harris (1884), Barber (1891, 1892) and Storrie (1892). The sporomorphs from here have recently been described by Burgess and Richardson (1995).

Interpretation

In terms of the Cardiff Silurian succession, the Cae Castell Formation in Rumney Quarry succeeds the Pen-y-Lan Mudstone. A Wenlock age can be assigned to the Rhymney Grit and younger beds of the Cae Castell Formation on the basis of acritarchs from the Rumney Borehole (Waters and White, 1980; Waters and Lawrence, 1987); in particular, the upper part of the formation is of late Wenlock age. The formation is constrained in age also by the mid- to late Wenlock age of the Pen-y-Lan Mudstone below, together with the early Gorstian, Ludlow age of the overlying Hill Gardens Formation, the latter assignment being based on acritarch and graptolite evidence from the borehole (Waters and Lawrence, 1987). The Cae Castell Formation can thus be regarded as a late Wenlock equivalent of the Much Wenlock Limestone Formation of the Welsh Borderland (Waters and Lawrence, 1987), the latter formation ranging from the *lundgreni* to *ludensis* biozones (see Dudley and Easthope–Harley Hill site reports). One report (Cocks *et al.*, 1992) has the Cae Castell formation spanning this time, with the Rhymney Grit being approximately of *lundgreni* Biozone age. Another age assessment of the Rhymney Grit (Burgess and Richardson, 1995), based on sporomorphs, gives it as being no older than the *nassa* Biozone.

The Rhymney Grit is interpreted as a major subtidal sand bar, with the trough cross-bedding and other sedimentary structures indicating a high-energy environment (Waters and Lawrence, 1987). It represents a rapid shallowing event after the slightly more offshore, deeper conditions under which the Pen-y-Lan Mudstone was deposited. The presence of plant/algal remains and sporomorphs, and the rather fragmentary, low diversity nature of its fauna, accords with this nearshore, high-energy interpretation. The Cae Castell Formation sediments above the Rhymney Grit in Rumney Quarry formed in a shallow water, inner shelf situation.

Palaeogeographically, during this late Wenlock time the inshore facies of the Rhymney Grit marks the southern boundary of the Welsh Basin, that is the northern margin of Pretannia, the shoreline running roughly east to west through the Cardiff district (Bassett, 1974a; Hurst *et al.*, 1978; Siveter *et al.*, 1989; Holland, 1992). Other Wenlock age sites in the Bristol Channel area that reflect the proximity of Pretannia include those of Brinkmarsh Quarry and the Buckover Road Cutting to the east, in the Tortworth area.

Rumney Quarry has Wenlock strata intermediate in age between those at the Penylan and the Rumney River sites, the latter exposing higher beds of the Cae Castell Formation.

Conclusions

The Rhymney Grit, an important, distinctive late Wenlock clastic facies found in the Cardiff area, has its only surface exposure in Rumney Quarry. This lithostratigraphical unit, combined with its restricted fauna and the occurrence of plant/algal remains and sporomorphs, is of prime importance in palaeoenvironmental and palaeogeographical interpretations for this time concerning the position of the southern margin of the Welsh Basin and the bordering landmass of Pretannia. Additionally, the Cae Castell Formation strata exposed in the quarry complement those Wenlock sediments of the Penylan Quarry and River Rumney sites to give full stratigraphical and lithological coverage of Wenlock age rocks for the southern Wales region. Rumney Quarry is also the type locality for certain mollusc species and the presence of early plant/algal remains together with sporomorphs is noteworthy in a palaeobotanical context.

RUMNEY RIVER (ST 209 789)

Introduction

The River Rumney flows in an overall north to south direction through the north-east outskirts of Cardiff and into the mouth of the Severn. As it does so it cuts through Wenlock, Ludlow and Přídolí age sediments, the Wenlock and Ludlow strata forming part of the main Silurian inlier of this part of south Wales (Figure 4.19).

As with the other Cardiff sites discussed herein that have Wenlock age strata (Penylan and Rumney quarries), particularly important references relating to the detailed litho- and biostratigraphy of the present site are those of Sollas (1879) and Waters and Lawrence (1987). Sollas was the first to give a detailed, broadly accurate account of the Cardiff Silurian, for which Waters and Lawrence have lately presented a comprehensive revision. Strahan and Cantrill (1902, 1912) described the Rumney River section but their account (like their descriptions of Penylan and Rumney quarries) essentially mirrored that of Sollas. The palaeontological work of Bassett (1969) on the Cardiff Silurian was significant, as he determined that the oldest rocks in the inlier (at Penylan) were of Wenlock, not Llandovery, age. He subsequently (1974a) gave a synthesis of the Wenlock stratigraphy of the district, though did not comment specifically on the Rumney River locality.

This site exposes Cae Castell Formation, Wenlock age, strata; the site boundary also takes in beds of the Hill Gardens and Llanedeyrn formations of the Cardiff Group, which are all Ludlow in age (Figures 4.20 and 4.21).

Description

Discontinuous exposures of the three Wenlock and Ludlow formations noted above occur on the east bank of the River Rumney, along which the rocks young north-eastwards. The section stands as one of the type localities for the Cae Castell Formation and also as one for the Hill Gardens Formation. Waters and Lawrence (1987), who established these lithostratigraphical units, provided the following log:

Stratigraphy/lithology/fauna	Thickness (m)
LUDLOW SERIES:	
Cardiff Group:	
Llanedeyrn Formation:	
At NGR ST 2107 7919: Trenching shows sediments of Llanedeyrn Formation at about the level of Eastern Avenue Member–Chapel Wood Member boundary in faulted contact with basal sandstone of Raglan Mudstone, Přídolí Series.	
At NGR ST 2106 7918: Exposure high in river bank, has green-grey blocky weathering siltstones and mudstones, and a few brownish green weathering, thin, fine-grained sandstones, at about Eastern Avenue Member–Chapel Wood Member boundary. The (lowest Ludfordian) fauna includes *Favosites* sp., bryozoans, *Aegiria grayi*, *Atrypa reticularis*, *Coolinia pecten*, *Dayia navicula*, *Howellella elegans*, *Isorthis clivosa*, *I. orbicularis*, *Leptostrophia filosa*, *Microsphaeridiorhynchus nucula*, *Orbiculoidea* sp., *Protochonetes ludloviensis*, *Salopina lunata*, *Shagamella minor*, *Sphaerirhynchia wilsoni*, *Kionoceras angulatum*, *Orthoceras ibex* and *Dalmanites* sp..	0.45
Eastern Avenue Member:	
At NGR ST 2105 7917: Small pit high in river bank, with pale greyish-green, very silty, tough, calcareous, micaceous mudstones, locally reddened along joints and forming blocky beds up to 0.13 m thick, with 'nodules' and thin beds of silty green-grey shelly crinoidal limestone with corals. The (late Gorstian) fauna includes *Amphistrophia funiculata*, *Atrypa reticularis*, *Gypidula* sp., *Howellella* cf. *subinsignis*, *Isorthis orbicularis*, *Leptaena depressa*, *Leptostrophia filosa*, *Lingula* ? sp., *Mesopholidostrophia lepisma*, *Microsphaeridiorhynchus nucula*, *Protochonetes ludloviensis*, *Shaleria* aff. *ornatella*, *Sphaerirhynchia wilsoni*, *Ptychopteria* sp., *Bembexia lloydii*, *Dalmanites* ? sp. and a proetid.	2.5
At NGR ST 2105 7915: Many elements of the above fauna as well as bryozoans, *C. implicatus, H. elegans*, *I. clivosa*, *Salopina lunata* and *Calymene* sp..	
Hill Gardens Formation:	
At NGR ST 2102 7909: Siltstone; olive-green, laminated, locally cross-laminated, beds to 0.1 m; abundant thin interbeds of buff-weathered, shaly silty mudstone; subordinate green-grey, patchily purple stained, laminated or cross-laminated, fine-grained sandstones in beds to 0.2 m; in top third many sandstones have impure limestones weathering to rottenstones at their bases; sparse, thin, silty, shelly crinoidal limestone; scattered brachiopods and bivalves; burrows, commonest in the mudstones; *A. reticularis* and *G. galeata* common in lower part.	*c.* 70.0
Sandstone; purplish-grey and green mottled, fine-grained, hummocky cross stratification, planar-lamination and cross-lamination present, calcar-	

eous; in 5 prominent beds up to 0.3 m thick, some shelly and crinoidal at base; interbeds of olive-green silty shaly mudstone with scattered thin siltstone and very fine grained sandstones. 1.85

Ty Mawr Ironstone; red; oolitic, argillaceous, ferruginous limestone; rich shelly fauna including *Catenipora* ? sp., *Syringopora* ? sp., *A reticularis, G. galeata*, *Sphaerirhynchia wilsoni*, *S. euglypha*, crinoid columnals. 0.6

Mudstone; olive-green, very silty, burrowed, abundant beds of siltstone and sandstone; sandstones are grey-green, buff weathered, calcareous, fine grained, laminated, some cross-laminated; scattered disrupted silty shelly crinoidal limestone beds. 8.24

WENLOCK SERIES:
Cae Castell Formation:

At NGR ST 2096 7892–ST 2101 7898: Sandstone; green-grey, buff weathering, fine- and medium-grained, locally coarse, variably calcareous; finely and coarsely interlayered with grey silty mudstone; parallel- and cross-lamination, lenticular and flaser bedding common; abundant, scattered plant-like debris; scattered brachiopods, crinoid debris and bivalves; burrows. Some gaps in exposure. *c.* 23.0

Additionally, Silurian rocks from the Rumney River section, which must be lower in the Wenlock than those given in the above log, were recorded by Sollas (1879). They were observed by him at low tide, beginning from a point just upstream from Rumney Bridge. Included in his description were mudstones and sandstones, which he correlated with those at Penylan Quarry; these were succeeded by the Rhymney Grit. However there is no recent record of these rocks being exposed here at the present day. The sporomorphs described recently by Burgess and Richardson (1995) from the Cae Castell Formation (and also from the Hill Gardens and Llanedeyrn formations) of the Rumney River section, were from stratigraphically above the Rhymney Grit. From the Ludlow part of the section, Sollas (1879) established three gastropod and one bivalve species: *Cyclonema turbinatum*, *C. simplex*, *Murchisonia corpulenta* and *Leda* (?) *ambigua*.

Interpretation

Since the time of Sollas (1879) until recently, the precise age of parts of the Silurian succession in the Rumney River section was uncertain, and in particular the position there of the Wenlock–Ludlow boundary. Sollas believed that the 0.6 m thick Ty Mawr Ironstone (see log) together with the 4.26 m of strata above it and 8.53 m of strata below it (his Cae Castell sequence) were the equivalent of the 'Wenlock Limestone', thus making these beds latest Wenlock in age. Bassett (1974a) also thought that this red, calcareous, crinoidal ironstone probably correlated with part of the 'Wenlock Limestone', a view tentatively followed by Waters and White (1980) in their initial, summary log of the Rumney Borehole. Subsequently, Waters and Lawrence (1987) reported that acritarch evidence from the borehole showed that that part of the Hill Gardens Formation below the ironstone is of early Gorstian, Ludlow age and that the Wenlock–Ludlow series boundary should be taken at the junction of this formation and the Cae Castell Formation below it. Graptolites from the lower part of the Hill Gardens Formation of the borehole support this correlation.

That part of the Cae Castell Formation such as is detailed in the above log, that is, higher in the formation than the Rhymney Grit and excluding the Newport Road Member, was deposited in a shallow inner-shelf environment, mainly above storm-wave base and sometimes above normal-wave base; it has a restricted fauna. The Rhymney Grit is thought to be a subtidal sand bar whilst the Newport Road Member (recognized in the middle of the formation in the Rumney Borehole) represents a short, more open marine phase. The base of the Hill Gardens Formation marks a transgressive event accompanied by a high diversity fauna (brachiopods, molluscs, trilobites, bryozoans, crinoids) and a return to mid-shelf conditions similar to those in which the mid-Wenlock Pen-y-Lan Mudstone was deposited. Regression towards the top of the Cardiff Group heralds the arrival of the red mudstones, calcretes and dominantly fluviatile sandstones of the Přídolí Raglan Mudstone Formation.

Wenlock strata exposed in this Rumney River section follow on stratigraphically from those in the nearby Rumney Quarry site, where the lower part of the Cae Castell Formation (Rhymney Grit and slightly higher beds) crops out.

Conclusions

This site complements stratigraphically the other two listed sites of Wenlock age in the Silurian inlier of the Cardiff district, Penylan and Rumney quarries, to provide comprehensive coverage for this series in the south Wales region. Rumney River is the only locality in this area where the higher beds of the Wenlock Cae Castell Formation are exposed at the surface. The site is also of merit in containing the Wenlock–Ludlow boundary horizon, together with succeeding beds of the Ludlow Series up to lowest Ludfordian strata. Much of the late Homerian to lower Gorstian part of the section, which reflects a regressive then transgressive history, benefits from fairly continuous exposure. The Ludlow here is the type locality for several species of mollusc.

MARLOES (SM 7780 0772–SM 7882 0715)

Introduction

South-western Pembrokeshire is divided structurally into five main blocks that are bounded to the north and the south by faults that trend roughly east–west (Figure 4.23). The nature of the Silurian succession within each block varies in detail (Figure 4.24), reflecting differing geological histories. The Marloes Block, demarcated to the north by the Musselwick Fault and to the south by the Ritec Fault, is the smallest of them; it contains Silurian strata ranging in age from Llandovery to Přídolí.

Murchison (1839) was the first to recognize Silurian strata in various sections within the area; in particular he described the geology of Marloes Bay and provided sketches of the locality. De La Bêche (1846) followed with logs of the sections along the bay and to the north of

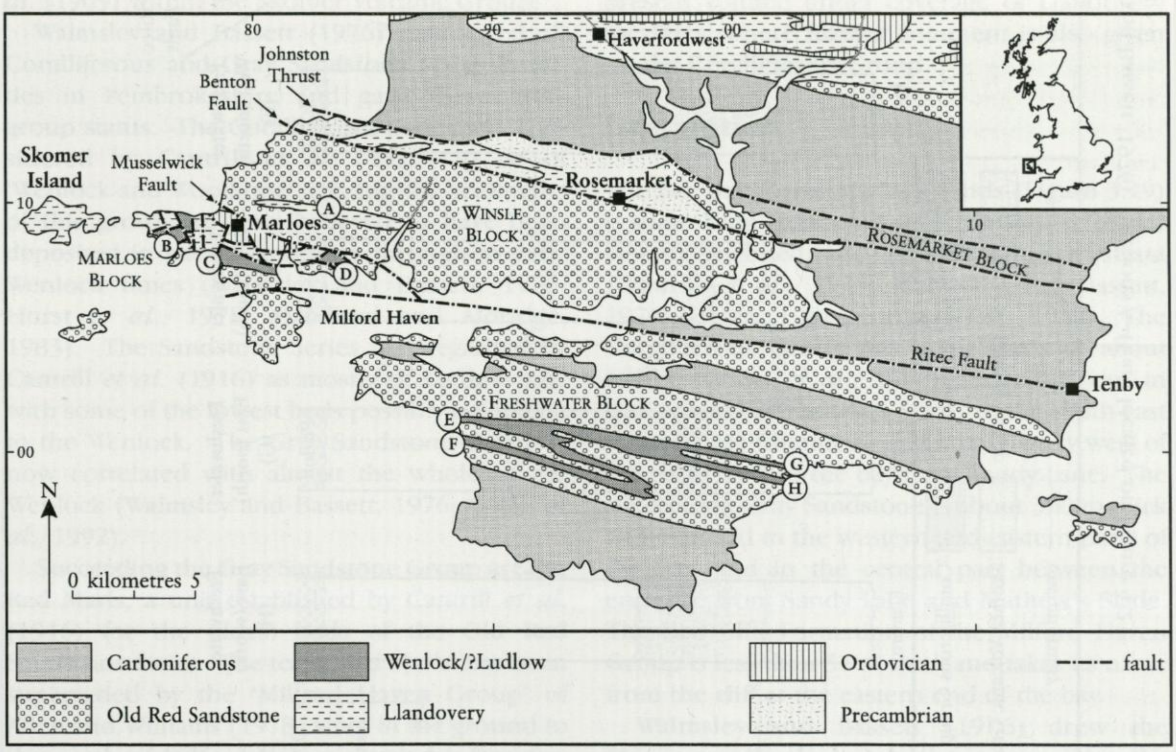


Figure 4.23 The geology of Pembrokeshire, showing the main structural blocks (after Walmsley and Bassett, 1976). The letters A–H refer to the successions in Figure 4.24.

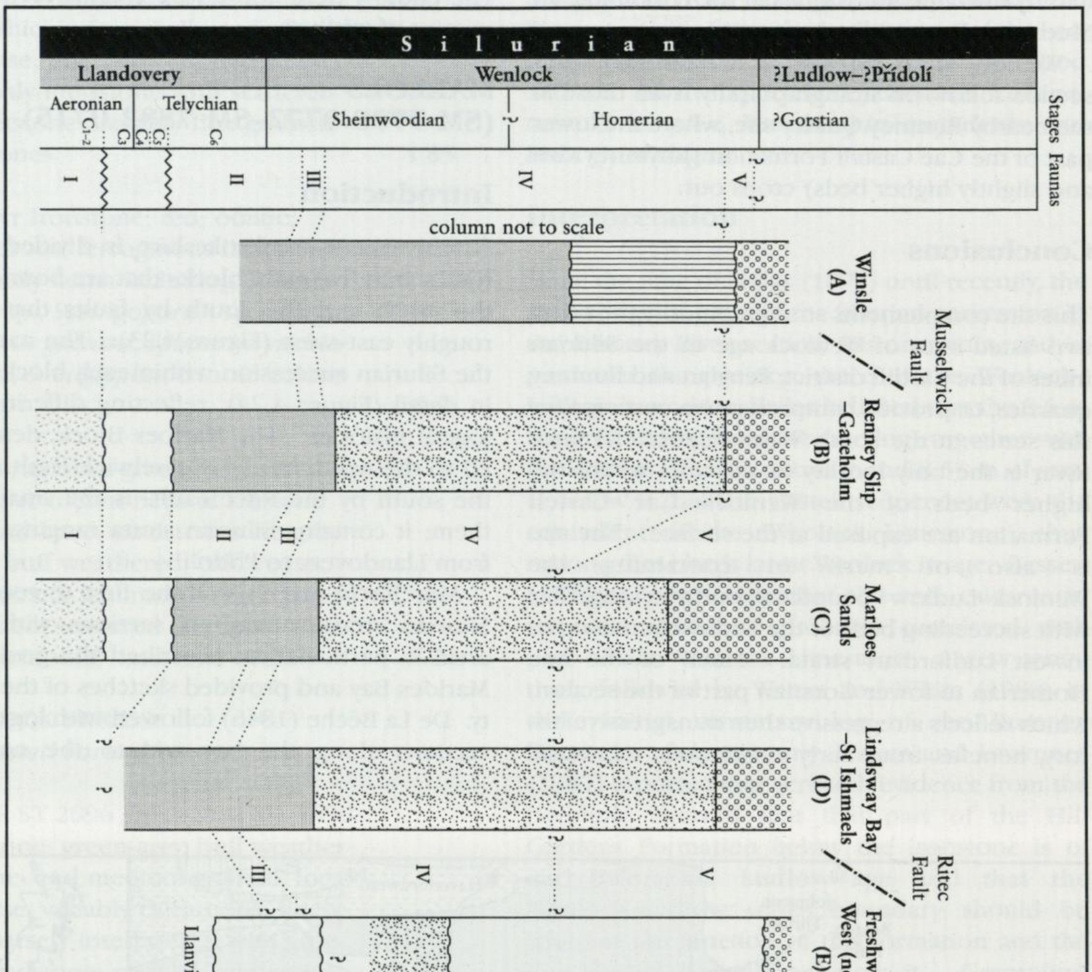


Figure 4.24 Correlation of Silurian sections in Pembrokeshire (after Walmsley and Bassett, 1976). Sections A–H are located on Figure 4.23.

Gateholm, and at the same time he introduced the terms Coralliferous Series and Gray Sandstone Series for two of the main rock units of Silurian age. Phillips (1848) made further short comment on Pembrokeshire Silurian localities, including Marloes.

The Geological Survey memoir of Cantrill *et al.* (1916) on the Milford area was the first comprehensive account of the local Silurian succession, in which they provided a detailed description, sketch section, map and faunal list pertaining to Marloes. Four lithostratigraphical units of Silurian age were recognized in this area by the survey officers: the Skomer Volcanic Series, the Conglomerate Series, the Coralliferous Series and the Sandstone Series. The Skomer volcanics were thought by them to be Ordovician, but ostracod evidence from Midland Island indicated to Zeigler *et al.* (1969) a Silurian age, and all modern accounts (e.g. Cocks *et al.*, 1992) assign this suite of lavas and pyroclastics to the Llandovery Series. Cantrill *et al.*, however, did originally distinguish those volcanics within the Marloes, Wooltack Park and Renney Slip sections as being of Llandovery age. The Conglomerate Series, placed by Cantrill *et al.* (1916) in the upper Llandovery, was subsumed by Zeigler *et al.* (1969) within the Skomer Volcanic Group.

Walmsley and Bassett (1976) resurveyed all Coralliferous and Gray Sandstone series localities in Pembrokeshire and gave these units group status. The Coralliferous Series was considered by Cantrill *et al.* (1916) to be of 'Wenlock and Woolhope' age, but the sediments of this group are now believed to have been deposited in latest Llandovery through to early Wenlock times (Walmsley and Bassett, 1976; Hurst *et al.*, 1978; Mabillard and Aldridge, 1983). The Sandstone Series was regarded by Cantrill *et al.* (1916) as mostly of Ludlow age, with some of the lowest beds possibly belonging to the Wenlock. The Gray Sandstone Group is now correlated with almost the whole of the Wenlock (Walmsley and Bassett, 1976; Cocks *et al.*, 1992).

Succeeding the Gray Sandstone Group are the Red Marls, a unit established by Cantrill *et al.* (1916) for the oldest beds of the Old Red Sandstone facies. The term 'Red Marls' has been superseded by the 'Milford Haven Group' of Allen and Williams (1978) who, in the ground to the north of Milford Haven, divided it into five formations beginning with the Red Cliff Formation. The basal beds of the Old Red Sandstone were thought by Walmsley and Bassett (1976; see also Cocks *et al.*, 1992) to 'hardly be younger than early Ludlow, and could even be of latest Wenlock age'. Allen and Williams (1978) found it difficult to support this view; they claimed that there is the strong possibility of a substantial break at the base of the Red Cliff Formation, and the age of the Milford Haven Group as a whole was given by them as late Silurian–Lower Devonian. Cocks *et al.* (1992) tentatively indicated the age of the Red Cliff formation as latest Wenlock to earliest Přídolí.

The Pembrokeshire coast is justly recognized as having some of the most superbly exposed and stratigraphically varied Palaeozoic geology anywhere in the British Isles. Outcrops of Silurian strata contribute considerably to this reputation and Marloes Sands (Figure 4.25) would be considered by most as the best locality in the area at which to study rocks of this age. Strata of the Skomer Volcanic Group, Coralliferous Group, Gray Sandstone Group and the Milford Haven Group (Red Cliff Formation) are all made available through the excellent cliff sections. The Skomer Volcanic Group of Marloes is fully described and discussed in the present volume under coverage of Llandovery localities, where further comment is also given on the Coralliferous Group.

Description

The bay that forms Marloes Sands (Figure 3.19) is some 2 km in extent and is formed entirely of steeply inclined and faulted Silurian strata (Cantrill *et al.*, 1916; Walmsley and Bassett, 1976; Bassett, 1982a; Siveter *et al.*, 1989). The Coralliferous Group has a thickness of about 100 m (Cocks *et al.*, 1992) and crops out in three areas: at Mathew's Slade, to the south-east of the Three Chimneys, and immediately west of the pathway into the bay from Sandy Lane. The succeeding Gray Sandstone is about 300 m thick and exposed in the western and eastern parts of the bay, and in the central part between the entrance from Sandy Lane and Mathew's Slade. The Red Cliff Formation of the Milford Haven Group is less than 52 m thick and takes its name from the cliff at the eastern end of the bay.

Walmsley and Bassett (1976) drew the Llandovery–Wenlock series boundary within the Coralliferous Group at a position within the beds containing their Fauna II, just below the

Figure 4.25 Marloes Sands, Pembrokeshire. View looking south-east and including exposures of the Skomer Volcanic, Coralliferous and Grey Sandstone groups. (Photo: Derek J. Siveter.)

level at which *Costistricklandia lirata lirata* and *Eocoelia sulcata* disappear from the sequence. *Costistricklandia* becomes uncommon, and then disappears, above about 30 m and 50 m respectively from the base of the group (Bassett, 1982a). The record from Marloes by Hurst *et al.* (1978) of *E.* cf. *sulcata* and *Palaeocyclus porpita* some 2 m below the top of the group indicated to them that this level is very close to the series boundary. The conodont evidence from Marloes of Mabillard and Aldridge (1983) indicates that the whole group is close to the boundary. The fauna from beds high in the Coralliferous Group, which constitutes Fauna III of Walmsley and Bassett (1976), includes (from nearby Deadman's Bay) *Eocoelia angelini*, a species indicative of a lower Sheinwoodian *riccartonensis* Biozone age.

Lithologically, the Coralliferous Group consists of basal conglomerates passing upwards into siltstones, silty mudstones, thin sandstones, thin bioclastic limestones and occasional bentonites (Sanzen-Baker, 1972; Siveter *et al.*, 1989). In the top 12 m of the group there is a coarsening of the siltstones, these giving way to the sandstones that herald those of the succeeding Gray Sandstone Group. The Coralliferous Group is, above its basal beds, very fossiliferous. An extensive faunal list for Marloes was provided by Cantrill *et al.* (1916), and Walmsley and Bassett (1976) recorded from the Wenlock part of the group a total of more than 25 brachiopod, coral, trilobite, gastropod, nautiloid, bryozoan and bivalve species. Mabillard and Aldridge (1983) recovered a diverse conodont fauna from the unit, and also acritarchs, scolecodonts and possible chitinozoans.

The Gray Sandstone Group, overall, shows a coarsening upwards sequence. Horizons low in the group comprise sandstones, siltstones and grey, sandy mudstones with rottenstone bands. Sandstones become more common up-sequence, with the top 60 m of the group consisting of greenish-grey quartzitic sandstones and mudstones, the latter weathering olive-yellow and featuring cross- and lenticular-bedding and bioturbation. Channelling, also, becomes a notable feature of these higher beds (Siveter *et al.*, 1989). Fauna IV of Walmsley and Bassett (1976) is characteristic of the Gray Sandstone Group, the fauna belonging to a post-*Eocoelia*, *Salopina* Community that indicates an age of post-early Wenlock and probably no younger than mid- to late Wenlock. Fauna V, a depleted one of *Lingula*, *Cornulites* and indeterminate bivalves, occurs towards the top of the group and is undiagnostic with respect to age, but continuity of these higher beds with lower horizons and their probable rapid deposition argue, also, for a Wenlock age.

The Red Cliff Formation (Allen and Williams, 1978; Siveter *et al.*, 1989), of possible latest Wenlock to later Silurian age, is formed of red to purple mudstones, some having weakly developed calcretes and desiccation cracks, together with very fine- to fine-grained red, purple or greyish-pink sandstones. Channelling is present, as is bioturbation in the fine sandstones and coarse mudstones. There are no marine fossils.

Interpretation

The succession from the Coralliferous Group through to the Milford Haven Group represents, overall, a regressive, shallowing upwards sequence (Sanzen-Baker, 1972; Walmsley and Bassett, 1976; Allen and Williams, 1978; Siveter *et al.*, 1989). The Coralliferous Group is of marine origin, storm conditions and transportation of its constituent benthos being suggested by concentration of fossils in shelly lenses. Walmsley and Bassett (1976) interpreted their fossil collections with respect to the nearshore to offshore Benthic Assemblages (BA1–5) of Boucout (1975). A brief deepening episode is indicated across the Llandovery–Wenlock part of the Coralliferous Group, by a shift from BA3 to BA3–4, after which, during the deposition of the rest of this group and until the end of Gray Sandstone times, shallowing is indicated by a shift to BA1. The Gray Sandstone Group has been interpreted as being of coastal marine origin in its lower part, and having shallow marine, intertidal and deltaic facies in its upper horizons. The Red Cliff Formation indicates a range of near-shore alluvial and fluviatile environments; if any part of it is indeed of pre-Přídolí age, it would, in comparison with events in the main part of the Welsh Basin, represent the early onset of Old Red Sandstone facies conditions.

During the Wenlock the Pembrokeshire region was situated north of the Pretannia landmass on the south-west margin of the Welsh Basin (Bassett, 1974a; Hurst *et al.*, 1978; Cope and Bassett, 1987; Holland, 1992). The palaeoslope here was steeper than that of the central part of the basin margin in the Welsh Borderland area. Also, rocks of this age in Pembrokeshire are in the main siltstones and sandstones, unlike in the Welsh Borderland where carbonate muds and limestones predominate.

The Freshwater East site in the adjacent Freshwater Block shows a more restricted Silurian sequence, having only the Gray Sandstone and Milford Haven groups represented. Other linked sites of Wenlock age on or close to the southern margin of the Welsh Basin, all of them having clastic facies, include Penylan Quarry, Rumney Quarry and Rumney River in the Cardiff area, and Brinkmarsh Quarry and Buckover Road Cutting in the Tortworth Inlier.

Conclusions

This is an outstanding and historic site for interpreting the geology of the whole of the Silurian sequence of the south-western margin of the Welsh Basin, providing data on the stratigraphy, biota, sedimentology, palaeoenvironment, palaeogeography and structure of the region. It boasts magnificent coastal sections exposing the Coralliferous Group, which straddles the Llandovery–Wenlock boundary, the Gray Sandstone Group, wholly Wenlock in age, and the Red Cliff Formation of the Milford Haven Group, the basal part of which may belong to the Wenlock. This sequence is a regressive one charting the change from fully marine to Old Red Sandstone facies fluviatile environments. Brachiopods and corals feature strongly amongst the marine macrofauna, the former being useful for interpretation of depth and for biostratigraphical purposes. Conodonts aid dating of the Coralliferous Group.

The site is a most valuable resource to students at all levels, from school parties to research workers internationally.

FRESHWATER EAST (SOUTH) (SS 017 975)

Introduction

The geology of south-west Pembrokeshire to the north and south of Milford Haven is set within five main structural areas that are separated by major E–W trending faults (Figure 4.23). Each of these areas has Silurian strata, though the succession and therefore geological history of each differs in detail (Figure 4.24). The present locality lies within the Freshwater Block, to the south of the Ritec Fault.

Murchison (1839) described the Silurian and Old Red Sandstone rocks of Freshwater East. Shortly afterwards De la Bêche (1846) gave a log of these strata on the north side of Freshwater East Bay, and in the same work he set up the Coralliferous Series and Gray Sandstone Series for two of the main divisions of the Silurian of Pembrokeshire as a whole. Phillips (1848) added further comment on the Silurian strata of Freshwater East as well as other rocks of this age elsewhere in the region.

The most detailed description of Freshwater East is that by Dixon (1921) in the Pembroke and Tenby Memoir, in which he assigned the fossiliferous Silurian strata below the Old Red Sandstone to the Wenlock Series and the Ludlow Series, without recourse to using either the Coralliferous or Gray Sandstone divisions of De la Bêche. Walmsley and Bassett (1976), in their investigation of the biostratigraphy and correlation of these divisions, assigned lithostratigraphical group status to both of them, and determined that the Coralliferous Group straddles the Llandovery–Wenlock boundary and that the Gray Sandstone Group is entirely of Wenlock age. The lower part of the succeeding Old Red Sandstone in Pembrokeshire (Allen and Williams, 1978; Williams *et al.*, 1982), comprising the older formations of the Milford Haven Group, is also of (probably variable) Silurian age. The Skomer Volcanic Group, the fourth major lithostratigraphical division of the system in the region, belongs to the Llandovery Series (Zeigler *et al.*, 1969).

At Freshwater East (South) the Gray Sandstone Group includes relatively numerous fossiliferous horizons (Walmsley and Bassett, 1976) that help to provide a Wenlock age for this unit which is widespread in south-west Pembrokeshire. In addition the succession at this site – the absence of any Silurian sediments beneath the Gray Sandstone Group, with the latter lying above Ordovician sediments – is representative of that within the Freshwater Block as a whole.

Description

A broadly anticlinal structure with a WNW–ESE trending axis runs through the bay at Freshwater East (Dixon, 1921; Bassett, 1982a; Williams *et al.*, 1982). The core of the fold, here inferred to be formed of Llanvirn rocks as are present at Freshwater West along strike, is not exposed, though the northern and southern limbs of the fold are represented by outcrops of the Gray Sandstone Group and the Old Red Sandstone on both the north and south sides of the bay. The site described here takes in only those exposures of the Gray Sandstone Group on the south side of the bay, with the north side of the bay meriting GCR status in its own right as a (Přídolí Series) site of palaeobotanical importance (Edwards, 1979; Cleal and Thomas, 1995).

Some 60 m of the Gray Sandstone Group occur in cliff and foreshore exposures, the strata dipping 40–50° to the SSW (Dixon, 1921; Walmsley and Bassett, 1976; Bassett, 1982a; Siveter *et al.*, 1989; Figure 4.26). The lowest 10 m are made up of grey-green sandy siltstones, mudstones and decalcified sandstones, the latter commonly known as rottenstones. These beds have yielded *Pembrostrophia freshwaterensis*, *Atrypa reticularis*, *Leptaena* sp., *Howellella* sp., *Obturamentella* ? sp., *Microsphaeridiorhynchus* ? sp., *Salopina conservatrix*, *Acaste subcaudata*, favositid corals, bivalves, cephalopods and gastropods. The next 50 m comprise sandstones, sandy mudstones and occasional

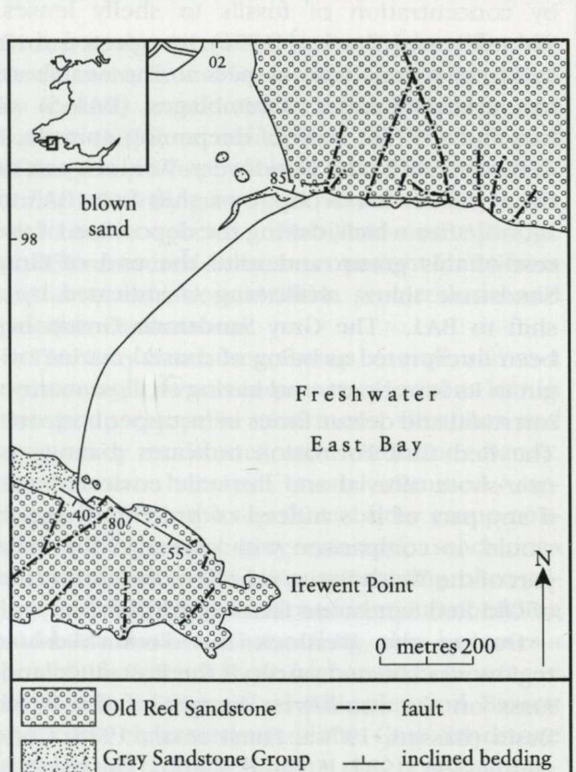


Figure 4.26 Geology of the Freshwater East area, Pembrokeshire (after Walmsley and Bassett, 1976).

horizons of granulestones and shales, with rottenstone horizons becoming more common. In addition to the above fauna, *Marklandella giraldi*, *Lingula* sp., *Nucleolites* sp., *Holopella*, sp., tentaculitids and *Trimerus* sp. have been recorded (Bassett, 1982a). These faunal elements as a whole form part of Fauna IV of Walmsley and Bassett (1976), which indicates an age no younger than mid- to late Wenlock. Chitinozoans recovered from horizons high in the Gray Sandstone Group may be of Wenlock age and have an upper age limit no younger than early Gorstian (Lister in Walmsley and Bassett, 1976).

Invertebrate material from the Gray Sandstone of Freshwater East (South) was figured in several early, important publications, those of Murchison (1839) and Phillips (1848) for example, and the site represents the type horizon and locality for species of various groups, for instance the brachiopod *P. freshwaterensis* (Bassett, 1971), and the bivalve *Nucula coarctata* Phillips, 1848.

The Old Red Sandstone succeeds the Gray Sandstone Group in the form of basal conglomerates, then sandstones and siltstones of the Freshwater East Formation. The contact between these two units at Freshwater East (South) is apparently marked by a minor strike fault, though at Freshwater East (North) they show an unconformable relationship (without angular discordance).

Interpretation

Hurst *et al.* (1978) suggested that the Gray Sandstone Group of Freshwater West was of Ludlow age, on the basis that the sediments of the group were deposited as part of a transgression which they compared with the deepening event that is typical of the basal Ludlow; they argued that the palynological evidence from Freshwater East (see above) supported this claim. However this age determination for the Gray Sandstone is at variance with that of Walmsley and Bassett (1976) based on the macrofauna.

The macrofaunal assemblages obtained from 14 fossiliferous horizons within the Gray Sandstone Group of Freshwater East (South) indicate depth fluctuations between BA2 and BA3 (of Boucot, 1975) for nearly the whole group, with one horizon close to the top of the section being assigned to BA1 (Walmsley and Bassett, 1976). Thus in this region the group was deposited in alternating moderately to relatively shallow water, with particularly regressive and shallowest water conditions occurring in latest Gray Sandstone Group times. In general, in its lower part the group has been interpreted (Sanzen-Baker, 1972) as being of coastal marine origin, and having shallow marine, intertidal and deltaic facies in its upper horizons. The shallowing upwards of the Gray Sandstone anticipates the fluviatile floodplain facies of the succeeding Old Red Sandstone.

The Pembrokeshire region was situated on the south-western margin of the Welsh Basin, north of the Pretannia landmass, during the Wenlock (Bassett, 1974a; Hurst *et al.*, 1978; Cope and Bassett, 1987; Holland, 1992). At this time the palaeoslope here was steeper than that in the area of the Welsh Borderland.

In comparison with Marloes, which is the other Pembrokeshire site described herein with Wenlock age rocks, and which is located to the north of the Ritec Fault within the Marloes Block, Freshwater East (South) lacks the Coralliferous and lower part of the Gray Sandstone groups, and the Llandovery Skomer Volcanic Group is also missing. Moreover, the base of the Old Red Sandstone at Marloes may be as old as uppermost Wenlock (Walmsley and Bassett, 1976) whereas spore evidence from the lower part of the Old Red Sandstone (Milford Haven Group; Freshwater East Formation) of the north side of the bay at Freshwater East indicates a Přídolí age (Richardson and Lister, 1969). These two sites show the type of differences that exist between the Silurian successions of separate tectonic blocks in Pembrokeshire. Such discrepancies, together with the present juxtaposition of these blocks, have been related to a telescoping effect caused by northward thrusting during the Hercynian orogeny (Sanzen-Baker, 1972).

Conclusions

Freshwater East (South) lies structurally within the Freshwater Block and has exposures of the Gray Sandstone Group (Wenlock Series) – one of the four major lithostratigraphical units of the Pembrokeshire Silurian. Sediments of this group were deposited, generally, in relatively shallow water and the group as a whole shows a shallowing upwards sequence. In comparison with other localities in Pembrokeshire where the

Gray Sandstone Group is exposed, the group here has relatively many fossiliferous horizons that have been very useful in assigning to it a Wenlock age. Freshwater East (South) provides a contrasting Silurian section in Pembrokeshire to that of Marloes, which lies within the Marloes Block where the succession of rocks of this age is more complete. The site thus serves to demonstrate stratigraphical differences between Silurian sequences within the various structural blocks of the region. It is, also, the type locality for several species of invertebrates.

HUGHLEY BROOK (SO 566 984–SJ 599 011)

Introduction

Hughley Brook is situated in Ape Dale at the foot of Wenlock Edge in the type Wenlock area; it runs into Harley Brook, which also forms part of this site, their combined length being about 10 km (Figure 4.27). Both streams have an overall NE–SW alignment that is parallel with the Caledonoid strike of the Silurian strata locally, their joint course meandering frequently across the boundary between the Llandovery and the Wenlock series. Since the benchmark works of Murchison (1833, 1835, 1839, 1854), Salter and Aveline (1854) and Davidson and Maw (1881) in which the stratigraphical units of the Wenlock Series were established and largely refined, the Silurian geology of the Wenlock Edge–Apedale area has been described by numerous authors, in particular Lapworth and Watts (1894, 1910), Watts (1925), Whittard (1928, 1932, 1952), Pocock *et al.* (1938), Bassett *et al.* (1975) and Bassett (1989a).

Pocock *et al.* (1938) drew attention to the Hughley Brook–Harley Brook section with respect to the contact there between the Purple Shales (Formation) of the Llandovery Series and the overlying Buildwas Beds (= Formation) of the Wenlock Series. The importance of this combined stream course in exposing this contact was given formal stratigraphical recognition by Bassett *et al.* (1975) when they selected the Hughley Brook section at Leasows to stand as the international stratotype for the base of the Wenlock Series, coincident with the bases of the Sheinwoodian Stage and the Buildwas Formation. The site also contains the type area for the Buildwas Formation, and the standard section for the base of the Coalbrookdale Formation (Apedale Member).

The Llandovery succession of this site is described in Chapter 3.

Description

The stratotype section is situated 0.5 km north-east of Hughley church and 200 m south-east of Leasows Farm, on the north-west bank of a sharp northerly meander of Hughley Brook (Figure 4.28). The beds here (Bassett *et al.*, 1975) strike at 140°, have an average dip to the east of 15° and show the following boundary sequence.

Unit	Thickness (m)
Buildwas Formation (Wenlock Series, Sheinwoodian Stage)	
I. Mudstone, grey, with nodule band (14 cm), the base of which lies 107 cm from base of the unit.	2.2+
H. Mudstone, blue-grey, with bentonite band (1 cm) at 70 cm from base and nodule band (14 cm) at top.	1.5
G. Mudstone, grey-green at base, blue-grey above, with variable shelly debris/crinoids, brachiopods, etc.. Nodule band (14.5 cm thick) at top.	2.14
Purple Shales Formation (Llandovery Series, Telychian Stage)	
D. Mudstone, green; with one impersistent hard siltstone band, 8 cm thick (unit E), the top of which lies 15 cm below the top of the formation. These uppermost 15 cm (unit F) are of a mixed facies within unit G.	0.6
C. Siltstone, hard.	0.08
B. Mudstone, purple and green variegated.	0.32
A. Mudstone, purple, with sporadic brachiopods; thin (2 cm) green mudstone bands and a few thin (6 cm) calcareous siltstone bands with crinoid fragments.	Up to 1 m thick; seen over a length of 4 m of the stream.

There is a colour transition in the sediments over about 1 m between the Purple Shales and the Buildwas formations, from mottled green, grey and purple into olive-buff and grey (Bassett, 1989a). Similarly there is a decrease in the occurrence of hard siltstones up-section, the Buildwas Formation containing only calcilutites and lacking almost entirely terrigenous sand and silt. This gradational nature notwithstanding, the base of the Buildwas Formation is readily mapped at the base of the first grey-green rubbly mudstones with comminuted shell debris.

The following brachiopods have been recorded (Bassett *et al.*, 1975) from the top 10 m of the Purple Shales Formation in Hughley Brook: *Eoplectodonta penkillensis*, *Glassia obovata*, *Visbeyella pygmaea*, *Atrypa reticularis*, *Aegiria grayi*, *Mesopholidostrophia salopiensis*, *Leptaena purpurea*, *Skenidioides lewisii*, *Craniops implicatus*, *Dicoelosia alticavata*, *Amphistrophia whittardi*, *Eocoelia sulcata*, *Coolinia applanata*, *Cyphomenoidea wisgoriensis*, *Clorinda undata*, *Pentlandina parabola*, *Cyrtia exporrecta*, *Eospirifer* aff. *radiatus*, *Dictyonella* sp. and *Resserella* sp. together with other less common species. Trilobites (more than 12 types), rugose and tabulate corals, crinoids, bryozoans, orthoconic nautiloids, gastropods and bivalves also occur, as well as an abundant microfauna and microflora as indicated below. Graptolites have not been recovered from the top 10 m of the Purple Shales, but regionally the presence nearby in Devil's Dingle, Buildwas, of *Monograptus parapriodon*, *Monograptus priodon* and *Monograptus discus* indicates that the top of this unit belongs to the *crenulata* Biozone (Bassett *et al.*, 1975).

Brachiopods also dominate the macrofauna of the lowest part of the Buildwas Formation, including: *Dicoelosia biloba*, *Leangella segmentum*, *A. reticularis*, *Eoplectodonta duvalii*, *C. exporrecta*, *Atrypina barrandii*, *E. radiatus*, *Streptis grayii*, *Isorthis elegantulina*, *Resserella sabrinae*, *G. obovata*, *Dictyonella capewelli*, *Dalejina* sp. and indeterminate rhynchonellids. Trilobites, rugose and tabulate corals, crinoids, orthoconic nautiloids, gastropods and bivalves are also present.

Graptolites have not been found in the Buildwas Formation at Leasows, but *Monoclimacis* aff. *vomerina*, which is indicative of a late Llandovery–early Wenlock age, is recorded from 3–4.5 m above the base of the Buildwas Formation in Harley Brook (SJ 5961 0075), and *Pristiograptus watneyae* from 18.3 m above the base in the type Wenlock area at Ticklerton (SO 4858 9042) 12 km to the south-west, the latter species indicating the *centrifugus* Biozone (Bassett *et al.*, 1975). The *riccartonensis* Biozone was recognized in the lowest part of the Coalbrookdale Formation by the eponymous species occurring 3 m above its base, in Hughley Brook (SO 5711 9840).

Rich microfossil assemblages have been recovered from across the Llandovery–Wenlock boundary stratotype at Leasows (Figure 4.28) and from nearby localities in Hughley and Harley brooks, in particular from Domas 0.75 km south of Harley (e.g. Downie, 1959, 1960, 1963; Dorning, 1981b, 1981c; Mabillard and Aldridge, 1982, 1985; Lundin *et al.*, 1991). Sixty-two species of acritarch are known from Leasows, the series boundary occurring 15 cm above the base of acritarch Biozone 5 (of Hill, 1974). The latter is characterized by the appearance of *Duenffia brevispinosa*, *D. ramusculosa* and *D. amphora*, all of which enter the type section in unit F of the Purple Shales. Chitinozoans are represented at the stratotype by species of *Angochitina*, *Margachitina*, *Eisenackitina* and *Ancyrochitina*. Some 18 000 conodonts were examined from Leasows and over 22 000 from Domas (Aldridge and Mabillard, 1981; Mabillard and Aldridge, 1985), these comprising more than 20 species. The base of the *Pterospathodus amorphognathoides* interval occurs 65 cm below the Llandovery–Wenlock boundary at Leasows, near the top of unit B, this interval straddling the boundary, with the local disappearance of *P. amorphognathoides* occurring in unit G 30 cm into the Buildwas Formation.

Foraminiferan assemblages from the Purple Shales of Leasows and Domas are dominated by *Ammodiscus exsertus*, with *Hyperammina* species, *Webbinelloidea tholus*, *Psammosphaera cava*, *Hemisphaerammina* sp. and *Turritellella* and *Thurammina* species occurring (Mabillard and Aldridge, 1982, 1985). The basal Buildwas Formation has decreased numbers of specimens, which are dominated by assemblages of *Hyperammina* spp., *Lagenammina* sp., and *Lituotuba* sp.. Both palaeocope and non-palaeocope ostracods occur, Leasows and Domas having yielded for one study (Mabillard and Aldridge, 1985) a combined total of about 20 000 specimens belonging to more than 25 species (see also Siveter, 1978, 1980; Lundin *et al.*, 1991). At the basal Wenlock stratotype and elsewhere, characteristic species of the Purple

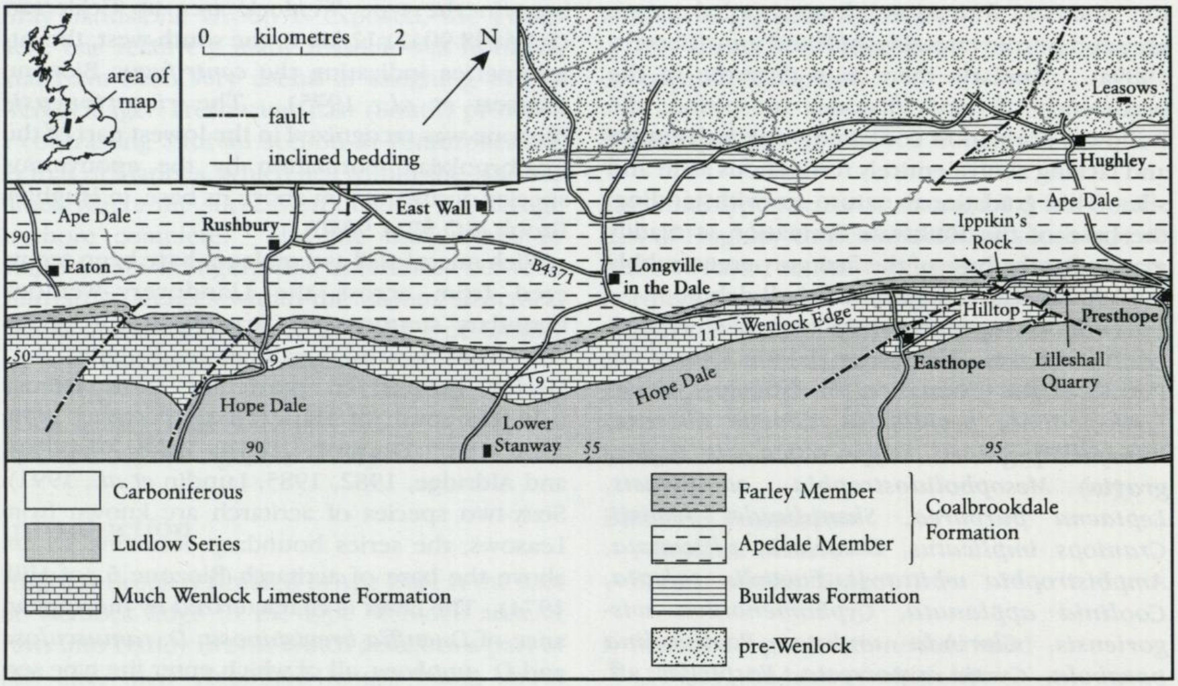


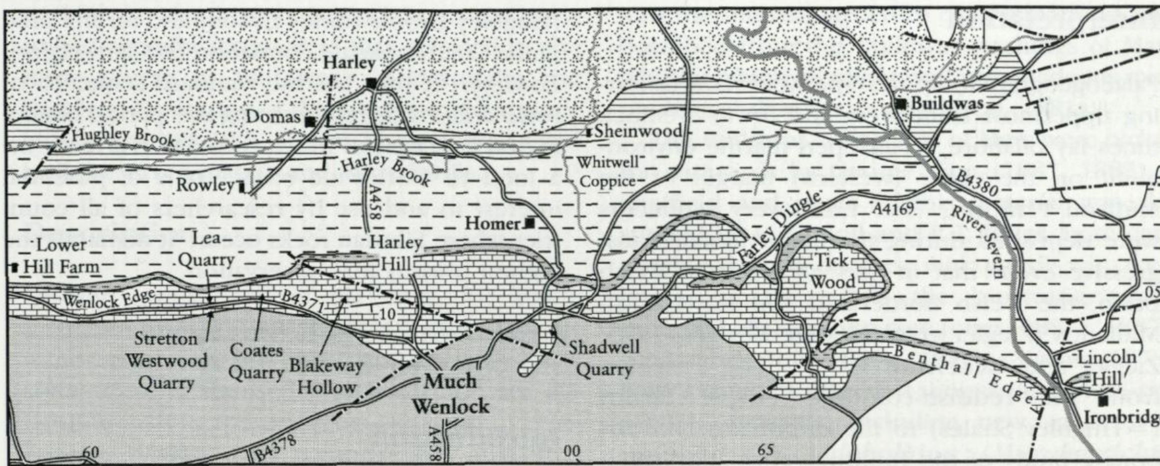
Figure 4.27 Geology of the Wenlock Edge–Benthall Edge area between Eaton and Ironbridge, Shropshire (after Bassett *et al.*, 1975).

Shales include *Craspedobolbina* (*Mitrobeyrichia*) *hipposiderus*, *C.* (*Artiocraspedon*) *glabra* and *Menoeidina lavoiei*, with the Buildwas Formation seeing the introduction of *Tubulibairdia alabamensis*, *Parulrichia diversa*, *Beyrichia admixta*, *Thlipsura martinssoni* and *Bollia bicollina*; other species such as *Craspedobolbina* (*M.*) *interrupta* and *Macrocypris*? *vinei* enter the section just below the boundary and range into the Buildwas Formation. Also, sporomorphs have been documented from the Buildwas Formation of Hughley Brook (Burgess and Richardson, 1991).

The whole of the Buildwas Formation (27 m thick in outcrop) is transected by Hughley and Harley brooks, where it comprises grey to olive-green mudstones, shales and siltstones with intercalations of more limey, nodular horizons. Shelly fossils are scattered throughout, but are generally small and fragmentary. *Dicoelosia*, *Atrypa*, *Atrypina*, *Isorthis*, *Resserella*, *Leangella*, *Eoplectodonta* and *Eospirifer* are the most common genera. Rugose and tabulate corals, trilobites, orthoconic nautiloids, bivalves, gastropods, bryozoa and various microfossil groups occur. The formation in the type area ranges through the *centrifugus*, *murchisoni* and lowermost part of the *riccartonensis* biozones, though the presence of the *murchisoni* Biozone there is unproven.

There are numerous bentonite layers up to 15 cm thick in the Buildwas Formation. Ross *et al.* (1978, 1982) produced fission-track dates from zircons obtained from bentonites from the top 5 m of this formation in Hughley Brook (SO 5703 9833) and from the lower 10 m from the north bank of the River Severn at Buildwas (SJ 6435 0445), giving ages of 423 ± 11 Ma and 422 ± 11 Ma respectively, and a subsequent age (see Bassett, 1989a) for the basal Buildwas Formation (*centrifugus* Biozone) of 422 ± 14 Ma.

The lower part of the Coalbrookdale Formation together with its transitional contact with the Buildwas Formation is exposed in a small tributary that runs from near the farmstead at Rowley into Harley Brook (Bassett *et al.*, 1975; Figure 4.27). The highest nodular horizons of the Buildwas Formation pass over 3–9 m into the Apedale Member of the Coalbrookdale Formation, which overall is less calcareous and consists of olive-grey to blue-grey mudstones, again with numerous bentonite horizons.



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G. obovata, *L. segmentum* and *R. sabrinae* are the commonest brachiopods of the Coalbrookdale Formation, with trilobites, graptolites, nautiloids and bivalves also occurring.

In addition to the Hughley Brook–Harley Brook sections, a very important ancillary sequence for detailing the faunal and sedimentary changes through the Buildwas and Coalbookdale formations is provided by the core from the Lower Hill Farm Borehole, sunk in Ape Dale 1 km to the ESE of Leasows (Bassett *et al.*, 1975).

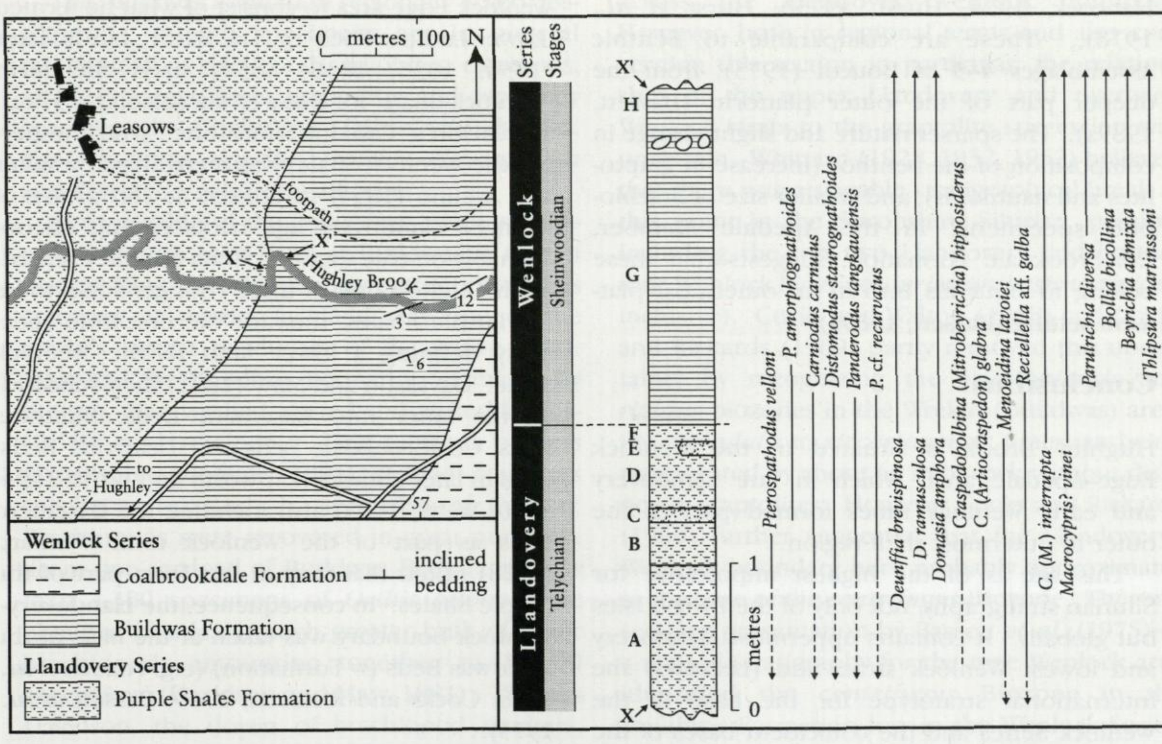


Figure 4.28 Hughley Brook, Shropshire. Location and summary section for the stratotype base of the Wenlock Series, Sheinwoodian Stage and the Buildwas Formation, with the ranges of some important microfossil species used in correlation (after Bassett, 1989a).

Interpretation

Palaeogeographically, the type Wenlock area during uppermost Llandovery and lower Wenlock times lay offshore, in an open marine environment on the outer (western) margin of the Midland Platform. The Llandovery sediments were deposited during the major global transgressive event that in part affected the Welsh Basin, the Welsh Borderland and the English Midlands (Ziegler *et al.*, 1968b; Bridges, 1975; Ziegler and McKerrow, 1975). The transition from the reddish-coloured Purple Shales (= Hughley Shales) to the carbonates and carbonate muds of the Buildwas Formation, then the carbonate muds of the Coalbrookdale Formation (Apedale Member), was accompanied by a somewhat more distal palaeogeographical position, a decrease in the supply of terrigenous material, and lower water energy levels (Bassett, 1989a).

Ecologically, the benthic macrofauna of the Purple Shales in the Wenlock Edge area has been referred to the *Clorinda* or mixed *Clorinda–Costistricklandia* Community (Ziegler *et al.*, 1968b), and that of the Buildwas Formation to the *Dicoelosia biloba* Community (Calef and Hancock, 1974; Hurst, 1975b; Hurst *et al.*, 1978). These are comparable to Benthic Assemblages 4–5 of Boucot (1975), from the deeper part of the outer platform (Bassett, 1989a). The sparser nature and slight change in composition of the benthos (increase in graptolites and nautiloids), and smaller size of brachiopod specimens, in the Apedale Member, Coalbrookdale Formation, suggests that these belong to Boucot's BA6 in an outermost platform setting (Bassett, 1989a).

Conclusions

Hughley Brook is situated in the Wenlock Edge–Apedale area, which in late Llandovery and early Wenlock times formed part of the outer to outermost shelf region.

This site is of the highest importance for Silurian stratigraphy, not only of the British Isles but globally. It contains uppermost Llandovery and lowest Wenlock strata and (Leasows) the international stratotype for the base of the Wenlock Series and the coincident bases of the Sheinwoodian Stage and Buildwas Formation in the type Wenlock area. The site also stands as the type area for the Buildwas Formation (Hughley Brook–Harley Brook) and for the base of the Coalbrookdale Formation (stream section, Rowley). It thus has the standard sequence of rocks and fossils representing this period of geological time against which correlation is made on a local to worldwide basis. It is of potential interest to and use by researchers of all countries where Silurian rocks occur. It demands the highest priority for conservation.

BUILDWAS RIVER SECTION (SJ 638 045–SJ 641 045)

Introduction

In the northernmost part of the type Wenlock area, about 1 km to the south of where Silurian strata disappear under Carboniferous sediments, the River Severn flows towards Ironbridge Gorge and cuts obliquely through almost the whole Wenlock succession. At Buildwas the Llandovery–Wenlock boundary occurs in the river bed, with the Wenlock Buildwas Formation overlying the Llandovery Purple Shales Formation (Figure 4.27).

Murchison (1833) initially considered the lower part of the Wenlock sequence of the Wenlock Edge area to consist of what he termed 'Lower Ludlow Rock' or 'Die Earth', but he later (1834, 1835, 1839, 1854) used the term 'Wenlock Shale' for these strata (Bassett, 1974a). Murchison's 'Caradoc Sandstone', which underlies the Wenlock Shale, was recognized by Salter and Aveline (1854) to consist in Shropshire of younger Llandovery age rocks resting unconformably on true Caradoc strata and they regarded the highest unit of these younger rocks to be the Purple Shales, thus for the first time effectively defining a lower limit to the Wenlock Shale. Davidson and Maw (1881) then subdivided the latter into Basement Beds, Buildwas Beds, Coalbrookdale Beds and Tickwood Beds. Certain later authors (Lapworth and Watts, 1894, 1910; Watts, 1925) also included the Basement Beds as part of the Wenlock until Whittard (1928) noted that they in fact form part of the Purple Shales. In consequence, the Llandovery–Wenlock boundary was taken at the base of the Buildwas Beds (= Formation) (e.g. Pocock *et al.*, 1938; Cocks and Rickards, 1969; Bassett *et al.*, 1975).

Following the work of Pocock *et al.* (1938) and up until the revision by Bassett *et al.* (1975) of the type Wenlock area, the unofficial type section for the Llandovery–Wenlock boundary came to be generally accepted as that afforded by the River Severn at Buildwas. Additionally, the Buildwas Formation of this site has yielded since at least the late 19th century very abundant and well-preserved macro- and microfossils.

Description

On the north bank of the river, for 100 m upstream from a point about 200 m west of the minor road running north to Little Wenlock, some 25 m of the Buildwas Formation are discontinuously exposed (Pocock *et al.*, 1938; Bassett, 1989a). They comprise grey and olive-green shelly siltstones and shales with more nodular, calcareous horizons which sometimes form continuous limestone ribs; there are also many thin, cream-coloured horizons of bentonitic clay. The Purple Shales consist of maroon mudstones with thin beds of shelly limestone and fine-grained sandstone. The passage from Purple Shales formation to the Buildwas Formation is apparently conformable, gradational over 0.5–1 m, and involves a colour change from purple to grey-green; it can be observed at times of low water.

The Buildwas Formation regionally is very fossiliferous, though specimens are in general rather small in size; corals, trilobites, ostracods, orthoconic nautiloids, graptolites and especially brachiopods (including *Dicoelosia biloba*, *Eoplectodonta duvalii*, *Isorthis elegantulina* and *Resserella sabrinae*) all occur.

Most notable of the collections made specifically from the river bank at Buildwas is that of George Maw, the 19th century entrepreneur (his company at nearby Jackfield was one of the world's largest producers of decorative tiles). Maw had the Buildwas Formation extracted by the ton, then washed, sorted and picked for fossils by paid retainers. This retrieval process (Davidson and Maw, 1881) yielded countless specimens for study by specialists of the day. Brachiopods were recovered in great numbers: 'from one cartload of Buildwas Beds ... no less than 4,300 specimens of *Orthis biloba* were obtained besides a much greater bulk of other brachiopods amounting together to 10,000 specimens' (Davidson and Maw, 1881). Thomas Davidson, the doyen of brachiopod workers, used Maw's collections in his monographic studies (e.g. Davidson, 1881b). The Rev. Norman Glass, who in Britain pioneered investigation into the internal structure of brachiopods, also benefited from the Buildwas washings of Maw, without which he might not have made his morphological discoveries (Davidson, 1881a).

The Buildwas collections of Maw were picked for ostracods by George Vine (1887, 1888) of Sheffield and much of this material was also studied by H.B. Holl and R.T. Jones, both early notable workers on these microfossils who were beginning to realize the biostratigraphical potential of the group (see Jones, 1887a, 1887b; Jones and Holl, 1886a, 1886b; Siveter, 1978). Maw's samples provided thousands of well-preserved ostracods, including new species, for example *Craspedobolbina* (*Mitrobeyrichia*) *interrupta* Jones (1887b), and the locality still yields superb material (see Siveter, 1978, 1980; Lundin *et al.*, 1991). Other work utilizing material from Buildwas includes that of Vine (1882) on bryozoans, Andrew (1925b) on *Pachytheca* (plant material), Bassett (1970a) on brachiopods and Thomas (1978) on trilobites.

Interpretation

Pocock *et al.* (1938) highlighted the fact that this Buildwas locality provides an important section across the Llandovery–Wenlock boundary. However, both in regional terms and also concerning this section in particular, the relationship of the upper Llandovery and overlying Wenlock strata to the graptolite succession was uncertain. Whittard (1928, 1932, 1952) believed that there was a sizeable stratigraphical break at this point in the Shropshire Silurian, possibly including the top two Llandovery and bottom four Wenlock biozones (*griestoniensis* to *rigidus* inclusive). Cocks and Walton (1968) and Cocks and Rickards (1969) partly removed this uncertainty by recognizing the *griestoniensis* and *rigidus* biozones in the Wrekin (Buildwas) area, the *crenulata* to *riccartonensis* timespan being represented by about 60 m of rock without diagnostic graptolites. However Cocks and Rickards (1969) further suggested that the Llandovery–Wenlock boundary here probably approximates to the base of the *centrifugus* Biozone. The subsequent presentation by Bassett *et al.* (1975) of a revised stratigraphy for the type Wenlock area identified the *centrifugus* Biozone in the Buildwas Formation low in the Wenlock Series, but this was based on collections made to the south-west in Ape Dale. Thus stratigraphically this site overlaps with and has been superseded in importance by the sections in the Hughley Brook site.

Conclusions

This River Severn locality at Buildwas is important mainly for historical reasons, both in terms of stratigraphy and palaeontology. Following the 19th century works of Murchison, Salter and Aveline, and Davidson and Maw, and those in the 1920s and 1930s of Whittard and Pocock and co-workers, all of these concerning or touching on the scope and composition of the Wenlock Series, the locality was generally recognized as the stratotype for the Llandovery–Wenlock boundary. This status, however, has now lapsed in favour of Leasows, Apedale (see Hughley Brook site report). The locality, also, has been a rich source of fossils from the Buildwas Formation for over a century, many of them featuring in various publications during this time.

WHITWELL COPPICE (SJ 617 021–SJ 620 020)

Introduction

Whitwell Coppice is located in the north-east of the type Wenlock area, 2 km NNE of Much Wenlock (Figure 4.27). Although being included within the boundaries of regional geological and mapping surveys of this district (e.g. Whittard, 1928; Pocock *et al.*, 1938), the strata here did not receive detailed attention until the work of Bassett *et al.* (1975; see also Bassett, 1989a). The latter authors recognized the usefulness of the rocks at this site in terms of Wenlock stratigraphy and established here the standard section for the base of the Homerian Stage, which is coincident with the base of its (lower) Whitwell Chronozone, these bases coinciding with that of the *lundgreni* Biozone. All of the strata exposed belong to the middle part of the Coalbrookdale Formation (Apedale Member).

Description

The section consists in particular of exposures in the banks of a small side-stream together with those in the north-westerly flowing tributary of Sheinton Brook, into which the side-stream flows (Figure 4.29). At the junction of the side-stream and tributary there is a small, 1.5 m high waterfall. The Coalbrookdale Formation here consists of olive to grey-green, blocky, thinly-bedded mudstones which dip very gently east at about 2–3°. In the south bank of the side-stream, at the S-shaped bend near where it runs into the tributary of Sheinton Brook (SJ 6192 0204), occur *Monograptus flemingii, Pristiograptus dubius, Cyrtograptus ellesae* and *Cyrtograptus* sp. of the *ellesae* Biozone, Sheinwoodian Stage. About 1.5 m stratigraphically higher in the sequence, on a small bend some 15 m upstream (SJ 6193 0204), the north bank of the side-stream has yielded *Cyrtograptus lundgreni*, *M. flemingii*, *P. dubius*, *Dendrograptus* sp. and *Cyrtograptus* sp. indicative of the *lundgreni* Biozone (Bassett *et al.*, 1975). The base of the *lundgreni* Biozone and of the Homerian Stage is drawn in this north bank immediately below the occurrence of this faunal assemblage. Orthoconic nautiloids occur in the section as well as graptolites (Bassett *et al.*, 1975).

In the tributary to Sheinton Brook, further graptolite exposures are known. The following

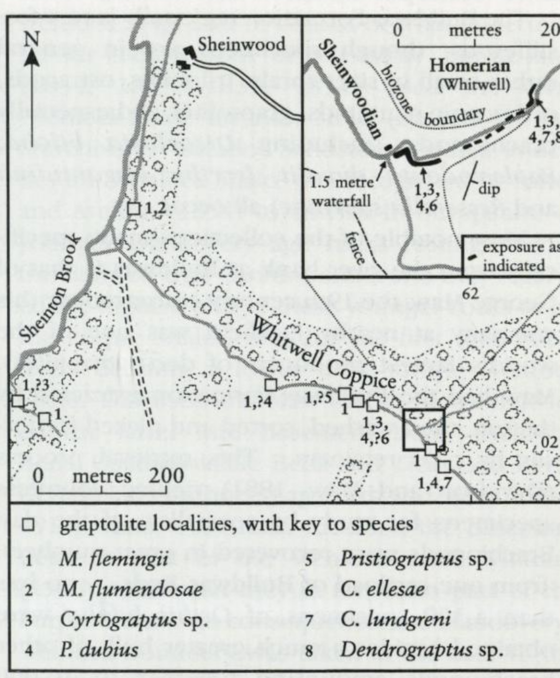


Figure 4.29 Whitwell Coppice, Ape Dale, Shropshire. Location of the standard section for the base of the Homerian Stage, coincident with the base of the Whitwell Chronozone, together with the graptolites recorded from strata above and below this base (after Bassett, 1989a).

species have been recovered from localities 60–250 m downstream from the entrance point of the side-stream, in strata of late Sheinwoodian age: *M. flemingii*, *P. dubius*, *Cyrtograptus* sp., *Pristiograptus* sp. and *C.* ex gr. *ellesae*. In the tributary 30–75 m upstream from the side-stream confluence, in earliest Homerian age strata, *C. lundgreni*, *M. flemingii* and *P. dubius* occur. The trilobite *Dalmanites* has also been recorded from this tributary (Pocock *et al.*, 1938).

An abundant acritarch microflora is also known from the side-stream and the tributary to Sheinton Brook, numbering at least 33 genera and 66 species (Downie, 1959; Swire, 1993); these include species of *Micrhystridium*, *Baltisphaeridium*, *Veryhachium*, *Domasia*, *Ammonidium*, *Leiofusa* and *Leiosphaeridia*. The chitinozoans *Cingulochitina* and *Margachitina* also occur.

Interpretation

Quiet, low-energy conditions on the most distal part of the shelf prevailed during deposition of the fine-grained carbonate muds of the Apedale Member, Coalbrookdale Formation (Bassett, 1974a, 1989a; Holland, 1992). These muds contain a fauna assignable to Benthic Assemblage (BA) 6 of Boucot (1975).

Whitwell Coppice forms one of the network of sites which are stratigraphically linked to provide more or less complete coverage for the Wenlock Series in its type area. The upper Sheinwoodian–lower Homerian strata it includes succeed those of the lower Sheinwoodian Buildwas and Coalbrookdale formations present in the Hughley Brook site and preface the upper Sheinwoodian–lower Homerian rocks belonging to the Coalbrookdale Formation of Eaton Track.

Conclusions

The strata in Whitwell Coppice are of late Sheinwoodian to early Homerian age and belong to the Apedale Member, middle Coalbrookdale Formation. They were deposited in an outermost platform, open marine setting. In terms of Wenlock stratigraphy this is an internationally important site. It is the designated section for the base of the Homerian Stage, coincident with the base of the Whitwell Chronozone and with the boundary between the *ellesae* and *lundgreni* graptolite biozones. It is thus of global chrono- and biostratigraphical significance for rocks of mid-Silurian age.

EATON TRACK (SO 500 900–SO 504 902)

Introduction

This site, located in the hamlet of Eaton in Ape Dale, nestles close to the scarp face of Wenlock Edge (Figure 4.27). Situated in the sunken track adjacent to St Edith's Church, it comprises exposures high in the Coalbrookdale Formation (Figure 4.30). It achieved significance in terms of the stratigraphy of the Wenlock Series when Bassett *et al.* (1975; see also Bassett, 1989a) chose it to stand as the stratotype for the base of the Gleedon Chronozone, Homerian Stage, coincident with the base of the *nassa* Biozone. Thus it forms part of the network of such internationally important sites for the chronostratigraphy of the Wenlock in the type area.

Description

The track section runs to the east from St Edith's church for about 250 m and cuts obliquely across the NE–SW strike of the mid- to late Wenlock strata that young eastwards; fairly continuous exposure is available along both banks, the beds dipping to the south-east from 5–10°. Most of the section is in the upper part of the Apedale Member, Coalbrookdale Formation, which consists of blocky, olive-grey micritic mudstones. The youngest strata belong to the basal few metres of the Farley Member, uppermost Coalbrookdale Formation, which is characterized by an increase in carbonate content giving rise to calcareous nodules that sometimes coalesce and which alternate with thin mudstone horizons. The lithological change between the Apedale and Farley members is transitional over a few metres.

For some 180 m east of the church, strata of the *C. lundgreni* Biozone (Whitwell Chronozone, Homerian Stage) occupy the section, these rocks having yielded the following graptolites (Bassett *et al.*, 1975; Figure 4.30): *Monograptus flemingii*, *Pristiograptus dubius*, *Pristiograptus pseudodubius*, *Gothograptus nassa* and ?*Pristiograptus jaegeri*. At 182 m east of the church (SO 5016 8999) the *lundgreni* Biozone is succeeded by the base of the *nassa* Biozone and

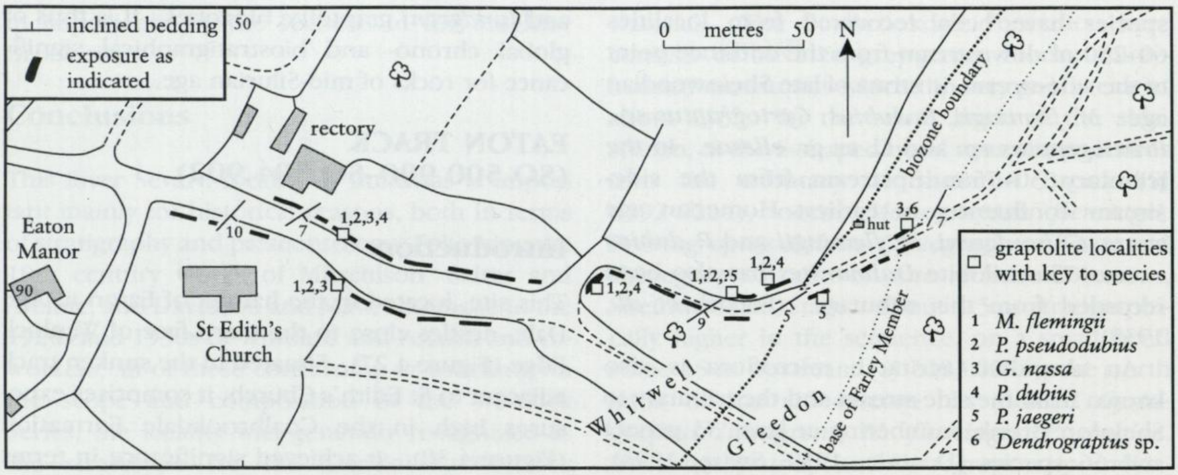


Figure 4.30 Eaton Track, Wenlock Edge, Shropshire. Location of the standard section for the base of the Gleedon Chronozone, Homerian Stage, together with the graptolites recorded either side the boundary (after Bassett, 1989a).

thus the base of the Gleedon Chronozone. *G. nassa*, *P. jaegeri* and *Dendrograptus* sp. are the graptolites identified from the track section stratigraphically above (east of) this point. The *nassa* Biozone, as recognized by Bassett *et al.* (1975) in the whole of the type Wenlock area, has an assemblage of species that includes *G. nassa* (common), *P. dubius*, *P. pseudodubius* and *P. jaegeri*; in particular it lacks *M. flemingii* (found in the *lundgreni* Biozone) and shows the first appearance of *jaegeri*. *G. nassa* and *Dendrograptus* sp. are the stratigraphically youngest graptolites in the section, from the uppermost part of the Apedale Member.

Shelly fossils do occur in Eaton Track (particularly in the more lime-rich Farley Member), but they are less common. Greig *et al.* (1968) recorded, for example, *Glassia obovata*, *Resserella elegantula* and *Leptaena rhomboidalis* (brachiopods), *Loxonema* sp. (gastropod), *Ctenodonta* sp. (bivalve), *Michelinoceras subundulatum* (nautiloid), and *Dalmanites caudatus* (trilobite). In their monographic studies, Bassett (1972; brachiopods) recorded *Resserella canalis*, *Resserella sabrinae* and *Dicoelosia biloba* and Thomas (1978; trilobites) established *Harpidella* (*Harpidella*) *aitholix* on the basis of specimens from this site. A rich microflora is also present, Downie (1959, 1963) in particular having noted over 50 species belonging to the following genera: *Micrhystridium*, *Polyedrixium*, *Pulvinosphaeridium*, *Estiastra*, *Baltisphaeridium*, *Veryhachium*, *Leiofusa*, *Cymatiosphaera*, *Pterospermopsis*, *Lophosphaeridium*, *Leiosphaeridia*, *Tasmanites* (acritarchs and prasinophyta algae) and ? *Punctatisporites* and *Lophotriletes* (spores). At least 15 of the acritarch species found at this site have it as their type locality, for example *Micrhystridium eatonensis* Downie (1959) and *Florisphaeridium wenlockensis* Dorning (1981b). The sporomorphs from the Apedale and basal part of the Farley members of Eaton Track have been specifically documented by Burgess and Richardson (1991).

Interpretation

The sediments of the Apedale Member were deposited in an open marine, outermost shelf environment as the Sheinwoodian–Homerian easterly transgression, which continued from Llandovery times, further submerged the land area that had previously occupied central England (Bassett 1974a, 1989a; Holland, 1992). The environment was one of low energy, below wave base, and was mud-dominated with a dominantly planktonic fauna and flora and a relatively sparse benthos. The Farley Member indicates the beginning of the shallowing and higher energy conditions that culminates with the reef formation of the Much Wenlock Limestone. This change may also reflect climatic warming (Jeppsson *et al.*, 1995).

Stratigraphically, the Eaton Track site lies up-sequence from the Whitwell Coppice site, which exposes middle Coalbrookdale Formation strata of late Sheinwoodian–early Homerian age, and it lies immediately down-sequence from the Longville in the Dale, Easthope–Harley Hill and Farley sites, though these last three link with it by exposing the Farley Member of mid–late Homerian age.

Conclusions

Eaton Track is of international importance for the chronostratigraphy of the Wenlock Series in the type area. It is the designated stratotype for the base of the Gleedon Chronozone, Homerian Stage, defined in the section at the base of the *nassa* Biozone. It also provides a more or less complete sequence through much of the upper part of the Coalbrookdale Formation in its type area and shows the transitional lithological change within this formation from the carbonate muds of the Apedale Member to the more calcareous, nodular Farley Member. Very quiet, followed by slightly higher energy conditions chart the deposition of the Apedale and Farley members, respectively. The site is noteworthy for its planktonic fauna and microflora, with the graptolites from here enabling construction of a biostratigraphy for the type Wenlock Series, and many acritarch species being based on specimens from its trackside exposures.

FARLEY ROAD CUTTING (SJ 637 026)

Introduction

This site is located on the A4169 road 2.5 km south-west of Buildwas, about mid-way between there and Much Wenlock (Figure 4.27). The originally selected railway-cutting section at Farley Dingle is no longer available owing to recent slight re-routing of the A4169 road to the east. The present cutting (Figure 4.31) represents that original section cut back a few tens of metres farther to the east, so that it now forms the easterly margin to the A4169. The new cutting impressively exposes the typical development in the type Wenlock area of the Farley Member, the highest lithological unit of the Coalbrookdale Formation, of mid-late Homerian age.

Figure 4.31 Farley Road Cutting, between Much Wenlock and Ironbridge, Shropshire. Farley Member, Coalbrookdale Formation, Homerian Stage. (Photo: Derek J. Siveter.)

When Davidson and Maw (1881) established the lithostratigraphical subdivisions of the 'Wenlock Shale' (see Buildwas River site report), they recognized at the top of this unit and beneath the Wenlock Limestone a transitional group of sediments linking the two. This gradational facies, above their 'Coalbrookdale Beds', they termed the 'Tickwood Beds' after Tick Wood, which is situated immediately to the north-east of Farley hamlet and the present site (Figure 4.27). Pocock *et al.* (1938) continued to use the term Tickwood Beds for strata immediately beneath the Wenlock Limestone, but in a more restricted sense, recognizing them as having a thickness of only about 30 m as opposed to the 90–150 m estimated by Davidson and Maw (1881). Bassett *et al.* (1975) followed the more limited usage of Pocock *et al.* (1938) for these beds. However they renamed them the Farley Member, after Farley Dingle, because Tick Wood is largely underlain by the Much Wenlock Limestone Formation; they also noted that the term 'Tickwood Beds' had been variously employed since its introduction, for example, Greig *et al.* (1968) included within this unit in the Church Stretton area lithologies, which even took in part of the Lower Elton Formation (Ludlow Series). Despite the initial objections of Lawson (1977a), who favoured that a redefined Tickwood Beds be regarded as a member of a 'Wenlock Shale Formation', all other authors subsequent to Bassett *et al.* (1975) have used the term 'Farley Member'.

Figure 4.32 Farley Road Cutting, between Much Wenlock and Ironbridge, Shropshire. Alternations of thin shaley mudstones and nodular limestones, Farley Member, Coalbrookdale Formation, Homerian Stage. (Photo: Derek J. Siveter.)

Description

About 25 m of the Farley Member are exposed on two levels in this long section, the younger horizons being accessed by a rock bench hewn into the face of the cutting from road level; in the type Wenlock area as a whole the thickness of this unit varies between 24–27 m (Bassett *et al.*, 1975). It consists of alternating thin bands of grey, shaly mudstones and yellow and buff limestone nodules, some of the latter coalescing to form nodular beds, with the unweathered centres of the nodules being blue-grey in colour (Figure 4.32). The grain size of the rocks places them in the range of medium calcilutites to fine calcarenites. Bioturbation is common in some of the calcilutites (Bassett, 1989a).

The fauna of the Farley Member is shelly in nature, comprising mostly (and often small) brachiopod and trilobite specimens and fragmentary pelmatozoans and bryozoans; graptolites are lacking. *Meristina obtusa*, *Nucleospira pisum*, *Ptychopleurella bouchardi*, *Resserella canalis*, *Striispirifer plicatellus* and *Kozlowskiellina strawi* are included amongst the brachiopods and *Warburgella* (*W.*) *stokesii* is the most typical trilobite. The section at Farley Road Cutting also yields very rich undescribed acritarch microfloras.

Interpretation

The return of higher energy conditions marks the transitional passage from the Apedale Member to the Farley Member, accompanied by a shallowing which culminated in the formation of the younger, reefal Much Wenlock Limestone Formation. The depositional environment of the Farley Member was on the mid- to outer platform region. The widespread change to more calcareous sedimentation has been interpreted to reflect climatic warming (Jeppsson *et al.*, 1995).

Biostratigraphically, on the basis of graptolite finds from the whole of the type Wenlock area, nearly all the Farley Member has been assigned to the *nassa* Biozone, with its uppermost part belonging to the *ludensis* Biozone. However there is some uncertainty about whether the *nassa* Biozone extends upwards to include beds towards its top as there are no records as yet of graptolites from much of this lithostratigraphical unit (Bassett *et al.*, 1975). The new road section offers the possibility of detailed sampling for micropalaeontology and chemostratigraphy.

The Farley Member is present in the north-east on the scarp face of Benthall Edge, and also along much of Wenlock Edge. Its stratotype base is defined on Harley Hill (see site report), though the Eaton Track site also exposes the lithologically transitional base from the underlying Apedale Member (Coalbrookdale Formation) and the Longville–Stanway site includes its uppermost part. Towards the south-west of the type Wenlock area the Farley Member passes laterally into mudstone facies typical of the Apedale Member (Bassett, 1989a).

Conclusions

This recently cut road section affords excellent exposures of the Farley Member, the youngest, more calcareous lithological unit of the Coalbrookdale Formation, in the eponymous district within the type Wenlock area. The sediments comprise thin shale and nodular limestone alternations which provide a transitional facies between the carbonate muds of the Apedale Member, Coalbrookdale Formation, below, and the full carbonate development of the Much Wenlock Limestone Formation above. Concomitant with this lithological change there was shallowing and higher energy conditions, perhaps accompanied by climatic warming.

EASTHOPE–HARLEY HILL (SO 566 953, SO 569 964, SO 575 968, SO 580 974, SO 595 983, SO 592 982–SO 605 995, SO 612 998, SJ 606 003– SJ 612 002)

Introduction

The Easthope–Harley Hill site is a composite one. It comprises various localities that all form part of Wenlock Edge – probably the most symbolic of topographical features globally for strata of Wenlock age. This escarpment runs for some 26 km between Much Wenlock in the north-east and Craven Arms in the south-west, owing its presence to the resistant Much Wenlock Limestone, which dips gently to the south-east at about 10° (Figure 4.27). The limestone ridge is often offset along its length as a result of dip faults. The more easily sculptured mudstones of the Coalbrookdale Formation (Wenlock Series) below the scarp face, and shales and siltstones of the Elton Group (Ludlow Series) above it, give rise to the adjacent, parallel valleys of Ape Dale and Hope Dale, respectively. The term 'Much Wenlock Limestone Formation' (Bassett *et al.*, 1975) is now universally applied to this lithological unit, notwithstanding the suggestion (Lawson, 1977a) that the name 'Wenlock Limestone' be retained.

Along its strike the Much Wenlock Limestone Formation can be divided in terms of facies into two main areas, an off-reef tract to the south-west and a reef tract to the north-east, the transition between the two taking place around Easthope. Localities constituting the present site all fall into the reef-tract (Figure 4.33); from the south-west to the north-east, they are: small exposures at Easthope; Ippikin's Rock, Hilltop; Lilleshall Quarry, midway between Hilltop and Presthope; the cliff and adjacent portion of the disused railway track, Presthope; Stretton Westward Quarry; Lea and Coates quarries combined; the old quarries, Blakeway Hollow; and the (A458) road section, Harley Hill.

These localities make available in particular the bioherms and associated fauna for which the Much Wenlock Limestone Formation has long been famous. In the type Wenlock area, the Harley Hill section displays better than any other the gradual lithofacies change from the Farley Member, Coalbrookdale Formation, to the Much Wenlock Limestone Formation; it provides, additionally, the designated stratotype base of the Farley Member and also that of the Much Wenlock Limestone Formation (Bassett *et al.*, 1975).

The geology of the Wenlock Edge area has been extremely well documented and specifically that of the Much Wenlock Limestone Formation. Publications include: the formative works of Murchison (1833, 1834, 1835, 1839, 1854) in which the Silurian System was estab-

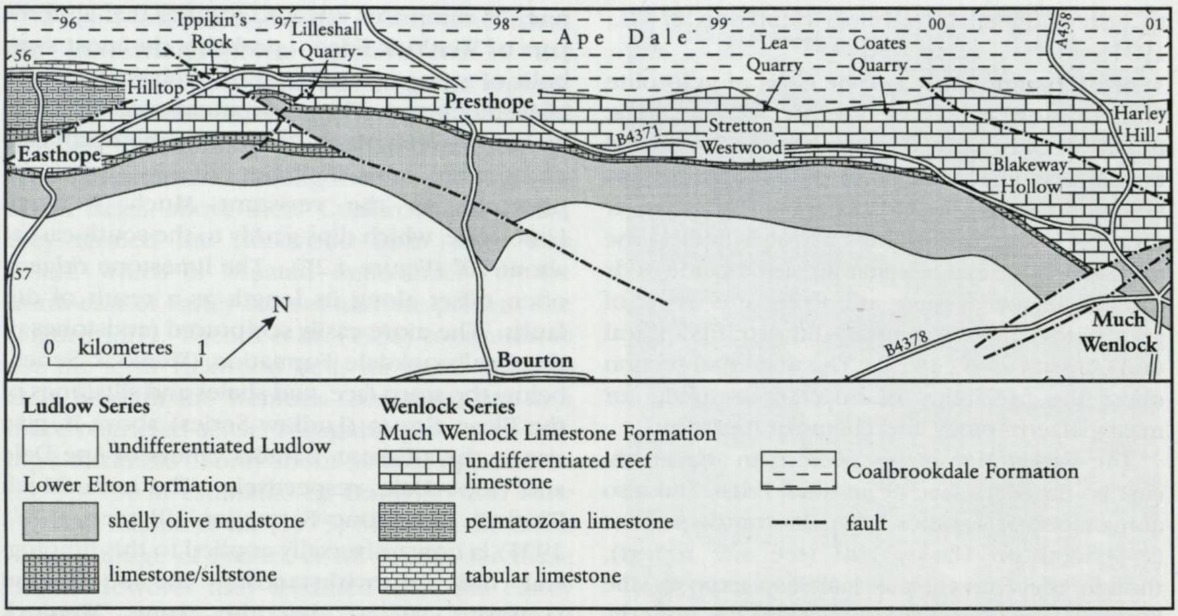


Figure 4.33 Easthope–Harley Hill, Wenlock Edge, Shropshire. Lithofacies distribution in the Much Wenlock Limestone and Lower Elton formations of the reef area between Easthope and Much Wenlock (after Shergold and Bassett, 1970).

lished; descriptions of Shropshire geology (e.g. La Touche, 1884; Davidson and Maw, 1881; Lapworth and Watts, 1894, 1910; Watts, 1925; Whittard, 1952); memoirs and reports of the Geological Survey (e.g. Pocock *et al.*, 1938; Greig *et al.*, 1968); stratigraphical, palaeogeographical and facies work (Das Gupta, 1932, 1933; Shergold and Shirley, 1968; Shergold and Bassett, 1970; Bassett, 1974a, 1989a; Bassett *et al.*, 1975; Hurst *et al.*, 1978; Holland, 1992); debate on diachronism and correlation at the Wenlock–Ludlow boundary (Hurst, 1975b; Bassett, 1976); sedimentological and associated faunal studies (Crosfield and Johnston, 1914; Hill *et al.*, 1936; Scoffin, 1971; Abbott, 1976; Riding, 1981); field guides (Harley, 1988; Siveter *et al.*, 1989); and palaeoecological (e.g. Colter, 1957; Hurst, 1975b), radiometric dating (Ross *et al.*, 1982) and isotope (Corfield *et al.*, 1992) investigations.

Description

The Much Wenlock Limestone Formation of Wenlock Edge has a maximum thickness of 29 m, in the north-east, the reef area; south-west of Easthope, in the Craven Arms area, it thins to about 21 m. The limestone facies of the reef tract comprise bedded, inter-reef carbonates as well as unbedded biohermal mounds.

Shergold and Bassett (1970) and Scoffin (1971) independently identified here more or less the same four lithofacies of the bedded limestones, which the former authors referred to as 'Bluestone', 'Jack's Soap', 'Measures', and 'Gingerbread', after the old quarrymen's terms, whilst the latter author termed them, respectively, Facies A–D. As listed in the order above there is a general stratigraphical younging to these facies, and they also generally coarsen upwards; however they do not always conform to this simple sequence, sometimes one is missing or they occur in a different vertical combination.

The Bluestone lithofacies contains abundant fossils and consists of blue-grey, muddy, pelmatozoan, 5–25 cm thick limestones interspersed with 5–7 cm thick dark grey shales. It is the commonest of the bedded limestones and is particularly in evidence at the base of the formation, being transitional from the Farley Member below. It is well displayed on Harley Hill and in Presthope Railway Cutting, and also occurs in Coates and Stretton Westwood quarries amongst others. Jack's Soap lithofacies comprises highly nodular, very irregularly bedded, blue-grey limestones that are separated by thin (5 cm and less) shale partings. It is gradational with the Bluestone lithofacies, though usually contains fewer fossils. Coates Quarry and Farley Quarry (1.5 km north-east of Much Wenlock) have examples of this type. Somewhat thickly bedded (up to 30 cm), light blue-grey argillaceous, pelmatozoan limestones with 2 cm shale partings make up the Measures lithofacies; fossils are fairly common. It is found towards the top of the formation and has been recorded from Stretton Westwood, Lea and Coates quarries, at least. The Gingerbread lithofacies is formed of pelmatozoan-rich limestones that are white or cream-coloured when fresh but are normally decalcified, brown and honeycombed. It occurs at the top of the formation and is exposed in, for example, Coates and Lea quarries; fossils are quite common.

The bioherms of the Much Wenlock Limestone Formation have attracted the attention of geologists since the time of Murchison (1839) and Lyell (1841) in the first half of the 19th century and Crosfield and Johnston (1914) in the early part of the 20th; more recently, the work of Scoffin (1971; see also Abbott, 1976; Riding, 1981) in particular has led to an understanding in modern terms of the origin, morphology and distribution of these organic build-ups.

Maximum bioherm development is at Hilltop although two small 'outlier' examples occur at Easthope (see Greig *et al.*, 1968), 1 km in front (south-west) of the largest of them. The bioherms can be observed in many of the quarries, Coates Quarry (Figure 4.34) being perhaps the best; small biohermal structures can also be seen in the Harley Hill Road section. The bioherms occur at various levels in the limestone, though they are scarce in the bottom 15 m and are more common and larger near (3–10 m below) the top. Their average width and thickness are 12 m and 4.5 m respectively, with the Hilltop reefs being some 100 m wide and 20 m thick. The larger bioherms tend to be irregularly outlined, the smaller ones bilaterally symmetrical with their upper and lower surfaces convex and their lateral margins interfingering with the bedded inter-reef limestones. The preferred orientation of reef growth, as indicated by their maximum width, is NE–SW.

The basal lenses of many bioherms have a distinct composition of abundant pelmatozoan remains as well as bryozoans, brachiopods and small corals which, when clustered together after death, formed a slight positive area on the sea floor onto which colonizing organisms attached themselves. Clay accumulation seen between the bedded limestones inhibited growth on the reef margins and so controlled reef shape, and the tops of the bioherms often coincide with bentonite horizons. Talus beds (coarse skeletal debris) and pelmatozoan flanking beds, both reef derived, sometimes provide a gradational, not sharp, passage from reef to bedded limestones.

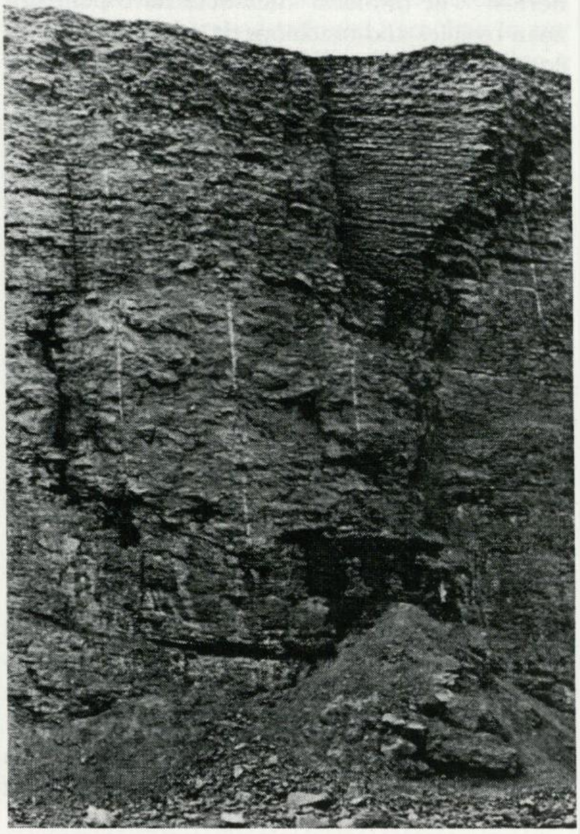


Figure 4.34 Bioherm, about 6 m wide by 4 m thick, within bedded limestones, Much Wenlock Limestone Formation, Coates Quarry, Easthope–Harley Hill site, Wenlock Edge, Shropshire. (Photo: Derek J. Siveter.)

The bioherm organisms consist of two main groups: the frame builders and binders and the loose skeletal bodies within the reef pockets. Tabulate corals (e.g. *Heliolites*, *Favosites*, *Halysites*) are the dominant frame builders, with stromatoporoids (*Actinostroma*, *Stromatopora*, *Labechia*), bryozoans (*Hallopora*, *Rhombopora*, *Fistulipora*) and branching rugose corals (e.g. *Entellophyllum*) assisting. Tabulate corals, stromatoporoids, bryozoans, calcareous algae and similar micro-organisms (e.g. *Girvanella*, *Rothpletzella* and *Wetheredella*) and, most importantly, stromatolites, bind and cement the bioherms. The bioherm interstices have pelmatozoan ossicles and brachiopods, with some ostracods, gastropods and trilobites.

Fossils of all the above groups from the Much Wenlock Limestone Formation of Wenlock Edge have figured in systematic and related palaeontological studies. For example: brachiopods in the papers of Davidson (1866–1871, 1883) and Bassett (1970–1977); trilobites in Owens (1973) and Thomas (1978); corals in Lonsdale (1839), Edwards and Haime (1854), Jones (1936) and Powell and Scrutton (1978); bryozoans in Owen (1969); and algae in Johnson (1966). Shergold and Bassett (1970) recorded from this formation 32 species of brachiopod, 17 corals, 4 stromatoporoids, 2 trilobites, 2 gastropods, 1 bivalve, and unidentified pelmatozoans and bryozoans. With respect to microfossils, Aldridge (1975, 1976) has investigated conodonts from the limestone; Siveter (1978, 1980) and Lundin *et al.* (1991) ostracods; Dorning (1981b) and Dorning and Bell (1987) acritarchs; Dorning (1981c) chitinozoans; and Aldridge *et al.* (1981) microfossils in general.

In terms of the graptolite sequence the Much Wenlock Limestone Formation, the lower part at least, belongs to *ludensis* Biozone (Bassett *et al.*, 1975; see Longville–Stanway site report). A zircon fission-track date of 416 ± 9 Ma was obtained from a bentonite from Coates Quarry (Ross *et al.*, 1982). Contact of the formation with the underlying Coalbrookdale Formation and the overlying Elton Group is seen, respectively, on Harley Hill and in Stretton Westward Quarry (Figure 4.35).

Interpretation

The bioherms of Wenlock Edge were deposited on the outer edge of a shallow shelf, facing the deeper water slope and graptolitic shale facies of the basin to the west (Scoffin, 1971; Bassett, 1974a, 1989a; Hurst *et al.*, 1978; Holland, 1992). Small bioherms also occur elsewhere on the shelf, for example the Malverns and May Hill to the south, and at Dudley and Walsall to the east. At Dudley, on the inner shelf, limestone deposition is believed to have commenced slightly earlier than at Wenlock Edge, during the *lundgreni* (not *ludensis*) Biozone (Bassett, 1976; see also Corfield *et al.*, 1992). Sea-level curves constructed for the Silurian indicate a

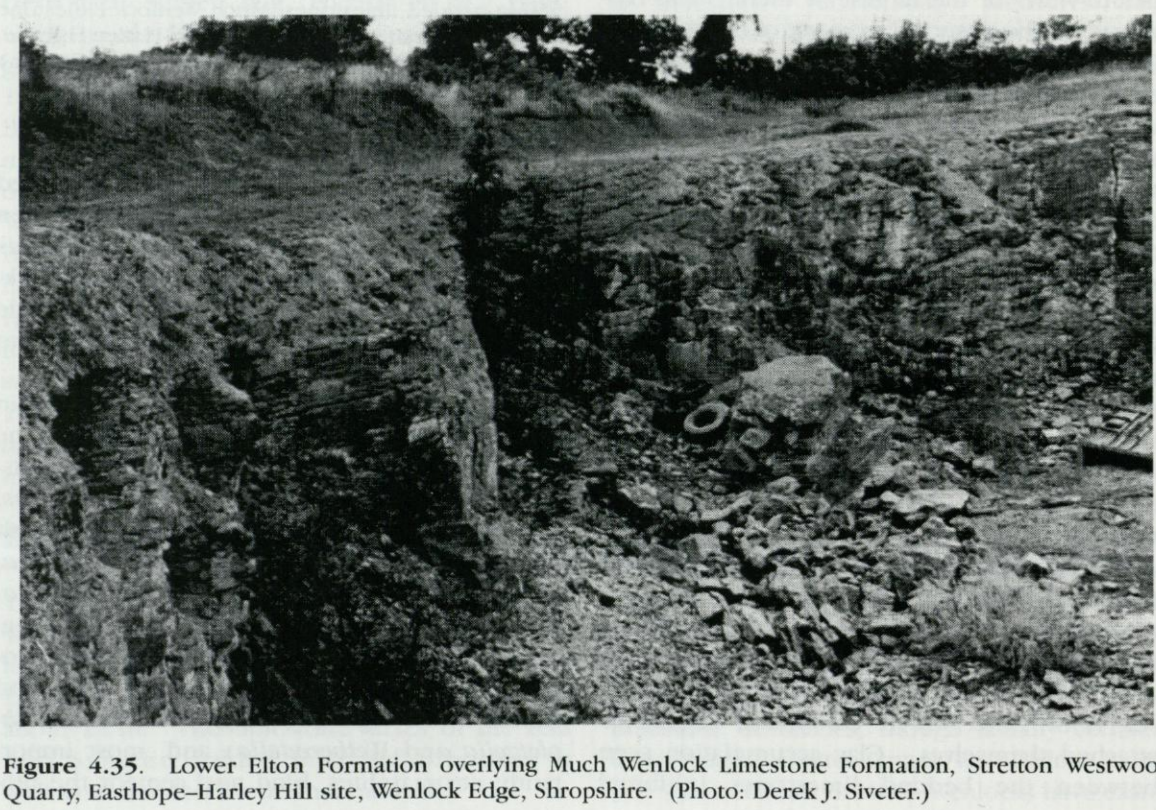


Figure 4.35. Lower Elton Formation overlying Much Wenlock Limestone Formation, Stretton Westwood Quarry, Easthope–Harley Hill site, Wenlock Edge, Shropshire. (Photo: Derek J. Siveter.)

shallowing in latest Wenlock times, not only for Eastern Avalonia of which the Welsh Basin, the Welsh Borderland and central England were a part, but also globally (e.g. Johnson *et al.*, 1991). A global warming at this time has also been postulated (Jeppsson *et al.*, 1995).

In size and shape the Wenlock bioherms are closely analogous to present-day patch reefs within the subtropics (Scoffin, 1971). They grew in fairly quiescent waters, the presence of blue-green algae (*Girvanella*) indicating depths of up to about 30 m. Many of the reefs rest on clay-rich sediments, the evidence suggesting that reef growth outwards onto soft muddy sediment, from the initial basal lens, was possible. The upper margins of the reefs seem to have been at variable depths as wave-generated talus bands are only associated with some of them. They probably had an elevation above the sea floor, which itself was fairly horizontal or slightly undulating, of between 0.5–3.0 m. Water circulation was adequate for coral growth, but not for major marine erosion – finely branched colonial organisms occurring in growth position. Local accumulations of clays indicate periodic water cloudiness. The constancy in composition of the reef fauna through time suggests that there was no marked change in water depth, though there is evidence of considerable shallowing at the end of the Wenlock, as indicated by the seaward spreading of the reefs at this time. Termination of the reefs in the latest Wenlock coincided with extreme shallowing and the formation of the pelmatozoan (Gingerbread) gravel facies. Mudcracks, even, have been recorded from beds high in the succession (Colter, 1957).

The Easthope–Harley Hill site is complemented in particular in the type Wenlock area by the Longville–Stanway site, which exposes the non-reef facies of the Much Wenlock Limestone Formation, and the Lincoln Hill site to the north-east in which the fossils of this unit are especially well preserved.

Conclusions

This is a site of international importance for the Wenlock Series. It has great stratigraphical, palaeontological, palaeoecological and sedimentological significance and is regularly used by research workers in these subdisciplines and by pupils of geology at all levels. Since the time of Murchison the Silurian ground that it covers and the fossils that it has yielded have been discussed in numerous publications. Biohermal structures are better developed here than in any other British Silurian locality, these providing a special focus of study. The site thus displays the classic reef facies of the Much Wenlock Limestone Formation in the type Wenlock area and has, on Harley Hill, the designated base of this unit and that of the underlying Farley Member, Coalbrookdale Formation. It also contains the type localities of many invertebrate species.

LONGVILLE–STANWAY ROAD SECTION (SO 539 927)

Introduction

This site is situated on the lower part of the scarp face of Wenlock Edge, about half-way between Ironbridge in the north-east and the Onny valley in the south-west (Figure 4.27). The strata in the roadside exposures comprising the site were described in the facies and faunal analysis of the upper Wenlock–lower Ludlow rocks of the Wenlock Edge area by Shergold and Bassett (1970; Figure 4.36; see also Scoffin, 1971), though recognition of the faunal (and main) importance of the strata here, specifically in helping construct a biostratigraphical framework for the Much Wenlock Limestone Formation in the type Wenlock area, did not occur until Bassett *et al.* (1975) undertook their revision of this region. Exposed in the section are the Longville and Edgton members of the Much Wenlock Limestone Formation, the bases of which are defined here (Bassett, 1989a), together with the uppermost part of the Farley Member, Coalbrookdale Formation.

Description

The section, which is more or less continuous, occurs on the east side of the minor (C-class) road connecting Longville in the Dale to Stanway. The upper Wenlock beds here dip south-east at about 9°. Several metres of mudstones and nodular limestones of the Farley Member are succeeded by some 12 to 18 m of the Longville Member, the base of which is taken at the point where the first continuous bed of limestone enters the sequence. The muddy and silty limestones of the Longville Member comprise the tabular limestone lithofacies of the

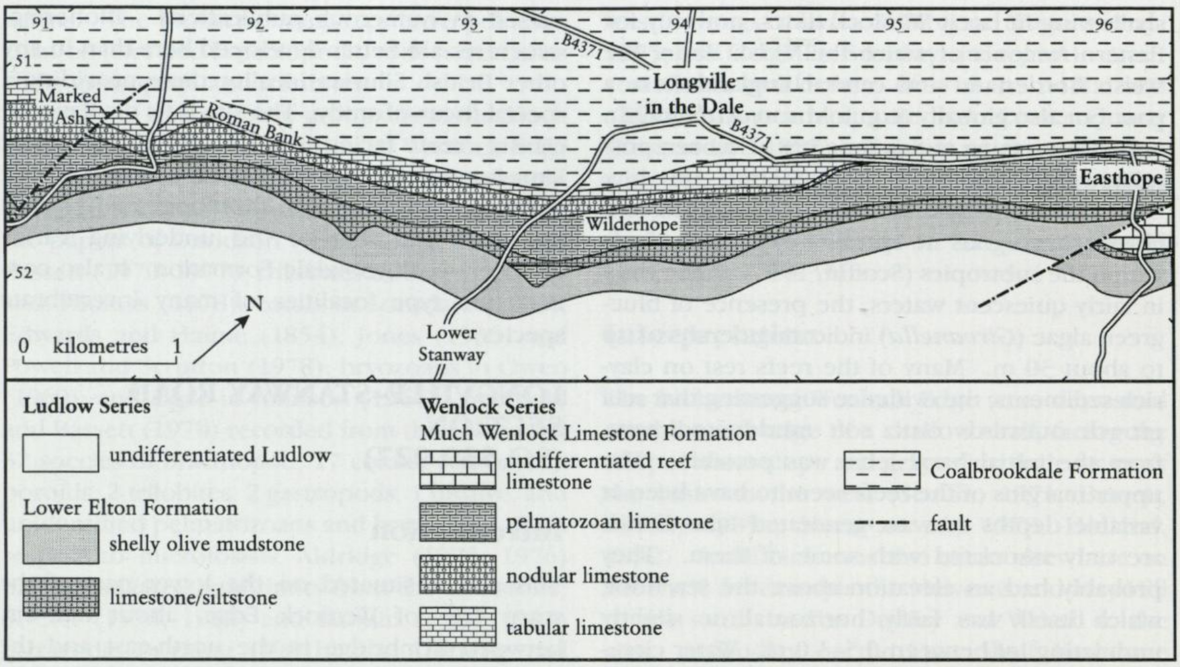


Figure 4.36 Longville–Stanway Road Section. Lithofacies distribution in the Much Wenlock Limestone and lower Elton formations of the non-reef area between Marked Ash and Easthope, Wenlock Edge, Shropshire. (after Shergold and Bassett, 1970).

Much Wenlock Limestone Formation; individual beds vary in thickness from 3–25 cm but in general they are 7–10 cm. Some of the limestones are very fine-grained, light grey to greenish in colour and of 'chinastone' appearance, others are fine-grained and light grey to buff coloured, whilst there are also coarser, more crinoidal and dark grey beds.

The Longville Member is succeeded by the Edgton Member, which is made up of two lithofacies: a (lower) nodular limestone and an (upper) pelmatozoan limestone. The base of the Edgton Member is taken at a point in the section where the nodular limestones replace the tabular limestones, about 18 m above the base of the Longville Member. The nodular beds are about 5 m thick here (thickening to about 9 m in the River Onny area) and consist of micrites and biomicrites which are typically well bioturbated. The pelmatozoan limestones form a thin (3–4 m) capping to the Much Wenlock Limestone escarpment, and represent a fine lateral facies of the pelmatozoan-coral gravels of the (reef) area to the north-east.

The section yields a mainly shelly fauna of brachiopods together with pelmatozoan and bryozoan debris, though trilobites also occur, for example *Calymene tuberculosa* (see Siveter, 1996). Most importantly, graptolites have been recovered (Bassett *et al.*, 1975). From the Farley Member, 0.9 m below the base of the Much Wenlock Limestone Formation, *Monograptus ludensis* and *Pristiograptus jaegeri* have been recorded. *M. ludensis*, *P.* aff. *jaegeri* and *Monograptus deubeli* have been found within the Much Wenlock Limestone Formation 0.6 m above its base, with *M. ludensis*, again, 3.9 m above, and *M.* cf. *ludensis* 5.7 m above. The Longville Member has also yielded conodonts, including *Ozarkodina bohemica bohemica* (R.J. Aldridge, pers. comm.).

Interpretation

The Much Wenlock Limestone Formation of Wenlock Edge is divisible along its length into two main areas, the reef tract north-east from Easthope to the River Severn, and the off-reef tract south-west of Easthope (Crosfield and Johnston, 1914; Shergold and Bassett, 1970; Scoffin, 1971; Bassett *et al.*, 1975; Bassett, 1989a). The Much Wenlock Limestone Formation of the reef area, unlike that of the non-reef area, is undifferentiated vertically into formal stratigraphical units, the Longville and Edgton members being confined to the non-reef area that includes the Longville–Stanway section.

The graptolites identified from here, from the uppermost Farley Member, Coalbrookdale Formation, and the lower part of the Longville Member, Much Wenlock Limestone Formation, allow a *ludensis* Biozone age to be assigned to these strata (Bassett *et al*., 1975); previously their age in terms of the graptolite sequence was very uncertain (Cantrill, 1927; Das Gupta, 1932, 1933; Pocock *et al*., 1938; Whittard, 1952; Shergold and Bassett, 1970). The graptolites also allow comparison of the age of, in particular, the Much Wenlock Limestone Formation in its type area with that of this limestone unit in the type Ludlow area. Work in the 1960s (Holland *et al*., 1963; Warren *et al*., 1966; Holland *et al*., 1969) showed that the *ludensis* (= *vulgaris*) Biozone, which had previously been regarded as the base of the Ludlow Series and correlated with the base of the 'Lower Ludlow Shales' (Wood, 1900) in the Ludlow area, in fact spanned the uppermost part of the 'Wenlock Shale' (= Coalbrookdale Formation) and at least the lower part of the 'Wenlock Limestone' in that area (see Burrington site report). Thus the basal part, at least, of the Much Wenlock Limestone Formation was established as coeval in the Wenlock and the Ludlow districts, and, though graptolites are lacking from the upper part of this unit, it is thought probable that the whole of it belongs to the *ludensis* Biozone (Bassett, 1989a).

An upper age limit on the Much Wenlock Limestone Formation of the Wenlock area is provided by the record (White, 1974) of *Monograptus uncinatus orbatus* from the basal 3–5 m of the Lower Elton Formation, Ludlow Series, of the Much Wenlock area, which indicates that the base of that series in this area lies at, or close to, the base of the *Neodiversograptus nilssoni* Biozone. A more recent graptolite find (Loydell and Fone, 1998), of *Colonograptus colonus*, from the Lower Elton Formation of the Much Wenlock area indicates either the *nilssoni* or the lower part of the succeeding *scanicus* Biozone. The base of the Ludlow Series in the Ludlow area has been assigned to the *nilssoni* Biozone (Lawson and White, 1989).

The occurrence of *C. tuberculosa* in the basal Much Wenlock Limestone Formation of the Longville–Stanway site is one of only two records from Britain of this species, which is typical of the late Wenlock Mulde Beds on Gotland (Siveter, 1996).

In terms of the regional framework of sites in the type Wenlock area, the Longville–Stanway section sits stratigraphically within the vertical range of strata exposed in the reefal Harley Hill section to the north-east, which, also, contains the uppermost part of the Farley Member succeeded by the Much Wenlock Limestone Formation.

Conclusions

The graptolites from this site are of critical importance in providing a biostratigraphical framework for upper Wenlock strata (uppermost part of the Coalbrookdale Formation and in particular the Much Wenlock Limestone Formation) in the type Wenlock area, and for linking this framework to that of the late Wenlock and early Ludlow rocks of the type Ludlow area to the south-west. The non-reef facies exposed here complement those facies of the reef area of the Easthope–Harley Hill site to the north-east. The bases of the Longville and the Edgton members of the Much Wenlock Limestone Formation are defined in this section.

LINCOLN HILL (SJ 669 038)

Introduction

Lincoln Hill is situated on the north side of the River Severn, at the north-east extremity of the resistant outcrop of the Much Wenlock Limestone Formation, which forms Wenlock Edge and its continuation, Benthall Edge (Figure 4.27). The south-westerly spur of the hill, around which the site boundary runs, forms the high ground above the river and separates the town of Ironbridge from Coalbrookdale.

The Much Wenlock Limestone Formation in its type area is very rich in fossils though it is hard and specimens are often somewhat intractable and difficult to recover from it. Lincoln Hill is noteworthy because of the abundance and in particular the excellent preservation of its fossils; many of them were obtained from exposures originally created by limestone mining in the 18th and 19th centuries.

Description

About 0.5 km to the north-east of Benthall Edge, north of the river, the Silurian disappears under the Carboniferous cover (Bassett *et al*., 1975). The Brosely Fault, which crosses the Severn between Lincoln Hill and Benthall Edge, has a downthrow to the north-east and causes misalignment of these two elevated features so that the Wenlock rocks of Lincoln Hill are offset slightly to the north-west.

Three informal stratigraphical divisions were formerly recognized in the 'Wenlock Limestone' of Lincoln Hill, upper and lower units of concretionary and flaggy beds separated by a central mass of thick-bedded limestone (Murchison, 1839; Prestwich, 1840; Whitehead *et al*., 1928; Pocock *et al*., 1938). The central mass of limestone contained bioherms ('ballstones'; see Easthope–Harley Hill site report), and as it was purer than the beds above and below, it was thus the main objective of the former quarrying operations. On Lincoln Hill just to the north-east of the site boundary, in the vicinity of the main limestone quarry (SJ 6721 0407; long since infilled), the 'Wenlock Limestone' is reported to dip south-east at about 30°; in the south-west above the River Severn, within the site confines, it dips at nearly 60° (see Whitehead *et al*., 1928; Hamblin and Coppack, 1995).

The main exposure of the limestone present day is the steeply dipping bedding plane surface (located south-east of Dale Coppice; SJ 6695 0380) that faces towards Ironbridge (Figure 4.37). Exposures in the old workings immediately south-east of and stratigraphically higher than this face are no longer available, but they can in places be recognized as overgrown scars. Probably some, at least, of these were the sites of bioherms. The geology of Lincoln Hill is summarized graphically as a wood-cut in Murchison's *Silurian System* (1839) and *Siluria* (1854). This shows the face of a steeply dipping bedding plane of limestone that lies stratigraphically beneath limestones that form knolls and from which bioherms have been extracted; Coal Measures overlie the Silurian strata in the distance (Figure 4.38).

The fine biosparite limestones of the steep dip slope are richly fossiliferous, especially in terms of well-preserved brachiopods and solitary corals (Crosfield and Johnston, 1914). Indicative of this is the study of Bassett (1970b), in which specimens of the orthacean brachiopod *Ptychopleurella bouchardi* (Davidson) were collected from here that allowed variation in the cardinalia of this species to be assessed. Taxonomic revision of articulate brachiopod material from Lincoln Hill (Bassett 1972, 1974b, 1977) has included *Resserella canalis* (J. de C. Sowerby), *Dalejina hybrida* (J. de C. Sowerby), *Isorthis amplificata* Walmsley, *Leptaena depressa* (J. de C. Sowerby), *Lepidoleptaena poulseni* (Kelly) and *Amphistrophia* (*A.*) *funiculata* (M'Coy). Brachiopod community analysis on specimens from the dip slope was conducted by

Figure 4.37 Lincoln Hill area, Ironbridge, Shropshire. Steeply dipping face of Much Wenlock limestone Formation. (Photo: Derek J. Siveter.)

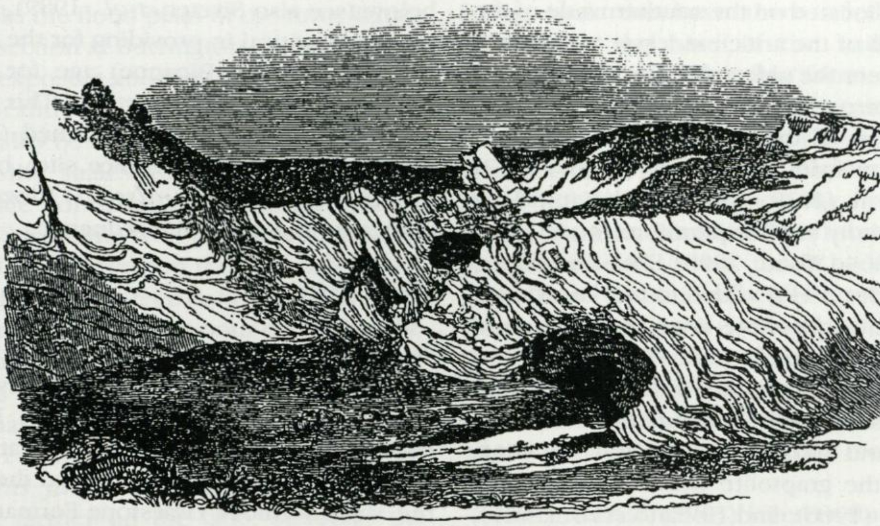


Figure 4.38 Lincoln Hill, Ironbridge, Shropshire. Reproduction of the wood-cut from *The Silurian System* (Murchison, 1839), showing sites (dark-shaded hollows) of extraction of the 'concretions' or 'ballstones' from the (Much) 'Wenlock Limestone' (Formation), with the 'coal grits' (Carboniferous) forming the small scarp in the distance (upper right).

Hurst (1975a), who assigned them to the *I. clivosa* Community. There is also a diverse, beautifully preserved ostracod fauna from here (Siveter, 1978, 1980; Lundin *et al.*, 1991) which includes the non-palaeocopes *Columatia variolata* and *Silenis longus*, and the palaeocopes *Sleia pauperata*, *Thlipsura corpulenta*, *Sarmatotoxotis phracta* and *Tinotoxotis velivola*. The last two species are the type species of their respective genera, and were established on the basis of Lincoln Hill material (Siveter, 1980).

Interpretation

The limestones of the steeply dipping bedding plane were formed slightly earlier than the small bioherms originally present in this area, and leeward of the main 'barrier' reef and patch reef complex which occurs to the south-west on Wenlock Edge as far as Easthope (Bassett, 1970b; Scoffin, 1971). Comparison of the cardinalia of *P. bouchardi* material from Lincoln Hill with those of conspecific material from Coates Quarry, Wenlock Edge, indicates relatively quieter water conditions in the former area, as specimens from there have their muscle attachment area and articulatory mechanism less well developed (Bassett, 1970b).

In combination with the Longville–Stanway and Easthope–Harley Hill sites, Lincoln Hill helps provide comprehensive faunal and lithofacies coverage of the Much Wenlock Limestone Formation in its type area.

Conclusions

Lincoln Hill has yielded numerous fossils from the Much Wenlock Limestone Formation that are amongst the best preserved and most easily obtained from this unit in its type area. The site represents the type locality for several invertebrate taxa. In a historical context the hill was both described and figured by Murchison.

BURRINGTON (SO 433 723 AND SO 443 726)

Introduction

At the south-west end of Wenlock Edge, near Craven Arms, the Silurian outcrop takes a slightly sinuous, S-shaped course, firstly as the Downton Syncline and then as the complementary Ludlow Anticline, thereafter continuing to the south-west into central Wales. The Ludlow Anticline plunges to the ENE under Ludlow town and is formed mainly of Ludlow strata for which it represents the type area; it also has an outer envelope of Přídolí age sediments and an inner core of Wenlock rocks. The hamlet of

Burrington is located on the southern side of the northern limb of the anticline, close to the anticlinal axis where the oldest (Wenlock) sediments crop out (Figure 4.39).

The geology of the Ludlow area has been commented on from the time of Wright (1832) and Murchison (1839, 1854) in the mid-19th century. Many subsequent authors (e.g. Lightbody, 1869; Wood, 1900; Elles and Slater, 1906; Alexander, 1936) added to our knowledge of the Silurian rocks of this area, but these were exclusively concerned with the dominant, Ludlow age strata. It was not until Holland *et al.* (1963) published their benchmark revision of the geology and faunas of the Ludlow Anticline, followed by the graptolite work in the area of Warren *et al.* (1966), and Holland *et al.* (1969), that the strata and fossils of Wenlock age from here received specific attention.

Wenlock rocks are not well exposed in the Ludlow Anticline. Even so in the 1960s they yielded, from the Burrington localities described below (see also Siveter *et al.*, 1989), graptolites that were critical in providing for the first time a precise (*ludensis* Biozone) age for the Much Wenlock Limestone Formation. This also led to a revision of where the re-defined (Holland *et al.*, 1963; see Pitch Coppice site) base of the Ludlow Series lay (*nilssoni* Biozone) with respect to the graptolite sequence.

Description

The Burrington site consists of two separate areas which are along strike (roughly E–W) and 0.75 km apart from each other. Both areas include ground underlain by beds at the top of the Coalbrookdale Formation and the bottom of the Much Wenlock Limestone Formation, which here have a general dip to the NNW of between about 20–40°. One area comprises the lane section which runs to the north-west from Burrington hamlet. The second area, to the west, comprises the western part of the bank

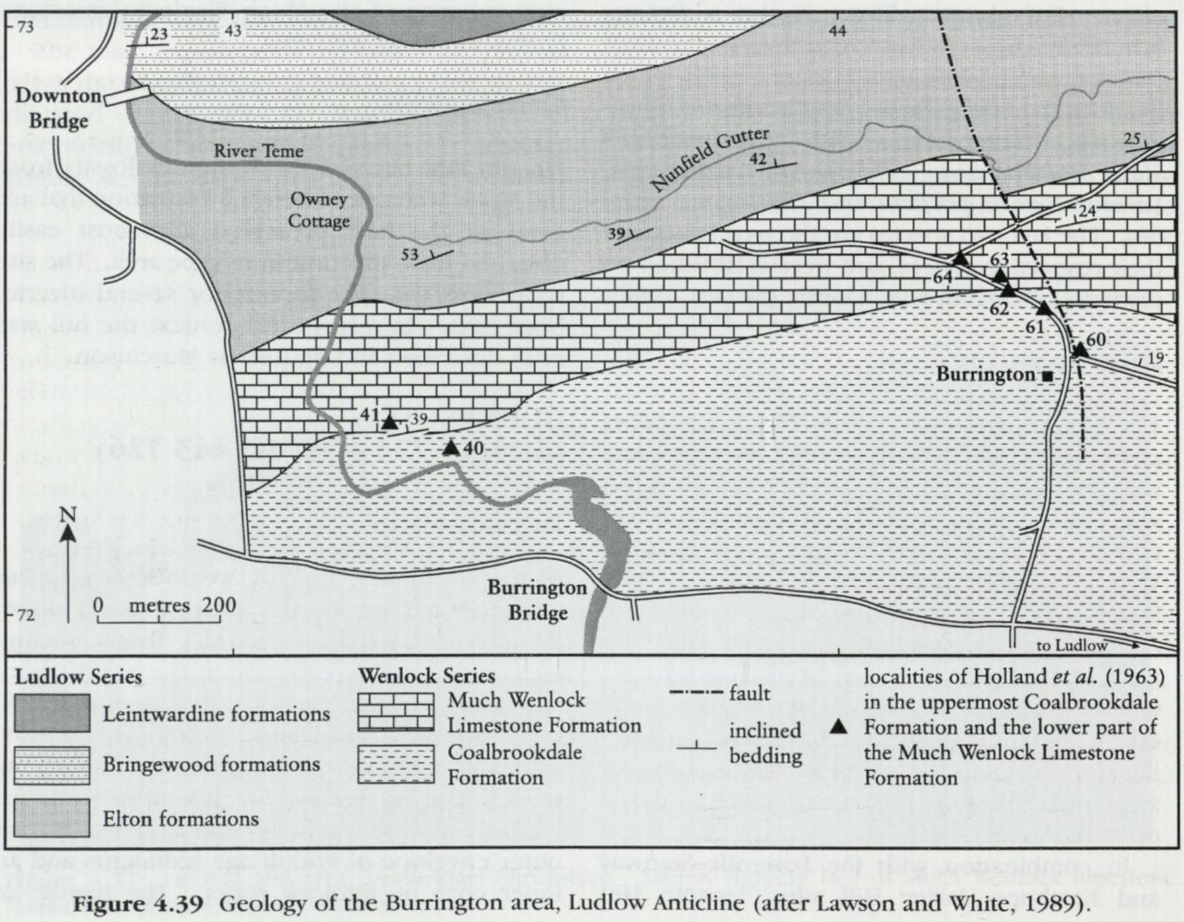


Figure 4.39 Geology of the Burrington area, Ludlow Anticline (after Lawson and White, 1989).

that overlooks the flood plain of the River Teme.

The lane section at Burrington has reasonably continuous exposure and the site boundary here includes localities 60–64 of Holland *et al.* (1963). Locality 60 is a bank with soft, grey, thinly bedded silty shales and mudstones of the Coalbrookdale Formation. It is on the eastern side of a N–S trending fault that downthrows to the east and offsets beds on the west side to the north. Locality 61 is a steep cutting slightly higher in the same formation. In both exposures the sparse fauna includes graptolites, nautiloids and the trilobite *Dalmanites*. Of the graptolites, locality 60 has yielded *Gothograptus nassa*, and locality 61 *Monograptus ludensis* and *Pristiograptus jaegeri* (Holland *et al.*, 1969). Locality 62, farther up the lane, straddles the boundary between the Coalbrookdale and Much Wenlock Limestone formations, the base of the latter being taken at the point of sudden increase in the occurrence of limestone ribs. The Coalbrookdale Formation here has yielded *M. ludensis*, *P. jaegeri*? and *Holoretiolites (Balticograptus) lawsoni*. Locality 63 is a small quarry showing flaggy limestone beds typical of the Much Wenlock Limestone Formation. Fossils are uncommon, but fragments of *M. ludensis* and small brachiopods have been found. Locality 64, at a sharp bend in the lane, is also in the lower, flaggy Much Wenlock Limestone Formation, but slightly higher in the sequence. *M. ludensis* has been recorded from here (Holland *et al.*, 1969), and it is the youngest horizon in this lithostratigraphical unit from the Ludlow Anticline to have produced graptolites.

The second area, hillside exposures above the River Teme, includes localities 40 and 41 of Holland *et al.* (1963). Locality 40 is a trackside cutting near the top of the Coalbrookdale Formation, from which *Pristiograptus dubius*, *G. nassa*, *M. ludensis* and *P. jaegeri* have been obtained. Locality 41 is a poor exposure of the basal part of the Much Wenlock Limestone Formation, above the wooded bank, which has yielded *M. ludensis* and *P. jaegeri*.

Interpretation

Only comparatively recently have the highest Wenlock strata of the Ludlow Anticline been known with confidence in terms of the standard graptolite biozonation. At the turn of the 20th century Elles (1900) and Wood (1900), who worked largely in the more offshore, graptolitic facies, took the base there of the *vulgaris* Biozone as the base of the Ludlow Series. Thereafter, in the graptolitic facies at least, the base of the *vulgaris* Biozone became the internationally accepted horizon for the Wenlock–Ludlow boundary. However, although Wood (1900) also assigned the lower Ludlow shales of the Ludlow district on the shelf to this biozone, she recorded these beds as lacking graptolites. Additionally, the precise relationship of the *vulgaris* Biozone with the latest Wenlock Much Wenlock Limestone Formation of the shelf region, which immediately underlies the Ludlow Rocks *sensu* Murchison (1834, 1835, 1839), was still uncertain (see Pocock *et al.*, 1938).

Holland *et al.* (1963) failed to find graptolites in the Much Wenlock Limestone Formation of the Ludlow Anticline and so the position of the base of the *vulgaris* Biozone with regard to this unit, and indeed also with regard to their newly defined standard section for the base of the Ludlow Series at Pitch Coppice, remained an open question. Shortly afterwards however, *M. vulgaris* was shown to be a junior synonym of *M. ludensis* and, based on graptolites from the Burrington localities of Holland *et al.* (1963), the upper part of the Coalbrookdale Formation and at least the bottom one-third of the Much Wenlock Limestone Formation in the Ludlow Anticline were shown to belong to the *ludensis* Biozone (Warren *et al.*, 1966; Holland *et al.*, 1969).

The Ludlow Series as recognized historically in the graptolitic facies, beginning with the base of the *ludensis* (= *vulgaris*) Biozone, would thus include the Wenlock Limestone, a situation that was clearly unsatisfactory. Therefore it was recommended (Warren *et al.*, 1966; Holland *et al.*, 1969) that in the graptolitic facies the base of the *nilssoni* Biozone be accepted as the base of the Ludlow Series, and that in any event it was probable that the base of this biozone lay at or close to the base of the Ludlow Series in Pitch Coppice. Subsequently, this has proved to be the case (see White 1974, 1981; Lawson and White, 1989).

The Burrington site, then, stratigraphically precedes and has relevance to the nearby Pitch Coppice (Ludlow Series) site. It also links with the Longville–Stanway Road Section GCR site on Wenlock Edge, this being the other locality in the type Wenlock and Ludlow areas where dating of the Much Wenlock Limestone Formation in terms of graptolites (also *ludensis* Biozone) has been achieved.

In terms of palaeogeography and facies, the Much Wenlock Limestone Formation exposed at Burrington represents the most north-westerly expression of the carbonate platform present in the English Midlands and adjoining areas to the west and south-west in latest Wenlock times. This platform is more typically, strongly manifest in such sites as Wren's Nest in the West Midlands and Easthope–Harley Hill on Wenlock Edge.

Conclusions

This is a site of prime biostratigraphical importance. It is where, for the first time, a firm assignment (*ludensis* Biozone) was determined for the Much Wenlock Limestone Formation in terms of the graptolite sequence. This allowed correlation between this carbonate facies on the shelf (margin) region and the graptolite-rich facies of the offshore, slope and basinal areas. The determination of a reliable graptolite biozonal assignment for the Much Wenlock Limestone Formation here also underpinned that for strata of the Ludlow Series in their type area.

DOLYHIR QUARRIES (SO 241 581)

Introduction

The Dolyhir area has a series of quarries in Wenlock and Precambrian rocks belonging to the Old Radnor Inlier. The Wenlock strata comprise the Dolyhir and Nash Scar Limestone Formation and the younger Coalbrookdale Formation. Murchison (1839, 1854), when discussing mainly the adjacent and geologically similar Nash area near Presteigne, commented on the nature and age of this limestone, which he first concluded to be identical in stratigraphical position and organic content to the (Much) Wenlock Limestone (Formation) and subsequently considered to be equivalent to the Woolhope Limestone (Formation). Calloway (1900) briefly commented on the so-called Woolhope (= Dolyhir) Limestone in his study of the Old Radnor Precambrian. However it was Garwood and Goodyear (1919) who first described the limestone and the other Silurian geology of this district in detail, producing a geological map of the whole inlier and a larger-scale map of some of the quarries. Bassett (1974a) and Hurst *et al.* (1978) considered aspects of dating and palaeogeography of the Old Radnor Silurian, whilst Bassett (1977) formally introduced the name 'Dolyhir and Nash Scar Limestone Formation'. Woodcock (1988) addressed the effects of tectonics on the Silurian and Precambrian rocks of the inlier.

The early Wenlock (Sheinwoodian) Dolyhir and Nash Scar Limestone Formation represents a uniquely rich facies of algal limestone within the British Silurian. This lithostratigraphical unit is superbly exposed and has its type development in the Dolyhir quarries. These workings also show evidence of the Welsh Borderland Fault System – a very important early Palaeozoic tectonic boundary for southern Britain (Woodcock, 1988; Woodcock and Gibbons, 1988).

Description

Extraction of limestone in this area appears to go back almost 400 years (Garwood and Goodyear, 1919). The present-day complex of workings at Dolyhir is generally referred to two main quarries: Dolyhir and Strinds (Figure 4.40). The current GCR site boundary encompasses almost all of these, plus (the subsidiary) quarries C and D of Garwood and Goodyear (1919). The northern end of Dolyhir Quarry has been extended beyond the existing site boundary in recent years. The overall succession consists of Precambrian basement followed by the Dolyhir Limestone and then Coalbrookdale Formation.

The Precambrian strata are sediments belonging to the Yat Wood and younger Strinds formations, the former comprising fine sandstones, siltstones and laminated mudstones, and the latter medium sandstones and pebbly sandstones. Such lithologies have analogues in the Longmyndian rocks of the Church Stretton area (Calloway, 1900; Woodcock, 1988; Woodcock and Pauley, 1989).

The Dolyhir Limestone is a pure carbonate (99% $CaCO_3$; Garwood and Goodyear, 1919), bluish-grey to white, highly crystalline and poorly to massively bedded; it is at least 24 m thick and lies with angular unconformity on the Precambrian. The bottom of the limestone often comprises a basal rudite up to some 2 m thick containing angular sandstone and mudstone clasts plus rounded quartz pebbles, all derived from the Precambrian; *Favosites* colonies occur amongst these Precambrian fragments.

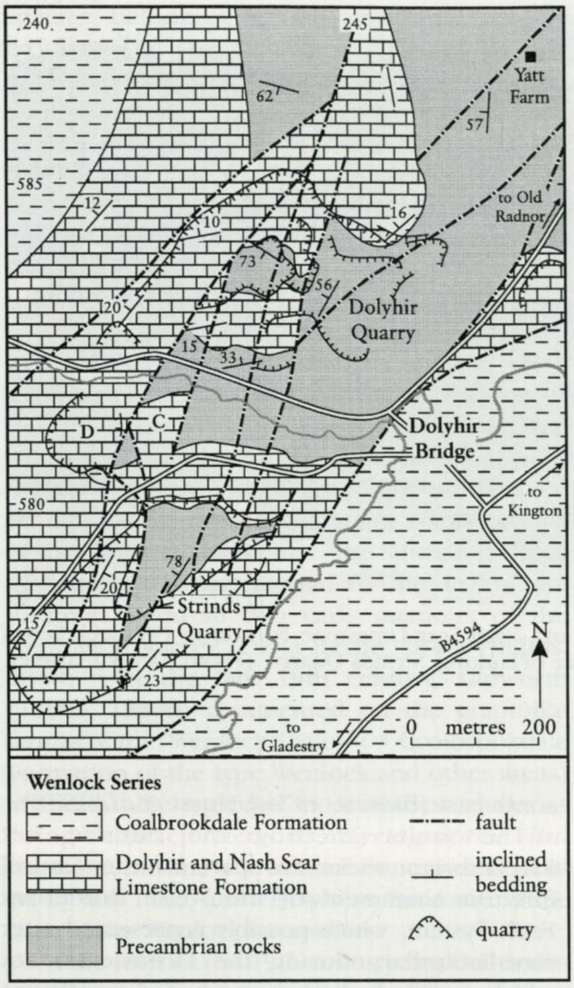


Figure 4.40 Geology of the Dolyhir area, Radnorshire (after Garwood and Goodyear, 1919, Woodcock, 1988, and Siveter *et al.*, 1989).

The dominant faunal elements of the limestone are calcareous algae (Johnson, 1966) in the form of oncolites up to 20 cm in diameter: for example *Solenopora gracilis*, *Rothpletzella gotlandica*, *Girvanella pusilla* and *Girvanella problematica*. These algal nodules have a typically porcellanous appearance, contrasting with the surrounding coarsely crystalline limestone. Bryozoans are also abundant in the limestone, and corals, crinoids, gastropods, bivalves, cephalopods, brachiopods and trilobites are also recorded in a faunal list of some 70 species (Garwood and Goodyear, 1919). Brachiopods from the limestone (Bassett, 1974a, 1974b, 1977) include *Streptis grayii*, *Antirhynchonella linguifera*, *Leptaena oligistis*, *Megastrophia* (*Protomegastrophia*) *quetra* and species of *Plectatrypa* and *Whitfieldella*; trilobites (Thomas, 1981) include *Radnoria syrphetodes*, *Cornuproetus peraticus*, *Planiscutellum kitharos* and *Dudleyaspis portlockii*. An abundant suite of conodonts has been recovered (see Aldridge, 1976; Aldridge *et al.*, 1981) that includes *Ozarkodina sagitta rhenana*, *Ozarkodina excavata*, *Dapsilodus obliquicostatus* and *Decoriconus fragilis*. The limestones have also yielded a fairly low diversity acritarch assemblage (Aldridge *et al.*, 1981), dominated by species of *Veryhachium*, *Micrhystridium* and thin-walled forms of *Diexallophasis*.

Included within the lower part of the limestone is a relatively thin shale horizon that is often tectonized and thus discontinuous and which sometimes contains greenish carbonate concretions plus abundant crinoid debris (Garwood and Goodyear, 1919; Woodcock, 1993). In detail the fauna from this horizon tends to be different from that in the main limestone. Trilobites include *Cyphoproetus depressus* and species of *Kosovopeltis* and *Scotoharpes*, together with *Tapinocalymene volsoriforma* (Thomas, 1978; Siveter, 1980).

Several of the species from the Dolyhir Limestone Formation at Dolyhir have their type horizon and locality here, for example *S. gracilis* Garwood and Goodyear, 1919, *M. (P.) quetra* Bassett (1977), *R. syrphetodes* Owens and Thomas (1975), *T. volsoriforma* Siveter (1980), *C. peraticus* Owens (1973) and *Bumastus? phrix* Lane and Thomas (1978).

On palaeontological grounds, using brachiopods, trilobites, conodonts and (from the regionally overlying Coalbrookdale Formation) graptolites, the limestone is believed to span the *centrifugus*, *murchisoni* and at least some part of the *riccartonensis* biozones, the presence of *O. sagitta rhenana* restricting at least part of the limestone to the eponymous conodont biozone (lower Sheinwoodian); on purely stratigraphical criteria the base could be as old as early Telychian (Kirk, 1951a, 1951b; Zeigler *et al.*, 1968b; Bassett, 1974a; Aldridge and Schönlaub, 1989; Cocks *et al.*, 1992; Jeppsson *et al.*, 1995).

The Coalbrookdale Formation is exposed in Quarry D and, now also, parts of the extended Dolyhir Quarry. In Quarry D it occurs as a small, downfaulted patch that may be conformable with the underlying limestone and contains calcareous concretions yielding well-preserved

Figure 4.41 Dolyhir Quarries, Radnorshire. Dolyhir and Nash Scar Limestone Formation (Wenlock Series) overlying Strinds Formation (Precambrian), with evidence of faulting, Strinds Quarry. (Photo: Derek J. Siveter.)

specimens of *Tapinocalymene nodulosa* and *Dalmanites*. The presence of *Monograptus flemingii* indicates an age within the *rigidus* to *lundgreni* biozones (Bassett, 1974a).

Precambrian and Silurian strata within the quarries are cut by three large, continuous faults striking NNE, dipping WNW, with apparent normal offsets (WNW downthrow) (Figure 4.41). However slickensides indicate that strike-slip, not dip-slip, displacement is responsible for the normal offsets and further evidence from related, minor fault sets implies a sinistral sense of movement. Imposition of this strike-slip component occurred in post-Wenlock time, probably during the early Devonian Acadian (late Caledonian) event (Woodcock, 1988).

Interpretation

The Dolyhir Limestone, with its algal nodules, represents deposition in a very shallow water, turbulent environment with minimum clastic input. It formed somewhat offshore (mid-outer shelf), on the topographical highs formed by the Precambrian basement, though it may have been part of a more continuous carbonate shelf extending to the probably coeval Woolhope Limestone Formation area of deposition of the Woolhope, May Hill and Malverns inliers to the south-east (Bassett, 1974a; Hurst *et al.*, 1978).

The faults affecting the Silurian and Precambrian rocks are part of the Church Stretton Lineament of the Welsh Borderland Fault System, which possibly represented a terrane boundary during the Ordovician, and which in Silurian times marked a transitional divide between the contrasting sedimentary regimes of the Midland Platform to the east and the Welsh Basin to the west (Woodcock, 1988; Woodcock and Gibbons, 1988). The Acadian event affecting these faults involved sinistral transpression and has been interpreted as representing a final collision between Avalonia and Laurentia (Soper and Hutton, 1984; Pickering *et al.*, 1988; Woodcock *et al.*, 1988).

Conclusions

The early Wenlock limestone at Dolyhir, together with the nearby development at Nash Scar, is the richest development of algal limestones in the British Silurian. These are finger-print environmental indicators for shallow water. The limestones were deposited offshore between the inner shelf and the basin on Precambrian highs, in an area caught up within movements along the Welsh Borderland Fault System. These quarries also represent the type locality for several species belonging to different invertebrate groups. The site is of great palaeontological, palaeoenvironmental, palaeogeographical and tectonic interest, and is used frequently for research and teaching purposes.

TRECOED–CASTLE CRAB (SO 053 552–SO 051 554)

Introduction

This section is to be found about 4.5 km north of Builth Wells in central Wales. Murchison (1839, 1854) gave only brief mention of the Builth area in his *Silurian System* and also in *Siluria*, though the former work contains cross-sections of the geology hereabouts. The Silurian geology of the area was summarized and the main fossil localities listed in two early memoirs of the Geological Survey (De la Bêche, 1846; Phillips, 1848). In the late 19th century, Lapworth (1880a, 1880b) commented on the graptolite faunas of the 'Wenlock Shales' (= Coalbrookdale Formation of the type Wenlock and other areas) at Builth. He regarded most of these shales as being characterized by *Cyrtograptus linnarssoni*, but the *murchisoni* Zone was separated by him here, and elsewhere, for rocks at the base of the Wenlock succession.

At the turn of the 19th century the Builth district figured prominently in the benchmark biostratigraphical works of Elles (1900) and Wood (1900), in which graptolites were used for zonation of Wenlock and Ludlow strata in Wales and the Welsh Borderland. The sequence of graptolite faunas and the biozones identified by these two authors at Builth have been modified elsewhere subsequently. Nonetheless, this faunal sequence provides much of the basis for the present standard biozonal scheme for rocks of Wenlock (in particular) and Ludlow age in the Welsh Basin and other areas in the UK, and also regions abroad.

The Wenlock of the Builth district was studied especially by Elles (1900). She recognized in the 'Wenlock Shales' sequence there, in ascending order, six biozones: *murchisoni*, *riccartonensis*, *symmetricus*, *linnarssoni*, *rigidus* and *lundgreni*. Additionally, the *ludensis* Biozone, which is now included in the Wenlock, was also recognized in the Builth district by Wood (1900), but it was originally named the *vulgaris* Zone and taken by her and by Elles (1900) to mark the base of the Ludlow Series (for full discussion see Burrington site report and Holland *et al.*, 1969). Further revision of the nomenclature used by Elles (1900) has seen her *symmetricus* and *rigidus* biozones later being termed the *rigidus* and *ellesae* biozones, respectively (see Rickards, 1976). Of the remaining graptolite biozones that make up the standard British sequence, the evidence for the presence in the Builth area (see Bassett, 1993; Harris, 1987; Corfield *et al.*, 1992) of the basal Wenlock *centrifugus* Biozone (defined in the Howgill Fells; Rickards, 1976) and the Homerian *nassa* Biozone (type locality Thuringia; Jaeger, 1959) has yet to be published in full.

Following the studies at Builth of Elles and Wood, Straw (1937) mapped and described the Ludlow succession to the south of Builth Wells, then Jones (1947) carried out the first detailed regional geological survey and mapping of the Silurian rocks in the ground to the north and west of the town. Jones separated the Wenlock of the Builth area into upper and lower divisions, the boundary between the two coinciding with that dividing the *rigidus* and *linnarsoni* biozones. Sediments of the upper division differ from those of the lower in being made up of three major slumped horizons which interfinger with normal bedded units. The lower slumped horizon varies from 0–75 m in thickness, the middle one from 0–105 m and the upper one from 10–155 m. In undisturbed strata the total thickness of the Wenlock, including *ludensis* Biozone rocks (Bassett, 1974a), is some 630 m, with the lower division comprising about 155 m of this. In areas where slumped horizons are developed the total thickness can reach up to 900 m.

The Trecoed–Castle Crab site is one of five of Wenlock age from the Builth area in this review, Pen-cerig, Coed-mawr, Dulas Brook and the River Irfon being the other four.' All figure, to different degrees, in the accounts of Elles (1900), Wood (1900) and Jones (1947), and are important for showing various graptolite horizons in the area, which, following Elles' work, was considered the type area in the UK for the Wenlock graptolite succession. This notwithstanding, modern, up-to-date knowledge of the graptolite biostratigraphy and faunas of the Wenlock of the Builth district, together with revision of the lithostratigraphy of these rocks, is now much needed. Harris (1987) has written a thesis that includes such data, and the British

Geological Survey are now completing further work on the area. The significance attached to any of the five Builth sites of Wenlock age described in the present JNCC volume will doubtless be modified when the results of these studies are published; also new, important sites may emerge.

The Trecoed–Castle Crab section exposes strata of *centrifugus–murchisoni* Biozone age, at the base of the local Wenlock, and rocks at least up to and including those of the *rigidus* Biozone.

Description

The site is located at the foot of the Carneddau hills, very close to where the Silurian rests on the middle Ordovician of that range. The section itself combines roadside, track, stream and quarry exposures (Figure 4.42).

The Wenlock beds here dip at between 25–35° to the north-west. The local base of the series is formed by the *c.* 50 cm thick Acidaspis Limestone, which lies immediately above the Llandovery Pale Shales, these lying on top of arenites of the Llandovery Trecoed Formation

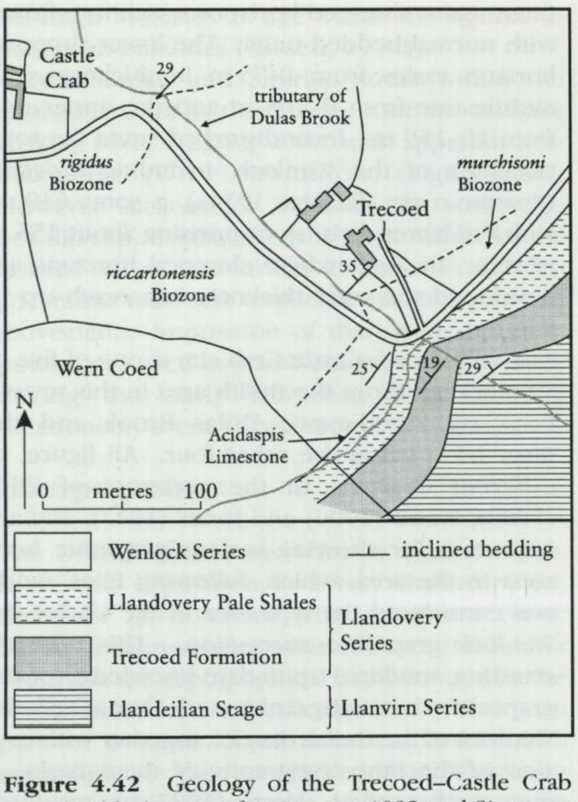


Figure 4.42 Geology of the Trecoed–Castle Crab area, Builth district (after Bassett, 1993 and Siveter *et al.*, 1989).

(Ziegler *et al.*, 1968b), the latter in turn resting unconformably on dark shales of Ordovician (Llandeilian) age. According to Jones (1947) there is an unconformity beneath the Acidaspis Limestone, but Hurst *et al.* (1978) found no evidence to support this conclusion. This so-called limestone is a calcareous, rubbly mudstone, and is exposed immediately south of Trecoed, where the road bends at a right-angle. It contains fragmentary shelly fossils, including brachiopods (mostly indeterminate) and cardiolid bivalves. Odontopleurid trilobite material from the Acidaspis Limestone has subsequently (Thomas in Siveter *et al.*, 1989) been referred to *Leonaspis*.

Elles (1900) and Wood (1900) both assigned the Acidaspis Limestone to the *murchisoni* Biozone, but the stratigraphically lower, basal Wenlock *centrifugus* Biozone had not been established at the time they were working. An equivocal, *centrifugus–murchisoni* Biozone age was given for this calcareous unit by Bassett (1993), based on graptolites listed by Elles from the adjacent stream and track at Trecoed. Conodont samples from the limestone yield *Pterospathodus amorphognathoides*, definitive of the *amorphognathoides* Biozone, which spans the Llandovery–Wenlock boundary (R.J. Aldridge, pers. comm.; Mabillard, 1981).

Above the Acidaspis Limestone, in the short track leading to Trecoed and the stream section as far as the bend in the road at Castle Crab, are grey-green mudstones of the 'Wenlock Shales'. Graptolites from this section indicate the *murchisoni* and *riccartonensis* biozones (Elles, 1990; Siveter *et al.*, 1989; Bassett, 1993), and brachiopods of the *Visbyella trewerna* Community have been recovered from the beginning of the section, 0.5 m above the limestone (Hurst *et al.*, 1978). The succeeding beds of the 'Wenlock Shales' of the small, old quarry to the east of Castle Crab have (Bassett, 1993) yielded a *rigidus* Biozone fauna, including *Cyrtograptus rigidus*, *Monograptus flemingii*, *Monograptus antennularius* and *Pristiograptus dubius*. The shelly fossils *Orbiculoidea*, *Chonetes*, *Cardiola* and *Orthoceras* have also been recorded (Elles, 1900) from this biozone, from another, small, but now infilled old quarry south-east of Castle Crab, though this faunal list needs updating. Strata of the *linnarssoni* Biozone (= *flexilis* Biozone of some authors) have been recognized farther downstream (Jones, 1947; Bassett, 1993).

Interpretation

The Trecoed–Castle Crab exposures of Wenlock rocks were of great utility in Elles' (1900) study, and the *murchisoni*, *riccartonensis* and *rigidus* (= *symmetricus*) biozones she identified there all have Builth as their type locality (Lapworth, 1880a, 1880b; Elles, 1900; Rickards, 1976).

During the whole of the Wenlock Epoch the Builth district was situated between shelf and basin, on the slope area (Bassett, 1974a; Hurst *et al.*, 1978; Holland, 1992). This intermediate position is reflected in both its sediments and fossils: dominantly graptolitic shales or calcareous mudstones, with occasional thin shelly horizons. These two main facies types are exemplified in the present site by, respectively, the bulk of the 'Wenlock Shales' and the Acidaspis Limestone.

The *Visbyella trewerna* Community is the most offshore of the benthic depth-related brachiopod communities identified in rocks of Wenlock age (Calef and Hancock, 1974; Hurst *et al.*, 1978), it being typical of low energy conditions.

Trecoed–Castle Crab is most closely linked to the other Builth Wenlock sites. In particular it has affinity with Pen-cerig, which is of about the same lower Wenlock age and which also has a mixed graptolite–trilobite fauna. Farther afield it ties in with the Buttington Brickworks site in the Long Mountain to the north-east, which provides an offshore, upper Llandovery to low Wenlock sequence. The Long Mountain district parallels that of Builth in being part of the slope area throughout Wenlock time.

Conclusions

Trecoed–Castle Crab is an important section for biostratigraphy in the Builth district – the historic type area for the graptolite biozones of the Wenlock Series. At this site there are at least three such biozones, which bracket 'Wenlock Shales' strata of early to mid-Wenlock age. The sediments (shales–mudstones) and fauna (dominantly graptolites) here are, overall, indicative of an offshore, deepish water environment, but the section also contains shelly (trilobite–brachiopod) horizons. Together with all other Builth Wenlock sites, it has palaeogeographical significance because it occupies an intermediate, slope position between shelf and basin. The site is used primarily for research purposes.

PEN-CERIG (SO 042 541)

Introduction

The Pen-cerig site is situated in the Builth district, an area that has attracted the attention of geologists from the early part of the 19th century, when it figured in the accounts of Murchison (1839, 1854) and in the early memoirs of the Geological Survey (De la Beche, 1846; Phillips, 1848). The area was also drawn attention to by Lapworth (1880a, b), in his papers on the stratigraphical distribution of graptolites. It was the turn of the 19th century work of Elles (1900) and Wood (1900), however, both of whom zoned the Silurian strata at Builth on the basis of graptolites, that led to this area being pre-eminent for the biostratigraphy of Wenlock age rocks. Elles investigated solely Wenlock strata and faunas, whilst Wood's study concentrated on the Ludlow of the area though it also embraced *ludensis* (= *vulgaris*) Biozone rocks and fossils, this biozone being now known to fall within the Wenlock (not Ludlow) Series. Since then, regional surveys of the Ludlow strata in the south of the district and Silurian strata north and west of Builth were accomplished, respectively, by Straw (1937) and by Jones (1947). More recently there has been a PhD thesis on the Builth Wenlock (Harris, 1987), and the British Geological Survey are presently finishing new research there. Both these studies may yield important data that will affect our understanding of the area, and our assessment of Pen-cerig and the other Builth Wenlock sites in this JNCC volume.

A fuller account of the contribution and significance of the above works to the geology of the Builth district, and to Wenlock biostratigraphy in general, is given in the introduction to the Trecoed–Castle Crab site, to which reference should be made. Pen-cerig has fossiliferous, *murchisoni* Biozone age strata that form the local base of the Wenlock in the district which, following the research of Elles, became the accepted type area in the UK for the Wenlock graptolite zones.

Description

The Pen-cerig site is located 3 km north of Builth Wells, at the western end of the lake of the same name. Uppermost Llandovery as well as basal Wenlock strata are included within the site boundary. Just below water level near the stream outlet, and at the stream outlet, the Llandovery is present; Wenlock strata are exposed immediately to the west (Elles, 1900; Jones, 1947).

The Llandovery beds just below water level comprise grey-blue 'fucoidal' mudstones; those near the point where the stream leaves the lake are massive green mudstones, with some harder horizons showing trace fossils, and also with two thin bentonite horizons.

The basal Wenlock consists of a 30–60 cm nodular, greenish, calcareous and ferruginous grit containing shelly debris. Above this are dark shales of the 'Wenlock Shales' (= Coalbrookdale Formation of the type Wenlock area) which dip north-west at about 30° and reportedly belong to the *murchisoni* Biozone. In addition to the eponymous biozone fossil, Elles (1900) listed another eight graptolite species from this horizon at Pen-cerig, including *Monograptus priodon*, *Monoclimacis vomerina*, and *Retiolites geinitzianus*. Some of these species records may not stand up to modern scrutiny and this faunal list as a whole needs revision. *R. geinitzianus*, for example, apparently does not anywhere range upwards into the *murchisoni* Biozone (Rickards, 1976); however it does occur in the *centrifugus* Biozone and if Elles' species identification is correct this may instead indicate an earlier Wenlock age for the shales at Pen-cerig (Bassett, 1974a). Shelly fossils, including an odontopleurid trilobite, orthoconic nautiloids, a cardiolid bivalve and small brachiopods are also recorded from these graptolite-bearing shales at this locality (Elles, 1900). Thomas (1981) has identified the odontopleurid from here, on the basis of over 1800 disarticulated exoskeletal parts, as *Odontopleura ovata*, this representing the earliest occurrence of the species.

Interpretation

Pen-cerig was one of four localities at Builth used by Elles (1900) in her account of the *murchisoni* Biozone, the others being Trecoed, an old quarry north of Llanelwedd Hall, and the River Wye. This zone was originally set up in this district by Lapworth (1880a, 1880b; Rickards, 1976).

Throughout the Wenlock the Builth area was in an intermediate, slope position between the shelf to the east and basin to the west (Bassett, 1974a; Hurst *et al.*, 1978; Holland, 1992). The mixed nature of the Wenlock sediments and fauna of this area – shales/carbonate muds, graptolites and shelly fossils – is testimony to this position, and the low Wenlock of Pen-cerig demonstrates clearly such combined aspects.

Pen-cerig is one of five sites of Wenlock age in the Builth area described in this volume, the others being Trecoed–Castle Crab, Coed-mawr, Dulas Brook and the River Irfon. Of these the Trecoed–Castle Crab section is most closely linked to Pen-cerig. Both display mixed facies and both have (upper Llandovery and) low Wenlock *murchisoni* Biozone rocks, though the Trecoed–Castle Crab section includes, in addition, at least *riccartonenis* and *rigidus* Biozone strata. Elles thought that the strata at Pen-cerig were lower in the *murchisoni* Biozone than the strata of this biozone at Trecoed, but this claim has not been independently confirmed. Also similar to Pen-cerig is the Buttington Brickworks site in the Long Mountain area, which has an offshore (upper Llandovery to) low Wenlock sequence. The Long Mountain, too, formed part of the palaeoslope in Wenlock times.

Conclusions

Pen-cerig is a very useful site for biostratigraphy in the Builth district, which historically has been taken as the type area for the sequence of Wenlock graptolite biozones. The site exposes shales belonging to a single, lower Wenlock graptolite biozone. These shales have also yielded trilobite and brachiopod material, thus demonstrating the mixed graptolitic–shelly nature of Wenlock age rocks at Builth. This mixed fauna is indicative of the intermediate palaeogeographical position of the Builth area during this time, between shelf and basin. The site is used mainly by research workers.

COED-MAWR (SO 045 548)

Introduction

Coed-mawr is located within the Builth district of central Wales. Murchison (1839, 1854) commented on this district in both the *Silurian System* and *Siluria*, and it also featured in the pioneering work for the Geological Survey of De la Bêche (1846) and Phillips (1848). Later in the 19th century Lapworth (1880a, b) made use of the graptolite fauna from the Wenlock of the Builth area in his classic work on the stratigraphical distribution of these fossils in the Lower Palaeozoic. This was followed by the very important studies of Elles (1900) and Wood (1900) who, respectively, determined the sequence of graptolite zones in the Wenlock and in the Ludlow rocks of the Builth area. Though the work of Wood was overwhelmingly concerned with the Ludlow, it also included what is now regarded as the last zone of the Wenlock Series, the *ludensis* (= *vulgaris*) Biozone. Subsequently, the Builth district attracted the attention of Straw (1937), who investigated Ludlow strata south of Builth Wells, and Jones (1947) who tackled the Silurian in the country north and west of the town. In more recent times Harris (1987) has re-investigated the Wenlock geology and graptolite faunas of the area, and currently these topics are also being researched anew by the British Geological Survey. When published, the conclusions of these two studies may have important consequences for presently-held ideas relating to the Silurian geology of Builth and thus for the significance attached in this JNCC volume to Coed-mawr, and to the four other Builth Wenlock sites.

More detailed comments on the work in the Builth area of Elles (1900) and Jones (1947) are given in the introduction to the Trecoed–Castle Crab site and this should be referred to also in connection with Coed-mawr. As a consequence of Elles' (1900) research, the Builth area came to be regarded as the type area in the UK for the Wenlock graptolite biozonal sequence. The Coed-mawr site is reported to contain rocks of the *rigidus* Biozone (= *symmetricus* Biozone of Elles) and the *linnarssoni* Biozone (= *flexilis* Biozone of some authors).

Description

This site is that of an old quarry, located 3.7 km north of Builth Wells where the minor road to Castle Crab meets the A470 to Llandrindod Wells.

The quarry was excavated across the strike of beds of Wenlock age that dip at about 25° to the north-west. These beds form part of the 'Wenlock Shales' (= Coalbrookdale Formation of the type Wenlock area), a unit for which, in this part of the Welsh Basin, a new formational name is needed. The relatively soft shales on the floor of the quarry belong to the *rigidus* Biozone; they yielded to Elles (1900) the eponymous biozone fossil together with *Pristiograptus dubius*. These are succeeded by harder, more calcareous horizons with carbonate concretions, which belong to the *linnarssoni* Biozone. Together with *Cyrtograptus linnarssoni*, Elles (1900) listed *Pristiograptus dubius* and *Monograptus flemingii* from this biozone at Coed-mawr.

Interpretation

Elles (1900) noted several localities in the Builth area that expose rocks of the *rigidus* Biozone, though her species occurrence table makes use for this biozone of just two: Coed-mawr and Castle Crab. Additionally, Coed-mawr is one of two localities used by Elles in her account of the *linnarssoni* Biozone, the other being the section on the road to Rhayader north-east of Builth Road Station. Lapworth (1880a, 1880b) originally used the *linnarssoni* Zone for the fauna comprising the bulk of the 'Wenlock Shales' at Builth, but Elles used it in a more restricted sense, for the fauna lying between the *rigidus* and the *ellesae* (= *rigidus* Zone *sensu* Elles) biozones (Rickards, 1976). Both the *rigidus* and the *linnarssoni* biozones, then, have the Builth region as their type locality (Lapworth, 1880a, 1880b; Elles, 1900; Rickards, 1976).

Throughout Wenlock times the Builth area was situated offshore, occupying an intermediate, slope position between the shelf to the east and the basin to the west (Bassett, 1974a; Hurst *et al.*, 1978; Holland, 1992). Most of the Wenlock sediments at Builth are deepish water shales and mudrocks, though the latter are often carbonate rich, and there are also occasional horizons with trilobites and brachiopods which give the faunal composition overall a mixed graptolitic–shelly aspect.

In the Wenlock of the Builth area there are five closely linked sites which in combination demonstrate the sequence of graptolite biozones and the distinctive nature of the facies in the region: Trecoed–Castle Crab, Pen-cerig, Coed-mawr, Dulas Brook and the River Irfon section. Stratigraphically, the strata at Coed-mawr fall in between those at the Trecoed–Castle Crab and those at Dulas Brook. To the north-east of the Builth region is the Long Mountain, which palaeogeographically also occupied a slope position during the Wenlock, and is networked to the Builth sites by the Buttington Brickworks and Trewern Brook sections. The Buttington site comprises slightly older rocks than those at Coed-mawr, but *linnarssoni* Biozone strata have been recorded (Elles, 1900) at Trewern Brook.

Conclusions

Coed-mawr is an important site for biostratigraphy in the Builth district, which from the turn of the 20th century has been regarded as the type area in the UK for the Wenlock graptolite biozonal sequence. The quarry exposes 'Wenlock Shales' strata belonging to two middle Wenlock graptolite biozones. The palaeoenvironmental setting is that of a deepish water, offshore, slope area between shelf and basin. Research workers, particularly those involved with graptolite biostratigraphy, will have most interest in the site.

DULAS BROOK (SO 042 552)

Introduction

Dulas Brook is located in the Builth district, central Wales. The geology of this district was commented on by Murchison (1839, 1854), and also De la Bêche (1846) and Phillips (1848) in their accounts for the Geological Survey. The area also featured in the work of Lapworth (1880a, 1880b), in the late 19th century, when he divided the Wenlock rocks here by use of different graptolite faunas. A more refined zoning of Wenlock age rocks at Builth and elsewhere was brought about through the graptolite-based research of Elles (1900), and at the same time Wood (1900) showed that the sequence of graptolites in the Ludlow here facilitated the subdivision of rocks of this age. The zonal schemes set up in these two historic papers largely provide the basis of the modern biostratigraphical framework for middle Silurian strata in the UK, and also many regions abroad. Subsequent to the work of Elles and Wood in the Builth area, the Ludlow geology to the south of Builth Wells was investigated by Straw (1937) and the Silurian north and west of the town by Jones (1947). Of late, the Wenlock geology and graptolite succession of Builth have been the subjects of a PhD thesis by Harris (1987) and the British Geological Survey are completing new work there, a century and a half after making their original summary remarks on the area. Both these studies may affect the interpretation and significance given to Dulas Brook, and the other four Builth Wenlock sites, in this JNCC volume, but as yet they are unpublished.

Further discussion on the Builth Silurian research outlined above is provided in the introduction to Trecoed–Castle Crab; this is also an adjunct to the present introduction to Dulas Brook. Elles (1900) and subsequent authors regarded the Builth district as the type area for the sequence of Wenlock graptolite zones. Strata and fossils of the *ellesae* Biozone (= *rigidus* Zone of Elles) are available at Dulas Brook.

Description

Dulas Brook flows in a south-westerly direction on the north-west side of the Carneddau hills to meet the River Wye at Builth Road. The site boundary takes in streamside exposures to the east of where the brook crosses the A483 road, at Brynsadwrn Bridge.

The beds here are hard calcareous shales that strike roughly parallel with the stream course and dip at about 30° to the north-west. They belong to the 'Wenlock Shales' (= Coalbrookdale Formation of the type Wenlock area), which in the Builth region is a unit that requires a new formational name. According to Elles (1900) the strata at Dulas Brook are very near the base of the *ellesae* Biozone and she identified six graptolite species from there: *Monoclimacis vomerina*, *Cyrtograptus ellesae* (= *Cyrtograptus rigidus* Tullberg of Elles), *Monograptus basilicus*, *Pristiograptus dubius*, *M. retroflexus*, and two varieties of *Monograptus flemingii*. However of these Rickards (1976) has more recently listed only *dubius*, *flemingii* and *ellesae* as being present in the *ellesae* Biozone, the most important single species for indication of this biozone being *ellesae*, which he gave as being confined to the *ellesae* and basal part of the succeeding *lundgreni* biozones.

Interpretation

Elles (1900) gave three localities where strata of the *ellesae* Biozone crop out. In addition to Dulas Brook there were two exposures in the Nant Prophwyd area about 2 km to the south-west. All these must be considered the type localities for the biozone, though Elles gave priority of description to Dulas Brook.

Palaeogeographically, during the Wenlock Epoch the Builth region was situated in an intermediate position, on the slope area between shelf and basin (Bassett, 1974a; Hurst *et al.*, 1978; Holland, 1992). The graptolitic shale facies of Dulas Brook reflects this offshore location, yet there are other horizons within the Builth Wenlock sequence that are more carbonate rich and contain shelly fossils, thus giving a mixed faunal aspect, overall, to this region at this time.

There are four other Wenlock sites in the Builth area discussed in this volume: Trecoed–Castle Crab, Pen-cerig, Coed-mawr and the River Irfon. All of these are closely linked in space and time, though Coed-mawr could be regarded as closest to Dulas Brook in terms of facies, as both are essentially graptolitic, whereas the other three sites all have shelly components. Coed-mawr exposes slightly older, *rigidus* Biozone (= *symmetricus* Biozone of Elles) and *linnarssoni* Biozone (= *flexilis* Biozone of some authors) strata, but the strata at Dulas Brook overlap in age with those of the River Irfon, both sites having *ellesae* Biozone rocks. The Long Mountain to the north-east of Builth is also situated on the slope area, and it contains two sites, Buttington Brickworks and Trewern Brook, which can be compared in broad terms to the Builth Wenlock sites including Dulas Brook. Trewern Brook, also, has *ellesae* Biozone strata.

Conclusions

Dulas Brook is an important biostratigraphical site in what has historically been taken as the type area for the Wenlock graptolite sequence – the Builth district. The 'Wenlock Shales' strata here belong to a single graptolite biozone of the upper middle part of the Wenlock Series. Palaeoenvironmentally, the site is set offshore, on the slope area of the Welsh Basin. It is, primarily, a research site for workers concerned with graptolite biostratigraphy.

RIVER IRFON (SO 033 515–SO 029 505)

Introduction

This section on the River Irfon is contained within its lowest reaches, where it joins the River Wye at Builth Wells in central Wales. Initial comments on the geology of the Builth area were provided by Murchison (1839, 1854), and by De la Bêche (1846) and Phillips (1848) in their work for the Geological Survey. Lapworth (1880a, b) also used the area in his investigations on the stratigraphical distribution of graptolites in the Lower Palaeozoic, the Wenlock rocks here being characterized by him into a lower *murchisoni* Zone and, for the most part, an upper *linnarssoni* Zone.

It was as a result of the studies of Elles (1900) and Wood (1900), however, on Silurian strata at Builth, that the area assumed great importance for the biostratigraphy of Wenlock (in particular) and Ludlow strata. These authors established there a sequence of graptolite zones that were then adopted as a standard for use elsewhere in the UK and also areas abroad. Some of these zones, in terms of nomenclature and extent, have been modified since, but in general they have held good. The most noteworthy amendment has been the subsequent inclusion of the *ludensis* Biozone (= *vulgaris* zone of Wood, and as used by Elles) in the Wenlock Series and not the Ludlow.

Straw (1937) next investigated Silurian rocks of the Builth area, producing a stratigraphical account and map of the Ludlow south of Builth Wells. Jones (1947) then described the Silurian geology north and west of the town, much of this work concerned with Wenlock rocks. More recently, a PhD thesis on the geology, biostratigraphy and graptolite fauna of the Builth Wenlock has been written by Harris (1987), and also the Geological Survey have been working there. These two studies, when published, may affect details of the interpretation and significance put forward in the present review of the Irfon site, and also those of the other four Builth Wenlock sites.

Additional comment on the research given in outline above, which has further relevance to the Irfon section, can be found in the introduction to the Trecoed–Castle Crab site. Since Elles' (1900) work Builth has been considered the type area for the Wenlock graptolite sequence. Wenlock rocks of the *ellesae* Biozone (= *rigidus* Zone of Elles) to *ludensis* Biozone are exposed in the Irfon site, though the site boundary continues, importantly, to include a Wenlock–Ludlow boundary section and also succeeding Ludlow strata.

Description

In the Builth Region the River Irfon flows from WSW to ENE and skirts the north-western fringe of Builth Wells, at which point it enters the River Wye. The site boundary includes both banks of the Irfon for about 1.25 km upstream from the suspension bridge situated near its confluence with the Wye. Most of the section is in Wenlock age rocks. Ludlow strata occur in the upper part of the section, on the eastern and southern parts of the meander loop approaching Caer-beris. Some horizons are available only in the river bed at times of very low water.

The Wenlock strata in the Irfon section, as in the Builth area as a whole, belong to the 'Wenlock Shales'. This lithostratigraphical unit approximates to the Coalbrookdale Formation of the type Wenlock area, but in the Builth district it is in need of a new formational name. The general dip of the beds in the section is to the south-east, but there is (J. Davies pers. comm.) a small, open anticline, plunging eastwards between the suspension bridge and the outfall of the Afon Chwefru. During a dry summer, Elles (1900) recorded *ellesae* Biozone rocks on the left bank from between the suspension bridge and Park Farm (now the Golf Club House). She listed six graptolites from this locality: *Cyrtograptus ellesae* (= *Cyrtograptus rigidus* Tullberg of Elles), *Pristiograptus dubius*, two varieties of *Monograptus flemingii*, *Monoclimacis vomerina vomerina* and *M. vomerina basilica*. Rickards (1976), more recently, gave only the first three of these species as being present in the *ellesae* Biozone. Slightly farther upstream and on the right bank, from opposite the Afon Chwefru which enters the Irfon at Park Bridge, Elles described *lundgreni* Biozone calcareous 'flags' and shales, the more calcareous horizons containing concretions up to a metre in diameter. The graptolites she recorded from here include *Cyrtograptus lundgreni*, *P. dubius*, and *M. flemingii* var. g; she also listed a *Cardiola* species, a phacopid trilobite and an orthocone. From a little farther upstream until the road bridge, on the left bank, strata of the *lundgreni* Biozone containing graptolites are discontinuously exposed.

Exposure is lacking for about 180 m upstream from the A483 road bridge. Approaching the large bend in the river *lundgreni* Biozone rocks, hard calcareous shales with concretions, and associated graptolites, occur again (Figure 4.43), as well as orthocones and a cardiolid bivalve. *P. dubius*, *M. flemingii*, *Monoclimacis flumendosae* and *Pristiograptus pseudodubius* are recorded from here (Bassett, 1993). Stratigraphically immediately above this latter exposure are hard, calcareous flaggy siltstones and limestones which form a prominent band of strata striking roughly NE–SW across the river (Figure 4.44). These beds were originally included by Elles (1900) and Wood (1900) within the Ludlow Series. Elles (1900) recorded only *P. dubius* and a phacopid from this more carbonate rich, pot-holed band, and did not assign the band to any graptolite horizon, though Wood (1900) said that *Monograptus ludensis* (= *Monograptus vulgaris*) probably occurs in it, and recently (Siveter *et al.*, 1989) a *ludensis* Biozone graptolite fauna has been recorded from it together with the dalmanitacean trilobite *Delops*. Additionally, about two metres of *nassa* Biozone strata have now been indicated as present in the Irfon section, between *lundgreni* and *ludensis* biozone rocks (Harris, 1987; Corfield *et al.*, 1992).

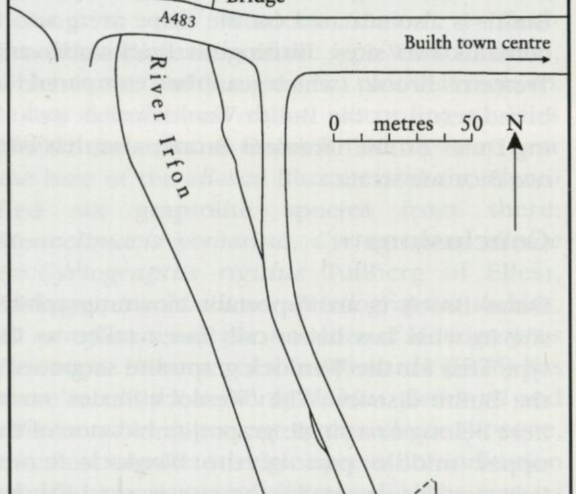


Figure 4.43 River Irfon, Builth Wells. Wenlock–Ludlow boundary section (after Siveter *et al.*, 1989 and Bassett, 1993).

Figure 4.44 River Irfon, Builth Wells. Right bank, looking south, about 180 m south of the bridge over the A483 road, showing *lundgreni* Biozone (foreground) and *ludensis* Biozone (river bluff, background) strata, Homerian stage, Wenlock Series. (Photo: Derek J. Siveter.)

The resistant, uppermost Wenlock *ludensis* Biozone beds are succeeded, at approximately the point where the road veers away from the river, by dark, laminated shales with a basal Ludlow *nilssoni* Biozone fauna. Graptolites from these shales include *Cucellograptus progenitor*, *Colonograptus colonus*, *Colonograptus compactus* and *P. dubius*, with *Saetograptus varians* and *Saetograptus leintwardinensis incipiens* entering in slightly younger beds (Bassett, 1993).

Interpretation

The River Irfon section figured prominently in the accounts of Elles (1900) and Wood (1900), and Jones (1947) devoted a separate section of his paper to it. The *ludensis* Biozone was originally defined by Wood (1900) at Builth together with the Long Mountain (Rickards, 1976).

The prominent, calcareous band of *ludensis* Biozone age forms part of the youngest of the three slump sheets identified in the upper Wenlock of the Builth region by Jones (1947). The same band is also the lateral equivalent on the palaeoslope, where the Builth area was positioned throughout the Wenlock (Bassett, 1974a; Hurst *et al.*, 1978; Holland, 1992), of the Much Wenlock Limestone Formation of the shelf area. The dominant faunal elements of the Irfon section are graptolites, but the occurrence also of shelly fossils gives a mixed aspect to the fauna, a characteristic shown by the Builth region during the Wenlock and one which reflects its intermediate palaeogeographical position. The trilobite *Delops* is also known from similar calcareous beds at the same stratigraphical level in north Wales, Powys (the Long Mountain), Cumbria, Scania, Gotland and the Prague Basin (Siveter *et al.*, 1989).

The River Irfon section has been used recently for isotopic analysis (Corfield *et al.*, 1992). Two $\delta^{13}C$ depletions have been recognized here, a lower one at the level of the *nassa* Biozone and a slightly higher, more gradual one in the *ludensis* Biozone that continues across the Wenlock–Ludlow boundary. The lower depletion, at least, may be a reflection in the carbon isotope record of the widespread graptolite extinction event that occurred at the end of *lundgreni* Biozone times.

Trecoed–Castle Crab, Pen-cerig, Coed-mawr and Dulas Brook are other Wenlock sites at Builth; together with the Irfon section they form a close network of sites in the area for rocks of this age. Stratigraphically, the Irfon section overlaps slightly with Dulas Brook, both having *ellesae* Biozone rocks, but of the five Builth Wenlock sites only the Irfon section has high Wenlock (and succeeding Ludlow) strata. Elsewhere, the Trewern Brook site in the Long Mountain district compares closely, in terms of stratigraphy, fauna, lithofacies and palaeogeographical position, with the Irfon section.

Conclusions

The River Irfon section is a very important site for biostratigraphy in the Builth district, the area where the succession of Wenlock graptolite zones was first demonstrated. It exposes 'Wenlock Shales' strata of middle to upper Wenlock age, which belong to four graptolite biozones, and their contact with overlying shales of the Ludlow Series. That part of the section with uppermost Wenlock to basal Ludlow strata and associated graptolite biozones is of particular importance. Shelly fossils also occur, the site demonstrating the rather mixed nature of the Wenlock age fauna at Builth, which was situated on the palaeoslope during this time. The section as a whole is used for research purposes; the Wenlock–Ludlow boundary part of it is visited by a much wider geological audience as it appears in field guides to the Welsh Basin. A high conservation value is attached to the site.

SAWDDE GORGE (SN 715 260–SN 728 245)

Introduction

The Sawdde is a tributary of the River Towy, entering it near Llangadog, midway between Llandeilo and Llandovery. The strata comprising the site form part of the Towy Anticline, one of the most important Lower Palaeozoic tectonic features of the Welsh Basin.

The rocks and fossils of the Sawdde and adjoining area have figured in the geological literature from the time of Murchison (1839) and Phillips (1848). Williams (1953) provided the first detailed, modern description and map of the (lower) Silurian rocks of the Sawdde River section, in his account of the geology of the Llandeilo (Sawdde–Llanarthney) district. He divided the Wenlock strata of this region into an 'Upper' and a 'Lower' Group. Potter and Price (1965) later included the Ludlow and Přídolí parts of the section in their study of rocks of this age between Llandovery and Llandeilo. Bassett (1974a) re-assessed the Wenlock strata and fauna of the Sawdde sequence, and at the same time Calef and Hancock (1974) used Wenlock brachiopod collections from here for community ecology work. Revision of the lithostratigraphy of the Wenlock sediments and the establishment of formational terms, together with further age refinement of the various units, was carried out by Hurst *et al.* (1978). The site has also figured in the field guides of Bassett (1982b) and Siveter *et al.* (1989).

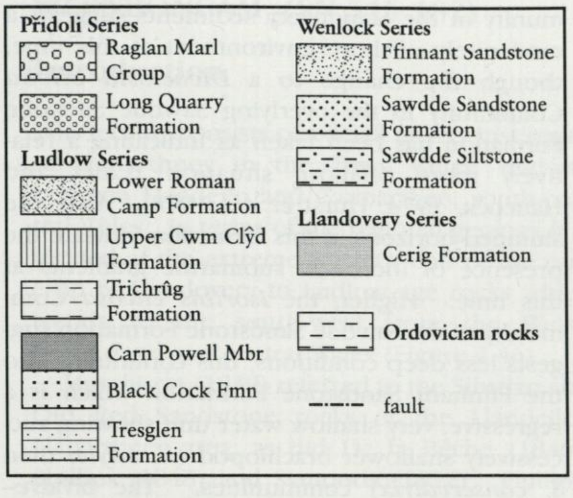
Movement on the Towy Anticline controlled lateral and vertical facies changes in this south-central area of the Welsh Basin during upper Ordovician and Silurian times. The Sawdde site is situated on the south-east flank of the anticline, the Silurian sediments here belonging essentially to those of the shelf, whereas those north-west of the fold axis are of a deeper water, basinal nature. The site provides almost continuous exposure of these shallower water sediments, which are not only of Wenlock age, but upper Llandovery, Ludlow and Přídolí too.

The deposits and fauna of the upper Silurian of the Sawdde are described in the Ludlow section of this volume.

Description

This site involves, in the main, exposures in the gorge of the River Sawdde, but in places it also takes in adjacent trackside and (in the Ludlow part of the sequence) quarry localities (Figure 4.45).

All Silurian rocks in the gorge dip steeply (up to 70°) to the south-east. The sequence begins with upper Llandovery (Telychian) strata – dark blue or grey mudstones and siltstones of the Cerig Formation – which rest unconformably on the Ordovician Llandeilo Flags (Williams, 1953; Bassett, 1974a, 1982b; Cocks *et al.*, 1984; Siveter *et al.*, 1989; Cocks *et al.*, 1992). At the beginning of the section, in the vicinity of Rhydsaint, the Llandovery is probably over 270 m thick. In the lower part of the Llandovery the mudstones contain thin bands of hard, blue, impure limestone, and in the upper part concretions. The mudstones (Williams, 1953) are poorly fossiliferous, yielding mainly occasional specimens of *Plectodonta* in the upper part of the succession. The limestones and some of the concretions are more richly fossiliferous, containing for example *Costistricklandia lirata*, *Plectodonta millinensis canastonensis* and *Clorinda globosa.* Other brachiopods recorded (Hurst *et al.*, 1978) from the upper Llandovery include forms of *Eocoelia* intermediate between *E. curtisi* and *E. sulcata*, and *Pholidostrophia* (*Mesopholidostrophia*) *salopiensis.*



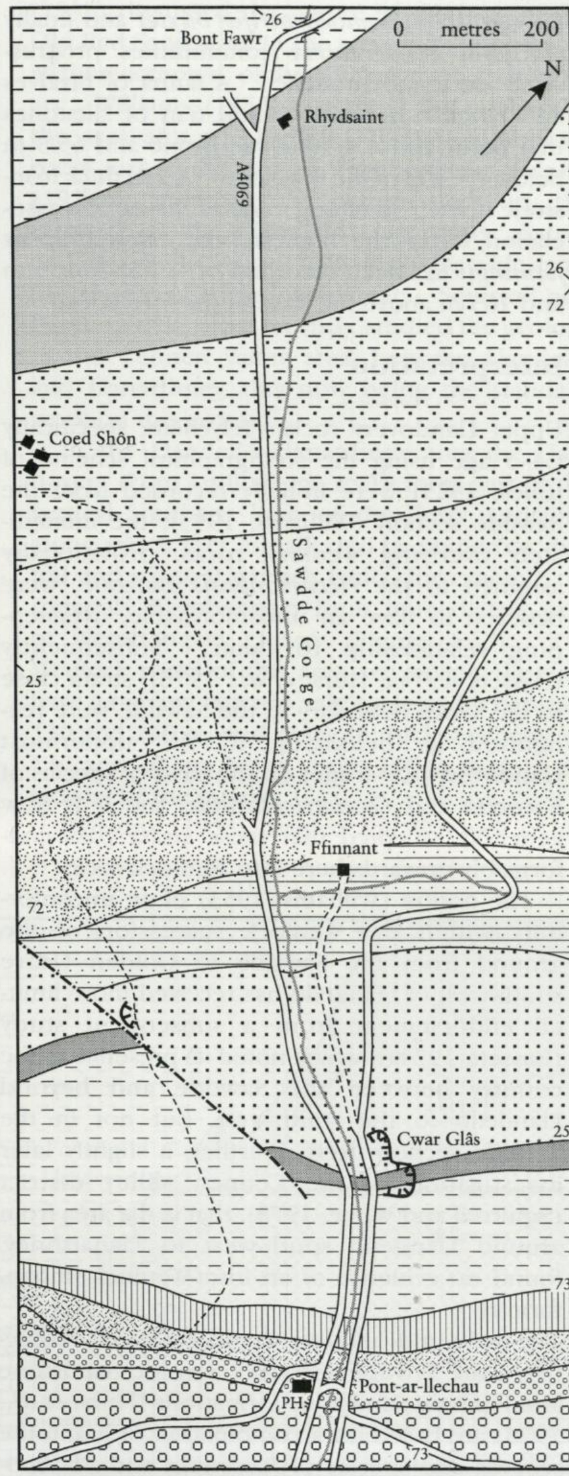


Figure 4.45 Geology of the Sawdde Gorge, Llandeilo–Llandovery area (after Bassett, 1982b and Siveter *et al.*, 1989).

The Wenlock succession and faunal aspects (Williams, 1953; Calef and Hancock, 1974; Hurst *et al.*, 1978; Bassett, 1982b; Figure 5.66), in ascending order, are:

Sawdde Siltstone Formation
325 m thick. Mainly grey siltstones and shales with slumped horizons in the upper half of the formation. Slurried beds occupy slumps near the base, which is taken at the bottom of a shale sequence 20 m below a 6 m siltstone with irregular bedding. Shales are dominant in the lower half and a shelly, 3 m thick mudstone occurs 134 m above the base. Brachiopods of the *Dicoelosia biloba* Community occur. *Calymene* and machaeridian plates are recorded from horizons in this formation. *Pristiograptus dubius* has been found 134 m above its base.

Sawdde Sandstone Formation
295 m thick. Interbedded olive, buff and grey sandstones, siltstones and shales. Parallel bedding with internal parallel lamination characterizes the sandstones, some of which are graded and some have basal groove and scour marks. There is no evidence of wave action. The formation contains an abundant shelly fauna, including brachiopods of the *Isorthis clivosa* Community, bivalves, gastropods, pelmatozoan columnals and tentaculitids.

Ffinnant Sandstone Formation
215 m thick. Grey to greenish-grey and buff, medium to coarse-grained micaceous sandstones interbedded with siltstones and shales. Many units display flaser and herring-bone cross-bedding. Brachiopods of the *Isorthis*

clivosa, then *Homoeospirifer baylei* and finally *Salopina conservatrix* communities progressively occur up sequence. A fauna of bivalves and *Lingula* is found within 6 m of siltstones that occur above a 10 m sandstone and 65.5 m below the top of the formation. A 1 m thick ironstone oolite containing a *Gypidula–Atrypa* association forms the highest bed. *Monograptus flemingii* has been recorded from horizons 5 m and 105 m above the base of the formation.

Interpretation

Upper Llandovery rocks (Telychian; specifically C4–5 age using the stratigraphical scheme of Jones, 1925) were initially recorded from the Sawdde section (Williams, 1953); the immediately overlying Wenlock rocks, provisionally assigned to the *riccartonensis* Biozone, were believed to have an unconformable, overstepping relationship to them. Subsequently (Bassett, 1974a; Hurst *et al.*, 1978), strata close to the series boundary in the Sawdde were recognized as belonging to the uppermost Llandovery (C5–6 age) on the basis of species of *Eocoelia* and *Costistricklandia*, and it is now generally accepted that these strata pass conformably upwards here into Wenlock rocks.

The notion (Williams, 1953) of an unconformity within the Wenlock succession of the ground from the Sawdde to Golden Grove south-west of Llandeilo has received more limited endorsement from a subsequent study (Bassett, 1974a), which noted its presence in the country between the Sawdde and beyond Llandeilo to the south-west, but not in the Sawdde section itself. Further, a slightly later investigation of the Cennen Valley district (Squirrell and White, 1978), that is the area from around Llandeilo south-west to Llanarthney, found no evidence of an intra-Wenlock unconformity.

The early, mid- and late Wenlock ages of, respectively, the Sawdde Siltstone, Sawdde Sandstone and Ffinnant Sandstone formations (Hurst *et al.*, 1978) are based on a combination of graptolite records and species of *Resserella* and *Pholidostrophia* (*Mesopholidostrophia*). The Sawdde district was situated north of the Pretannia landmass, which formed the southern margin of the Welsh Basin, throughout Wenlock times (Bassett, 1974a; Hurst *et al.*, 1978; Cope and Bassett, 1987; Holland, 1992).

The presence of a *Costistricklandia* Community in the Llandovery sediments suggests a moderately offshore environment at this time, though the change to a *Dicoelosia biloba* Community in the overlying Sawdde Siltstone Formation has been taken as indicating a relatively more offshore situation (Calef and Hancock, 1974, Hurst *et al.*, 1978). Also, the slumped horizons in this formation indicate the presence of increased submarine gradients at this time. Higher, the *Isorthis clivosa* Community of the Sawdde Sandstone Formation suggests less deep conditions, this continuing into the Ffinnant Sandstone Formation which is a regressive, very shallow water unit showing successively shallower brachiopod (*H. baylei* then *S. conservatrix*) communities. The bivalve–*Lingula* fauna two-thirds from the bottom of the Ffinnant Sandstone has been interpreted as a restricted lagoon assemblage, and the 10 m sandstone beneath this horizon as a barrier bar. Early Gorstian times saw a return to offshore, deeper water conditions, as evidenced by the reoccurrence of the *Dicoelosia biloba* Community in the Tresglen Formation.

The Wenlock strata of the Sawdde Gorge are, with respect to other Wenlock sites in this volume, most akin to those of Wernbongam Quarry near Llanarthney, but there they are of very limited vertical extent and they lie, according to most opinions, beneath unconformable Old Red Sandstone sediments of Přídolí age.

Conclusions

The Silurian rocks of this site are shelf deposits forming part of the south-east flank of the Towy Anticline, a Lower Palaeozoic structural feature that had significant effects on the pattern of sedimentation, both vertically and laterally, in this south-central part of the Welsh Basin. The site is a very useful one, providing near continuous exposure through, and the type section for, the Sawdde Siltstone, Sawdde Sandstone and Ffinnant Sandstone formations, which taken together span the whole of the Wenlock. In addition, exposure continues both up- and down-section to include rocks of upper Llandovery, Ludlow and Přídolí age. This makes the section as a whole one of the most complete for Silurian rocks anywhere in Wales. The nature of the Wenlock sediments combined with the sequence of brachiopod communities that they contain indicates a shallowing upwards sequence.

WERNBONGAM (SN 515 182)

Introduction

This locality consists of a small quarry just south of Llanarthney in the Towy Valley, midway between Llandeilo and Carmarthen, south-central Wales. In terms of the regional geology it is located at the extreme western end of the outcrop of Llandovery to Ludlow age rocks which trends to the south-west from the Welsh Borderland and central Wales (Figure 4.46).

Murchison (1839) referred to the Silurian and Old Red Sandstone rocks of the Llandeilo–Llanarthney area, as did De la Bêche (1846), Phillips (1848) and Symonds (1872). Phillips, for example, placed Llandovery ?, Wenlock and Ludlow strata in his Myddelton Series (see Squirrell and White, 1978), this series name being derived from Middleton Hall immediately east of Wernbongam. Cantrill and Thomas (in Strahan *et al.*, 1907) were the first to describe the geology of the area in detail and, with some additions (Price in Lawson *et al.*, 1956; Squirrell and White, 1978) the lithostratigraphical units they used for the Silurian are essentially those currently employed. Stamp (1923) and Straw (1930) discussed the nature of the base of the Old Red Sandstone in the area and the position, as then accepted, of the Siluro-Devonian boundary. Williams (1953) described the geology of the area around Llandeilo, including Wenlock rocks just to the east of Wernbongam. Bassett (1974a) subsequently commented on the Wenlock of the Llandeilo–Llanarthney district and the conclusions of Williams in his wide-ranging review of rocks of this age. Squirrell and White (1978), most recently, studied the geology of the Cennen Valley area, between Llandeilo and Llanarthney, this now being the standard work on this ground.

In the Llandeilo–Llanarthney area the Llandovery (?) to Ludlow age rocks form part of the vertical southern limb of the Towy Anticline, along which they are affected by numerous dextral and sinistral wrench faults, for example the (dextral) Wernbongam Fault immediately west of Wernbongam Quarry (Figure 4.47). The Wenlock rocks of this area are steeply dipping, have a narrow outcrop varying in width between 130 and 240 m, and range in thickness between 130 and 260 m, being about 150 m thick in the vicinity of the quarry.

Williams (1953) divided the Wenlock of the

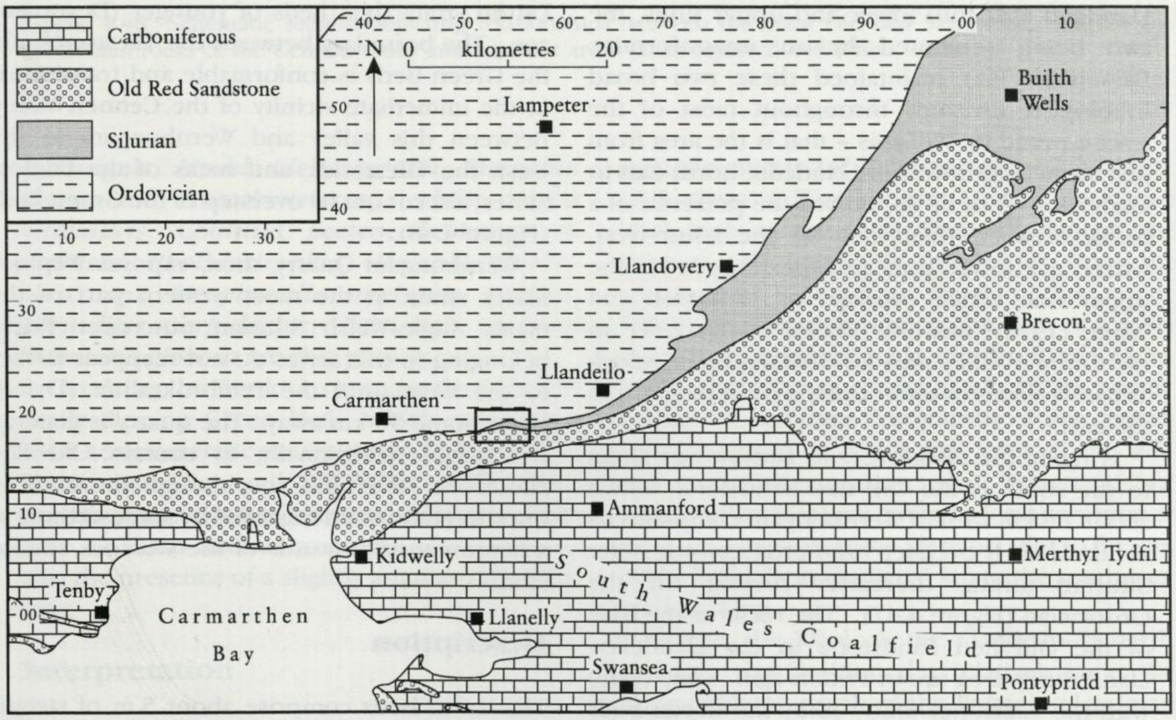


Figure 4.46 Geology of south-central Wales and location (rectangle, see Figure 4.47) of Wernbongam (after Squirrell and White, 1978).

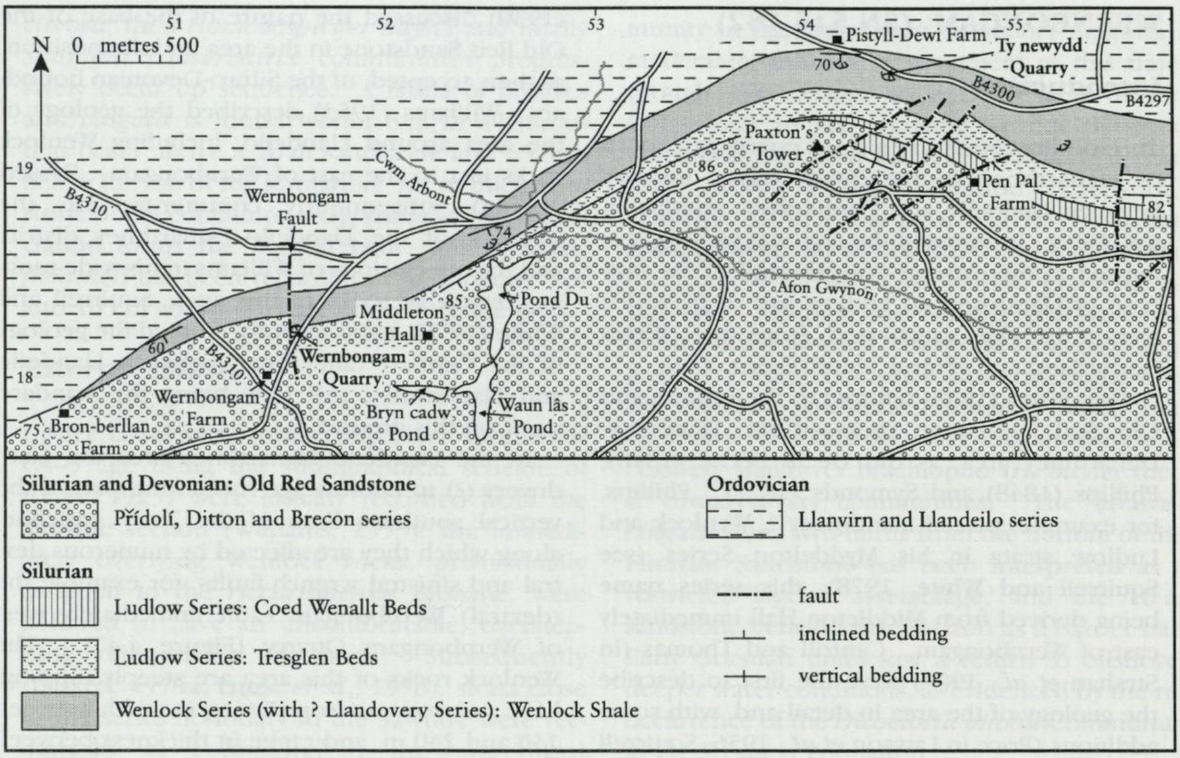


Figure 4.47 Geology of the area in the vicinity of Wernbongam Quarry, Llandeilo area (after Squirrell and White, 1978).

Llandeilo area into lower and upper units, the two being separated by an unconformity. Bassett (1974a) maintained these two broad lithological divisions throughout most of the tract covered by Williams – that is the area from just to the south-west of Llandeilo, north-east to Llangadog – but he supported the presence of a break between them only in the south-west, where the lower unit disappears beneath the upper one which overlaps it. Squirrell and White (1978), however, found no evidence in the Cennen Valley area for dividing the Wenlock as had Williams in the country a short distance to the east.

Fringing the Llandovery to Ludlow age strata to the south is the Old Red Sandstone, which about 1.5 km west of Wernbongam completes its south-westerly overstep onto progressively older Silurian strata, thereafter resting on the Ordovician (Figure 4.47). The rocks at the base of the Old Red Sandstone in the Llandeilo–Llanarthney area are of Přídolí age. They begin with the Tilestones followed by the Green Beds of the Raglan Marl Group, the succeeding Přídolí sediments passing conformably upwards into Ditton strata then beds of younger (Devonian) age. The boundary between the Tilestones and the Green Beds is conformable and transitional in the immediate vicinity of the Cennen Valley. Between this valley and Wernbongam to the west, the Tilestones, and rocks of the Ludlow Series, are cut out by overstep of the Green Beds (Figure 4.48).

Wernbongam Quarry, then, exposes Wenlock Series strata in the most western part of the main, Anglo-Welsh Silurian outcrop. Rocks belonging to this series do not reappear farther to the west until the Pembrokeshire (Dyfed) coast, some 50 km away. The quarry is generally thought, additionally, to contain Old Red Sandstone of Přídolí age, though the beds in question have been regarded by some authors as a continuation upwards of the Wenlock succession.

Description

The lower beds comprise about 5 m of steeply dipping Wenlock siltstones and silty mudstones. Common faunal elements are *Homoeospirifer*

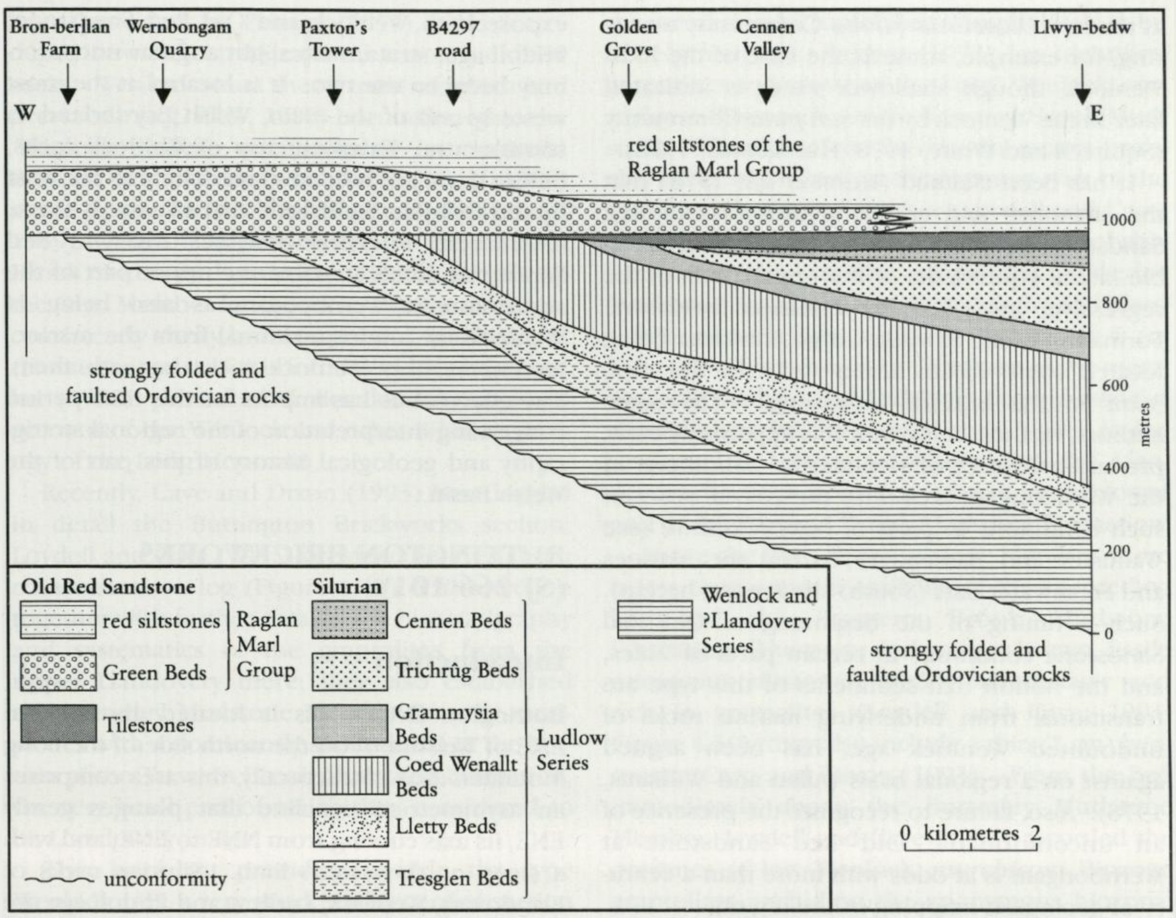


Figure 4.48 Schematic section depicting relationships between the basal Old Red Sandstone, Silurian and Ordovician rocks of the Cennen valley and adjacent areas (after Squirrell and White, 1978).

subinsignis, *Marklandella giraldi*, *Meristina obtusa* and *Protochonetes* sp., whilst *Atrypa reticularis*, *Coolinia pecten*, *Leptaena* cf. *depressa*, *Pholidostrophia* (*Mesopholidostrophia*) sp., *Strophonella euglypha gentilis*, *Cornulites serpularius*, *Favosites* sp. and *Poleumita globosa* are also present.

Overlying the Wenlock strata are the near vertically dipping Green Beds, which comprise a basal conglomeratic sandstone and siltstones of Přídolí age. Squirrell and White (1978) have described the contact between these two units here as sharp and uneven, and they detected also the presence of a slightly angular unconformity.

Interpretation

The Wenlock strata in the Llanarthney district that contain a *Salopina conservatrix* brachiopod community (of Calef and Hancock, 1974), as do those at Wernbongam Quarry, are from a level high in the local Wenlock, though the absence of identifiable graptolites from the whole of the Wenlock succession of the Cennen Valley area has prevented assignment of a more precise age for these rocks (Squirrell and White, 1978). One report (Hurst *et al.*, 1978), however, has the *Salopina* Community of this general area occurring at about the level of the *ellesae–lundgreni* boundary. Also, Bassett (1974a) claimed that Wenlock strata at least as young as the *linnarssoni* Biozone were present to the east in the Bethlehem Outlier, 3 km to the south-west of Llangadog.

During the Wenlock the Llandeilo–Llanarthney area was positioned a relatively short distance offshore, north of the Pretannia landmass (Bassett, 1974a; Hurst *et al.*, 1978; Holland, 1992). Moderately deep water was present here at times, a *Dicoelosia biloba* Community occurring, for example, towards the base of the local Wenlock, though shallower water is indicated later in the Wenlock by the *Salopina* Community (Squirrell and White, 1978; Hurst *et al.*, 1978).

It has been claimed (Hurst *et al.*, 1978) that the siltstones and conglomerates of Old Red Sandstone facies type at Wernbongam are possible lateral equivalents of the upper parts of the regressive, late Wenlock Ffinnant Sandstone Formation of the Sawdde Gorge, the latter being located some 25 km along strike to the east, 3 km to the SSE of Llangadog. The same authors, further, compared this apparently early, pre-Ludlow onset of non-marine conditions in the Wernbongam area with the coeval onset of such conditions in parts of Pembrokeshire (see Walmsley and Bassett, 1976; and the Marloes and Freshwater East (South) site reports herein). Such a timing of the beginning of Old Red Sandstone conditions in certain parts of Wales, and the notion that sediments of this type are transitional from underlying marine rocks of undoubted Wenlock age, has been argued against on a regional basis (Allen and Williams, 1978). Also, failure to recognize the presence of an unconformable Old Red Sandstone at Wernbongam is at odds with more than a century of geological mapping in the region.

The present site is most closely networked to that of the River Sawdde, which, however, shows a much fuller succession, having a sequence of beds representing the whole of the Wenlock, and strata belonging to the Llandovery, Ludlow and Přídolí series too. Wernbongam is located about midway along strike between the Pembrokeshire sites of Wenlock age and those representing this series in the Builth area (Trecoed–Castle Crab, Pen-cerig, Coed-mawr, Dulas Brook, River Irfon). It has much more in common with the Pembrokeshire localities, which are characterized by medium to coarse clastic facies and shelly faunas. The Builth sites, as a whole, have mainly fine, offshore muds together with rarer carbonate rich horizons, and the fauna there is largely graptolitic with some shelly component. The Pembrokeshire localities also, like Wernbongam, take in the Old Red Sandstone, whereas Builth lies to the north of the regional outcrop of this major division.

Conclusions

Wernbongam Quarry is generally considered to expose both Wenlock and Old Red Sandstone, Přídolí age, strata, with slight angular unconformity between the two. It is located at the most westerly end of the main, Welsh Borderland to south-central Wales outcrop of Wenlock rocks, before these are hidden immediately to the west by the Old Red Sandstone that oversteps them. A different interpretation has the Old Red Sandstone facies strata of the upper part of the succession at Wernbongam as also being of Wenlock age, and transitional from the marine, incontrovertibly Wenlock rocks beneath them. The quarry thus has import for this time period concerning interpretation of the regional stratigraphy and geological history of this part of the Welsh Basin.

BUTTINGTON BRICKWORKS (SJ 266 101)

Introduction

Buttington Brickworks is located about 4 km ENE of Welshpool on the north side of the Long Mountain area. Structurally, this area comprises an asymmetrical syncline that plunges gently ENE, its axis curving from NNE to ENE, and with a steep north-western limb. Silurian rocks of Llandovery, Wenlock, Ludlow and Přídolí age are successively exposed towards the axis of the syncline. The brickworks quarry site (Figure 3.16) comprises uppermost Llandovery through to lowermost Wenlock strata, the Llandovery part of which is described in detail in Chapter 3.

In the 19th century, both Murchison (1839, 1854) and Watts (1891) made observations on the geology of the Long Mountain area. The extreme north-west part of the area, encompassing that part around Buttington Brickworks, was later included by Wade (1911) in his coverage of the Ordovician and Silurian geology of the Welshpool district. In their classic biostratigraphical accounts of, respectively, the Wenlock and the Ludlow series, Elles (1900) and Wood (1900) made use of exposures in the Long Mountain for establishing the standard sequence of graptolite zones for rocks of this age. With reference to this graptolite zonal scheme, all the Wenlock and Ludlow rocks ('Salopian') of the area were then described by Das Gupta (1932), who also produced a geological map of the syncline.

In modern times, a short stratigraphical synopsis of the Silurian of the Long Mountain has been provided by Palmer (1970), who introduced new lithostratigraphical terms for these rocks. Wenlock strata there, most of which had previously (e.g. Elles, 1900) been referred to the 'Wenlock Shales', with *ludensis* (= *vulgaris*) Biozone strata having been placed (Wood, 1900) in the 'Lower Ludlow Shales' (see Holland *et al.*, 1969), were all assigned by him to the Trewern Brook Mudstone Formation. Palmer also set up the Glyn Member for the more calcareous, more consistently shelly horizon present in the upper (Homerian) part of this formation. Slightly later, he (1972) presented a detailed unpublished account of the Wenlock and other Silurian geology of the Long Mountain.

Recently, Cave and Dixon (1993) have logged in detail the Buttington Brickworks section. Loydell and Cave (1993) provided an even more comprehensive log (Figure 4.49) of the section together with further data on the biostratigraphy and systematics of the graptolites from the upper Llandovery there; they also established the Butterley Mudstone Member for silty mudstones with a dominantly shelly fauna at the bottom of the Trewern Brook Mudstone Formation, the very basal part of which they considered to be Llandovery in age.

This brick pit provides, outside the type Wenlock area, a very good, well-recorded section that straddles the Llandovery–Wenlock boundary.

Description

Palmer (1970) gave a thickness of 457–610 m for the Trewern Brook Mudstone Formation. The base of it is taken at the top of an 8 cm thick bentonite of the Llandovery (Telychian) Buttington Mudstone Formation (Cave and Dixon, 1993; Loydell and Cave, 1993). There then follow almost 9 m of tough, massive, olive- to buff-coloured calcareous and silty mudstones of the Butterley Mudstone Member. These mudstones are highly bioturbated and yield in their upper part a trilobite–brachiopod fauna, including (Cave and Dixon, 1993) *Dalmanites* sp., *Cyphoproetus binodosus*, *Sowerbyella* sp., *Glassia* sp. and *Skenidioides lewisii*. Graptolites sufficiently well preserved to allow identification are uncommon in the Butterley Mudstone Member. *Retiolites geinitzianus* was recorded from it by Cave and Dixon (1993), and a new, unnamed *Retiolites* species was noted by Loydell and Cave (1993) as the only species from the lower part of the member, which part they thought likely to be of Telychian age. Palmer (1972) has identified graptolites indicative of the basal Wenlock *centrifugus* Biozone from the Trewern Brook Mudstone Formation of the brickworks quarry, probably from an horizon in the topmost part of the Butterley Mudstone Member (Loydell and Cave, 1993). Thus the base of the Wenlock probably occurs in this section within the Butterley Mudstone Member. The recording by Mabillard (1981) of acritarchs of Acritarch Biozone 5 (of Hill, 1974) from 3 m above the base of the member, and the biozonal conodont *Pterospathodus amorphognathoides* from slightly higher in the section, led him to conclude that the Llandovery–Wenlock boundary occurs in the lower part of the Trewern Brook Mudstone Formation.

Above the Butterley Mudstone Member, there is less than a metre available of the succeeding beds of the Trewern Brook Mudstone Formation. These are darker, grey-brown, fissile calcareous siltstones, largely hemipelagic and rich in graptolites (Loydell and Cave, 1993; Figure 4.50); they also include a thin (1 cm) bentonite (Cave and Dixon, 1993). From the bed immediately above the Butterley Mudstone Member, Loydell and Cave (1993) recorded the presence of low Wenlock, *murchisoni* Biozone graptolites, including the eponymous biozonal species. Palmer (1972), similarly, identified this biozone in the quarry (Cave and Dixon, 1993). Cocks and Rickards (1969) recognized three graptolite horizons, representing a low Wenlock *centrifugus–murchisoni–riccartonensis* faunal succession, in the lower part of the Trewern Brook Mudstone Formation of the quarry. The lowest horizon was characterized by *R. geinitzianus*, *Monograptus priodon*, *Monoclimacis vomerina basilica*, *Cyrtograptus centrifugus* and *Pristiograptus* sp., the middle level by *Cyrtograptus murchisoni* and *Monograptus priodon*, and the upper one by *Monograptus riccartonensis*.

Interpretation

The Butterley Mudstone Formation, with its bioturbated beds and brachiopod–trilobite fauna, was deposited under oxic bottom conditions (Cave and Dixon, 1963). The overlying, darker, graptolite-rich beds probably represent a change to more anoxic bottom conditions. During Wenlock times the Long Mountain area was positioned on the palaeoslope (Bassett, 1974a; Hurst

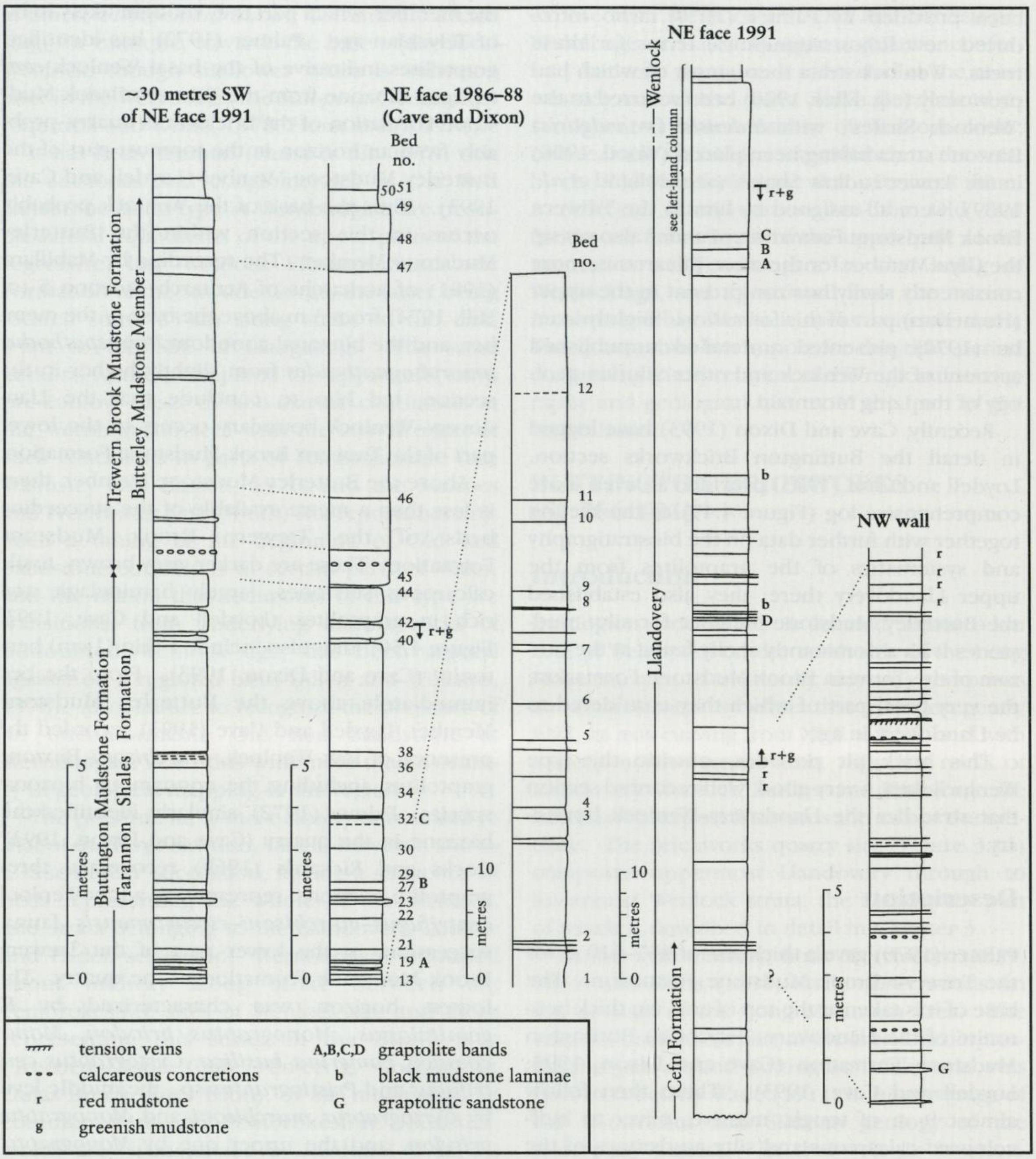


Figure 4.49 Buttington Brickworks, Long Mountain area. Log through the upper Llandovery (Telychian) and lower Wenlock (Sheinwoodian) strata (after Loydell and Cave, 1993).

et al., 1978; Holland, 1992). This intermediate palaeogeographical location is reflected in the sediments and fauna of the region: carbonate muds and shales with a dominantly graptolitic fauna, but with shelly horizons also. Hurst *et al.* (1978) recorded the *Dicoelosia* Community followed by the *Visbyella trewerna* Community from the Wenlock of the Long Mountain, both brachiopod communities being typical of deep water clastic locations. To the east of this area were the carbonates and shallow water faunas of the Midland Platform, and to the west turbidites, dominantly graptolitic, of the deeper parts of the Welsh Basin.

Buttington Brickworks links closely with the nearby, stratigraphically younger, Trewern Brook

Figure 4.50 Buttington Brickworks, Long Mountain area. Fissile, graptolite-rich calcareous rocks of the Trewern Brook Mudstone Formation, Wenlock Series. (Photo: Derek J. Siveter.)

site, the two combining to provide almost complete coverage of Wenlock age strata in the Long Mountain. Within the site network it is also close to the Banwy River locality just to the west of Welshpool, which, similarly, exposes a Llandovery–Wenlock boundary sequence. Trecoed–Castle Crab in the Builth region to the south-west is again broadly comparable, providing a Llandovery to lower Wenlock section, the Wenlock part yielding graptolites plus shelly fossils and having a palaeoslope setting. The Llandovery–Wenlock boundary stratotype section at Hughley Brook in the type Wenlock area is also broadly comparable in terms of stratigraphy, though it was situated on the margin of the Midland Platform and in consequence it has a less graptolitic sequence than that of the brickworks site.

Conclusions

Buttington Brickworks exposes a stratigraphically important Llandovery–Wenlock boundary section in which, in addition to five graptolite biozones of the upper Llandovery Telychian Stage, the three lowest graptolite biozones of the lower Wenlock Sheinwoodian Stage have been recorded. The section also contains shelly fossils (trilobites and brachiopods) and microfossils (acritarchs and conodonts, at least), the latter helping to indicate the base of the Wenlock Series. It is the type locality for the basal Wenlock Butterley Mudstone Member of the Trewern Brook Mudstone Formation. The mudstones and shales of this formation were deposited offshore on the palaeoslope, between shelf and basinal areas. The quarry is actively worked outside the present GCR site boundary, and is due to work out the whole of the Buttington Brickworks Formation and the overlying Butterly Mudstone Member, but a purposely designated trench at the north-east end of the workings will show the Llandovery and Wenlock boundary sequence, with proper allowance for its longer term conservation.

TREWERN BROOK (SJ 304 116–SJ 310 126)

Introduction

The Trewern Brook section is located some 10 km ENE of Welshpool on the north side of the Long Mountain area. This area is made up of Silurian strata folded into an asymmetrical syncline, with Llandovery rocks on its outer margins, then Wenlock, Ludlow and Přídolí deposits being in turn exposed towards its central, topographically highest part.

Murchison (1836, 1854) and, later in the 19th century, Watts (1891), were two early commentators on the Silurian geology of the Long Mountain. The graptolite faunas in various Long Mountain sections were subsequently studied in detail by Elles (1900) and Wood (1900) as part of their investigations into the biostratigraphy and systematics of this fossil group in Wenlock and Ludlow rocks of Wales and the Welsh Borderland. These were cardinal studies in the establishment of a biozonal scheme based on graptolites for rocks of this age, this scheme, with relatively minor amendments, remaining in current use. The most notable change has been, following the findings of Holland *et al.* (1969), the acceptance of the *ludensis* Biozone (= *vulgaris* Zone of Wood, and as used by Elles) within the Wenlock and not the Ludlow Series. The *ludensis* Biozone fauna was originally defined by Wood (1900) on the basis of the graptolite faunal sequence of the Long Mountain and Builth districts. After Elles' and Wood's studies, a geological map of the Long Mountain Syncline and description of all the Wenlock and Ludlow of the area was provided by Das Gupta (1932).

Modern revision of the Long Mountain was carried out by Palmer (1970, 1972), who presented a thesis and a stratigraphical synthesis of the Silurian of the area including a new lithostratigraphy. Rocks of Wenlock age, formerly assigned (Elles, 1900; Wood, 1900; Das Gupta, 1932) to the 'Wenlock Shales' and in part to the 'Lower Ludlow Shales', were in their entirety referred by Palmer to the Trewern Brook Mudstone Formation. A distinct horizon at the top of this formation, more calcareous and shelly in character, was distinguished by him as the Glyn Member. At the same time Cocks and Rickards (1969), in co-operation with Palmer, recognized the *centrifugus*, *murchisoni* and *riccartonensis* graptolite biozones of the lower Wenlock in the Buttington Brickworks section of the Long Mountain.

Cave and Dixon (1993) and Loydell and Cave (1993) have recorded in detail, at Buttington, the upper Llandovery to lowermost Wenlock part of the Long Mountain sequence, the latter authors establishing the thin, Butterley Mudstone Member at the base of the Trewern Brook Mudstone Formation. The bottom part of this member was considered to be of latest Llandovery age.

Trewern Brook is the type locality for the mudstone formation of the same name. It exposes, upstream, Trewern Brook Mudstone Formation (Wenlock) strata that are at least as old as *linnarssoni* Biozone age; downstream, it cuts through rocks of this formation that belong to, at least, the succeeding *ellesae*, *lundgreni* and *ludensis* biozones; thereafter, tributaries entering it from the south cross ground underlain by the Long Mountain Siltstone Formation of the Ludlow Series. The brook makes available the most complete section through Wenlock strata in the Long Mountain Syncline.

Description

Elles (1900), Wood (1900) and Das Gupta (1932) all, variously, described the Trewern Brook Mudstone Formation and associated graptolite sequence of Trewern Brook. However there is no modern published account of the section. The description that follows thus relies on data given by these three authors, which require revision, particularly the graptolite faunal lists. Das Gupta (1932), for instance, claimed that the Wenlock sequence of the northern part of the Long Mountain area starts with rocks of *linnarssoni* Biozone age, whereas, in the Buttington area, strata belonging to earlier Wenlock biozones are now known to be present (see above). The Trewern Brook section, only 6 km to the east of Buttington on the same, northern limb of the syncline, was reported by both Elles (1900) and Das Gupta (1932) to begin with *linnarssoni* Biozone strata.

A side-stream that enters Trewern Brook from the north, 200 m south of Gate Farm (SJ 310 127), exposes beds of Llandovery age. At the confluence of brook and side-stream are hard, calcareous and flaggy mudstones with fragmentary trilobites and brachiopods but no graptolites. *Calymene*, *Dalmanites*, *Cheirurus*, *Encrinurus*, *Acidaspis*, orthid and rhynchonellid brachiopods and *Orthoceras* remains have been recorded from this locality (Das Gupta, 1932). The beds here, and throughout much of the brook section, dip fairly steeply to the SSE at about 40–45°. *C. linnarssoni* Biozone strata follow a short distance downstream; these have yielded at least six species of graptolites, most importantly the eponymous biozonal species (Elles, 1900; Das Gupta, 1932).

The *ellesae* Biozone (= *rigidus* Zone of Elles) is represented in the section by beds located 20 to 200 m north of where the railway crosses the brook. From this biozone Elles (1900) noted four graptolite species, and she recognized it on the basis of *Monograptus retroflexus*; she failed to identify from here the key biozonal index species *Cyrtograptus ellesae* Gortani (= *Cyrtograptus rigidus* Tullberg of Elles), though Das Gupta did so, together with eight other graptolite species. The fact that *M. retroflexus* occurs, according to Rickards (1976), only as a component of the *rigidus* Biozone (= *symmetricus* Zone of Elles) fauna, merely serves to emphasize the need for systematic revision of the graptolites from this section.

Graptolite-bearing horizons of the *lundgreni* Biozone have been recorded in particular from that part of the brook immediately south of the railway bridge, where the brook flows only slightly across the ENE strike of the beds and its course parallels the line of the railway. Elles (1900) listed ten graptolite species from brook exposures belonging to this biozone, and Das Gupta (1932) eight, both authors noting amongst these the occurrence of *Cyrtograptus lundgreni*. Calcareous concretions are present, being numerous in horizons low in the biozone. Shells (often fragmentary) occur, for example cardiolids, and from horizons high in the biozone species of *Dalmanites*, *Atrypa*, *Leptaena*, *Meristina*, and orthids have been recorded (Das Gupta, 1932).

Strata of the *ludensis* Biozone are present in Trewern Brook southwards from about where the tributary from Glyn Common enters into it (SJ 303 116). It is at about this point also that the shelly calcareous mudstones of the lenticular Glyn Member occur. In the northerly flowing tributary that joins the brook from Ding Wood to the south, beds of the overlying Ludlow Siltstone Formation come in. A depleted graptolite fauna composed exclusively of *Monograptus ludensis* Murchison (= *Monograptus vulgaris* Wood) and *Pristiograptus dubius* is recorded from the top Wenlock *ludensis* Biozone rocks (Wood, 1900; Das Gupta, 1932). Trilobites, *Cardiola*, *Leptaena* and *Orthoceras* have also been noted (Das Gupta, 1932).

The *nassa* Biozone (of Jaeger, 1959), which is positioned between the *lundgreni* and *ludensis* biozones, has also been recognized in the Long Mountain, by Palmer (in Hurst *et al.*, 1978), though without reference to any specific locality. Palmer (in the same publication) gave the thickness of the strata belonging to each of the graptolite biozones in the Long Mountain as follows: *centrifugus*, 10 m; *murchisoni*, 5–10 m; *riccartonensis*, ?15 m; *rigidus*, ?42 m; *linnarssoni*, ?50 m; *ellesae*, 99 m; *lundgreni*, 298 m; *nassa*, 15 m; *ludensis*, 61 m. These thicknesses, for post-*rigidus* biozone beds at least, can thus be taken as approximate for the Trewern Brook section also.

The Wenlock of Trewern Brook stands as the type locality for certain taxa, for example *M. vulgaris* Wood, 1900, and *Visbyella trewerna* Bassett, 1972.

Interpretation

Throughout the Wenlock the Long Mountain district was located between shelf and basin, on the palaeoslope (Bassett, 1974a; Hurst *et al.*, 1978; Holland, 1992), with relatively deep water, soft, muddy conditions prevailing. Faunally, this palaeogeographical location is typified in the main by graptolite plankton, but a shelly benthic component is also present. The Trewern Brook Mudstone Formation of Trewern Brook is characterized by the *Visbyella trewerna* brachiopod community, which occupies the most offshore part of the Wenlock shelly benthic spectrum (Hurst *et al.*, 1978). The lime-rich and shelly Glyn Member represents on this part of the slope area a reflection of the increased carbonate build-up during late Wenlock times that gave rise to the Much Wenlock Limestone Formation on the shelf.

Trewern Brook is linked closely to the stratigraphically older, Buttington Brickworks site, the two providing nearly full coverage of Wenlock age rocks in the Long Mountain. It is also networked to the River Irfon site in the Builth Region, which has a middle Wenlock through to Ludlow sequence and a comparable fauna, lithostratigraphy and palaeoslope setting.

Conclusions

Trewern Brook is a site of considerable significance for the palaeontology, stratigraphy, and palaeogeography of the Wenlock of the Long Mountain Syncline. It represents the best section of Wenlock age in the area. It gives its name to the Trewern Brook Mudstone Formation, which spans the whole of the Wenlock Series here, and it also contains the type section of the more calcareous, shelly, upper Wenlock Glyn Member of this formation. Historically it has been an important section for demonstrating the succession of many of the Wenlock graptolite biozones; in particular, the latest, *ludensis* Biozone was defined in part on the basis of the fauna from here. During Wenlock times the Long Mountain area was positioned offshore, forming part of the palaeoslope. It thus occupied an intermediate position between shelf and basin, and in consequence has a mixed graptolite–shelly fauna. Trewern Brook is the type locality for Wenlock graptolite and brachiopod species.

BANWY RIVER (SJ 1330 1042–SJ 1340 1011)

POTENTIAL GCR SITE

Introduction

This site is located 3.5 km south-west of Meifod and 10 km WNW of Welshpool, Powys. The Meifod area was visited by Sedgwick in the 1830s and 1840s, sometimes together with Salter. In the mid-19th century, the Lower Palaeozoic strata hereabouts provided material for the working collections of the latter author and also those of M'Coy. It was not until King's (1928) account of the regional geology of the area that the upper Ordovician and lower Silurian rocks there were described in any detail. The Silurian ('Valentian' and 'Salopian') succession was divided by him into five lithostratigraphical divisions which, from oldest to youngest, he referred to as the V1–3, the VS passage beds and the banded mudstones units.

The Llandovery–Wenlock sequence of the Banwy River section (Figures 3.35, 3.36) has very recently been re-investigated by Loydell and Cave (1996). Fairly continuous exposure is present through the uppermost part of the Blue Silty Mudstones and the whole of the Tarannon Shales Formation (respectively, the V2 and V3 divisions of King, 1928), both of late Llandovery age, and into the lower part of the Nant-ysgollon Shales Formation (mainly 'Salopian' of King, 1928), of latest Llandovery to early Wenlock age. In terms of graptolites, of which over 8000 were collected by Loydell and Cave, these rock units here span the *turriculatus* to *riccartonensis* biozones. The base of the Wenlock, taken to be the base of the *centrifugus* Biozone, occurs near the base of the Nant-ysgollon Shales Formation, within the newly established (Loydell and Cave, 1996) Banwy Mudstone Member (the VS division of King, 1928).

The graptolite succession Loydell and Cave (1996) identified at this site is a more refined one than those hitherto recognized for rocks of a similar age elsewhere in Britain. This enables fine correlation of the upper Llandovery–lower Wenlock strata of this mid-Wales region with sections in mainland Europe, for example ones in Bohemia and Scandinavia.

Description and interpretation of the Llandovery rocks and fossils of the Banwy River site are given in Chapter 3 of this volume.

Description

The Banwy Member is 36 m thick and has a sharp base. It comprises mostly bioturbated, hard, medium grey silty mudstones, with some thin (< 30 cm) sandstones and layers (< 10 cm thick) having bundles of dark grey graptolitic laminae. Certain horizons show calcareous concretions, which in general are less than 20 cm in diameter, though at the top of the unit, drawn at level C (Figures 3.35, 3.36), they are a metre or more across. The top boundary of the member was somewhat arbitrarily placed, as the upper part of the unit is gradational lithologically into the overlying part of the Nant-ysgollon Shales Formation. From two metres below this boundary (in the *centrifugus* Biozone), to up to 14 m above it (in the *murchisoni* Biozone), burrowed horizons give way to hemipelagites. A thin bentonite layer occurs near the top of the member. The Nant-ysgollon Shales Formation as a whole is dominated by greyish black graptolitic laminated hemipelagites, which are often interbedded with thin bands of paler grey turbiditic mudstone.

Except for the top metre, the upper 20 m of the Banwy Member are made up of disturbed beds. These beds show no internal disruption but at their base they lie with marked discordance on the strata below, this discordant relationship being taken to represent a slide plane (Loydell and Cave, 1996). The rocks both immediately above and beneath this plane belong to the latest Llandovery *insectus* Biozone, so that probably only a small thickness of strata has been lost due to movement along it.

The Llandovery–Wenlock boundary was presumed (Loydell and Cave, 1996) to lie in the unfossiliferous 3 m interval of beds between the strata determined as belonging to the *insectus* and the *centrifugus* biozones. The incoming of *C. centrifugus* into the faunal succession is

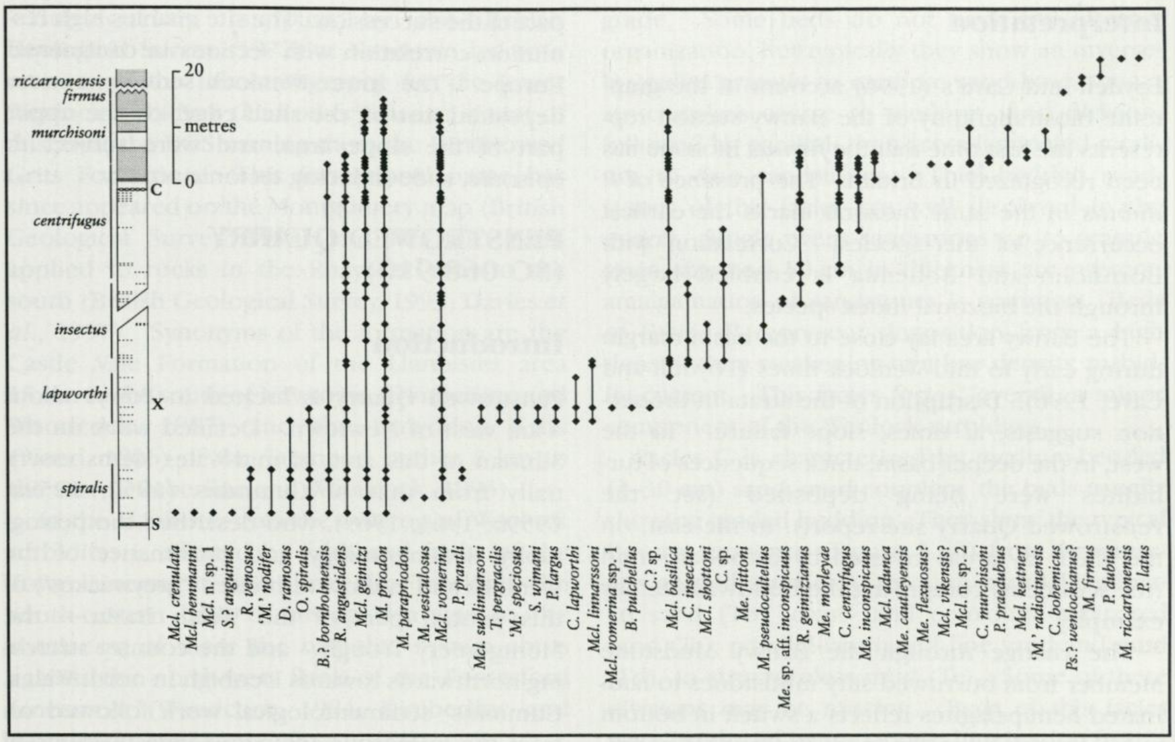


Figure 4.51 Range chart of graptolite species from the Banwy River section, Meifod area, Powys, from the *spiralis* Biozone (Telychian) to the *riccartonensis* Biozone (Sheinwoodian). The gap in the section indicates the position of a slide (within the *insectus* Biozone) (after Loydell and Cave, 1996).

important in differentiating basal Wenlock from upper Telychian strata, as is *Mediograptus inconspicuus*, which appears about midway through the *centrifugus* Biozone and continues into the *murchisoni* Biozone (Figure 4.51). *Monoclimacis shottoni* is apparently restricted to the lower three-quarters of the *centrifugus* Biozone.

The lowest *murchisoni* Biozone faunas are similar to those of the *centrifugus* Biozone but *C. murchisoni* and two monoclimacid species make their appearance. A change takes place within the first metre of the *murchisoni* Biozone, *Monoclimacis adunca* occurring abundantly and overlapping in range with *'Monograptus' radotinensis* that comes in slightly higher. Both the latter species are absent from the upper part of the biozone, which in comparison with the lower part is characterized also by the absence of *Retiolites* and *C. centrifugus*, the rarity of *Mediograptus* and *Monoclimacis geinitzi*, and the relative abundance of *Monoclimacis kettneri*. Towards the top of the biozone, *Monograptus sensu stricto* becomes the dominant form rather than *Monoclimacis*, and graptolite diversity decreases.

The base of the *firmus* Biozone is marked by the incoming of the eponymous species, *Monograptus firmus*, with *Pristiograptus dubius*, a very long ranging species, being the only other new element in this biozone.

The highest graptolitic horizons of the Banwy section occur some 110 m above the base of the *firmus* Biozone. They yield a graptolite fauna that remains to be investigated fully but which presently indicates a mid-late Sheinwoodian age. The base of the *riccartonensis* Biozone is thought to lie within 15 m above the base of the *firmus* Biozone and the former biozone as a whole is probably represented in the section by a substantial thickness of rocks.

Small brachiopods are dispersed throughout the sequence; they occur particularly in the Banwy Member. The upper part of the *murchisoni* Biozone has an horizon containing decalcified crinoids. Otherwise, shelly fossils are rare. Chitinozoans and acritarchs are known, but await detailed assessment.

Interpretation

Loydell and Cave's (1996) account of the graptolite biostratigraphy of the Banwy section represents the first time that the *firmus* Biozone has been recognized in Britain. The presence of *P. dubius* in the same biozone marks the earliest occurrence of this species. Correlation with Bornholm and Bohemia is enabled largely through the biozonal index species.

The Banwy area lay close to the basin margin during early to mid-Wenlock times (Loydell and Cave, 1996). Disruption of the strata in the section suggests, at times, slope failure. To the west, in the deeper basin, thick sequences of turbidites were being deposited (see the Penstrowed Quarry site report); to the east, on the shelf, lay areas covered by carbonate mud (the sediments comprising the Buildwas site, for example).

The change through the Banwy Mudstone Member from burrowed silty mudstones to laminated hemipelagites reflects a switch in bottom water oxicity from the dominantly oxic conditions under which the Tarannon Shales were formed to the anoxic conditions that prevailed during the deposition of the Nant-ysgollon Shales.

Sites in the GCR network with late Llandovery –early/mid-Wenlock age rocks, which may variously be linked to the Banwy river site, include Buttington Brickworks in the nearby Long Mountain; Trecoed–Castle Crab in the Builth area; the Sawdde Gorge section, south-central Wales; and most importantly Hughley Brook in the type Wenlock area. Chitinozoans and acritarchs, possibly bentonite horizons also, may enable correlation of the Banwy section with that at Hughley Brook (Loydell and Cave, 1996), the designated international stratotype for the base of the Wenlock Series.

Conclusions

The Banwy River site exposes upper Llandovery through to lower Wenlock (Sheinwoodian) strata that have yielded several thousand graptolites belonging to 12 biozones. This represents the most refined sequence of graptolite faunas known from rocks of this age from anywhere in Britain. Most importantly, it yields graptolites across the Llandovery–Wenlock boundary interval. The *firmus* Biozone has been recognized for the first time in Britain in the lower Wenlock part of the succession. The site enables high resolution correlation with sections in continental Europe. The lower Wenlock sediments were deposited just off the shelf edge, on the upper part of the slope area, and were subject to episodic, slide-inducing tectonic activity.

PENSTROWED QUARRY (SO 068 910)

Introduction

Penstrowed Quarry is located in Powys about 4 km west of Newtown. Detailed work on the Silurian of this area of mid-Wales stems essentially from that of Cummins (1957, 1959a, 1959b, 1963, 1969), who described the petrography, sedimentology and provenance of the Wenlock and Ludlow turbidites ('greywackes') of this central part of the Welsh Basin – the Montgomery Trough – and the country stretching northwards towards Denbigh in north Wales. Cummins' sedimentological work followed on from the numerous analogous investigations of Boswell (1949 and references therein) in the Denbigh Trough, the sediments and faunas of which were later scrutinized by Warren *et al.* (1984). Dimberline (1987), Dimberline and Woodcock (1987) and Dimberline *et al.* (1990) have, most recently, given fresh insights into the nature of the Wenlock turbidite system in mid-Wales.

Up until the 1970s, the lower Wenlock turbidites that make up Penstrowed Quarry were referred to the Denbigh Grits. This lithostratigraphical term was for many years applied to rocks of this general type and age throughout their outcrop – an almost continuous belt of strata from Conway in north Wales to near Llandrindod Wells in central Wales (see Cummins, 1957). The term 'Denbigh(shire) Grits' was apparently (Warren *et al.*, 1984) first used by Murchison (1859), though Sedgwick had slightly earlier (1843a) recognized such a unit under a different name ('Denbighshire Sandstones'). Ramsay (1881), in the second edition of the Geological Survey Memoir on north Wales, refers to the Denbighshire flags, grits and shales of Sedgwick. Boswell (1949 and previous papers) used the terms 'Denbigh Grits' or 'Denbigh Grits Series', and Cummins (1957) used 'Denbigh Grits'. Warren *et al.* (1984) differentiated a 'Denbigh Grits Group' for these rocks in their type area.

Subsequently, mapping by the British Geological Survey (1972) at Newtown led to a revision of the lithostratigraphy for the lower Wenlock turbidites (and other Silurian strata) of this area, the BGS naming them the Penstrowed Grits Formation. This formational name has since appeared on the Montgomery map (British Geological Survey, 1994) and has also been applied to rocks in the Rhayader area to the south (British Geological Survey, 1993; Davies *et al.*, 1997). Synonyms of the formation are the Castle Vale Formation of the Llanbister area 15 km to the south of Newtown (Dimberline and Woodcock, 1987) and the Fynyddog Grits (Wood, 1906) of the Tarannon outlier 8 km to the east (Dimberline and Woodcock, 1993).

In the Llanbister area the outcrop of Wenlock turbidites is affected by folds and faults of the Towy Lineament, this line also marking the south-eastern limit of strong cleavage; to the south-east of there the turbidite system abuts against the north-west flank of the Pontesford Lineament (Woodcock, 1984; Dimberline and Woodcock, 1993).

Penstrowed Quarry gives its name to the Penstrowed Grits Formation. The site superbly exposes the turbidites and associated sedimentary structures of this unit – features that are typical of the basin during the Wenlock. The Penstrowed Grits probably span at most the *riccartonensis* and *rigidus* biozones of the Sheinwoodian, with their age span (and thickness) decreasing to the south-east towards the basin margin, where they are probably confined to the *riccartonensis* Biozone (Dimberline, 1987).

Description

The faces of this quarry, which ceased working in 1994, were constantly changing during its active life. About 90 m of the Penstrowed Grits Formation are exposed, the beds dipping at about 50° to the north-west and having a steep NW-dipping cleavage. In their reviews of the deep water realm, Pickering *et al.* (1986, 1989) recognized a total of 7 facies classes (A–G). Five of these (B, C, D, E and G) are present in Penstrowed Quarry, which has been described by Dimberline (1987) and Dimberline and Woodcock (1993), after earlier, brief comments on certain sedimentary structures there by Cummins (1957).

Facies B comprises medium to thick beds (10 cm to > 100 cm) of granule to medium sand grade. Some beds do not have any internal organization, but typically they show an inversely graded granule to medium sand base, then a structureless coarse to medium sand division, followed by parallel- then cross-laminated medium to fine sandstones. Thick-bedded sandstones of this facies are well displayed in the quarry. Single event sandstones up to granule grain size and 50 cm in thickness are present; amalgamation of sandstones is common. Beds of Facies B represent deposition from a high density, then weakening to a low density, turbidity current. This facies forms, overall, a minor component of the Wenlock turbidites.

Facies C is characterized by medium-bedded (3–30 cm) sand–mud couplets, the beds usually showing graded bedding. They show the typical Bouma sequence (Figure 3.40) from structureless graded sand (Ta), through parallel-laminated sand (Tb), cross- and convolute-laminated sand (Tc), parallel-laminated fine sand and mud (Td), to structureless mud (Te). Some of these divisions may be missing. Beds of this facies were produced by traction sedimentation from a low density turbidity current, preceded for coarser beds by suspension sedimentation from a high density turbidity current. In the quarry, flute marks (corkscrew and nested types) and other sole structures can be seen on blocks of Facies C sandstones (Figure 4.52), this facies type being the most dominant of the Wenlock turbidite system.

Facies D is made up of thinly to thickly laminated (1–10 mm), graded silt-muds having, variously, parallel-, cross-, and convolute-lamination. These beds are the products of low-concentration, slow-moving, fine-grained turbidity currents.

Facies E comprises very thin to thin beds (1–10 cm) of graded mud, a very thin silt lamina often occurring at the base of a bed. Such beds received their sediment from muddy turbidity currents.

Facies G mainly consists of very thinly laminated siltstone, with silt laminae alternating with organic carbon-rich laminae, three to four of these couplets being present per millimetre. Graptolites occur on lamination surfaces, and bioturbation is sometimes in evidence. This facies is interpreted as hemipelagic fallout, with each couplet possibly representing a near-annual cycle of phytoplankton blooms alternating with intensified silt input into the basin. Bottom waters were generally anoxic, though brief inter-

Figure 4.52 Penstrowed Quarry, Newtown, Powys. Flute casts on the base of a sandstone bed within a turbidite sequence. (Photo: Derek J. Siveter.)

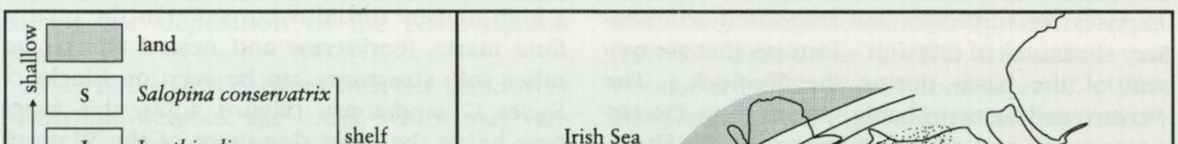


Figure 4.53 Map of Wales showing outcrop of Wenlock and Ludlow rocks, selected palaeogeographical features and depth-related faunal communities for *rigidus* Biozone time. Facies boundaries are conjectural away from outcrop control (after Dimberline *et al.*, 1990).

vals when more oxic conditions prevailed are indicated by the bioturbated hemipelagites (Dimberline and Woodcock, 1987; Dimberline *et al.*, 1990).

Interpretation

During the time the Penstrowed Grits and the Denbigh Grits were laid down, the Montgomery Trough and the Denbigh Trough were the two main basins of deposition within the deepest parts of the Welsh Basin (Figure 4.53; see also Hurst *et al.*, 1978 and Holland, 1992). The grits of the Castle Vale Formation and the Fynyddog Grits were probably deposited in continuity with the Penstrowed Grits of the type area, though original continuity of the Penstrowed Grits with the approximately coeval Denbigh Grits Group of north Wales is less certain (Dimberline and Woodcock, 1993).

In the Montgomery Trough, four sediment distribution systems were in operation (Dimberline and Woodcock, 1987, 1993; Figure 4.54): sand-bearing turbidity currents, muddy turbidity currents, hemipelagic fallout and submarine slumping. The sand-bearing turbidity currents received supplies from the south-western end of the basin, flow direction, as indicated by sole structures, being to the NNE as far as Newtown, thereafter swinging more towards the north. The palaeoslope to the south-east, which was underlain and controlled by the Welsh Borderland Fault System, constrained the turbidity currents on this flank. The muddy turbidity currents probably received more local supplies, from the adjacent platform and slope. These muddy currents were more frequent and of less volume than the sand-bearing currents. Mean repeat times of 120 years have been estimated for those of the Penstrowed Grits Formation, this timespan being compatible with the mobilization of sediment during strong storms. Hemipelagic fallout (pelagic organisms, their faecal pellets, terrigenous silt) was the typical background sedimentation throughout the basin. Submarine slumping, probably induced

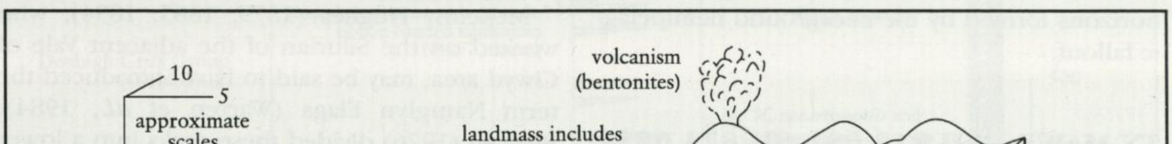


Figure 4.54 Reconstruction of the Wenlock turbidite system in relation to the contemporary tectonic setting of the Welsh Basin (after Dimberline and Woodcock, 1987).

by fault/seismic activity, took material downslope.

In the Denbigh Trough, the dominant direction of sediment transport was towards the east (Figure 4.53).

Penstrowed Quarry is linked most closely to the Ty Mawr site on the Denbigh Moors, where younger Wenlock (Homerian) basinal sediments of the Lower Nantglyn Flags Group occur. The latter are turbidites, but deposited overall under less turbulent conditions.

Conclusions

Penstrowed Quarry is an important site for demonstrating the sedimentology of the deep-water part of the Welsh Basin during early Wenlock times. It stands as the type locality for the Penstrowed Grit Formation, a lower Wenlock turbidite unit the sediments of which were deposited offshore, in the Montgomery Trough. Many of the facies and sedimentary structures classically associated with turbidity current derived sediments are displayed, together with horizons formed by the background hemipelagic fallout.

TY MAWR (SH 815 681–SH 823 685 AND SH 824 679)

POTENTIAL GCR SITE

Introduction

The Denbigh Moors region is underlain entirely by Silurian sediments; to the north and east it is surrounded by Carboniferous rocks, and to the south and west by the Ordovician. The Silurian is mostly of Wenlock or Ludlow age, though Llandovery strata are also present on its southern and western flank. Above the eastern side and at the southern end of the Conway Valley, about 6 km north of Llanrwst, there are two small headwater streams which unite immediately south of the farm at Ty Mawr to form an unnamed tributary which flows west into the Afon Hiraethlyn. Upper Wenlock (Homerian) through to lower Ludlow (Gorstian) strata, beds of the Lower and Upper Nantglyn Flags groups respectively, are exposed in the bed and along the banks of this tributary and its headwaters, which together form the Ty Mawr site.

Work on the Silurian of this general region of north Wales can be traced back to Bowman (1838, 1841a), but Sedgwick (1843a) provided the first reasonably full account of the rocks here. Other important 19th century contributions were those of the British Geological Survey, who (1850) published maps and (Ramsay, 1866, 1881) memoirs on the area. The next major period of investigation into the Silurian of the Denbigh region dates from the work of Boswell, who researched this theme intensively between 1921 and 1961, producing 19 publications on it, most notably his book of 1949 in which he referenced all previous work on the subject. Jones (1937, 1940, 1943) was particularly interested in the origin of the Silurian slumped horizons in the district. The Silurian sediments there were then addressed by Cummins (1957, 1959a, b), who determined their petrography and provenance. The most comprehensive, significant and recent work on the Silurian geology of the Denbigh area is the detailed account and accompanying maps of Warren *et al.* (1984). Slightly earlier, Holland *et al.* (1969) and Warren (1971) presented data on the graptolite biostratigraphy of the district.

McKenny Hughes (1879, 1885, 1894), who worked on the Silurian of the adjacent Vale of Clwyd area, may be said to have introduced the term Nantglyn Flags (Warren *et al.*, 1984). Boswell (1926) divided these rocks into a lower and an upper part, the latter including only the Nantglyn Flags of the type area and their correlatives (lower *nilssoni* Biozone), to which in his *magnum opus* (1949) he restricted the term. Warren *et al.* (1984) failed to justify a lithological division of the Nantglyn Flags, but on chrono- and biostratigraphical grounds they found it convenient to subdivide the sequence into upper and lower groups at the base of the *nilssoni* Biozone. They also recognized several formations within the lower group, and within both upper and lower groups noted several disturbed beds.

That part of the Lower Nantglyn Flags Group exposed at the Ty Mawr site is of *lundgreni* to *ludensis* Biozone age and includes the Upper and Lower Mottled Mudstone formations together with the Brynsyllty Formation – an uppermost Wenlock, disturbed unit (Figure 4.55). The site is principally important for indicating the nature of some of the sediments and the fauna of Wenlock age of the Denbigh Trough, a major depositional area in the offshore part of the Welsh Basin during this time.

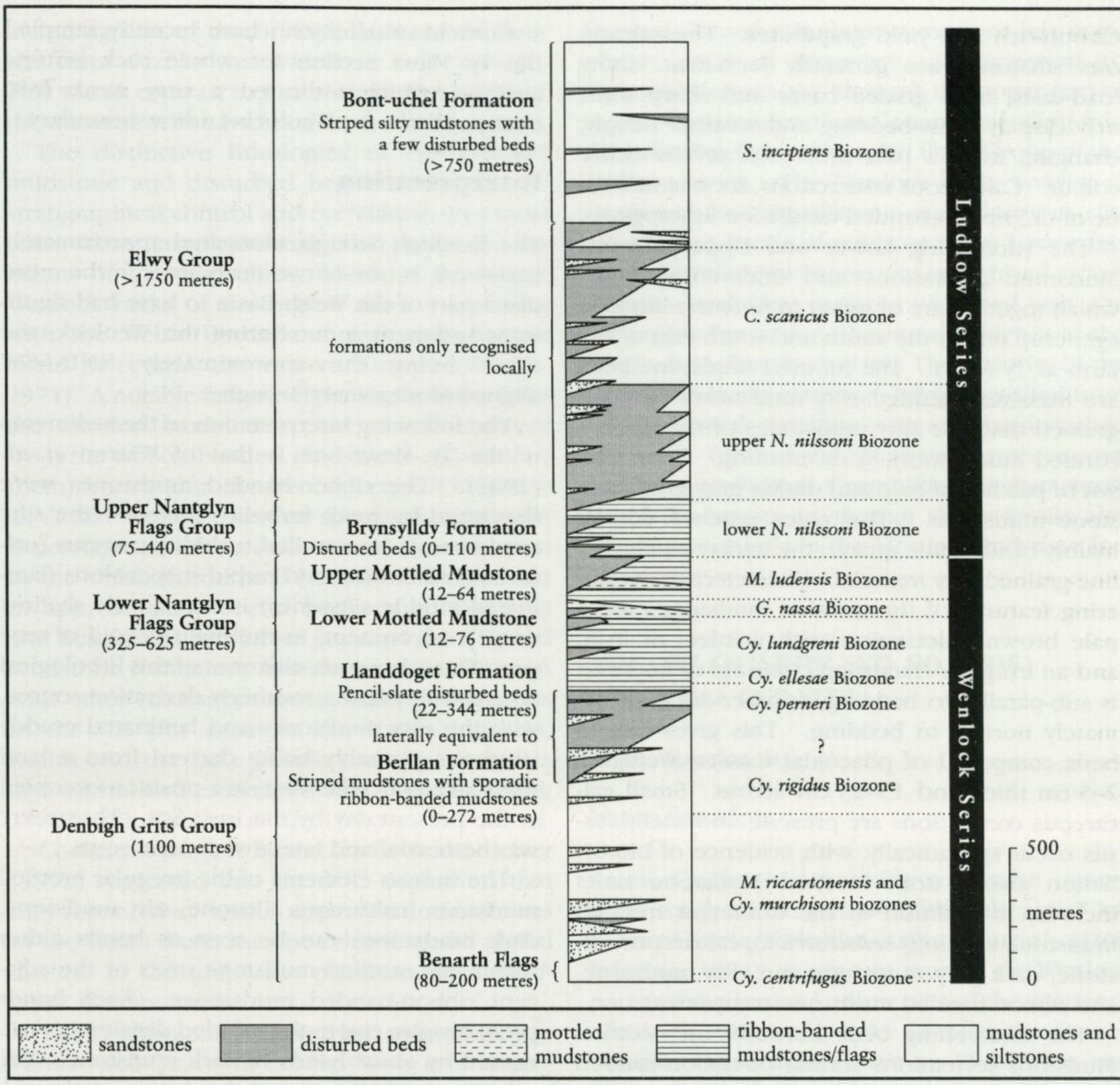


Figure 4.55 Stratigraphical section of Wenlock and Ludlow strata, Denbigh Region, north Wales (after Warren *et al.*, 1984).

Description

Boswell (1949), Holland *et al.* (1969) and Warren *et al.* (1984) all provided data specifically on the geology of the Ty Mawr stream section. In the Denbigh area overall, the thickness of the Lower Nantglyn Flags Group ranges from about 325 m to an estimated maximum of 660 m, with the Lower and Upper Mottled Mudstone formations being 12–76 m and 12–64 m thick respectively. In the general area of Ty Mawr, the group is about 600 m thick.

The stratigraphically lowest horizons of the site – measures of the Lower Nantglyn Flags Group of *lundgreni* Biozone age beneath the Lower Mottled Mudstone – occur in the lower part of the tributary which flows into the Afon Hiraethlyn. These beds consist largely of ribbon-banded mudstones, a lithology comprising a regular alternation of three elements: silty mudstone bands, laminated muddy siltstone bands, and thin, locally developed calcareous siltstones. The silty mudstone bands are tough, poorly fissile, blue-grey rocks that weather to brown; they lack sedimentary structures and fossils. The laminated muddy siltstones are of the same colour but they are coarser grained, the silt fraction being mainly quartz, and they are relatively carbon-rich and yield graptolites. The calcareous siltstones are generally lenticular, show load-casts, have graded bases and sharp tops, may display cross-bedding and weather deeply, changing from a pale grey to a yellow ochre colour. Calcareous concretions are characteristic of the ribbon-banded mudstone lithology.

The succeeding Lower and Upper Mottled Mudstone formations and intervening beds, which together are of *nassa to ludensis* Biozone age, crop out to the south and south-east of the farm at Ty Mawr. The mottled mudstone beds are massively bedded silty mudstones (coarser grained than the silty mudstones of the ribbon-banded mudstones), with mottling. They consist of patches of pale and darker grey-green siltstone–mudstone. The paler patches consist mainly of silt-grade quartz; the darker patches of fine-grained clay material. Characteristic weathering features of the mottled mudstones are a pale brown colouration with veinlets of iron, and an irregular fracturing. One set of fractures is sub-parallel to bedding, another set approximately normal to bedding. This gives rise to beds composed of phacoidal masses averaging 2–5 cm thick and 15–23 cm across. Small calcareous concretions are present, and shelly fossils occur sporadically, with evidence of bioturbation also. Both Mottled Mudstone units include, in addition to the dominant mottled mudstone lithology *sensu stricto*, calcareous siltstone, dark grey mudstone and silty mudstone, and ribbon-banded mudstone components.

The intervening beds between the Mottled Mudstone formations consist of ribbon-banded mudstones that produce graptolites.

Beds of the Lower Nantglyn Flags Group above the Upper Mottled Mudstone Formation, which are of *ludensis* Biozone age, occur in the two headwater streams to the north-east and south-east of Ty Mawr. The southerly of the two headwaters exposes 4.5 m of the Brynsylldy Formation, this unit, along strike, lensing out to the north but continuing to the south as a resistant, feature-forming horizon. With the exception of the Brynsylldy Formation, which consists of disturbed silty mudstones, this part of the sequence is entirely one of ribbon-banded silty mudstones, with graptolites.

Graptolites from the Ty Mawr section have been used, in part, to compile species range charts for the Wenlock of the Denbigh area and north Wales (Holland *et al.*, 1969; Warren, 1971; Warren *et al.*, 1984).

Corfield *et al.* (1992) have recently sampled the Ty Mawr section for whole rock isotope analysis, which indicated a very weak $\delta^{13}C$ decline across the Wenlock–Ludlow boundary.

Interpretation

The Denbigh Trough, elongated approximately east–west, is one of two main areas in the more distal part of the Welsh Basin to have had significant sediment input during the Wenlock, the other being the approximately NNE–SSW aligned Montgomery Trough.

The following interpretation of the sediments of the Ty Mawr site is that of Warren *et al.* (1984). The ribbon-banded mudstones were deposited by weak turbidity currents (the silty mudstones), far travelled turbidity currents (calcareous siltstones) and turbid suspensions (laminated muddy siltstones) in a relatively shallow water environment, in the main devoid of oxygen. The calcareous siltstones of this lithological type possibly had a southerly derivation source, with the silty mudstones and laminated muddy siltstones probably being derived from a land mass located to the west, in a position occupied at the present day by the Irish Sea. Thus there was both axial and lateral sediment input.

The various elements of the irregular mottled mudstone (calcareous siltstone, silty mudstone, dark mudstone) can be seen as bands either within the mottled mudstone units or the adjacent ribbon-banded mudstones. Such bands probably give rise to the mottled divisions as witnessed by ghost bands of dark mudstone. The calcareous siltstone bands in the mottled mudstones are, as in the ribbon-banded mudstones, thought to have been derived from turbidity currents that have travelled long distances. However, the darker mudstone element of the mottled mudstones, which was probably derived from turbidity currents, is relatively rich in carbonaceous matter and so possibly had a more proximal origin.

There are many disturbed horizons in the Silurian of the Denbigh area and their genesis has been the subject of much historic debate (Boswell, 1932, 1949, 1953; Jones 1937, 1940, 1943). Warren *et al.* (1984) supported the generally accepted view, put forward by Jones, that such deposits represent the result of penecontemporaneous slumping or sliding across the sea floor. They also concluded that the general sense of movement of the Silurian slumps, including that of the Brynsylldy disturbed bed, was from west to east within an E–W 'trough'. This was in contrast to Jones' view, who believed the movement to have been from north to south.

The distinctive lithologies of the mottled mudstone and disturbed bed horizons enable stratigraphical control and correlation on a local basis, thus supplementing that achieved by means of the graptolites, which in the upper Wenlock rocks of the region allow correlation with the Welsh Borderland and areas farther afield in central and eastern Europe (Warren, 1971). A notable feature of the shelly fauna from the mottled mudstones (and to some extent from the ribbon-banded mudstones adjacent to them) from within the Denbigh region in general, is that there are several species, for example *Bractoleptaena bracteola,* which are unknown in the Welsh Borderland but which are present in approximately coeval horizons in Bohemia and Scania. The trilobite fauna of the Mottled Mudstone formations has elements in common with other contemporaneous offshore locations in the UK (for example the Long Mountain, Builth and the Lake District), and with Scania and central and eastern Europe (Thomas, 1978, 1980, 1981; Thomas *et al.*, 1984).

Corfield *et al.* (1992) and Corfield and Siveter (1992) suggested that the $\delta^{13}C$ depletions that they recorded in various upper Wenlock sections in the Welsh Basin may be related to the global decline in the graptolite plankton after *lundgreni* Biozone times.

The Ty Mawr site is networked most closely to Penstrowed Quarry in the Newtown area of central Wales, where lower Wenlock turbidites of the Denbigh Grits Group deposited within the Montgomery Trough are exposed. In contrast to the deposits of that group, the younger sediments of the Lower Nantglyn Flags were deposited, overall, during a period of relatively quieter sedimentation. The Mottled Mudstone formations show similarity to the Glyn Member of the Trewern Brook Mudstone Formation, Trewern Brook site, Long Mountain area: both are late Wenlock, relatively carbonate-rich mudstone horizons in offshore, respectively basin and slope, settings.

Conclusions

This site is important for indicating the nature of late Wenlock sediments and fauna from an offshore location within the Welsh Basin – the Denbigh Trough. It shows a more or less completely exposed sequence, of *lundgreni* to *ludensis* Biozone age, through the upper part of the Lower Nantglyn Flags Group, extending into the overlying Upper Nantglyn Flags Group of the Ludlow Series. The Wenlock rocks consist of mudstone, muddy siltstone and calcareous siltstone. Two bands of mudstone, the Lower and Upper Mottled Mudstone, are recognized as formations, and there is also a disturbed unit, the Brynsylldy Formation, the top of which is at the Wenlock–Ludlow boundary. The majority of the sediments in the sequence were deposited from relatively weak turbidity currents; the disturbed bed was formed by penecontemporaneous slumping or sliding. Graptolites are characteristic of the sequence, though shelly fossils also occur, particularly in the Mottled Mudstone formations.

ARCOW QUARRY (SD 802 705)

POTENTIAL GCR SITE

N. H. Woodcock

Introduction

Arcow Quarry is a working roadstone quarry, 2 km south of Horton-in-Ribblesdale and 7 km north of Settle, Yorkshire (Arthurton *et al.*, 1988; Johnson, 1994). It exposes most of the Wenlock part and the lowest Ludlow part of the sequence of Lower Palaeozoic rocks forming the Craven inliers. These inliers have an Ordovician and Silurian stratigraphy that can be correlated with the Howgill Fells and the Lake District to the west. However, they show significant differences, particularly in a Wenlock sequence dominated by coarse clastic rocks. The inliers are the most easterly outcrops of Lower Palaeozoic rocks in northern England, before they are totally covered by Carboniferous and later rocks farther east.

The quarry exposes three formations, the nomenclature of which has been reviewed most recently by Arthurton *et al.* (1988) and Kneller *et al.* (1994). The Austwick Formation is wholly of Wenlock (Sheinwoodian to Homerian) age, whilst the Arcow Formation, although mostly of latest Wenlock (late Homerian) age, probably spans the Wenlock–Ludlow boundary (see Rickards, 1989a). The overlying Horton Formation is wholly of lower Ludlow (Gorstian) age. The description that follows concentrates on the Wenlock part of the succession.

Description

Arcow Quarry cuts the southward-dipping fold limb between the Crag Hill Anticline to the north and the Studrigg–Studfold Syncline to the south (Figure 4.56). The north part of the quarry exposes a gently ESE-plunging anticline, parasitic to the major structures. The anticline and the main part of the quarry are in the Austwick Formation (Figure 4.57). This comprises two main lithological components. Predominant are packets of medium- to thick- bedded sandstones, mainly of fine- to medium-grained sand grading up to mud, but with occasional coarse bases to the thicker beds. The sandstone beds have flute moulds on their bases, indicating flow from the ESE and internal ripple cross-lamination recording currents from the WSW. The sandstone packets are intercalated with intervals of dark grey finely-laminated siltstones, each some metres thick. The lamination in the siltstones is defined by alternation of silty mud laminae with carbonaceous laminae hosting graptolites. This facies has been described extensively from other Lower Palaeozoic successions, often by the term 'laminated hemipelagite' (e.g. Dimberline *et al.*, 1990; Kemp, 1991). Thin-bedded non-laminated mudstones are sporadically intercalated with the laminated facies.

The basal 80 m of the Austwick Formation, as defined by McCabe (1972) following King and Wilcockson (1934), is dominated by laminated siltstones and has been reassigned to the Brathay Formation by Kneller *et al.* (1994). Their Austwick Formation begins at the incoming of the first sandstone beds, no later than the *rigidus* Biozone and possibly as early as the *centrifugus* Biozone (King and Wilcockson, 1934; Arthurton *et al.*, 1988). The Brathay Formation siltstones are exposed to the north of the quarry (SD 8015 7113). The redefined Austwick Formation has yielded graptolites diagnostic of the *rigidus* and *lundgreni* biozones. A more continuous sedimentary record through Wenlock time is probable, but remains to be proved. About 100 m of the Austwick Formation are exposed in Arcow Quarry, out of a total thickness of about 220 m in this area.

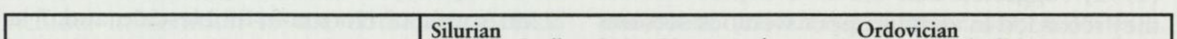


Figure 4.56 Location of Arcow Quarry, near Horton-in-Ribblesdale, and geology of the Craven inliers (after Arthurton *et al.*, 1988).

Figure 4.57 Arcow Quarry, near Horton-in-Ribblesdale. Sandstone beds of the Austwick Formation. (Photo: David J. Siveter.)

The top of the Austwick Formation is marked by a 25 m thick laminated siltstone unit. The overlying Arcow Formation (McCabe, 1972) comprises 9 m of light grey, calcareous siltstone, previously (King and Wilcockson, 1934) included with the overlying Horton Formation. The lowest metre of the Arcow Formation is thin-bedded, with some ripple cross-lamination, but bioturbation has destroyed the lamination in the remainder of the interval so that massive or burrow-mottled, thick-bedded units remain. Orthoconic nautiloids dominate a sparse shelly fauna. Graptolites have not been found, and dating rests on correlation with the Coldwell Formation, formerly the Middle Coldwell Beds, of the Howgill Fells and Lake District. Here, Rickards (1970b) dated the formation as latest Wenlock (*ludensis* Biozone) to earliest Ludlow (*nilssoni–scanicus* biozones). The Arcow Formation passes upwards through a 2 m transition into the dark-grey laminated siltstone at the base of the Horton Formation.

Interpretation

The laminated siltstone intervals in the Brathay and Austwick formations represent the background deep-marine sedimentation in the absence of coarse clastic input. Their precise origin has been much debated, particularly whether they were deposited lamina by lamina as a hemipelagic sediment, or by low-concentration turbidity flows that produced internal parallel lamination. This debate is outlined for the typical Brathay Formation deposits in the interpretation section of the River Rawthey network site. On either hypothesis, the lack of bioturbation in the laminated siltstone implies a sparse or absent benthic fauna, and probable dysaerobic to anaerobic bottom waters.

The graded sandstones in the Austwick Formation are the products of intermediate- to high-concentration turbidity flows (McCabe and Waugh, 1973; Arthurton *et al.*, 1988). These flows entered the region moving WNW and cut erosional sole structures. However, by the time that the waning flows were generating ripple cross-lamination, they were moving ENE, perpendicular to their original flow direction. The possible reasons for this palaeoflow divergence in the Windermere Supergroup have been discussed by Kneller *et al.* (1991), and include adjustment of along-slope flowing currents to the local basin slope and reflection of internal waves off a bounding lateral slope to the turbidite basin.

The Arcow Formation contrasts with the Brathay and Austwick Formations in recording a period of oxygenated marine bottom waters. Preservation of organic carbon was inhibited, deposition of carbonate was enhanced, and burrowing organisms and a shelly benthos colonized the sea floor. The onset of the oxic environment was due to basin ventilation, probably triggered by the eustatic marine lowstand during the *nassa* and *ludensis* biozones of the late Wenlock (Kemp, 1991; Johnson *et al.*, 1991). The rise in sea level at the beginning of Ludlow time (*nilssoni* Biozone) re-introduced anoxia to the basin bottom waters, now recorded in laminated siltstones in the Horton Formation.

The Arcow site displays the first sand turbidites to enter the Lake District Basin, and contrasts with the fine-grained deposits more typical of Wenlock sections in the basin, these finer sediments being well exposed in the Rawthey, Brathay and Torver–Ashgill GCR sites. Only in the central and western Lake District do comparable sandstones occur, in the Birk Riggs Formation (Kneller *et al.*, 1994; see Torver–Ashgill and Brathay site reports). These sandstones represent the start of more rapid infilling of the Lake Distict Basin, exemplified by the Ludlow turbidites at the Tebay GCR site.

Conclusions

Arcow Quarry provides a continuous section through much of the Wenlock and lowest Ludlow succession in the Craven inliers. The site is an important display of the anoxic hemipelagic facies that characterizes this time interval, and of the sandstone turbidites and anoxic mudstones that punctuate this background sedimentation. The succession in the Craven inliers also offers instructive comparisons with the Lake District and Howgill Fells sections farther west, particularly in the early incoming of turbidite sandstones. The inliers are the easternmost outcrop of Lower Palaeozoic rocks in northern England, before they are covered by Carboniferous and younger rocks.

RIVER RAWTHEY (SD 7087 9785–SD 6984 9696)

N. H. Woodcock

Introduction

The River Rawthey section, between its confluences with Wandale Beck and Backside Beck, lies 7 km north-east of Sedbergh, Cumbria, on the eastern flank of the Howgill Fells (Figure 3.49). It exposes the most complete section through the 250 m thick Wenlock succession of the Howgills. Watney and Welch (1911) first subdivided this succession using graptolites, but Rickards (1967) established a full graptolite biostratigraphy that was capable of correlation with the Shropshire type area for the Wenlock Series (e.g. Cocks *et al.*, 1992). This biostratigraphy was later extended to the main Lake District outcrop (Rickards, 1969, 1970b, 1989a).

The Howgill Fells lie along strike from the thick succession of Ludlow and Přídolí rocks that forms the southern Lake District. However older Silurian rocks (Wenlock and Llandovery) and uppermost Ordovician (Ashgill) rocks crop out in the eastern Howgills in a series of inliers, structurally related to Variscan displacement on the Dent Fault zone. The NNE-striking fault zone lies about 1 km east of the Rawthey section.

The Rawthey section contains three formations within the Windermere Supergroup, the nomenclature of which has been fully reviewed by Kneller *et al.* (1994). The Browgill Formation is of upper Llandovery (Telychian) age and has at its top the Far House Member, the Grey Beds of Rickards (1967). These pass up into the Brathay Formation through the basal Dixon Ground Member. Above the Brathay Formation is the Coldwell Formation, which spans the Wenlock–Ludlow boundary in this area (Rickards, 1970b).

Description

Wenlock rocks are exposed along the length of the Rawthey section, although the most informative segments are at its northern (Figure 4.58) and southern ends. Rocks of Wenlock age also crop out in Near Gill, Middle Gill and Far Gill, which join the central portion of the main Rawthey valley section on its south-eastern side and which also form part of this site.

The lithological transition from Llandovery to Wenlock rocks is seen in the north-west bank of the River Rawthey, 50 m upstream from its junction with Wandale Beck (SD 7073 9778). Southward-dipping light grey mudstones with thin beds of green-grey ash, the Far House Member of the Browgill Formation, pass up into bioturbated blue-grey mudstones with intercalations of finely laminated graptolitic mudstone. These lowest 20 m of the Brathay Formation comprise the Dixon Ground Member. A 0.1 m thick limestone near the top of the member forms a useful lithological marker across the Howgills and the Lake District. The Dixon Ground Member lies entirely within the *centrifugus* Biozone. Rickards (1967) recorded the following graptolite assemblage from this horizon: *Monoclimacis vomerina vomerina*, *M. vomerina basilica*, *Monoclimacis shottoni*, *Monoclimacis linnarssoni*, *Monoclimacis griestoniensis nicoli*, *Pristiograptus watneyae*, *Pristiograptus* cf. *praedubius*, *Monograptus priodon*, *Monograptus minimus cautleyensis*, *Monograptus danbyi*, *Monograptus simulatus*, *Cyrtograptus centrifugus*, *Cyrtograptus insectus*, *Cyrtograptus murchisoni*, *Retiolites*

Figure 4.58 River Rawthey, Howgill Fells. Basal strata of the Wenlock Series at the junction of Wandale Beck and the River Rawthey. (Photo: Derek J. Siveter.)

geinitzianus geinitzianus, and *R. geinitzianus angustidens*. There are rare cephalopods, crinoids, conulariids and, in the bioturbated mudstone units, brachiopods and trilobites (*Aulacopleura* sp.).

Followed up section, the lithology becomes dominated by the finely-laminated mudstone that characterizes the main part of the Brathay Formation. The top of the Dixon Ground Member is taken above the last thick intercalation of bioturbated mudstone, near the mouth of Wandale Beck (SD 7067 9778). The distinctive lamination in the Brathay Formation is defined by alternation of carbonaceous laminae, hosting graptolites, with silty mud laminae. The thickness of each silty mud–carbon couplet is remarkably regular, and averages about 0.2 mm (King, 1992). This facies has been described extensively from other Lower Palaeozoic sequences, often by the term 'laminated hemipelagite' (e.g. Dimberline *et al.*, 1990; Kemp, 1991). Other lithologies only sporadically interrupt the uniformity of the laminated mudstone between the top of the Dixon Ground Member and the base of the Coldwell Formation: very thin homogeneous mudstone layers, thin-graded fine sandstone to mudstone layers (in the *riccartonensis* Biozone), and calcareous nodules.

Between Wandale Beck and Handley's Bridge (SD 7056 9764) the south or SW-dipping units of the Brathay Formation span the *murchisoni* to *lundgreni* graptolite biozones. About 200 m of strata are represented, cut by occasional small faults, particularly within the *linnarssoni* Biozone. The *murchisoni* Biozone is represented by 3 m of laminated mudstone exposed in the left bank and bed of the Rawthey at the mouth of Wandale Beck (SD 7067 9778). This level yields *C. murchisoni*, *M. vomerina sensu lato*, *M. vomerina basilica*, and *M. priodon*. The *riccartonensis* Biozone is marked by the incoming of *Monograptus riccartonensis* at SD 7068 9777. This species typically occurs with *M. vomerina basilica* throughout the lowest 18 m of the biozone, joined by *Monograptus antennularius* and *Pristiograptus dubius* at its top. These latter two species continue through the succeeding 7.5 m of strata, but are joined by *Monoclimacis flumendosae* marking the *antennularius* Biozone. Some 5 m of strongly cleaved rocks yield no graptolites, but above them are about 9 m of strata assigned to the *rigidus* Biozone, although without finds of the eponymous fossil. The *linnarssoni* Biozone is characterized by *Cyrtograptus linnarssoni*, *Cyrtograptus rigidus cautleyensis*, *Monograptus flemingii flemingii*, *Monograptus flexilis flexilis*, and *Monoclimacis flumendosae flumendosae*. The biozone has a thickness of at least 33 m (SD 7061 9766). The succeeding *ellesae* Biozone is probably about 5 m thick here, characterized by *Cyrtograptus ellesae*. This is followed, upstream of Handley's Bridge (SD 7062 9768), by the lower part of the 135 m thick *lundgreni* Biozone. The lowest 60 m of this biozone yield *Cyrtograptus lundgreni*, *M. flemingii flemingii*, *M. flemingii primus*, *Monoclimacis flumendosae kingi*, *P. dubius*, *Pristiograptus pseudodubius* and species of *Favosites*. Above this level, *C. lundgreni* and *M. flumendosae kingi* are absent.

At Handley's Bridge, and for 400 m downstream, the Brathay Formation is affected by E–W folds, which repeat the *lundgreni* Biozone. The next 400 m, from the confluence with Middle Gill (SD 7043 9734) to the mouth of Backside Beck (SD 7005 9710), is a strike section of *lundgreni* Biozone rocks, cut by a NE-striking fault zone. Downstream from the fault, between Backside Beck and the river footbridge, the bed of the Rawthey exposes some 15 m of slumped calcareous siltstones. These are the lithostratigraphical equivalent of the Coldwell Formation, which, in unslumped sequences in the Howgills, comprises two limestone units separated by graptolitic mudstones. The Coldwell Formation in the Lake District is assigned to the *nassa* and *ludensis* biozones at the top of the Wenlock (Rickards, 1970b). However Rickards (1967) reported a Ludlow (*nilssoni–scanicus* biozones) fauna from below the upper limestone in the Howgills sequence, and suggested that the poor development of the *nassa* and *ludensis* biozones here may indicate a local non-sequence.

Collectively, the Wenlock exposures in Near, Middle and Far gills include *centrifugus* to *lundgreni* biozone strata, with the graptolite successions of Near and Middle gills having been documented in detail (Rickards, 1967). Further, some of these exposures represent graptolite type localities, for example for *Cyrtograptus rigidus cautleyensis* Rickards (1967), *M. flumendosae kingi* Rickards (1965b) and *P. dubius pseudolatus* Rickards (1965b).

Interpretation

The laminated mudstones that form the bulk of the Wenlock strata occur in many successions around the former Iapetus Ocean (Kemp, 1991) and their origin has been much debated. Earlier views on the examples in the Howgills are summarized by Rickards (1964), who developed the idea of Marr (1927) that each couplet of silt and carbon laminae may represent an annual cycle of deposition. Rickards envisaged a constant rain of algal organic carbon deposited in anaerobic bottom waters, interrupted periodically, though not necessarily annually, by silt deposition from low concentration turbidity currents. Kemp (1991) suggested alternatively that a number of carbon and silty-mud laminae could be deposited during one turbidity flow event. The carbonaceous laminae would represent discontinuous films of algal organic material deposited in intimate association with clay and fine silt, their apparent continuity being enhanced by later compaction. In support of the first hypothesis of discrete lamina-by-lamina deposition, Dimberline *et al.* (1990) drew analogies between the Wenlock hemipelagites in Wales and recent sediments in basins on the California Borderland (Thornton, 1984). There the lamination represents an annual climatic cycle of high warm-season productivity with high wet-season sediment runoff. The silt component of the lamination may be sedimented by vertical fallout from nepheloid suspensions rather than directly from turbidity flows. On either hypothesis, the lack of bioturbation in the laminated mudstone implies a sparse or absent benthic fauna, and probable dysaerobic to anaerobic bottom waters.

Estimates of the lamination frequency in the Brathay Formation of the Howgills, using graptolite biozonation and its chronometric calibration (King, 1992), suggest a periodicity of three or four years. A near-annual driving influence is not precluded by this observation, given the potential for erosion and non-preservation of laminae. The Rawthey section offers one of the best opportunities for refining this time calibration in the future.

The basal Dixon Ground Member to the Brathay Formation represents alternating periods of marine basin anoxia with better oxygenated conditions characteristic of the underlying Browgill Formation. The green-grey siliceous mudstones of the Browgills become progressively less common through the Dixon Ground Member, reflecting a waning source of siliceous debris, possibly volcanic ash, as well as a change in oxicity.

The Coldwell Formation, overlying the Brathay Formation, also records a period of oxygenated marine bottom waters. Preservation of organic carbon was suppressed and of carbonate was enhanced. Burrowing organisms and a shelly benthos colonized the sea floor and, for reasons poorly understood, soft-sediment slumping of the oxic muds was promoted. The *nassa* and *ludensis* biozones of the late Wenlock coincide with a eustatic marine lowstand that probably initiated the overturn of marine basin waters and the onset of the oxic environment. Anoxic bottom conditions returned with the rise in sea level at the beginning of Ludlow time (*nilssoni* Biozone) and the succeeding Wray Castle Formation is dominated by laminated hemipelagic mudstones similar to those in the Brathay Formation.

The Rawthey GCR site demonstrates the refinement in graptolite biozonation that is possible in the continuous sequences of laminated mudstone that typify basinal marine deposits of Wenlock age. This site provides a regional reference for northern England and southern Scotland, correlatable with the shallower marine sequences of the world stratotype area for the Wenlock Series in the Wenlock district of the Welsh Borderland. Together with the other Wenlock sites in the Lake District (Torver–Ashgill and Brathay Quarries), the Rawthey section offers a contrast with sites in areas that during this time have a more voluminous sediment supply, containing more abundant sandstone turbidites. Sites with the latter type of sedimentary regime are Arcow Quarry in the nearby Horton-in-Ribblesdale area, and the Balmae and Borgue coasts in the Scottish Southern Uplands.

Conclusions

The Rawthey section provides near-continuous exposure through much of the Wenlock strata of the Howgill Fells, and it has much biostratigraphical and sedimentological importance. Together with numerous subsidiary sections in the same area, it has allowed Wenlock time to be finely subdivided into ten biozones using graptolites, thus allowing correlation with other areas in Britain and abroad. Future refinement of this subdivision will rely on this section above all others in northern England. The section also displays the typical laminated mudstone facies of Wenlock sedimentary rocks deposited in anoxic marine basins. It is important in the debate about the origin of this facies, and of the more oxic mudstones at the base and top of the Wenlock succession. The site also contains the type localities of various graptolite species.

TORVER–ASHGILL (SD 276 955)

N. H. Woodcock

Introduction

This site is located in the western part of the Lake District, near Coniston (Figure 3.49). It comprises the nearly continuous stream sections of Torver Beck (SD 2763 9617–2847 9545) and Ashgill Beck (SD 2700 9532–2757 9484), together with considerable rock exposure in the intervening ground that includes the disused Banishead quarries (SD 2782 9600). Historically, the Wenlock strata of the Lake District were studied in particular by Marr (1878, 1892, 1916, 1927). More recent revision of the lithostratigraphy and biostratigraphy of these rocks has been made through, notably, the work of Rickards (1969, 1970b, 1978, 1989a), Kneller (1990) and Kneller *et al.* (1994).

The Wenlock succession of the Torver–Ashgill site displays the three component formations (of Kneller *et al.*, 1994) – Brathay, Birk Riggs, and Coldwell – typical of the western and central Lake District. Additionally, Torver and Ashgill becks offer exposure through the underlying Stockdale Group (Llandovery Series) down into the Dent Group (Ashgill Series, upper Ordovician), and upsequence into the overlying Wray Castle Formation and Coniston Group (Ludlow Series).

Thus, the Wenlock succession characteristic of the western and central parts of the Lake District can be examined here both in its own right and in its regional stratigraphical context. The site also contains a nearly complete suite of Wenlock graptolite biozones, which enable long-range correlation.

Description

The structure hosting the Wenlock succession is relatively simple (British Geological Survey, 1998). Beds, which form part of the Windermere Supergroup, strike NE–SW and dip to the south-east at between 40° and 60° (Figure 4.59). A cleavage cuts fine-grained lithologies, dipping north-west at about 60°. The Park Gill Thrust follows the top of the Wenlock succes-

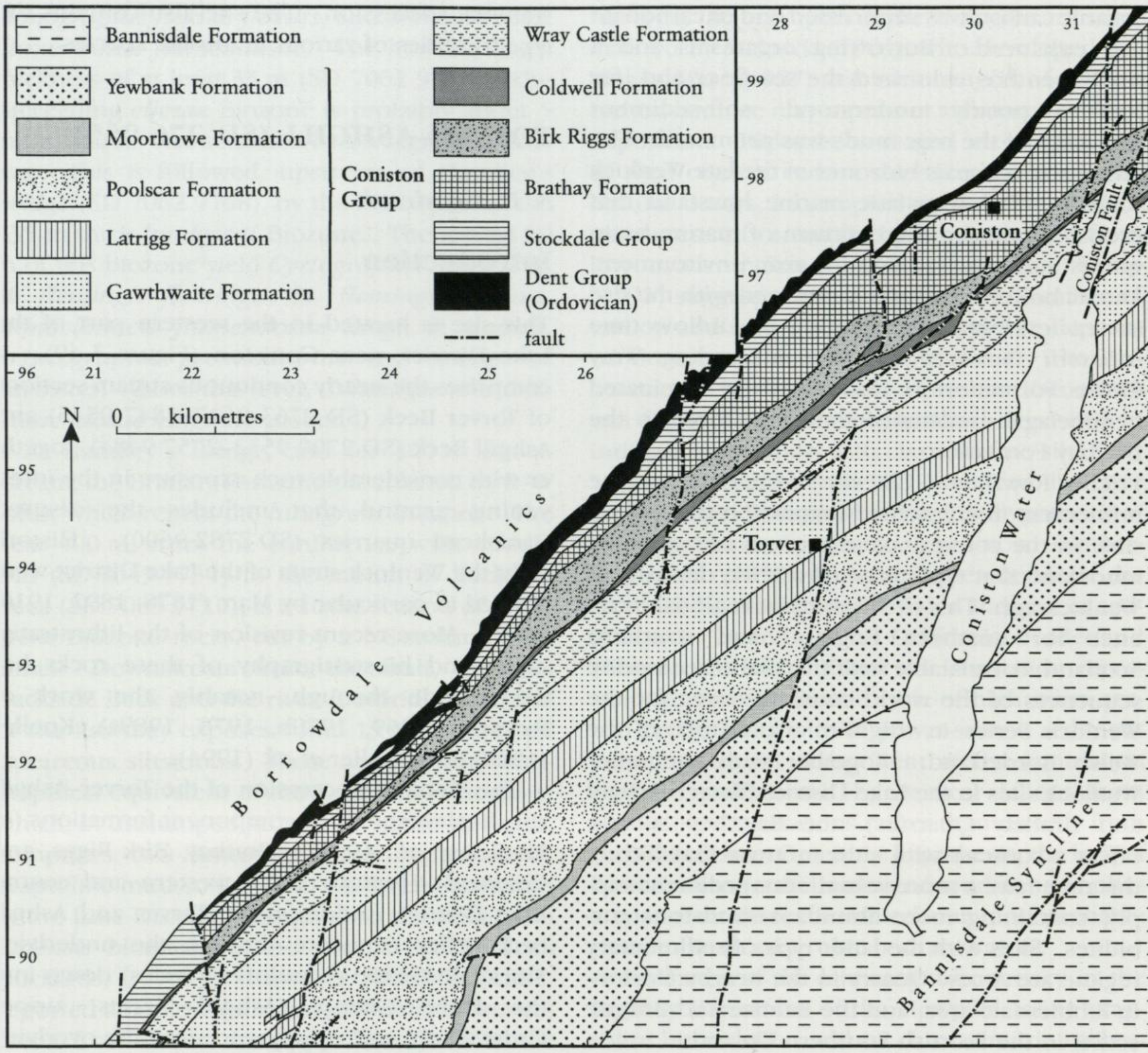


Figure 4.59 Lithostratigraphical map of the Windermere Supergroup around Coniston Water, south-west Cumbria (after Kneller *et al.*, 1994).

sion, but the amount of structural repetition here is minor. Sub-vertical faults, mostly north-trending, cause some displacement.

The Brathay Formation, the Brathay Flags of Marr (1878), makes up the lower 160 m of the Wenlock succession. Although the formation was originally defined at Brathay Quarries (see GCR site report), Kneller (1990) proposed an alternative type section in Ashgill Beck (SD 2711 9525). The typical lithology of the formation is dark grey laminated siltstone. The lamination comprises couplets of muddy quartzose silt overlain by carbonaceous mudstone, on a scale of about 3 couplets to a millimetre. However, the basal 10–30 m of the formation is transitional from more homogeneous grey siltstones at the top of the underlying Browgill Formation (Llandovery Series). It contains burrow mottling, diffuse at the base, and better-defined higher up, together with intercalated bands of the laminated siltstone facies. This basal unit is termed the Dixon Ground Member (Kneller *et al.*, 1994).

Rickards (1969) established eight graptolite biozones in the Brathay Formation, ranging from *centrifugus* to *lundgreni* (Figure 4.60). The *ellesae* Biozone was not verified by him, but he thought it unlikely that it is missing. This bio-

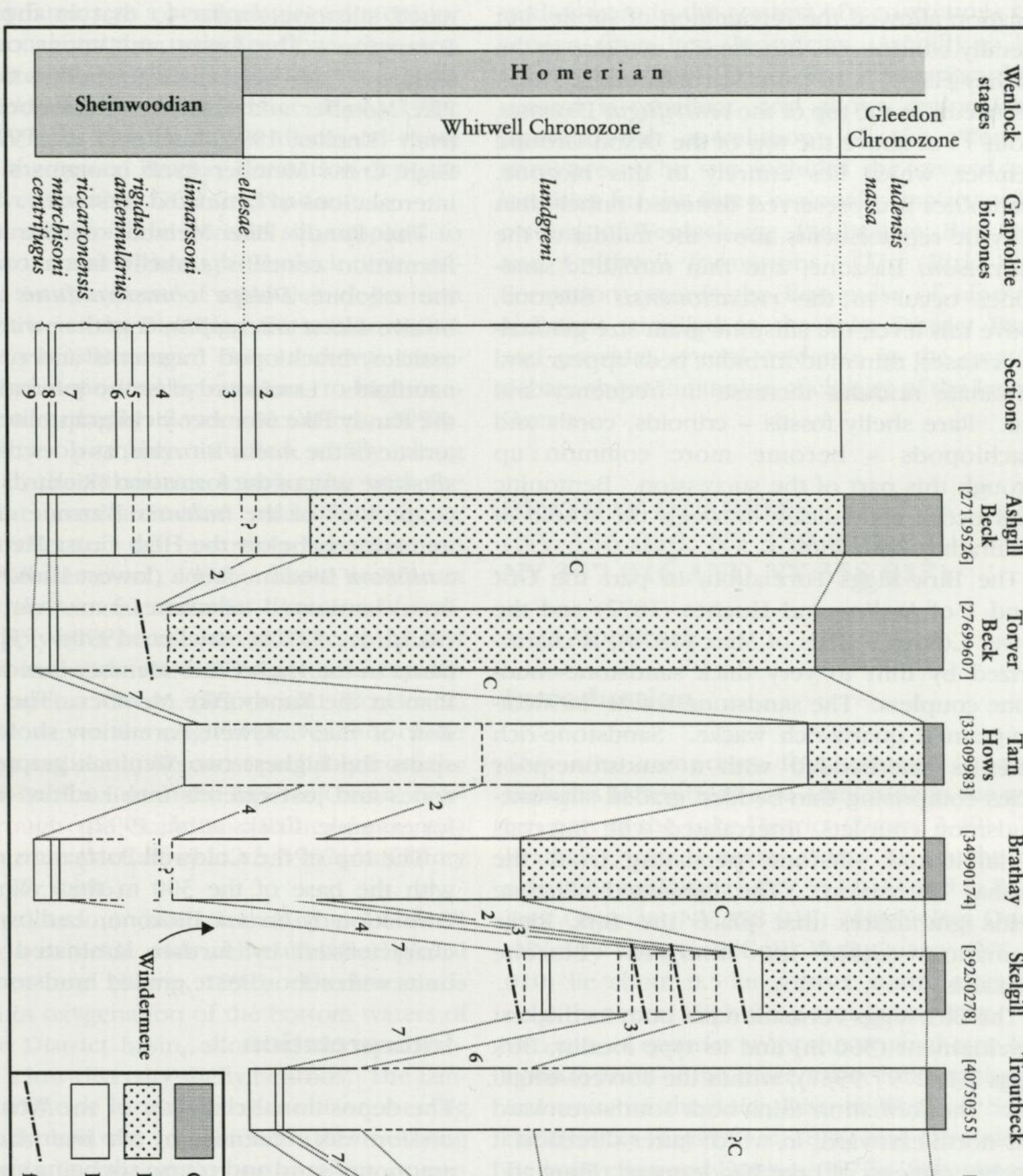


Figure 4.60 Torver–Ashgill. Logs of the best exposed Wenlock sections across the Lake District with the lines indicating the correlation of graptolite biozones (after Rickards, 1969, 1989a, with revision of lithostratigraphy after Kneller *et al.*, 1994).

zonation allowed the recognition of subtle, but laterally continuous, lithological markers in the Brathay Flags. A 10 cm calcareous nodule horizon occurs at the top of the *centrifugus* Biozone, about 15 m above the top of the Dixon Ground member, which lies entirely in this biozone. Graptolites are preserved flattened rather than as pyrite replacements above the middle of the *murchisoni* Biozone, and thin turbiditic sandstones occur in the *riccartonensis* Biozone. Above this level, the siltstone grain size gradually increases, thin mud turbidite beds appear, and carbonate nodules increase in frequency and size. Rare shelly fossils – crinoids, corals and brachiopods – become more common up through this part of the succession. Bentonitic clays occur sporadically through the whole of the Brathay Formation.

The Birk Riggs Formation, in part the Grit Band 1 of Aveline and Hughes (1872) and the Lower Coldwell Beds of Marr (1878), is characterized by thin to very thick sandstone–mudstone couplets. The sandstone is fine- to medium-grained quartz-rich wacke. Sandstone-rich facies is interbedded with a sandstone-poor facies comprising thin-bedded graded siltstone-mudstone couplets, intercalated with intervals of laminated siltstone persisting from the Brathay Formation. The laminated siltstone yields graptolites that place the Birk Riggs Formation within the *lundgreni* Biozone (Rickards, 1969, 1970b).

The Birk Riggs Formation has both its thickest development (360 m) and its type locality, Birk Riggs (SD 2797 9537), within the Torver–Ashgill site. The formation thins both south-westward and north-eastward, in which latter direction it pinches out east of Lake Windermere. Flute and groove moulds suggest palaeoflow to the N–NE, and ripple cross-lamination flow to the S–SE (Kneller, 1990; McCaffrey, 1991).

The top of the Wenlock succession is marked by the Coldwell Formation, the Coldwell Beds of Aveline and Hughes (1872) and the Middle Coldwell Beds of Marr (1878). This unit was named after Cold Well Quarry, which is part of the Brathay Quarries GCR site, but the alternative type section proposed by Kneller (1990) lies within the Torver–Ashgill site, east of Birk Riggs (SD 2808 9536–2814 9529). Here the Coldwell Formation is 30 m thick, although it thickens north-eastward to over 80 m. The formation is distinguished by two units of pale blue-grey calcareous siltstone separated by dark grey laminated siltstone similar to that in the Brathay Formation. The lower and upper calcareous siltstones have been distinguished as the Randy Pike Member and High Cross Member respectively (Kneller, 1990; Kneller *et al.*, 1994). The High Cross Member itself contains significant intercalations of laminated siltstone.

The Randy Pike Member of the Coldwell Formation contains a shelly fauna comprising the trilobite *Delops obtusicaudatus* and the bivalve *Slava interrupta,* together with crinoid ossicles, brachiopod fragments and orthoconic nautiloids. Laminated siltstone intercalations in the Randy Pike Member yield graptolites characteristic of the *nassa* Biozone, as does the central siltstone unit of the formation (Rickards, 1970b). Graptolites of the *ludensis* Biozone are found immediately below the High Cross Member and a *nilssoni* Biozone fauna (lowest Ludlow Series) in a laminated siltstone 3 m from its top (Rickards, 1970b; Kneller, 1990). The shelly fauna in the High Cross Member is more sparse than in the Randy Pike Member. The biozonation of the Coldwell Formation shows that it spans the highest two Wenlock graptolite biozones and just extends into Ludlow time (see, for example, Cocks *et al.*, 1992).

The top of the Coldwell Formation coincides with the base of the 300 m thick Wray Castle Formation (*nilssoni* Biozone, Ludlow Series), characterized by further laminated siltstone units with subordinate graded mudstone beds.

Interpretation

The depositional character of the Wenlock succession was influenced by two main factors: the amount of sand and coarse silt being supplied to the depositional basin and the degree of oxygenation of the marine bottom waters.

No sand reached the Lake District Basin during early Wenlock (Sheinwoodian) time. The base of the Wenlock coincides with the beginning of a transition from the oxic conditions recorded by the thoroughly bioturbated mudstones of the Browgill Formation (Llandovery Series), through the dysaerobic deposits of the Dixon Ground Member to the anaerobic conditions that characterize the bulk of the Brathay Formation. This environment is implied by the lack of bioturbation in the laminated siltstone together with the sparse or absent benthic fauna. There has been some debate as to whether the laminated siltstones were deposited lamina by lamina as a hemipelagic sediment, or by low-concentration turbidity flows that produced internal parallel lamination (see Marr, 1927; Rickards, 1964; Dimberline *et al.*, 1990; Kemp, 1991). This debate is discussed more fully for the typical Brathay Formation deposits in the River Rawthey GCR site report.

The amount of land-derived silt supplied to the basin increased through Wenlock time, culminating in the burst of sand-rich deposition that gave rise to the Birk Riggs Formation within the *lundgreni* Biozone. This sand was transported and deposited by medium- to high-concentration turbidity flows (McCaffrey, 1991). These flows probably travelled axially along troughs in the submarine topography, with the discrepant cross-lamination palaeoflows being due to reflection off bounding topographical slopes (Kneller *et al.*, 1991). These south-east directed slopes and apparent direction of sediment supply have been taken to indicate the first influx of Laurentian sediment across a rapidly-closing Iapetus Ocean (Soper and Woodcock, 1990). However, the original provenance of the Birk Riggs sediment was most probably from the Avalonia–Baltica side of the Iapetus Ocean, recycled through the Scandian (Baltica–Laurentia) collision zone (McCaffrey *et al.*, 1992; McCaffrey and Kneller, 1996).

The calcareous horizons of the Coldwell Formation coincide with well-established global falls in sea level (Kemp, 1991). The lowstands resulted in oxygenation of the bottom waters of the Lake District basin, allowing the establishment of a low-diversity shelly benthos. The laminated siltstone horizons record intervening highstands, and the transition to the overlying Wray Castle Formation the return to more persistent anaerobic conditions during early Ludlow time.

The Torver–Ashgill site is very closely linked to the nearby, historically important Brathay Quarries site, which has similar lithostratigraphical units of Wenlock age exposed, though less completely so. Other related northern England sites include the River Rawthey in the Howgill Fells and, to a lesser extent, Arcow Quarry in the Horton-in-Ribblesdale area.

Conclusions

The Torver–Ashgill site provides high-quality sections through the typical Wenlock succession of the western and central Lake District. It can be studied here in the context of a continuous succession from late Ordovician (Ashgill) to late Silurian (Ludlow) strata. The biostratigraphical control is excellent, and allows regional and international correlation of the Wenlock sequence. The site includes the revised type localities for the three regionally important formations of Wenlock age, the Brathay, Birk Riggs and Coldwell formations. The Birk Riggs Formation records the first pulse of sand-rich sediment supplied to the Lake District Basin, and provides crucial evidence in the ongoing debate about the timing of closure of the Iapetus Ocean.

BRATHAY QUARRIES (NY 356 010, NY 359 010, NY 357 016 AND NY 358 017)

N. H. Woodcock

Introduction

This site comprises four disused quarries between Hawkshead and Ambleside in the western part of the Lake District (Figure 3.49). The Brathay Quarries *sensu stricto* lie on the east side of Great Brathay (NY 357 016) and in Renny Park Coppice (NY 358 017). High Crag Quarry (NY 356 010) and Cold Well Quarry (NY 359 010) lie about 0.5 km farther south, along the ridge between High Crag and Randy Pike. The two sets of quarries were the original type locations for two of the three major lithostratigraphical units of the Lake District Wenlock Series: the Brathay Flags (Marr, 1878) and the Coldwell Beds (Aveline and Hughes, 1872). Subsequently, Kneller *et al.* (1994) have formalized the Brathay and Coldwell formations, and also established the intervening Birk Riggs Formation.

The Brathay Flagstone was named after this locality by Sedgwick (e.g. 1845). However, Sedgwick (1846) came to prefer the term Coniston Flagstone, and it was Marr (1878) who reverted to the original name, but for the lower part only of Sedgwick's Coniston Flags. Moseley (1984) used the term Brathay Flags Formation. In formalizing the Brathay Formation, Kneller *et al.* (1994), following Kneller (1990), offered an alternative type section for the formation in Ashgill Beck (SD 2711 9525), within the nearby Torver–Ashgill GCR site. The latter site, incidentally, also contains the type section for the Birk

Riggs Formation, a unit that corresponds in large part to the Grit Band 1 of Aveline and Hughes (1872) and the Lower Coldwell Beds of Marr (1878).

The Coldwell Formation is characterized by calcareous siltstone units, the presence in this area of such relatively lime-rich beds having been noted by Sedgwick (1845). These units, together with an intervening laminated siltstone unit, constitute the Coldwell Beds of Aveline & Hughes (1872). Marr (1878) expanded the term Coldwell Beds and divided it into three divisions, and included within it both the underlying sandstone-rich unit – the present Birk Riggs Formation – and the overlying unit dominated by laminated siltstone – the present Wray Castle Formation (of Kneller *et al.*, 1994) which is of early Ludlow age. This illogical grouping of the Lower, Middle and Upper Coldwell Beds, all of contrasting lithology, persisted for a century (e.g. Moseley, 1984; Lawrence *et al.*, 1986). Kneller *et al.* (1994), wisely, reverted to the original sense for their formalized Coldwell Formation, although they based it on a type section east of Birk Riggs (SD 2808 9536–2814 9529), again within the Torver–Ashgill GCR site. The constituent lower and upper calcareous siltstone units have been distinguished as the Randy Pike Member and High Cross Member respectively (Kneller, 1990; Kneller *et al.*, 1994). The type section for the Randy Pike Member is near the Brathay Quarries site at Randy Pike Quarry (NY 3622 0097), 250 m east of Cold Well Quarry; that for the High Cross Member is some 3 km to the south-west of Cold Well near High Cross (SD 329 984).

The Brathay Quarries site remains a historically important reference area for the lithostratigraphical divisions of the Wenlock Series of the Lake District. The quarries, additionally, provide valuable confirmatory sections within the region for the graptolite biozonation of the Wenlock sequence, important for correlation of the western and eastern Lake District sections, and for international correlation (Rickards, 1969, 1989a).

Description

The Wenlock rocks in this area of the Lake District dip south-south-eastward at 30° to 40°. They form part of the continuous, tilted succession here of Windermere Supergroup rocks which range from late Ordovician (Ashgill Series) to late Silurian (Ludlow Series) in age (British Geological Survey, 1998). Minor north-verging anticline–syncline pairs affect the contact between the Coldwell Formation and overlying Wray Castle Formation south-east of Cold Well Quarry, and the area is cut by steep NNE-striking sinistral faults and NW-striking dextral faults.

The Brathay Quarries *sensu stricto* (Figure 4.61) expose the bluish-grey laminated siltstone that characterizes the Brathay Formation throughout the region. The lamination comprises couplets of muddy quartzose silt overlain by carbonaceous mudstone, on a scale of about 3 couplets to a millimetre. This facies also contains common carbonate nodules, rare massive grey mudstone beds a few centimetres thick, and beds of bentonitic clay up to 15 cm thick. The quarried units mostly lie within the *rigidus* or

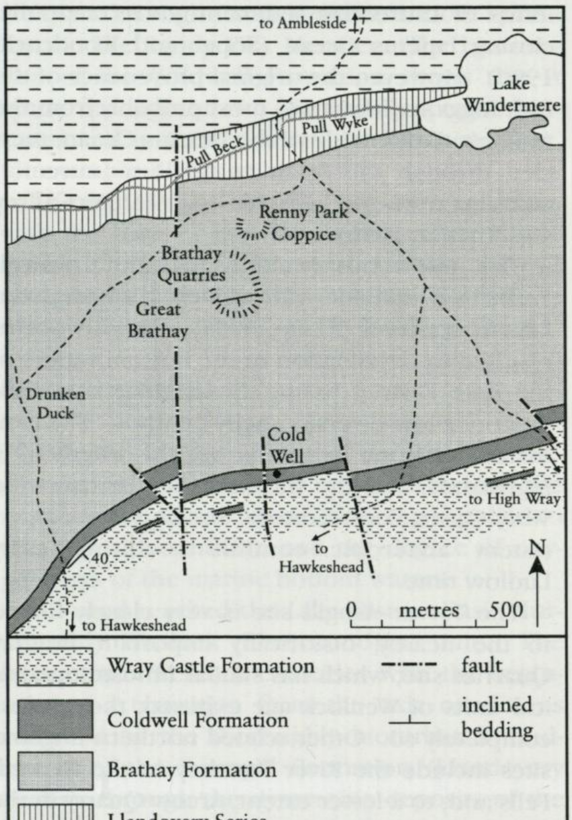


Figure 4.61 Geology of the original type areas of the Brathay and the Coldwell formations, the Lake District (after Rickards, 1989a, with revision of lithostratigraphy after Kneller *et al.*, 1994).

the *linnarssoni* Biozone of the middle Wenlock.

The ground between the Brathay Quarries *sensu stricto* and the High Crag and Cold Well quarries is only intermittently exposed. It contains the upper part of the Brathay Formation and the whole of the Birk Riggs Formation. The latter, sandstone-rich unit comprises thin to very thick, fine- to medium-grained sandstone–mudstone couplets, together with interbedded siltstone–mudstone couplets, intercalated with laminated siltstone typical of the Brathay Formation. The Birk Riggs Formation is of late Wenlock, *lundgreni* Biozone age (Rickards, 1969).

The High Crag and Cold Well quarries expose a 15 m unit of pale blue-grey calcareous siltstone, typically mottled due to bioturbation, which represents the Randy Pike Member of the Coldwell Formation. *Chondrites* burrows are evident in less bioturbated units, as are thin-graded beds of laminated or cross-laminated coarse siltstone. Dark grey laminated siltstone, similar to that in the Brathay Formation, occurs near the top and bottom of the unit. The Randy Pike Member is overlain by a thicker (about 25 m) unit of laminated siltstone and then by a further band of calcareous siltstone (e.g. NY 3575 0087), the latter representing the High Cross Member.

The Randy Pike Member contains a shelly fauna of trilobites, bivalves, crinoid ossicles, brachiopod fragments and orthoconic nautiloids, and its laminated siltstone intercalations yield graptolites characteristic of the *nassa* Biozone. The Coldwell Formation as a whole, however, ranges through the *ludensis* Biozone of the uppermost Wenlock and, based on the presence of *Monograptus varians* near the top of the High Cross Member, into the *nilssoni* Biozone of the lowest Ludlow (Kneller, 1990; Rickards, 1970b).

Cold Well Quarry is the type locality for the trilobite *Delops obtusicaudatus* (Salter, 1849), and the type material from here has subsequently been used by M'Coy (1851c), Salter (1864), Rickards (1965a) and Morris (1988).

Interpretation

The Brathay Formation and Coldwell Formation represent deposition in, respectively, anaerobic and aerobic marine bottom waters of the Silurian Lake District Basin. During times of anaerobic deposition, fallout of silt and organic carbon produced a laminated deposit that remained undisturbed by any benthic fauna. When the bottom waters were aerated in late Wenlock time, probably by a sea-level fall (Kemp, 1991), a relatively rare shelly benthic fauna became established and the sediments were strongly bioturbated. There has been particular debate over the origin and time-calibration of the lamination of the Brathay facies (see Rickards, 1964; Dimberline *et al.*, 1990; Kemp, 1991). This debate is reviewed in the description of the River Rawthey GCR site.

A more complete history of Wenlock deposition can be deduced from the more continuously exposed successions within the very closely linked Torver–Wenlock GCR site, located some 13 km along strike to the south-west. Other complementary GCR sites in northern England include those of the River Rawthey in the Howgill Fells and Arcow Quarry in the Horton-in-Ribblesdale area. All these are relatively offshore sites, and appear to be connected during Wenlock times to similar, deeper water basinal or slope environments in the Welsh Basin, central Ireland, and the East Anglian Basin (see Holland, 1992).

Conclusions

The Brathay Quarries site is historically important in the early development of a lithostratigraphy for the Lake District rocks. Brathay and Cold Well still lend their names to two of the three Wenlock age formations, even though alternative type sections have been proposed within the Torver–Ashgill GCR site. The Brathay and Coldwell formations can be mapped across the Lake District and Howgill Fells, and have direct analogues in other Lower Palaeozoic basins of the old Avalonian continent. The Randy Pike Member of the Coldwell Formation is well displayed within the site, and defined in adjacent ground.

BALMAE COAST (NX 676 465–NX 724 433)

P. D. Lane

Introduction

The Balmae Coast site occupies about 8 km of the cliffs and foreshore of the northern coast of the Solway Firth and eastern side of

Kirkcudbright Bay. Occurring a few kilometres to the south and south-east of Kirkcudbright itself, the rocks included stretch from just north of the Lifeboat Station to the eastern end of White Port (Figure 4.62).

The strata over the whole site have a general strike of ENE–WSW, and are exposed in a number of blocks that are bounded by five major faults. Of these faults, the four to the north and west have a generalized NE–SW trend, whilst that farthest to the east trends approximately NW–SE. These fault blocks contain exposures of strata now recognized as belonging to the Raeberry Castle and Ross formations, which are Wenlock in age (White *et al.*, 1992; Cocks *et al.*, 1992). Both these formations (Kemp and White, 1985; Kemp, 1986; Cocks *et al.*, 1992), or just the Raeberry Castle Formation (White *et al.*, 1992), have been recently considered to comprise the Riccarton Group. The NE-trending fault farthest to the north, just south of the Lifeboat Station, in addition brings exposures of the Hawick Group to feature at this site; this group is now believed to be partly of Wenlock and partly of Llandovery age.

The stratigraphical problems imposed by this tract of land were recognized as long ago as 1851 by Murchison, but the general geology of the area was first described by Lapworth (1878). The latter author recognized the structural com-

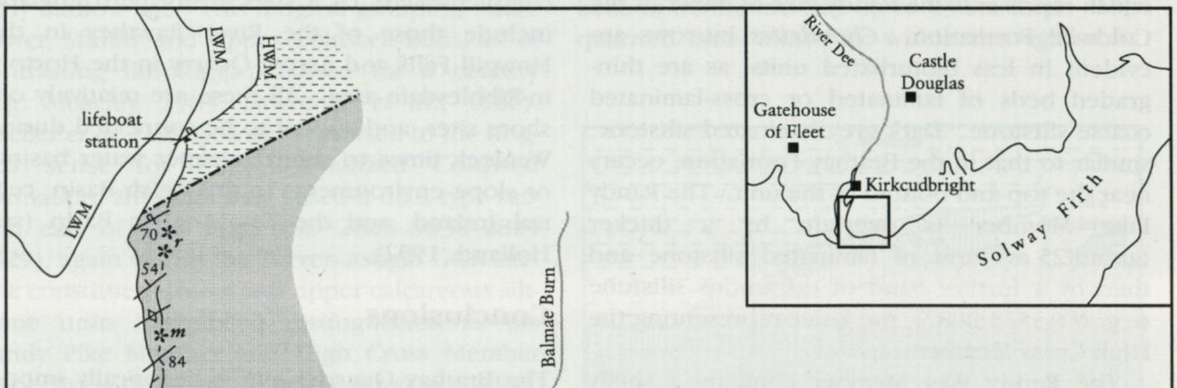


Figure 4.62 Geology of the Balmae coast area, south of Kirkcudbright, Southern Uplands (modified from Clarkson *et al.*, 1975, with minor revision of lithostatigraphical terminology after White *et al.*, 1992).

plexity of the Southern Uplands as a whole, and although only making brief reference to the Kirkcudbright area, stated that the Riccarton Beds were of Wenlock age. Peach and Horne (1899) summarized Lapworth's work; they too considered that the Riccarton Beds more or less equated with the whole of the Wenlock, and they believed that the Hawick Rocks and Queensberry Group below were of Llandovery age, and the Raeberry Castle Beds were of Ludlow age (Figure 4.63). The much later stratigraphical schemes of Craig and Walton (1959) and Clarkson *et al.* (1975) differed radically from earlier ones; in particular, the Raeberry Castle Beds were considered as the oldest and the Hawick Rocks as the youngest units in this area. More recent studies (Kemp, 1985; Kemp and White, 1985; White *et al.*, 1992) have brought general agreement about the stratigraphical order and age of the major lithostratigraphical divisions, the differences being more about questions of stratigraphical terminology rather than stratigraphical relationships (Figure 4.63). The different opinions and the resolution of the problems stemmed from the recognition of the true age relationships of the major groups of rocks preserved in this general area as determined from graptolite biostratigraphy, and through detailed sedimentological and structural analysis.

This Balmae Coast site, and that of Meikle Ross (Borgue Coast) 5 km to the west (see site report), have major geological importance for two particular reasons. The first is that both are important historically, since they played a part in the many interpretations of the complex stratigraphy and structural history of the Lower Palaeozoic rocks of the Southern Uplands. Secondly, they illustrate the effect on a sedimentary sequence of the subduction that finally destroyed the Iapetus Ocean, as Laurentia and Avalonia approached and finally docked. In addition, the Balmae site includes the type section (Kemp, 1986) of the Raeberry Castle Formation.

Description

At the north-west end of the section, the Ross Formation is faulted against the Hawick Group along the structurally important Riccarton Line (Kemp, 1986). To the south and then east, alternating sections of the Ross and Raeberry Castle formations occur with faulted contacts as far as the middle of Mullock Bay. Beyond this to White Port, a stratigraphical section upwards from the Ross to Raeberry Castle formations may be traced; the latter is eventually overstepped to the east by Lower Carboniferous rocks (Clarkson *et al.*, 1975).

The Ross Formation, which is considered (White *et al.*, 1992) to form the upper part of the Hawick Group is more fully described in this chapter in the Meikle Ross site report, its type locality to the west. The formation comprises (Kemp, 1986) various turbidite facies (Figure 4.64). Monotonous thin- to medium-bedded calcareous sandstones of the turbidite facies C and D predominate. Massive facies B sandstones up to 10 m in thickness occur occasionally, and lithologies of larger grain size are very rare. Slumped units of Facies F occur up to a maximum thickness of 3 m. The hemipelagite units are usually 0.1 to 3 m beds in Facies C mudstones and siltstones, and they also occur as rather thinner units in Facies D units.

The Raeberry Castle Formation is characterized by a diverse association of turbidite facies, including:

1. Coarse rudites and arenites of Facies A and B, which occur in channels, and are associated with thinly bedded overbank siltstones and mudstones of Facies E. The coarser sediments (sandstones and conglomerates) contain bioclasts of coral, bryozoan and brachiopod fragments, and rarely limestone boulders, and sandstone clasts, which because of the occurrence in them of haematite are identical to the lithology of the Hawick Rocks.
2. Classic turbidites of Facies C and D.
3. Hemipelagic-dominated, Facies E sediments.

Extensive collection and identification of the graptolite faunas from the area led White in Kemp (1986), to the conclusion that the *murchisoni* and *riccartonensis* biozones could be identified at a number of localities in the Riccarton Group. The following graptolite species were identified there (British Library Supplementary Publication No. 24023, Kemp (1985)): *Cyrtograptus linnarssoni*, *Cyrtograptus* cf. *rigidus cautleyensis*, *Cyrtograptus* sp., *Monograptus capillaceus*, *Monograptus flemingii flemingii*, *Monograptus flexilis flexilis, Monograptus flexilis belophorus*, *Monograptus firmus sedberghensis*, *Monoclimacis flumendosae*, *Monograptus radotinensis inclinatus*, *Monograptus riccartonensis*, *Monograptus* cf.

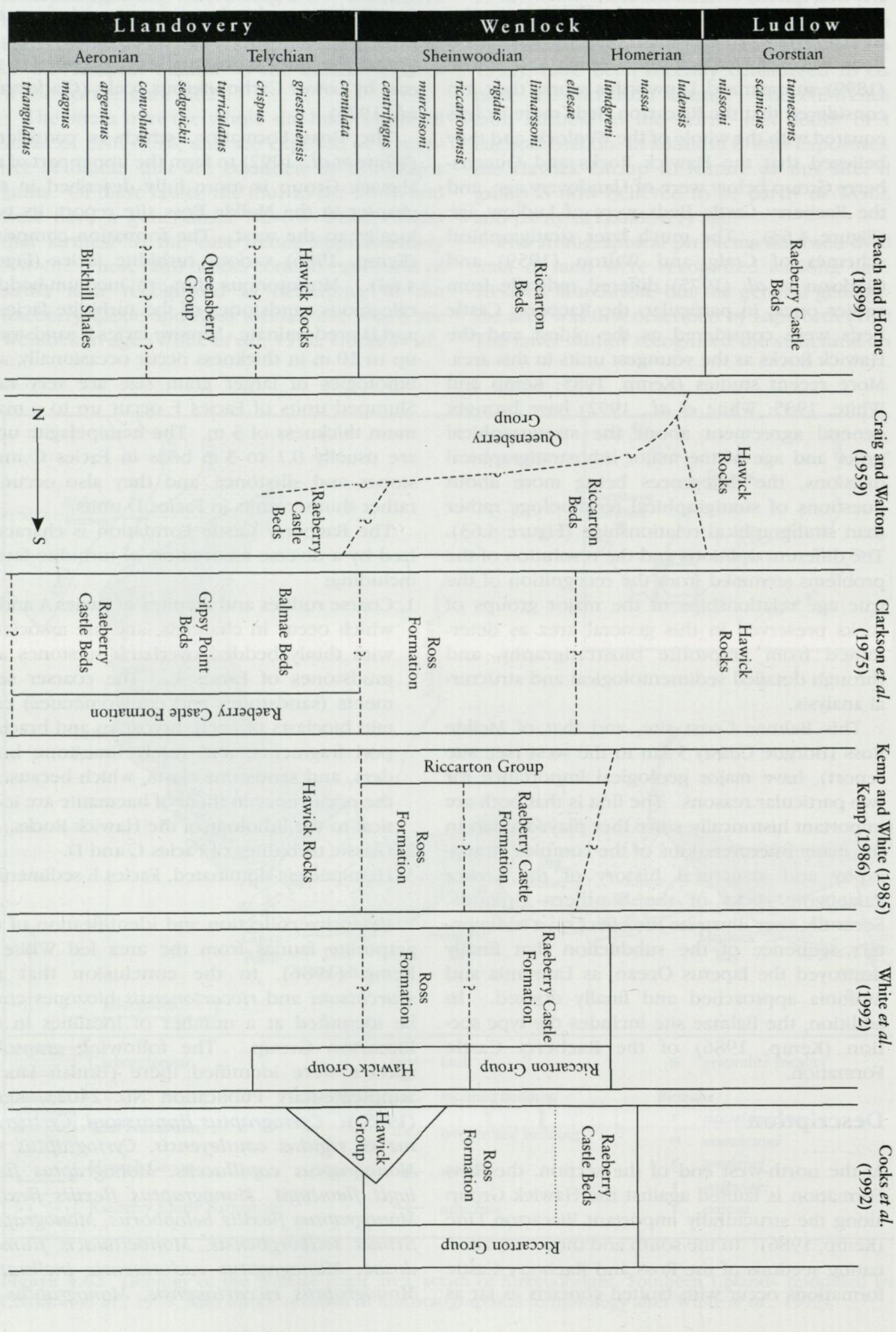


Figure 4.63 Stratigraphical schemes for Silurian strata occurring in the Balmae coast area, south-east of Kirkcudbright, Southern Uplands (after quoted published sources).

Figure 4.64 Balmae Coast. Turbidites of the Ross Formation, Riccarton Group, Wenlock Series, south-east of Torrs Point, Kirkcudbright Bay, Southern Uplands. (Photo: Derek J. Siveter.)

retroflexus*, *Plectograptus bouceki*, *Pristiograptus dubius*, *Pristiograptus pseudodubius*, *Pristiograptus meneghinii meneghinii and ***Monoclimacis vomerina basilica***. More recently White *et al.* (1992), on the basis of graptolite and new acritarch evidence, have proposed that the Ross Formation is of ***centrifugus*** to upper ***riccartonensis*** Biozone age, whilst the Raeberry Castle Formation is of upper ***riccartonensis*** to ***lundgreni*** Biozone age.

Interpretation

Peach and Horne (1899) summarized the earlier work of Lapworth (1878). Compared to his study, some of the subsequent research suggested that the Silurian sequence was in fact reversed (Figure 4.63). For example, Craig and Walton (1959) considered that the stratigraphical interval represented by the sequence now believed to be of uppermost Llandovery to Wenlock in age, spanned the Llandovery to Ludlow, with the Raeberry Castle Beds oldest, and Hawick Rocks youngest. Clarkson *et al.* (1975), with some revision of stratigraphical terminology, had the same order of stratigraphy as Craig and Walton (1959), but with the Silurian sequence encompassing a greater time interval (Figure 4.63). More recently, stratigraphical schemes much closer to that of Peach and Horne (1899) have been proposed (Kemp and White, 1985; Kemp, 1986). In these schemes, the Hawick Rocks were considered oldest and entirely of Llandovery age, whilst the Riccarton Group (embracing the Ross and Raeberry Castle formations) was of earliest Wenlock to mid- or late Wenlock (*ellesae* to *lundgreni* Biozone) age. The stratigraphical scheme proposed by White *et al.* (1992) was similar to that of the earlier proposals of Kemp (1985) and Kemp and White (1985); it differs in that the Ross Formation was now considered to comprise the upper, early Wenlock part of the Hawick Group, with a stratigraphical range of ***centrifugus*** to upper ***riccartonensis*** biozones. The Raeberry Castle Formation was equated by White *et al.* (1992) with the entire Riccarton Group, and correlated with the uppermost *riccartonensis* to *lundgreni* biozones. The stratigraphy and stratigraphical range for the sequence which Cocks *et al.* (1992) illustrated, differed from that of Kemp and White (1985) in having the Hawick Group with a stratigraphical range of middle Telychian to lower Wenlock, and being partly a lateral equivalent of the lowest part of the Riccarton Group, the base of which was coincident with the base of the Wenlock; their Riccarton Group embraced the whole of the Ross Formation and the Raeberry Castle Beds (Figure 4.63).

There are at present two major types of geotectonic model for the evolution of the rocks of the Southern Uplands. The work of McKerrow *et al.* (1977) and Leggett *et al.* (1979a, b, 1982), which was based in part on the rocks exposed at this site, resulted in the formulation of the 'accretionary prism' model, whilst Stone *et al.* (1987) proposed that the rocks comprising the Southern Uplands region were deposited in a back-arc basin. Both of these models include the development of an imbricate thrust stack, but involving a sedimentary sequence deposited in different geotectonic positions. During the later Ordovician and the Silurian, the area lay on the northern margin of the Iapetus Ocean, which finally closed along a NE–SW line through the Solway Firth (Cope *et al.*, 1992). In these two models, the Southern Uplands Massif as a whole is composed of a series of NE–SW trending fault blocks; in general, from north-west to south-east, each block shows rocks of successively younger age, yet within each block the younging direction is to the north-west (Figure 3.68). As a variation on these models Moseley (1977, 1978) considered that the Iapetus Ocean had been closed by the end of the Ordovician, so that there was no subduction in the Southern Uplands during the Silurian.

In this, the Kirkcudbright area, the Raeberry Castle Formation comprises three internally coherent tectonic units separated by relatively narrow (< 50 m) shear zones (Kemp, 1986). These three units probably represent successively accreted (underthrust) packets of sediment, which had accumulated on the northern margin of the Iapetus Ocean in the final stages of the ocean's existence. The 0.8 to 1.2 km thickness of these packets accords with the dimensions inferred from some modern active margins, such as in the Amlia sector of the Aleutian Trench (McArthy *et al.*, 1984). Thus, the northern subduction, which finally destroyed Iapetus as Laurentia and Avalonia approached, was responsible for the stratigraphy now displayed. Kemp (1987) has integrated sedimentological and structural information to try to understand the control on the sequence by the interaction and interdependence of these two aspects.

The imbricate stack model of Leggett *et al.* (1982) is that which is now generally accepted as the most plausible for the Southern Uplands. It has been shown to hold for the Balmae Coast site and also for the Kirkcudbright area in general, particularly following a refinement of the graptolite biostratigraphy (Rushton *et al.*, 1996). This model, however, does not explain the sequences seen in the whole of the Southern Uplands tract. Some 100 km to the north-east in the Peebles–Hawick area the greywacke sequence, which is of the same general age as the sequence in the Kirkcudbright area, conforms to the imbricate stack model only in its lowest and the uppermost parts. In the north-east part of the Southern Uplands, however, in the middle part of the greywacke sequence (mid- to late-Llandovery in age), out-of-sequence thrusting has been recognized, which has been attributed to the presence of some obstacle to simple forward-thrust propagation (Rushton *et al.*, 1996).

The Balmae Coast site is the stratigraphical, structural and sedimentological complement of its sister site, Meikle Ross (Borgue Coast). Particularly in exhibiting a fully marine, graptolitic sequence, the Balmae Coast site contrasts with other Scottish Silurian sites showing rocks of similar age, but of contrasting tectonostratigraphical position. To the north, in the Midland Valley of Scotland, sites in the Pentland Hills (Lyne Water and Lynslie Burn), the Hagshaw–Lesmahagow area (Ree Burn–Glenbuck Loch), and in the eastern part of the Girvan area (Knockgardner), all illustrate the early onset of non-marine conditions at about the Llandovery–Wenlock boundary interval, or at the latest in early Wenlock times.

Conclusions

This site (and its sister site of Meikle Ross) has much historical importance. The difficulties of the structural interpretation of the Scottish Southern Uplands, including this area, were first recognized in the mid-19th century by Murchison, and have been under detailed study since that time. The site is crucial for understanding the structural development of the Southern Uplands, and its impact on the details of the progressive closing of the Iapetus Ocean during the Silurian. The regular southward-propagating thrust model, which has been demonstrated at this site contrasts with the less regular, partly out-of-sequence thrust model developed in rocks of similar age and facies in the Peebles–Hawick area about 100 km to the north-east. These thrust models have been largely constrained by the fine-scale biostratigraphy that has been performed on the graptolites and acritarchs preserved in this and nearby sections. In addition the sediments, which are well exposed in these coastal sites, afford fine examples of all facies of classical Lower Palaeozoic turbidite sedimentation in a deep marine environment. The contrast with the mainly non-marine, red-bed Wenlock sequences of sites in the Midland Valley serves to illustrate the complex Lower Palaeozoic history shown by the rocks of southern Scotland.

MEIKLE ROSS (BORGUE COAST) (NX 634 446–NX 656 460)

P. D. Lane

Introduction

The Meikle Ross (Borgue Coast) site lies on the north margin of the Solway Firth, Kirkcudbrightshire. It embraces the cliff and foreshore of both the southern extremity of the Borgue coastline and, across a narrow stretch of water (The Sound) to the south-east, the island of Little Ross. The cliff and foreshore exposures of about 4 km of the mainland coastline, stretching from Mull Point on the west coast, to 200 m east of the ruins of Senwick Church in the east, and on Little Ross, the whole of the coastline (about 1 km), are included (Figure 4.65).

The strata exposed at the site have a general strike of ENE–WSW, and those of Wenlock age belong to what are now recognized as the younger part of the Hawick Group, and the Ross Formation, which is considered by most authors to form the lower part of the Riccarton Group (Kemp and White, 1985; Kemp, 1986; Cocks *et al.*, 1992). The contact between the two stratigraphical divisions is everywhere mapped as a fault; this fault, like the strike of the sediments, trends ENE–WSW. All the strata are steeply to highly inclined, or inverted.

The problems posed by the rocks of this site, and those on the nearby Balmae Coast to the east (see above in this chapter), are in an area the geological complexity of which was first recognized by Murchison (1851). The initial description was by Lapworth (1878), who recognized the structural complexity of the Southern Uplands as a whole, and although only making brief reference to the Kirkcudbright area, stated that the Riccarton Beds were of Wenlock age. Peach and Horne (1899) summarized Lapworth's work; they too considered that the Riccarton Beds approximated to the whole of the Wenlock, and they believed the Hawick Rocks to be older (Figure 4.63). The later stratigraphical schemes of Craig and Walton (1959) and Clarkson *et al.* (1975) differed radically from earlier ones. In these schemes, the Raeberry Castle Beds were considered the oldest and the Hawick Rocks as the youngest units in this area. More recent studies (Kemp, 1985; Kemp and White, 1985; White *et al.*, 1992) have brought general agreement about the stratigraphical order and age of the major lithostratigraphical divisions, the differences being more about questions of stratigraphical terminology rather than relative stratigraphical position (Figure 4.63).

The different opinions and the resolution of the problems have stemmed from the recognition of the true ages and relationships of the major groups of rocks that are preserved in this general area. Particularly, ages determined from graptolite and palynomorph biostratigraphy have contributed to the debate, and sedimentological and structural analysis have added to an understanding of the whole geological history.

The Meikle Ross (Borgue Coast) site and that of the Balmae Coast have particular geological importance for two major reasons. Firstly, they are crucial in the resolution of the dispute which extends back to the 19th century about the relative ages of the major groups of rocks exposed (the Hawick Group and the Riccarton Group), and secondly, they are important in the understanding of the overall geological structure of the Scottish Southern Uplands; their study culminated in the formulation of the 'accretionary prism' model of Leggett *et al.* (1982), a model that although generally accepted, has been challenged and refined more recently (see 'Interpretation' section below). In addition, the Meikle Ross site gives its name to and includes the type section of the Ross Formation (Kemp, 1986), and the site is crucial in understanding the character of the Riccarton Line in the southern part of the Southern Uplands.

Description

The Hawick Group comprises very monotonous thinly to thickly bedded turbiditic greywackes and calcareous sandstones of Facies C and D

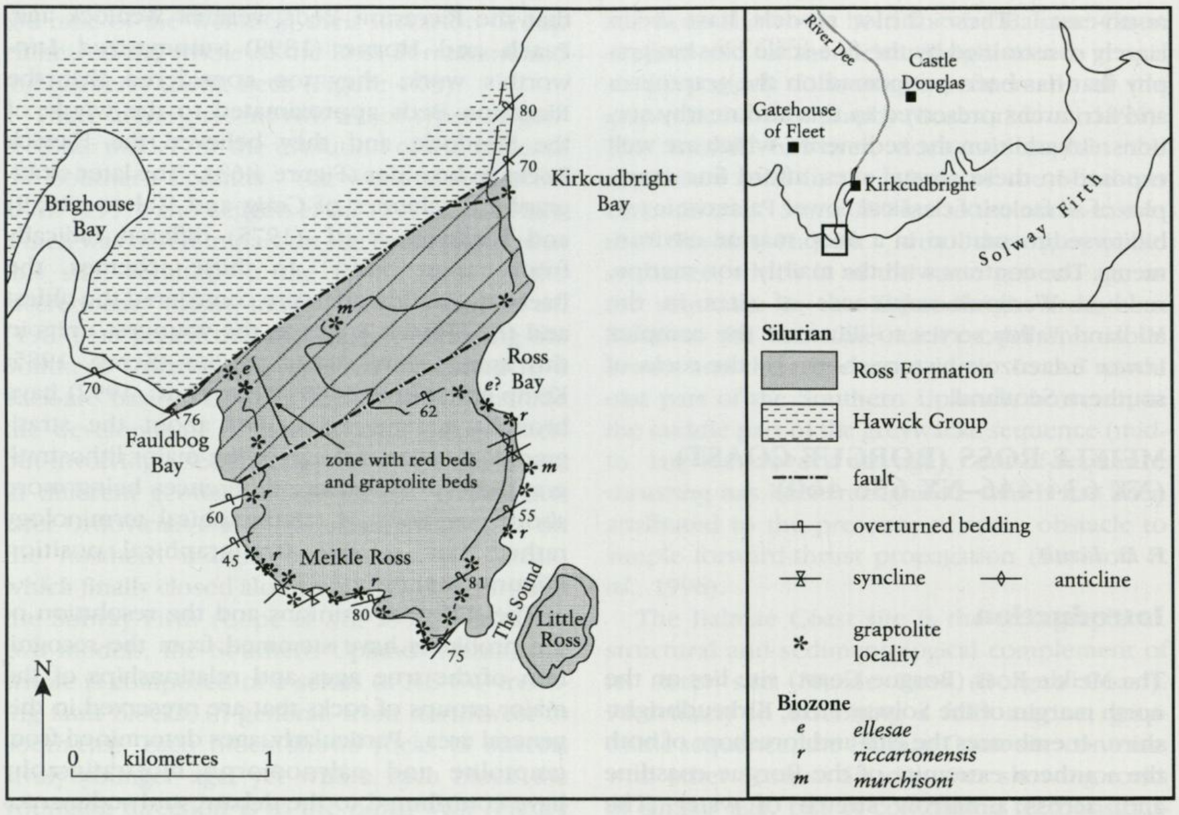


Figure 4.65 Geology of the Meikle Ross (Borgue coast) area, SSW of Kirkcudbright, Southern Uplands (modified from Clarkson *et al.*, 1975, with minor revision of lithostatigraphical terminology after White *et al.*, 1992).

type, with intercalated Facies F horizons of slumped sediment (Kemp, 1986). Interbedded with the turbidite facies are structureless red and olive-grey mudstones. The red mudstones are up to 5 m thick, and in the olive-grey mudstones display distinctive packets of fine red laminae. As a whole, both in the general area and at the Meikle site, there are no body fossils. Diverse trace fossil assemblages are common, however; *Paleodictyon*, *Dictyodora scotica*, *Protovirgularia*, *Gordia* and forms of *Planolites* have been recorded (Benton, 1982).

The Ross Formation is predominantly characterized by monotonous thin- to medium-bedded calcareous sandstones of the classical turbidite Facies C and D. Massive coarse sandstones with a maximum thickness of 10 m referable to Facies B occur sporadically, and lithologies of very coarse sand or larger grade are very rare. Facies F slumped units occur to a maximum thickness of 3 m; these hemipelagite units are usually developed as 0.1 to 3 m beds within Facies C turbidite mudstone and siltstones, and as rather thinner units (of 1–100 mm thickness) in Facies D units. The type section of the Ross Formation lies on the west side of the Meikle Ross peninsula.

The Ross Formation, unlike the Hawick Group, has an almost total absence of trace fossils. Graptolites, the major group available for biostratigraphical dating of the formation, have been obtained from many localities at the Meikle Ross site (White in Kemp, 1986). Although they are not well preserved, they have enabled most of the Wenlock succession to be recognized here, although the very top of the series has not been proven. Of the macrofossils, other than the graptolites, only orthoconic cephalopods have been collected. Graptolites have been collected from both the lower and the upper units, which have been recognized in the Ross Formation. The lower unit yielded *Cyrtograptus centrifugus*, *Cyrtograptus insectus*, *Retiolites geinitzianus geinitzianus*, *Retiolites geinitzianus angustidens*, *Monoclimacis vomerina vomerina*, *Monoclimacis vomerina basilica*, and *Monograptus priodon*, which together indicate a *centrifugus* to *murchisoni* Biozone age. The upper unit contains a fauna in which *Monograptus riccartonensis* is dominant, and which also includes *Monograptus firmus sedberghensis*, *Monograptus radotinensis inclinatus*, *M. priodon*, *M. vomerina vomerina* and *M. vomerina basilica*. These indicate the presence of the *riccartonensis* Biozone.

Separating the Hawick Group in the north of the site from the Ross Formation in the south is a major fault, which here represents the presence in the area of an important structural feature, the Riccarton Line. This line can be traced in the sequences of the Southern Uplands (and their stratigraphical equivalents) from the east coast of Scotland to Dundalk in Northern Ireland. Everywhere, it is taken to mark the southern boundary of the Hawick Group (Kemp, 1986). At the Meikle Ross site, a 500 m wide, highly complex and tectonized zone immediately south of the Riccarton Line (the 'zone with red beds and graptolite beds'; Figure 4.65), indicates the complex tectonic intercalation of rocks of the distinctive red mudstones of the Hawick Group and the contrasting, dark, argillaceous and graptolitic turbidites of the Ross Formation.

Interpretation

In the Southern Uplands many NE–SW trending strike faults are present, and although the sequence as a whole youngs to the south-east, individual fault-bounded sequences young to the north-west. There are at present two major geotectonic models that have been proposed to explain the evolution of the rocks of this region, to which the Meikle Ross site has contributed. McKerrow *et al.* (1977) and Leggett *et al.* (1979a, b; 1982) suggested that the Southern Uplands, including the rocks exposed at this site, resulted from the formation of an 'accretionary prism'. However, Stone *et al.* (1987) proposed that the rocks of the Southern Uplands were deposited in a back-arc basin. Both of these models include the development of an imbricate thrust stack, but on a sedimentary sequence deposited in different geotectonic positions. These two models are fully described in the Balmae Coast site report above.

This Meikle Ross (Borgue Coast) site networks very closely with the Balmae Coast site to the east. Each of the two exhibit a fully marine, offshore, graptolitic sedimentary sequence that is in stark contrast to the Scottish Midland Valley sites, which are now not far geographically removed, but which were deposited in very different tectonostratigraphical situations. The Midland Valley sites in the Pentland Hills (Lyne Water and Lynslie Burn site), in the Hagshaw-Lesmahagow area (Ree Burn–Glenbuck Loch site), and the eastern part of the Girvan Inlier (Knockgardner site), all illustrate the early onset of non-marine conditions at about the Llandovery–Wenlock boundary, or at latest in early Wenlock times.

Conclusions

This Meikle Ross (Borgue Coast) site and its sister site to the east (Balmae Coast) have much historical importance. Lapworth in the late 19th century was first to describe the rocks of this area in an attempt to resolve the geological problems that had been earlier recognized by Murchison. The sites have great significance for understanding the structural development of the Southern Uplands of Scotland, and for the interpretation of the mechanisms involved in the progressive narrowing and destruction of the Iapetus Ocean. Recent biostratigraphical refinement has allowed new insights into the differences of this closure in this area as compared to that in the Peebles area about 100 km to the north-east.

The site houses the type section of the Ross Formation, and illustrates the complex structural interdigitation of the Hawick Group and the Ross Formation at, and just south of, the structurally important Riccarton Line. In addition, the well-exposed sediments in this coastal site show excellent examples of most of the facies of Lower Palaeozoic turbidite sedimentation.

KNOCKGARDNER (NS 355 036)

D. Palmer

Introduction

This site comprises a small field quarry some 350 m east of Knockgardner, 14 km ENE of Girvan in the south-western part of the Midland Valley of Scotland. The quarry exposes Wenlock age strata of the Knockgardner Formation within an inlier of Silurian rocks surrounded and

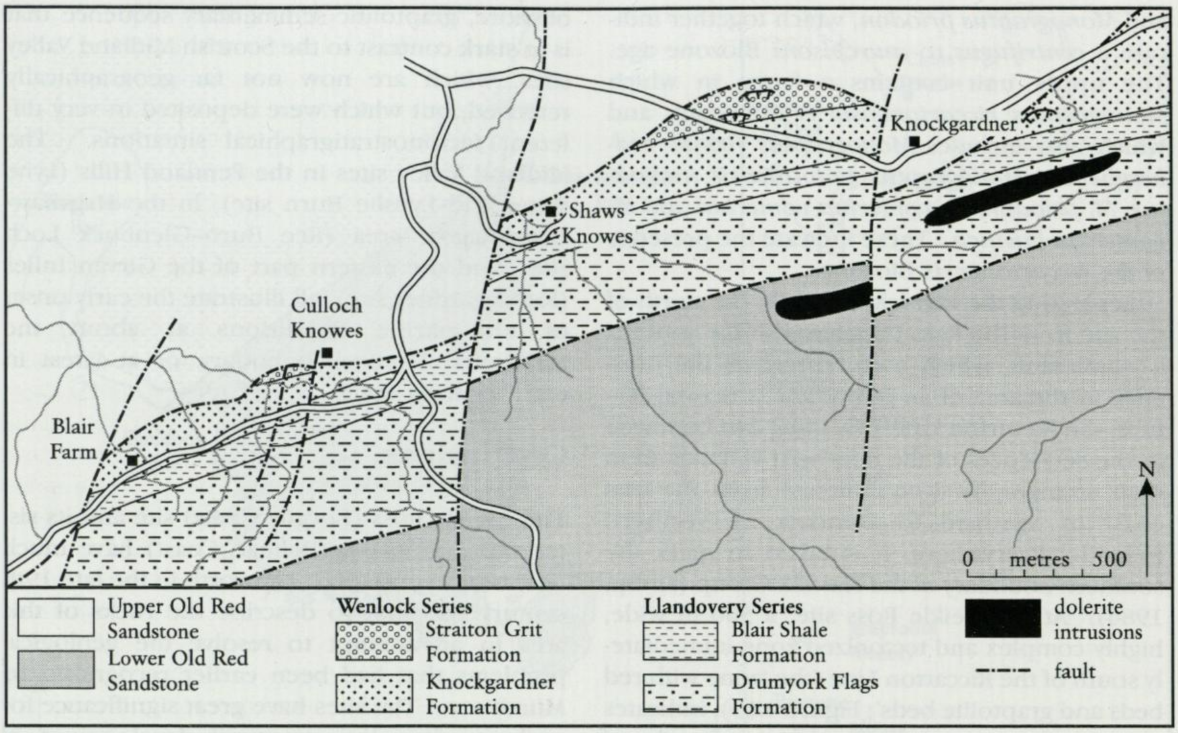


Figure 4.66 Geology of the area between Knockgardner and Blair Farm, Girvan District (after Clarkson *et al.*, 1998, and Cocks and Toghill, 1973).

unconformably overlain by younger Old Red Sandstone (Figure 4.66). Overall, the inlier exposes a sequence, some 700 m thick, of Silurian flags and shales passing up into grits and conglomerates.

The most significant early mapping and description of these strata by Lapworth (1882) named them as the Straiton Group and subdivided the sequence into the same basic units that are recognized today – in ascending order, Drumyork flags, Blair flags and shales, Knockgardner shales and Straiton grits and conglomerates. Peach and Horne (1899) developed their palaeontological diagnosis of the age of the strata through the discovery of new fossiliferous localities in the Blair and Knockgardner beds, and notably through the rich shelly fossil assemblage obtained from the Knockgardner beds at the present site. They recognized a Wenlock age for the Blair to Straiton beds, and for the same sequence this was refined to early Wenlock by Pringle (1948).

Lamont (1965, 1978) described and discussed trilobites from the Midland Valley of Scotland (revised by Howells, 1982). These were overwhelmingly from the Pentland and Hagshaw hills, though he also alluded to trilobites from the Knockgardner area and disputed the correlation of the Knockgardner Formation with the lower Wenlock. However, in their wide-ranging revision of the biostratigraphy of the Silurian of the Girvan area, Cocks and Toghill (1973) reaffirmed an early Wenlock age for this formation, and this has been supported by Dorning (1982) and by Wellman and Richardson (1993) on the basis of palynofacies studies. This age has also been accepted by Clarkson *et al.* (1977) in their study of Silurian phacopid trilobites from Scotland, and further endorsed most recently by Clarkson *et al.* (1998) on the basis of their review of the basal Wenlock biofacies of the Knockgardner area. These last authors developed a new palaeoenvironmental interpretation for the Drumyork through to Straiton formations, in particular for the Knockgardner Formation, and they discussed the nature and distribution of the faunas of the site within the overall context of the Midland Valley. They also formalized the stratigraphical terminology of the Drumyork Flags, Blair, and Straiton Grit formations, the Knockgardner Formation having been formalized earlier by Cocks and Toghill (1973).

The shelly fauna and microflora from the Knockgardner Formation of this site are, thus, very important in proving that the Silurian succession in the Girvan area of the Midland Valley extends upwards to include rocks of Wenlock age, and that fully marine albeit shallow water conditions existed there at this time.

Description

The site itself comprises only the Knockgardner Formation, and there are a limited number of other exposures of Straiton Group strata along the ENE–WSW strike over a distance of 4 km between Blair Farm and Knockgardner. Recent remapping of the area by Clarkson *et al.* (1998) has added considerable detail to that provided by Cocks and Toghill (1973).

The lowest unit of the Straiton Group, the Drumyork Flags Formation, consists of some 380 m of generally unfossiliferous thinly bedded siltstones and shales alternating with thicker turbidites, in which three lithofacies variants have been recognized. Above, the Blair Shale Formation, exposed around Blair Farm, is made up of alternating thin shales, silt laminae and thicker sandstones. Some units of this formation are bioturbated and a graptolite fauna recorded by Cocks and Toghill (1973) indicates, in contrast to the Wenlock age for these beds recognized by Peach and Horne (1899), the presence of the *crenulata* Biozone, which lies at the top of the Telychian Stage of the Llandovery Series. A Llandovery age for the Blair Shale Formation has been subsequently confirmed by reassessment of its graptolite fauna by Loydell (Clarkson *et al.*, 1998).

The overlying Knockgardner Formation, which is up to 141 m thick, also consists of alternations of laminated shales, siltstones and thin-bedded sandstones. Clarkson *et al.* (1998) recognized three successive facies, of which the lowest is some 40–50 m thick with dark shales and graded sandstones up to 14 cm thick, some with shell accumulations near the base and occasionally trace fossils.

The middle facies, which is about 100 m thick, is best exposed in the stream south of Shaws Knowes and at the present quarry site. According to the sediment log of the site (Clarkson *et al.*, 1998; Figure 4.67), there is an equal proportion of sandstone beds (up to 16 cm thick) and shale. These laterally extensive sandstones display delayed grading, cross-stratification and herring-bone cross-sets. Dark laminae within finer and lighter-coloured sandstones are highly fossiliferous in places.

The highest facies of the Knockgardner Formation, estimated at 30–40 m thickness, comprises thin shales and silts, and is best exposed in a stream near Craigens Wood, west of Straiton. Shales dominate the sequence and occasionally show desiccation cracks and abundant trace fossils.

The top unit of the Straiton Group, the Straiton Grit Formation, is some 90 m thick and is best exposed in Shiel Burn and two small quarries north of the Kirkbride–Knockgardner road. Two laterally interfingering facies can be distinguished with brown sandstones, up to 1.2 m thick, passing into coarser conglomeratic and cross-stratified sandstones, up to 1.5 m thick. The largest pebbles reach 6 cm in size and consist predominantly of quartz and jasper.

Palaeontologically, the Knockgardner Formation has long been recognized as containing a very important and interesting fauna, ever since Lapworth (1882) found abundant shells of the ostracod '*Beyrichia kloedeni*' in the shales near Knockgardner Farm. Peach and Horne (1899) made the more important find of abundant brachiopods and trilobites in rocks of the same formation and, from this and associated discoveries, they assessed the age of the Silurian strata hereabouts.

Details of the fauna and sediments were not published until Cocks and Toghill (1973) published their revision of the Girvan Silurian and described from the Knockgardner Formation a shallow-water assemblage dominated by species of the brachiopods *Protochonetes* and *Resserella*, and *Atrypa reticularis* and *Howellella elegans*. Similar assemblages are found in the Anglo-Welsh Basin, the Baltic region and Bohemia. Dorning's analysis (1982) of the acritarch flora showed comparisons with early Wenlock assemblages from the Anglo-Welsh Basin and contemporary carbonate sediments on Gotland.

The shelly fauna of the Knockgardner Formation has been reviewed in further detail by Clarkson *et al.* (1998). Their analysis of the brachiopods broadly agrees with that of Cocks and Toghill (1973), with three of the above-listed species dominating the overall fauna of 12

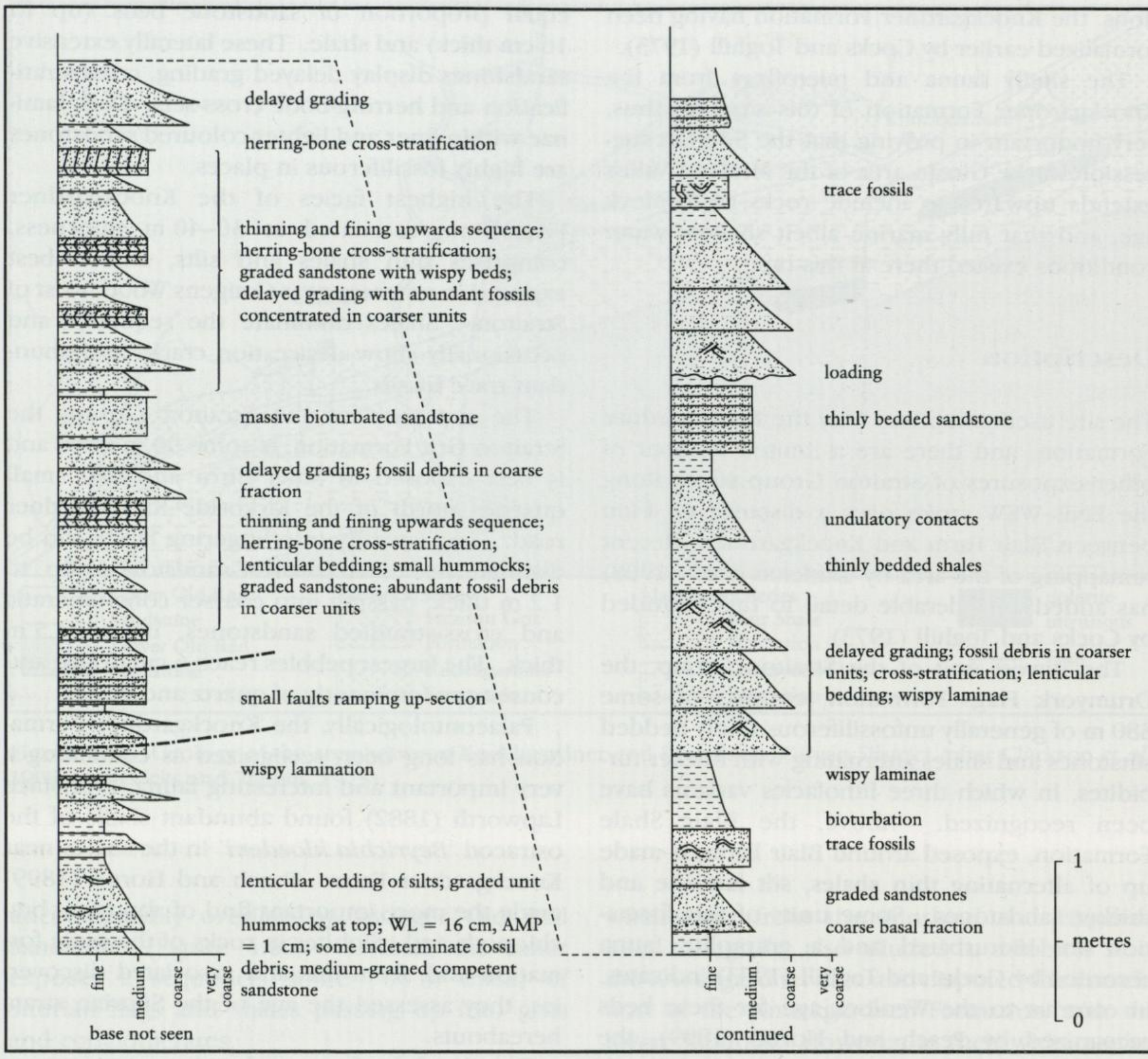


Figure 4.67 Sedimentary log through the Knockgardner Formation, Knockgardner Quarry, 350 m east of Knockgardner Farmhouse, Girvan district (after Clarkson *et al.*, 1998).

species of brachiopod in a total fauna of 20 or so taxa, including trilobites, bryozoans, gastropods, ostracods and small solitary corals. Of the trilobites, four species occur at Knockgardner: *Podowrinella straitonensis*, the last recorded survivor of the Pterygometopidae, *Wallacia hagshawensis*, *Richterarges rolfei* and *Warburgella (Warburgella) capetos*, all of which are fully described by Howells (1982). These trilobites, named the *Podowrinella* assemblage by Clarkson *et al.* (1998), have been found to recur as a resedimented and endemic fauna throughout the Silurian inliers of the Midland Valley. The well-known Silurian trilobite assemblages of the Anglo-Welsh and Bohemian basins are quite different.

Lamont (1978), Dorning (1982), Howells (1982), Clarkson *et al.* (1977) and especially Clarkson *et al.* (1998) all figure and describe invertebrate fossils from this Knockgardner site, and it stands as the type locality for, at least, *Warburgella* (*Warburgella*) *capetos* Howells (1982).

Interpretation

The coarsening upwards sequence of Silurian strata reflects a regressive shallowing succession

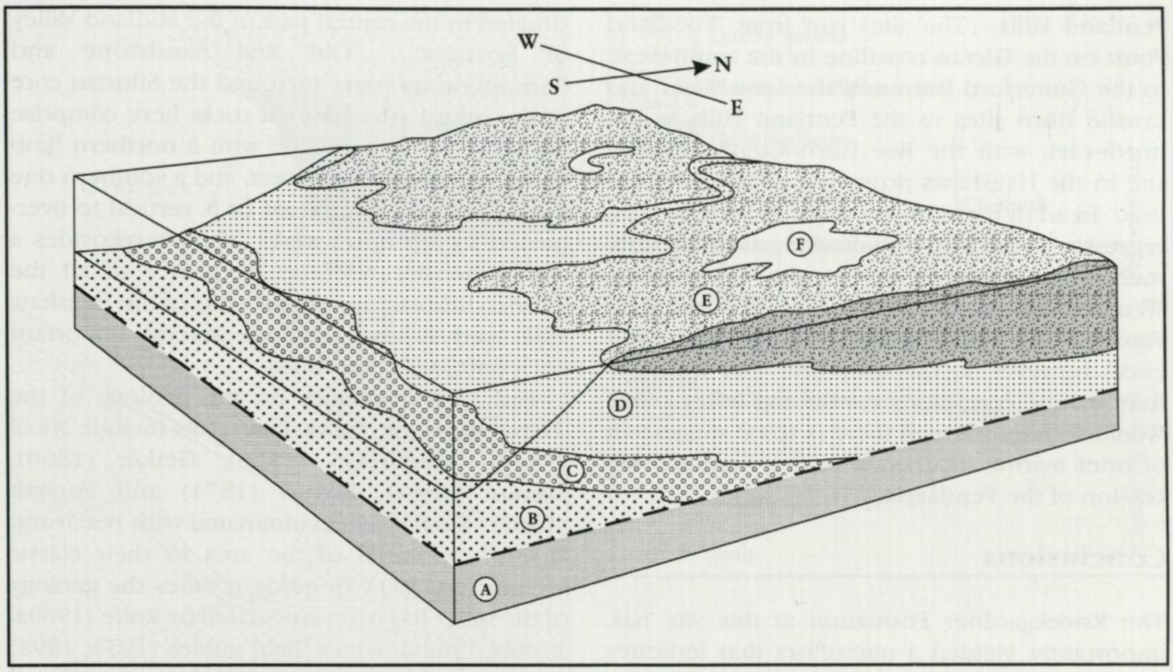


Figure 4.68 Schematic block diagram illustrating depositional environments within the middle and upper part of the Straiton Group (latest Llandovery to early Wenlock in age), Knockgardner area, Girvan district. (A), Deep water graptolitic shales of the Blair Formation. Tectonic excision along the contact with the overlying Knockgardner Formation may have removed the more proximal mid to outer shelf facies to juxtapose deep-water sediments with shallow water facies at the junction between the two formations. (B), (C), and (D), in upward sequence, through the Knockgardner Formation, shallow-water prodelta facies (B), overlain by intertidal deposits subject to storm surges (C), and then shallow-water delta front sediments (D). (E) and (F), coarse grained back barrier facies (E) and lagoonal facies (F) of the Straiton Formation (after Clarkson *et al.*, 1998).

of marine to freshwater deposits (Figure 4.68) with associated biotic changes. The Drumyork Flags and Blair Shales were relatively deep-water marine deposits in quiet waters with repeated influxes of low-velocity density currents that brought in fine sands.

There is some dispute over the interpretation of the overlying Knockgardner Formation deposits, with Cocks and Toghill (1973) characterizing them as relatively deep-water turbidites, whilst Dorning (1982) and Clarkson *et al.* (1998) re-interpreted them as shallow water in origin. According to this last study, the three successive facies of the formation reflect shelf-prodelta deposits, followed by intertidal and then delta-front to lagoonal conditions of deposition. The succeeding Straiton Formation represents marine to non-marine flooding of coastal lagoons, with coarse-grained sediments and the development of back-barriers on the shore-side that migrated seawards as sea level fell.

The *Podowrinella* assemblage is interpreted by Clarkson *et al.* (1998) as a specialized and mobile but endemic fauna in the Midland Valley of Scotland, adapted for life in shallow water, high-energy conditions. By contrast, the sessile benthic brachiopod assemblage of *Protochonetes*, *Atrypa reticularis* and *Howellella elegans* is much more cosmopolitan. Its main faunal elements have wide spatial and temporal distributions within mid-Silurian deposits on both sides of a closing Iapetus Ocean (Watkins, 1978b). Clarkson *et al.* (1998) speculated that the differences between the two faunal assemblages reflects contrasting reproductive strategies and larval longevities.

Knockgardner forms part of an important network of sites in the Midland Valley that links together various Silurian inliers, all of which have Llandovery–Wenlock sequences. In addition to the Girvan area, these inliers comprise the Hagshaw Hills, the Lesmahagow area and the

Pentland Hills. The sites run from Woodland Point on the Girvan coastline in the south-west, to the Gutterford Burn and the Lyne Water and Lynslie Burn sites in the Pentland Hills in the north-east, with the Ree Burn–Glenbuck Loch site in the Hagshaws providing an intermediate link. In all of these inliers there is evidence of a regressive, marine to non-marine palaeoenvironmental transition at about the Llandovery–Wenlock boundary interval (see, for example, Figure 3.83). The Knockgardner, Girvan sequence, however, is the only one that indicates fully marine conditions continuing into earliest Wenlock times, though there is some suggestion of brief marine incursions in the Wenlock succession of the Pentlands.

Conclusions

The Knockgardner Formation at this site has, importantly, yielded a microflora that indicates an early Wenlock age for what is almost the youngest part of the Silurian succession of the Girvan area, in the south-western part of the Midland Valley of Scotland. In addition, the rich shelly fauna and sediments of this formation present at the site indicate that marine conditions persisted in this area at this time, unlike in other Silurian areas (inliers) of the Midland Valley where the change to non-marine conditions has been placed at the slightly earlier Llandovery–Wenlock boundary level. The brachiopods and trilobites from the site have been interpreted as representing two different types of ecological association, the former cosmopolitan and the latter endemic to the Midland Valley.

The site can be networked in particular to two other sites in the Midland Valley (Ree Burn–Glenbuck Loch in the Hagshaw Hills, and Lyne Water and Lynslie Burn in the Pentland Hills). Altogether these sites preserve a record of the Silurian marine regression in the region as the Iapetus Ocean closed.

REE BURN–GLENBUCK LOCH (NS 7618 2737–NS 7604 2865)

David J. Siveter

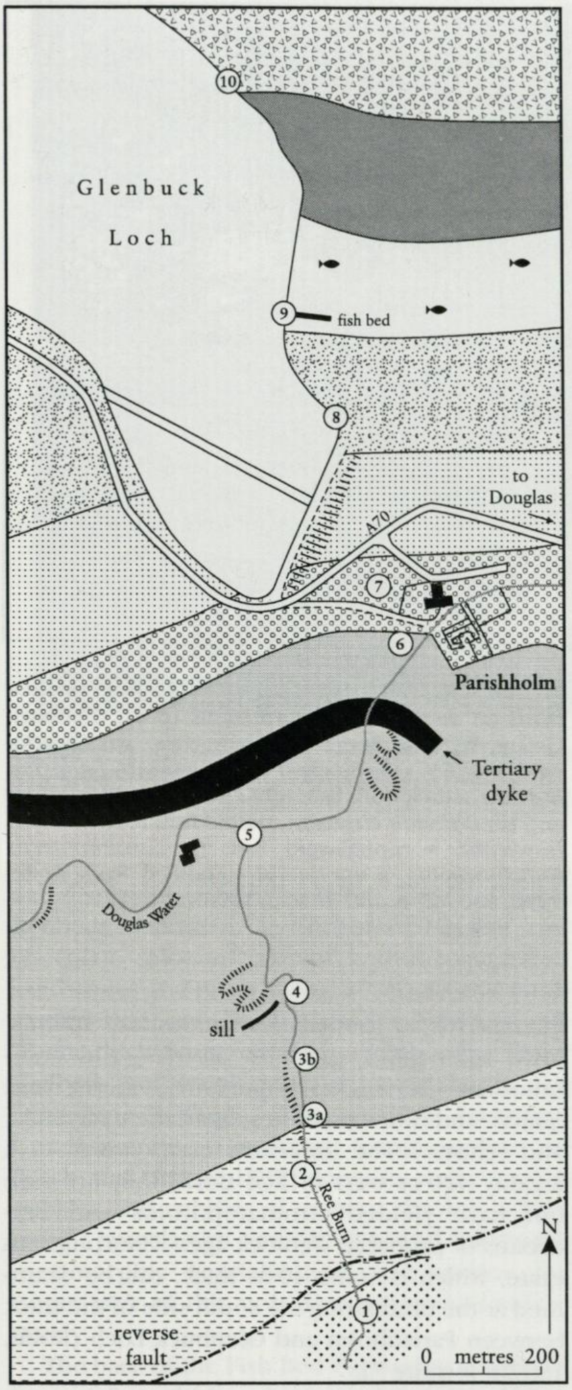
Introduction

This site consists of numerous exposures along Ree Burn and the eastern shores of Glenbuck Loch in the Silurian inlier of the Hagshaw Hills, situated in the central part of the Midland Valley of Scotland. Old Red Sandstone and Carboniferous strata surround the Silurian core of the inlier. The Silurian rocks here comprise an asymmetrical anticline with a northern limb that dips steeply north-west, and a southern one that dips to the south-east or is vertical to overturned to dip north-west. The site provides a comprehensive reference sequence of all the Silurian lithostratigraphical units of the Hagshaw Hills and it also includes several important palaeontological localities.

Early commentators on the geology of the 'Haughshaw' or 'Hawkshaw' Hills include Nicol (1844), Murchison (1856), Geikie (1860), Slimon (1864), Brown (1874) and Forsyth (1881). Such studies culminated with Peach and Horne's appraisal of the area in their classic Memoir of 1899. In modern times the geology of the inlier has been elucidated by Rolfe (1960a, 1960b, 1962a), whose field guides (1973, 1992) provide excellent summaries of the Ree Burn–Glenbuck Loch site.

The specific age of the Silurian strata of the Hagshaw Hills and their correlation with those of other Midland Valley Silurian inliers is often somewhat uncertain. The rocks of nearby inliers at Lesmahagow, Carmichael and the Pentland Hills are of broadly similar age and facies to those of the Hagshaw Hills. Dating and correlation has focused particularly on the use of lithostratigraphical markers, such as conglomeratic beds, and the occurrence of horizons with fish, arthropods, and rare graptolites and various other invertebrates. Papers by Lamont (e.g. 1947a, 1947b, 1952), Rolfe (1960a, 1962a, 1973, 1992b), Walton (1965), Rolfe and Fritz (1966), Clarkson *et al.* (1977), Bull (1987), Walton and Oliver (1991), Cocks *et al.* (1992), Wellman and Richardson (1993) and Lovelock's thesis (1998) detail the evolution of views on the age of the Silurian of the Hagshaws and associated inliers. The current consensus is that 'much of what was called Downton by Peach and Horne (1899) is now regarded as no younger than Wenlock, or perhaps early Ludlow, and that considerable thicknesses of Llandovery are present' (Cocks *et al.*, 1992). The lower to mid-Palaeozoic tectonic evolution of the Silurian inliers of the Midland Valley has been analysed by Phillips *et al.* (1998).

The Silurian fauna of the Hagshaw Hills is summarized in Rolfe (1962a, 1973, 1992b). Papers featuring particular fossil groups include those on fish (e.g. Westoll, 1951; Ritchie, 1963,



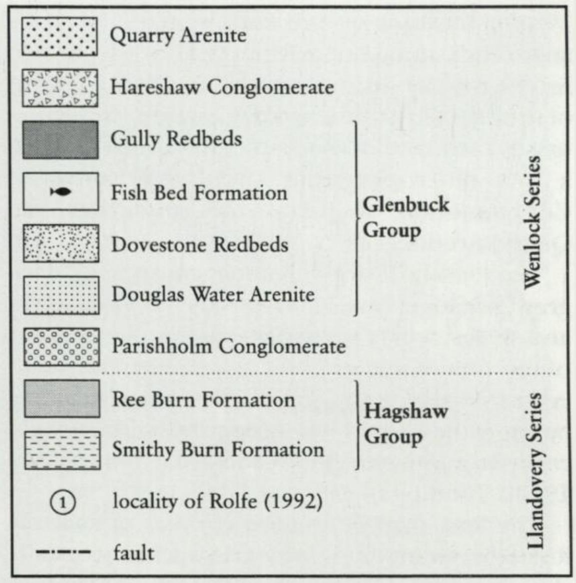


Figure 4.69 Geology of the Ree Burn–Glenbuck Loch area, Hagshaw Hills (after Rolfe, 1962a, 1992).

1967; Blieck and Janvier, 1991; Märss and Ritchie, 1998), arthropods (e.g. Lamont, 1955, 1965; Rolfe, 1962b; Ritchie, 1968; Clarkson *et al.*, 1977; Rolfe and Beckett, 1984), and palynomorphs (Wellman and Richardson, 1993).

Description

The Silurian at Ree Burn–Glenbuck Loch (Figure 4.69) mostly youngs to the north-west with dips between 45° and 80°. It is essentially an uppermost Llandovery and Wenlock clastic sequence in which fossils are typically disarticulated, fragmentary and not especially common. The following description is mostly derived from papers by Rolfe (1962a, 1992b).

In the southern part of Ree Burn, about 460 m south of its confluence with Douglas Water (Rolfe, 1992b, locality 1), there are vertical sandstones of the youngest Silurian unit of the inlier, the Quarry Arenite (maximum thickness 610 m) of Wenlock age, which consists mainly of subgreywackes showing some cross-stratification. The topographically higher area farther south is formed of the basal unit of the local Devonian Old Red Sandstone, the Greywacke Conglomerate. These two units essentially form the southern limb of the anticline. The other stratigraphical units of the Ree Burn–Glenbuck Loch section are on the northern limb.

Cropping out north of the Quarry Arenite in Ree Burn are the two oldest Silurian units in the inlier, both of them Llandovery in age (Cocks *et al.*, 1992), the Smithy Burn Siltstone (120+ m thick; base not seen) and the overlying Ree Burn Formation (275 m). These are cut by minor Caledonian igneous intrusions that include at least eight sills (e.g. as at locality 4 of Rolfe, 1992b). A major reverse fault, which dips north and trends along the axis of the anticline, brings up the Smithy Burn Siltstone about 46 m north of the exposure of the Quarry Arenite. Immediately to the north of this fault a dyke cuts through a tiny outcrop of the (Wenlock) Hareshaw Conglomerate, the unit that underlies the Quarry Arenite.

The Smithy Burn Siltstone consists of dark grey, homogenous siltstones, silty mudstones and shales, with a very sparse fauna. An outcrop of this unit in the left bank of Ree Burn has yielded, extremely rarely, graptolites, the specimens being indicative of the uppermost Llandovery *crenulata* Biozone (Rolfe and Fritz, 1966; Rolfe, 1992b, locality 2).

The Ree Burn Formation consists of sparsely fossiliferous medium grey greywackes (typically showing graded bedding), siltstones, mudstones and shales, which display a variety of depositional, bottom and soft-sediment deformational structures (e.g. at NS 762 277; Rolfe, 1992b, locality 3a, 3b). Rock fragments in the greywackes include rhyolites, spilites, andesites and metamorphic rocks. The formation has yielded numerous brachiopod species, bivalves, gastropods, trilobites, ostracods, hyolithids and tentaculitids. Just south of the confluence of Ree Burn with Douglas Water (Rolfe, 1992b, locality 5), the Ree Burn Formation consists of laminated siltstones containing calcareous concretions from which plant fragments, orthoconic nautiloids, fish (the agnathan *Loganellia scotica*; see Märss and Ritchie, 1998) and, most notably, both complete and disarticulated remains of the phyllocarid crustacean *Ceratiocaris papilio* have been recovered (Figure 4.70). About 150 m south-west of Parishholm, the waterfall in Douglas Water is formed by a 20 m thick Tertiary dolerite dyke cutting through the Ree Burn Formation, some 18 m south of which thick sandstones show well-developed load moulds (Rolfe, 1992b, locality 6).

The Parishholm Conglomerate (the 'Igneous Conglomerate' of Peach and Horne, 1899) contains highly coloured pebbles and cobbles and is typical of the so-called 'haggis rock' type of lithology found in the Midland Valley Silurian inliers. Its grey-green sandy matrix contains a wide variety of metamorphic, sedimentary, and especially igneous (> 80%) fragments, some of which are matched with possible sources in Ordovician exposures within 20 km to the south (McGiven, 1968). Clasts include keratophyres,

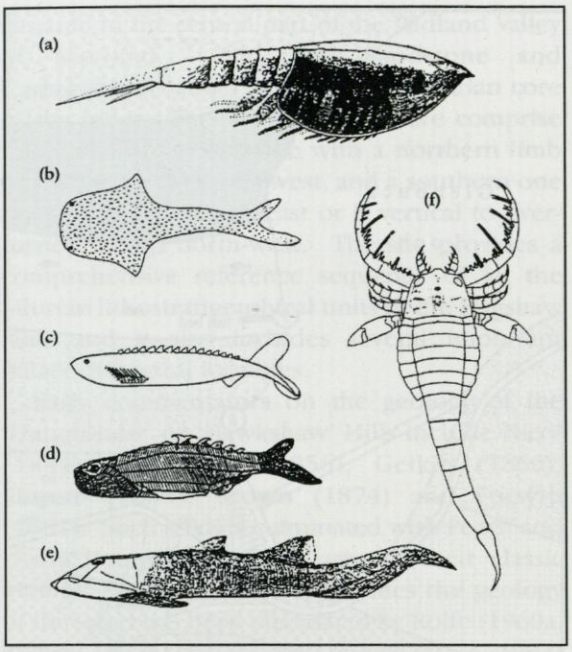


Figure 4.70 Some arthropods and fish from the Ree Burn (a) and Fish bed Formations (b–e), Glenbuck Group, Wenlock Series, Hagshaw Hills. (a) *Ceratiocaris papilio*, a phyllocarid crustacean; (b) *Lanarkia horrida*, a thelodont fish; (c) *Lasanius problematicus* and (d) *Birkenia elegans*, anaspid fish; (e) *Ateleaspis tessellata*, a cephalaspid fish; (f) *Lanarkopterus dolichoschelus*, a eurypterid (modified from Rolfe, 1992, and Märss and Ritchie, 1998).

quartz-feldspar porphyries, andesites, spilites, tuffs, adamellites, granites, diorites, and granodiorites; greywackes, mudstones, cherts, vein quartz, and rare limestones; quartzites, phyllites, and schists. The limestone clasts are from a locality 320 m west of Ree Burn; they are rare but have yielded stromatoporoids and bryozoans of probable Wenlock age. The conglomerate, which is some 40 m thick, can be examined at the bluff along the south side of the track between Parishholm and Glenbuck Loch (Rolfe, 1992b, locality 7).

The stratigraphically succeeding Silurian units, namely the Glenbuck Group (330 m thick, comprising Douglas Water Arenite, Dovestone Redbeds, Fish Bed Formation and Gully Redbeds) and the Hareshaw Conglomerate (75 m), occur along the east and south-east shores of Glenbuck Loch (e.g. Rolfe, 1992b, localities 8–10). The Douglas Water Arenite is a pale red to (when weathered) light brown sandstone–greywacke containing mudstone clasts

Figure 4.71 Glenbuck Loch, Hagshaw Hills. Dovestone Redbeds, Glenbuck Group, Wenlock Series. (locality 8 of Rolfe, 1992). (Photo: Derek J. Siveter.)

and displaying current bedding. The Dovestone Redbeds (Figure 4.71) consist of reddish and chocolate coloured, rippled and cross-stratified sandstones and mudcracked siltstones and mudstones that are mostly arranged into about 25 cm thick fining-upwards cycles. The Gully Redbeds are lithologically very similar to the Dovestone Redbeds. The overlying Hareshaw Conglomerate (Quartzite Conglomerate of Peach and Horne, 1899) contains well-rounded pebbles and cobbles of granite, rhyolite, schist, chert, pyroclastics, mudstones and especially metamorphic quartzite and vein quartz; the upper part of this unit displays cross-stratification.

The base of the Fish Bed Formation is marked by a 6.5 m thick subgreywacke (seen 110 m north of the dam on the loch), but most of the unit consists of fining-upwards cycles of grey-green sandstones, siltstones, and mudstone, with some desiccation cracks. The unit also contains two fish-rich laminated siltstone levels, one 12 m stratigraphically above a lower horizon, which sits on top of the basal subgreywacke. These celebrated deposits have yielded remains of the fish *Lasanius,* the eurypterid *Lanarkopterus* (Figure 4.70), *Spirorbis* worm tubes, and the probable calcareous alga *Glauconome*. Another famous fossil locality in the Fish Bed Formation, that at Shiel Burn about 2 km to the north-east (NS 777 291; see Rolfe, 1992b, locality 12), has produced material, including complete specimens, of the same and additional species; its biota includes the fish *Birkenia*, *Lanarkia*, *Shielia*, and *Ateleaspis* (Figure 4.70 and see Märss and Ritchie, 1998); the eurypterids *Brachyopterella*, *Parastylonurus*, and *Hughmilleria*; the crustacean *Dictyocaris*; and remains of the algae *Pachytheca* and *Tatia*. Palynomorph assemblages comprising sporomorphs and cuticle-like sheets and tubular structures of probable early Wenlock age also occur in the Fish Bed (Wellman and Richardson, 1993).

Interpretation

This site shows the transition during the Silurian from fully marine sedimentation to terrestrial, Old Red Sandstone conditions, this reflecting the closure of the Iapetus Ocean. The sediments were deposited in one of what was possibly a linear series of sub-basins that occupied much of the southern part of the present day Midland Valley, and which lay on the southern margin of Laurentia (North American palaeocontinent) and north of a possibly emergent accretionary prism centred on the Southern Uplands (see discussion under Pentland Hills GCR site Lyne Water and Lynslie Burn). The onset of red bed sedimentation in the Hagshaw Hills and other Midland Valley inliers is relatively early in the Silurian compared to its timing elsewhere in Britain, such as in the Lake District and most parts of the Welsh Basin. Accretion of the Midland Valley Terrane to the Laurentian continent by sinistral strike-slip controlled the development of the various Midland Valley Silurian sub-basins through to early Devonian times (Phillips *et al.*, 1998).

The Smithy Burn Siltstone and Ree Burn Formation are marine. Most of the sediments of especially the greywacke-dominated lower part of the Ree Burn Formation are turbidite-generated and derived from the south. Much of the fauna of the Ree Burn Formation, which is preserved chiefly as moulds at the bases of the greywackes, is essentially of shallow water aspect and has clearly been transported downslope. The 'concretion fauna' (fish, orthocones, crustaceans) in the siltstones in the upper part of the Ree Burn Formation accumulated in somewhat less energetic regimes. The Parishholm Conglomerate and the younger Hareshaw Conglomerate probably represent alluvial fan deposition, formed by sheet- and stream-floods derived largely from the south and south-east (McGiven, 1968). Much of the Dovestone Redbeds and the younger Gully Redbeds are thought to reflect terrestrial playa-type environments, which were subject to frequent flooding and drying-out episodes. The sandstones of the Quarry Arenite probably formed in braided streams, and the intercalated and in places sun-cracked mudstones are interpreted as overbank 'fines' (McGiven, 1968).

The Fish Bed Formation may have formed in a lagoonal or lacustrine setting and the fish faunas of these laminated ('varved') deposits may be explained by 'mass killing off due to rapid (? seasonal) overturning of thermally stratified waters of the lake bringing up anaerobic waters' (see Rolfe, 1992b). Other explanations have it that many of the fish from the various Silurian fish beds in the Midland Valley are marine forms that were transported in by marine incursions (Blieck and Janvier, 1991). Palynofacies evidence supports the traditional view that the red bed sequence of the Hagshaw Hills is 'entirely non-marine and that they are probably lacustrine and fluvial rather than marginal marine deposits' (Wellman and Richardson, 1993). Some of the fish taxa are also known from rocks along strike in Clew Bay, Ireland, thus suggesting that the Midland Valley and western Ireland were once part of the same basin(s) of deposition during the Silurian (Palmer *et al.*, 1989).

Ree Burn–Glenbuck Loch is the only GCR Silurian site in the Hagshaw Hills. This and other Silurian GCR sites in the Lesmahagow Hills (Birk Knowes), the Pentland Hills (Gutterford Burn, and Lyne Water and Lynslie Burn) and the Girvan area (Roughneck Quarry, Blair Farm, Penwhapple Burn, Woodland Point and Knockgardner Quarry) form a network that provides an overview of the geological evolution of the Midland Valley region during the Silurian. With reference to other Midland Valley sites listed specifically for their Wenlock interest, the Lyne Water and Lynslie Burn site in the Pentlands has, palaeoenvironmentally, similar Wenlock deposits to those of Ree Burn–Glenbuck Loch in having an essentially non-marine sequence (Figure 3.83), whereas Knockgardner Quarry in the Girvan area has lowermost Wenlock deposits that are of shallow water marine origin.

Conclusions

This site excellently displays the lithostratigraphical divisions of the Silurian of the Hagshaw Hills in the Midland Valley of Scotland. For more than 100 years it has yielded fossils of international importance, including rare arthropods and some of the best, earliest fish faunas in the world. Moreover, the plant microfossil assemblages of this site (together with those of other Midland Valley Silurian localities) has much palaeobotanical significance: it provides one of the few Wenlock palynomorph assemblages globally that has been interpreted as being of continental origin and as such provides important evidence about the nature of early land plants. The Ree Burn–Glenbuck Lock sequence also superbly demonstrates the marine to non-marine palaeoenvironmental changes which characterized the Midland Valley area of the northern margin of the Iapetus Ocean during early to mid-Silurian times.

LYNE WATER AND LYNSLIE BURN (NT 1300 5626–NT 1380 5772)

David J. Siveter

Introduction

This site is within the SSSI named Baddingsgill Reservoir and is situated in the south-western part of the North Esk Inlier (Figure 4.72), the largest and most west of three Silurian 'windows' in the central part of the Pentland Hills, about 25 km south-west of Edinburgh. The inlier is surrounded by Lower and also Upper Old Red Sandstone clastic sediments and volcanics of Devonian age, its north-west margin being marked by a major fault that downthrows in the same direction. In common with other Silurian inliers in the southern part of the Midland Valley of Scotland, the North Esk Inlier has a Llandovery and Wenlock sequence and lacks upper Silurian rocks. The site itself consists of many small exposures along the north shore of Baddingsgill Reservoir and the course of Lyne Water and its tributary Lynslie Burn. The rocks included in the site belong entirely to the (Wenlock) Henshaw Formation, the youngest Silurian formation in the inlier.

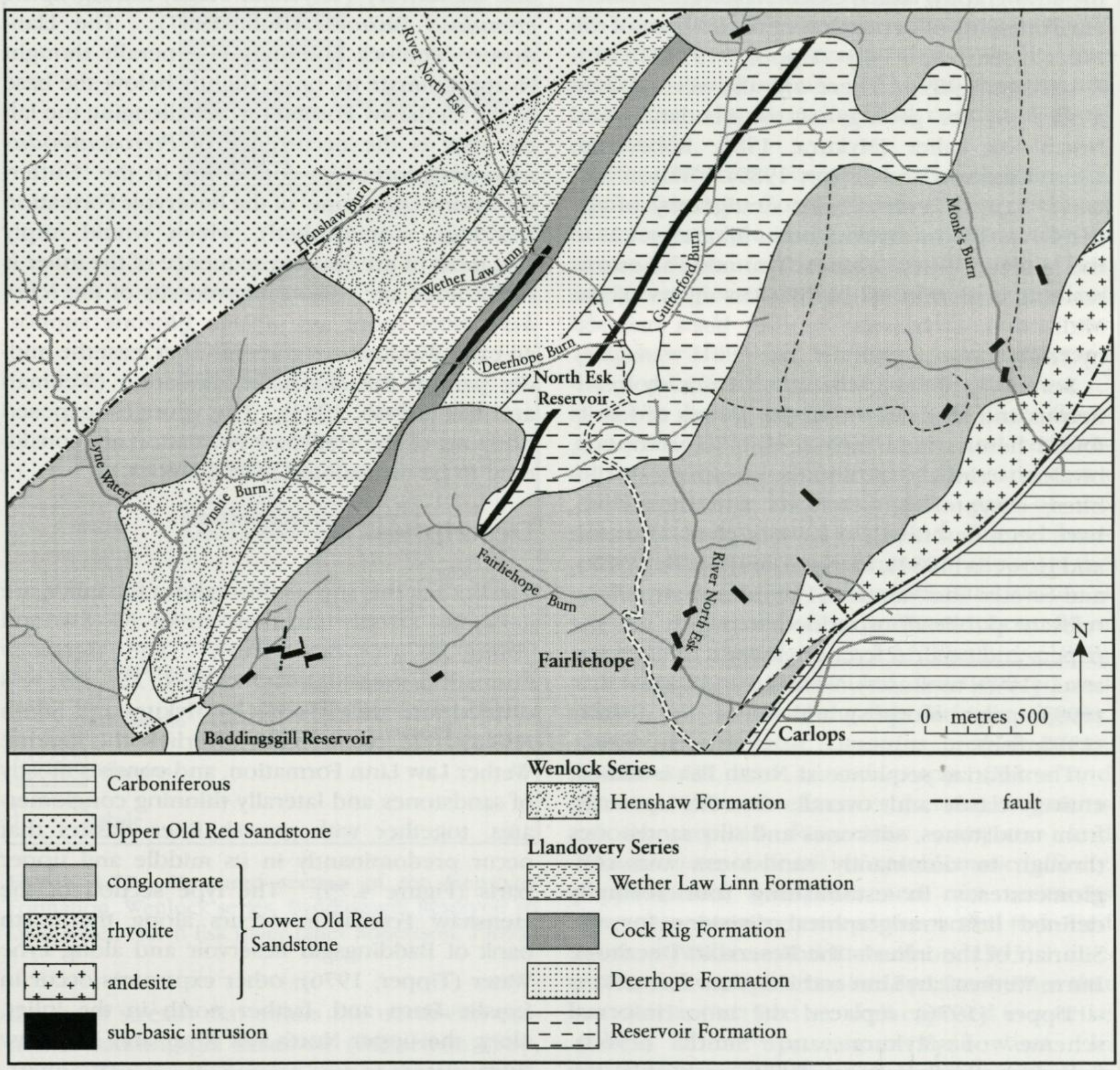


Figure 4.72 Geology of the North Esk Inlier and location of Lyne Water and Lynslie Burn (after Robertson, 1986, and the British Geological Survey, 1977).

Notes on the geology of the Pentland Hills were published as early as 1839, in MacLaren's account of Fife and the Lothians. The area was subsequently mapped by the Geological Survey – first by Howell and Geikie (1861) then, most notably, as a part of Peach and Horne's classic study on the Silurian rocks of Scotland (1899), and more recently by Mykura and Smith (1962). Members of the Edinburgh Geological Society have also made important contributions to unravelling the geology of the North Esk Inlier (e.g. Haswell, 1865; Brown and Henderson, 1867; Henderson and Brown, 1870). In modern times detailed collecting and high resolution mapping has produced a much clearer picture of the stratigraphy, faunal assemblages and palaeoenvironments of deposition of the Silurian of the inlier (see especially Tipper, 1975, 1976; Robertson, 1989). There are also several field guides on the geology of the Pentlands and North Esk Inlier (Mykura, 1986; Robertson, 1986; Clarkson and Taylor, 1989). Walton and Oliver (1991) reviewed the stratigraphy of the Pentlands in context with other Silurian areas in the Midland Valley. The early to mid-Palaeozoic tectonic evolution of the Silurian inliers of the Midland Valley has very recently been analysed by Phillips *et al.* (1998).

Several localities in the inlier are richly fossiliferous and many of the major groups of fossils found here, which include fish, brachiopods, bivalves, crinoids, echinoids, graptolites, trilobites, eurypterids, ostracods and microflora, have been described, at least in part. Clarkson and Howells (1981), Clarkson and Taylor (1989), and Siveter and Vannier (1990) list many of the relevant publications, added to which are the papers and other references therein of Clarkson *et al.* (1995; molluscs), Wellman and Richardson (1993; palynomorphs) and Märss and Ritchie (1998; fish).

The Silurian sequence at North Esk is almost entirely clastic and, overall, coarsens upwards, from mudstones, siltstones and silty sandstones through to dominantly sandstones and conglomerates. In establishing four formally defined lithostratigraphical divisions for the Silurian of the inlier – the Reservoir, Deerhope Burn, Wether Law Linn and Henshaw formations – Tipper (1976) replaced the more informal scheme of Mykura and Smith (1962). Subsequently, Robertson (1989) established the Cog Rig Formation in between the Deerhope and Wether Law Linn formations and divided the last of these into three members.

The exact age of the Silurian rocks of the inlier has generated much debate, with many early authors maintaining that not only Wenlock but also Ludlow and possibly 'Downtonian' rocks are represented (e.g. Henderson and Brown, 1870; Peach and Horne, 1899). Lamont made valuable contributions (though often published privately) to our understanding of the stratigraphy and palaeontology of the North Esk Inlier. It was he (1947a, b) who first demonstrated the currently held view that the Silurian deposits here are largely of Llandovery age. The four oldest Silurian formations contain graptolites, assigned with various degrees of certainty to the late Llandovery (Telychian Stage) *Monograptus crenulata* Biozone (Bull, 1987). The Llandovery–Wenlock boundary is generally thought to approximate to, or lie slightly below, the base of the Henshaw Formation. Challenging the latter view is the occurrence of *Pterospathodus amorphognathoides* conodonts in the 'Gutterford Burn Limestone' of the Reservoir Formation (Aldridge, unpublished), which would imply that most of the Silurian sequence of the inlier is of Wenlock age. Plant microfossils of the *?chulus–nanus* spore assemblage Biozone support an early Wenlock assignment for at least the middle part of the Henshaw Formation (Wellman and Richardson, 1993). The youngest exposed horizons of the Henshaw Formation are considered to be no younger than Wenlock.

Description

The beds at this site, as throughout the inlier, are generally steeply inclined, strike NE–SW and young to the north-west. The Henshaw Formation (minimum thickness 724 m) was divided into six divisions by Mykura and Smith (1962). It conformably overlies the marine Wether Law Linn Formation, and consists mostly of sandstones and laterally thinning conglomerates, together with greyish finer clastics that occur predominantly in its middle and upper parts (Figure 4.73). The type section of the Henshaw Formation occurs along the north bank of Baddingsgill Reservoir and along Lyne Water (Tipper, 1976); other exposures occur in Lynslie Burn and, farther north in the inlier, along the upper North Esk River and Henshaw Burn.

Fossiliferous siltstones of the Upper Member of the Wether Law Linn Formation crop out in

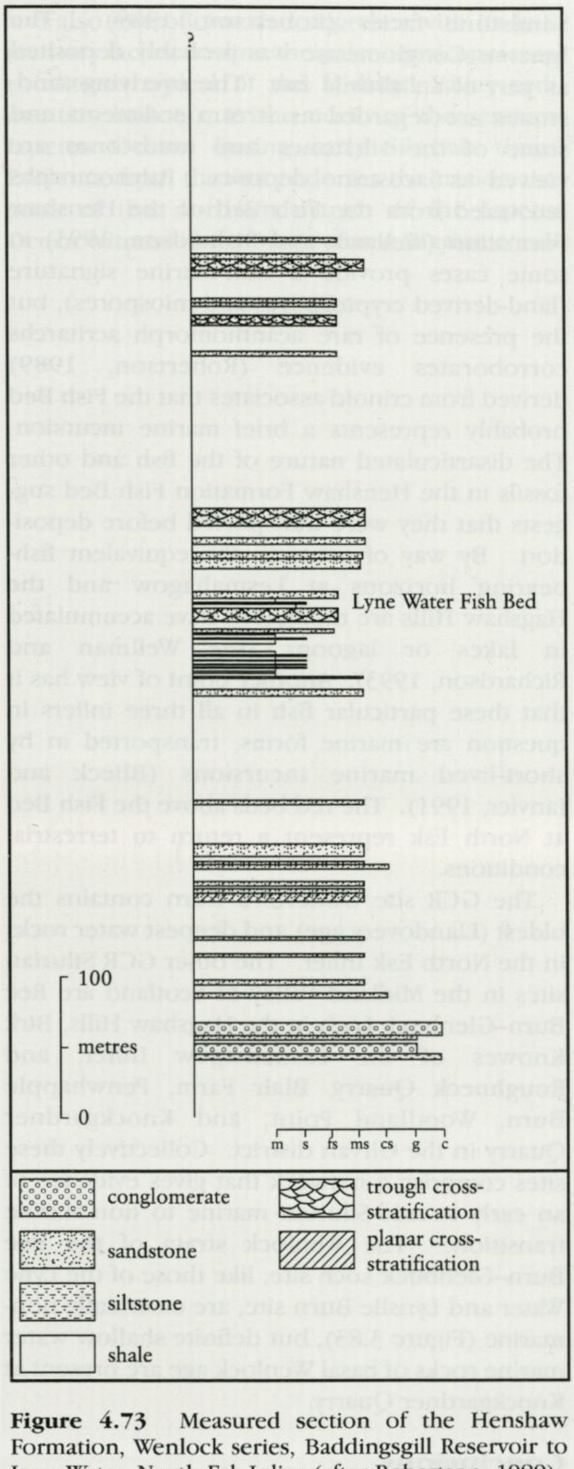


Figure 4.73 Measured section of the Henshaw Formation, Wenlock series, Baddingsgill Reservoir to Lyne Water, North Esk Inlier (after Robertson, 1989).

the small stream that enters the north-east corner of Baddingsgill Reservoir (Robertson 1986, 1989). The southernmost part of the site itself, along the north shore of Baddingsgill Reservoir (NT 1300 5626), has exposures of the distinctive near basal unit of the overlying Henshaw Formation, the Igneous Conglomerate, there interbedded with thick beds of red medium-grained sandstones. This conglomerate, which contains well-rounded, haematite-stained clasts of granite, various lavas, porphyry, cherts, and quartzites, has been considered to be the lateral equivalent of similar coarse clastic horizons in other Silurian inliers of the Midland Valley; for example, the Parishholm Conglomerate of the Hagshaw Hills and the Fence Conglomerate of the Carmichael Inlier. Farther along the shore of the reservoir, towards Lyne Water, the red sandstones predominate.

Exposures in the lower reaches of Lyne water, below its junction with Lynslie Burn, also show the virtually unfossiliferous red sandstones and mud-flake conglomerates that overlie the Igneous Conglomerate. The sandstones are micaceous, ripple-marked and contain desiccation cracks.

The Henshaw Formation also contains an upper Quartzite Conglomerate (7.5 m thick), as seen for example in the North Esk River section about 2.5 km north-east of Lynslie Burn. This upper conglomerate may be a lateral equivalent of the Kirk Hill (Carmichael), Hareshaw (Hagshaw Hills) and Middlefield (Lesmahagow) conglomerates along strike to the south-west.

Above the red sandstones in Lyne Water, finer-grained sediments – olive, grey and reddish-brown shales and siltstones and fine sandstones – characteristic of the middle part of the Henshaw Formation, are exposed. The celebrated Lyne Water Fish Bed occurs in this part of the sequence, in fine grey-green laminated siltstones on the east bank of Lyne Water, about 25 m north of the sheepfold. One of Traquair's (1899) fish localities, it has yielded disarticulated and broken specimens of the fish *Birkinia elegans*, *Ateleaspis tessellata*, *Lasanius problematicus*, *Shielia taiti*, and *Lanarkia* spp. (Märss and Ritchie, 1998 and references therein), fragments of the crinoid *Pisocrinus campana* and *Glauconome*, a fossil of problematic affinity. Cryptospores, miospores and rare acritarchs have also been recovered from the Fish Bed horizon (Wellman and Richardson, 1993).

The red, trough cross-bedded sandstones that overlie the Fish Bed are well exposed in a strike section farther upstream in Lyne water. In Lynslie Burn, just above its junction with Lyne Water, there is another outcrop of the Fish Bed (Robertson, 1986, 1989). Some authors (e.g.

Peach and Horne, 1899; Mykura and Smith, 1962) have regarded this as a separate fish-bearing horizon (the Lynslie Burn Fish Bed; see discussion in Märss and Ritchie, 1998). In the upper part of Lyne Water, above its junction with Lynslie Burn, the youngest exposed beds of the Henshaw Formation are red, trough cross-bedded sandstones. They are overlain with angular unconformity by Lower Old Red Sandstone deposits, including conglomerates.

Interpretation

The Silurian of the North Esk Inlier is generally accepted to have accumulated in one of a series of linear Silurian sedimentary sub-basins in the southern part of the Midland Valley, with land areas at times probably to the north and south. These sub-basins, which were possibly connected at various times, also encompass the Silurian deposits of the Hagshaw Hills, Carmichael, Lesmahagow Hills and the Girvan area and may have continued into Northern Ireland (e.g. Pomeroy and Charlestown areas) and south-west to County Mayo. In broad terms, the southern Midland Valley Scottish inliers show a history of early Silurian regression, in which distal turbidites are succeeded by a variety of shallow marine, mostly clastic sediments and, finally, terrestrial (alluvial) deposits. However, the particular tectonic setting of these sub-basins of deposition, on the southern margin of the Laurentian continent (see Pickering *et al.*, 1988; Pickering and Smith, 1995; Phillips *et al.*, 1998), has provoked much discussion. Leggett (e.g. 1987) envisaged that these Silurian sediments formed in an upper slope basin of deposition to the north of an emergent accretionary prism (Southern Uplands of Scotland) and associated northerly dipping subduction zone. Bluck (1984) considered that the Silurian deposits of the Midland Valley accumulated in inter-arc basins sourced mainly from the south-east. The various tectonic models are discussed by Phillips *et al.* (1998), who demonstrated that within the Midland Valley Terrane sinistral strike-slip controlled basin development, sedimentary facies distribution, and deformation from Ordovician through to, at least, early Devonian times.

The predominantly red-coloured and mostly unfossiliferous Henshaw Formation succeeds marine deposits and is thought to largely represent terrestrial deposition in arid, fluviatile-influenced environments typical of the Old Red Sandstone facies (Robertson, 1989). The Igneous Conglomerate was probably deposited as part of an alluvial fan. The overlying sandstones are regarded as stream sediments and some of the siltstones and mudstones are viewed as lacustrine deposits. Palynomorphs recovered from the Fish Bed of the Henshaw Formation (Wellman and Richardson, 1993) in some cases provide a non-marine signature (land-derived cryptospores and miospores), but the presence of rare acanthomorph acritarchs corroborates evidence (Robertson, 1989) derived from crinoid associates that the Fish Bed probably represents a brief marine incursion. The disarticulated nature of the fish and other fossils in the Henshaw Formation Fish Bed suggests that they were transported before deposition. By way of contrast, the equivalent fish-bearing horizons at Lesmahagow and the Hagshaw Hills are thought to have accumulated in lakes or lagoons (see Wellman and Richardson, 1993). Another point of view has it that these particular fish in all three inliers in question are marine forms, transported in by short-lived marine incursions (Blieck and Janvier, 1991). The red beds above the Fish Bed at North Esk represent a return to terrestrial conditions.

The GCR site Gutterford Burn contains the oldest (Llandovery age) and deepest water rocks in the North Esk Inlier. The other GCR Silurian sites in the Midland Valley of Scotland are Ree Burn–Glenbuck Loch in the Hagshaw Hills, Birk Knowes of the Lesmahagow Inlier, and Roughneck Quarry, Blair Farm, Penwhapple Burn, Woodland Point, and Knockgardner Quarry in the Girvan district. Collectively these sites comprise a network that gives evidence of an early to mid-Silurian marine to non-marine transition. The Wenlock strata of the Ree Burn–Glenbuck Loch site, like those of the Lyne Water and Lynslie Burn site, are essentially non-marine (Figure 3.83), but definite shallow water marine rocks of basal Wenlock age are present at Knockgardner Quarry.

Conclusions

This is an internationally known site from which fossils have been collected for more than a century. It provides the type section for the youngest Silurian lithostratigraphical unit, the Henshaw Formation (Wenlock Series), in the North Esk Inlier. It has early vertebrate faunas and also microfloras that, together with its sedimentary facies, outline the palaeoenvironmental conditions typical of the Midland Valley sedimentary basin(s), to the north of the remnant Iapetus Ocean, during early Silurian times. Evidence from the site endorses the notion that parts of this northern margin of the Iapetus Ocean witnessed the onset of non-marine conditions very early in the Silurian compared to other British Silurian basins. The sporomorph (plant microfossil) assemblages found here (and in the younger horizons of other Midland Valley Silurian inliers) are of much palaeobotanical significance, because they represent globally rare, early, lower Silurian occurrences of presumed continentally-derived forms.