British Silurian Stratigraphy

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Chapter 3

The Llandovery Series

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INTRODUCTION

The lowest series of the Silurian System is named the Llandovery Series, after the town of Llandovery in South Wales. The base of the series is coincident with the base of the Silurian System, and was defined in 1984 by the Ordovician–Silurian Boundary Working Group of the International Commission on Stratigraphy (ICS) at the base of the *acuminatus* graptolite biozone at Dob's Linn in the Southern Uplands of Scotland (see Figure 1.2, and description of the GCR site at Dob's Linn). The history leading to this decision and to the decisions of the Silurian Subcommission of the ICS regarding stages within the Llandovery Series has been fully documented by Holland (1989).

The term 'Llandovery Series' was introduced by Murchison (1839), and is effectively synonymous with the 'Valentian Series' of Lapworth (1876c). For many years it was customary to use the latter term for the graptolitic facies of the earliest Silurian, such as the succession in the Southern Uplands of Scotland (e.g. Jones, 1909, 1921), while the former term was applied to shelly sequences such as that at Llandovery (Jones, 1925). The history of usage of the two names was discussed by Toghill (1969), who advocated dropping the term 'Valentian Series' in favour of the earlier name. The use of the name 'Llandovery Series' was ratified at the International Geological Congress in 1984 (Holland, 1985).

There are three stages within the Llandovery Series, the Rhuddanian, Aeronian and Telychian stages (Cocks *et al.*, 1984; Bassett, 1985). The base of the Rhuddanian Stage is coincident with the base of the Llandovery Series and the base of the Silurian System, and is defined at the GCR site at Dob's Linn. The bases of the Aeronian and Telychian stages are defined within the Llandovery type area, at the GCR sites of Trefawr Track and Fron Road, respectively, although there has been some debate regarding these definitions (e.g. Temple, 1988). The division of the Llandovery Series into these three stages supersedes the earlier proposal for four named stages (Cocks *et al.*, 1970).

PALAEOENVIRONMENTAL SETTING

The palaeogeography and palaeoenvironments of the British Silurian have been summarized in a number of publications, most recently by Bassett *et al.* (1992), and are also outlined in Chapter 1 of this volume (see also Figure 3.1). The early Llandovery was marked by a general eustatic rise in sea level following the glacial episode in the latest Ordovician (see Figure 1.4), and by a slow recovery of biotic diversity, which had been depleted by the extinction events associated with the glaciation. In the Welsh Basin, Llandovery history is marked by a pulsed transgression of the sea eastwards and south-eastwards across the margins of the Midland Platform (see Figure 1.9a). The progressive flooding of the coastal areas is evident at several GCR sites in Wales and the Welsh Borderland, which record the varying times of deposition of the first Silurian marine sediments, and the nature of the deeper-water deposits that succeeded them (Ziegler *et al.*, 1968b). Benthic faunal communities, dominated by brachiopods, have proved particularly useful in tracing the progress of this Llandovery transgression, and have enabled recognition of temporary local regressive episodes (Ziegler *et al.*, 1968a; Ziegler *et al.*, 1968b). By the end of the Llandovery epoch, much of the Welsh Borderland area, which was emergent during the latest Ordovician, had been inundated. In the deeper parts of the basin, deposition was dominated by turbidity flows, initially mostly generated from the eastern or south-eastern margin of the basin; from the early Telychian, however, the major source of turbidity currents shifted to the south-south-west. Deposition was controlled by major faults within the basin, with subsidence making space for thick accumulations of turbidites (Wilson *et al.*, 1992). In quieter areas of the basin and between the turbidite systems, hemipelagic shales were deposited, sometimes with rich graptolite faunas. In comparison with much of the Ordovician, Llandovery times in the Welsh region were relatively volcanically quiescent, although lava and ash flows are evident in the Skomer Volcanic Group of west Pembrokeshire and in the succession in the Tortworth Inlier. Other evidence of some continuing volcanic activity is found in the occurrence of bentonite bands in many areas.

In the Lake District Basin, mudstone deposition was dominant throughout the Llandovery, with anoxic black graptolitic shales particularly prevalent in sections of Rhuddanian strata. In the lower part of the Aeronian Stage, paler non-graptolitic mudstones become interbedded with the black shales; Rickards (1964, 1989a) sug-

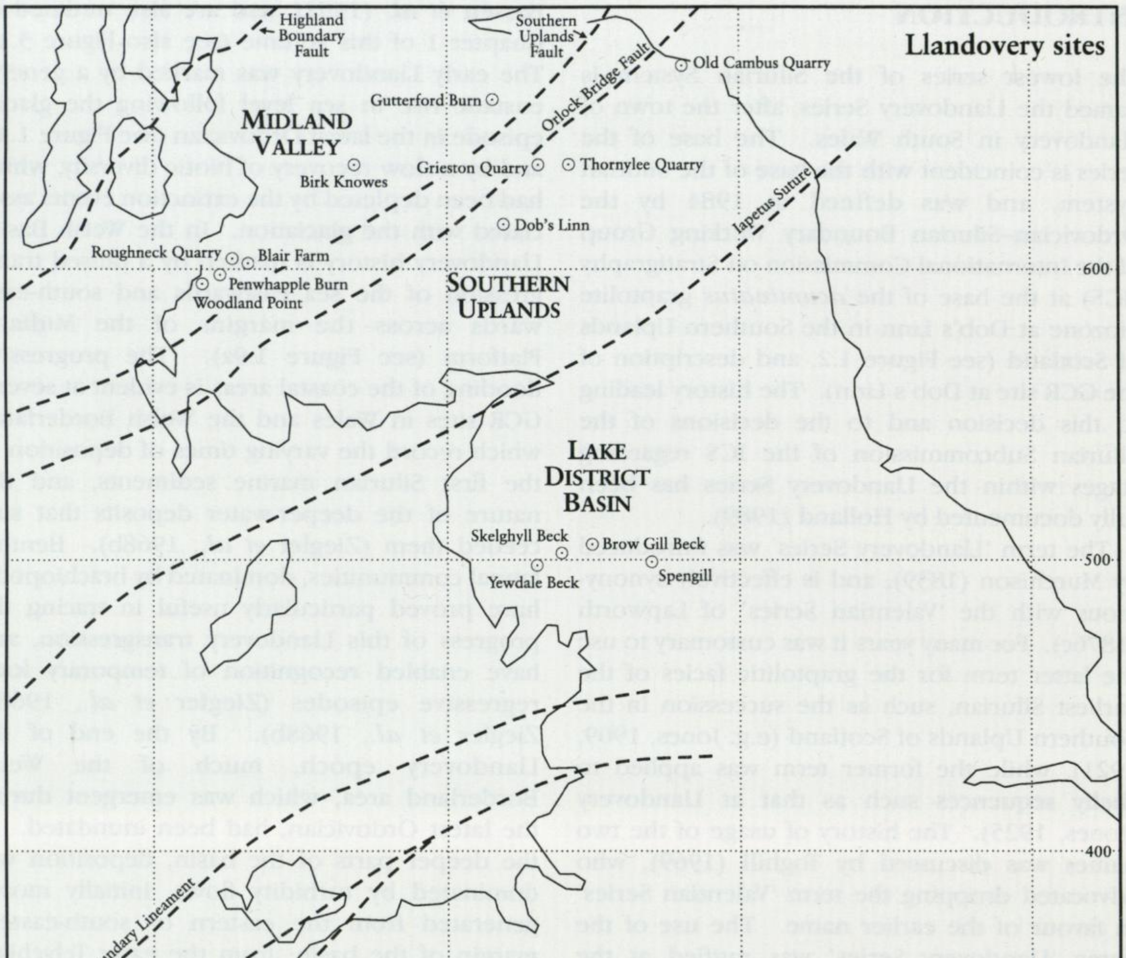

Figure 3.1 Distribution of the Geological Conservation Review sites for the Llandovery Series, set against the palaeogeographical elements of Silurian Britain.

gested that these represent brief periods of oxic bottom conditions. This alternation continues through the Aeronian, with fine turbiditic sands, perhaps generated from a reactivated horst, coming into many sections in the uppermost part of the stage. Black shales become thinner and more infrequent in Telychian sections, which are dominated by pale mudstones, regarded at least in part to represent distal turbidites by Rickards (1964, 1989a). The changes in bottom oxygenation here and elsewhere have been related to a model of alternating greenhouse (secundo) and coldhouse (primo) climatic conditions; in primo states there would have been vigorous vertical circulation in oceanic and marginal basins, with consequent oxygenation of deeper waters, whereas secundo states were characterized by stagnant oceans with deep-water anoxia (Jeppsson, 1990; Aldridge *et al.*, 1993a).

To the north of the Iapetus Suture, in Scotland, a diachronous thrust stack of greywackes and deep-marine graptolitic mudstones occurs to the south of the Southern Uplands Fault (see Figure 1.6). These represent an accretionary accumulation of sediments that built up during the late Ordovician and Llandovery on the northern margin of the ocean or of an associated back-arc basin. North of this, in the Midland Valley area, Llandovery sedimentation is represented in a suite of marine to non-marine successions, deposited in narrow sub-basins generated by strike-slip activity (Williams and Harper, 1988; Phillips *et al.*, 1998). In the Girvan sub-basin much of the sequence was deposited in relatively deep water, with graptolitic shales and turbidites or storm-generated sandstone bodies characteristic; some horizons with shelly fossils, particularly at the bottom of the succession, testify to shallow water or offshore shelf conditions. The deepening through the Llandovery in this area relates to the general eustatic rise in sea level also recognized in the Welsh Basin. In the Pentland Hills area, at the south-eastern end of the Midland Valley, marine deposition also occurred in a sedimentary basin that was physically or ecologically isolated from other parts of the region; faunal similarities, however, suggest that there was a link between this area and Balto-Scandia. Evidence of brackish water conditions during the Llandovery is found in the succession exposed in the Lesmahagow Inlier, in the south-central part of the Midland Valley, where laminated siltstones contain gastropods, eurypterids, phyllocarids and agnathan fishes.

Subsurface Llandovery strata are also known from boreholes to the east of the Midland Platform, in East Anglia and Kent. The sediments here include turbidites and graptolitic shales, suggestive of a basinal environment (see Bassett *et al.*, 1992).

BIOSTRATIGRAPHY

The primary fossil group for biostratigraphy in the Llandovery is the graptolites. The standard biozonal scheme (Rickards, 1976, 1989b; see Figure 1.2) has been modified recently by the recognition of additional biozones and the division of some biozones into sub-biozones (Figure 3.2). Conodonts, acritarchs, chitinozoans and brachiopods also provide valuable biostratigraphical information, although a considerable amount of work remains to be done to tie zonations based on these groups into the graptolite scheme.

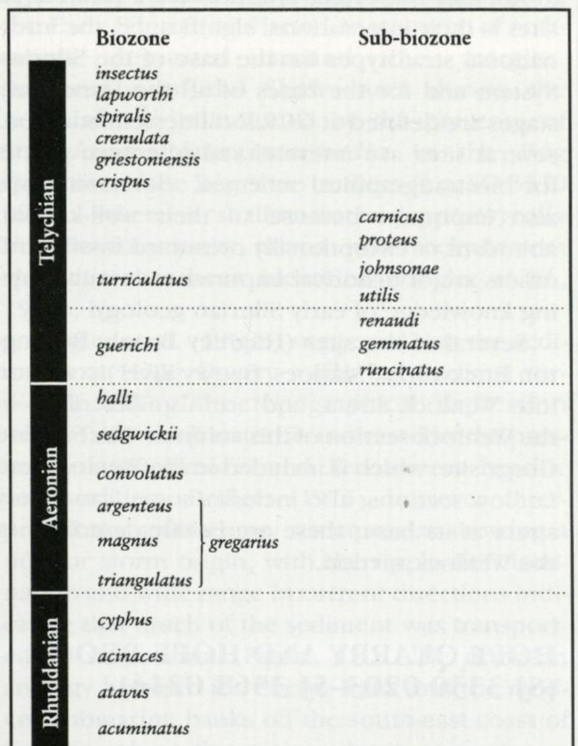

Figure 3.2 Graptolite biozonation in the Llandovery Series of Britain, after Rickards (1976, 1989b), Loydell (1991, 1993), Loydell and Cave (1993, 1996) and Zalasiewicz (1994).

SITE SELECTION

GCR sites have primarily been selected to illustrate the range of Llandovery palaeoenvironments documented above. Localities in the Welsh Basin are representative of the shelf, basin margin and basinal depositional environments and their characteristic biotas, and also record the progressive transgression of the sea across the Midland Platform. The sites in the Lake District together provide coverage of the lithostratigraphical and biostratigraphical changes in the area through the Llandovery Epoch, and illustrate the major regional variations. The network of localities in the Southern Uplands of Scotland illustrate the early Silurian stratigraphy of this ancient continental margin, and exemplify the exposures that have led to the different interpretations of its depositional and tectonic history. Finally, the Midland Valley localities demonstrate the various environments, from deep marine to brackish water, developed in this area and allow comparison with the very different successions developed in the Southern Uplands immediately to the south.

Another important criterion for a number of sites is their international significance; the international stratotypes for the base of the Silurian System and for the bases of all the Llandovery stages are defined at GCR localities. In addition, several sites are international reference points for biostratigraphical schemes. Some sites are also important because of their well-known, abundant or exceptionally preserved fossils, and others are of historical importance in our evolving knowledge of early Silurian geology.

Several of the sites (Hughley Brook, Buttington Brickworks, Marloes, Banwy River) continue into Wenlock strata, and are also described in the Wenlock section of this volume. The Sawdde Gorge site, which is included in the Wenlock and Ludlow sections, also includes some Llandovery strata at its base; these are briefly described in the Wenlock section.

HOPE QUARRY AND HOPE BROOK (SJ 3530 0203–SJ 3568 0214)

Introduction

The exposures in and around Hope Quarry form part of the Llandovery outcrop that fringes the north-western side of the Shelve Inlier in the western part of South Shropshire. The section was briefly described by Whittard (1932, pp. 875–6) and, in a little more detail, by Ziegler *et al.* (1968b, p. 743). An exposure at the entrance to Hope Quarry shows the unconformable contact of the Llandovery Venusbank Formation on the Ordovician Hope Shales; this unconformity can be traced into Hope Brook. The type section of the Venusbank Formation is in the brook, extending eastwards from near the quarry, and typical sediments of the lower part of the formation are exposed in the quarry face. Fossils, primarily graptolites, brachiopods and conodonts, show that the Venusbank Formation is of Aeronian age; it is the lateral equivalent of part of the Pentamerus Beds exposed around the Long Mynd and near Wenlock Edge to the east. Mapping shows that it oversteps various units of the underlying Ordovician succession of the Shelve Inlier (Whittard, 1932), resting at Hope Quarry on Llanvirn shales of the Hope Group.

This is one of a number of key sites that demonstrate the nature and timing of the eastward transgression of the sea from the Welsh Basin during the Llandovery Epoch. The exposures show the nature of the first sediments deposited locally by the invading mid-Llandovery sea, and provide a representative section of the Venusbank Formation and its fossil fauna.

Description

The base of the Venusbank Formation in Hope Quarry comprises a calcareous sandstone that contains scattered subangular shale fragments. Above this is a sequence of sandstone beds up to 1 m thick, variably calcareous and sometimes showing parallel lamination or low angle cross-stratification (Figure 3.3). The bases of the beds are sharp but irregular, with patches of coarser clasts and transported brachiopod shells, which are occasionally concentrated to form lenses. Each bed tends to fine upwards and become less calcareous; occasional ripple cross-lamination occurs on the tops of some of the sandstones (Ziegler *et al.*, 1968b; Bridges, 1975). Towards the top of the 10 m section exposed in Hope Quarry, the beds become more flaggy and less calcareous and there are more interbedded thin mudstones. Sandstone beds similar to those in the quarry can also be seen in Hope Brook, and the top of the Venusbank Formation is taken at a

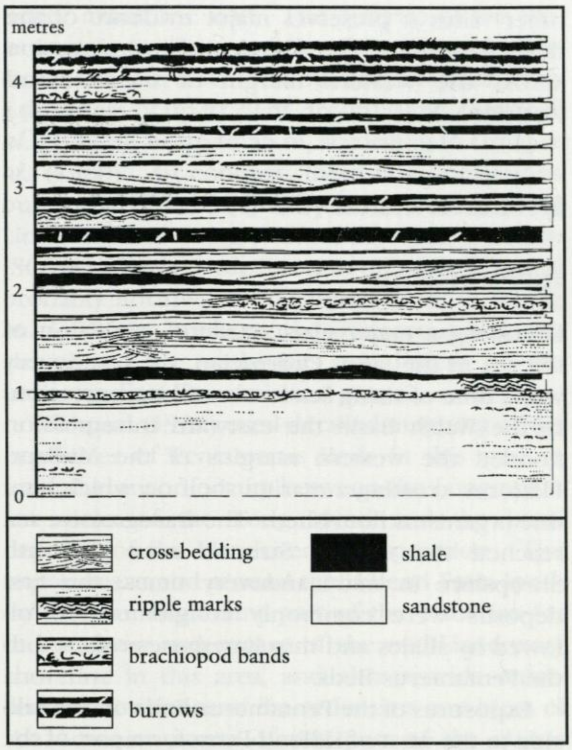

Figure 3.3 Sedimentary log of representative open marine sandstones in the main face at Hope Quarry (after Bridges, 1975).

prominent sandstone with calcareous concretions exposed below a footbridge.

Ziegler *et al.* (1968b) reported the occurrence of the graptolite *Climacograptus* aff. *rectangularis* near the base of the main face at Hope Quarry, indicative of an Aeronian age. They also noted the presence of brachiopods of the *Stricklandia* Community in the Venusbank Formation, with the subspecies of the eponymous genus present being intermediate between *S. lens intermedia* and *S. lens progressa*. Whittard (1932) also recorded abundant *Atrypa reticularis* and *Tentaculites anglicus* in the lowest beds of the formation, with *Pentamerus oblongus* common in the higher units.

Samples from the more calcareous levels in Hope Quarry, including the basal sandstone, have yielded abundant conodont elements. Important taxa include *Icriodella deflecta*, *Kockelella abrupta*, *Distomodus* sp., *Ozarkodina hassi* and *Ozarkodina oldhamensis* (revised from Aldridge, 1972). Hope Quarry is the type locality for the stratigraphically important conodont species *Icriodella deflecta* Aldridge, 1972, and *Kockelella abrupta* (Aldridge, 1972), and for other taxa including the brachiopods *Leptostrophia compressa* (J. de C. Sowerby, 1839), *Coolinia semicircularis* (J. de C. Sowerby, 1839) and *Leptaena contermina* Cocks, 1968.

Interpretation

Mapping of the Venusbank Formation in the Hope area and in the Bog Mine outliers within the Shelve Inlier has shown that the Llandovery rocks have a regionally irregular base with a relief of up to 100 m (Whittard, 1932; Ziegler *et al.*, 1968b), reflecting the Llandovery land topography prior to flooding by the transgressing sea. Whittard (1932) concluded that the modern Hope Valley closely corresponds to a pre-existing Llandovery depression, which became filled with the sediments of the Venusbank Formation and the succeeding Minsterley Formation. Evidence from the Hope area, and from other sites including the GCR site at Hillend Farm, shows that the Shelve–Long Mynd area formed a topographical high during the Early Silurian and acted as a source of sediments deposited around the margins. Submersion of the Shelve area during the Aeronian age is indicated by the presence of *Stricklandia lens intermedia* in the Bog Quartzite of the Bog Mine outliers (e.g. SO 3510 9815), where a shallow-water *Cryptothyrella* benthic community mixed with rocky-bottom specialists has been identified (Ziegler *et al.*, 1968a, b).

Ziegler *et al.* (1968b) suggested that the sediments at Hope Quarry might be proximal turbidites, filling the topographical depression under fairly deep water, as indicated by the presence of *Stricklandia* and *Pentamerus* benthic communities. Bridges (1975), however, interpreted the sedimentary structures as showing a tidal or storm origin, with the ripple drift lamination and wide range in current directions indicating that much of the sediment was transported in suspension (Figure 3.3). He drew an analogy between the Shelve Bank and the modern submarine banks off the south-east coast of Canada, where the coarser detritus remains as lags on the summit, while the sand is dispersed on the slopes.

This locality relates to other GCR sites at Hillend Farm in Shropshire and at Gullet Quarry in the Malvern Hills, both of which expose shoreline deposits of the Llandovery transgression, and to the site at Wistanstow, Shropshire, where younger (Telychian) strata also rest unconformably on Ordovician shales. Together these sites enable interpretation of the nature of the eastern shoreline of the Welsh Basin during middle and upper Llandovery times.

Conclusions

The exposures in and around Hope Quarry display the important regional unconformity between Ordovician and lower Silurian strata, resulting from the late Ordovician glacially-induced regression followed by early Silurian sea-level rise and transgression. Mapping of the Hope Quarry, Hope Brook and other local exposures provides significant evidence for reconstructing the nature of the local topography transgressed by the invading early Silurian sea. The type section of the Venusbank Formation is situated in Hope Brook, and the sandstone successions here and in the quarry are instructive in displaying the initial marine sedimentary cover and faunal colonization of the pre-existing Llandovery land surface of the western Shelve Inlier. The conservation of this site is of more than local importance, as in conjuction with other sites it preserves major evidence of the development of the Llandovery transgression across the western margin of the Midland Platform.

HILLEND FARM (SO 3956 8756)

Introduction

Following a major glacio-eustatic regression of the sea in the latest Ordovician, the Llandovery was a time of rising sea levels and transgression. In the Welsh Basin the eastward transgression flooded the western margins of the Midland Platform, creating a marine shelf on which benthic organisms flourished. The transgressive sea reached the Church Stretton area of South Shropshire in mid-Llandovery times; the first deposits were commonly conglomeratic, followed by shales and thin limestones referred to the Pentamerus Beds.

Exposures of the Pentamerus Beds on the hillside to the west of Hillend Farm form part of the outcrop of this formation that borders the southern and south-eastern margins of the Long Mynd (Figure 3.4). Whittard (1932) recognized two lithological phases within the Pentamerus Beds of this area, a lower arenaceous unit and an

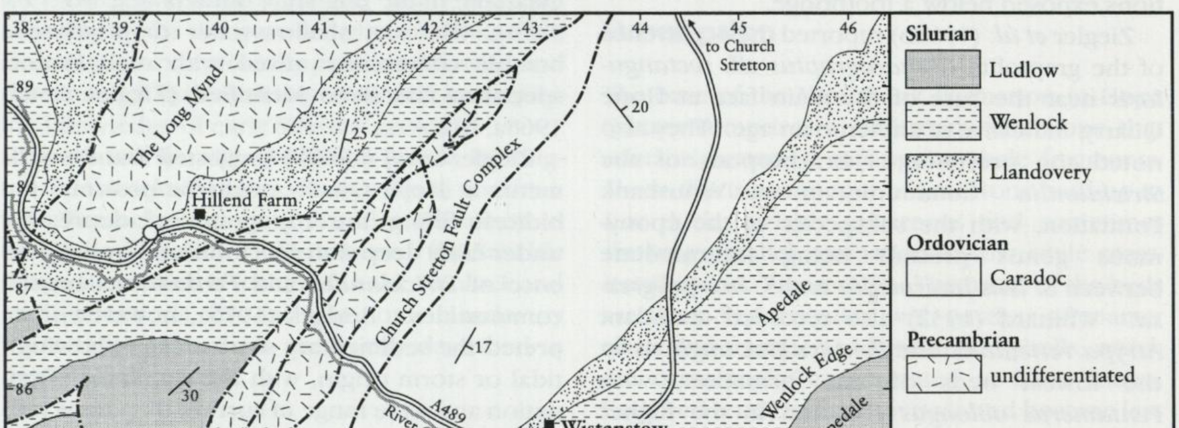

Figure 3.4 Geological map of the area to the south-east of the Long Mynd, Shropshire, showing the sites at Hillend Farm and Wistanstow (modified after Siveter *et al.*, 1989).

upper mudstone unit. The outcrop of the arenaceous unit (Grits and Conglomerates of Greig *et al.*, 1968) is discontinuous and irregular, with a thickness of up to 20 m, according to Ziegler *et al.* (1968b), or up to 55 m, according to Greig *et al.* (1968). In contrast, there is a continuous outcrop of the mudstone unit (Shales and Limestones of Greig *et al.*, 1968) from Plowden (SO 382 874) to Little Stretton (SO 445 921) and probably northwards to Church Stretton (Greig *et al.*, 1968). In places, the arenaceous beds are absent and the mudstones rest directly on the Longmyndian (Precambrian) strata.

Whittard (1932) used detailed mapping of the exposures of Pentamerus Beds in this area to trace the unconformity between the Longmyndian rocks of the Long Mynd and the basal deposits of the Llandovery transgression. The exposures at and around the Hillend Farm locality form an important part of the evidence for the position and nature of the mid-Llandovery shoreline in this area, and also provide representative evidence of the sediments and biota of the Aeronian strata of this part of the classic region of South Shropshire.

Description

The road cutting west of Hillend Farm, on the north side of the A489, exposes typical mudstones and thin limestones of the Pentamerus Beds; the basal arenaceous beds, comprising coarse sandstones and conglomerates, are exposed in the hillside above (Greig *et al.*, 1968, p. 164), where they occasionally contain specimens of the brachiopod *Lingula.* Strata of the Pentamerus Beds can also be seen in a small old quarry behind the road cutting.

Some 5 m of mudstones are exposed in the road cutting and the old quarry, striking at 075° and dipping 25°S. The mudstones are grey, weathering to buff, with sphaeroidal weathering evident in the more homogeneous horizons. Several discontinuous bands of argillaceous limestone are interbedded with the mudstone (Figures 3.5, 3.6) and are characterized by abundant transported shells of *Pentamerus oblongus* and other brachiopods. The mudstones also contain diverse brachiopods (especially *Coolinia*), together with gastropods, tentaculitids, corals, bryozoans, orthocone cephalopods,

Figure 3.5 Mudstones of the Pentamerus Beds at the road cutting near Hillend Farm; a thin limestone lens rich in *Pentamerus* shells is exposed above the hammer head (arrowed). (Photo: R.J. Aldridge.)

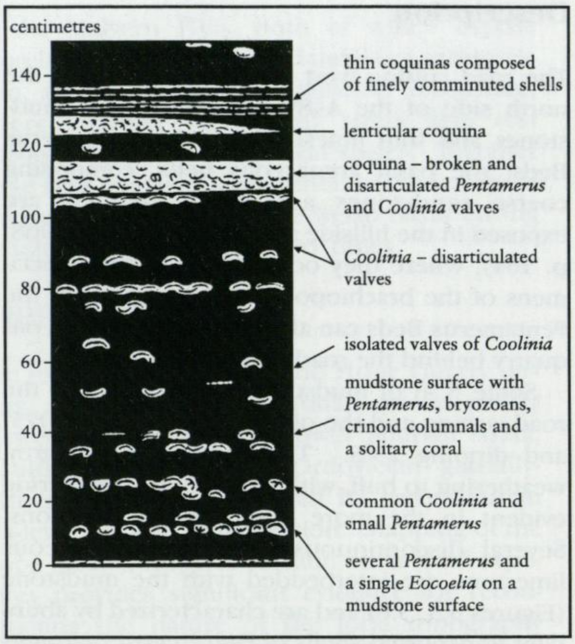

Figure 3.6 Representative sedimentary log through the mudstones and thin limestones of the Pentamerus Beds at Hillend Farm (after Bridges, 1975).

crinoid columnals and the trilobite *Encrinurus*. Ziegler *et al.* (1968b) assigned the fauna to the *Pentamerus* benthic community (Figure 3.7) and reported the occurrence of *Eocoelia hemisphaerica*, indicative of an Aeronian age. Conodont elements occur in small numbers in the limestone bands, representing a diverse fauna characterized by *Pranognathus tenuis*, *Icriodella deflecta*, *Kockelella abrupta*, *Ozarkodina hassi* and *O. oldhamensis* (Aldridge, 1972; Aldridge and Smith, 1985); the road cutting is the type locality for the stratigraphically important conodont species *Pranognathus tenuis* (Aldridge, 1972). The mudstones also contain a rich and well-preserved microflora, which has yet to be studied.

Interpretation

During the Aeronian age, the sea advanced eastwards from the Welsh Basin, flooding the borderlands. At this time, the Long Mynd remained emergent, forming a southward facing peninsula (Bridges, 1975). Detailed mapping of the Silurian/Longmyndian unconformity led Whittard (1932) to conclude that the flanks of the Long Mynd presented an intricate coastline to the invading sea, with inlet gulfs, embayments, channels and sea stacks. He interpreted the conglomerates and sandstones at the base of the Pentamerus Beds as beach, bar and pebble-bank deposits irregularly distributed along this coastline. This interpretation is supported by the recognition of a shallow-water *Lingula* benthic community in these rocks (Ziegler *et al.*, 1968b). From a more detailed sedimentological study, Bridges (1975) considered the coarser, immature sandstones and conglomerates to represent stream derived material accreted on beaches near river mouths, while the mature quartz sands compare with those deposited on modern wave-cut platforms.

A deepening of the sea is indicated by the development of a *Pentamerus* Community in the overlying mudstones (Ziegler *et al.*, 1968b). This community is represented in both the shale and limestone lithologies, but in the limestone coquinas the shells are clearly disoriented and

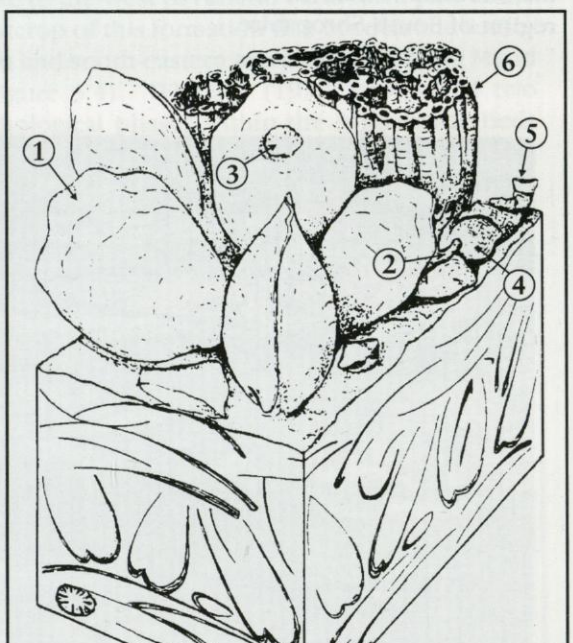

Figure 3.7 Reconstruction of the *Pentamerus* benthic community, based on a collection from the Pentamerus Beds of Shropshire (after Ziegler *et al.*, 1968a). The fossils represented are: (1) *Pentamerus oblongus*; (2) a bryozoan; (3) *Eocoelia hemisphaerica*; (4) *Atrypa reticularis*; (5) a rugose coral; (6) *Halysites* sp..

have been transported. Bridges (1975) considered that the muds built up on the sheltered eastern side of the Long Mynd, with the majority of the coquinas deposited by bedload transport, possibly during storms.

This site relates to the GCR site at Hope Quarry to the north-west, where Aeronian rocks lie unconformably on Upper Ordovician strata, and to the site at Wistanstow to the east, where younger (Telychian) strata also rest directly on shales of Upper Ordovician age. Another related site is at Gullet Quarry in the Malvern Hills, where Telychian shoreline deposits of the Llandovery transgression are also exposed. Together these sites enable interpretation of the pattern and nature of the transgressive events along the western margin of the Midland Platform during the middle and late Llandovery.

Conclusions

The exposures in the vicinity of the road cutting west of Hillend Farm display typical facies of the arenaceous and mudstone phases of the Pentamerus Beds. The irregular unconformity between the Silurian and the Longmyndian can be mapped in the hillside and demonstrates the nature of the coastline in this area at the time of the Aeronian transgression. These exposures are particularly instructive in showing the development of sedimentary facies and the nature of colonizing faunas during this transgressive event. The conservation of this site is important, as it provides a representative section in local mid-Llandovery sediments with typical fossils, and in conjunction with other sites it preserves fundamental evidence of the development of the Llandovery transgression across the western flanks of the Midland Platform.

WISTANSTOW (SO 4257 8534)

POTENTIAL GCR SITE

Introduction

A river cliff exposure on the left bank of the River Onny, WSW of Wistanstow and 350 m north-west of the Cheney Longville footbridge (Figure 3.4), exposes Hughley Shales of Telychian age resting unconformably on Onny Shales of Caradoc (Ordovician) age (Figure 3.8). The unconformity here is subtle, as the discordance in dip between the two formations is small (18°SE as against 22°SE) and the lithologies of the two units are similar. The unconformable relationship was first recognized by Salter and Aveline (1854), who realized its importance in separating two units that had been combined by Murchison (1839) in the formation he termed the 'Caradoc sandstone'. Salter and Aveline (1854) substantiated the scale of the unconformity by documenting the different fossils in the two shales and confirmed earlier observations of the continuity of the Hughley Shales (assigned by them to the 'Pentamerus limestone') with the overlying Wenlock shale. They provided a brief description and sketch of the locality (Salter and Aveline, 1854, pp. 69–70), which was followed by a fuller description by Salter in 1868. Further information has been added by, among others, Cobbold (1900), Whittard (1928) and Greig *et al.* (1968). Whittard (1928, pp. 747–52) proved a particularly full description, with a revised drawing and comprehensive faunal list.

This classic locality is of historical importance in demonstrating the relationship between strata now referred to the Ordovician and Silurian systems, and is also important in helping to illustrate the pattern of development of the Llandovery transgression in the Church Stretton area.

Description

The state of this exposure varies because of erosion and slipping. Whittard (1928) recorded a conglomeratic limestone at the base of the Hughley Shales, observable in 1925 in the river bed, but it is not certain that the same limestone has been recognized subsequently. From Whittard's description this band is 2.5 cm thick and contains green and blue mudstone pellets, a few pebbles derived from the Longmyndian, abundant broken shells and other calcareous fragments. The fossils include fragments derived from the underlying Ordovician strata and numerous broken shells of *Pentamerus oblongus*.

Above the unconformity about 10 m of Hughley Shales are exposed, comprising greenish to purple shales, bands of micaceous fine sandstone up to 20 cm thick and a few impersistent thin limestones. At the unconformity, the successive Telychian beds overlap each other to the north-west (Whittard, 1928; Greig *et al.*, 1968). Some 2 m above the unconformity, Whittard (1928) recorded a 1 m interval of tec-

Figure 3.8 The unconformity between Onny Shales of Caradoc age and the Hughley Shales of Llandovery age in the bank of the River Onny at Wistanstow; the Hughley Shales are exposed in the upper third of the river cliff, dipping at a lower angle than the Onny Shales. (Photo: R. J. Aldridge.)

tonically disturbed strata, bounded by two horizons that Cobbold (1900) had referred to as 'dirt-planes'.

The shales contain a diverse fauna of brachiopods, trilobites and ostracods. Whittard's (1928) list includes the brachiopods *Lingula symondsi*, *Dicoelosia biloba*, *Atrypa reticularis*, *Schuchertella applanata*, *Dalmanella elegantula*, *Leptaena rhomboidalis*, *Brachyprion fletcheri*, *Skenidioides lewisii*, *Barrandella* aff. *undata*, *Cyrtia exporrecta*, *Streptis grayi*, *Eospirifer radiatus* and species of *Plectambonites* and *Meristella*, although these identifications are in need of some revision. Whittard also recorded several trilobite genera, including *Acidaspis*, *Illaenus*, *Encrinurus*, *Cheirurus*, *Calymene*, *Phacopidella* and *Dalmanites*, graptolites, beyrichiacean ostracods, and the cephalopod *Dawsonoceras annulatum*. Conodont samples have yielded poorly preserved elements, including *Pterospathodus celloni* and *Astropentagnathus irregularis* (Aldridge and Smith, 1985), indicating a horizon low in the *P. celloni* Biozone.

Ziegler *et al*. (1968b) considered that graptolites from this locality indicated the *turriculatus* Biozone and that the brachiopods were typical of the *Clorinda* benthic community.

Interpretation

The eastward transgression of the Llandovery sea from the Welsh Basin onto the western margin of the Midland Platform reached the south Shropshire area in the Aeronian, with initial deposition of sandstones and conglomerates, followed by mudstones and argillaceous shelly limestones of the Pentamerus Beds. Further deepening led to deposition of the fine-grained Hughley Shales (= Purple Shales of some authors), which outcrop in the Wenlock Edge and Church Stretton areas of south Shropshire. The Hughley Shales are not well exposed south and east of the Long Mynd, although they are present in four boreholes drilled in the region by the British Geological Survey in 1961 (see Cocks and Rickards, 1969). The greatest thickness, 184 m, is seen in the Eaton Farm Borehole

(SO 3723 8978) although this figure may be affected by faulting (Ziegler *et al.*, 1968b); in this borehole the Hughley Shales rest unconformably on Precambrian rocks of the Western Longmyndian. In the Hamperley Borehole (SO 4217 8912) the Hughley Shales are only 49 m thick and rest conformably on Pentamerus Beds (Greig *et al.*,1968; Cocks and Rickards, 1969). These boreholes, together with the exposures at Wistanstow and Hillend Farm, show that the Llandovery unconformity regionally oversteps the underlying Precambrian and Ordovician strata, and that the Hughley Shales overlap the Pentamerus Beds in places to lie directly upon the older rocks.

This is the only surface exposure in the south Shropshire area where the Hughley Shales can be seen to rest directly on pre-Silurian strata. Elsewhere, for example near the GCR site at Hillend Farm, it is the Pentamerus Beds that lie on the pre-Silurian, so the unconformity at Wistanstow indicates that here the Hughley Shales have overlapped the Pentamerus Beds to rest on Ordovician sediments. Whittard (1928) regarded the presence of broken specimens of *P. oblongus* in the basal conglomeratic limestone as evidence that local Pentamerus Beds were partly denuded during initial deposition of the Hughley Shales; this brachiopod is very abundant in the Pentamerus Beds of the region but is otherwise absent from the Hughley Shales. The presence of a relatively deep water *Clorinda* benthic community in the basal beds of the Hughley Shales suggests that there was not a shallowing event at this time, but that the first beds were deposited in deeper water than obtained during deposition of the Pentamerus Beds. It is probable that local conditions were tectonically controlled, as the Wistanstow section lies close to the line of the Church Stretton Fault Complex.

Conclusions

This is an important site for geological and historical reasons. Geologically, it displays the important regional unconformity between the Silurian and older strata, and more specificially it shows that the unconformity in the south Shropshire region displays both overstep and overlap. From this, it provides key evidence for the pattern of eastward transgression of the Llandovery marine facies across the Midland Platform. Historically, the recognition of the unconformity by Salter and Aveline (1854) proved of major importance in distinguishing rocks subsequently accommodated in two separate geological systems, the Ordovician and the Silurian.

HUGHLEY BROOK (SO 5688 9839)

Introduction

Hughley Brook flows along Ape Dale in Shropshire, below the scarp of Wenlock Edge in the type area for the Wenlock Series. Occasional exposures occur in the stream bed and in small river cliffs on the outsides of meanders. These include small exposures of the upper beds of the Hughley Shales (= Purple Shales of some authors), of Telychian age, and of the Buildwas Formation, of Sheinwoodian (lower Wenlock) age. By far the most important locality is situated 0.5 km north-east of Hughley Church and 200 m south-east of Leasows Farm (Figure 4.28), where the international stratotype for the base of the Wenlock Series has been defined (Bassett *et al.*, 1975). This locality is dealt with in detail in the Wenlock chapter of this volume and only the Llandovery part of the section is briefly considered here.

Description

Small exposures of the upper beds of the Hughley Shales occur intermittently in the stream, for example at SO 5658 9830, where blocky purple mudstones and purple shales with persistent and impersistent grey layers can be seen in a low river cliff. At the stratotype section (SO 5688 9839), the uppermost 2 m of the formation were divided by Bassett *et al.* (1975) into four units:

D. Green mudstone, with an impersistent hard calcareous siltstone 15 cm below the top of the formation	60 cm
C. Hard calcareous siltstone	8 cm
B. Purple and green mudstone	32 cm
A. Purple and green mudstone with thin impersistent calcareous sandstone bands	seen to 1 m

Brachiopods are diverse and common in the upper 10 m of the Hughley Shales, and trilobites, corals, crinoids, bryozoans, orthocones, gastropods and bivalves also occur; graptolites have not been recorded. Microfossils are very abundant and very diverse in the Llandovery beds at the stratotype section (Mabillard and Aldridge, 1982, 1985). Several thousand specimens of arenaceous foraminifera have been recovered, with assemblages dominated by *Ammodiscus exsertus*, and the diverse ostracod fauna includes the characteristic species *Craspedobolbina (Mitrobeyrichia) hipposiderus*. Acritarchs, prasinophyte algae and chitinozoans are also abundant, with the base of acritarch biozone 5 (of Hill, 1974) identifiable 15 cm below the base of the Wenlock Series. Conodonts from the Hughley Shales in Hughley Brook include *Pterospathodus celloni* and *Astropentagnathus irregularis* (at SO 5658 9830); at the stratotype section only the uppermost part of the *P. celloni* conodont biozone occurs, with the base of the succeeding *P. amorphognathoides* Biozone recognizable 65 cm below the Llandovery–Wenlock boundary in unit C. The microfossil residues also contain scolecodonts, miospores (*Ambitisporites* sp.) and rare thelodont dermal denticles.

Interpretation

The Hughley Shales were deposited in an offshore shelf setting on the western margin of the Midland Platform. Ziegler *et al.* (1968b) recorded a *Clorinda* benthic community (= Benthic Assemblage 5 of Boucot, 1975), reflecting the relatively deep water environment. The wide diversity of macrofossils and, particularly, microfossils provides a good basis for local and international correlation of these latest Llandovery strata.

Conclusions

This is a site of major international importance as the stratotype locality for the base of the Wenlock Series (see the Wenlock chapter of this volume). The same boundary level marks the base of the Sheinwoodian Stage and of the Buildwas Formation. The lower 2 m of the section, below the Llandovery–Wenlock boundary, displays typical strata of the uppermost Hughley Shales, and contains a diverse macrofauna and a very wide variety of microfossils. Other small exposures in the vicinity of the stratotype section provide evidence of the lithology and biota of strata lower in the formation. The locality is frequently visited by national and international specialists and has the highest conservation priority.

GULLET QUARRY (SO 7612 3811)

Introduction

Gullet Quarry is situated within the Malvern Hills at the southern end of Swinyard Hill, to the north of the Gullet Pass (Figure 3.9). The main quarry face is excavated in sheared and metamorphosed late Precambrian (Malvernian) diorites cut by pink granitic veins, but in 1959 quarrying activity in the top north-western corner of Gullet Quarry revealed a contact with the overlying Silurian strata (Reading, 1960). Further quarrying extended the exposures of the Wyche Formation, a sequence of shales, siltstones, sandstones and bioclastic limestone lenses dipping westwards at 60° near the contact and containing fossils demonstrating a Telychian age. Descriptions of the exposures, especially at the contact, have been provided by several authors, most of whom have interpreted the junction as an unconformity (among others Reading and Poole, 1961, 1962; Butcher, 1962; Shelford, 1964; Tucker, 1964; Ziegler, 1964; Brooks and Druce, 1965; Ziegler *et al.*, 1968b; Penn and French, 1971; Aldridge, 1972; Bullard, 1989; Worssam *et al.*, 1989). Whitworth (1962) and Phipps and Reeve (1964, 1969), however, regarded the contact as faulted, consistent with the regional view forwarded by Groom (1900), who believed that a Western Boundary Fault delimited all of the western margin of the Malvern Hills.

While slickensides and shear zones testify to faulting in the vicinity of the contact, the rounded boulders, some exotic, in the basal conglomeratic limestone and the presence of a neptunian dyke containing rounded pebbles within the Malvernian high in the quarry attest to the unconformable nature of the contact (Brooks and Druce, 1965). Movement along the contact zone has certainly occurred during adjustment to the tectonic tilting of the succession, but the evidence supports an original sedimentary contact between the Precambrian and Llandovery rocks. This is, therefore, a key locality in displaying the nature of the eastern margin of the Welsh Basin during the late Llandovery epoch and in demonstrating that an early Silurian shoreline existed in this area.

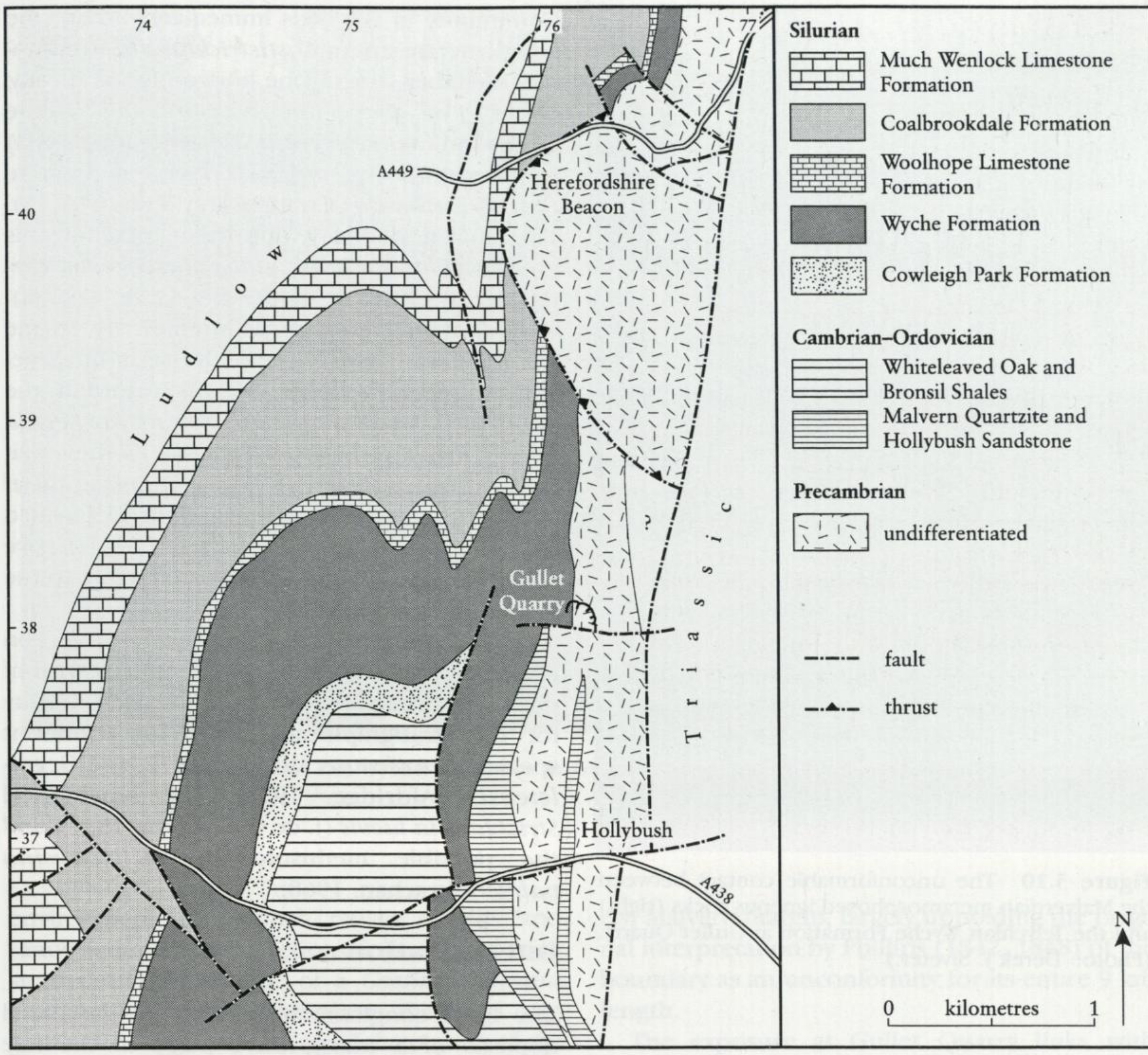

Figure 3.9 Outline geological map of the southern Malvern Hills, showing the location of Gullet Quarry (after Aldridge and Smith, 1985).

Description

The basal conglomerate is discontinuous, occurring as patches up to 1 m thick along the Malvernian surface (Figure 3.10). It is extremely variable, with a matrix of limestone, sand or clay, but is generally non-calcareous and haematite-stained immediately above the contact. Boulders are up to at least 80 cm in size and include diorite, dolerite, granite and quartz, consistent with derivation from the adjacent Malvernian. Some pebbles of fine-grained tuff are probably derived from the nearby Warren House Volcanic Group, also of late Precambrian age (Brooks and Druce, 1965). The limestone matrix contains shelly layers with a diverse assemblage of corals, brachiopods, stromatoporoids, bryozoans and crinoid ossicles. Ziegler *et al*. (1968a) regarded this fauna as a mixture of rocky bottom and soft bottom forms. Conodont elements have been recovered by dissolution of the limestone (Brooks and Druce, 1965; Aldridge, 1972), and include the stratigraphically useful taxa *Ozarkodina gulletensis* and *Aulacognathus kuehni*, indicative of a position low in the *Pterospathodus celloni* Biozone. The stratigraphically important brachiopod *Eocoelia curtisi* occurs in the basal conglomerate and in the beds immediately above (Ziegler *et al*., 1968b).

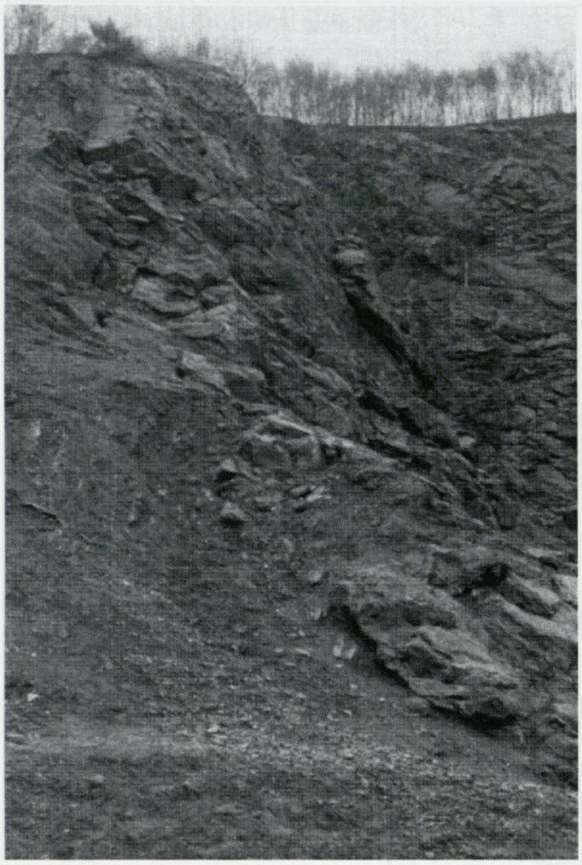

Figure 3.10 The unconformable contact between the Malvernian metamorphosed igneous rocks (right) and the Telychian Wyche Formation at Gullet Quarry. (Photo: Derek J. Siveter.)

The section in the Wyche Formation (Figure 3.11) is dominated by shales and siltstones, with some thicker sandstone beds, mostly 8–20 cm thick, but with one prominent bed of 80 cm. Thin limestone lenses occur sporadically and the bases of some of the sandstones are uneven with patches of calcareous bioclastic material. Scours, groove casts and prod marks are common on the lower surfaces of many of the sandy beds, and some of the upper surfaces display ripple marks.

Fossils are abundant, particularly in shelly lags at the bases of sandstone units and in decalcified sandy limestones. Corals and brachiopods dominate the macrofauna, with crinoid ossicles, nautiloids, gastropods, bryozoans, trilobites and rare graptolites also recorded. The trace fossil *Chondrites* is common. Ziegler *et al.* (1968b) reported two benthic marine communities in the rocks above the basal unit: a *Pentameroides* Community in the beds immediately above the conglomerate and a *Costistricklandia* Community in higher strata. One horizon in the quarry, about 9 m above the base of the Wyche Formation, was selected by Ziegler *et al.* (1968a) as providing the typical collection for the *Costistricklandia* Community (Figure 3.12). The stratigraphically important brachiopods *Costistricklandia lirata alpha* and *Eocoelia curtisi* occur at this level (Ziegler *et al.*, 1968a). Conodont elements occur sporadically in the shale and are abundant and diverse in the limestone lenses. Aldridge (1972) recorded the important taxa *Icriodella inconstans*, *Kockelella ranuliformis* and *O. gulletenesis* in the main face, with the addition of *Pterospathodus celloni* and *Apsidognathus tuberculatus* in an isolated lens found above the main sequence (Figure 3.13). All the exposed beds are referable to the *P. celloni* conodont biozone.

As well as providing a representative section for Telychian fossil biotas on the eastern shelf of the Welsh Basin, the quarry is the type locality for the stratigraphically important conodont species *I. inconstans* Aldridge, 1972, and *O. gulletensis* (Aldridge, 1972), the brachiopod *Stricklandia laevis* (J. de C. Sowerby, 1839), and the possible medusoid *Duodecimedusina palmeri* Strachan, 1968.

Interpretation

The basal conglomerate represents the initial deposits of a transgressive pulse in the late Llandovery, with the Wyche Formation overstepping the underlying Cowleigh Park Formation (late Aeronian) to onlap directly onto the Malvernian. Reading and Poole (1962) noted that rounded boulders within the conglomerate are embedded in a matrix of undistorted, and often unbroken, brachiopods and corals and that the horizon could not represent a fault breccia. They interpreted the irregular surface of the Malvernian below the contact to represent the remains of sea stacks in front of a retreating clifline. Fragments of various sizes would have fallen occasionally into the sea and become incorporated into whatever sediment was being deposited in the immediate vicinity of the stack (Brooks and Druce, 1965). Some rounding of the blocks may have been caused by weathering processes before they became detached.

The overlying strata of the Wyche Formation record the development of a shallow marine

Figure 3.11 The Wyche Formation at Gullet Quarry (Photo: Derek J. Siveter).

environment, into which pulses of silty and sandy sediment were delivered, perhaps during storms. The presence of a *Costistricklandia* Community a few metres above the basal conglomerate suggests fairly rapid deepening of the sea.

Gullet Quarry is one of two local exposures that show an unconformable contact of Telychian strata on the Malvernian; the other, less well exposed, is at Sycamore Tree Quarry (SO 7646 4594) at West Malvern, 8 km to the north of Gullet Quarry. Other temporary exposures of the contact that have been reported from time to time have been variously interpreted as unconformable or faulted; a full summary of all the literature on these localities was provided by Barclay *et al.* (1997). As pointed out by Reading and Poole (1962), it is beside the point that some localities may display a faulted junction; the demonstration of an unconformity at any one locality is sufficient to establish the case for an original sedimentary contact. Some authors (e.g. Brooks, 1970), indeed, have considered that there is little evidence for major faulting of the contact along much of the western Malvern margin, largely upholding the original interpretation by Phillips (1842, 1848) of the boundary as an unconformity for its entire 9 km length.

The exposure at Gullet Quarry links with other sites in the Welsh Borderland (Hope Quarry, Hillend Farm, Wistanstow) to provide evidence of the position and nature of the eastern margin of the Welsh Basin during late Llandovery time. Open marine shelf deposits are also exposed to the south in the Tortworth Inlier at Damery Bridge, where two lava flows testify to volcanic activity in that area (e.g. Cullimore's Quarry); the only evidence for Telychian volcanicity in the Malverns, including Gullet Quarry, comes from occasional thin bentonite (volcanic ash) beds.

Conclusions

As well as displaying the unconformable contact between the Malvernian igneous rocks and the Telychian sediments, Gullet Quarry provides the largest exposure of the Wyche Formation in the Malvern Hills. The locality, therefore, has con-

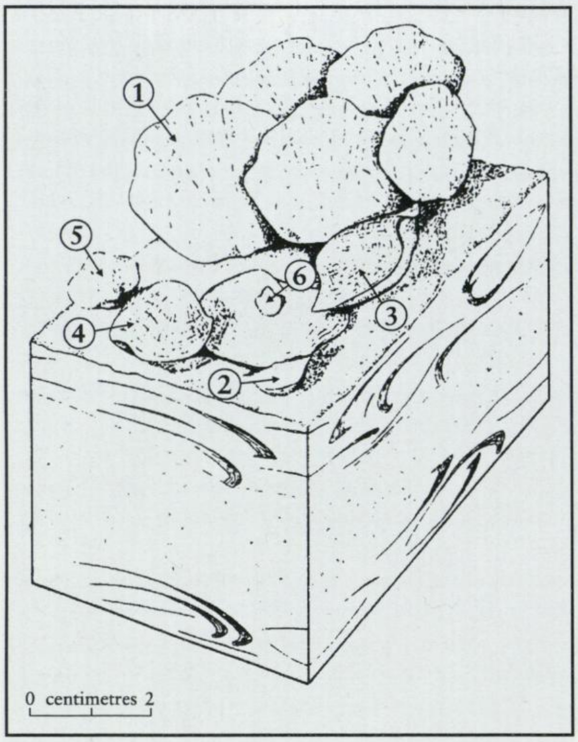

Figure 3.12 Reconstruction of the *Costistricklandia* benthic community, based on a collection from Gullet Quarry (after Ziegler *et al*., 1968a). The fossils represented are: (1) *Costistricklandia lirata alpha*; (2) *Pholidostrophia salopiensis*; (3) *Eospirifer radiatus*; (4) *Atrypa reticularis*; (5) *Clorinda globosa*; (6) *Protathyris* sp.

siderable local importance in demonstrating the nature of the Early Silurian sediments and their stratigraphical relationships. On a regional scale, the quarry provides significant evidence for the position of the late Llandovery eastern shoreline of the Welsh Basin and for the development of the eastward transgression of the Early Silurian sea. Gullet Quarry has also provided a major focus for the debate on the nature of the Malvernian–Llandovery contact and, consequently, on the structural evolution of the Malvern Hills and surrounding areas of the Welsh Borderland. It is a site of major scientific and historical importance and has a very high conservation value.

DAMERY BRIDGE (ST 7055 9428)

Introduction

The marine Silurian rocks of the Tortworth area form an inlier, and are unconformably overlain by Old Red Sandstone strata to the south. In the north-west there is a faulted contact with the Lower Old Red Sandstone, but in the north, east and west the Lower Palaeozoic rocks disappear under a Mesozoic cover (Figure 3.14). The Llandovery strata of the Tortworth area were assigned to two formations, originally termed the Damery Beds and the Tortworth Beds, by

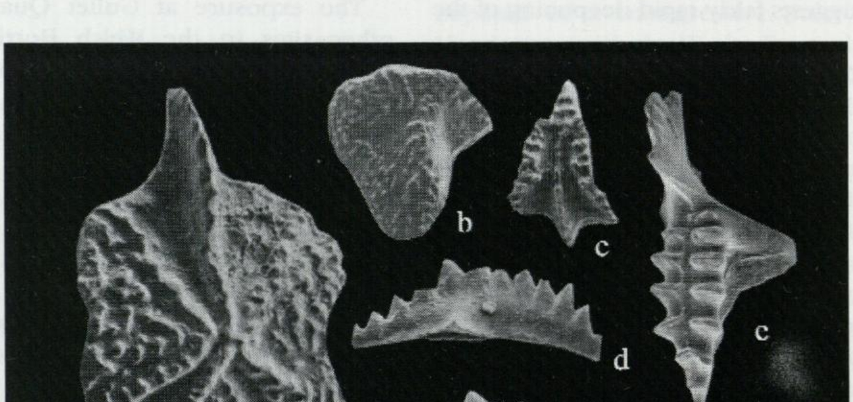

Figure 3.13 Representative conodont elements from Gullet Quarry. (a–c) *Apsidognathus tuberculatus*, platform, lenticular and lyriform elments, × 40; (d) *Pterospathodus celloni*, Pa element, × 40; (e) *Icriodella inconstans*, Pa element, × 50; (f) *Ozarkodina gulletensis*, Pa element, × 40. (Photos: from Aldridge, 1975.)

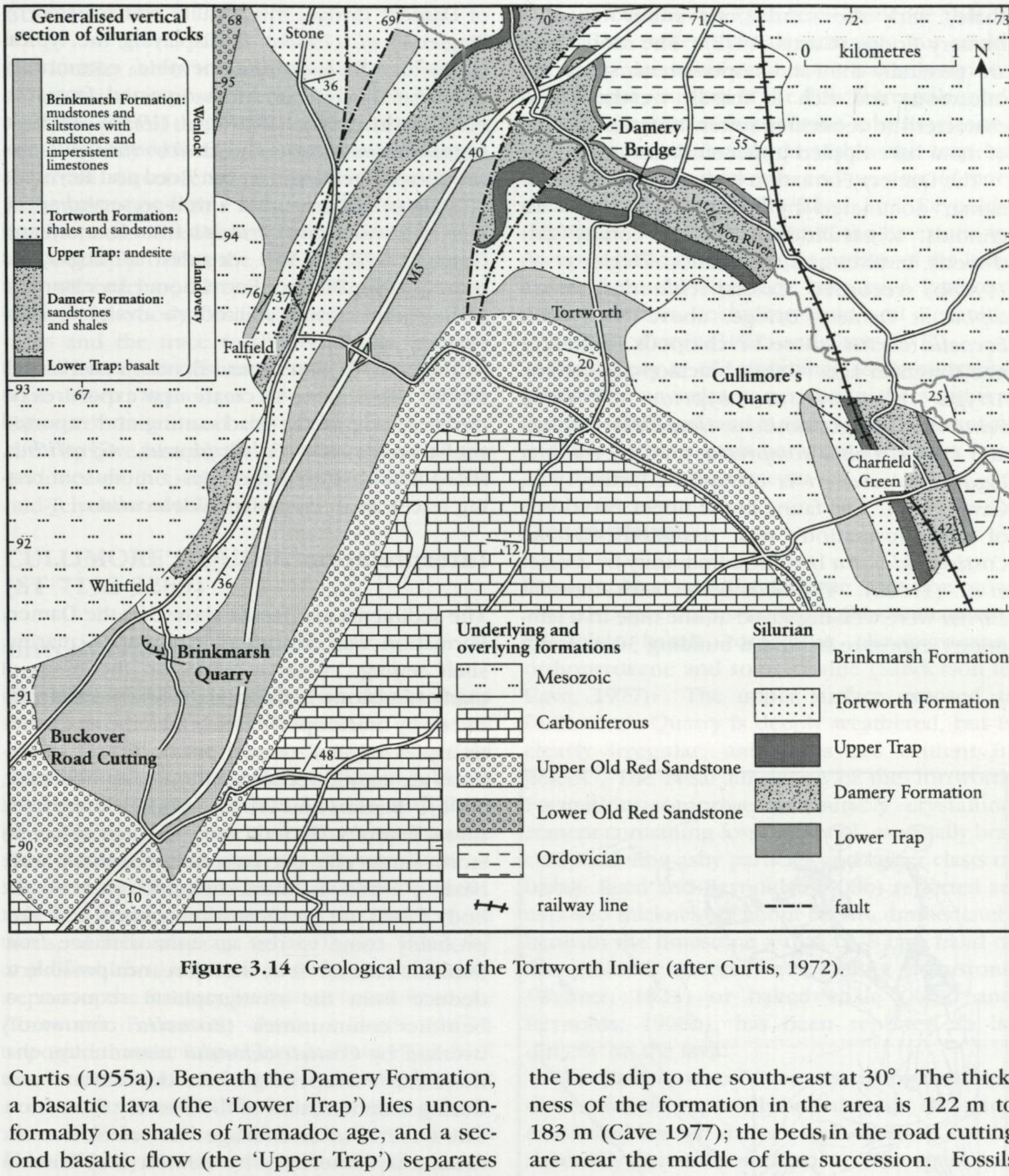

Figure 3.14 Geological map of the Tortworth Inlier (after Curtis, 1972).

Curtis (1955a). Beneath the Damery Formation, a basaltic lava (the 'Lower Trap') lies unconformably on shales of Tremadoc age, and a second basaltic flow (the 'Upper Trap') separates the Damery and Tortworth formations. The lower flow is exposed in Damery Quarry (ST 7045 9440), to the north of Damery Bridge, and the upper flow at the Cullimore's Quarry site. The type locality of the Damery Formation is the valley of the Little Avon River near Damery Bridge, and Curtis (1972) noted that the beds are particularly well exposed in the roadside 50 m south of the bridge itself (see also Reed and Reynolds, 1908b, who recorded a small quarry, now disappeared, at this point). Here the beds dip to the south-east at 30°. The thickness of the formation in the area is 122 m to 183 m (Cave 1977); the beds in the road cutting are near the middle of the succession. Fossils from at or near this locality have been listed by several authors, principally Reed and Reynolds (1908a), Curtis (1972) and Cave (1977). These beds are not now well exposed, but the road cutting provides the best site for opening representative exposures of the Damery Formation.

Description

The Damery Formation comprises alternating beds of fine sandstone, siltstone, mudstone and shale, with the sandstones subordinate at Damery Bridge (Curtis, 1972). The sandstones are generally thin and impersistent; some are calcareous and rich in fossils, weathering to characteristic decalcified rottenstones, and many of them have rippled upper surfaces.

The Damery Formation contains a rich marine fauna, dominated by brachiopods but with crinoids, tentaculitids, trilobites, corals, gastropods, bivalves and conodonts. Ziegler *et al.* (1968b) recorded *Costistricklandia lirata alpha* at Damery Bridge, above beds with *Eocoelia curtisi*; these brachiopods indicate a mid-Telychian age. Other brachiopods include *Atrypa reticularis, Brachyprion arenacea, Pentameroides gotlandicus, Howellella anglica* and *Leptostrophia compressa,* and the trilobite *Lygdozoon weaveri* is common (Curtis, 1972; Cave, 1977). The fauna in the upper two-thirds of the formation was assigned to the *Costistricklandia* benthic community by Ziegler *et al.* (1968b). The beds below with *Eocoelia curtisi* were well displayed at one time in a temporary exposure behind a building 30 m south of Damery Bridge; this locality was selected by Ziegler *et al.* (1968a) as displaying the typical fauna of the *Eocoelia* benthic community (Figure 3.15). Conodonts reported from the road cutting by Aldridge (1972) include *Icriodella inconstans* and *Ozarkodina gulletensis.* Graptolites are rare, but Reed and Reynolds (1908b, p. 517) reported a well-preserved specimen of *Monograptus priodon* from Damery, and Curtis (1972, p. 16) recorded *Monograptus marri* in the Damery Formation. An extensive acritarch and spore microflora awaits description.

Trace fossils also occur. Benton and Hiscock (1996) cut trenches to create new exposures on the west side of the road cutting and reported the trace fossils *Palaeophycus, Gyrolithes, Palaeosemaeostoma* (perhaps a medusoid resting trace), *Rusophycus* and *Tomaculum.*

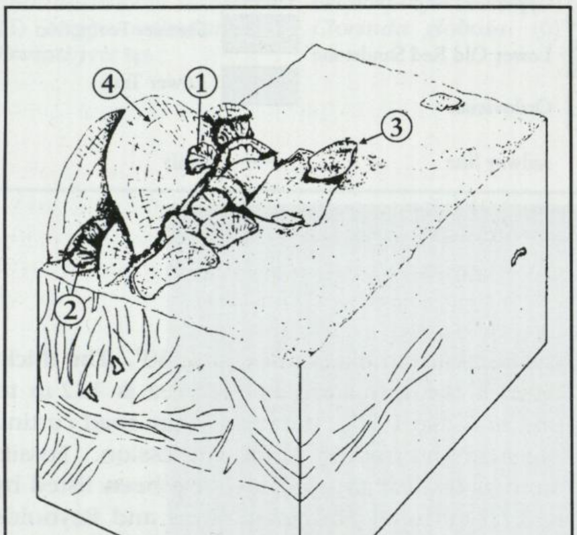

Figure 3.15 Reconstruction of the *Eocoelia* benthic community, based on a collection from the Damery Formation 30 m south of Damery Bridge (after Ziegler *et al.*, 1968a). The fossils represented are: (1) *Eocoelia curtisi*; (2) *Ferganella* aff. *decemplicata*; (3) *Dalejina* sp.; (4) a leptostrophiid brachiopod.

Interpretation

The sediments and fossils show that the Damery Formation was deposited in an open marine, shelf setting. Groove marks on the bases of many sandstone beds appear to have been produced by brachiopod valves and indicate chaotic transport of shell debris; palaeocurrent indications are multidirectional (Benton and Hiscock, 1996). Benton and Hiscock (1996) interpreted these features as indicative of deposition by storm-surge ebb currents below normal wave base in a mid- to distal-shelf environment; the body fossils are preserved in coquinas and have probably come to rest at some distance from their life habitat. It is, therefore, not possible to deduce from the stratigraphical sequence of benthic communities (*Eocoelia* community overlain by *Costistricklandia* community) that there was a deepening of the depositional area during sedimentation of the Damery Formation. The trace fossil assemblage was referred to the *Cruziana* Ichnofacies by Benton and Hiscock (1996), which they considered to indicate an offshore location below normal wave base.

This site links with others in the Welsh Borderland (Hughley Brook, Gullet Quarry, Wistanstow) to provide a picture of the pattern of deposition across the western margin of the Midland Platform during the Telychian. It also links with the nearby site of Cullimore's Quarry to illustrate the developing local tectonic, depositional and volcanological setting during the late Llandovery.

Conclusions

This locality serves to illustrate the development of late Llandovery sediments and faunas in the southern part of the Welsh Borderland. It is the type locality of the Damery Formation, a Telychian sequence of interbedded sandstones and mudstones with a rich fauna dominated by brachiopods. The Damery Formation at or near this locality provides the type horizons of several fossil brachiopod species. The transported nature of the body fossils, the sedimentary structures and the trace fossil assemblage indicate deposition in an offshore setting, below normal wave base. Exposures are uncommon in the Tortworth Inlier, and this locality and others close by have historically provided almost all the evidence on the sedimentology and biota of the mid-Telychian of this region.

CULLIMORE'S QUARRY (ST 7198 9269)

Introduction

This disused quarry is a classic site that has been widely documented in the literature. Situated 450 m N40°W of the level crossing at Charfield Green in the Tortworth Inlier (Figure 3.14), it exposes the higher of two Silurian lava flows found in the Tortworth area. The lower basaltic flow, commonly termed the 'Lower Trap', is exposed in Damery Quarry (ST 7045 9440), where it lies unconformably on the Micklewood Beds, of Tremadoc age. The 'Upper Trap', the top of which is exposed in Cullimore's Quarry, separates the Damery Formation below from the Tortworth Formation above. Curtis (1972) reported that the Upper Trap is about 50 m thick on the eastern side of the inlier, but wedges out westwards; Cave (1977), however, gave a thickness of 64 m at Charfield Green, from where it thins slightly southwards and markedly northwestwards. The first reports of the two lavas were published in the early 19th century, and a history of the early work has been provided by Curtis (1955b). Detailed petrographical studies of both lavas have been published by Reynolds (1924) and Cave (1977), and Van de Kamp (1969) gave several chemical analyses including results from a sample from Cullimore's Quarry (also listed by Cave, 1977). Curtis (1972) regarded the constant stratigraphical position of the Upper Trap, together with the contact features at Cullimore's Quarry, as evidence that it was a flow rather than an intrusion, but could not determine whether or not it was submarine.

The upper surface of the flow is irregular and contains pockets of fossiliferous ashy limestone, first reported as interbeds within the trap by Weaver (1824). A sketch and section of one pocket was provided by Reed and Reynolds (1908b, p. 515), who observed the limestone to occupy a hollow in the upper surface of the lava. Fossils from the limestone have been listed by several authors, including Reed and Reynolds (1908a, b), Curtis (1972) and Cave (1977).

The quarry is of importance to demonstrate lower Silurian volcanic activity in the southern Welsh Borderland, and is especially significant as it displays the contact between the upper lava and the overlying sediments.

Description

Petrographical studies indicate that the now altered Upper Trap was originally a contaminated felsic basalt containing clinopyroxene, orthopyroxene and some olivine (Sanderson in Cave, 1977). The upper surface exposed at Cullimore's Quarry is deeply weathered, but is clearly irregular; amygdales are evident in places. The basal limestone of the Tortworth Formation comprises a coarsely crystalline cement containing fossil material, especially brachiopods, fine ashy particles and larger clasts of basalt; Reed and Reynolds (1908b) reported an exposed thickness of about 60 cm. Immediately beneath the limestone a thin (2–8 cm) band of fine-grained material, resembling hornstone (Weaver, 1824) or baked shale (Reed and Reynolds, 1908b), has been reported to lie directly on the lava.

The limestone contains abundant and very diverse fossils, especially brachiopods, including *Costistricklandia lirata,* and tabulate corals, especially *Favosites multipora*. The small and important rugose coral *Palaeocyclus porpita* was reported by Curtis (1972) from a thin calcareous sandstone band just above the limestone. Reed and Reynolds (1908a, b) also listed bryozoans, gastropods, trilobites and cornulitids from the hollows. Acetic acid dissolution of a limestone sample has yielded the conodonts *Distomodus staurognathoides, Ozarkodina gulletensis, Kockelella ranuliformis* and *Aulacognathus* sp.. The entire fauna is indicative of a late, but not latest, Telychian age.

Interpretation

Although widespread bentonite bands provide evidence of volcanic activity in the Welsh Basin from the Llandovery to early Ludlow epochs, there are few examples of lava flows. These are largely restricted to the southern part of the Welsh Basin and can be seen, for example, at the sites at Marloes, Cullimore's Quarry and Moons Hill Quarry; these sites expose lavas of early Llandovery, late Llandovery and Wenlock age respectively. The relatively localized distribution of these outcrops indicates that volcanicity was much more restricted in Silurian times than during the preceding Ordovician Period. The two lavas in the Tortworth Inlier are essentially of similar basaltic composition, with the differences attributed to different cooling histories and to contamination of the magma (Sanderson in Cave, 1977).

The stratigraphical setting shows that the Upper Trap was a submarine lava flow. The relatively deep water *Costistricklandia* benthic community is present in the upper two-thirds of the underlying Damery Formation, and Ziegler *et al.* (1968b) reported the *Eocoelia* and *Costistricklandia* communities at two localities in the basal beds of the Tortworth Formation on top of the lava. At Cullimore's Quarry, the fauna in the limestone on top of the flow can also be attributed to the *Costistricklandia* Community (Cave, 1977), indicating little difference in local sea depth before and after the extrusion.

There is some uncertainty as to whether the ashy material and volcanic clasts in the limestone indicate that this is a calcite-cemented tuff, or whether the volcanic material was incorporated from the decomposing lava surface (Cave, 1977). In either case, the inclusion of volcanic clasts in the basal limestones indicates that the igneous rock was a lava, not an intrusion.

Conclusions

This site displays one of the few lava flows in the Silurian succession of the Welsh Basin and gives direct evidence of volcanic activity in the Tortworth area in late Llandovery times. The presence of ashy material and clasts of volcanic rock in the overlying limestones provides evidence that this basaltic igneous body is extrusive rather than intrusive, and the marine faunas that bracket the flow locally indicate that it was submarine. The limestones, which represent the basal beds of the Tortworth Formation, occur in pockets and hollows in the upper surface of the lava and contain a rich fauna, dominated by diverse brachiopods and corals.

This locality, along with those at Marloes and Moons Hill Quarry provides direct evidence of early Silurian volcanicity in the southern part of the Welsh Basin. It is of particular importance as it demonstrates the nature of the upper surface of the flow and its contact with the overlying sediments. The macrofauna and microfauna in the overlying limestone pockets provide a good example of the late Telychian biota of the Midland Platform shelf sea. This is a key locality for the study of the regional Lower Silurian faunas, sedimentation and volcanicity.

BUTTINGTON BRICKWORKS (SJ 266 101)

Introduction

The first full account of the rocks of the area around Welshpool, Powys, was published by Wade (1911), who briefly reviewed earlier references to the geology of the district, including observations by Murchison (1839), Ramsay (1866, 1882) and Watts (1885). Wade (1911) divided the Llandovery strata of the district to the east of Welshpool into two units, the 'Cefn Group' and the 'Buttington Group'. He also noted the complex structure of the area, recognizing a general folding along north-north-easterly axes that produced steep dips in some places.

Whittard (1932) also dealt with the rocks of the Buttington district as part of his investigation of the Llandovery strata of Shropshire. He did not follow the stratigraphical scheme proposed by Wade (1911), but applied the same terms he had used for Llandovery strata throughout Shropshire. Thus, the Cefn Group of Wade was assigned to the Pentamerus Beds, and the Buttington Group to the Purple Shales. Ziegler *et al.* (1968b), however, reinstated the local names introduced by Wade, as the Cefn Beds and Buttington Shales; Palmer (1970) subsequently formalized these as the Cefn Formation and the Buttington Mudstone Formation. Cave and Dixon (1993) used the name Buttington Shales Formation for the upper unit, noting, as had Wade (1911), the equivalence of this formation to the Tarannon Shales of the Geological Survey (Ramsay, 1882). Loydell and Cave (1993) preferred to use the name Tarannon Shales Formation for this unit.

The Cefn and Buttington Mudstone formations are exposed intermittently along an 8 km strip of country to the north-east of Buttington Railway Station. The largest exposures by far are in the quarry at Buttington Brickworks (Figure 3.16), 4 km north-east of Welshpool, where a continuous section is exposed from the upper Cefn Formation, through the entire Buttington Mudstone Formation and into the lower part of the overlying Trewern Brook Mudstone Formation. Lower beds in the Cefn Formation can be seen in a small, overgrown old quarry (SJ 2638 1004) by the roadside west of the brickworks quarry. Cocks *et al.* (1992) gave the thickness of the Cefn Formation as 91 m and that of the Buttington Mudstone Formation as 107 m, while Loydell and Cave (1993) measured the thickness of the Buttington Mudstone Formation at Buttington Brickworks as just under 80 m. A full description of the brickworks locality was given by Cave and Dixon (1993), with further details, particularly on the graptolites of the Buttington Mudstone Formation, being provided by Loydell and Cave (1993).

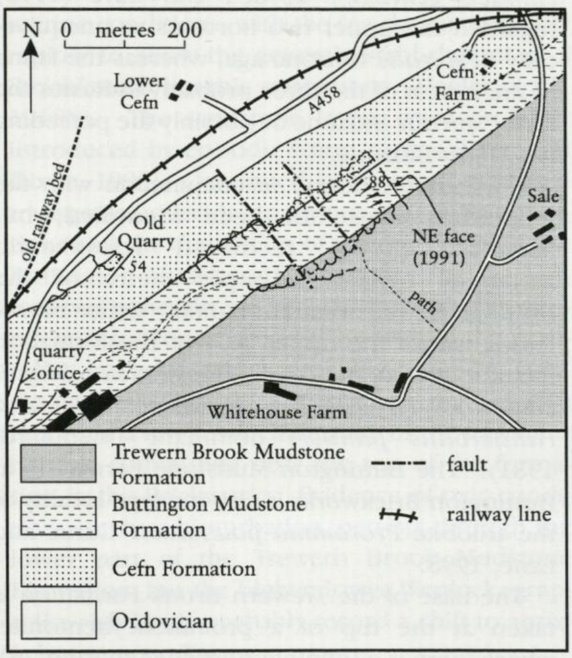

Figure 3.16 Geological sketch-map and lithostratigraphy for Buttington Brickworks (modified after Loydell and Cave, 1993).

While the brick pit was active, this locality provided excellent continuous exposures through representative Telychian and lower Wenlock strata of the area within the western part of the Welsh Borderland Fault System. The exposures are now somewhat degraded, but still show the lithological characteristics of the units and yield occasional graptolites. Microfossils of various types occur in the strata close to the boundary between the Buttington Mudstone Formation and the Trewern Brook Mudstone Formation, and together with the graptolites enable location of the Llandovery–Wenlock boundary in this section (Figure 3.17). The Wenlock strata are described in Chapter 4 of this volume.

Description

The basal beds of the Cefn Formation lie unconformably on Ordovican strata, and can be seen in the old quarry at SJ 2638 1004. The lowest metre is conglomeratic and contains pentamerid brachiopods; above this are bioturbated pale grey-green silty mudstones with interbedded fine sandstones in beds about 8 cm thick. Ziegler *et al.* (1968b) recorded *Stricklandia lens* cf. *intermedia* in the lower part of the formation, indicative of an Aeronian age. In contrast, the recognition of *Spirograptus turriculatus* near the top of the formation (Zalasiewicz, in Cave and Dixon, 1993) led Cave and Dixon (1993) to suggest that most, if not all, of the Cefn Formation may be of Telychian age. An unpublished conodont collection from low in the old quarry includes fragmentary specimens comparable with *Ozarkodina oldhamensis*, which would be consistent with an Aeronian age for this part of the section.

The top 6 m of the Cefn Formation are exposed in the north-west face of Buttington Brick Pit. Here, grey mudstones are interbedded with thin sandstones, ranging from less than 2 cm to 5 cm thick; the tops of some of the sandstones are rippled, giving a direction of flow from east to west (Ziegler *et al.*, 1968b). Detailed measured sections from this point, through the nearly vertically bedded Buttington Mudstone Formation and into the Trewern Brook Mudstone Formation were given by Cave and Dixon (1993, pp. 71–3) and Loydell and Cave (1993). The lithology is entirely of mudstones, which are grey at the base, red and green through the bulk of the formation, and increasingly buff towards the top. At least nine ben-

Figure 3.17 The south-eastern part of the main (north-east) face at Buttington Brickworks, showing the upper part of the Buttington Mudstone Formation (to the left) and the lower part of the Trewern Brook Mudstone Formation. (Photo: Derek J. Siveter.)

tonitic horizons occur, cream or pink in colour, with the thickest towards the top of the formation.

Graptolites have been reported from five horizons in the Buttington Mudstone Formation (Loydell and Cave, 1993). The lowest horizon is near the base of the formation and has yielded *Spirograptus turriculatus, Streptograptus johnsonae* and *Pseudoplegmatograptus obesus*, indicating the *turriculatus* Biozone (*johnsonae* Subbiozone). A second horizon, 30 m above the base, contains chitinozoans, tiny brachiopods and well-preserved graptolites; these include abundant *Stimulograptus clintonensis*, together with smaller numbers of *Streptograptus exiguus, Monograptus veles, Pristiograptus nudus, Petalolithus wilsoni* and *'Monograptus' arcuatus.* Loydell and Cave (1993) referred this fauna to the *crispus* Biozone, or possibly the lower *griestoniensis* Biozone. The top three horizons are close together, 10–15 m below the top of the formation. They have yielded a diverse graptolite fauna, including *Monograptus spiralis, Monograptus priodon, Monograptus parapriodon, Monoclimacis vomerina* and *Monoclimacis geinitzi.* Loydell and Cave (1993) regarded the upper two horizons as unequivocally of *spiralis* Biozone age, whereas the fauna of the lowest of the three probably indicates the lower *spiralis* Biozone or possibly the preceding *crenulata* Biozone.

Chitinozoans found in conjunction with the graptolites have not been identified, but Mabillard (1981) recovered leiosphaerid acritarchs from the upper metre of the Buttington Mudstone Formation. Other microfossils within the upper part of the formation include conodonts, with *Dapsilodus obliquicostatus, Panderodus langkawiensis* and *Panderodus panderi* dominant (Mabillard, 1981). The Buttington Mudstone Formation at Buttington Brickworks is also the type locality of the trilobite *Proromma powysensis* Curtis and Lane, 1998.

The base of the Trewern Brook Formation is taken at the top of a prominent bentonite, where there is a lithological change to more calcareous sediments. The lowest 9 m of the formation are bioturbated silty mudstones, with rare brachiopods and trilobites and very sparse, fragmentary graptolites, including *Retiolites geinitzianus*. Loydell and Cave (1993) referred these strata to a new member, the Butterley Mudstone Member, of the Trewern Brook Mudstone Formation. Mabillard (1981) recorded the incoming of diverse acritarchs of Acritarch Biozone 5 (of Hill, 1974) 3 m above the base of the member, and reported the biozonal conodont *Pterospathodus amorphognathoides* a little higher. He concluded that the base of the Wenlock Series probably occurs in the lower part of the Trewern Brook Mudstone Formation, a conclusion echoed by Loydell and Cave (1993). Higher levels in the Trewern Brook Mudstone Formation have yielded *Cyrtograptus centrifugus* and *Cyrtograptus murchisoni* (Cocks and Rickards, 1969).

Interpretation

Situated within the Welsh Borderland Fault System, the Buttington area is regarded as being part of the platform region, lying east of the line of the Towy Anticline and the Severn Valley Fault (Loydell and Cave, 1993). The spread of the sea from the Welsh Basin probably reached the area in late Aeronian times, and the first sediments of the Cefn Formation represent the shoreline deposits of this eastward transgression. The rest of the formation was deposited in shallow marine conditions, with the sea deepening fairly rapidly to allow the general establishment of a *Stricklandia* benthic community (Ziegler *et al*., 1968b). The sandstone layers were probably introduced by episodic storm surges (Cave and Dixon, 1993). Continued, or renewed, eastward transgression led to an abrupt change in conditions and the deposition of the mudtones of the Buttington Mudstone Formation. The sea bottom was generally oxygenated through this period, as trace fossils are evident even in the graptolitic horizons, which probably represent brief dysaerobic intervals. Ziegler *et al*. (1968b) recorded a few fossils indicative of the *Clorinda* benthic community near the top of the formation in the Brickworks. Evidence of oxic conditions, such as bioturbation, persists through the lower part of the Trewern Brook Mudstone Formation, but the higher, lower Wenlock, graptolite-rich levels probably record a shift to anoxic bottom conditions.

Together with the sites at Hope Quarry, Hillend Farm and Wistanstow, this locality records the progress of the eastward transgression of the Llandovery sea across the Welsh Borderland Fault System. The benthic fauna at Buttington is much less abundant than at the other localities, but the reasons for this are not clear.

Conclusions

This locality exposes a continuous section through the Telychian sedimentary sequence on the western part of the Midland Platform, within the area affected by the Welsh Borderland Fault System. The basal Llandovery beds, of Aeronian age, are exposed nearby, and the succession records the flooding and deepening of the sea during its eastward transgression across this area in the late Llandovery. Typical sediments of the Cefn and Buttington Mudstone formations and of the Butterley Mudstone Member are well exposed, and contain graptolitic horizons, which provide a basis for international correlations. Microfossils, including conodonts, acritarchs and chitinozoans are reasonably common in the upper beds exposed, and indicate that the base of the Wenlock Series is probably within the lower part of the Butterley Mudstone Member. These are by far the best exposures of Llandovery strata in this area, and have a high conservation value.

MEIFOD (SJ 1135 1013)

Introduction

The Meifod district is a classic area, visited several times in the first half of the 19th century by Sedgwick, who established the general succession; collections of fossils made during this time were among those described by M'Coy (in Sedgwick and M'Coy, 1852) and listed by Salter (1873). The area was mapped and the stratigraphy revised by King (1928), who reported a basal Silurian sandstone unconformably overlying Ordovician mudstones in Graig Wen Quarry (SJ 1012 0928), but that junction has subsequently been shown to represent the Rawtheyan–Hirnantian boundary within the Ashgill Series (Brenchley and Cullen, 1984; Brenchley, 1993). There are no formal formation names available for the Silurian rocks of this area, but King (1928) introduced an informal terminology with his 'basal sandstone' designated 'V_1' and the overlying blue silty mudstones assigned to 'V_2'.

The site lies on the north side of the forestry track that leaves the A495 road northwards 5.2 km south-west of Meifod, Powys. The exposures are located on the south-western flanks of Ffridd Mathrafal, 550 m ESE of the farm of Tanhouse (Temple, 1970), and are referable to the V_2c subdivision of King (1928). Temple (1970, 1987) collected a prolific fauna from this locality and described the trilobites and brachiopods; from the brachiopod fauna he tentatively suggested a late Rhuddanian age, correlatable with the boundary between the Crychan and Trefawr formations at Llandovery.

This locality is important in displaying the nature of the early Llandovery strata of this marginal portion of the Welsh Basin and for providing a representative suite of the fossils that succeed the typical upper Ordovician *Hirnantia* fauna of the strata below.

Description

The exposures show bedding planes of blue-grey siltstones with interbedded micaceous horizons dipping 57° at 152° (Temple, 1970). Fossils are abundant and mostly well preserved, although many specimens are distorted. Burrows of infaunal organisms are common. Temple's (1970) monograph includes descriptions of the brachiopods *Dolerorthis sowerbyiana*, *Schizonema capillatum*, *Ravozetina rava silvicola*, *Resserella llandoveriana*, *Streptis altosinuata*, *Leangella scissa*, *Anisopleurella gracilis*, *Eoplectodonta duplicata undulata*, *Katastrophomena woodlandensis*, *Leptaena valentia*, *Laevicyphomena reedi*, *Plectatrypa gaspeensis*, *Meifodia subundata* and many others in open or equivocal nomenclature, together with representatives of the trilobite families Proetidae, Otarionidae, Illaenidae, Harpidae, Calymenidae, Cheiruridae, Encrinuridae, Phacopidae, Odontopleuridae and Lichidae. Other elements of the biota await systematic description. The brachiopod taxa were re-assessed and redescribed by Temple (1987). The Meifod site is the type locality for several taxa, including the brachiopods *Schizonema capillatum* Temple, 1970, *Ravozetina rava silvicola* Temple, 1970, and *Meifodia subundata* (M'Coy, 1851b).

Interpretation

Ziegler *et al.* (1968b) noted that *Clorinda* was reported as common in the V_2c division of King (1928); together with the diverse other brachiopods this suggests an offshore, relatively deep water, shelf setting. The penetrative burrows show that the sea bottom and the upper levels of the sediment were oxygenated. This site is one of the most prolific fossil localities in the lower Llandovery strata of the Welsh Basin and links with the slightly older Rhuddanian site at Gasworks Lane, Haverfordwest and the sites at Scrâch Track and in the Ydw Valley in the type Llandovery area, to provide evidence of the earliest Silurian biota of the basin. There is a need for modern stratigraphical, sedimentological and palaeoenvironmental studies in the Meifod area, and this site will be important in any such investigation.

Conclusions

This site is currently most important for the diverse early Llandovery fauna it has yielded, which has formed the basis of monographical studies of the brachiopods and trilobites (Temple, 1970, 1987). Together with other sites of similar age it provides evidence of the earliest Silurian shelly fauna of the Welsh Basin, which contrasts with the characteristic fauna of the preceding Late Ordovician.

GASWORKS LANE (SM 9568 1557–SM 9585 1528)

Introduction

This site comprises exposures on New Road and alongside the lane leading to Fortune's Frolic, opposite the gasworks in Haverfordwest, Pembrokeshire. Cantrill and Jones (in Strahan *et al.*, 1914) established the Llandovery succession in the area, naming six units, the Basement Beds, the Cartlett Beds, the Gasworks Mudstone, the Gasworks Sandstone, the Uzmaston Beds and the Canaston Beds. The nomenclature was revised by Cocks and Price (1975), who renamed the Basement beds as the Portfield Formation, combined the Cartlett Beds and the Gasworks Mudstone into the Haverford Mudstone Formation, and united the Uzmaston and Canaston beds as the Millin Mudstone Formation. The Gasworks Lane locality provides intermittent exposures of the upper part of the Haverford Mudstone Formation and the contact with the Gasworks Sandstone Formation, which is displayed opposite to the gasworks entrance;

these are the best-available exposures of the local lower Silurian. Cocks and Price (1975) gave the total thickness of the Haverford Mudstone Formation as 350–390 m, whereas Cocks *et al.* (1992) gave a figure of 300 m; the Gasworks Sandstone Formation is 85 m thick. The marine fauna of the Haverford Mudstone Formation is well known as one of the richest in the Rhuddanian of Britain, containing numerous brachiopods, trilobites, corals, bryozoans, crinoids, orthocones, ostracods and tentaculitids. Most of the recorded fossils come from the section along Gasworks Lane, and this is a key site for the study of lower Silurian stratigraphy and biotas.

The Llandovery succession in this area is typical of that north of the Variscan Front in Pembrokeshire, and offers a contrast with the very different succession found at the Marloes Sands site some 20 km to the south-west (Figure 3.18).

Description

The buff silty mudstones at this site show no sedimentary structures to give evidence of wave or current agitation. The fauna is extremely diverse; a list was provided by Strahan *et al.* (1914, pp. 90–1), and includes numerous brachiopod species together with trilobites, tabulate and rugose corals, orthocones, tentaculitids, a cystid and the dendroid *Dictyonema.* Many of these taxa are in need of revision, but Temple (1975) has reviewed the trilobites and redescribed several species. Several workers have examined the brachiopods, including Williams (1951), Cocks (1968, 1970), who revised the strophomenids, and Temple (1987). The brachiopods include *Stricklandia lens lens* and indicate a Rhuddanian age (Cocks and Price, 1975; Cocks *et al.*, 1992). Cocks and Price (1975) recognized three main brachiopod assemblages in the upper beds of the Haverford Mudstone Formation in the Haverfordwest area, with the assemblage found in the exposures opposite the gasworks entrance being most variable and diverse. In this fauna *Eoplectodonta duplicata*, *Resserella llandoveriana*, *Leangella scissa*, *Eopholidostrophia sefinensis ellisae*, and *Katastrophomena scotica* are common. Other characteristic fossils include the trilobites *Dekalymene crassa*, *Acernaspis* sp. and *Encrinurus* sp., corals, bryozoans, gastropods, pelmatozoan columnals, including the crinoids *Pisocrinus, Macrostylocrinus, Dimerocrinites* and *Floricolumnus*, and the calcareous green alga

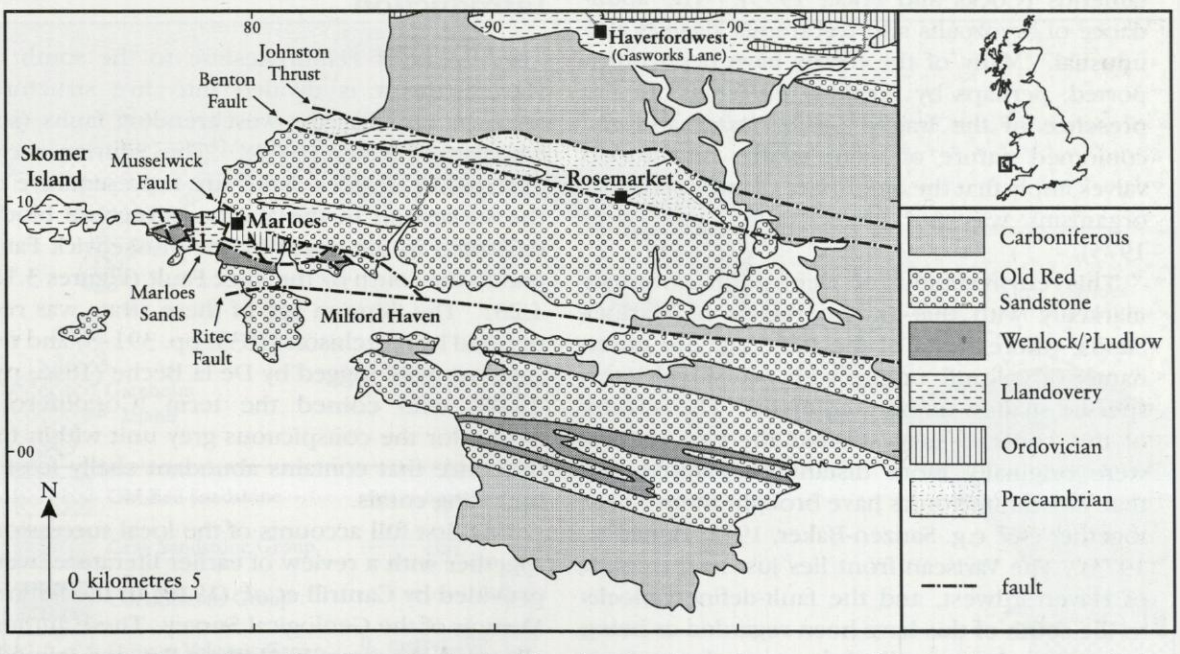

Figure 3.18 The geology of southern Pembrokeshire, showing the major structural blocks, the important faults, and the network localities at Gasworks Lane (Haverfordwest) and Marloes Sands; modified after Sanzen-Baker (1972).

Cyclocrinites favus (Cocks and Price, 1975; Siveter *et al.*, 1989; Donovan and Clark, 1992).

The site is the type locality for several fossil species, including the trilobite *Dekalymene crassa* (Shirley, 1936) and the brachiopods *Katastrophomena scotica* (Bancroft, 1949), *Leptaena haverfordensis* Bancroft, 1949, *Dolerorthis sowerbyiana* (Davidson, 1869), *Leptostrophia antecedens* Williams, 1951, *Leptostrophia reedi* (Bancroft, 1949), *Eopholidostrophia sefinensis ellisae* Hurst, 1974, *Strophonella (Eostrophonella) eothen* Bancroft, 1949, *Fardenia (Saughina) geoffreyi* Bancroft, 1949, and *Leangella scissa* (Davidson, 1871).

Interpretation

The sediments and fauna suggest that the deposition of the Haverford Mudstone Formation took place in an offshore shelf area where silty background sedimentation dominated. Sandstones within this unit and in the overlying Gasworks Sandstone Formation show upward grading, sharp erosive bases, sole marks and slump structures and were interpreted to be the products of turbidity flows by Sanzen-Baker (1972). The benthic assemblage appears to be assignable to the *Clorinda* Community, although *Clorinda* itself is absent, as are other pentamerids (Cocks and Price, 1975). The abundance of bryozoans and calcareous algae is also unusual. Many of the fossils have been transported, perhaps by turbidity currents, but the presence of the fragile *Cyclocrinites* and the conjoined nature of many of the brachiopod valves imply that the amount of disruption of the organisms was not great (Cocks and Price, 1975).

This environment of deposition contrasts markedly with that in the region of Marloes Sands, where strata of the same age are dominantly of volcanic origin, with occasional interspersed shallow-marine sediments. The severity of this contrast suggests that the two regions were originally more distantly separated and that Variscan tectonics have brought them closer together (see e.g. Sanzen-Baker, 1972; Hancock, 1973). The Variscan front lies just to the south of Haverfordwest, and the fault-defined blocks to the south of this have been regarded as being to varying degrees allochthonous, thrust from the south (Sanzen-Baker, 1972; Hancock *et al.*, 1981). The tectonic history of these blocks records early Palaeozoic N–S extension along the basin-bounding faults, which were then reactivated as thrusts during Variscan north–south crustal shortening and inversion (Powell, 1987).

Conclusions

This site displays the best exposures of lower Silurian strata in the Pembrokeshire area north of the area significantly deformed by late Carboniferous tectonics (marked by the Variscan Front). The siltstones and sandstones of the Haverford Mudstone Formation and Gasworks Sandstone Formation in Gasworks Lane contrast with the coeval volcanic succession in the Marloes block just 20 km to the south-west, and the two areas were probably more distantly separated at the time of deposition. The rocks at Gasworks Lane and the very rich biota they contain provide evidence for an offshore shelf environment of deposition invaded by occasional distal turbidity flows. The site is very important for early Silurian fossils in the Welsh Basin, and is the type locality for several species, especially of brachiopods.

MARLOES (SM 7780 0772–SM 7882 0715)

Introduction

The region of Pembrokeshire to the south of Haverfordwest is divided into five structural areas by broadly east–west trending faults (see e.g. Sanzen-Baker, 1972). The Silurian rocks exposed at Marloes Sands are representative of the succession in the Marloes structural block, delimited in the north by the Musselwick Fault and to the south by the Ritec Fault (Figures 3.18, 4.23). The Silurian age of these strata was recognized by Murchison (1839, pp. 391–3) and the sections were logged by De la Bêche (1846, pp. 25–8), who coined the term 'Coralliferous Series' for the conspicuous grey unit within the sequence that contains abundant shelly fossils, including corals.

The first full accounts of the local succession, together with a review of earlier literature, were provided by Cantrill *et al.* (1916) in the Milford Memoir of the Geological Survey. These authors allocated the strata in Marloes Bay and immediately inland to four units: the 'Skomer Volcanic Series', which they regarded to be of early

Ordovician age; the 'Conglomerate Series' of late Llandovery age; the 'Coralliferous Series' of 'Wenlock and Woolhope' age; and the 'Sandstone Series', which they considered to be chiefly Ludlow in age. Ziegler *et al.* (1969) later demonstrated that the Skomer Volcanic Series graded upwards and laterally into the Conglomerate Series and combined the two in the Skomer Volcanic Group. Ostracods found within the lower part of the group on Midland Island (SM 7463 0901) suggest a Silurian age (Ziegler *et al.*, 1969), and Llandovery fossils are common in the upper beds. The entire group, or most of it, is therefore probably of Llandovery age.

The Coralliferous Series was renamed the Coralliferous Group by Walmsley and Bassett (1976) to accord with modern stratigraphical terminology. The unit can be seen to lie unconformably on the Skomer Volcanic Group on the south-east side of Renney Slip (SM 7600 0865) and at Marloes Sands (SM 7870 0725), but the contact is complicated by a small fault at the latter locality (Cantrill *et al.*, 1916; Ziegler *et al.*, 1969). The lower part of the Coralliferous Group contains Llandovery macrofossils (Cantrill *et al.*, 1916), and conodont microfaunas indicate that the group spans the Llandovery–Wenlock boundary (Mabillard and Aldridge, 1983).

The exposures in Marloes Sands are transected by several faults (Figure 3.19), but an almost unbroken sequence of excellent and accessible cliff exposures is available from within the upper part of the Skomer Volcanic Group to the top of the Coralliferous Group from SM 7849 0741 to SM 7882 0715. Additional fault-bounded exposures of the Coralliferous Group occur at the western end of the bay (SM 7780 0772–SM 7811 0765) and at Mathew's Slade (SM 7837 0748). Together these exposures provide the most complete accessible section through the Llandovery and early Wenlock strata of Pembrokeshire. Fossils date the upper beds of the Skomer Volcanic Group as Aeronian in age; the Coralliferous Group begins in the upper part of the Telychian and extends into the lower Wenlock (see Figure 4.24).

This is a site of major national importance, showing the development of sedimentary and volcanic facies on the southern margin of the Welsh Basin. Fossils occur throughout the succession, but are more abundant and diverse in the Coralliferous Group. The unconformity between the Skomer Volcanic Group and the Coralliferous Group is of regional tectonic significance, and is related temporally to a period of southerly-sourced turbidite deposition in the Welsh Basin to the north.

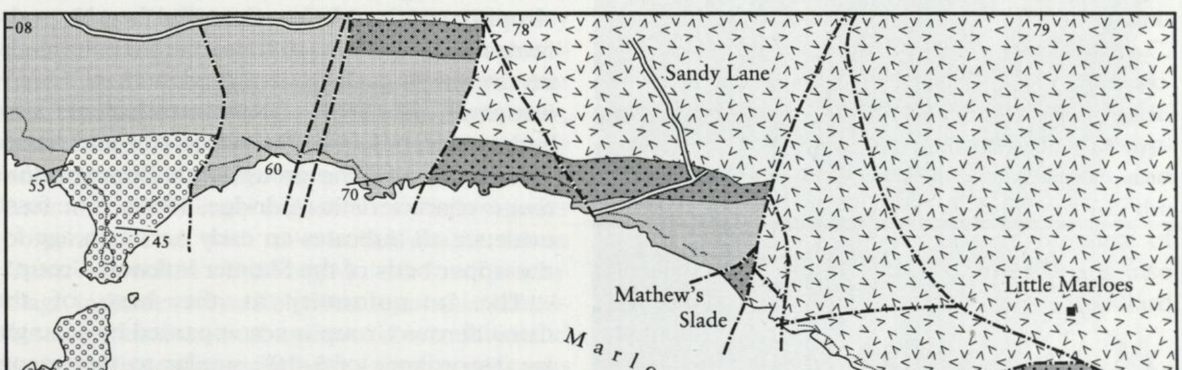

Figure 3.19 Geological map of Marloes Sands (after Walmsley and Bassett, 1976).

Description

Only the upper part of the Skomer Volcanic Group is exposed at Marloes Sands; lower units crop out in the cliffs around Wooltack Point at the western end of the Marloes Peninsula (SM 755 094) and on Skomer and Midland islands west of the peninsula. The total thickness of the group is approximately 1000 m (Ziegler *et al.*, 1969). The oldest beds in Marloes Bay are at the eastern side of Mathew's Slade (SM 7845 0742), where about 6 m of arkosic sandstones overlain by a basalt flow can be seen in a heavily faulted outcrop (Ziegler *et al.*, 1969). Immediately to the east the more completely exposed and nearly vertically inclined succession begins with a grey sandstone followed by two basalt flows, the Lower and Upper Marloes basalts (Figure 3.20). The lower basalt is 23 m thick (Ziegler *et al.*, 1969) with a vesicular base and a reddened top; the upper flow is 19 m thick and also displays a vesicular base (Ziegler *et al.*, 1969). Above the basalts are up to 3 m of thin- to medium-bedded sandstones and siltstones, largely faulted out, followed by a 9 m thick conglomerate containing quartz and rhyolite pebbles. The remainder of the Skomer Volcanic Group, some 150 m in thickness, comprises sandstones, silty mudstones and conglomerates with numerous tuffaceous bands; a measured section was provided by Ziegler *et al.* (1969, pp. 432, 434). Several of the siltstone and sandstone beds show scoured bases, rippled tops and bioturbation. Some 70 m above the basalts is a prominent 6 m band of brecciated tuff with a rippled upper portion (Ziegler *et al.*, 1969; Siveter *et al.*, 1989). Fifteen metres above the tuff and 57 m below the top of the Skomer Volcanic Group, three prominent sandstone beds, almost vertical and separated by dark siltstones, form a landmark known as the Three Chimneys (SM 7860 0732; Figure 3.21).

Figure 3.20 The base of the Lower Marloes Basalt (to the right), within the Skomer Vocanic Group, Marloes Sands. (Photo: R. J. Aldridge.)

Fossils occur in some of the mudstones and siltstones and in rare calcareous beds; there is a general increase in the number and diversity of organisms towards the top of the Skomer Volcanic Group. The most characteristic fossil is the brachiopod *Lingula*, and some horizons yield little else; these were referred to a restricted *Lingula* benthic community by Ziegler *et al.* (1969). The more diverse fauna, referred to as a diverse *Lingula* community, also contains strophomenid and rhynchonellid brachiopods, favositid corals, tentaculitids, crinoid columnals, bivalves and gastropods (Ziegler *et al.*, 1969; Siveter *et al.*, 1989). Conodont elements have been recovered from limestone ribs and lenses near the top of the group, with *Pranognathus tenuis* characteristic (Aldridge, 1985). The fossil evidence all indicates an early Aeronian age for the upper beds of the Skomer Volcanic Group.

The unconformity at the base of the Coralliferous Group is accompanied by an angular discordance of 5–10°, similar to that recognized at the better-exposed section in Renney Slip, 3 km to the WNW. Above the unconformity the lowest 10 m of the Coralliferous Group comprises sandstones and conglomerates with large asymmetric ripples, which pass upwards into hard blue-grey silty cleaved mudstones with shelly limestone lenses and thin sandstones (Siveter *et al.*, 1989). Occasional metamorphosed bentonite bands and tuffaceous horizons also occur. The entire group is about 100 m thick (Cocks *et al.*, 1992).

Figure 3.21 Marloes Sands, with the Skomer Volcanic Group, including the Three Chimneys, to the left and the Coralliferous Group, dipping at a lower angle, to the right. (Photo: R. J. Aldridge.)

The conglomeratic basal beds contain only rare fossils (Sanzen-Baker, 1972), but the rest of the Coralliferous Group is richly fossiliferous. Lists of macrofossils have been provided by Cantrill *et al.* (1916, pp. 66–7) and by Walmsley and Bassett (1976, p. 201). The fauna is dominated by diverse brachiopods and corals, but also includes trilobites, crinoids, bryozoans, orthocones, bivalves, gastropods, tentaculitids and cornulitids. In the lower beds, *Eocoelia sulcata* and the solitary rugose coral *Palaeocyclus porpita* occur, with *Costistricklandia lirata lirata* abundant a little higher; this fossil assemblage indicates a late Telychian age. *Costistricklandia* decreases in abundance above 30 m and is absent from the upper half of the Coralliferous Group. Hurst *et al.* (1978) reported *E.* cf. *sulcata* and *P. porpita* 2 m below the top of the group, indicating that the entire unit is close to the Llandovery–Wenlock boundary. This age is supported by the abundant conodont elements reported from limestone lenses through the lower 70 m of the group by Mabillard and Aldridge (1983); these include *Pterospathodus amorphognathoides*, *Kockelella ranuliformis*, *Distomodus staurognathoides*, *Apsidognathus ruginosus*, and *Icriodella? sandersi*. The Coralliferous Group at Marloes Sands is the type locality for the conodont species *Apsidognathus ruginosus* Mabillard and Aldridge, 1983, and *Icriodella? sandersi* Mabillard and Aldridge, 1983, and for the stratigraphically important brachiopod *Costistricklandia lirata lirata* (J. de C. Sowerby, 1839). Siltstone samples from the section have also yielded small numbers of blackened, poorly preserved acritarchs, with *Domasia trispinosa*, *Micrhystridium stellatum* and *Veryhachium trispinosum* identified in the lower half; blackened, fractured remains of scolecodonts and possibly of chitinozoans also occur in palynological preparations (Mabillard and Aldridge, 1983).

Interpretation

Murchison (1839, pp. 392–3) originally regarded the Marloes basalts as intrusive, but subsequent workers (e.g. Cantrill *et al.*, 1916; Ziegler *et al.*, 1969) have recognized their extrusive features, including the reddened upper surfaces of the individual flows. The basalts flowed into a transgressive sea, with the flows gradually submerged by a sequence of transgressive sediments (Bridges, 1976). Bridges (1976) intepreted the beds immediately above the Marloes basalts as representing a lagoon to barrier island to offshore marine sedimentary sequence (Figure 3.22), and identified other comparable sequences within the Marloes Sands succession; these environmental sequences can be correlated westwards into other successions at Anvil Bay (SM 7565 0884) and Renney Slip (SM 7604 0876). The lagoonal deposits are dominantly muddy with some silts and sands; burrowed horizons with small phosphatic nodules compare with the intense bioturbation in modern lagoons, where phosphatization is known to occur in semi-arid hypersaline conditions (Phleger and Ewing, 1962, cited in Bridges, 1976). Restricted marine conditions are also indicated by the very low diversity shelly fauna, dominated by the euryhaline *Lingula*. The barrier island conglomerates and sandstones range in thickness from 0.15 m to 9.0 m, with granules and pebbles concentrated into lenticles; large symmetrical ripples are suggestive of wave reworking close to the shoreline. Fossils are rare in these coarser sediments, and specimens are broken and abraded. The open marine sediments comprise fossiliferous sandstones and mudstones, and dominate the upper part of the Skomer Volcanic Group section in Marloes Sands. A richer fauna is present than evident in the lagoonal facies, and includes brachiopods, corals, crinoids and conodonts.

The evidence from macrofossils and from conodonts is that the unconformity at the base of the Coralliferous Group cuts out all or most of the upper Aeronian and much of the Telychian. The top of the Skomer Volcanic Group is an erosion surface; reddening of the uppermost 50 cm suggests that erosion was subaerial, at least in the latest stages (Sanzen-Baker, 1972). The presence of this intra-Llandovery unconformity attests to an interval of local uplift; this has been ascribed to the initial phases of Avalonian and Laurentian plate collision by Soper and Woodcock (1990).

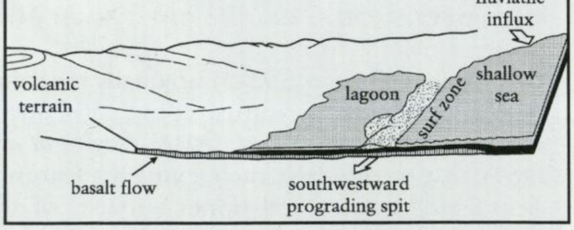

Figure 3.22 Reconstruction of the depositional environment of interbedded sediments and volcanic rocks in the lower part of the Skomer Volcanic Group, Marloes (after Bridges, 1976).

The basal conglomerates of the Coralliferous Group suggest origin on a shoreline, with rapid transgression above shown by the development of a *Costistricklandia* benthic community (Ziegler *et al.*, 1969). Many of the fossils are concentrated in shelly lenses, suggesting transport during storm conditions. Shallowing in the upper part of the group is indicated by the incoming of coarser sediments and a change in brachiopod faunas (Siveter *et al.*, 1989); shallow water may also be indicated by the development of a prominent bed of algal oncolites in the upper part of the unit.

Structural features throughout the section give evidence of the tectonic history of the Pembrokeshire area, and particularly of the Marloes block. Small faults, en echelon tension gashes and other features give evidence of Variscan S–N compression, and there is a pervasive cleavage. At the Three Chimneys, an anomalous bedding/cleavage relationship occurs, which suggests younging to the north-west in beds that can be observed to young to the south-east. This has been explained by the tectonic tilting of the Skomer Volcanic Group prior to deposition of the Coralliferous Group and the subsequent development of the Variscan cleavage (Graham *et al.*, 1977).

Altogether, the Marloes Sands sections provide excellent evidence of the volcanic, sedimentological, palaeoenvironmental and tectonic history of this area of South Wales. The sequence contrasts with that of the Haverfordwest area to the north of the Variscan deformation front in Pembrokeshire (see site description for Gasworks Lane), where a quieter, more offshore, depositional environment obtained, and where there is little evidence of volcanicity. Basalts and tuffs in the Skomer Volcanic Group of Marloes Sands and other nearby exposures give direct evidence, along with the Telychian site at Cullimore's Quarry and the Wenlock site at Moons Hill Quarry, of the extent of early Silurian volcanicity in the southern part of the Welsh Basin. The unconformity between the Skomer Volcanic Group and the Coralliferous Group coincides with the initiation and development of southerly sourced turbidite flows into the Welsh Basin, as seen at Aberarth and

Aberystwyth; these features may all be related to uplift resulting from plate collision.

The succession at Marloes Sands extends into younger Silurian units, the Gray Sandstone Group and the Red Cliff Formation, which are described and discussed in later chapters of this volume (see site report for the Wenlock strata of Marloes in Chapter 4).

Conclusions

This site provides continuously exposed, excellent representative sections through the upper part of the Skomer Volcanic Group and the entire Coralliferous Group, and exemplifies the unconformable relationship between the two units. There is a long history of study of these classic exposures, beginning with Murchison (1839). The sedimentary successions enable interpretation of the environmental conditions along the southern margin of the Welsh Basin, and there is a rich and diverse macrofauna and microbiota. The Skomer Volcanic Group records the development of early Silurian volcanic islands in this area and, with other sites on the southern margin of the Welsh Basin, gives evidence of the extent of Silurian volcanism in this region. The Coralliferous Group records somewhat deeper environments of deposition, lacking volcanic activity except for occasional ash-falls, and hosting a varied fossil fauna dominated by corals, brachiopods and conodonts. In addition, structural features provide evidence of the local and regional effects of late Carboniferous (Variscan) folding and faulting.

These natural exposures provide a very valuable national teaching and research resource, and are also frequently visited by overseas specialists.

SCRÂCH TRACK (SN 8415 3942–SN 8465 3959)

Introduction

The Llandovery district has long acted as a national and international reference area for strata now assigned to the lowest series of the Silurian System. The initial work by Murchison (1839) was followed by Geological Survey mapping in 1855–1856, and a major study of the geology was undertaken by Jones (1925, 1949). Jones applied a set of informal lithostratigraphical terms to the succession, using the letters A (Lower Llandovery), B (Middle Llandovery) and C (Upper Llandovery) for his major divisions. In the southern part of the Llandovery area these were subdivided into A_1–A_4, B_1–B_3 and C_1–C_6 (Jones, 1925), whereas in the northern part, where there are differences in facies, the subdivisions used were Aa–Ac, B and Ca–Cc (Jones, 1949). More recently, Cocks *et al.* (1984) remapped the area, revised the lithostratigraphy and completed new biostratigraphical investigations. They renamed the 'basal Llandovery sandstones' (A_1, Aa) of Jones (1925, 1949) as the Scrâch Formation, and suggested that it is of latest Ordovician (Hirnantian) age rather than earliest Silurian. They also established new formation names for the Llandovery strata of the southern and northern parts of the area, replacing Jones' informal system of letters and numbers (Figures 3.23, 3.24).

The Scrâch section lies on the eastern limb of the Cefn-y-gareg Syncline in the northern Llandovery area (Jones, 1949; Cocks *et al.*, 1984). Jones (1949) showed the eastern edge of this limb as faulted, with his Aa unit absent, but the map provided by Cocks *et al.* (1984, fig. 3; Figure 3.23) shows an unfaulted contact in this area with the Scrâch Formation present. The Scrâch track section exposes the Scrâch Formation, overlain by the Bronydd and Crychan formations, of Rhuddanian age; the section was logged, as section i2, by Cocks *et al.* (1984, fig 4).

This is an important site as it exposes an almost continuous section of strata across the Ordovician–Silurian boundary, from the top of the Scrâch Formation, through the Bronydd and Crychan formations. The base of the Silurian System is defined outside this area, at Dob's Linn in Scotland, but it is important to identify its position in the type area for the Llandovery Series. According to Cocks *et al.* (1984), the boundary lies at or near the base of the Bronydd Formation, low in which are graptolites of the *acuminatus* Biozone.

Description

The Scrâch section is situated on the south side of the forestry trackway north to WNW of Scrâch. In this section, the beds dip 33–35° to the west (Jones, 1949; Siveter *et al.*, 1989); the Scrâch Formation is 70 m thick, the Bronydd Formation is 120 m thick, and the Crychan Formation is

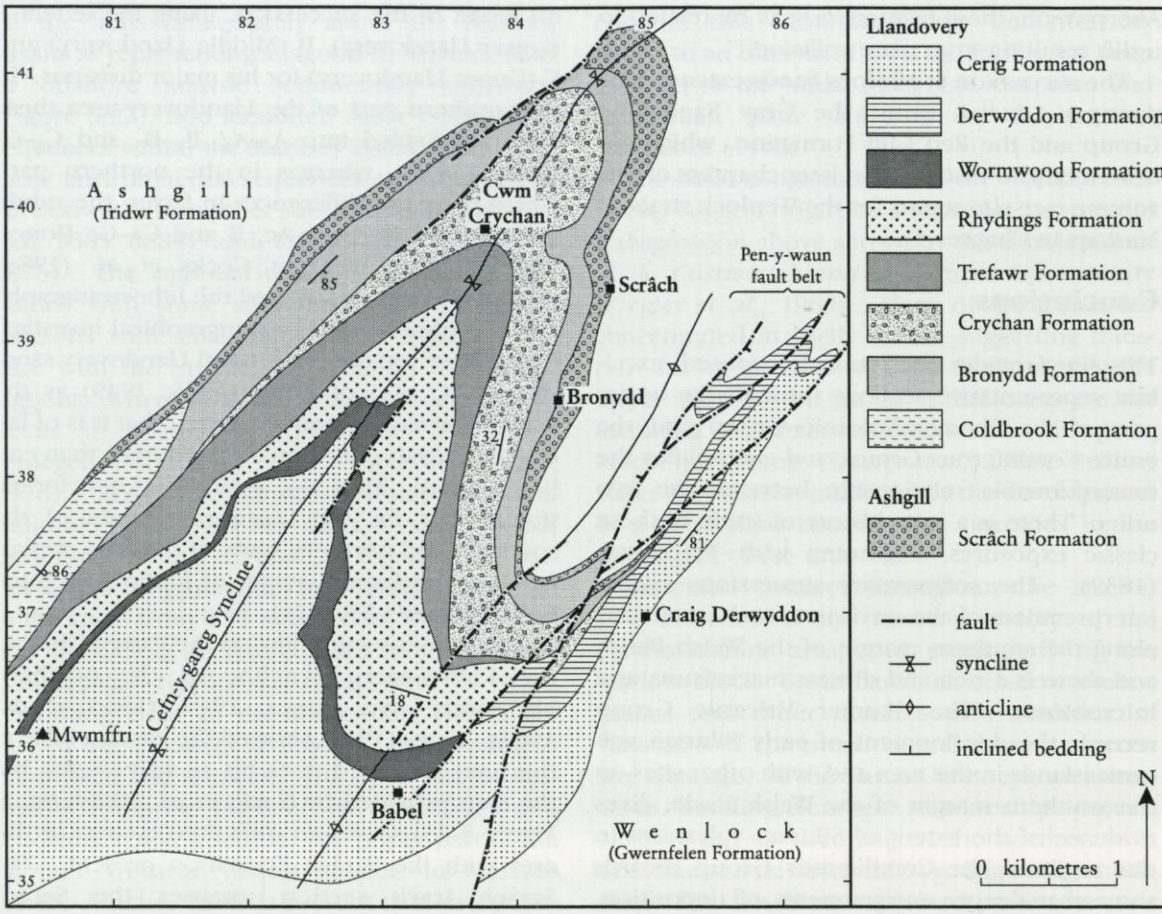

Figure 3.23 Geological map of the northern part of the type Llandovery area (after Cocks *et al.*, 1984).

250 m thick (Cocks *et al.*, 1984). Site clearance has shown that the Scrâch Formation commences with thick conglomerates, passing upwards into cross-laminated sandstones and cleaved shales. The contact with the Bronydd Formation is complicated by faulting (J. Davies pers. comm.), above which the formation is dominated by mudstones, with interbedded sandstones increasing upwards. The Crychan Formation consists of massive, bioturbated sandy mudstones and muddy sandstones, commonly with coarser bases; occasional thin shelly sandstones occur. The top of the Crychan Formation is not seen in this section.

Cocks *et al.* (1984) recorded a *Hirnantia* fauna in the Scrâch Formation, demonstrating a Hirnantian age. Close to the base of the Bronydd Formation in the Scrâch section, the graptolite *Climacograptus normalis* occurs, indicating the *perscultus* or *acuminatus* biozone (Rickards in Cocks *et al.*, 1984, p. 144). Other graptolites from higher in the formation include *C.* cf. *normalis* and *C. rectangularis*, assignable approximately to the *atavus* and *acinaces* biozones (Cocks *et al.*, 1984). The Crychan Formation has yielded several graptolites, including *Rhaphidograptus toernquisti*, and a locality in the very top of the formation beyond the Scrâch section at SN 8397 3907 has produced *Atavograptus? strachani* and some possible triangulate monograptid thecae; thecae of this type first appear in the *cyphus* Biozone (Cocks *et al.*, 1984). Cocks *et al.* (1984, table 1) provided full lists of brachiopods and other fossils in the Bronydd and Crychan formations. Brachiopods are relatively common, with *Eoplectodonta duplicata*, *Leangella scissa*, *Mendacella mullochiensis* (= '*Resserella*' sp.)

and *Dolerorthis sowerbyana* present throughout; the Bronydd Formation also includes *Hyattidina? angustifrons* and *Skenidioides* sp., with *Clorinda undata*, *Cryptothyrella crassa* and *Meifodia prima prima* in the upper beds; the Crychan Formation also has *Stricklandia lens lens* and diverse less common forms. Among the other fossils, pelmatozoan columnals and bryozoans are most common, but occasional corals, trilobites and gastropods also occur.

Interpretation

Environmental interpretations of the sedimentological features were given by Cocks *et al.* (1984), who considered the flaser-bedded sands of the Scrâch Formation to be characteristic of intertidal or shallow subtidal conditions, with coarser sand bodies representing tidal bars or channels. The environment is shallower than that represented by underlying Ordovician sediments and probably reflects late Ordovician glacio-eustatic lowering of sea level. Subsequent deepening is indicated by the marine shelf mudstones of the Bronydd Formation, in which the discrete sand beds may represent occasional storm events; the general coarsening upwards in this formation indicates prograding sedimentation, perhaps pro-deltaic. The further coarsening in the Crychan Formation is probably the result of deposition on a more proximal part of a pro-delta lobe, although, as the fauna shows, this is still in a fully marine regime. The diverse brachiopods, including *S. lens lens*, show that a *Stricklandia* benthic community was developed. Palaeocurrent directions indicate a sediment source from the south-east, with evidence for storm events from winnowed sand beds.

This is a key site in the type Llandovery area that demonstrates the environmental development in the early Silurian of this part of the Welsh Basin and provides a representative section through the Scrâch, Bronydd and Crychan formations. Together with the local sites in the Ydw Valley and the sites at Gasworks Lane and Meifod, it provides evidence of the marine fauna that succeeded the characteristic late Ordovician *Hirnantia* fauna in the Welsh Basin.

Conclusions

These trackside exposures are of major importance as they display the local base of the Silurian System in the international type area for the Llandovery Series. They also provide representative sections in the Scrâch, Bronydd and Crychan formations, and present lithological evidence for the development of early Silurian marine environments in this part of the Welsh Basin. The strata contain characteristic latest Ordovician and earliest Silurian faunas. The international importance of this site as a reference section in the Llandovery type area renders it of high conservation value.

CILGWYN–YDW VALLEY (SN 748 298–SN 748 299, SN 7534 3086, SN 757 309, SN 762 308)

Introduction

In his pioneer mapping of the southern part of the Llandovery area, Jones (1925) established a set of informal lithostratigraphical divisions, using letters and numbers: A_1–A_4 for the Lower Llandovery, B_1–B_3 for the Middle Llandovery and C_1–C_6 for the Upper Llandovery. These terms subsequently became used in various ways, with some authors employing them essentially as chronostratigraphical units, so Cocks *et al.* (1970) set out to resolve this ambiguity by defining formal stage names within the Llandovery Series. The stratotype localities for the lower boundary of each stage, with the exception of the lowest, were selected from exposures in the central portion of the southern Llandovery area. The four names introduced by Cocks *et al.* (1970) were: Rhuddanian (initially regarded as equivalent to A_1–A_4), Idwian (equivalent to B_1–B_3), Fronian (equivalent to C_1–C_3) and Telychian (equivalent to C_4–C_6).

This set of related discrete localities in the Ydw Valley includes the sites used to define the bases of the (now defunct) Idwian and Fronian stages of the Llandovery Series. The base of the Idwian Stage was defined at the locality at SN 757 309, a site that had also been described by Jones (1925, p. 363) as '80 yards south' of the (now non-existent) farm Gloigoed-fach. The basal outcrop of the Fronian was identified in a series of crags (SN 762 308) near the lane leading from Myrtle Hill to Pont Pwll-defaid.

As part of their revision of the stratigraphy of the type Llandovery area, Cocks *et al.* (1984) recognized that the 'basal Llandovery sandstones' (A_1) of Jones (1925) were late Ordovician in age, so should be excluded from the Rhuddanian.

They also noted that the Idwian and Fronian stages appeared to represent shorter intervals than the Rhuddanian and Telychian stages, and that the Subcommission on Silurian Stratigraphy had accepted that there should be three stages for the Llandovery Series, rather than four. They therefore proposed a new tripartite stage system, with new stage boundaries defined within continuously exposed fossiliferous sections, rather than in isolated outcrops of the kind originally used for the bases of the Idwian and Fronian stages. The Rhuddanian and Telychian stages were retained, with the base of the latter slightly redefined, and a new stage name, the Aeronian, introduced to replace the Idwian and Fronian. The basal stratotype for the Aeronian Stage was defined at the Trefawr Track site (Cocks *et al.*, 1984). The localities at SN 757 309 and SN 762 308, therefore, no longer have international relevance as stratotype sections, but are of historical importance in the development of the reference stratigraphical scheme for the lowest series of the Silurian System.

The stratigraphical revisions introduced by Cocks *et al.* (1984) also included the introduction of new formation names. The Goleugoed Formation, which encompasses divisions A_2–A_4 and B_1–B_3 of Jones (1925), is displayed in a number of natural exposures, quarry sections and tracksides around the farm of Goleugoed in the Ydw Valley (Figure 3.24). The suite of localities described here has been selected to illustrate the lithological characteristics and fauna of this unit.

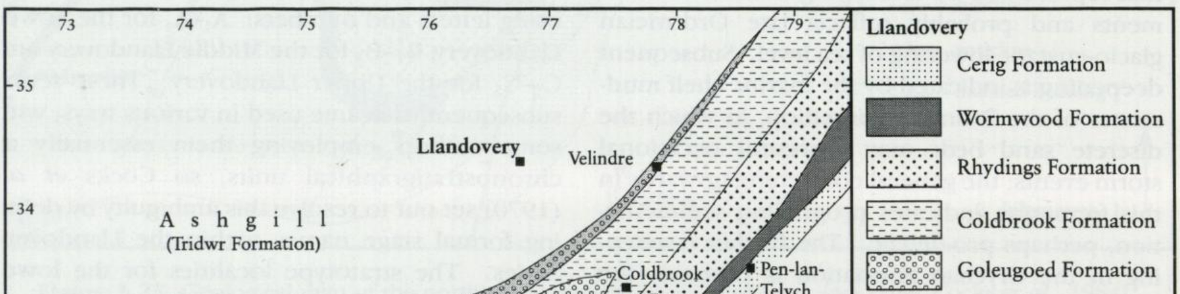

Figure 3.24 Geological map of the southern part of the type Llandovery area (after Cocks *et al.*, 1984).

Description

The four localities that make up this GCR site span the Goleugoed Formation, with the lower beds apparent at SN 748 298. This locality is within transect b2 of Cocks *et al.* (1984) and displays unlaminated silty greenish mudstones typical of the lower Goleugoed Formation; higher in the transect, beyond the locality, there is an increase in frequency of sandy mudstones and sandstones. Clearance work on the nearby track section at SN 748 299 has exposed a continuous section through the underlying Scrâch Formation, which here comprises two thick sandstone units separated by alternating thin sandstones and shales (J. Davies pers. comm.); the junction with the Goleugoed Formation is not exposed.

The old quarry at Allt Cwar-mawr (SN 7534 3086) is probably that mentioned by Murchison (1839) as 'Goleugoed' (discussed by Jones, 1925, and Temple, 1987), and from that time has held a reputation as a source of Llandovery fossils. It has also been referred to as Cwar Goleugoed and Cwar-mawr Cilgwyn. The quarry is in mudstones and thin sandstones, occasionally calcareous enough to weather as 'rottenstones', dipping 28° to the north-east. They have yielded a fauna dominated by brachiopods, especially *Eoplectodonta duplicata*, *Leangella scissa, Cryptothyrella crassa* and *Stricklandia lens* (Jones, 1925; Temple, 1987; Siveter *et al.*, 1989). Trilobites, orthocones, corals and bryozoans also occur. The quarry at Allt Cwar-mawr is the type locality for the brachiopods *Giraldiella protensa protensa* (J. de C. Sowerby, 1839) and *Plectatrypa tripartita tripartita* (J. de C. Sowerby, 1839).

The natural exposures at SN 757 309, SSW of Pont Pwll-defaid, comprise light sandstones separated by some 16 m that lack exposure from massive dark mudstones with abundant brachiopods referable to the *Pentamerus* community (Cocks *et al.,* 1970); the latter were defined as the basal deposits of the Idwian Stage. These exposures are all within the Goleugoed Formation.

A set of natural and old quarry exposures around SN 762 308 were used by Cocks *et al.* (1970) to delimit the base of the Fronian Stage, which is coincident with the base of the Rhydings Formation (Cocks *et al.*, 1984). An old quarry at SN 7606 3090 exposes mudstones of the uppermost Goleugoed Formation, which contain brachiopods of the *Clorinda* Community. The basal outcrop of the Rhydings Formation comprises poorly fossiliferous sandstone exposed in crags in a field to the south of the lane at SN 7615 3089. More fossiliferous beds are displayed in a disused quarry some 100 m away (SN 7625 3090); these contain brachiopods of the *Pentamerus* Community.

Interpretation

Cocks *et al.* (1984) interpreted the strata of the Goleugoed Formation as representing shallow marine sedimentation, with coarsening-upward sequences suggesting a pro-deltaic setting. These beds record the deepening of the early Llandovery sea in this part of the Welsh Basin, following the late Ordovician glacio-eustatic regression. Variations in depth are broadly indicated by the changing benthic communities, with the *Stricklandia* Community developed at Allt Cwar-mawr, the *Pentamerus* Community near Pont Pwll-defaid, and the *Clorinda* Community in the uppermost beds.

The localities in the Ydw Valley are among a number of scattered local exposures in the Goleugoed Formation. Those selected for the GCR display the basal and uppermost beds of the unit and constrain its boundaries with the Scrâch Formation below and the Rhydings Formation above. The quarry at Allt Cwar-mawr is important as a classic fossil site, and the network of localities that comprise the Cilgwyn–Ydw valley GCR site includes the historical exposures used to delimit the bases of the now superseded Idwian and Fronian stages. This network links with the site at Scrâch Track in the northern Llandovery area to display the development of early Llandovery transgressive deposits in the type area. Together with the sites at Gasworks Lane and Meifod, it also serves to illustrate the nature of the Rhuddanian and early Aeronian fauna of the Welsh Basin.

Conclusions

This is an important set of exposures spanning the Goleugoed Formation in the Llandovery type area. There is a long history of study of these sections, dating back to Murchison (1839) in *The Silurian System*, and two of them were used to define the bases of the Idwian and Fronian stages in the first attempt to provide a formal chronostratigraphical framework for the type Llandovery Series (Cocks *et al.*, 1970). These sites, therefore, have considerable historical significance, and are also of value in demonstrating the development of early Silurian sedimentation and faunas in the southern part of the type Llandovery region.

TREFAWR TRACK (SN 8347 3916–SN 8398 3960)

Introduction

This reference section in the Llandovery type area exposes much of the Trefawr Formation, which comprises sandy mudstones with a fauna of graptolites, brachiopods and other fossils. It is a long trackside section extending from 500 m south-west to 150 m north of the farm of Trefawr, to the north of the Crychan Forest in the northern area of the Llandovery district. Geologically, the section is situated almost directly on the axial planar trace of the Cefn-y-gareg Syncline (Cocks *et al.*, 1984, fig. 3; Figure 3.23), and traverses the Trefawr Formation from north-east to south-west (Figure 3.25). The Trefawr Formation was named and defined by Cocks *et al.* (1984) to replace the informal unit B (Middle Llandovery) of Jones (1949). These exposures have been opened up since the work of Jones (1949), who recorded that the formation was not well exposed around the nose of the Cefn-y-gareg Syncline.

The Aeronian Stage is named after Cwm-coed-Aeron Farm, 500 m south of the Trefawr track (Cocks *et al.*, 1984), and was proposed to replace the Idwian and Fronian stages of Cocks *et al.* (1970; see report on the network site at Cilgwyn–Ydw Valley). The base of the Aeronian Stage is defined in the Trefawr Track section, within gently dipping mudstones at SN 8380 3953, 92 m above the base of the Trefawr Formation, at the first appearance of the graptolite *Monograptus austerus sequens*; this was taken by Cocks *et al.* (1984) to be equivalent to the base of the *triangulatus* Biozone. This biozone, or the broader *gregarius* Biozone which has a similarly defined base, is recognized in many areas globally; the incoming of triangulate monograptids and of the genera *Rastrites* and *Petalograptus* is generally indicative of this level (Cocks et al., 1984).

The base of the Aeronian Stage is somewhat higher than the base of its precursor, the Idwian Stage, which was defined at the locality at SN 757 309 in the Ydw Valley GCR site in the southern Llandovery area. The Aeronian Stage encompasses the majority of the Trefawr Formation plus the Rhydings and Wormwood formations in the Llandovery type area (Cocks *et al.*, 1992).

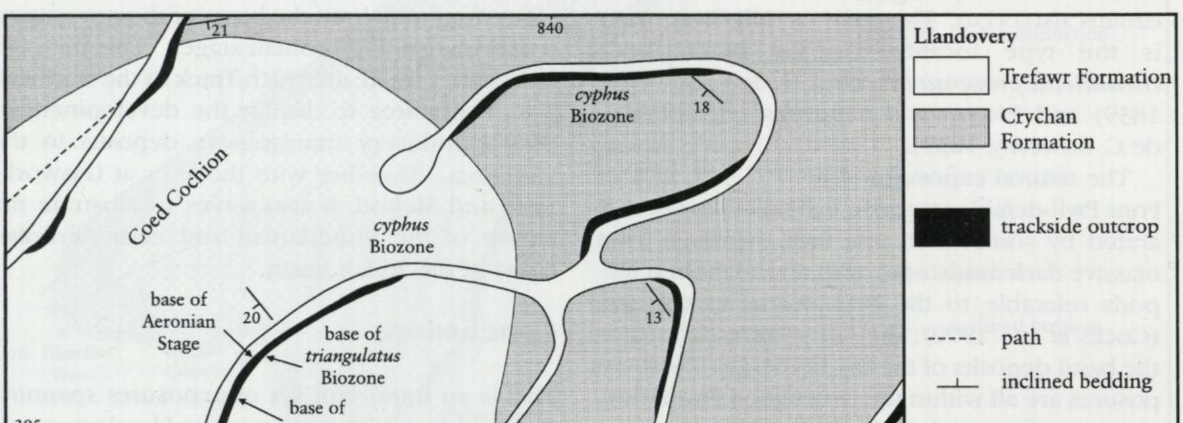

Figure 3.25 Exposures along and around the Trefawr Track, including the stratotype section for the base of the Aeronian Stage (modified after Cocks *et al.*, 1984).

Description

The Trefawr Formation is 240 m thick (Cocks *et al.*, 1992), and comprises unlaminated silty mudstones with beds of micaceous sandstone. Strata from the upper part of the underlying Crychan Formation are exposed in a trackside section 160 m north-east of the Trefawr track site, at SN 8410 3963; these muddy sandstones yield a brachiopod fauna that includes *Stricklandia lens intermedia* (Siveter *et al.*, 1989). The lowest exposed beds of the Trefawr Formation are generally finer-grained, and there is a general coarsening up-sequence. The beds dip south-westwards at 10–20°.

The Trefawr track section has yielded a large fauna of brachiopods, together with smaller numbers of graptolites, corals, trilobites, ostracods, gastropods, cephalopods, echinoderm fragments and bryozoans (Cocks *et al.*, 1984, table 2; Siveter *et al.*, 1989). The distribution of brachiopods and graptolites across the Rhuddanian–Aeronian boundary is shown in Figure 3.26. Fossils reported from the lower part of the section, referable to the upper part of the Rhuddanian Stage, include the brachiopods *Eoplectodonta duplicata*, *Plectatrypa tripartita*, *Aegiria garthensis*, *Mendacella mullochiensis*, *Leangella scissa*, *Anisopleurella gracilis* and *Skenidioides* sp., and the graptolites *Rhaphido-*

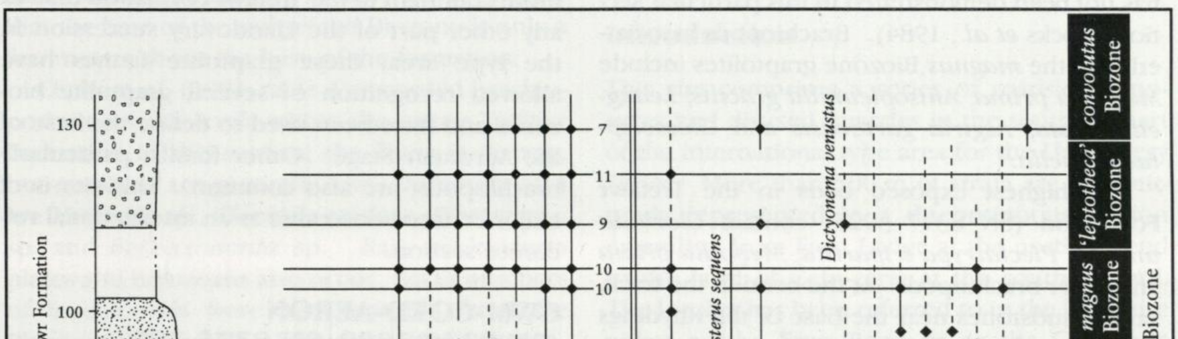

Figure 3.26 Range chart of brachiopod and graptolite taxa across the Rhuddanian–Aeronian boundary in the Trefawr Track section (after Cocks *et al.*, 1984).

graptus toernquisti, Monograptus austerus vulgaris, Diplograptus aff. *elongatus,* cf. *Lagarograptus acinaces, Climacograptus* sp. and *Dictyonema corrugatellum.*

Immediately above the base of the Aeronian Stage, *Clorinda undata, Plectatrypa tripartita* and *Skenidioides* sp. occur, as well as *Monograptus austerus sequens.* Four metres above the boundary the presence of the *magnus* Biozone is demonstrated by the occurrence of the graptolites *Glyptograptus (Pseudoglyptograptus) vas, Orthograptus insectiformis* and *Glyptograptus tamariscus* cf. *linearis.* Graptolites of the *magnus* Biozone, including *Diplograptus magnus* and similar forms, are present through the section up to beds at SN 8371 3943, and a change to the *convolutus* Biozone probably takes place near SN 8363 3937, although it has not been demonstrated in this particular section (Cocks *et al.*, 1984). Brachiopods associated with the *magnus* Biozone graptolites include *Meifodia prima, Anisopleurella gracilis, Leangella scissa, Aegiria garthensis* and *Glossoleptaena? bella.*

The highest exposed beds in the Trefawr Formation (SN 8347 3925) contain *Clorinda undata, Plectatrypa tripartita, Meifodia prima* and other brachiopods. At the bend in the track, sandy mudstones near the base of the Rhydings Formation contain *Monograptus* cf. *sedgwickii,* indicative of the *sedgwickii* graptolite biozone (Cocks *et al.*, 1984).

Interpretation

The Trefawr Formation is generally finer-grained than the underlying Crychan Formation, as seen at the GCR site at Scrâch Track. Cocks *et al.* (1984) interpreted the lithology to indicate deposition of the Trefawr Formation in a pro-delta marine setting, but more distal than the Crychan Formation. The sandier beds were probably introduced by storm events. The brachiopod faunas do not fit well into well-defined communities, but the *Meifodia* and *Plectatrypa* assemblages typical of the Trefawr Formation are more diverse than the *Stricklandia* community of the Crychan Formation and this would be consistent with a more offshore marine environment.

In combination with others in the type Llandovery area, this site serves to illustrate the early Silurian stratigraphical and sedimentological succession in this part of the Welsh Basin. Together with the upper beds of the Skomer Volcanic Group at the network site of Marloes Sands, this locality provides evidence of the early Aeronian fauna of the southern part of the basin, and is particularly important for the relative abundance of graptolite specimens that have been recovered.

Conclusions

This is a site of international stratigraphical importance in the Llandovery type area, as it includes the international reference section for the base of the Aeronian Stage of the Llandovery Series. An almost complete section through the Trefawr Formation is displayed, delimited by exposures of the upper beds of the Crychan Formation below and the lower beds of the Rhydings Formation above. Graptolites are more abundant in the Trefawr Formation than in any other part of the Llandovery succession in the type area; these graptolite faunas have allowed recognition of several graptolite biozones and have been used to define the base of the Aeronian Stage. Other fossils, particularly brachiopods, are also common. This site is of major conservation value as an international reference section.

CWM-COED-AERON (SN 8338 3889–SN 8375 3903)

Introduction

This is a key stratigraphical site in the international type area for the Llandovery Series. It comprises a well-exposed trackside section, extending from 150 m to 400 m west of Cwm-Coed-Aeron, in the Crychan Forest. It is situated in the northern part of the Llandovery type area, on the eastern limb of the Cefn-y-gareg Syncline, close to the axial plane trace (Figure 3.23). The section, which displays strata of the upper part of the Trefawr Formation and the lower Rhydings Formation, of Aeronian age, was logged by Cocks *et al.* (1984) as their transect i3. The sandy mudstones of the Trefawr Formation pass gradually and conformably into laminated muddy sandstones and sandstones of the Rhydings Formation. This formational boundary is coincident with the boundary between the Middle Llandovery (B) and Upper Llandovery (C), as used by Jones (1949). Jones considered this boundary to be unconformable, and an angular unconformity is indeed developed at this level towards the Pen-y-waun fault belt to the south of Cwm-Coed-Aeron (Cocks *et al.*, 1984). However, the transitional relationship seen at this GCR site confirms the conclusion of Cocks *et al.* (1970) that the period represented by this unconformity was not long.

Description

Grey sandy mudstones of the upper 25 m of the Trefawr Formation are exposed at this locality and have yielded the graptolite *Orthograptus amplexicaulis*. Cocks *et al.* (1984) also reported the sandstones of the Rhydings Formation to contain *Orthograptus* cf. *bellulus*, *Rastrites* aff. *linnaei*, and specimens of *Glyptograptus* and *Monograptus*. These graptolites, together with those found low in the Rhydings Formation at other localities including Trefawr Track, suggest that the base of the *sedgwickii* Biozone is only a few metres above the base of the formation.

Cocks *et al.* (1984, table 3) recorded brachiopods at several levels within the upper Trefawr Formation in this section; the fauna is diverse, but numbers are generally low. Dominant taxa are *Meifodia* sp., *Clorinda undata*, *Plectatrypa* sp. and *Eoplectodonta* sp.. Rare echinoderm plates and bryozoans also occur. Small numbers of brachiopods were also reported from the Rhydings Formation, including *Meifodia* sp., *Triplesia* sp., and *Katastrophomena* sp..

Interpretation

The environment of deposition of both formations was interpreted by Cocks *et al.* (1984) to be on a marine pro-delta lobe, with the coarsening in the Rhydings Formation representing a shallower facies. The diverse *Meifodia*-dominated brachiopod assemblage of the upper Trefawr Formation is comparable with that seen at a similar level in the nearby Trefawr Track section, and is consistent with a relatively distal setting.

The network of sites of Scrâch Track, Trefawr Track and Cwm-Coed-Aeron are all close to each other, and together give a full coverage of the stratigraphical, sedimentological and faunal sequence in the Rhuddanian to mid-Aeronian of the northern part of the Llandovery type area.

Conclusions

This is one of a set of sites in the Crychan Forest in the northern part of the type Llandovery area that together give a full coverage of the stratigraphy, sedimentological history and faunal development in the lower to middle Llandovery of this internationally important region. It comprises good trackside exposures displaying strata of the Trefawr Formation and the lower part of the Rhydings Formation, both units of Aeronian age. The key contribution of this section is that it demonstrates a transitional relationship between the Trefawr and Rhydings formations, showing that the sedimentary record is fully preserved. It also yields characteristic fossils, particularly brachiopods and graptolites, of the Aeronian strata of this part of the Welsh Basin.

FRON ROAD (CEFN-CERIG ROAD) (SN 776 334–SN 775 323)

Introduction

This site comprises a series of roadside exposures and disused quarries in the southern part of the international type area for the Llandovery Series. More than 500 m of strata are intermittently represented in a discontinuous section extending from Fron Lodge at the northern end to the farm of Cefn-cerig at the southern end. The locality has been referred to in the literature either as the Fron Road or as the Cefn-cerig Road; Cocks *et al.* (1984, figs 2, 4) recorded this section as their transect d3 (Figure 3.24). The exposures along this road (Figure 3.27) provide the best-available sequence in the southern Llandovery area through strata referred by Jones (1925) to his Upper Llandovery (C_1–C_6) division. In their revision of the stratigraphy of the Llandovery area, Cocks *et al.* (1984) erected three formations to replace the numbers and letters used by Jones for this part of the sequence: the Rhydings, Wormwood and Cerig formations. The lower beds belong to the Aeronian Stage, as defined by Cocks *et al.* (1984), and the upper beds are referable to the Telychian Stage. The Telychian Stage was first proposed by Cocks *et al.* (1970), with its base defined in roadside exposures on the the Fron Road at SN 7743 3243, where a bioturbated sandstone is underlain by light-grey siltstone; this level coincides with the base of the Wormwood Formation and is equivalent to the base of the C_4 division of Jones (1925). Cocks *et al.* (1984), however, subsequently revised the base of the Telychian Stage, moving it to near the top of the

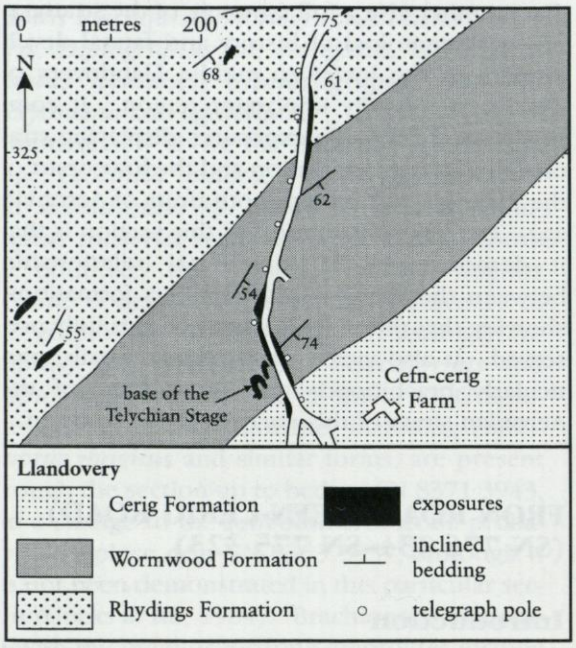

Figure 3.27 Exposures along and around the Fron Road, showing the stratotype locality for the base of the Telychian Stage (modified after Cocks *et al.*, 1984).

Wormwood Formation and selecting as the stratotype a section in an old quarry west of the Fron Road at SN 7742 3233. The base of the stage as defined here is regarded as approximately coincident with the base of the *turriculatus* graptolite biozone.

This site is generally important as a reference section for upper Llandovery stratigraphy in the type area, and is of special importance for its inclusion of the stratotype section for the base of the Telychian Stage.

Description

The beds throughout the section generally dip SSE, at angles of 54– 80°. The oldest beds, belonging to the top of the Coldbrook Formation (equivalent to the upper Goleugoed Formation farther south in the Llandovery area and to the Trefawr Formation of the northern Llandovery area), outcrop on the east side of the road at SN 7759 3326 to SN 7759 3318. These are silty mudstones with occasional micaceous sandstones that have yielded graptolites, including *Climacograptus rectangularis*, *Monograptus triangulatus fimbriatus*, *Glyptograptus (Pseudoglyptograptus) vas*, *G. incertus*, *G. tamariscus tamariscus*, *Diplograptus magnus*, *Petalograptus minor*, and *Orthograptus cyperoides* (Cocks *et al.*, 1984); this assemblage is representative of the *magnus* Biozone.

The Rhydings Formation is present in intermittent exposures along 630 m of the road south of the entrance to Fron Farm; the true thickness of the formation is about 400 m in this area (Cocks *et al.*, 1992). The rocks are sandy mudstones and muddy sandstones, generally moderately well sorted. Apart from *Monograptus* sp., graptolites have not been reported from the formation in this section, but brachiopods do occur; the fauna in a small disused quarry at SN 7755 3304 has been referred to the *Clorinda* benthic community, while that found in the roadside opposite Rock Farm at SN 7754 3295 to SN 7757 3283 is representative of the *Pentamerus* benthic community (Cocks *et al.*, 1984). Higher in the section at SN 7749 3257, light-grey siltstones near the top of the Rhydings Formation again contain *Clorinda* Community brachiopods, including *Dicoelosia alticavata*.

The Wormwood Formation crops out along the road as far as Cefn-cerig Farm (Figure 3.27); the thickness was given by Cocks *et al.* (1992) as 70 m, although other publications give a thickness in excess of 100 m (Cocks *et al.*, 1984; Cocks, 1989). The best exposures are in the upper beds, particularly well displayed in the old quarry (SN 7743 3232) just to the west of the road and a little to the north of the entrance to Cefn-cerig (Figure 3.27). The lithology comprises siltstones, muddy siltstones and sandy siltstones, mostly bioturbated. The Aeronian–Telychian stage boundary is defined within a prominent 29 cm thick bioturbated siltstone bed with calcareous nodules (Cocks *et al.*, 1984, figs 65–67; Figure 3.28). Brachiopods occur throughout the Wormwood Formation, and Cocks *et al.* (1984) listed taxa from several localities, including the quarry (Figure 3.29). A particularly fossiliferous horizon just below the base of the Telychian provided the highest records of *Eocoelia intermedia* and *Stricklandia lens progressa*, although these occur only in small numbers. More abundant are *Eoplectodonta penkillensis, Coolinia applanata, Clorinda globosa*, *Pentamerus oblongus, Leangella segmentum* and *Resserella* sp.; this assemblage is indicative of the *Pentamerus* benthic community. Grapto-

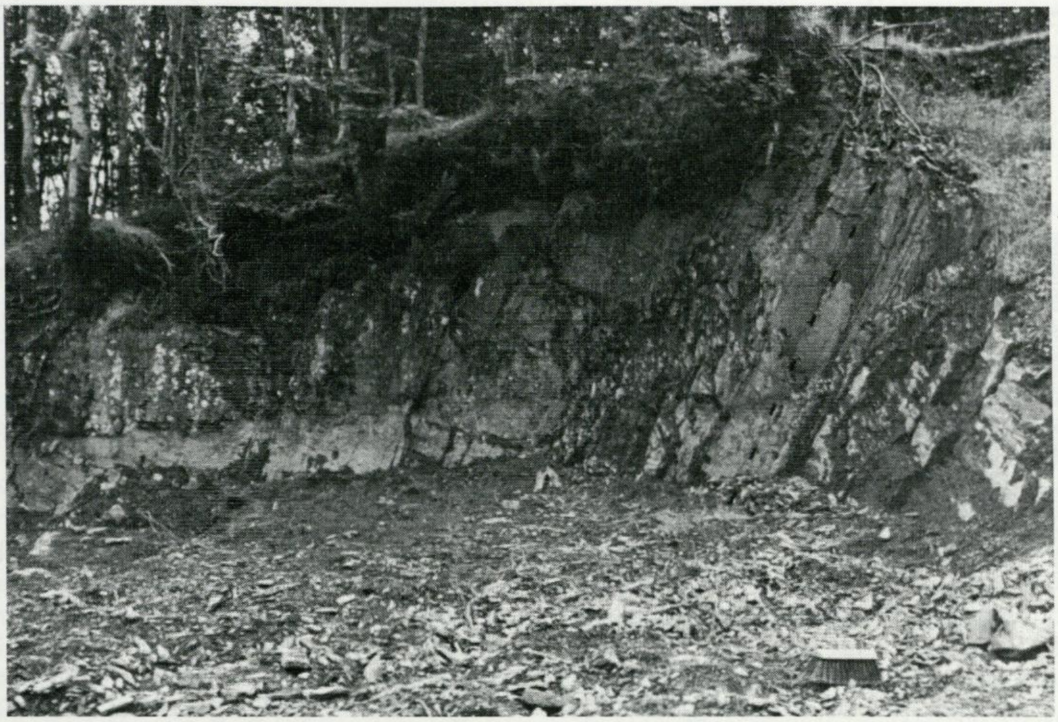

Figure 3.28 Stratotype section for the base of the Telychian Stage; the position of the Aeronian–Telychian boundary is within the bed with its base marked by the broken line. The section youngs to the left (south). (Photo: P.D. Lane.)

lites have not been found in the quarry section, but acritarchs reported by Hill and Dorning (in Cocks *et al.*, 1984) from the uppermost Aeronian include *Eupoikilofusa striatifera, Micrhystridium inflatum* and *Cymatiosphaera prismatica* (Figure 3.29); the absence of any of the characteristic taxa of acritarch biozone 4 suggests that the assemblage falls within Zone 3 of Hill (1974), and specifically biozone 3b of Hill and Dorning (in Cocks *et al.*, 1984). Other fossils reported by Cocks *et al.* (1984) include streptalasmid corals, encrinurid trilobites, bryozoans and pelmatozoan columnals. A conodont sample from 50 cm below the base of the Telychian has yielded a fauna that includes *Icriodella* sp. nov., *Distomodus* sp., *Pseudooneotodus beckmanni* and coniform taxa (Wang and Aldridge, 1997).

To the south of the quarry, beds low in the Cerig Formation can be seen in the roadside opposite Cefn-cerig farm (SN 7747 3227). These mudstones have yielded diverse brachiopods of the *Clorinda* benthic community, including *Eocoelia curtisi* and *Stricklandia laevis*. Other fossils listed by Cocks *et al.* (1984) include bryozoans, favositid corals and trilobites, but no graptolites have been found at this locality. The acritarch assemblage contains *Deunffia monospinosa, D. furcata* and *Domasia bispinosa*, definitive of acritarch biozone 4 (Hill and Dorning in Cocks *et al.*, 1984). At another locality (SN 8546 3841), Cocks *et al.* (1984) recorded the graptolite *Monograptus runcinatus* near the base of the Cerig Formation, indicating that this horizon should be placed in the lower half of the *turriculatus* graptolite biozone.

Interpretation

Environmental interpretations of the strata exposed along the Fron Road were given by Cocks *et al.* (1984). The graptolite-bearing mudstones of the upper Coldbrook Formation suggest deposition rather farther from the sediment source than apparent in the coeval Goleugoed and Trefawr formations to the south-west and north-east. The sandier facies of the Rhydings Formation indicate an open marine

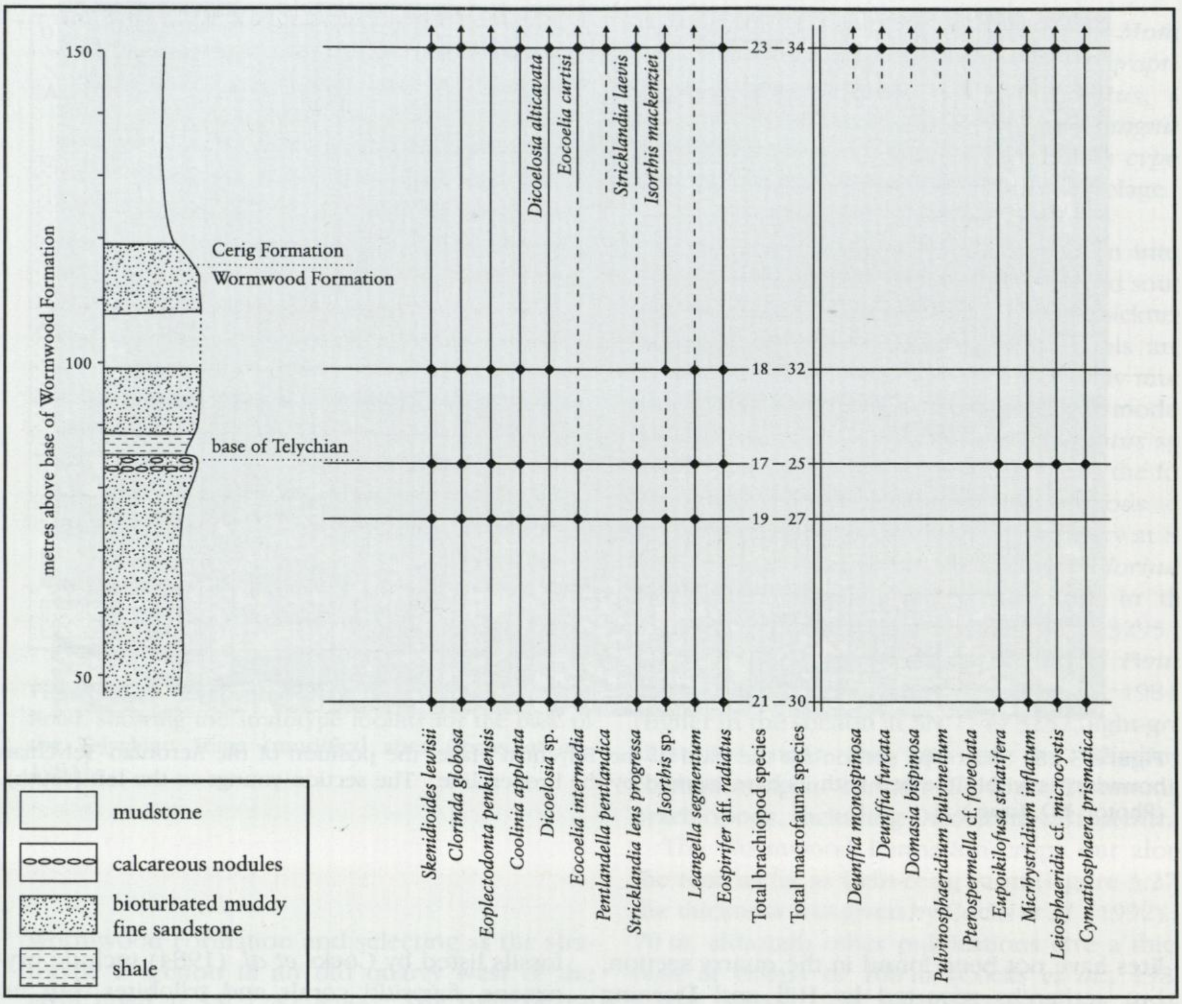

Figure 3.29 Distribution of selected brachiopod and acritarch species across the Aeronian–Telychian boundary in the Fron Road section (after Cocks *et al.*, 1984).

shelf setting, perhaps between delta lobes, with changing water depths indicated by the fluctuating brachiopod-dominated benthic communities. Cocks *et al.* (1984) suggested that a general slight shallowing might be indicated by the development of a *Pentamerus* benthic community; the more intensive bioturbation evident in this formation suggests better oxygenation of the sea floor, perhaps linked with increased oceanic circulation. A further transgressive pulse may be shown by the distribution of the Cerig Formation, which shows open marine sedimentation over the whole Llandovery area, with *Clorinda* community faunas developed.

This site provides key evidence for the sedimentological and environmental development of the type Llandovery area in the later half of the Llandovery Epoch. Combined with the sites in the Cilgwyn-Ydw Valley area, it provides almost complete coverage of the stratigraphical succession in the southern part of the Llandovery type area. In combination with the other sites throughout the Llandovery region it allows interpretation of the depositional events that shaped this area of the southern Welsh Basin. It also provides a record of the changing biota of the basin during this interval, especially with respect to the shelly benthos. It is complemented by the Coed Glyn-môch Track section in the northern Llandovery area, which displays a comparable section through the Rhydings, Wormwood and lower Cerig formations; the general thickness of these formations is lower in the northern area than at Fron Road.

Conclusions

This is a section of international stratigraphical importance in the Llandovery type area because it includes the global reference locality for the base of the Telychian Stage of the Llandovery Series. It also provides the most complete exposures available through the upper part of the Llandovery Series in the southern part of the type area. The roadside and small quarries intermittently expose a sequence from the upper part of the Coldbrook Formation, through the Rhydings and Wormwood formations, and into the lower beds of the Cerig Formation. Brachiopods are common through much of the succession, and evolutionary changes in species of *Eocoelia* and *Stricklandia* help to delimit the base of the Telychian Stage. Changes in sediment type and faunal assemblages can be used to interpret the changing depositional regimes within this early Silurian marine shelf environment. This is a key site nationally for understanding the development of upper Llandovery stratigraphy, sedimentology and biotas, and is of major conservation value as an international reference section.

COED GLYN-MÔCH TRACK (SN 8158 3760–SN 8195 3765)

Introduction

This is an important reference locality in the northern part of the international type area for the Llandovery Series. It comprises a well-exposed trackside section on the western limb of the Cefn-y-gareg Syncline (Figure 3.23). The rocks exposed at this site belong to the Upper Llandovery (C) division of the Llandovery Series formulated by Jones (1925, 1949). Formal formation names were introduced by Cocks *et al.* (1984) to replace the letters and numbers used in the Llandovery area by Jones; for the upper Llandovery part of the succession the same formations were identified in the southern, central and northern Llandovery regions. These are the Rhydings, Wormwood and Cerig formations. As part of their remapping and revision, Cocks *et al.* (1984) logged a number of major sections, and the Coed Glyn-môch Track section is equivalent to their transect f3; it spans the entire thickness of the Rhydings and Wormwood formations and incorporates the lower beds of the Cerig Formation.

Description

The beds on this part of the western limb of the Cefn-y-gareg Syncline dip very steeply to the east and in places become vertical or overturned. The section in the track youngs to the east, and begins in the lowest beds of the Rhydings Formation. This formation comprises silty and sandy mudstones and is here more than 200 m thick (Cocks *et al.*, 1984, fig. 4); the overlying Wormwood Formation is about 60 m thick and comprises well-bedded but poorly laminated muddy sandstones with considerable bioturbation. Jones (1949) showed a faulted relationship between beds now assigned to the Wormwood and Cerig formations, but Cocks *et al.* (1984) did not map a fault at this boundary. Only the lowest beds of the Cerig Formation are exposed; the lithology returns to silty mudstones, and Cocks *et al.* (1984) reported the occurrence of the graptolite *?Pseudoclimacograptus (Metaclimacograptus)* sp. at this locality. Brachiopods can be found throughout the section, with the faunas comparable with those seen in the southern area (see site report for the Fron Road GCR site), but details of occurrences have not been tabulated in the literature.

Interpretation

The Coed Glyn-môch Track is important in that it provides a complementary section in the northern Llandovery area to the Fron Road site in the southern area. There are minor differences in lithological development and more striking differences in thickness. The Wormwood Formation is less strongly differentiated from the Rhydings and Cerig formations in the northern area (Cocks *et al.*, 1984), and both the Rhydings and Wormwood formations are thinner. In transect d3 of Cocks *et al.* (1984), along the Fron Road, the Rhydings and Wormwood formations are 370 m and 108 m thick respectively; on the Coed Glyn-môch Track, the thicknesses are 220 m and 60 m. The Coed Glyn-môch Track section also provides a fauna of brachiopods and other shelly benthic fossils, showing local development of the *Pentamerus, Stricklandia* and *Clorinda* benthic communities. The sediments suggest a relatively deep shelf setting for the Rhydings Formation, a more oxygenated and perhaps shallower environment for the Wormwood Formation, and a further transgressive deepening for the lower Cerig Formation.

The exposures in the Coed Glyn-môch Track, combined with those at Scrâch Track, Trefawr Track and Cwm-Coed-Aeron, form a network that gives a complete coverage of the stratigraphical succession through the Llandovery Series in the northern part of the international type area.

Conclusions

This important locality in the northern part of the international reference area for the Llandovery Series, combined with other GCR sites, gives a complete coverage of the stratigraphical succession in this area. It exposes the Rhydings and Wormwood formations and the lower part of the Cerig Formation, and comparisons of sedimentology, stratigraphical thickness and faunal sequence can be made with the classic parallel section in the Fron Road, in the southern part of the Llandovery type area. As a key reference site in the international type area, the Coed Glyn-môch Track section is of major conservation importance.

CWM CLYD QUARRY (GARTH BANK QUARRY) (SN 946 509)

Introduction

Strata of latest Ordovician and earliest Silurian age are exposed to the north-west of the village of Garth, 30 km north-east of Llandovery. The first geological map of the area was produced by officers of the Geological Survey in 1850, who demonstrated the presence of lower Llandovery rocks on Garth Bank. The area has subsequently been remapped by Andrew (1925a), by Williams and Wright (1981) and by the British Geological Survey (Davies *et al.*, 1997). Andrew (1925a) applied the lithostratigraphical scheme of letters he developed jointly with O.T. Jones, which were used by the latter in the type Llandovery area (Jones, 1925, 1949). Williams and Wright (1981) subsequently introduced formal lithostratigraphical names for the succession in the Garth area: the Wenallt Formation, the Cwm Clyd Formation and the Garth Bank Formation (Figure 3.30).

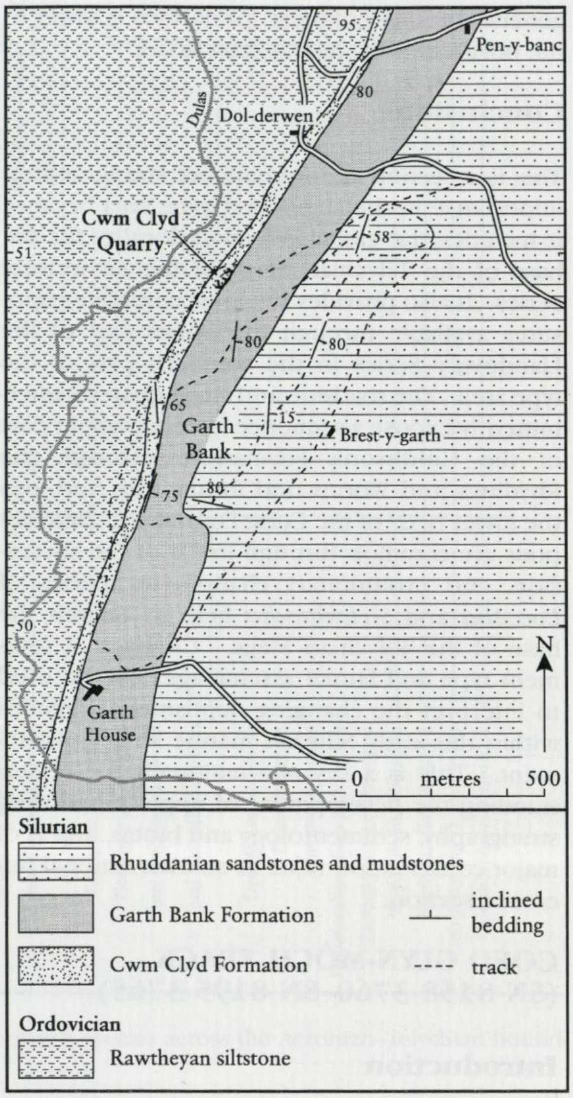

Figure 3.30 Geological map of the Garth Bank area, Powys, showing the location of Cwm Clyd Quarry (after Williams and Wright, 1981).

The Wenallt Formation, of Ashgill age but excluding the highest Hirnantian, comprises siltstones, sandstones and mudstones. The upper unit of this formation, named the Speckly Sandstone Member by Williams and Wright (1981) has a *Hirnantia* shelly fauna, and this is probably the level from which Andrew (1925a) reported *Glyptograptus* cf. *persculptus*. The lower part of the Cwm Clyd Formation has yielded *Eostropheodonta hirnantensis*, indicative of a Hirnantian age. The lower boundary of this unit is unconformable in the south of the area, where the Wenallt Formation is cut out completely, but becomes transitional when traced northwards (Williams and Wright, 1981). The Garth Bank Formation comprises strongly bioturbated siltstones and mudstones, but skeletal fossils have not been found. Sandstones and mudstones overlying the Garth Bank Formation have yielded brachiopods of Rhuddanian age.

Cwm Clyd Quarry is situated on the north-west end of Garth Bank, in the southern part of the area (Figure 3.29). It provides an important exposure of the unconformity between Rawtheyan (Ashgill) siltstones and the Cwm Clyd Formation, with the Wenallt Formation unrepresented. This unconformity is close to the Ordovician–Silurian boundary, which appears to be transitional in the Llandovery type area (see the report for the Scrâch Track GCR site). The break in deposition displayed at Cwm Clyd Quarry is, therefore, of regional stratigraphical, palaeogeographical and tectonic significance.

Description

The most recent descriptions of the rocks in Cwm Clyd Quarry were given by Williams and Wright (1981). The lowest beds exposed are dark-grey bioturbated sandy and muddy siltstones, with pyritous nodules towards the top. These siltstones have produced a diverse shelly fauna, several species of which were illustrated by Williams and Wright (1981, fig. 2). The dominant fossils are the trilobite *Sphaerocoryphe thomsoni* and plectambonitacean brachiopods. Some of the brachiopods suggest assignment to the deep-water *Foliomena* benthic association, and the presence of the trilobites *Tretaspis* cf. *seticornis* and *Lonchodomas* aff. *portlocki* indicates a mid- to late Rawtheyan age.

The Cwm Clyd Formation in the quarry is 15 m thick, although elsewhere it varies from 11 to 51 m. The base of the formation has been re-exposed by clearing work in February 2000 (J. Davies pers. comm.), although an unconformable base was inferred from biostratigraphy and local mapping by Williams and Wright (1981); these authors reported an exposure of the unconformable junction with Rawtheyan siltstones in a roadside cutting north-east of Dol-Derwen farm (SN 949 515).

In the quarry, the Cwm Clyd Formation comprises medium- to coarse-grained, buff-weathering, blue-grey sandstones displaying trough ripple sets. Small pebbles of quartz, chert and rhyolite up to 1 cm in size occur sporadically, and there are a very small number of clay clasts. Body fossils have not been reported, but Andrew (1925a) recorded the presence of 'worm-tracks'. In nearby Garth House Quarry (SN 943 499) the formation is considerably more conglomeratic (Andrew, 1925a).

Interpretation

The rocks and fossils show that late Ordovician and early Silurian sedimentation in the Garth area took place in a shelf sea, contiguous with the Llandovery area to the south-west. The localized nature of the late Ordovician unconformity is evidence of differential local uplift or subsidence at this time, coincident with the Hirnantian glacio-eustatic shallowing. Williams and Wright (1981) concluded that this uplift was an expression of cross-folding superimposed on the emergent structural lineament of the Towy Anticline. An anticline uplifting to the south of the Garth area plunging WNW would explain the increasing completeness of the sequence northwards and the variability of sedimentation in the Cwm Clyd Formation.

The first post-glacial transgressive deposits of the Cwm Clyd Formation are of latest Hirnantian age, from the record of *E. hirnantensis* in beds in the north of the area; the base of the Silurian may occur within the formation. The Cwm Clyd Formation was interpreted by Woollands (in Williams and Wright, 1981) as representing a deltaic channel, but the conglomerates and grits of Garth House and Cwm Clyd quarries were viewed by Williams and Wright (1981) as foreshore deposits derived from the uplifted area to the south. The transition to the finer-grained strata of the Garth Bank Formation would then represent a falling off in the supply of terrigenous material as the uplift ceased.

Conclusions

This quarry shows typical late Ordovician (Rawtheyan) offshore shelf sediments unconformably overlain by latest Ordovician (late Hirnantian) and Silurian pebbly sandstones. This unconformity diminishes and disappears as it is traced northwards, suggesting an area of active uplift to the south during the late Ordovician. The locality is therefore important in displaying the results of this local tectonic activity and in the interpretation of the nature of the earliest Silurian sedimentation in this part of the Welsh Basin.

CABAN CÔCH (SN 925 647)

Introduction

Llandovery strata exposed in the area around Rhayader, to the north-west of the Towy Lineament, were deposited in slope and basinal environments on the eastern margin of the Welsh Basin. Both Murchison (1839) and Sedgwick (1847) assigned the rocks of the Rhayader district to the Cambrian System, but the Geological Survey map and sections, published in 1850 on the basis of mapping undertaken by Ramsay and Aveline, used fossil evidence to refer them to the Lower Llandovery.

The first exhaustive study of the area was completed by H. Lapworth (1900), who drew particular attention to strata referred to the Caban Group, which occupies a band of country about 3 km long extending from Caban Côch to the confluence of the rivers Elan and Wye. Lapworth divided the Caban Group into two main units, the Caban Conglomerates and the Gafallt Beds, and designated a typical section extending from Cnwch Hill, to the south of the Afon Elan, across to the north side of the river. The Caban Conglomerates were further subdivided into three: the Lower Conglomerates, the Intermediate Shales and the Upper Conglomerates. The Gafallt Beds were divided into the '*Monograptus-Sedgwickii* Grits' below and the Gafallt Shales above. Lapworth (1900, pp. 112–18) also noted the lenticular geometry of the Caban Group and discussed its relationship to the strata above and below, concluding that the group lay with erosional unconformity on the underlying Gwastaden Group. The overlying Rhayader Group was observed to overlap the Caban Group, but not necessarily unconformably. Lapworth thus considered the Caban Group to have been deposited during the transgression of the sea across a pre-existing, subaerially eroded hollow, with the conglomerates, by implication, of shallow-water origin.

The Rhayader district was remapped by Davies (1928), who noted that the unconformity identified by Lapworth at the base of the Caban Group (referred by Davies to the 'Upper Birkhill Series') was not detectable to the west and south, towards and around the village of Abergwesyn. A further map, highlighting the distribution of grits and conglomerates, was produced by Davies and Platt (1933), who also discussed the composition of the coarse clastic bands, and attributed their origin to longshore drift.

Kelling and Woollands (1969) also mapped the Rhayader area, paying particular attention to the stratigraphical and sedimentological framework of the deposits, and concluded that Lapworth's interpretation of an erosional unconformity at the base of the Caban Group could not be upheld. They instead considered the rudite and coarse arenite bodies to represent the sites of major offshore submarine channels, in which erosion and infilling were almost simultaneous. This idea was developed by Davies and Waters (1995), who reconstructed the architecture and evolutionary history of the channel and lobe system; further details are included in the British Geological Survey Memoir on the geology of the country around Llanilar and Rhayader (Davies *et al.*, 1997).

The quarry and the crags above at Caban Côch (Figures 3.31, 3.32) provide excellent representative exposures of the Caban Conglomerate Formation (approximately equivalent to Lapworth's Caban Group). They expose the western part of a channel complex, and enable detailed study of the character of the entire complex and of the nature and relationships of the individual conglomerate and sandstone units.

Description

The rocks exposed in the quarry belong to Lapworth's 'Lower Conglomerate' and are dominated by clast-supported pebble and cobble conglomerates, with subordinate coarse sandstones (Figures 3.32, 3.33). The conglomerate bands have erosional bases, and in several cases can be seen to occupy channels, which can be traced for up to 20 m; they sometimes have steep sides and display undercutting. The coarser conglomerates are normally disorganized, but finer conglomerates commonly display normal and reverse grading and there is some evidence of imbrication. Sole marks are rare, and restricted to linear or elliptical gouge structures up to 15 cm deep. Angular clasts of mudstone are common within the conglomerates, and reach up to 2 m in size; some are armoured by small pebbles and granules. The rounded and subrounded clasts are dominated by quartz,

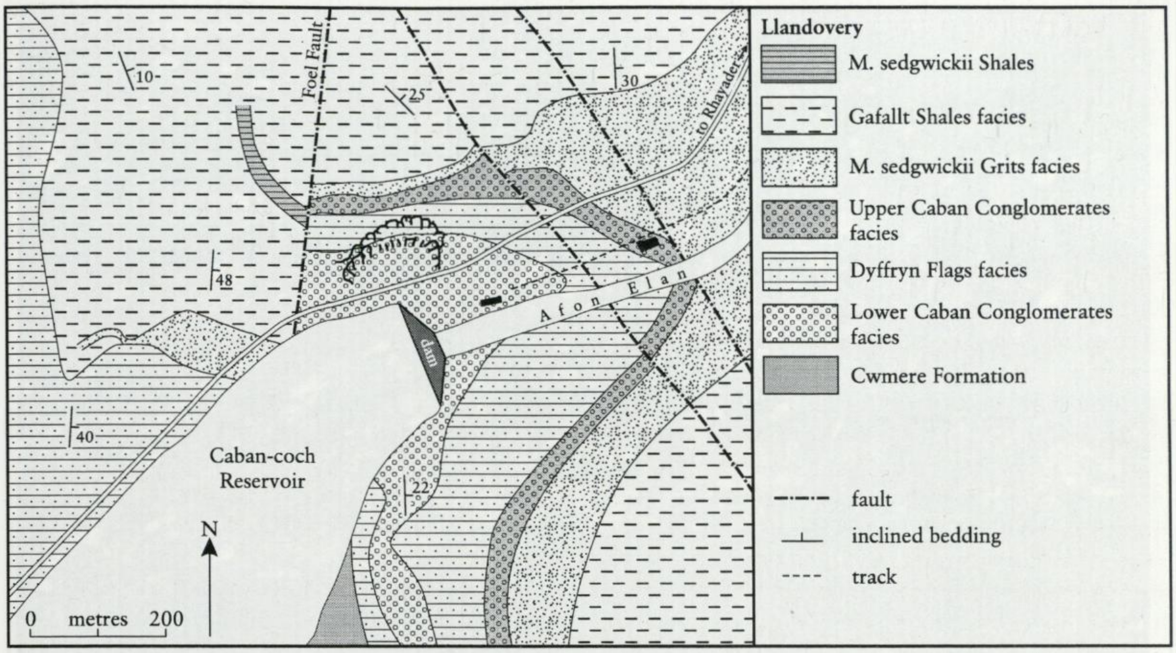

Figure 3.31 Geological sketch-map of the area around Caban Côch quarry (after Waters *et al.*, 1993).

Figure 3.32 Turbiditic sandstones and conglomeratic submarine channel fills, Caban Côch quarry. (Photo: R.J. Aldridge.)

quartzites and sandstones, together with acid and basic igneous rocks, pyroclastics, and occasional broken fossils. The conglomerate bands each pass up into coarse, pebbly sandstones, which commonly show grading and may be more laterally persistent than the lenticular conglomerate horizons; some display megaripple cross-lamination on a scale of 15–25 cm. Some units of thin-bedded sandstone and mudstone also occur, reaching 60 cm in thickness; one of these units, near the bottom of the quarry, has produced graptolites referred to the *acinaces* or *cyphus* Biozone (Davies *et al.*, 1997).

Above the quarry, at the foot of the crags on Caban Côch, shales of the 'Dyffryn Flags facies' (Waters *et al.*, 1993; 'Intermediate Shales' of Lapworth, 1900) crop out. , These comprise cleaved mudstones interbedded with thin (1–30 cm thick) grits and sandstones, which are graded and parallel laminated or may show ripple drift lamination. The proportion of coarser clastic horizons increases upwards, and small lenses of conglomerate with scoured bases occur in the upper 5 m of the unit. At SN 9253 6470, in the uppermost mudstones, graptolites have been recovered from a thin laminated hemipelagite (Siveter *et al.*, 1989). These include *Rhaphidograptus toernquisti, Orthograptus cyperoides, Climacograptus rectangu-*

Figure 3.33 Detail of the conglomeratic infill of a submarine channel, Caban Côch quarry; the lower part of the conglomerate unit shows reverse grading. (Photo: R.J. Aldridge.)

laris sensu lato and *Pseudoclimacograptus? retroversus*, an assemblage indicative of the *triangulatus* or *magnus* Biozone.

The upper conglomerate member is exposed in the crags above the quarry and descends to the road 200 m east of the quarry (SN 9267 6469). The unit displays a channelized base, and is similar in character to the lower conglomerate member. Large contorted and angular clasts of the underlying mudstone are present in the basal conglomerates.

The overlying '*M. sedgwickii* Grits' are exposed in a buttress at SN 9260 6477. The transition from the conglomerates is gradational, and the unit comprises turbiditic sandstones and mudstones with rare burrowed hemipelagites. The sandstone beds are normally up to 40 cm thick and commonly display flute casts and basal shelly lags; a few thicker, coarser, sometimes pebbly sandstones occur. A little higher in the hillside, at Craig Gigfran (SN 9260 6488), the crags display strata of the overlying Gafallt Shales (Davies *et al.*, 1997). These comprise thin turbiditic mudstone and siltstone couplets, with occasional fine to coarse sandstones up to 4 cm thick. The turbidite units are interspersed with burrowed hemipelagites.

Interpretation

The Caban conglomerates and sandstones accumulated in a north-westerly trending channel complex, which probably developed at the base of a fault-controlled slope (Kelling and Woollands, 1969). The complex is situated on the north-west side of the Towy Lineament, which during the Rhuddanian to early Telychian defined the south-eastern margin of the deep-water region of the Welsh Basin. Along this margin, a westwardly thinning wedge of mud-dominated slope-apron sediments built out into the basin, locally punctuated by a complex system of nested channel fills and associated sandy lobes (Davies and Waters, 1995). The Caban Conglomerate Formation comprises the proximal lobe and channelled facies of this system, with the median and distal lobe facies represented by the Ystrad Meurig Grits Formation to the west.

Davies and Waters (1995) showed that the Caban conglomerates were confined to broad

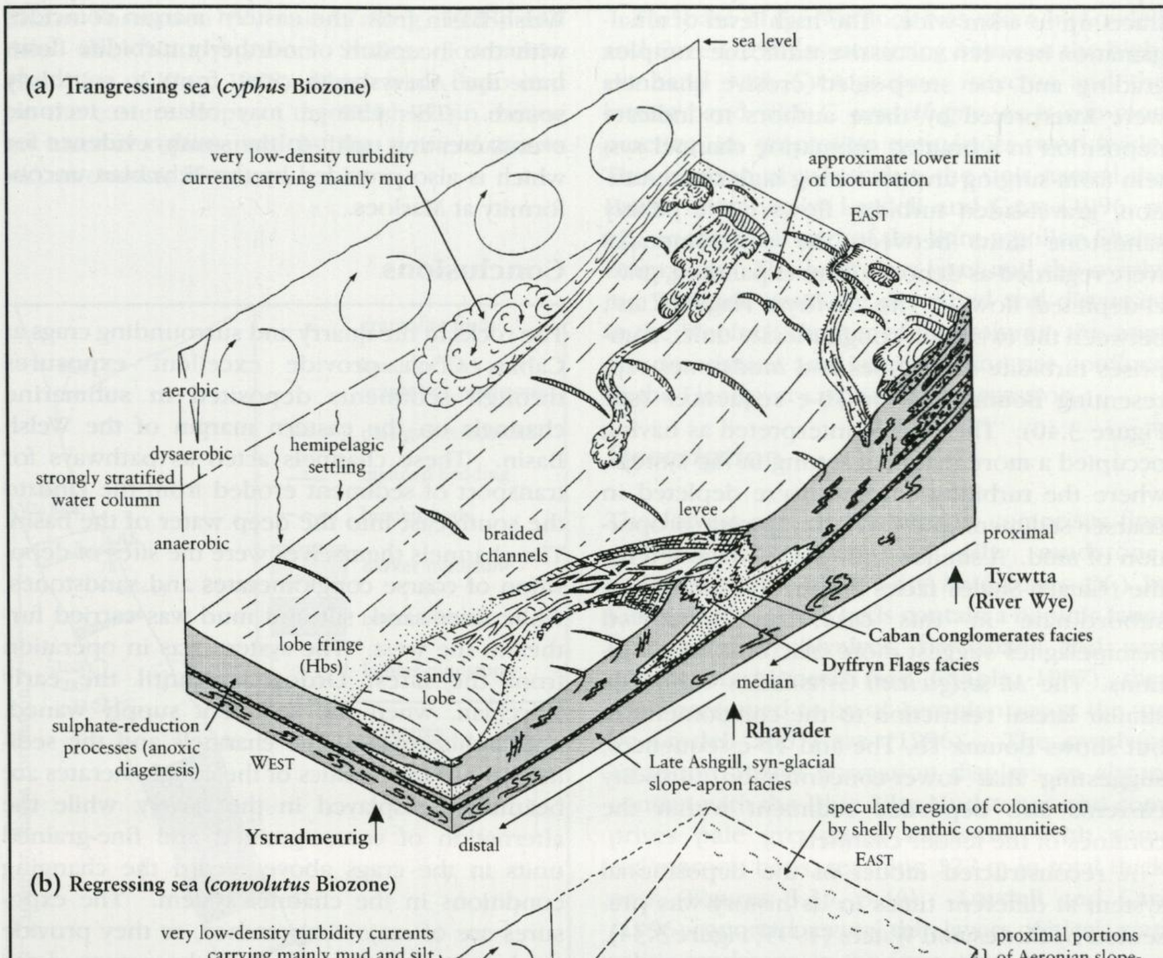

Figure 3.34 Depositional model for the development of nested channels and lobes in the Caban Côch area during the Llandovery Epoch (after Davies and Waters, 1995; Davies *et al.*, 1997).

tracts up to 4 km wide. The high level of amalgamation between successive units, the complex grading and the steep-sided erosive channels were interpreted by these authors to indicate deposition in a braided submarine channel system from surging and switching high-concentration, gravel-laden turbidity flows. The pebbly sandstone units between the conglomerates were regarded as deposits from expanding, gravel-depleted flows. The 'Dyffryn Flags facies', between the two main conglomerate units, comprises turbidite sandstones and mudstones representing Bouma Tc-e or Tb-e sequences (see Figure 3.40). These were interpreted as having occupied a more marginal setting in the system, where the turbidity currents were depleted in coarser sediment and carried a greater proportion of mud. A similar setting was suggested for the 'Gafallt Shales facies', with Tb-e units very subordinate in this case; the burrowed hemipelagites suggest more oxic bottom conditions. The '*M. sedgwickii* Grits facies' exhibits a similar lateral restriction to the conglomerates, but shows Bouma Tb, Tbe and Tb-e sequences, suggesting that lower-concentration turbidity currents also deposited sediment within the confines of the feeder channels.

A reconstructed model of the depositional system at different times in its history was presented by Davies and Waters (1995; Figure 3.34), who also discussed the evolutionary history of the complex. The system was initiated in latest Ordovician (*persculptus* Biozone) times, when the feeder channel advanced over the underlying turbidites, followed by expansion during the Rhuddanian. A brief cessation of coarse clastic deposition occurred in the main Caban channel during the early Aeronian (*triangulatus* Biozone), with gravel supply being re-established during *magnus* to *argenteus* Biozone times. This may reflect tectonic rejuvenation of the sediment source areas. The onset of deposition of the 'sedgwickii Grits facies' in the *convolutus* Biozone marked an abrupt decrease in the sediment-carrying efficiency of the system. The transition to the 'Gafallt Shales facies' during the earliest Telychian (lower *turriculatus* Biozone) records a gradual decline of the supply of coarse clastics and the abandonment of the Caban channel complex. During this final phase, low-concentration turbidity currents were routed across the slope-apron area via the relict channel system.

The cessation of turbidite supply into the Welsh Basin from the eastern margin coincides with the inception of northerly turbidite flows into the Aberystwyth area from a southerly source. This change may relate to tectonic events creating uplift to the south, evidence for which is also provided by the Telychian unconformity at Marloes.

Conclusions

The rocks in the quarry and surrounding crags at Caban Côch provide excellent exposures through sediments deposited in submarine channels on the eastern margin of the Welsh Basin. These channels acted as pathways for transport of sediment eroded from the land to the south-east into the deep water of the basin. The channels themselves were the sites of deposition of coarse conglomerates and sandstones, while finer sand, silt and mud was carried further to the west. The system was in operation from the latest Ordovician until the early Telychian, when the sediment supply waned. The architecture of the channels and the sedimentary characteristics of the conglomerates are beautifully displayed in the quarry, while the alternation of coarse-grained and fine-grained units in the crags above record the changing conditions in the channel system. The exposures are of major importance, as they provide the best evidence available of the nature of the sedimentary feeder channels into the Welsh Basin during the early Silurian, and they also give important clues to the tectonic events that caused variations in the sediment supply. The site is frequently visited by students and by national and international researchers and has a high conservation value.

BANWY RIVER (SJ 1330 1042–SJ 1340 1011)
POTENTIAL GCR SITE

Introduction

The Banwy river section, 3.5 km south-west of Meifod in Powys, has recently come to prominence because it yields abundant graptolites through the uppermost part of the Llandovery Series and across the Llandovery–Wenlock boundary (Loydell and Cave, 1996). Graptolites are otherwise poorly known at this level in the Silurian of Britain. The section provides a continuous exposure of strata through the Tarannon

Shales Formation (V_3 unit of King, 1928) and into the Nant-ysgollon Shales Formation (Salopian of King, 1928), which were deposited on the eastern slope of the Welsh Basin during an interval represented by the *turriculatus* to *riccartonensis* biozones.

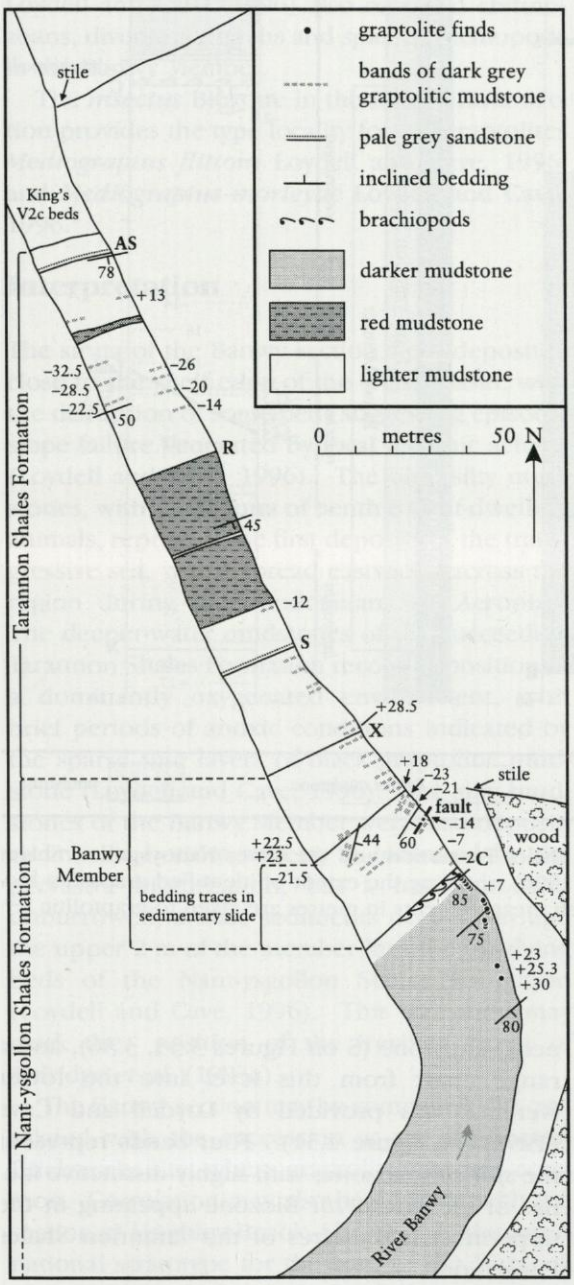

Figure 3.35 Geological sketch map of the Banwy River section (after Loydell and Cave, 1996). The letters represent marker horizons from which measurements in metres are taken to graptolitic levels.

The base of the Wenlock was taken by Loydell and Cave (1996) as occurring between the highest band with *Cyrtograptus insectus* and the lowest band with *C. centrifugus*, as is common practice in graptolitic sequences worldwide. This horizon occurs within the unit named the Banwy Member by Loydell and Cave (1996, p. 47), in the basal part of the Nant-ysgollon Shales Formation. The boundary level and the overlying Wenlock strata are described and discussed in the Wenlock chapter of this volume; the present description and interpretation are confined to the Llandovery part of the succession.

Description

The lowest part of the section comprises fine-grained sandstones and silty mudstones assigned to the Blue Silty Mudstones (V_2) by King (1928). These beds contain a benthic fauna dominated by bivalves, bryozoans and very diverse brachiopods (see Temple, 1987); they were presumed to be of Aeronian age at the top by Loydell and Cave (1996). The overlying Tarannon Shales Formation displays an abrupt contact with the Blue Silty Mudstones and comprises pale grey-green mudstone with some red/maroon beds, reaching 122 m in total thickness (Figures 3.35, 3.36). Loydell and Cave (1996) reported several thin layers of black graptolitic mudstone in the formation, with some of the bands occurring in bundles reaching up to 0.5 m in thickness. A distinctive pale-grey sandy mudstone (Bed 85 of King, 1928) occurs 7.6 m above the base of the formation (AS on Figures 3.35, 3.36). A second prominent sandstone (S on Figures 3.35, 3.36) is present about 20 m below the top of the formation. Thin bentonite bands also occur. There are no graptolites recorded from the basal part of the formation in the Banwy River section, but Loydell and Cave (1996, p. 48) reported a collection at this level from nearby Llanfyllin indicative of the highest part of the *turriculatus* Biozone. King (1928, p. 690) noted the presence of graptolites, considered by him to indicate the *turriculatus* Biozone, low in the Tarannon Shales Formation in the Banwy River (see Figure 3.36); however, a re-examination of these specimens by Loydell and Cave (1996, p. 48) revealed the presence of *Stimulograptus clintonensis*, which has not been positively recorded below the *crispus* Biozone. Higher in the formation, between the two red mudstone units, graptolite horizons

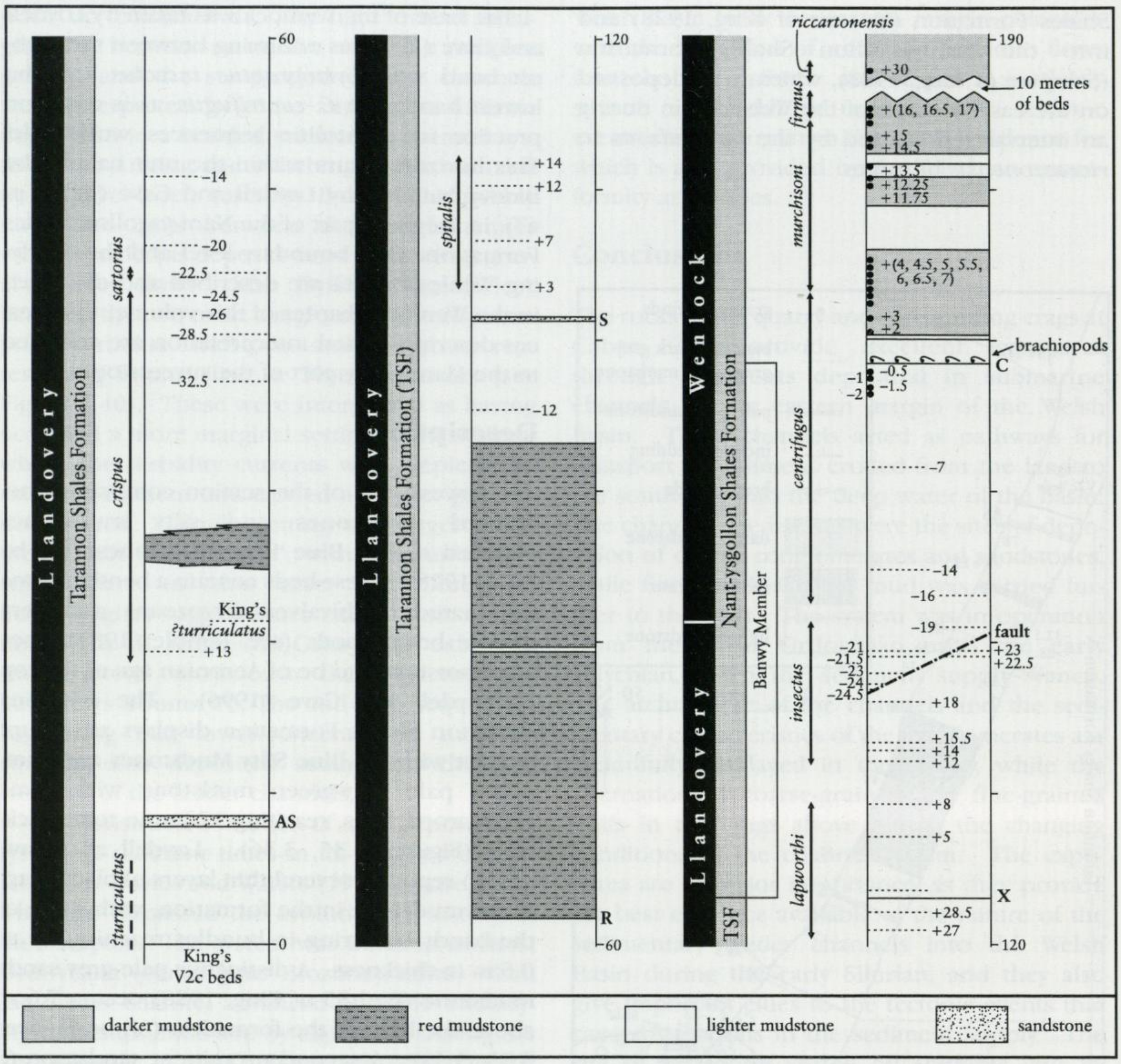

Figure 3.36 Measured section through the Tarannon Shales Formation and the lower Nant-ysgollon Shales Formation in the Banwy River (after Loydell and Cave, 1996), showing the extent of identified graptolite biozones. The letters represent marker horizons from which measurements in metres are taken to graptolitic levels.

become more common and can be found on both banks of the river, but the strata are disturbed so that individual bands cannot be matched across the stream (Loydell and Cave, 1996). The faunas include *S. clintonensis* and other graptolites of the *crispus* Biozone, with the highest band on the west side of the river also containing *Streptograptus sartorius*, suggesting assignment to the *sartorius* Sub-biozone, the highest subdivision of the *crispus* Biozone (see Zalasiewicz, 1994). Graptolites become particularly significant above the prominent sandstone (S on Figures 3.35, 3.36), and a range chart from this level into the lower Wenlock was provided by Loydell and Cave (1996, see Figure 4.51). Four bands represent the *spiralis* Biozone, with highly distinctive faunas of the *lapworthi* Biozone appearing in the uppermost few metres of the Tarannon Shales Formation.

The lowest beds of the Banwy Member also contain a *lapworthi* Biozone fauna, with the uppermost band yielding in addition *Monoclimacis basilica*, a species often taken as an indication of a Wenlock age (see Loydell and Cave, 1996). Above this about 10 m of strata are referable to the *insectus* Biozone, although a prominent slide plane disrupts the sequence, and the original thickness may have been greater. There is a 3 m interval lacking graptolites above the highest *insectus* band, and it is within this interval that the presumed level of the Llandovery–Wenlock boundary occurs. Loydell and Cave (1996) also reported chitinozoans, diverse acritarchs and sparse brachiopods in the Banwy Member.

The *insectus* Biozone in the Banwy River section provides the type locality for the graptolites *Mediograptus flittoni* Loydell and Cave, 1996, and *Mediograptus morleyae* Loydell and Cave, 1996.

Interpretation

The strata of the Banwy section were deposited close to the shelf edge of the Welsh Basin, with the disruption of some beds suggesting episodic slope failure generated by local tectonic activity (Loydell and Cave, 1996). The blue silty mudstones, with their fauna of benthic shelf-dwelling animals, represent the first deposits of the transgressive sea, which spread eastwards across the region during the Rhuddanian and Aeronian. The deeper-water mudstones of the succeeding Tarannon Shales Formation record deposition in a dominantly oxygenated environment, with brief periods of anoxic conditions indicated by the sparse thin layers of black graptolitic mudstone (Loydell and Cave, 1996). The silty mudstones of the Banwy Member were also deposited in oxic bottom waters, as indicated by the pervasive bioturbation, but a transition into unburrowed, anoxic sediments occurs through the upper 2 m of the member into the overlying beds of the Nant-ysgollon Shales Formation (Loydell and Cave, 1996). This transition may mark the position of the Ireviken Event of Aldridge *et al.* (1993a).

The Banwy section may be compared and correlated with the succession at the Buttington Brickworks site, where graptolites are less common. Correlation may also be possible with the section at Hughley Brook, Shropshire, the international stratotype for the base of the Wenlock Series; although the stratotype lacks graptolites, there is potential for using chitinozoans, acritarchs and bentonites to relate the two localites (Loydell and Cave, 1996).

Conclusions

The Banwy River section is of special importance as it has produced the most completely known sequence of graptolite faunas in Britain through the uppermost part of the Llandovery Series and across the Llandovery–Wenlock boundary. The presence of acritarchs, chitinozoans and bentonite bands in the section provides a potential for correlation of this graptolitic sequence with the non-graptolitic stratotype section for the base of the Wenlock Series in Hughley Brook, Shropshire. This site may well become an international reference locality for graptolite biostratigraphy across the Llandovery–Wenlock boundary.

ABERARTH–MORFA (SN 485 645–SN 497 654)

Introduction

Strata of the Aberystwyth Grits Group form a broad crescentic outcrop in west-central Wales sub-parallel to the shoreline of Cardigan Bay (Figure 3.37). They are particularly well exposed in cliff sections along the coast extending intermittently for some 40 km. The name 'Aberystwyth Grits' was introduced by Keeping (1881), who completed the first detailed study of these rocks, including a listing of the graptolite fauna. Jones (1912) also reported a number of graptolites, including *Spirograptus turriculatus*, from the grits, discussed their age and correlation, and interpreted the geological structure of the area; later, he suggested that the source of the greywackes in the unit lay to the west (Jones, 1938). It appears that Jones regarded the coarser sediment layers in the unit to have been deposited in fairly shallow water (see Wood and Smith, 1959), but Bailey (1930) considered that graded beds such as those seen in the Aberystwyth Grits indicated a deeper environment. In his view, the graded sandstones 'mark the intermittent delivery of a mixture of grit, sand and mud into the waters that overlie the mud floor of the sea *beyond the reach of ordinary sand-pushing bottom currents*' (Bailey 1930, p. 88). A similar conclusion was reached by Rich (1950), who thought that the sediments had been deposited from density currents flowing down a continental slope; his evidence came from flow markings and groove marks preserved on the undersides of the greywacke beds,

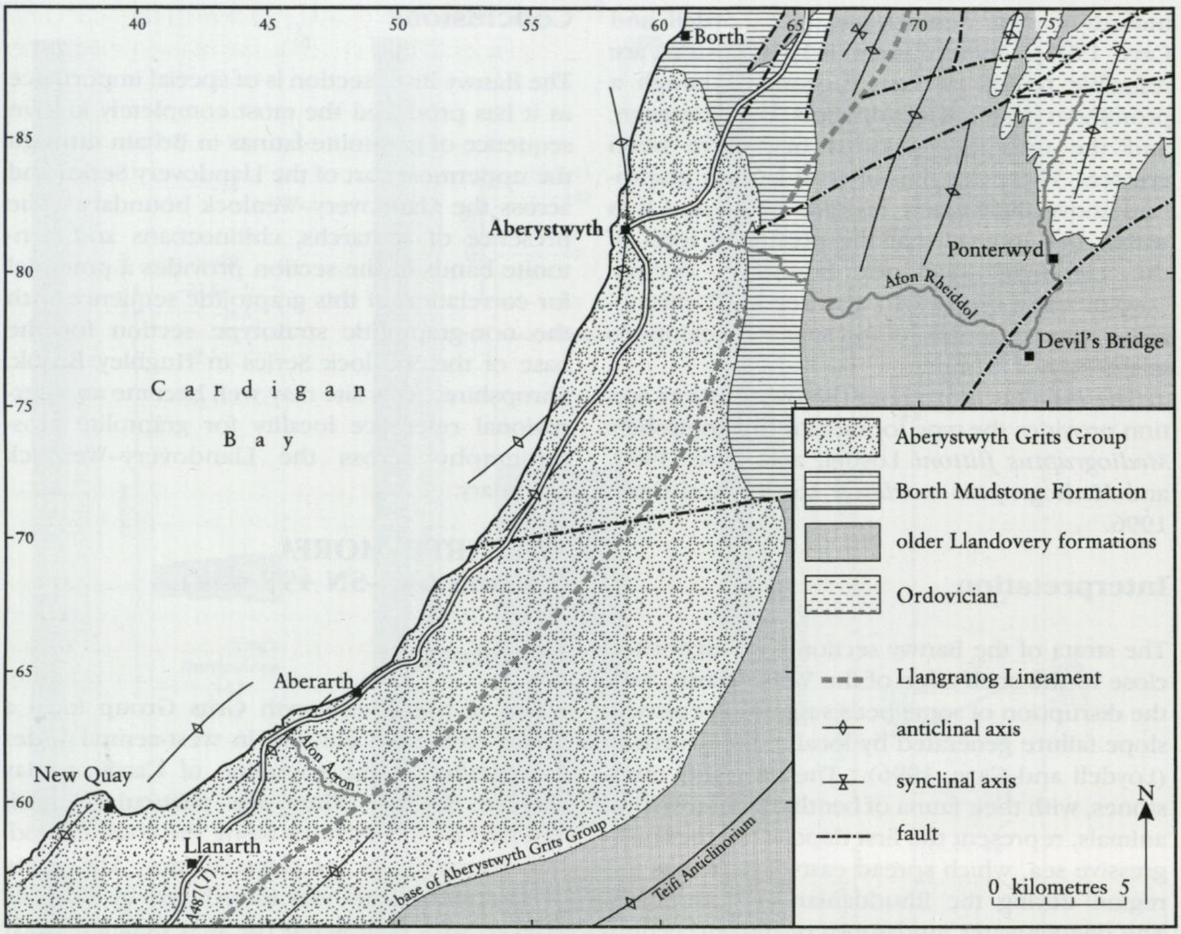

Figure 3.37 Geological sketch-map of central western Wales, showing the extent of the Aberystwyth Grits Group and the GCR network sites at Aberarth and Craigyfulfran (Aberystwyth) (after Siveter *et al.*, 1989).

together with the presence of convoluted laminations, which he attributed to the movement of beds downslope. Keunen (1953) also considered the greywackes to be the product of density flows, noting especially the grading in the beds. Rich (1950) and Keunen (1953) both used the evidence from the sedimentary structures to conclude that the greywackes, at least in the Aberystwyth district, were introduced into the area from the SSW. Wood and Smith (1959) produced a detailed report on the grits throughout their outcrop, providing several lines of evidence to support the growing consensus that they were deposited in relatively deep water from turbidity currents that flowed close to the sea floor. Bailey (1930) had suggested that submarine tremors ('seaquakes') were necessary to generate such flows, and this mode of origin was supported by Wood and Smith (1959). They envisaged the rise of a 'whale-backed ridge' to the south-west or SSW from which previously deposited sediments were remobilized by uplift accompanied by earthquakes. They also suggested that some, maybe many, of the currents may have originated from terraces of sediment that had been built out beyond the position of stability.

Graptolites are not uncommon in darker, muddier horizons in the Aberystwyth Grits Group. The first specimens were recorded and illustrated by Hopkinson (1869), and lists were produced by several subsequent workers, indicating that the group should be assigned to the *turriculatus* Biozone. The taxonomy and biostratigraphy of graptolites from the area was revised and refined by Loydell (1991, 1992–93), who divided the lower Telychian *turriculatus sensu lato* Biozone into two new biozones (the *guerichi* and *turriculatus* biozones) and subdivided the two into a total of seven sub-biozones. He also showed that the base of the turbidite system was everywhere within the *geurichi* Biozone and that diachroneity at the base of the unit equates to approximately one sub-biozone, rather less than previously believed. The production of a high-resolution biostratigraphy also provided a framework for detailed facies analysis of the turbidite fan, allowing consideration of such variables as sediment supply, sea-level changes and tectonic activity (Dobson, 1995). The whole sequence was viewed by Dobson (1995) as the remains of a small, deep water (perhaps about 500 m) submarine fan built by sediment deposition from turbid flows. In general, the flows were from the south-west or SSW, and the more proximal turbidite facies are therefore found in the southern part of the outcrop. Wilson *et al.* (1992), however, regarded a simple turbidite fan model to be inappropriate for the Aberystwyth Grits, and attributed control of the depositional system to syndepositional faulting to the east, represented in part by the Bronnant Fault Zone. A thorough summary of this model for the development of the Aberystwyth Grits Group, as a fault-controlled sandstone-lobe turbidite system, has been presented by Davies *et al.* (1997, pp. 126–32, 145–50).

The rocks in the Aberystwyth area are highly folded and faulted, with structural trends dominantly NNE to SSW. Davies and Cave (1976) interpreted much of the smaller-scale folding and some of the faulting to be attributable to soft-sediment deformation caused by the sliding of thick packets of turbidites westwards down the palaeoslope. Fold axes are more or less parallel to the coastline of Cardigan Bay (Figure 3.37); in the south of the region the strata plunge northwards, and in the north they plunge southwards, so the youngest beds are found in the central region, around Llanrhystud (SN 539 697).

The cliffs between Aberarth and the farm of Morfa, 3 km to the north-east, show excellent representative sections in turbidite beds of the Aberystwyth Grits Group; the strata here were referred to the Mynydd Bach Formation by Wilson *et al.* (1992). The area is a few kilometres south of Llanrhystud, so the beds here gen-

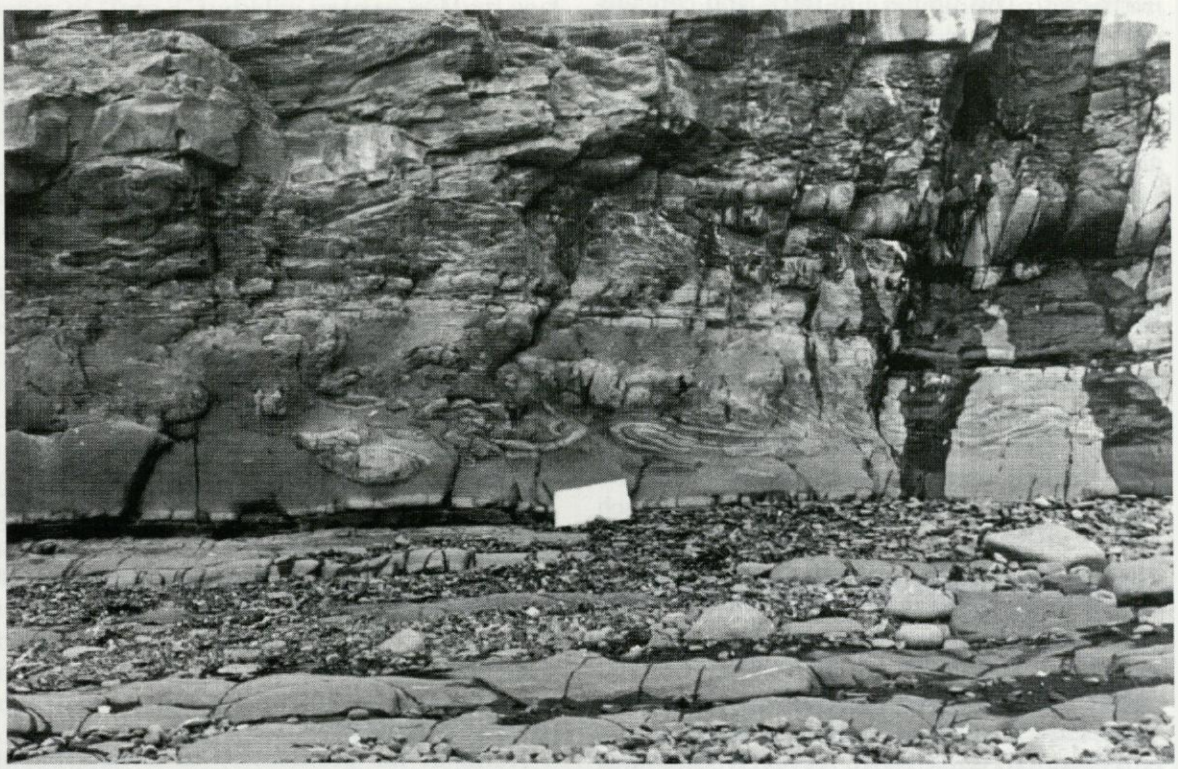

Figure 3.38 Deformed bedding in the Aberystwyth Grits Group (Subzone 4b) at Aberarth. (Photo: M.R. Dobson.)

erally young northwards. One of the noteworthy features of the Aberarth section is the occurrence of structures referred to as 'prolapsed bedding' by Wood and Smith (1959, p. 172), in which a set of flat-lying folds in alternating mudstones and greywackes are incorporated in an otherwise normal greywacke–mudstone sequence (Figure 3.38).

Description

The cliffs 500–800 m north-east of Aberarth display a sequence of turbidite beds 30–50 m thick, dipping at 40° to the south-east. These beds belong to Subzone 4b (*utilis* b), at the base of the *turriculatus* graptolite biozone (Dobson *et al.*, 1995a). Graded greywacke beds form the base of each turbidite unit; the bases are irregular or undulate and many display flute and groove marks. The greywackes grade up into fine sandstones and are separated by mudstone horizons up to 8 cm in thickness. Several levels show examples of the 'prolapsed bedding' described by Wood and Smith (1959); one such horizon can be seen immediately north of a small fault 36 m north of the start of the exposure and can be traced for about 100 m to the north-east. This unit is 1 m thick, and contains rafts of folded and contorted thin-bedded strata in a slurried matrix (Bates, 1982a).

About 325 m north-east of the beginning of the section a fault brings in a sequence of finer-grained beds, with most turbidite units less than 10 cm thick. At Clochtyddiau Pridd (SN 4877 6468), a normal fault occurs, beyond which a sequence of thick turbidites can be seen (Figure 3.39). One particularly prominent bed, 5 m thick and comprising an amalgamation of several greywackes persists to the small promontory at SN 4909 6498. The base of this bed displays prominent horseshoe-shaped flute moulds.

Dobson *et al.* (1995a) described the sequence from the beginning to this promontory as comprising five successive packets of strata, each with a thickness between 25 and 50 m. The basal units of each package include massive coarse sandstones and conglomerates with deeply scoured bases and containing ripped-up mudstone clasts; the packages generally fine upwards, with bed thicknesses also decreasing. Palaeocurrent directions measured from the cross-bedded units range between eastwards and north-eastwards, whereas the orientations of flute moulds are consistently towards the north-east (Dobson *et al.*, 1995a).

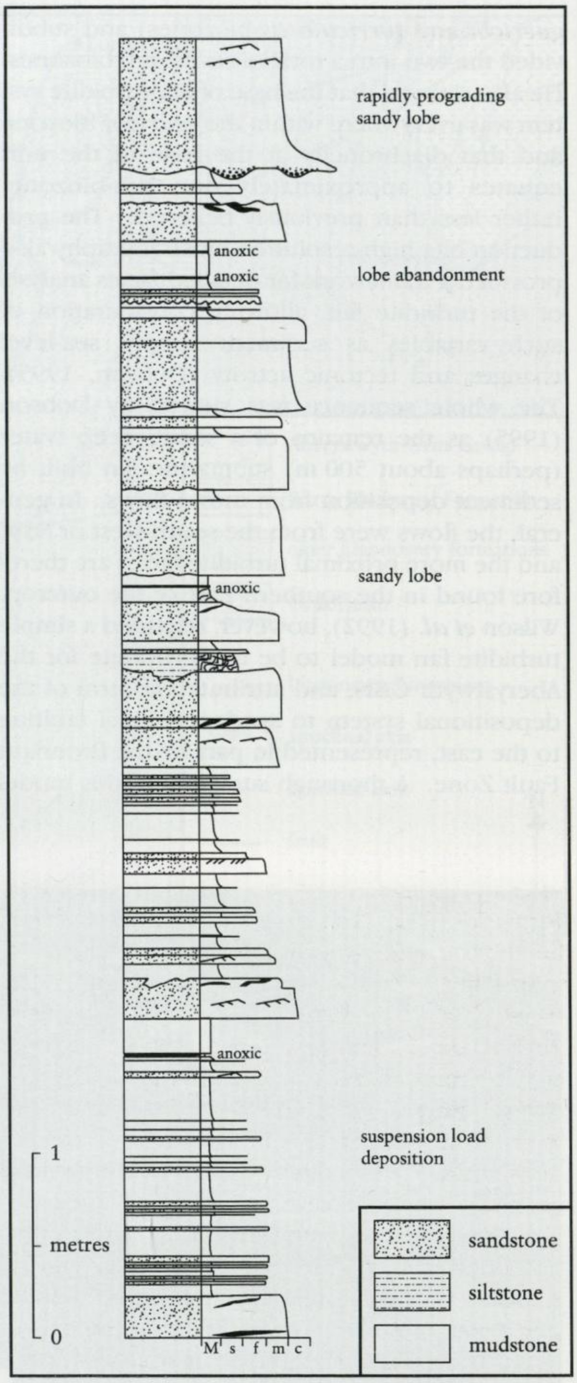

Figure 3.39 Representative measured section in the turbidite sequence, Aberystwyth Grits Group, between Aberarth and Morfa, with environmental interpretations (after Dobson *et al.*, 1995a).

North of the promontory an alternation of groups of thick and thin greywackes continues for some 700 m to the end of the exposure.

Interpretation

During the latest Aeronian and early Telychian submarine fans built out north-eastwards into the Welsh Basin from the marginal areas to the south. Sediment was transported by turbidity flows, which eroded the upper levels of the underlying beds and produced scour features such as flutes, which are preserved as moulds on the bases of the overlying greywackes. As the flows waned, the finer sediments settled out, and in the quiet periods between flows a background deposition of fine hemipelagic muds pertained. Nearer to the sediment source, in the south, the energy of the flows was highest and greywacke deposition predominated, resulting in a turbidite sequence with a high sand–mud ratio. To the north-east, smaller amounts of coarse material reached the area, and the proportion of fine sand and mud is much higher.

At Aberarth, the fining-up turbidite packages were interpreted by Dobson *et al.* (1995a) as episodic sandy lobe progradations reflecting pulsed sediment supply. This may itself relate to periods of rising and falling sea level. The sandstone lobes in the Cardigan Bay area do not show evidence of channelling, and represent a series of 'Type 1' turbidite systems of Mutti and Normark (1987). The elongate SW–NE shapes of the lobes suggest derivation from a series of point sources to the south-west, perhaps large rivers or delta systems. The relatively high greywacke/mud ratio in the Aberarth sections suggests that these are relatively proximal sandy lobe sequences (Figure 3.39), and this interpretation is supported by the presence of coarse sands and conglomerates and the recognition of upward coarsening (reverse grading) at the base of each greywacke bed followed by upward fining (Dobson *et al.*, 1995a). The amalgamation of successive sandstone beds into multiple units is evidence of erosive downcutting by successive flows. The turbidite beds at Aberarth mostly preserve only the Ta, Tab or Tabc portions of a typical Tabcde Bouma turbidite cycle (Figure 3.40). The thicker finer-grained units reflect periods of lobe abandonment. The 'prolapsed beds' have been interpreted either as rafts of previously deposited turbidites that have slumped down the slope or as levels that have foundered and experienced soft-sediment deformation during deposition.

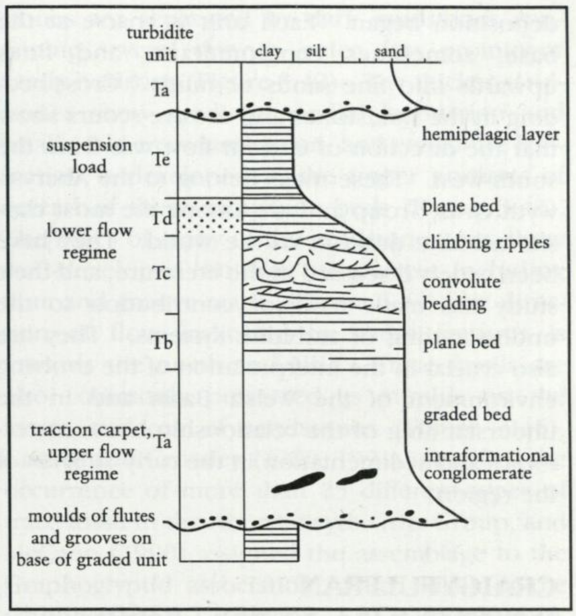

Figure 3.40 Idealized graphic log of the full Tabcde Bouma turbidite cycle (modified from Selley, 1978, after Bouma, 1962).

The exposures between Aberarth and Morfa, therefore, display excellent sections in typical deposits of the Aberystwyth Grits Group in the proximal to intermediate part of a series of sandy lobes. Similar exposures in proximal sandy lobe sequences can be seen to the south-west, beside the sea-food factory at New Quay (SN 3868 6044). The sequences at Aberarth and New Quay contrast with the more mud-dominated sections to the north-east at Craigyfulfran, Aberystwyth. They also relate temporally to the unconformity in the shelf section at Marloes; it is likely that this unconformity and the generation of the turbidites are both causally linked to uplift of part of Eastern Avalonia (Pretannia), perhaps during collision with the Laurentian plate (Soper and Woodcock, 1990).

Conclusions

These excellent coastal exposures provide sections through sandy submarine lobes that built out into the deeper parts of the Welsh Basin during latest Aeronian and early Telychian times. The sediments on the lobes were deposited from turbid currents of sediment and water that flowed close to the sea floor, eroding the pre-existing sediments until the flow waned and deposition began. Each unit is coarse at the base, sometimes conglomeratic, and fines upwards into fine sands or muds. Cross-bedding in the sandstones and erosive scours show that the direction of current flow was from the south-west. These rocks belong to the Aberystwyth Grits Group and are among the most classic turbidite deposits in the world. They have been widely discussed in the literature, and their study has made a major contribution to the understanding of turbidite systems. They are also crucial in the interpretation of the evolving environment of the Welsh Basin and in the understanding of the relationship between tectonics and sedimentation in the early Silurian of the region.

CRAIGYFULFRAN (SN 5821 8253–SN 5867 8360)

Introduction

The cliff exposures along the coast to the north of Aberystwyth (Figure 3.37) provide the classic section of the Aberystwyth Grits Group. They have been described and discussed by numerous authors since the term 'Aberystwyth Grits' was introduced by Keeping (1881). Along with other sections in the region, including the site at Aberarth–Morfa, they have played a major part in the development of the concept that the Aberystwyth Grits were deposited by submarine turbidity currents that flowed into the deeper parts of the Welsh Basin from shallower areas to the south-west.

Geological mapping of the Aberystwyth area goes back to 1848, when maps at the scale of 1 inch to 1 mile were published by the Geological Survey of England and Wales. Keeping (1878, 1881) produced the first detailed study specifically directed at the rocks of the Aberystwyth neighbourhood, but misinterpreted the stratigraphical order of the strata. This error was corrected by Marr (1883) and Jones (1909), who recognized the true superpositional sequence. In the 1900s, the numerous papers on the geology of Central Wales by O.T. Jones included two referring specifically to the Aberystwyth district (Jones and Pugh, 1935a, b), in which it was noted that the lithology and fauna of the strata show that they belong to a distinctive environmental suite, termed the graptolitic facies. Studies on the sedimentology of the Aberystwyth Grits include the seminal paper by Wood and Smith (1959), and the petrological and geochemical evidence for the provenance of the sediments was assessed by McCann (1991). The tectonics of the Aberystwyth Grits were studied by Price (1962), who identified an anticlinal structure in the Aberystwyth region with the axis running north–south. The British Geological Survey returned to the area in 1965–1975, and undertook geological mapping for the production of Sheet 163 (England and Wales). The accompanying memoir (Cave and Hains, 1986) provides a detailed summary of the geology in the area that includes Aberystwyth and Machynlleth. A number of excursion guides also provide details of rocks in the general area and in the specific exposures between Aberystwyth and Clarach.

The section of cliff exposures extending from the north end of Aberystwyth North Bay in the south to Clarach Bay in the north makes up the type locality for the Aberystwyth Grits Group. The section incorporates Craigyfulfran ('Cormorant Rock'), after which the locality is named (Figure 3.41). Typical greywacke-mudstone tubidite rhythms are displayed, with the finer-grained sediments predominant. Sedimentary structures indicating flow directions; trace fossils are common.

This classic section, therefore, displays a wide variety of characteristic features of the distal deposits of turbidity flows. It has been very widely referred to in the literature, and has played a major part in the development of ideas on the sedimentology of turbidite systems. The readily accessible coastal cliffs provide excellent evidence of the nature of depositional systems in this area of the Welsh Basin during early Silurian times. The mud-dominated turbidite units at Craigyfulfran contrast with the sand-dominated more proximal units seen in sections to the south (e.g. Aberarth–Morfa), and together with these sections allow reconstruction of the elongate submarine lobe complex that developed in the area that is now central western Wales. Detailed summaries of the Aberystwyth Grits Group and of its deposition in a fault-controlled sandstone-lobe turbidite system were given by Wilson *et al.* (1992) and Davies *et al.* (1997, pp. 126–32, 145–50). These deep-water sediments with their fauna of trace fossils and occasional graptolites contrast markedly with the shallow water facies seen in Aeronian and Telychian network sections to the south (e.g. Marloes) and east (e.g. Hillend Farm, Gullet Quarry).

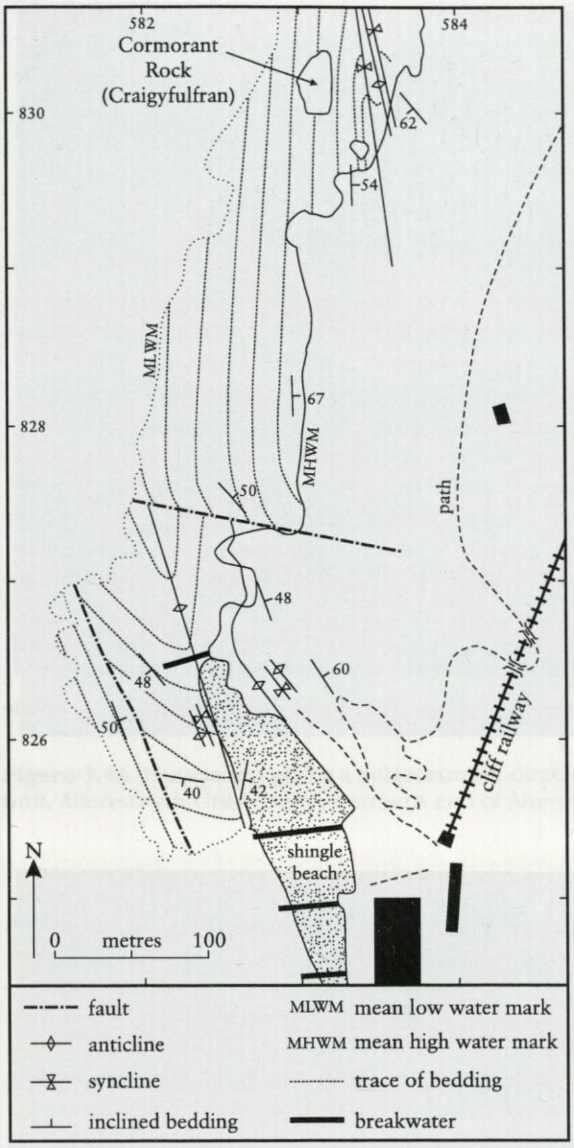

Figure 3.41 Sketch map of the area from Craigyfulfran to the north end of the Aberystwyth promenade (after Bates, 1982a).

Description

The best-known and most visited part of the section is immediately north of the northern termination of Aberystwyth promenade, where the beds at the base of the cliff dip ENE at about 50°. At the top of the cliff some beds dip steeply westwards, and there are conspicuous folds and faults. The turbidites along the shore are mud dominated, with sandstone units 1– 10 cm thick occurring in packages, in which the thicker sandstones are separated by dark mudstones containing several thinner, paler, less prominent sandy horizons (Figure 3.42). The thicker sandstones show grading, parallel lamination and small-scale cross-lamination, and convolute lamination is developed in the upper portions of several of these sandstone beds (Figure 3.43). The bases of many of the sandstone units show well-developed bottom structures, including flute and groove marks (Figure 3.44); the direction of flow indicated by these features is towards the north and NNE. Trace fossils are also commonly preserved as moulds on the lower surfaces of sandstones (Figure 3.45). Crimes and Crossley (1980, 1991) identified the occurrence of more than 25 different types of trace fossil in the Aberytstwyth Grits Group, and McCann (1990) assigned the assemblage to the Graphoglyptid association, which includes the ichnogenera *Gordia, Helminthoida, Helminthopsis, Paleodictyon, Protopaleodictyon* and *Spirophycus*, among others. Body fossils are rare in this part of the section; one specimen of the brachiopod *Eocoelia* has been reported, but graptolites are not known.

To the north of the breakwater similar strata continue, with a prominent sinistral strike-slip fault trending 095° apparent at SN 5820 8273. The beds from here northwards again dip to the east and the strike section shows the lateral continuity of the beds; there is no pinching out or thickness variation in the sandstones. Towards Craigyfulfran (Cormorant Rock, SN 5828 8296), the beds become more complexly folded and faulted. Some of the smaller fold structures do not relate to the larger folds, and have been interpreted as a response to downslope movement of material, occurring after considerable dewatering and diagenesis but before regional tectonic deformation (Fitches *et al.*, 1986; Siveter *et al.*, 1989). At Craigyfulfran there is a transition between turbidites with trace fossils, which indicate oxic bottom conditions, to anoxic turbidites with rare graptolites; pyritized burrows occur in the transition zone (Dobson *et al.*, 1995b). Loydell (1992) recorded that the graptolites found on the eastern face of Craigyfulfran are referable to the *utilis* Sub-biozone, which spans the base of the *turriculatus* Biozone.

From Craigyfulfran to Clarach Bay a steadily descending succession, totalling about 140 m in thickness, is exposed. Dobson *et al.* (1995b) reported that there is a marked disparity between the current directions displayed by the

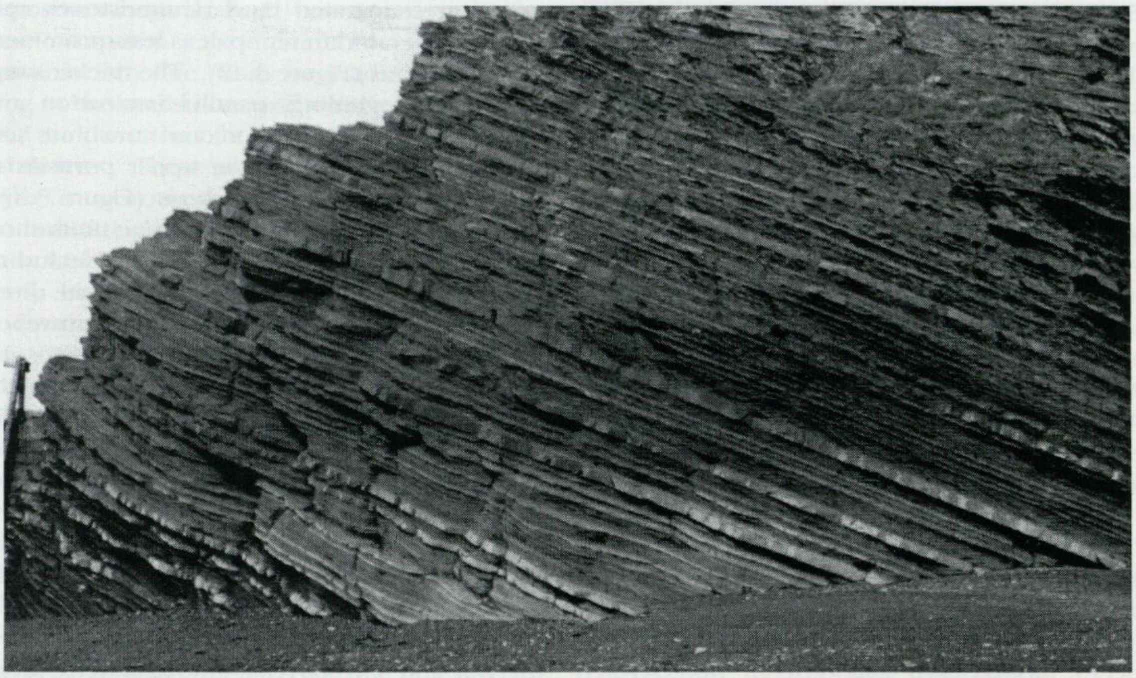

Figure 3.42 Turbidite units of the Aberystwyth Grits Group at the northern end of Aberystwyth promenade. (Photo: R.J. Aldridge.)

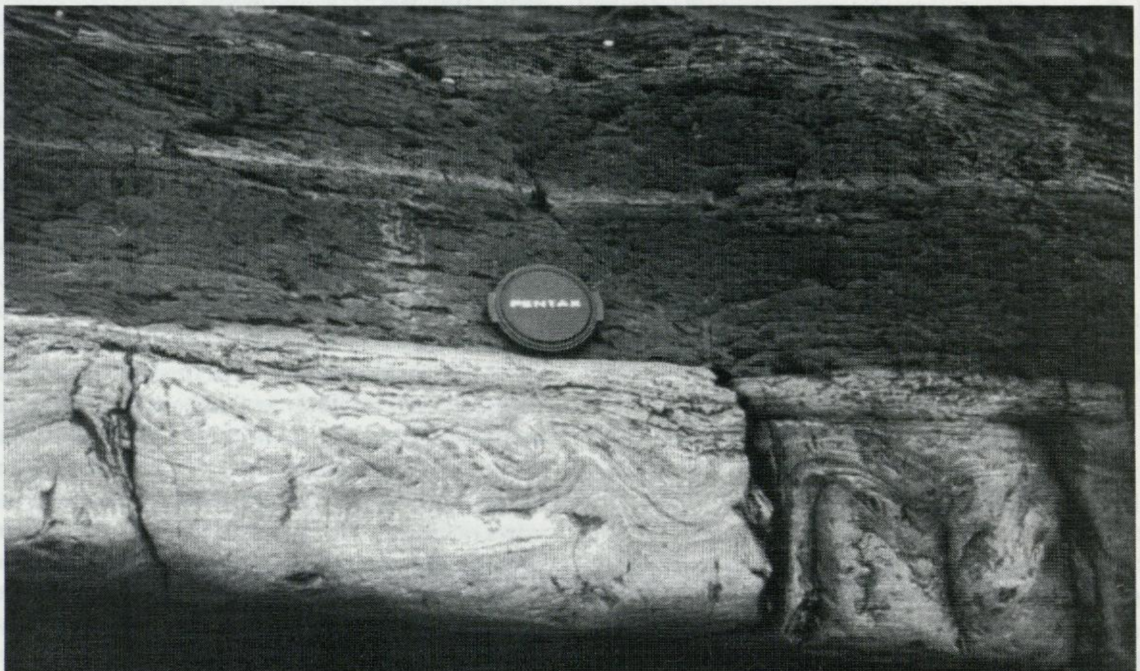

Figure 3.43 Convolute lamination in a sandstone bed, Aberystwyth Grits Group, northern end of Aberystwyth promenade. (Photo: R.J. Aldridge.)

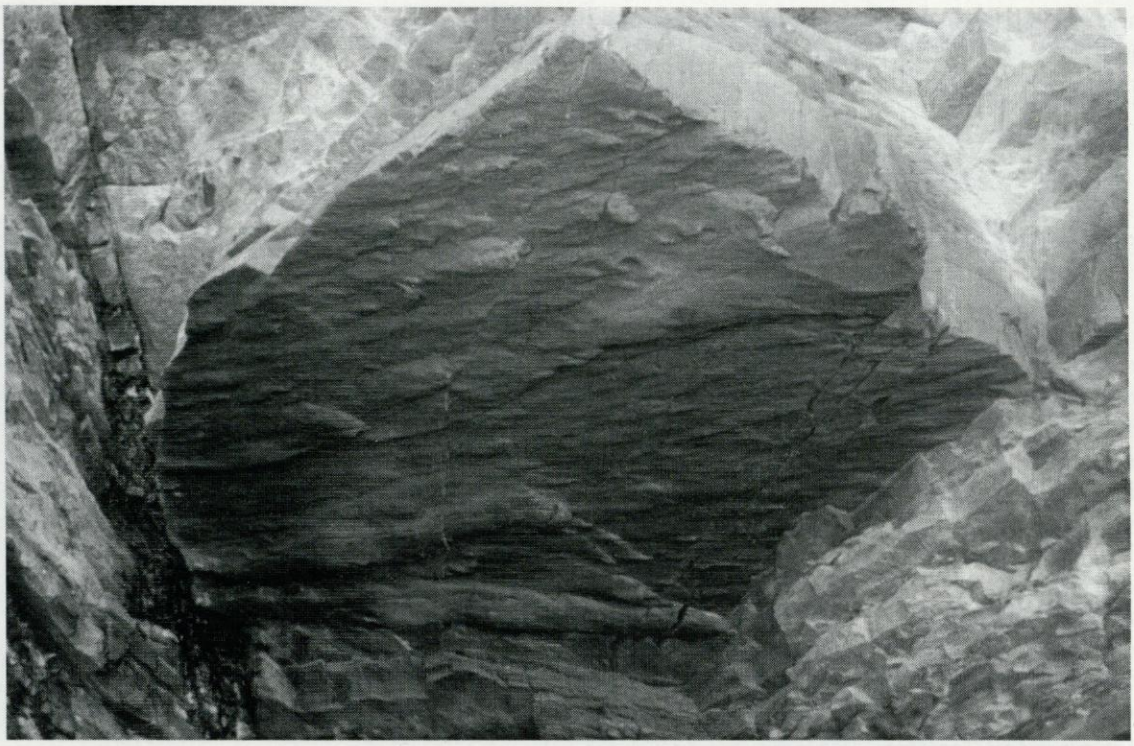

Figure 3.44 Flute marks giving a palaeocurrent direction from the SSW, on the base of a 15 cm-thick sandstone unit, Aberystwyth Grits Group, northern end of Aberystwyth promenade. (Photo: R.J. Aldridge.)

flute marks and the cross-bedding in this part of the succession, with the cross-bedding direction varying considerably. At Clarach Bay the section includes a band of pale volcanic ash, about 2 cm thick.

Interpretation

The Aberystwyth Grits Group in the Craigyfulfran section represents part of the submarine lobe complex that built north-eastwards into the Welsh Basin during latest Aeronian and early Telychian times (see 'Interpretation' of the Aberarth–Morfa site report). In contrast to the sections at Aberarth–Morfa and New Quay (SN 3868 6044) to the south, the turbidite sequences at Craigyfulfran have a low greywacke sand/mud ratio, with siltstones and mudstones strongly dominant. This indicates that these strata were deposited in the more distal parts of the lobe system, consistent with a source to the south or south-west. The orientations of flute marks on the undersides of some sandstone beds confirm a flow from the SSW. The turbidite beds mostly display only the Tcd, Tcde or Tde portions of the typical Bouma Tabcde cycle (Figure 3.46), indicating that the flow was not strong enough to carry the coarser detritus typical of Ta and Tb beds this far across the fan. Although the bases of many of the turbidite units are clearly erosive, there is only occasional evidence of amalgamation of successive sandstone beds into composite units as a result of downcutting; multiple beds, comprising more than two successive sandstones, have not been recorded. The rare dark, graptolitic beds represent the background sedimentation of fine hemipelagic mud, but these layers have been removed by erosion from the tops of many of the turbidite units.

The trace fossil associations displayed on the lower surfaces of many of the sandstones represent burrow systems that were excavated during the quiet periods between flows. At these times, the muds deposited by the preceding flow were colonized by a variety of soft-bodied infaunal organisms, several of which excavated complex tunnel systems (e.g. *Paleodictyon*). These tunnels were exhumed during the erosive episode of the succeeding flow, and preserved by casting

Figure 3.45 Trace fossils on the base of a sandstone unit, Aberystwyth Grits Group, northern end of Aberystwyth promenade. Width of frame, approximately 1 m. (Photo: R.J. Aldridge.)

when the flow waned and sand filled the sea-bed topography. Other trace fossils represent trails of surface-dwelling organisms. According to McCann (1990), this characteristic 'Graphoglyptid association' is confined to sediments deposited as sandstone lobes and in channel-margin and interchannel environments.

A feature of the section, particularly well-displayed in the southern part, is the pattern of prominent Tcde turbidite units, with basal greywackes some 10 cm thick, separated by a number of Tde units with thin, inconspicuous siltstones at the base. This rhythmicity may be due to fluctuating tectonic control or, more likely, to the influence of rises and falls in sea level (e.g. Mutti and Normark, 1987). The maximum input of detritus to the system would be expected during low sea-level stands when rivers and deltas could prograde over the shelf area to unload sediment directly into the deeper marine basin. Another explanation might be that the rhythms reflect a climatic influence, perhaps related to orbitally-controlled variations in insolation.

Conclusions

The cliffs between Aberystwyth and Clarach Bay comprise the type section of the Aberystwyth Grits Group, a classic deposit of interbedded sandstones and muds. These sediments have been interpreted as the products of turbidity flows, which carried vast amounts of detritus into the Welsh Basin from a source to the south-west. As the flows waned, they deposited their sedimentary loads, with coarser sands dominant to the south, nearer the source, and mud dominant in the more distal regions to the north, such as at Craigyfulfran. The turbidite deposits constructed a large, elongate submarine lobe that built north-eastwards out into the basin; the eastern boundary of the turbidite system was controlled by synsedimentary faulting. Areas of the lobe were colonized by soft-bodied marine animals, which have left traces of their activity as surface trails or as burrow systems in the sediments. Rare graptolites occur in the muds deposited in the quieter periods between the turbidity flows, and these have enabled dating of

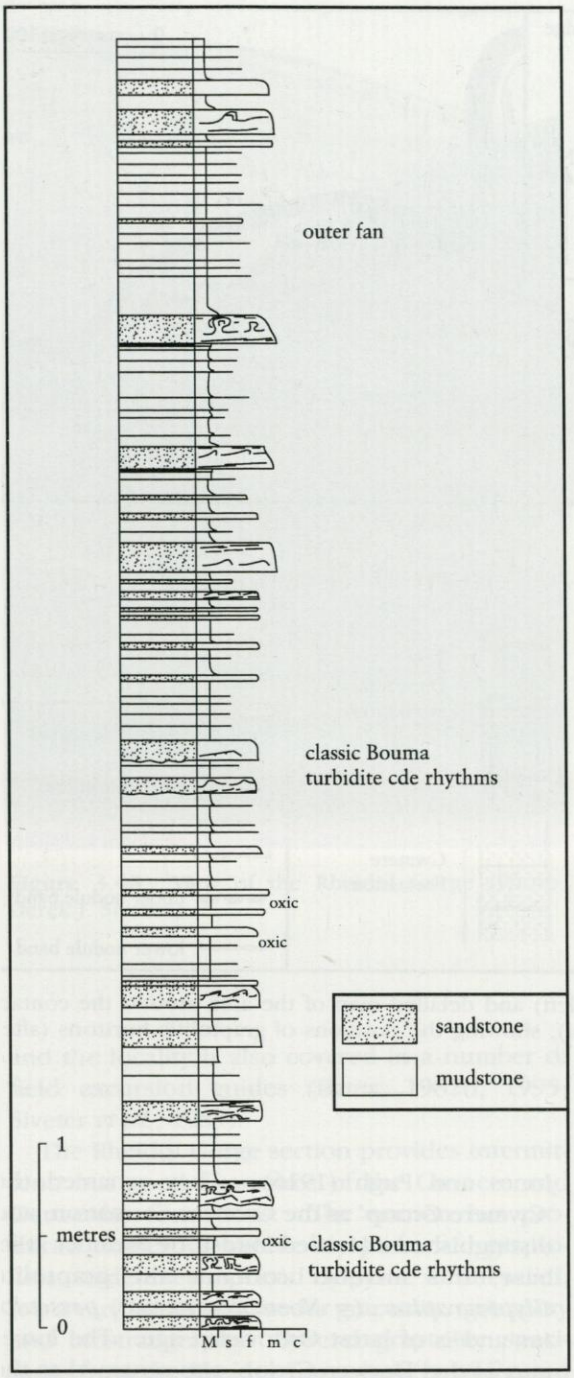

Figure 3.46 Representative sedimentary log of the turbidite Tcde rhythms measured at the headland at the north end of Aberystwyth promenade (after Dobson *et al.*, 1995a).

the strata as late Aeronian to early Telychian in age.

The section at Craigyfulfran has been very widely referred to in the literature, and is one of the most classic turbidite sequences in the world. It is of considerable national and international importance, is widely used as a teaching resource and is frequently visited by overseas scientists. It has major conservational value.

RHEIDOL GORGE (SN 7495 8090–SN 7488 7905)

Introduction

The rocks of the hilly country around Plynlimon in Central Wales, inland from Aberystwyth, were first examined by Sedgwick in 1832 and 1846. From these studies he believed the strata to be below the 'Upper Silurian' and above the 'Bala Limestone', and attempted a broad classification (Sedgwick, 1847). At about the same time, officers of the Geological Survey of England and Wales were producing the first maps of the area, which were published in 1848. These showed the solid rocks as being of Silurian (Lower Llandovery) age. The first full account of the rocks of the area was provided by Keeping (1881), who identified three units, but misinterpreted their superpositional order. This error was detected by Marr (1883) and by Jones (1909), the latter of whom undertook a very detailed and careful study of the strata exposed around Plynlimon and Pont Erwyd, in which he determined the lithostratigraphical succession, investigated the biota and produced a geological map.

The Rheidol Gorge is near the western margin of the area mapped by Jones (1909). The GCR site extends roughly north–south, following the meandering course of Afon Rheidol (Figures 3.47, 3.48); the northern limit is at Ponterwyd and the southern at Parson's Bridge. The strata exposed in and alongside the river span the entire thickness of the 'Pont Erwyd Stage' as defined by Jones (1909). Within this 'stage', Jones recognized three subdivisions, in ascending order the 'Eisteddfa Group', the 'Rheidol Group' and the 'Castell Group'. Graptolites suggested that the 'Eisteddfa Group' could be assigned to the *persculptus* and *acuminatus* biozones, that the 'Rheidol Group' spanned the *atavus* to *communis* biozones, and that the 'Castell Group' represented the *convolutus* and *sedgwickii* biozones. Some of the graptolites from the area were figured by Elles and Wood (1901–18), and Sudbury (1958) later studied the triangulate monograptids from the Rheidol

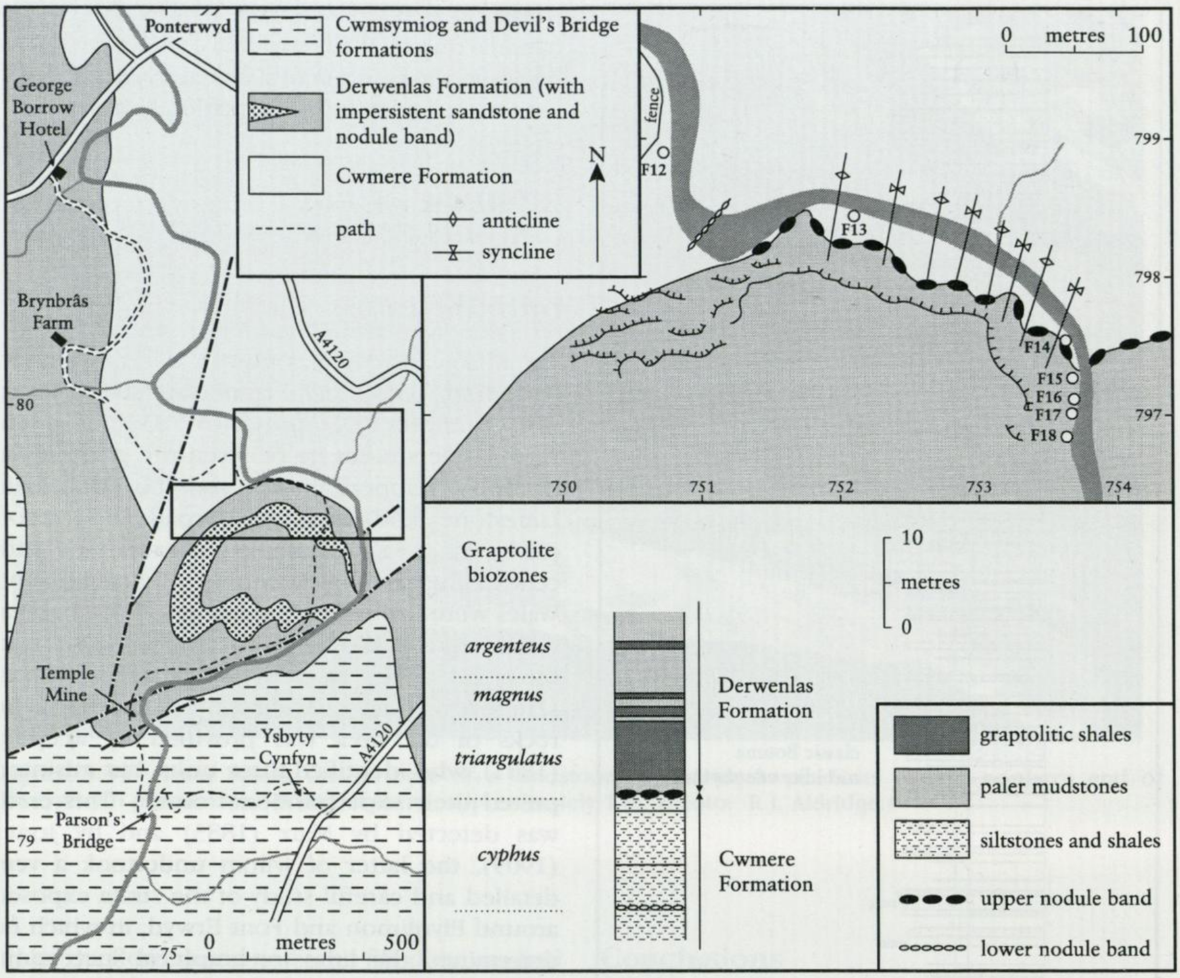

Figure 3.47 Geological map of the Rheidol Gorge (left) and detailed map of the area around the contact between the Cwmere and Derwenlas formations (right), showing the positions of graptolitic horizons (after Siveter *et al.*, 1989).

Gorge; graptolites from this section were also included in the studies of Packham (1962) and Zalasiewicz and Tunnicliff (1994). The lithostratigraphy was extended northwards and modified by Jones and Pugh (1916, 1935a), who subdivided the 'Pont-erwyd Stage' into two, rather than three, units: the 'Cwmere Group', which spanned the *persculptus* to *triangulatus* graptolite biozones, and the 'Derwen Group' which ranged from the *magnus* Biozone to the *halli* Biozone.

The Aberystwyth and Machynlleth areas were remapped by the British Geological Survey between 1965 and 1975, and a 1:50 000 map (solid edition) published in 1984. In the accompanying memoir, Cave and Hains (1986) broadly followed the lithostratigraphy established by Jones and Pugh (1916). They renamed the 'Cwmere Group' as the Cwmere Formation, and distinguished a Mottled Mudstone Member at its base; this member contains the graptolite *Glyptograptus* (= *Normalograptus*?) *persculptus* and is of latest Ordovician age. The lower part of the 'Derwen Group' was renamed as the Derwenlas Formation, with its base revised to include strata referable to the *triangulatus* Biozone. The Cwmere Formation above the Mottled Mudstone Member is, therefore, of Rhuddanian age, and the Derwenlas Formation spans the Aeronian Stage. Cocks *et al.* (1992) gave the thickness of the Cwmere Formation as 70–160 m, and that of the Derwenlas Formation as 20–80 m. Cave and Hains (1986) commented briefly on the exposures in the Rheidol Gorge,

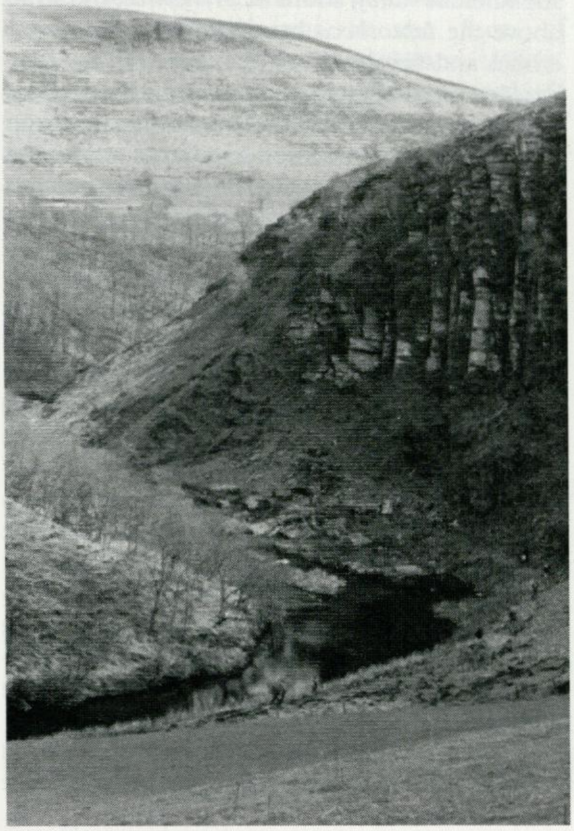

Figure 3.48 View of the Rheidol Gorge (Photo: Derek J. Siveter.)

and the locality is also covered in a number of field excursion guides (Bates, 1982b, 1995; Siveter *et al.*, 1989).

The Rheidol Gorge section provides intermittent, but good exposures of the Cwmere and Derwenlas formations. The section has produced numerous excellently preserved graptolites, sometimes replaced by pyrite in full relief; it is a very important site for graptolite taxonomy and biostratigraphy. Several graptolite specimens from the Rheidol Gorge have been figured in the literature, and it is the type locality for the biozonal species *Atavograptus atavus* (Jones, 1909) and other graptolite taxa including *Monograptus pseudoplanus* Sudbury, 1958, *M. walkerae walkerae* Rickards *et al.*, 1977, *Climacograptus tamariscoides* Packham, 1962, *C. alternis* Packham, 1962, *Glyptograptus enodis* Packham, 1962, *Metaclimacograptus slalom* Zalasiewicz, 1996, and *Neodiplograptus peggyae* Cullum and Loydell, 1997.

Description

The fullest descripton of the strata in the Rheidol Gorge section was given by Jones (1909, pp. 483–92, 502–5). He recorded that structural measurements of the strata in and around the gorge revealed a faulted anticline, to the east of which is a shallow syncline. The lowest beds recognized by Jones (1909) are exposed on the east side of the river some 500 m SSE of the bridge at Ponterwyd; here hard sandy flags and shales have yielded the graptolites *Parakidograptus acuminatus* and *Normalograptus scalaris normalis*. These strata belong to the Cwmere Formation, presumably only a little above the top of the Mottled Mudstone Member. On the western bank a fault brings down higher flags and shales, within which three bands of coarse sandstone are prominent, the highest and thickest is about 5 m thick. These beds are probably about 40 m above the top of the Mottled Mudstone Member, and are referable to the upper part of the *acuminatus* Biozone (Cave and Hains, 1986).

The succeeding strata are exposed between the sandstone outcrop and the next bend in the Rheidol, where a small tributary enters from the west; these again comprise flags and shales, with the hemipelagic shale component increasing upwards. Jones (1909) recorded *N. scalaris normalis* as almost the only fossil present in the lower part of this exposure, but in the upper, shalier, units it is joined by *Atavograptus atavus*, the diagnostic species of the *atavus* Biozone. At the bend, the rocks are sharply folded, and here Jones (1909, p. 485, his locality F.11; SN 7490 8005) reported the occurrence of *A. atavus, N. scalaris normalis, Dimorphograptus erectus* and *Rhaphidograptus toernquisti*.

The succession can be picked up again on the eastern limb of the anticline at Jones' locality F.12 (SN 7510 7988). A change in lithology is marked by a bed of small calcareous nodules, which is followed by somewhat harder and sandier beds. The characteristic graptolite is *Lagarograptus acinaces* (= *Monograptus rheidolensis* of Jones), with *R. toernquisti, Orthograptus mutabilis, Glyptograptus tamariscus* and *N. scalaris normalis* also common. A higher band of larger calcareous nodules occurs at the bend, where the river turns to the east. For the next 200 m the shales are folded and faulted, and Jones (1909, p. 486) determined that only about 13 m of strata were represented; the top of this unit is marked by another band of large calcareous nodules (individual nodules are up to 30 cm across). Some of the bedding planes in this interval are covered with large graptolites, principally specimens of *A. atavus*. Exposures in the leat (Jones' localities F. 13 and F. 14) also yield abundant and diverse graptolites, especially horizons 8 m and 1.8 m below the upper nodule bed. Many of the specimens are exquisitely preserved in three dimensions in pyrite, with the fauna in the upper horizon containing *O. mutabilis, G. tamariscus, R. toernquisti, A. atavus* and *Coronograptus cyphus*, indicative of the *cyphus* Biozone.

The upper bed of calcareous nodules marks the boundary between the Cwmere and Derwenlas formations, approximately coinciding with a change from dark grey, thinly bedded, graptolitic mudstones to paler, bluish-grey, thickly bedded, poorly fossiliferous mudstones within which dark-grey graptolitic bands occur. Jones (1909) identified four particular graptolite bands (F.15–F.18) in the lower part of the Derwenlas Formation around SN 7538 7970, spanning the *triangulatus*, *magnus* and *argenteus (leptotheca)* biozones. In the lowest band (F.15), 1.9 m above the base of the formation, *Monograptus revolutus* and *R. toernquisti* dominate, with *A. atavus, Pristiograptus concinnus* and *Monograptus triangulatus* common; bivalves, orthid brachiopods and fragmentary orthocones also occur. The second band (F.16), 9.1 m above the base of the formation also has common *R. toernquisti, M. communis, P. concinnus* and *M. triangulatus*, but *Orthograptus insectiformis* and species of *Rastrites* are also characteristic. A little higher, at 10 m above the base, the third band (F.17) is distinguished by abundant *Diplograptus magnus*, which first appears at this level; rastritids and several monograptid species are also common. The highest graptolite band (F.18), 17 m above the base, was designated the *leptotheca* band by Jones (1909, p. 489), reflecting the abundance of *Pribylograptus leptotheca*; other common species include *Monograptus* cf. *argenteus, Monograptus* cf. *millipeda* and *Pseudoclimacograptus (Metaclimacograptus) hughesi*. This band can be widely traced throughout the area, and was used by Jones (1909) to delimit the top of his 'Rheidol Group'.

The rocks of Jones' 'Castell Group' are now incorporated in the Derwenlas Formation. In the Rheidol valley, south of Bryncwith, the strata above the *leptotheca* band comprise pale mudstones and flags, which are exposed in the inaccessible walls of the gorge. Intermittent sections are also available in an old leat above the gorge, where the pale mudstones contain numerous graptolitic bands, in which *Monograptus convolutus* and *'Monograptus' lobiferus* are characteristic. The stretch of the river from SN 7540 7957 to SN 7488 7935 follows the line of the mineralized Castell Fault, but the course turns southwards again some 300 m north of Parson's Bridge. The strata here are cleaved sandy mudstones with few fossils, but Jones (1909, p. 503) found one locality 60 m south of the bend (F.40) that again yielded *M. convolutus* and *'M.' lobiferus,* showing the presence of the *convolutus* Biozone. Nearby, above the eastern bank of the river (F.41) a graptolite fauna with *Monograptus sedgwickii* indicates the latest Aeronian *sedgwickii* Biozone. Jones (1909) suggested that the top of the *sedgwickii* Biozone must lie somewhere in the neighbourhood of the Parson's Bridge.

The GCR site area also includes the ravine at the north end of the locality, below the George Borrow Hotel (SN 7474 8055). This is a glacial diversion channel (Challinor, 1933), with precipitous walls, within which Jones (1909) identified the calcareous nodule band that defines the base of the Derwenlas Formation, together with good specimens of *L. acinaces* in beds some distance below.

Interpretation

The sequence of strata in the Plynlimon and Ponterwyd areas is representative of deposition in the deeper, quieter parts of the Welsh Basin during the earliest Silurian. The Mottled Mudstone Member shows that, during the latest Ordovician, bottom waters and near-surface sediments were oxic, allowing colonization by a burrowing infauna and the bioturbation that produced the mottled appearance. Above this member, the sediments of the Cwmere Formation show that sea-floor conditions abruptly became dominantly anoxic, perhaps reflecting the onset of stagnant, warm conditions of the Spirodden Secundo Episode (Aldridge *et al.*, 1993a). Some sediments were brought into this part of the basin by extremely distal, low-density turbidity currents that introduced mainly mud grade detritus, but the dominant sedimentation was in the form of hemipelagic mud (Cave and Hains, 1986). Occasionally, turbidity currents introduced silt or fine sand into the district, and this process appears to have been dominant for a short interval represented in the middle part of the Cwmere Formation. The source of the turbidity currents appears to have been from the east or south-east, as indicated by rare bottom structures and by the thinning of the turbidite units northwestwards (Cave and Hains, 1986).

The Derwenlas Formation records an increase in turbiditic sedimentation and a change to more oxygenated bottom conditions (Cave, 1979). The sequence has been interpreted as an outer fan, or a sedimentary lobe, which was prograding into the basin (Cave and Hains, 1986). Quieter periods were marked by a return to hemipelagic sedimentation with the incorporation of graptolitic faunas.

Conclusions

This is an important, well-exposed site that displays typical basinal sediments of the quieter parts of the Welsh Basin during the earliest Silurian. Good sections through the Cwmere and Derwenlas formations are available, and yield rich and diverse graptolite faunas representing all the biozones of the Rhuddanian and Aeronian stages. The graptolites are often exquisitely preserved, with three-dimensional details evident through replacement by pyrite. This is a very significant locality for studies of graptolite morphology, taxonomy and biostratigraphy. It has featured widely in the graptolite literature, and will undoubtedly be incorporated in any future revisions of Rhuddanian and Aeronian graptolite faunas. The section is frequently visited by national and international specialists and is of high conservation value.

YEWDALE BECK (SD 3073 9858–SD 3073 9850)

Introduction

The Llandovery rocks of the Lake District are exposed in a narrow ENE–WSW strip of outcrop extending from Broughton Mills in the west, across the heads of Coniston Water and Lake Windermere to Browgill, near Shap, in the east (Figure 3.49). The term 'Stockdale Shales' was first applied to these strata by Aveline and Hughes (1872), who referred them to the upper Silurian. Some debate followed, in which several authors (e.g. Nicholson, 1874; Hicks, 1876; Lapworth, 1876b) argued that these strata were of Llandovery, not upper Silurian, age. Marr and Nicholson (1888) used the terms Skelgill Beds and Browgill Beds for the two subdivisions of the Stockdale Shales, confirmed that they were conformable on the underlying Ashgill shales, and affirmed their Llandovery age. They also introduced a biozonation using graptolites and trilobites. This biozonation, as applied to the Lake District and the Howgill Fells, was refined by Rickards (1970a) and Hutt (1974), who based their biozones entirely on graptolites. The stratigraphy and palaeogeography of the Llandovery strata in the Lake District have been summarized by Rickards (1978).

The lithostratigraphy of the Windermere Supergroup (Late Ordovician to late Silurian) of northern England has been formalized by Kneller *et al.* (1994), who defined a Stockdale Group divided into the Skelgill and Browgill formations. They also identified a Spengill Member at the base of the Skelgill Formation, equivalent to the 'Basal Beds' of previous authors (Marr and Nicholson, 1888; Hutt, 1974; Rickards, 1978). This member comprises pale mudstones mainly referable to the *persculptus* Biozone (latest Ordovician), but locally extending up to the lower *atavus* Biozone.

Four GCR sites in the Lake District together form a network that provides a coverage of the lithostratigraphical and biostratigraphical units in the area and illustrates regional variations. These localities are at Yewdale Beck, Skelghyll Beck, Brow Gill Beck, and Spengill. The Ordovician– Silurian boundary can only be recognized unequivocally, on the basis of graptolites, in the western Lake District, where a particularly well-exposed continuous section is displayed in Yewdale Beck (Rickards, 1988; Figure 3.50). This is, therefore, an important site for regional and national Lower Palaeozoic lithostratigraphy and biostratigraphy. It has yielded rich graptolite faunas and is the type locality for a number of taxa, including *Pristiograptus fragilis pristinus* Hutt, 1975, *Atavograptus ceryx* (Rickards and Hutt in Rickards, 1970a), *Coronograptus cirrus* Hutt, 1975, *Monograptus capis* Hutt, 1975, and *Mongraptus cerastus* Hutt, 1975.

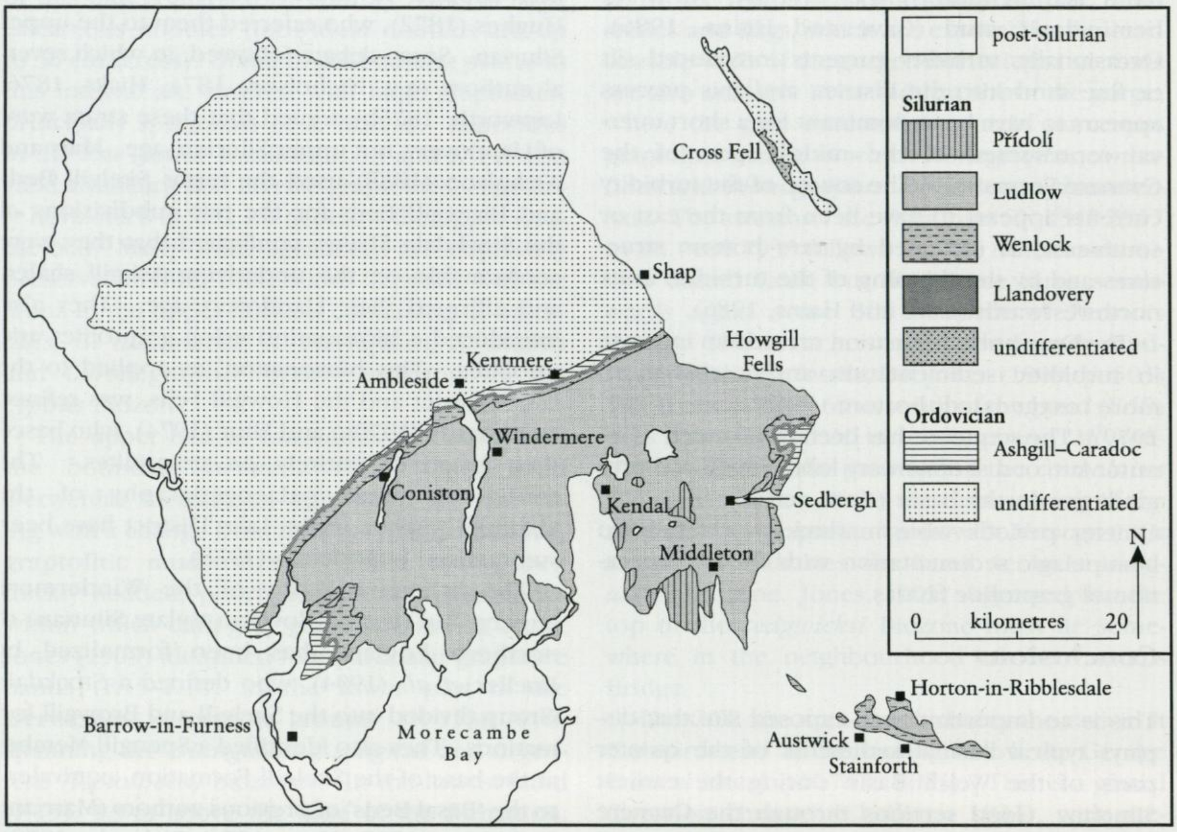

Figure 3.49 Outline geological map of the Lake District and Howgill Fells (modified after Rickards, 1989a).

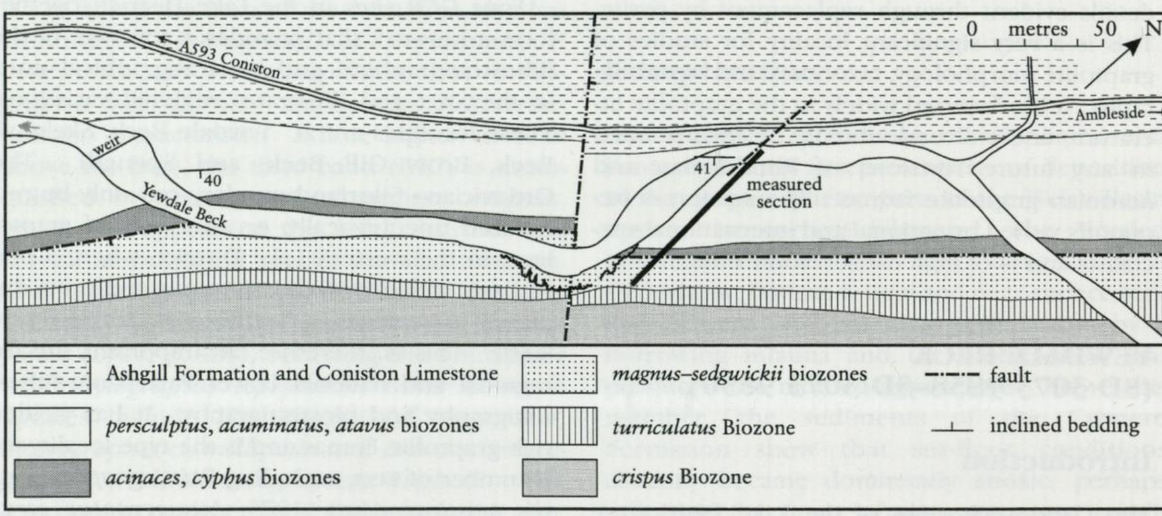

Figure 3.50 Geological sketch-map of Yewdale Beck showing the distribution of graptolite biozones (after Hutt, 1974).

Description

A measured section across the boundary in Yewdale Beck was illustrated by Rickards (1988, fig. 4). At the base are 7 m of Ashgill Formation, comprising grey shales and siltstones with calcareous nodules and containing a fauna of abundant brachiopods and some trilobites; these are of Hirnantian (late Ashgill, Ordovician) age. Succeeding these are 0.3 m of blue-grey shales with a good graptolite fauna including *Glyptograptus persculptus* and other indicators of the *persculptus* Biozone; shelly fossils, including abundant specimens of the brachiopod *Kayserella* sp. also occur (Hutt, 1974). These shales mark the base of the Skelgill Formation, and Hutt (1974) presented a detailed measured section through the exposed 31.5 m of the formation from the base of the *persculptus* Biozone (Figure 3.51). *Parakidograptus acuminatus* first occurs at 0.3 m, together with other typical members of the *acuminatus* Biozone fauna, and marks the base of the Silurian System. Graptolites are found throughout the remainder of the section, with the greatest abundance in the pyritous, blackest mudstones of the *acuminatus* and *atavus* biozones. The *triangulatus* Biozone is cut out by a strike fault, but otherwise the section is complete up to the basal *convolutus* Biozone, which is exposed on the right bank of the stream.

Interpretation

The Lake District Basin was developed in the late Ordovician and Silurian on the subsiding remnants of an Ordovician volcanic arc terrane (see Chapter 1). The Rhuddanian and Aeronian black shales of the basin reflect a deepening environment following the glaciogenic sea-level lowering of the late Ordovician. Rickards (1978), following Hutt (1974), presented a general interpretation of the depositional setting of the basal Silurian strata in the Lake District, envisaging a westward or north-westward facing fault scarp against which the black offshore shales of the Yewdale Beck area were deposited (Figure 3.52). Regional evidence suggests that the scarp feature was buried by the accumulating black shale deposits by upper *atavus* Biozone times. The blackness of the shales and the richness of their graptolite faunas suggests an anaerobic environment pertained on the sea bed in this western area throughout the

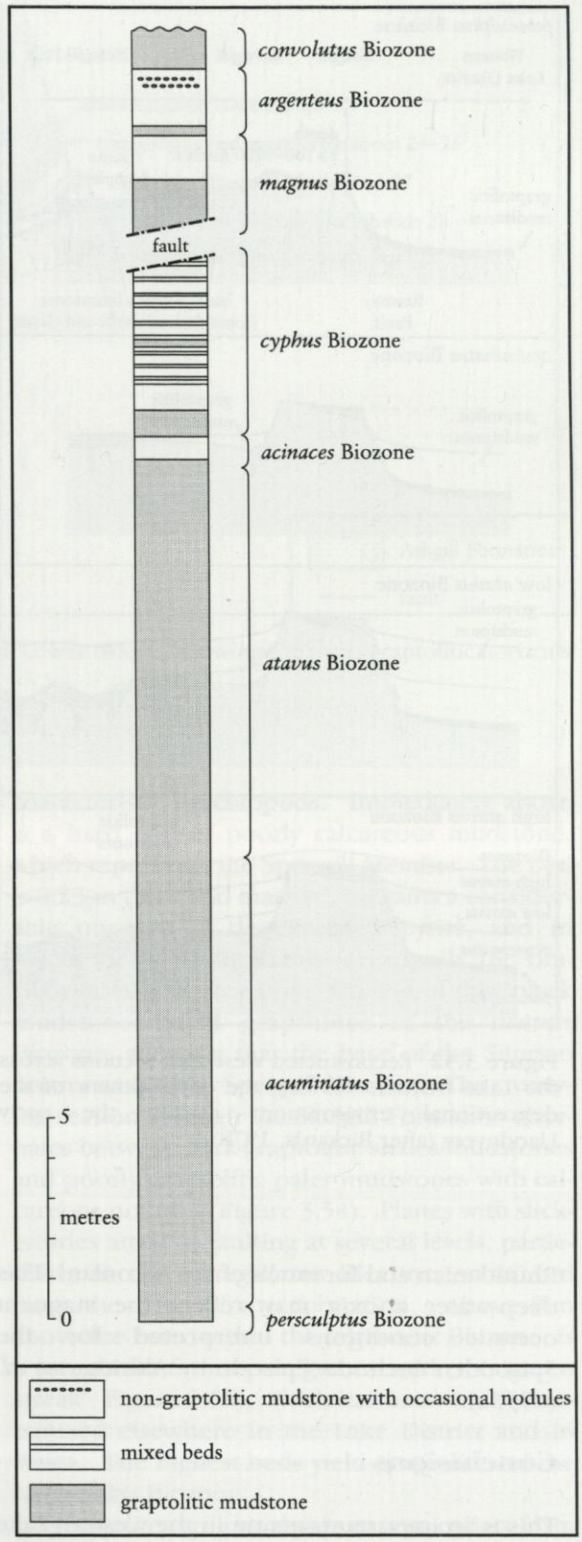

Figure 3.51 Measured sedimentary succession through the Skelgill Formation in Yewdale Beck, showing the graptolite biozonation (modified after Hutt, 1974).

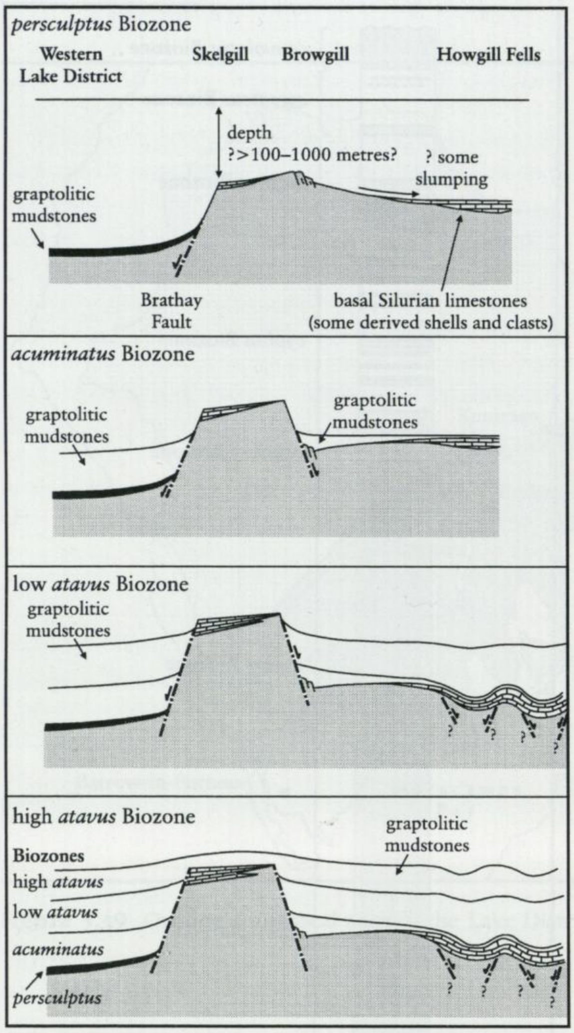

Figure 3.52 Reconstucted west–east sections across the Lake District, showing the development of the depositional environment during the early Llandovery (after Rickards, 1978).

Rhuddanian and for much of the Aeronian. This deep-water anoxia may reflect the stagnant oceanic conditions interpreted for the Spirodden Secundo Episode by Aldridge *et al.* (1993a).

Conclusions

This is an important section in the western Lake District, straddling the Ordovician–Silurian boundary. Biozonal graptolite faunas of the latest Ordovician *persculptus* Biozone and the earliest Silurian *acuminatus* Biozone allow precise recognition of the position of the boundary. A nearly complete sequence through much of the Skelgill Formation, rich in graptolites throughout, is well exposed and provides a representative sequence through the local Rhuddanian–Aeronian black shales. The sections in this area can be contrasted with those farther east in the Lake District to develop a model of the fault-controlled topography of the sea bed during the early Silurian eustatic deepening.

SKELGHYLL BECK (NY 3964 0320–NY 3935 0293)

Introduction

The stream of 'Skelgill Beck' was selected by Marr and Nicholson (1888) as the type section of their 'Skelgill stage', the lower unit of the 'Stockdale-Shale series'. These beds had previously been referred to as the 'Graptolitic Mudstones', following Aveline and Hughes (1872), but Marr and Nicholson (1888, p. 659) considered that this term did not distinguish them sufficiently from other graptolitic beds in the district. More recently, Kneller *et al.* (1994) have formalized this lithostratigraphical unit as the Skelgill Formation, the lower formation of the Stockdale Group.

South-west of the Brathay Fault, for example in the area around Yewdale Beck, the Skelgill Formation is 40 m thick, but to the east of the fault it reaches only 28 m (Hutt, 1974). In the latter region, the lower part of the formation, spanning the *persculptus, acuminatus* and most of the *atavus* biozones, is represented by a 127–178 mm bed of pale calcareous mudstone, the Spengill Member of Scott and Kneller (1990). A particularly well-exposed continuous section through the Skelgill Formation is displayed in Skelghyll Beck at Skelghyll Lower Bridge (NY 3964 0320), where a footpath crosses the stream (Figure 3.53). Here all the graptolite biozones from *atavus* to *sedgwickii* were recognized by Hutt (1974), who also provided a measured log of the section (Figure 3.54). The formation, therefore, spans the Rhuddanian and Aeronian stages.

The GCR site of Skelghyll Beck follows the stream course south-westwards from Skelghyll Upper Bridge, which carries the Hundreds Road from Troutbeck, past the Lower Bridge to the point where the ground becomes marshy and exposure is lost. The stream flows approximately parallel to the strike of the beds, so that the

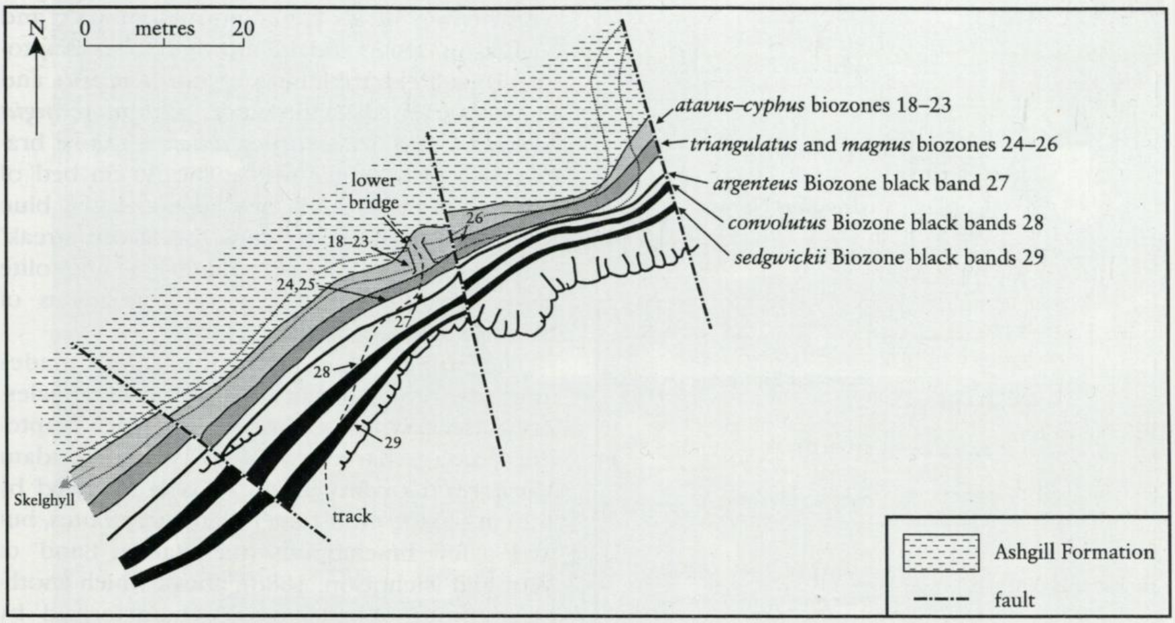

Figure 3.53 Geological map of the area around Skelghyll Lower Bridge, showing the main graptolitic horizons within the Skelgill Formation (after Hutt, 1974).

various horizons in the Skelgill Formation are repeatedly exposed in the banks. This site is of importance as the type locality of the Skelgill Formation and for its extensive graptolite fauna.

The Skelghyll section is the type locality for a number of fossil taxa, including the trilobites *Acernaspis glabra* (Marr and Nicholson, 1888), *Youngia moroides* (Marr and Nicholson, 1888), *Scotoharpes judex* (Marr and Nicholson, 1888) and *Raphiophorus aloniensis* (Marr and Nicholson, 1888) (see Curtis and Lane, 1997–8), the brachiopod *Plectatrypa flexuosa* (Marr and Nicholson, 1888) and the graptolites *Glyptograptus sinuatus sinuatus* (Nicholson, 1869), *Diplograptus diminutus* Elles and Wood, 1907, and *Monograptus argenteus* (Nicholson, 1869).

Description

A very full description of the strata exposed in Skelghyll Beck was provided by Marr and Nicholson (1888), and a long list of graptolite localities and horizons was given by Hutt (1974, localities 18–52; see also Figure 3.54). The cliff on the left bank at the Lower Bridge exhibits the best continuous section (Figure 3.55), and was highlighted by Marr and Nicholson and by Hutt. At this point, the stream flows over the highest beds of the Ashgill Formation, which contains characteristic brachiopods. Immediately above is a hard bed of poorly calcareous mudstone, which represents the Spengill Member. The bed is 0.23 m thick and massive, contains a considerable quantity of disseminated pyrite, and in places yields shelly fossils, principally the brachiopod *Atrypa flexuosa*. On top of this, black mudstones yield graptolites of the *atavus* Biozone, showing that the base of the Silurian occurs within the Spengill Member. The overlying section through the Skelgill Formation alternates between dark graptolitic shales/mudstones and poorly graptolitic paler mudstones with calcareous nodules (Figure 3.54). Planes with slickensides attest to faulting at several levels, particularly in the *triangulatus* Biozone, some 4 m from the base of the formation. About 8 m above the base, within the *argenteus* Biozone, is a prominent 6 mm pale-green band (the 'green streak'; Figure 3.56), which has been widely recognized elsewhere in the Lake District and in Wales. The highest beds yield graptolites of the *sedgwickii* Biozone.

Graptolites are not always easy to collect from the cliff section itself, but excellently preserved specimens occur in other exposures in the stream banks. The faunas are diverse, with the lowest beds particularly characterized by swarms of *Dimorphograptus confertus confertus* and

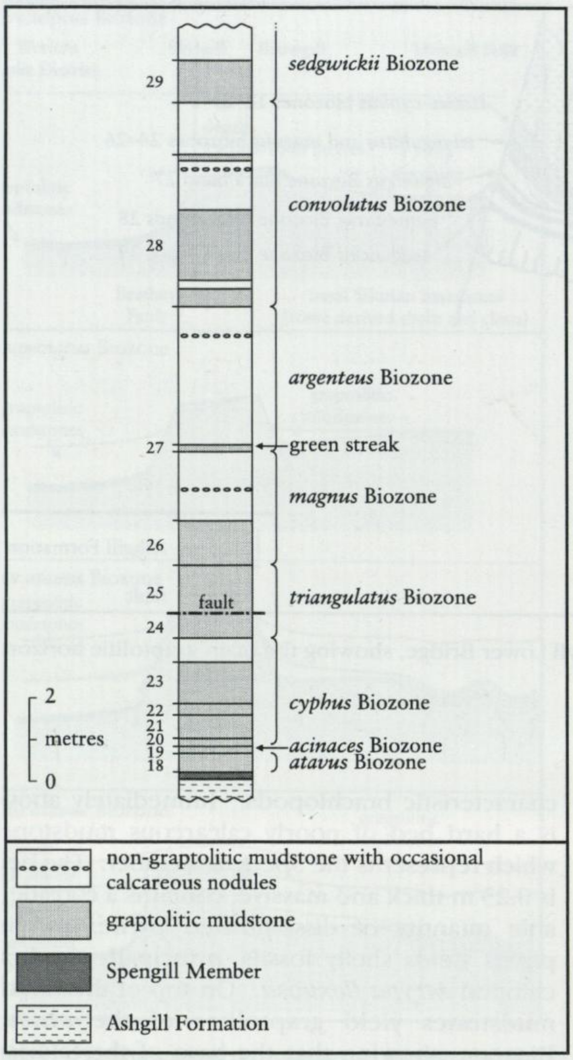

Figure 3.54 Sedimentary log of the succession of the Skelgill Formation at Skelghyll Lower Bridge, showing the graptolite biozonation and the positions of the main graptolitic horizons (after Hutt, 1974).

abundant monograptids of the *Monograptus revolutus–M. austerus* group (Marr and Nicholson, 1888). The *triangulatus* Biozone is marked by numerous specimens of *M. triangulatus fimbriatus*, with *M. triangulatus triangulatus* largely absent; this suggests that only the upper part of the biozone is represented by graptolitic beds, with the lower part represented by pale beds succeeding the strata of the *cyphus* Biozone (Hutt, 1974).

The middle part of the Skelgill Formation is almost continuously exposed between the two bridges. These beds comprise blue mudstones with nodule bands (A*b*2 and A*b*4 of Marr and Nicholson, 1888) and are mostly poor in graptolites, but yield triblobites (*?Johntempleia* and *Eolenaspis* in A*b*2, *Acernaspis glabra, Youngia moroides* and *Scotoharpes judex* in A*b*4), brachiopods and orthocones. The 30 cm bed of black mudstone (A*b*3) that separates the blue mudstone horizons contains the 'green streak' and has yielded a very rich and diverse graptolite fauna, including well-preserved specimens of *Monograptus argenteus*.

The upper blue mudstone (A*b*4) grades upwards into a unit of finely laminated shales, 2.5 m thick, which again contains a rich graptolite fauna, characterized by very abundant *Monograptus convolutus*. This is followed by 1.25 m of blue mudstone lacking graptolites, but with a few brachiopods (the 'Barren Band' of Marr and Nicholson, 1888), above which another graptolite band occurs, characterized by numerous specimens of *Campograptus clingani*. The succeeding blue mudstones contain a

Figure 3.55 The Lower Bridge section, Skelghyll Beck. (Photo: R.B. Rickards.)

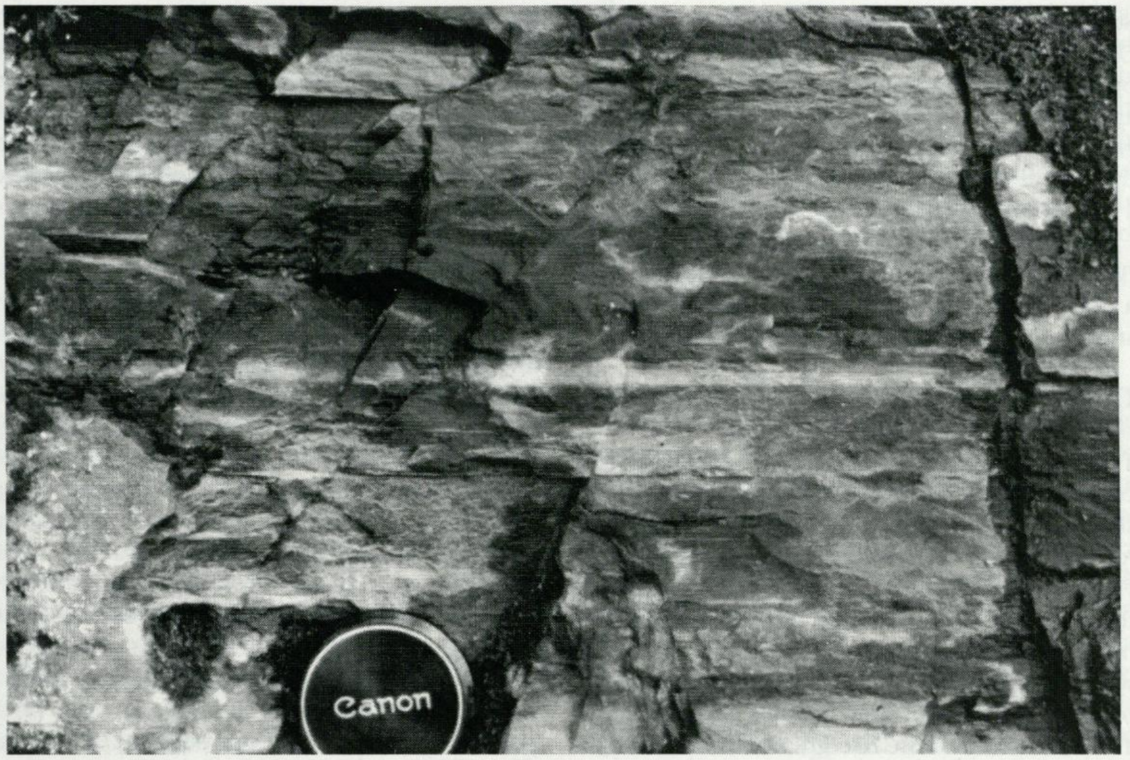

Figure 3.56 The 'green streak' within the *argenteus* Biozone, Lower Bridge section, Skelghyll Beck. (Photo: R.B. Rickards.)

variety of trilobites, among which *Raphiophorus aloniensis* is particularly characteristic, and these are overlain by 1 m of predominantly black mudstones crowded with graptolites, including abundant *Stimulograptus sedgwickii* and *Lagarograptus tenuis*. Above these are the uppermost beds of the Skelgill Formation, comprising poorly fossiliferous blue mudstones some 3 m thick. Pale-green shales of the lowermost Browgill Formation can be found in the moorland by the Lower Bridge, but the actual junction is not evident at this point; elsewhere in the gill the junction can be seen to be abrupt (Marr and Nicholson, 1888).

Interpretation

The Lake District Basin was situated on the northern part of Avalonia, where it succeeded the mid-Ordovician development of an island arc system (see Chapter 1). The Skelghyll section is situated immediately east of the Brathay Fault, and was interpreted as occupying a relatively shallow-water position on the footwall block of the fault (Hutt, 1974; Rickards, 1978; Figure 3.52). This resulted in condensed deposition in the latest Ordovician and earliest Silurian, with the 0.23 m of the Spengill Member equivalent to 16 m of black shales to the west, for example at Yewdale Beck. Although very thin, and possibly containing non-sequences, there is no direct evidence of the development of a hardground within the Spengill Member (Rickards, 1988). By the time of deposition of shales belonging to the high *atavus* Biozone, the block had become swamped by sediment, and the succeeding succession is more comparable with that to the west, although sedimentation rates throughout deposition of the Skelgill Formation remained lower.

The alternation between graptolitic black shales and paler graptolite-poor mudstones reflects changing bottom conditions, from anaerobic to aerobic. This variation may be related to influxes of carbonaceous matter, perhaps algal (Rickards, 1978), or may have been influenced by sea-level or climatic fluctuations. The patterns seen in Skelghyll are maintained coevally throughout the Lake District Basin, and can also be identified in Wales and in the

Southern Uplands of Scotland (Rickards, 1978). One band, the 'green streak', is also widely recognized in the Lake District and Wales; it is apparently not a bentonite, but has the same geochemistry as the black shales, simply lacking the pyrite and carbonaceous matter (Rickards, 1964; Spencer, 1966).

Together with the GCR sites in Yewdale Beck, Brow Gill Beck and Spen Gill, this site provides a representative coverage of the Llandovery stratigraphy of the English Lake District.

Conclusions

The stream banks of Skelghyll Beck display a continuous, well-exposed section through black shales and pale mudstones of Rhuddanian and Aeronian age. These are referred to the Skelgill Formation, for which this is the type locality. At the base a thin, condensed, hard calcareous mudstone represents the Spengill Member, which can be contrasted with coeval black graptolitic shales to the west, around Yewdale Beck. The remainder of the Skelgill Formation is highly fossiliferous, with many black shale horizons providing very rich and diverse graptolite faunas. The paler mudstones yield shelly fossils, including trilobites, and the section is the type locality for several important graptolite and trilobite species. The section is, therefore, of primary importance for local lithostratigraphy and for national and international biostratigraphy.

BROW GILL BECK (NY 4982 0590–NY 4916 0540)

Introduction

The small stream of Brow Gill runs into Stockdale Beck near Stockdale Farm, some 6 km north of Kendal. The sections exposed in the two streams extend for 800 m north-east of Stockdale and include the type locality for the Browgill Formation, the upper division of the Stockdale Group. The term 'Browgill Shales' was introduced for this unit by Marr and Nicholson (1888) to replace the earlier names of 'Pale Slates' (Aveline and Hughes, 1872) and 'Knock Beds' (Nicholson and Lapworth, 1875). Cocks *et al.* (1992) gave a thickness of 40 m for the Browgill Formation.

This locality provides an almost complete section through the entire Stockdale Group and into the overlying Brathay Formation. The Browgill Formation is particularly well exposed in Stockdale Beck, with complementary exposures available in Brow Gill Beck. The site has provided important graptolite faunas, especially from the *turriculatus* and *crispus* biozones, and is the type locality of the graptolite *Pseudoretiolites perlatus perlatus* (Nicholson, 1868).

Description

A full description of the rocks in Brow Gill Beck and Stockdale Beck was provided by Marr and Nicholson (1888). The course of Brow Gill approximately parallels the strike of the beds, with the south-east (left) bank formed by steep cliffs. In the lower part of the cliffs the Skelgill Formation is exposed, with the upper part formed by the Browgill Formation; a representative section can be seen in a cleft in the cliff at NY 4965 0580 at a point termed 'The Rake' by Marr and Nicholson (1888, fig. 2). Here, a strike fault occurs between the lower and middle parts of the Skelgill Formation, cutting out some of the beds. At the base of the section, the Ashgill Formation is succeeded by at least 1 m of pale shales yielding an *acuminatus* Biozone graptolite fauna, so there may be a non-sequence at the level of the *persculptus* Biozone (Rickards, 1978). At places in the stream, however, a weathered rottenstone 0.05 m thick occurs below the *acuminatus* Biozone and may be the lithological and stratigraphical equivalent of the Spengill Member (Rickards, 1988). Above this at The Rake, the Skelgill Formation is disturbed by the faulting, but Hutt (1974) recorded graptolitic black mudstone horizons representing the *magnus* and *convolutus* biozones. The paler, occasionally calcareous, layers yield a variety of trilobites and brachiopods, and can be matched with similar bands in the Skelghyll Beck section (Marr and Nicholson, 1888).

The highest beds of the Skelgill Formation at The Rake comprise 3 m of blue mudstones, from which fossils have not been recorded. These are succeeded by pale-green laminated shales of the lower Browgill Formation. Marr and Nicholson (1888) reported a band of black mudstone crowded with specimens of *Spirograptus turriculatus* 6.5 m above the base of the formation, and Hutt (1974) found three 50 mm black layers with graptolites indicating the *maximus* Subbiozone of the *turriculatus* Biozone at a similar level. Some 6 m higher, graptolitic layers become more frequent, and contain a diverse fauna with *Monograptus crispus, Streptograptus exiguus* and *Retiolites geinitzianus* abundant. These are referable to the *crispus* Biozone. At the top of The Rake, 2 m of unfossiliferous pale calcareous shales mark the bottom of the upper part of the Browgill Formation (Marr and Nicholson, 1888).

A complete section through the Browgill Formation is available in Stockdale Beck, north of the farm (Figure 3.57). Here, most of the Skelgill Formation is cut out by a strike fault, and predominantly black beds with a *sedgwickii* Biozone fauna are juxtaposed with the Ashgill Formation. The lower Browgill Beds compare with those at The Rake, with the three *turriculatus* Biozone bands identifiable and at least 23 graptolitic bands of the *crispus* Biozone (Hutt, 1974; Rickards, 1989a). Above the last graptolitic band are about 6 m of pale, non-graptolitic mudstones, followed by a prominent red mudstone horizon containing abundant calcareous nodules. A conodont sample from the nodular material has yielded a small number of blackened fragments of *Dapsilodus* sp. and *Decoriconus* sp. (Wang and Aldridge, 1997). The uppermost 4 m of the Browgill Formation comprise pale unfossiliferous mudstones, with calcareous nodules or patches developed towards the base. These were termed the 'Grey Beds' by Rickards (1978) and have been assigned to the Far House Member by Kneller *et al.* (1994). The junction with the flags of the overlying Brathay Formation approximately coincides with the Llandovery–Wenlock boundary, and is fairly sharp.

Interpretation

Brow Gill Beck is situated in the eastern part of the Lake District, and lies to the east of a major north–south fault, the Brathay Fault, which appears to have separated a relatively shallow submarine block from a deeper depositional basin to the west during the early Llandovery (Hutt, 1974; Rickards, 1978; Figure 3.52). The whole Lake District area shows evidence of subsidence during the late Ordovician and Silurian (see Chapter 1). As in other sections, the Skelgill Formation displays an alternation of graptolitic black mudstones and paler, sometimes calcareous mudstones, reflecting periods of anoxic and oxic bottom conditions respectively. During

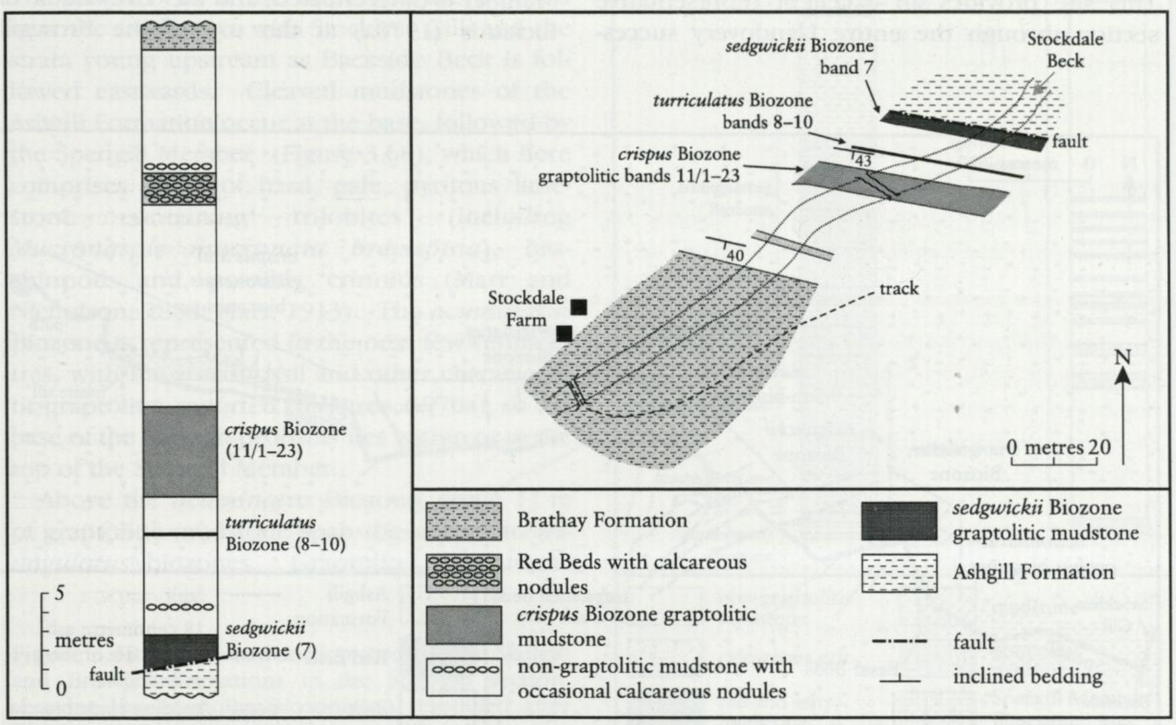

Figure 3.57 Stratigraphical log and geological plan of the Browgill Formation in Stockdale Beck, showing the main graptolitic horizons (after Hutt, 1974).

deposition of the more calcareous levels the sea bed was able to support benthic faunas, with trilobites particularly characteristic. In the Browgill Formation, the graptolitic mudstones are still present, but are reduced in relative thickness within a sequence of pale, unfossiliferous mudstones, which have been interpreted to at least partially represent distal turbidites (Rickards, 1964, 1989a). With the lack of fossils, it is impossible to determine the completeness of this sedimentary sequence, and Rickards (1989a) suggested that there might be a non-sequence in the lower part of the formation. The red beds in the upper part of the Browgill Formation can be correlated lithologically with similar beds to the east, where they contain thin dark bands with a *crenulata* Biozone graptolite fauna (Rickards, 1973). The red mudstones are not, however, represented in the Lake District in sections to the west of Stockdale Beck. Ziegler and McKerrow (1975) interpreted the red beds as being possibly derived from erosion of a desert landscape, and Rickards (1978) considered that in the Lake District they accumulated in hollows on the sea floor.

Conclusions

This site provides an excellent representative section through the entire Llandovery succession in the eastern Lake District. It is the type locality for the Browgill Formation, and includes Stockdale Beck, after which the Stockdale Group is named. Graptolitic horizons occur in the Skelgill Formation and in the lower part of the Browgill Formation, and the locality is particularly important for the faunas of the Telychian *turriculatus* and *crispus* biozones. The upper part of the Browgill Formation includes the most westerly development of red mudstones in the Lake District area; these are interpreted as being deposited in hollows on the sea floor during periods of active erosion of a terrestrial desert landscape.

SPENGILL (BACKSIDE BECK) (SD 699 998)

Introduction

The Howgill Fells lie to the east of the town of Kendal in the south-east of the English Lake District (Figure 3.49). Llandovery strata are exposed in the eastern part of the Fells, and as elsewhere in the Lake District are accommodated in the Skelgill and Browgill formations of the Stockdale Group (Kneller *et al.*, 1994). At the base of the Skelgill Formation, the Spengill Member is differentiated, and the 'Grey Beds' of Rickards (1970a) at the top of the Browgill

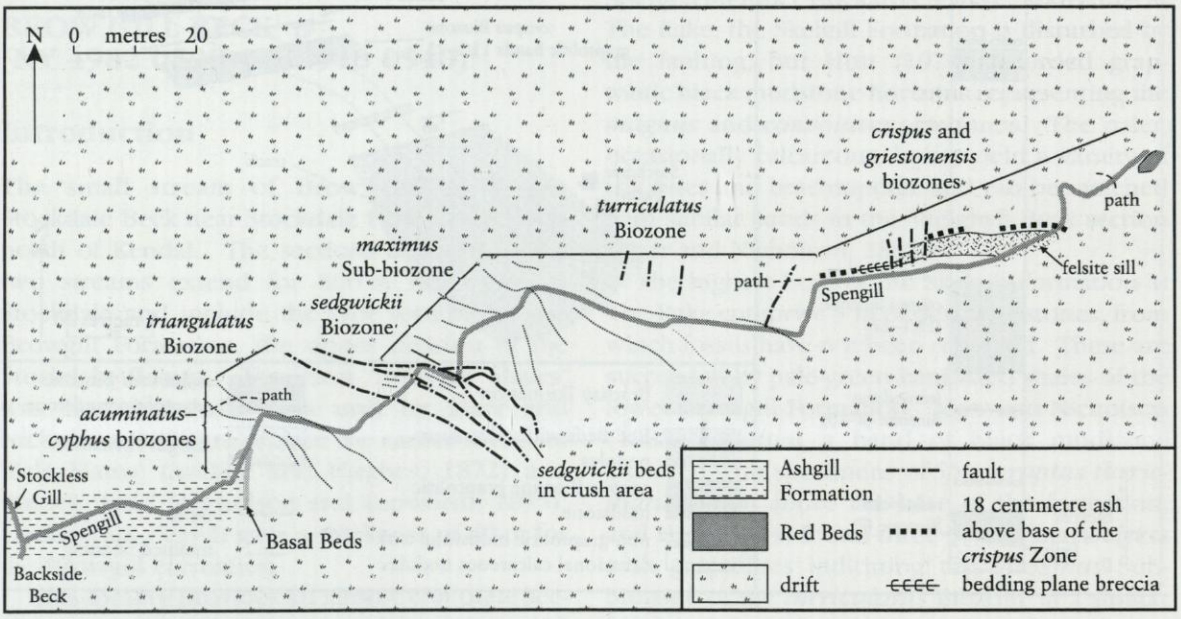

Figure 3.58 Plan of the Spengill section, showing the outcrops of the graptolite biozones represented in the Skelgill and Browgill formations (after Rickards, 1970a).

Formation have been formalized as the Far House Member (Scott and Kneller, 1990).

By far the most complete section through the Stockdale Group in this area is exhibited in the stream of Backside Beck, which Marr and Nicholson preferred to refer to as 'spengill' (Figure 3.58). The succession in Spengill was described by Marr and Nicholson (1888), with some observations added by Marr (1913); more recently, the section was logged in detail by Rickards (1970a; Figure 3.59), who also documented the graptolite faunas. The site provides the type section of the Spengill Member. There are numerous graptolitic horizons in the Skelgill Formation and in the lower part of the Browgill Formation, and the graptolite faunas are rich and extremely diverse. Spengill is the type locality for the graptolite species *Climacograptus simplex* Rickards, 1970a, *Glyptograptus packhami* Rickards, 1970a, *Petalolithus kurcki* (Rickards, 1970a), *Dimorphograptus epilongissimus* Rickards, 1970a, *Pribylograptus angustus* (Rickards, 1970a), *Pristiograptus fragilis fragilis* Rickards, 1970a and *Rastrites spengillensis* Rickards, 1970a.

Description

The lowest beds in the succession are exposed near the confluence with Stockless Gill, and the strata young upstream as Backside Beck is followed eastwards. Cleaved mudstones of the Ashgill Formation occur at the base, followed by the Spengill Member (Figure 3.60), which here comprises 1.0 m of hard, pale, pyritous limestone containing trilobites (including *Mucronaspis mucronata brevispina*), brachiopods and, possibly, crinoids (Marr and Nicholson, 1888; Marr, 1913). The *acuminatus* Biozone is represented in the next few centimetres, with the zonal fossil and other characteristic graptolites reported (Rickards, 1970a), so the base of the Silurian probably lies within or at the top of the Spengill Member.

Above the *acuminatus* Biozone, some 11 m of graptolitic mudstone span the *atavus* to *triangulatus* biozones. Graptolites are diverse

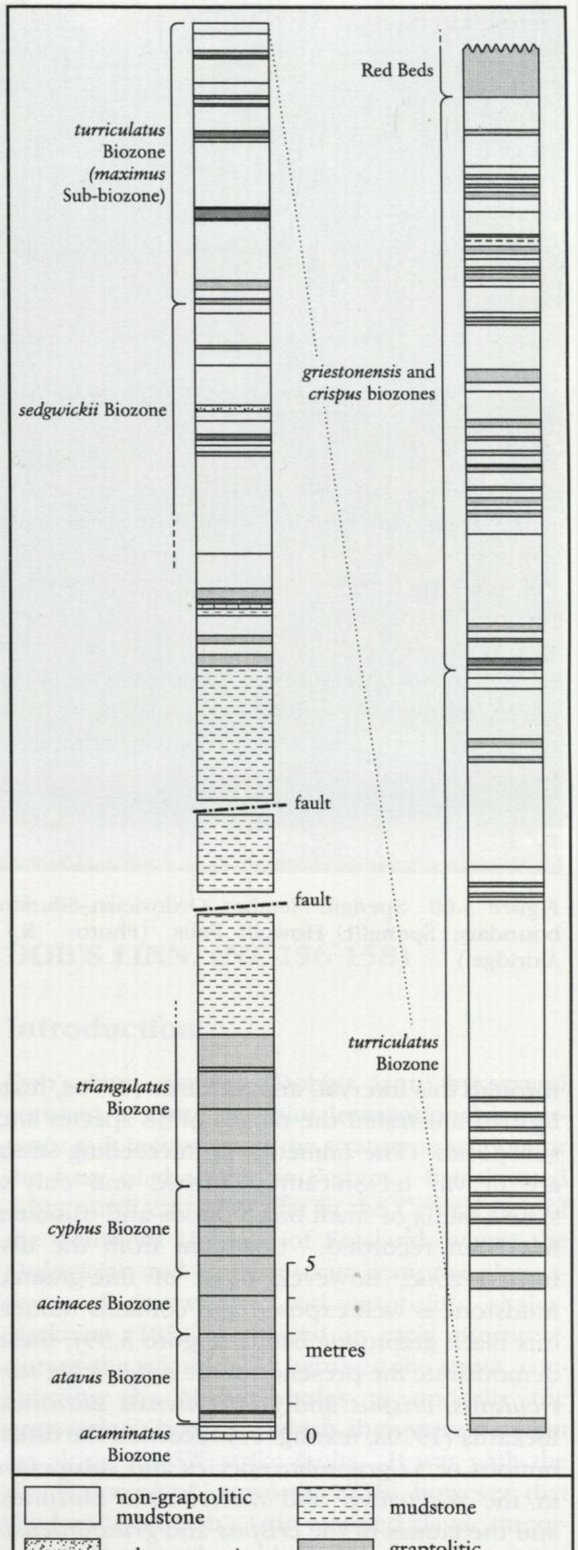

Figure 3.59▸ Measured section through the Skelgill and Browgill formations in the Spengill section, showing the graptolite biozonation (modified after Rickards, 1970a).

Figure 3.60 Spengill Member, Ordovician–Silurian boundary, Spengill, Howgill Fells. (Photo: R.J. Aldridge.)

through this interval, and Rickards (1970a, text-fig. 10) illustrated the ranges of 38 species and subspecies. The immediately succeeding strata are heavily tectonically disturbed and only a sparse fauna of small brachiopods and trilobites has been recorded. Upstream from the disturbed zone, however, 60 m of fine-grained mudstone is well exposed and contains numerous black graptolitic bands (Figure 3.59); these demonstrate the presence of the *sedgwickii, turriculatus, crispus* and *griestoniensis* biozones. Rickards (1970a, text-fig. 11) recorded the distributions of 52 graptolite species and subspecies in the *sedgwickii* and *turriculatus* biozones, and the faunas of the *crispus* and *griestoniensis* biozones have been recorded in the unpublished thesis of Wilson (1954). The base of the Browgill Formation (Figure 3.61) is taken as coincident with the base of the *turriculatus* Biozone. High in the Skelgill Formation, within the *sedgwickii* Biozone, a calcareous horizon occurs, from which Marr and Nicholson (1888) reported trilobites, brachiopods and corals. Near the top of the *turriculatus* Biozone, and marking the boundary with the *crispus* Biozone, is a prominent felsite sill (Rickards, 1970a).

Above the footpath, green non-graptolitic mudstones pass up into a thick unit of red shales and occasional sandstones, becoming greenish-grey towards the summit. Marr and Nicholson (1888) estimated a thickness of about 50 m for this unit. Rickards (1973, 1978) found *crenulata* Biozone graptolites within the red mudstones at Spengill and in nearby Watley Gill (SD 692 989). The red beds are succeeded by 8 m of unfossiliferous grey siltstones, representing the Far House Member.

Interpretation

The Silurian rocks of the Howgill Fells were deposited in the Lake District Basin, which developed on a subsiding volcanic arc terrane on the northern part of Avalonia (see Chapter 1). The intepretative cross-sections of the basin published by Rickards (1978; Figure 3.52) show the development of thin limestones in the Howgill Fells during latest Ordovician (*persculptus* Biozone) times, perhaps generated in part through slumping from horsts or uplifted extensional faults to the west. This was followed by the development of graptolitic shales in the earliest Silurian. Tectonic features in the *atavus* Biozone and above attest to the possible development of some horsts in this area, too. Although the lowest Silurian *acuminatus* Biozone is very thinly developed in the Howgill Fells, the thickness of the Stockdale Group is overall greater than in sections to the west (Yewdale Beck, Skelghyll Beck and Brow Gill Beck) and it may be that the sequence is more complete here than elsewhere. This may account for the greater number of graptolitic bands identified in the Browgill Formation in this region (Rickards, 1978). The thick, haematitic, red beds in the upper part of the Browgill Formation are attributed to sediment input from an eroding desert landscape (Ziegler and McKerrow, 1975), with the deposits accumulating in hollows between submarine ridges (Rickards, 1978). These beds thin and disappear westwards across the Lake District, presumably reflecting the greater distance from the shoreline to the south-east.

Figure 3.61 Exposure of the Browgill Formation in Spengill, Howgill Fells, showing strata of the *turriculatus* Biozone. (Photo: R.J. Aldridge.)

Conclusions

The section in Spengill (Backside Beck) provides the most complete section through the Stockdale Group of the Howgill Fells. The succession is thicker, and possibly more complete, here than in areas of the Lake District to the west. At the base of the Stockdale Group is the thin Spengill Member, of *persculptus* Biozone age, for which this is the type locality. The lower and uppermost parts of the Skelgill Formation and the entire Browgill Formation are well exposed in the stream and in the cliffs, and there are numerous graptolite horizons from which very diverse faunas have been reported. Towards the top of the Browgill Formation, a thick unit of red beds is interpreted as the product of deposition of desert-derived sediments in hollows on the sea floor; similar red beds are widespread globally at this level. Spengill is an important representative site for the lithostratigraphy of the south-eastern part of the Lake District Basin, and is of international interest for its graptolite biostratigraphy.

DOB'S LINN (NT 196 158)

Introduction

Dob's Linn (written 'Dobb's Linn' by several authors) is a site of major international importance as it incorporates the stratotype section for the base of the Silurian System. It is located 6 km north-east of Moffat in the Central Belt of the Southern Uplands of Scotland, where the Ordovician and Silurian strata comprise alternations of greywackes and graptolitic shales. Harkness (1851) produced an early interpretation of the relationship between the strata, considering the Moffat shales to underlie the greywackes, between which they were brought up along NE–SW strike faults. It was with the detailed work of Lapworth (1878), however, that the locality at Dob's Linn attained classic importance. Lapworth published a description and map of the site, determined the stratigraphical divisions, and interpreted the structure, which he considered to be primarily anticlinal, but cut by a number of faults including a 'Main Fault' along the axis of the shale inlier. There is a considerable subsequent literature referring directly or indirectly to Dob's Linn; Peach and Horne (1899) and Ingham (1979), in particular, have provided revised maps and redescriptions. The major exposures at the GCR site occur at two points: on the Main Cliff on the western side of Long Burn, and on the steep banks on both the north and south sides (the 'North Cliff' and the 'South Cliff') of the Linn Branch (Figure 3.62).

Dob's Linn has long been known as a major graptolite locality, exhibiting the most extensive late Ordovician to early Silurian graptolite sequence in Britain, and it was the principal section employed by Lapworth (1878) in demonstrating the biostratigraphical value of these fossils. Species described from the site by Lapworth and by other early workers were incorporated and revised by Elles and Wood (1901–18) in their major monograph, and further studies have been published by Davies (1929), Packham (1962), Toghill (1968, 1970), and Williams (1982a, b, 1983, 1987, 1995). A summary of the graptolite distribution across the Ordovician–Silurian boundary was provided by Williams (1988) and by Williams and Ingham (1989).

The graptolitic rocks of Dob's Linn were assigned by Lapworth (1878) to the 'Moffat Series', subsequently termed the Moffat Shale Group (Ingham, 1979). The Moffat Shale Group is divided into the Glenkiln Shale, Lower Hartfell Shale, Upper Hartfell Shale and Birkhill Shale formations (Figure 3.63). The Birkhill Shale

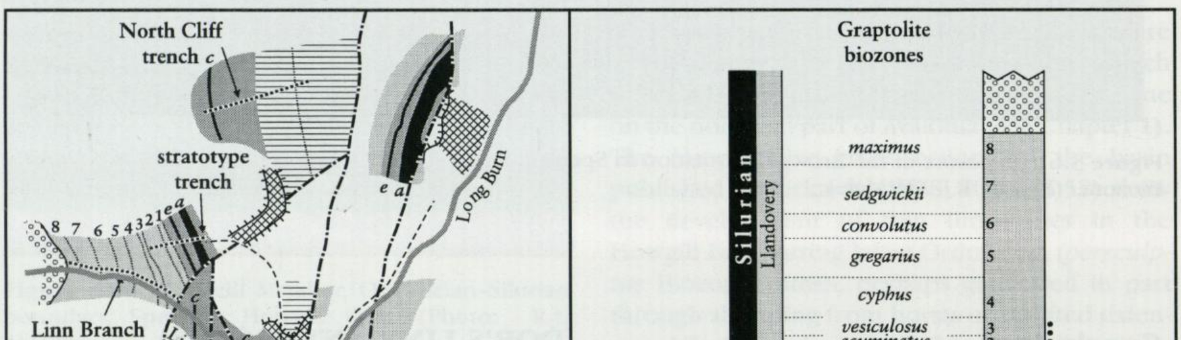

Figure 3.62 Simplified geological map of Dob's Linn, with a stratigraphical section; inset shows location relative to the A708 (after Williams, 1980).

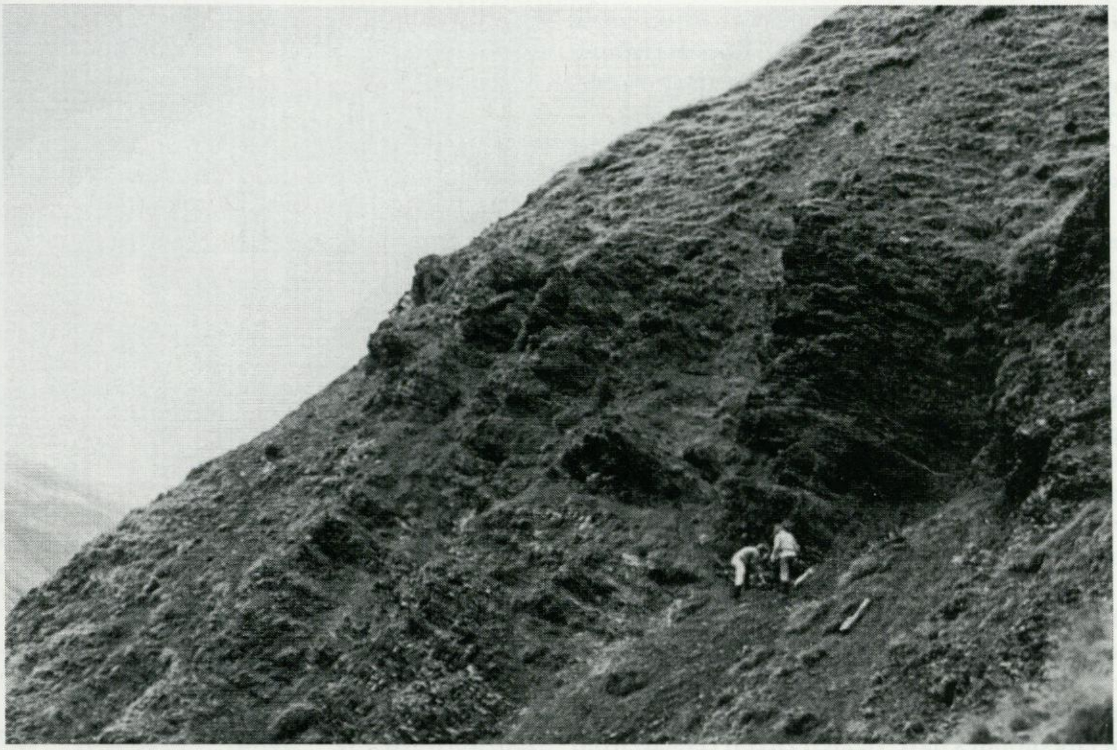

Figure 3.63 Section on the Main Cliff at Dob's Linn, showing the Upper Hartfell Shale Formation and the Birkhill Shale Formation. The two geologists are standing approximately at the position of the Ordovician–Silurian boundary. (Photo: David J. Siveter.)

Formation is overlain by greywackes of the Gala Group. The base of the Silurian System is defined at the base of the *acuminatus* Biozone, 1.6 m above the bottom of the Birkhill Shale Formation in the Linn Branch (Bassett, 1985; Cocks, 1985; Williams, 1988; Holland, 1989; Williams and Ingham, 1989) (Figure 3.64).

Few fossils other than graptolites have been found in the rocks of Dob's Linn, and this has led to some criticisms of its selection as the basal Silurian stratotype (e.g. Berry, 1987; Lespérance *et al.*, 1987). Barnes and Williams (1988) reported and illustrated a small number of conodont specimens from shale surfaces within the Silurian part of the Birkhill Shale Formation; these are dominantly blackened coniform elements, but one broken specimen identified as *Oulodus? kentuckyensis* was recorded from 1.75 m above the base of the formation. Conodont specimens are a little more numerous in the Hartfell Shale formations; and the lowermost Birkhill Shale Formation, below the base of the Silurian, has yielded the Ordovician genera *Amorphognathus* and *Scabbardella* (Barnes and Williams, 1988). Whelan (1988) also recovered blackened chitinozoans and acritarchs from Ordovician shales of the *anceps, extraordinarius,* and *persculptus* biozones, and a few chitinozoans and sphaeromorph acritarchs from the *acuminatus* Biozone. The graptolites, however, are indubitably the prime fossils at Dob's Linn, and the site is the type locality for numerous graptolite taxa, including the Silurian species *Glyptograptus elegans* Packham, 1962, *Glyptograptus avitus* Davies, 1929, *Torquigraptus involutus* (Lapworth, 1876a), *Climacograptus normalis* Lapworth, 1877, *Climacograptus innotatus* Nicholson, 1869, *Orthograptus insectiformis* (Nicholson, 1869), *Orthograptus mutabilis* Elles and Wood, 1907, *Petalolithus minor* Elles, 1897, *Dimorphograptus elongatus* Lapworth, 1876a, *Dimorphograptus decussatus decussatus* Elles and Wood, 1908, *Dimorphograptus erectus erectus* Elles and Wood, 1908, *Rhaphidograptus toernquisti* (Elles and Wood, 1906), *Akidograptus ascensus* Davies, 1929, *Monoclimacis? crenularis* (Lapworth, 1880c), *Atavograptus strachani* (Hutt and Rickards in

Rickards, 1970a), *Campograptus communis communis* (Lapworth, 1876a), *Coronograptus cyphus cyphus* (Lapworth, 1876a), *Coronograptus gregarius* (Lapworth, 1876a), *Pribylograptus argutus* (Lapworth, 1876a) and *Rastrites hybridus hybridus* Lapworth, 1876a.

In an attempt to supplement the biostratigraphical data with another correlative tool, Underwood *et al.* (1997) have undertaken a study of carbon isotope patterns in kerogen samples across the Ordovician–Silurian boundary. They found a marked positive $\delta^{13}C$ excursion in the uppermost Ordovician strata, and used the architecture of the isotope curve to correlate with coeval successions in carbonate shelf environments that lack graptolites. These data clearly enhance the global utility of the Dob's Linn section as a boundary stratotype.

Metabentonites are common in the Moffat Shale Group; a detailed study by Merriman and Roberts (1990) recorded 135 horizons of Ashgill and Llandovery age, representing a total accumulation of about 6 m of volcanic ash. These metabentonites have yielded zircon crystals from which radiometric U-Pb dates have been determined by Tucker *et al.* (1990). Dates of 438.7 ± 2.0 and 445 ± 2.4 Ma were found to bracket the Ordovician–Silurian boundary.

This GCR site is important for both its Ordovician and Silurian strata. The account given here deals only with the uppermost Ordovican shales and with the Silurian rocks. The Ordovician rocks, assigned to the Glenkiln Shale, Lower Hartfell Shale, Upper Hartfell Shale and lowermost Birkhill Shale formations, are described in the companian GCR volume on British Cambrian to Ordovician stratigraphy (Rushton *et al.*, 1999).

Description

Much of the succession at Dob's Linn is overturned with a high angle of dip to the north-east. However, the Main Cliff has become rotated through slumping during the Pleistocene, and the beds here are the right way up, dipping at 45° to the west. The Lower and Upper Hartfell Shale formations are well exposed on the Main Cliff and the North Cliff. The Upper Hartfell Shale comprises 28 m of grey mudstone and shale, in which three graptolitic bands have been identified. The uppermost of these is a very thin dark-brown mudstone with *Climacograptus? extraordinarius* and other graptolites (the

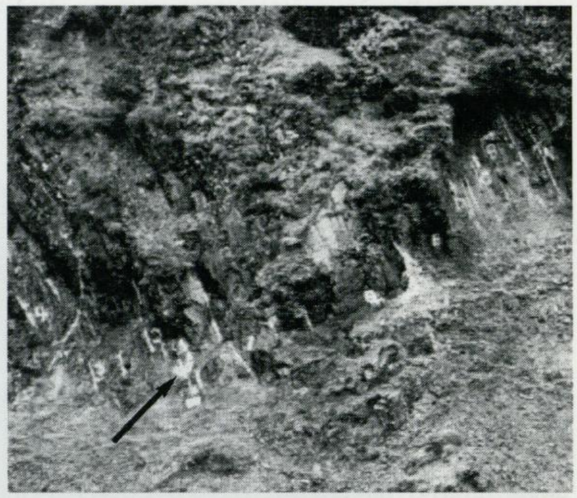

Figure 3.64 Strata incorporating the internationally recognized base of the Silurian System, northern side of the Linn Branch gorge, Dob's Linn. For scale see sketch opposite (Figure 3.65). The section youngs to the left and the Ordovician–Silurian boundary is arrowed between beds 1 and 2. (Photo: S.H. Williams.)

Extraordinarius Band) (Ingham, 1979; Williams, 1983). The base of the Birkhill Shale Formation is recognized 1.17 m above the *Extraordinarius* Band by a lithological change to dark mudstones and shales with metabentonites (Williams, 1983). The formation is 43 m thick (Toghill, 1968); at the base is 0.15 m of black shale, above which 1.45 m of graptolitic shales represent the *persculptus* Biozone.

The base of the *acuminatus* Biozone is marked by the appearance of *Akidograptus ascensus* and *Parakidograptus acuminatus sensu lato* at 1.6 m above the base of the Birkhill Shale Formation. This level has been adopted as the global standard for the Ordovician–Silurian boundary, marked by the first occurrence of *A. ascensus*. The first monograptid, *Atavograptus ceryx*, appears 0.3 m higher, and *Climacograptus trifilis* first occurs 0.6 m above the bottom of the *acuminatus* Biozone (Williams, 1983). Typical examples of *P. acuminatus* appear higher in the biozone. The stratotype section for the base of the Silurian System is in a trench (the Linn Branch Trench) dug on the North Cliff of the Linn Branch gorge (Figures 3.64, 3.65).

The Birkhill Shale Formation comprises massive black graptolitic mudstones interbedded with grey mudstones that lack graptolites; there are numerous soft, pale metabentonites, several of which contain bands of calcareous nodules

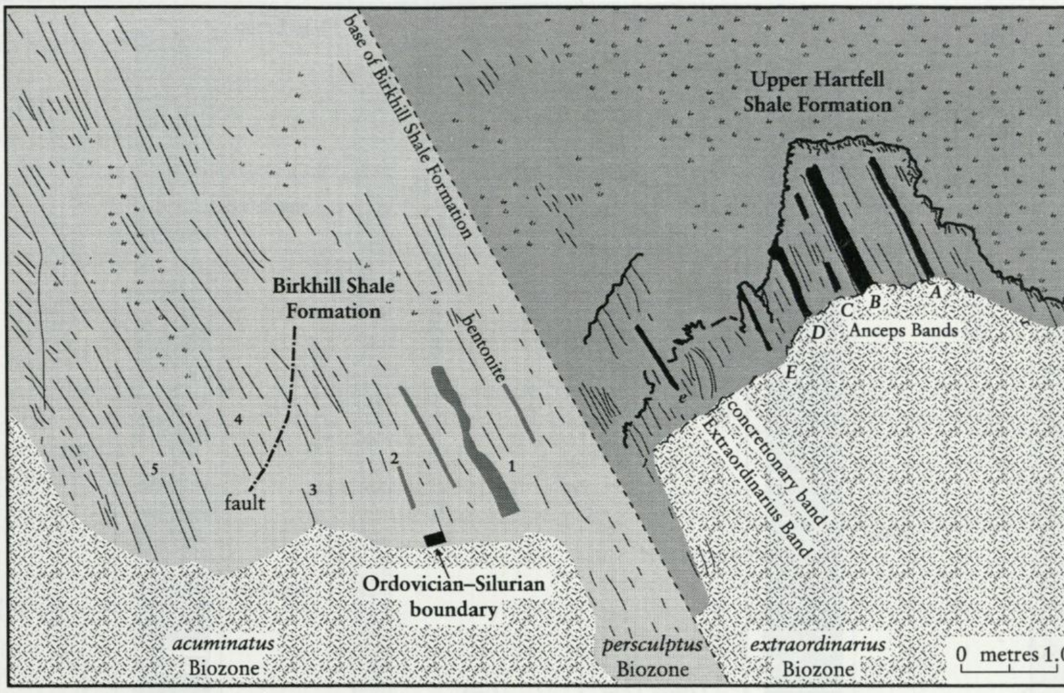

Figure 3.65 Sketch of the geology of the northern side of Linn Branch gorge (after Williams, 1988).

(Figure 3.66). The lower part of the unit is dominated by the black mudstones, with the paler mudstones becoming thicker and more frequent in the upper half. Two greywacke horizons were reported from within the *cyphus* Biozone along the western side of Long Burn by Rushton and Stone (1991). The graptolite faunas through the formation were documented by Toghill (1968), who recognized the presence of the *persculptus, acuminatus, vesiculosus* (= *atavus*), *cyphus, gregarius, convolutus, sedgwickii* and *turriculatus* biozones. *Atavograptus atavus* is present from the base of the *vesiculosus* Biozone to the lowest beds of the *gregarius* Biozone. *Lagarograptus acinaces* occurs in beds referred by Toghill (1968) to the upper *vesiculosus* and basal *cyphus* biozones, allowing separation of the *acinaces* Biozone (Webb *et al.*, 1993). The *gregarius* Biozone has been divided into three sub-biozones, identifiable at Dob's Linn (Webb *et al.*, 1993): (1) the *triangulatus* Sub-biozone, marked by the appearance of *Monograptus triangulatus* with *Petalograptus*, (2) the *magnus* Sub-biozone characterized by *Diplograptus magnus* and *Monograptus triangulatus fimbriatus* and (3) the *leptotheca* Sub-biozone, defined by the appearance of *Pribylograptus leptotheca* and *Monograptus argenteus*. The highest graptolitic band, referable to the *turriculatus* Biozone (*maximus* Sub-biozone), is about 4 m below the top of the Birkhill Shale Formation. The graptolites indicate that the Birkhill Shale Formation spans a chronostratigraphical range from the uppermost Ordovician (Hirnantian) to the lower Telychian; key biostratigraphical taxa are illustrated in Figure 3.67.

In the upper Linn Branch, the lithological change to greywackes of the Gala Group results in the development of a waterfall. The first of these greywackes appears below the waterfall and is taken as the base of the Gala Group (Lapworth, 1878; Toghill, 1968); above this, 4.5 m of massive grey mudstones, thin greywackes and metabentonites are exposed below the massive greywackes at the base of the waterfall.

Interpretation

Throughout the Southern Uplands the strata strike at approximately 060° and are mostly steeply inclined. At individual outcrops the younging direction is dominantly towards the north-west, but the oldest rocks of the Southern Uplands are found in the north-west of the

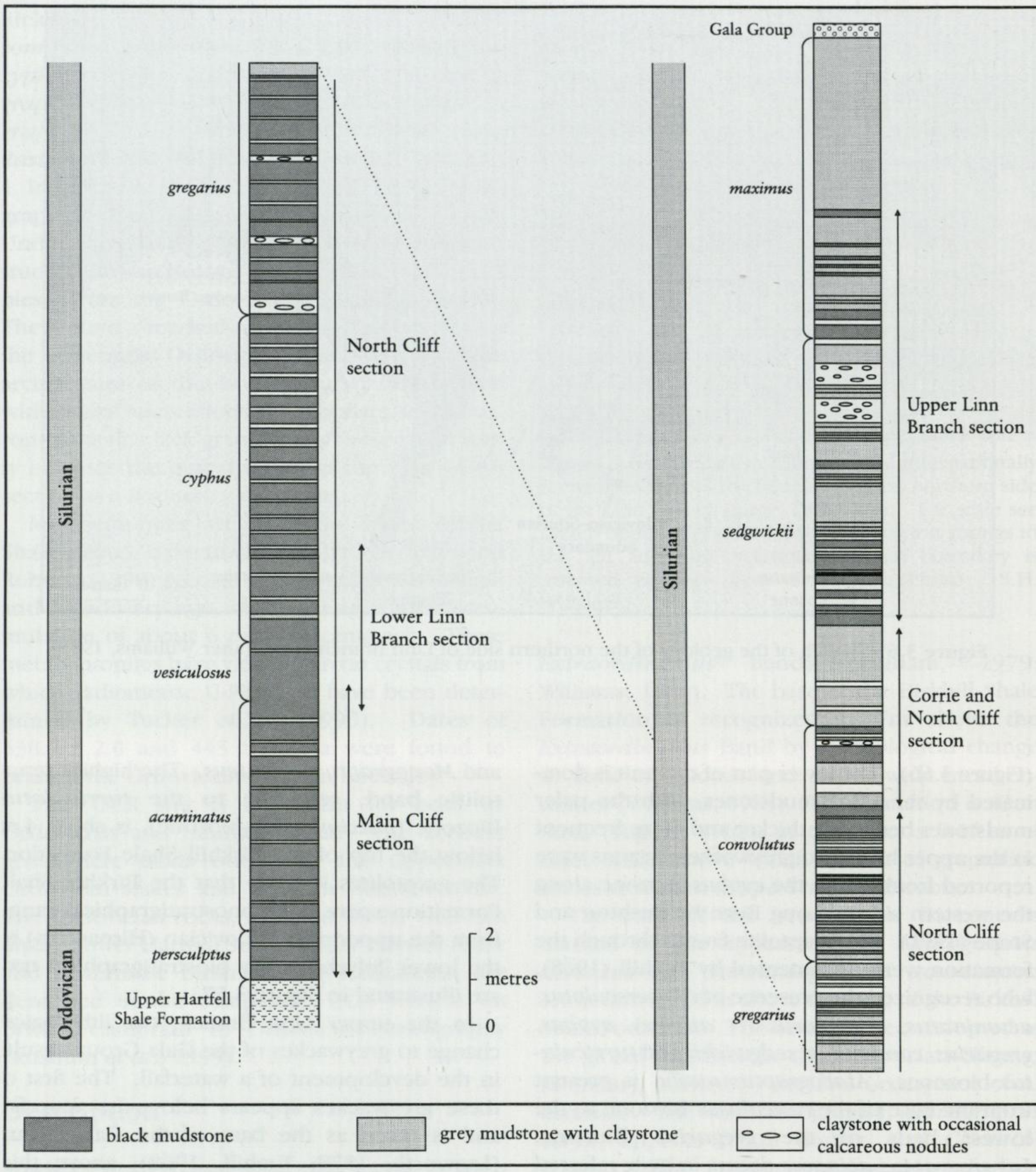

Figure 3.66 Section through the Birkhill Shale Formation at Dob's Linn, showing the graptolite biozonation (after Toghill, 1968). The base of the Silurian System is at the base of the *P. acuminatus* Biozone.

region and the youngest in the south-east. This apparent paradox is the result of multiple strike faults, which create a series of blocks within each of which the youngest rocks are in the north-west. Progressing from the south-east, however, each block has older strata at the base, resulting in an overall increase in age north-westwards (see Figure 1.6). This structural and stratigraphical pattern has been elegantly explained by accumulation of the deposits on an accretionary prism at the northern margin of the subducting Iapetus Ocean (Leggett *et al.*, 1979a; Leggett, 1987). In this model, the black graptolitic shales were deposited on oceanic crust that became

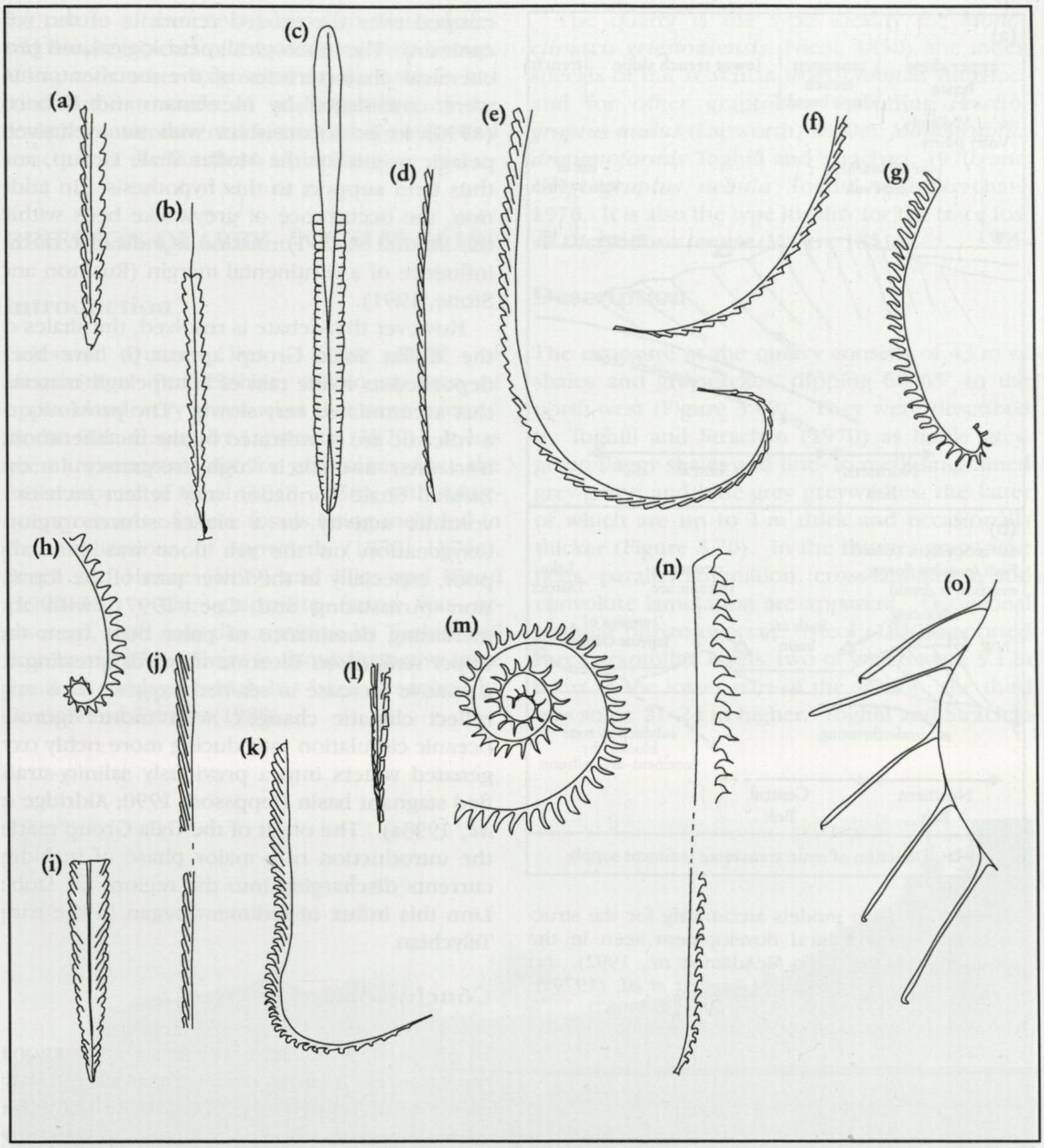

Figure 3.67 Some biostratigraphically important graptolite taxa from the Birkhill Shale Formation of Dob's Linn (after Webb *et al.*, 1993). (a) *Glyptograptus persculptus*; (b) *Parakidograptus acuminatus*; (c) *Cystograptus vesiculosus*; (d) *Atavograptus atavus*; (e) *Coronograptus cyphus cyphus*; (f) *Coronograptus gregarius*; (g) *Monograptus triangulatus triangulatus*; (h) *Monograptus triangulatus fimbriatus*; (i) *Diplograptus magnus*; (j) *Pribylograptus leptotheca*; (k) *Monograptus argenteus*; (l) *Rhaphidograptus toernquisti*; (m) *Monograptus convolutus*; (n) *Monograptus sedgwickii*; (o) *Rastrites maximus*. Figure (c) × 1.3, all other figures approximately × 2.

the site of greywacke distribution as it reached the deep ocean trench bordering the active northern continental margin of the ocean (Figure 3.68a). As the oceanic plate became subducted, the sedimentary cover was scraped off and added to the accretionary stack by underthrusting. Each slice that was accumulated in this way comprised black shales at the base with greywackes above, and the age of each successive slice was younger at the base and at the top

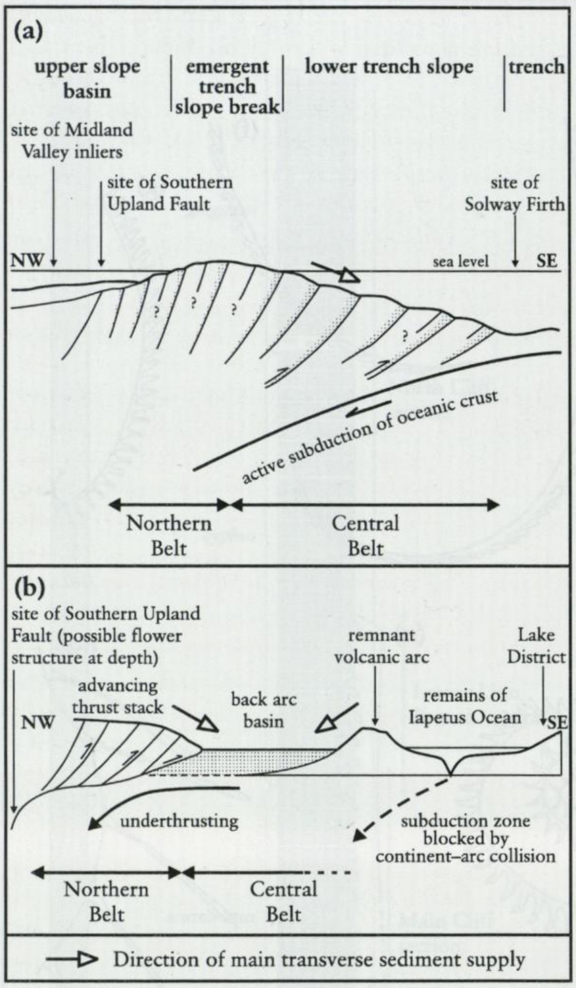

Figure 3.68 Two models accounting for the structural and stratigraphical development seen in the Southern Uplands (from McAdam *et al.*, 1992). (a) accretionary prism model of Leggett *et al.* (1979a); (b) back-arc basin model of Stone *et al.* (1987).

than its predecessor. During final collision as the ocean closed during the later Silurian the entire stack was rotated to the vertical.

An alternative interpretation, presented by Stone *et al.* (1987), views the strata of the Southern Uplands as having been deposited in a back-arc basin, with a continental landmass to the north and a rifted continental fragment containing an active volcanic arc to the south (Figure 3.68b). In this model, collision of the opposing continental margins during the Llandovery was accompanied by underthrusting of the southern margin, initiating a south-eastward propagating thrust stack that may have ramped over the eroded remnants of the volcanic arc. The lithological, petrological and geochemical characteristics of the metabentonites were considered by Merriman and Roberts (1990) to be inconsistent with an exclusively pelagic origin for the Moffat Shale Group, and thus lend support to this hypothesis. In addition, the occurrence of greywacke beds within the Birkhill Shale Formation is indicative of the influence of a continental margin (Rushton and Stone, 1991).

However this debate is resolved, the shales of the Moffat Shale Group appear to have been deposited as a fine rain of hemipelagic material that accumulated very slowly. The proximity of a volcanic arc is indicated by the metabentonite horizons, and their high frequency in the Birkhill Shale Formation may reflect increased volcanic activity or a closer source region. Oxygenation on the sea floor was generally poor, especially in the lower part of the formation (Armstrong and Coe, 1997), with the increasing dominance of paler beds from the upper *sedgwickii* Biozone upwards attesting to a relative increase in sea-bed oxygen. This may reflect climatic changes, with more vigorous oceanic circulation introducing more richly oxygenated waters into a previously salinity-stratified stagnant basin (Jeppsson, 1990; Aldridge *et al.*, 1993a). The onset of the Gala Group marks the introduction of a major phase of turbidity currents discharging into the region. At Dob's Linn this influx of sediment began in the early Telychian.

Conclusions

Dob's Linn is a site of primary international importance. It incorporates the internationally recognized stratotype section for the definition of the base of the Silurian System, and is thereby also the locality at which the bases of the Llandovery Series and the Rhuddanian Stage are defined. It is also historically and biostratigraphically important for the relatively complete graptolitic sequence it displays through strata representing the upper part of the Ordovician System and the lower part of the Silurian System. Several major papers on graptolite faunas have been fully or largely based on the Dob's Linn sequence, and the site is the type locality for numerous species. In addition, it provides a representative section through the Moffat Shale Group of the Southern Uplands, and displays the nature of the contact between these shales and the greywackes of the overlying Gala Group. Along with other exposures in the area, it has contributed towards an understanding of the complex environmental history, stratigraphy and structure of the Southern Uplands.

GRIESTON QUARRY (NT 3135 3618)

Introduction

Grieston Quarry lies 1.6 km WSW of Innerleithen, Peeblesshire, within an area of upper Llandovery greywackes that were referred to the Gala Group by Lapworth (1870). It has been an important site for graptolites since the initial reports of Nicol (1848, 1850), with subsequent records of these fossils being included in the publications of Lapworth (1870, 1876a), Peach and Horne (1899) and Elles and Wood (1901–18). The graptolite fauna was re-assessed, with new descriptions, by Toghill and Strachan (1970). There is also a distinctive trace fossil assemblage, which has been described by Benton and Trewin (1980).

The quarry is the type locality for *Monoclimacis griestoniensis* (Nicol, 1850), the index species of the Telychian *griestoniensis* Biozone, and for other graptolites including *Pristiograptus nudus* (Lapworth, 1880c), *Monograptus drepanoformis* Toghill and Strachan, 1970, and *Glyptograptus nebula* Toghill and Strachan, 1970. It is also the type locality for the trace fossil *Dictyodora tenuis* (M'Coy, 1851a).

Description

The exposure in the quarry consists of 43 m of shales and greywackes, dipping 60–65° to the north-west (Figure 3.69). They were described by Toghill and Strachan (1970) as fissile grey-green flaggy shales and fine- to medium-grained grey-green and blue-grey greywackes, the latter of which are up to 1 m thick and occasionally thicker (Figure 3.70). In the thinner greywacke beds, parallel lamination, cross-lamination and convolute lamination are apparent. Occasional nodular horizons occur. Nicol (1850) reported three graptolitic levels, two of which were 3.1 m apart in the lower part of the section; the third was some 21–24 m higher. Toghill and Strachan

Figure 3.69 The Gala Group in Grieston Quarry, Innerliethen. (Photo: TS1455, reproduced by kind permission of the Director, British Geological Survey, © NERC.)

Figure 3.70 Fissile thin greywackes and shales of the Gala Group, Grieston Quarry, Innerliethen. (Photo: TS1457, reproduced by kind permission of the Director, British Geological Survey, © NERC.)

(1970), however, were able to find only two fossiliferous horizons *in situ*, at 0.9 m and 3.7 m above the base of the section, and equated the upper one of these with Nicol's lowest horizon. They also reported graptolitic debris in the quarry with a different lithology from the material from the quarry face, and suggested that these loose blocks may represent Nicoll's middle or highest level. Trewin (1979) managed to find seven graptolite-bearing horizons, which he considered to include all those previously mentioned. He noted that the graptolites almost all occur in finely-laminated coarse silts or ripple-laminated fine sands, and concluded that they had been transported. He also found tool marks on the bases of sandy beds that had clearly been formed by graptolites during transport, as they show unmistakable impressions of thecae.

Graptolites recorded by Toghill and Strachan (1970) from 3.7 m above the base of the section include *Monograptus discus* (restricted to this horizon), *Monoclimacis griestoniensis* (only common at this horizon), *Monograptus priodon* and *Oktavites spiralis*. The micaceous greywackes found as loose blocks contain *Monograptus drepanoformis, Pristiograptus nudus, Glyptograptus nebula* (all restricted to this material), *M. priodon, O. spiralis,* and rare *M. griestoniensis,* among others. These faunas are indicative of the *griestoniensis* Biozone, of late Telychian age.

Tail spines of the phyllocarid *Ceratiocaris* also occur (Trewin, 1979; Benton and Trewin, 1980), and tool marks produced during the transport of these rigid, three-pronged structures were described by Trewin (1979). Benton and Trewin (1980) also documented the trace fossil assemblage, which is dominated by meandering burrows of *Dictyodora,* together with straight traces referred to *Caridolites* by Nicholson (1873). The ichnofauna is a typical deep-water mud association assignable to the *Nereites* ichnofacies.

Interpretation

The fine-grain size of most of the greywackes, the dominance of mud, and the sedimentary structures, indicate a distal environment on a turbidite fan (Trewin, 1979; Weir, 1992). The beds represent units Tcde of the Bouma (1962) sequence (Figure 3.40), and were deposited by weak turbidity currents that are shown from measurements on tool marks and flutes to have come from a variety of directions (Trewin, 1979). Trewin (1979) also showed that some of the coarser beds (between 6 and 6.5 m above the base of the exposed section) contain original and replaced grains of volcanic origin, suggesting that they were derived from a petrographically distinct source from the rest of the strata. The ichnofauna and the evidence of current activity attest to deep but oxygenated bottom waters.

The graptolite fauna at Grieston Quarry is the youngest known in the area. The absence of *Monoclimacis crenulata* and *Monograptus marri* was taken by Toghill and Strachan (1970) to indicate that the highest part of the *griestoniensis* Biozone is not represented in the quarry. To the east and south-east, including the network site at Thornylee, graptolitic horizons within the Gala Group indicate the *crispus* and *turriculatus* biozones (Lapworth, 1870; Peach and Horne, 1899). The ground to the north-west of the quarry is occupied by unfossiliferous greywackes as far as the Ordovician–Silurian boundary, which is about 4 km away (Toghill and Strachan, 1970). There is no local representation of the highly graptolitic Birkhill Shale Formation seen, for example, in the Moffat area (e.g. Dob's Linn), and the onset of greywacke deposition in the Innerleithen area was evidently much earlier than in the Moffat tract of the Southern Uplands (see Figure 1.6).

The presence of relatively young Telychian rocks in the northern part of the Southern Uplands is an anomaly, and the implications remain a topic for future research. One possibility is that these strata were deposited in an isolated perched basin above the developing Southern Uplands complex (Weir, 1992).

Conclusions

This is a classic and important graptolite locality in the Southern Uplands, with a diverse fauna of local and international importance for biostratigraphy and correlation. It is the type locality for the biozonal graptolite species *Monoclimacis griestoniensis*. The quarry also provides a representative section in the Telychian greywackes of this part of the Southern Uplands; these are otherwise poorly exposed.

THORNYLEE QUARRY (NT 420 363)

Introduction

This quarry and the cuttings in the adjacent dismantled railway expose a 300 m long section in Telychian greywackes and shales referred to the Queensberry Formation of the Gala Group. The site is situated on the north bank of the River Tweed, some 8 km east of Galashiels and 8 km west of Innerleithen, Peeblesshire. Nicol (1850) provided the first description of the rocks and noted the presence of graptolites and abundant 'annelid impressions'; the locality was also mentioned by Peach and Horne (1899, pp. 204–5), who recorded three graptolite species and trace fossils that they referred to *Crossopodia* and *Myrianites*. These trace fossils (Figure 3.71), which were re-examined and described by Benton and Trewin (1980), are exceptionally well displayed at this locality. Thornylee Quarry is the type locality for the ichnofossil referred to *Crossopodia scotica* by M'Coy (1851a), which was transferred to the genus *Dictyodora* by Benton and Trewin (1980).

Description

The entire sequence comprises greywackes interbedded with red, purple and green shales. The greywackes are mostly medium-grained and graded, sometimes with tool marks and load casts on the bases of beds (Benton and Trewin, 1980). Occasional graptolites occur, and Peach and Horne (1899) recorded *Monograptus exiguus, M. priodon* and *Monoclimacis*? *galaensis*. Trace fossils are abundant, particularly in the shales, with meandering traces especially frequent in the purple shales exposed in the quarry itself. Benton and Trewin (1980) recorded that the ichnofauna is dominated by meandering burrows of *Dictyodora scotica* (larger) and *Dictyodora tenuis* (smaller and more irregular), with *Caridolites* common, and *Nereites* and burrows comparable with *Planolites* present. The assemblage is referable to the *Nereites* ichnofacies.

Interpretation

Thornylee Quarry is situated within the Southern Uplands, where a thick, faulted complex of greywacke and graptolitic shale units has variously been interpreted to represent an accre-

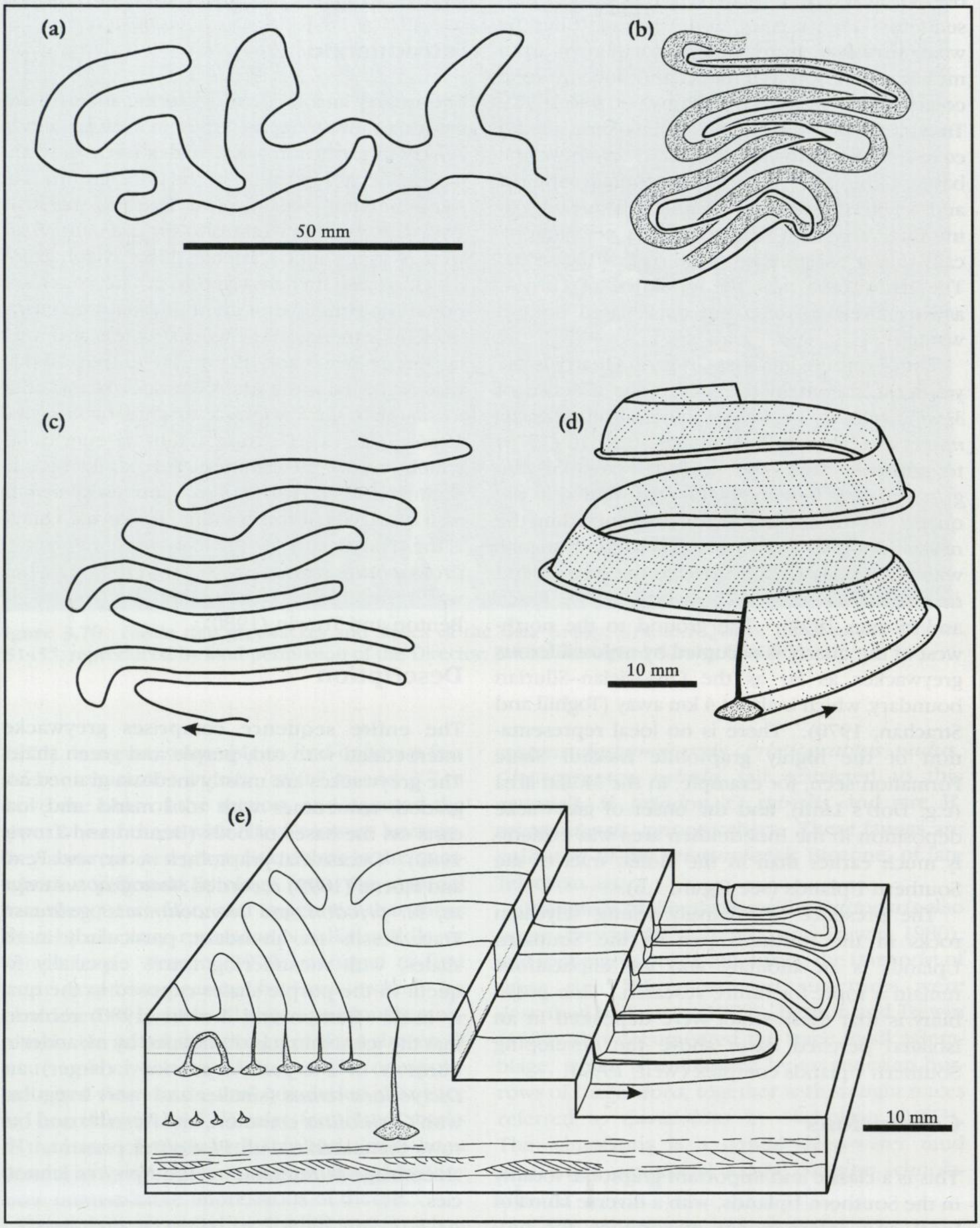

Figure 3.71 The ichnospecies *Dictyodora scotica* from Thornylee Quarry (after Benton and Trewin, 1980). (a) irregular meanders; (b) plan view of basal burrow (stipple) and top wall (solid line); (c) regular meanders; (d) reconstruction of three-dimensional morphology showing basal burrow and wall; (e) block diagram to illustrate different preservational aspects of burrows in plan and in section. Arrows indicate direction of travel of burrowing animal.

tionary prism or a back-arc accumulation (see the Dob's Linn site report). At Thornylee, the thin greywacke units and abundance of shale indicate deposition in a low-energy turbidite environment (Benton and Trewin, 1980). The ichnofauna is assignable to the deep-water *Nereites* association, with the meandering trails typical of animals exploiting a food resource with maximum efficiency. Benton and Trewin (1980) interpreted the small, straight burrows of *Caridolites* as probably representing the juvenile burrows of the same animal as responsible for the *Dictyodora* traces.

This site, together with those at Dob's Linn, Grieston Quarry and Old Cambus Quarry, illustrates the lithologies, stratigraphy and fossils of the early Silurian rocks of the Southern Uplands.

Conclusions

This is a good representative site for the interbedded greywackes and shales of the Queensberry Formation, which were deposited in a low energy, distal turbidite environment. The locality is particularly important for the abundant and well-preserved trace fossil assemblage preserved in the shales; this ichnofauna is dominated by meandering feeding burrows, which are typical of deep-water muddy sediments.

OLD CAMBUS QUARRY (NT 806 705)

Introduction

Old Cambus Quarry is situated 800 m southwest of the locality of Siccar Point, Berwickshire, which achieved classic status with Hutton's recognition in 1788 of the significance of the unconformity exposed there. At Siccar Point, vertical Llandovery shales and greywackes are covered by gently dipping breccias and sandstones of the Upper Old Red Sandstone, clearly representing two depositional episodes separated by a long period of time. However, the local Silurian rocks, referred to the Queensberry Formation of the Gala Group, are better displayed in the Old Cambus slate quarry (Figure 3.72). The strata here were mentioned by Geikie (1864) and briefly described by Peach and Horne (1899), who recorded an important and well-preserved graptolite fauna that they related to that of the Tarannon beds of Wales. Graptolites from the quarry were re-studied by Strachan (1982), who noted that not all of the species listed by Peach and Horne (1899) could be substantiated, but described a fauna that can be assigned to the lower part of the Telychian Stage.

Description

Peach and Horne (1899) described the strata in the quarry as grey and red fissile shales and grey flaggy shales, weathering brown and dipping at 30° to the SSE. Several horizons rich in graptolites occur, and Strachan (1982) tentatively recorded an assemblage of eight taxa, including *Monoclimacis galaensis* and specimens subsequently referred to *Streptograptus tenuis* and *Torquigraptus proteus* (Loydell, 1993). The fauna is indicative of a horizon in the uppermost *turriculatus* Biozone or the lowermost *crispus* Biozone (Strachan, 1982; Loydell, 1993; Zalasiewicz, 1994).

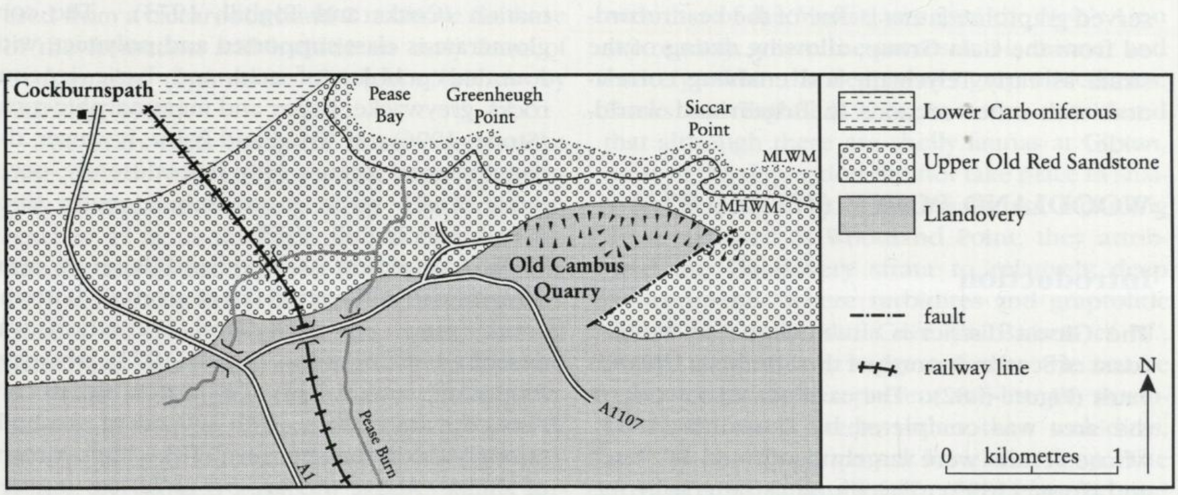

Figure 3.72 Geological map of the area around Siccar Point and Old Cambus Quarry (after Craig, 1986).

As well as the graptolites the strata contain diverse trace fossils, principally meandering tracks of *Dictyodora* (see Figure 3.71).

Interpretation

Old Cambus Quarry is at the north-eastern end the Southern Uplands, which have been interpreted to represent an accretionary prism or a back-arc accumulation that was deposited during the late Ordovician to early Silurian (see the Dob's Linn site report). The Queensberry Formation in Old Cambus Quarry compares closely with the rocks of the same unit exposed at the network site of Thornylee Quarry. Both localities display mud-dominated greywackes and shales deposited in a low-energy turbidite environment. The trace fossil assemblage, dominated by meandering tracks, and referable to the *Nereites* ichnofacies, is indicative of deep water. The major difference between the two localities is the abundance and diversity of graptolites at Old Cambus Quarry, allowing accurate dating of the local Llandovery sequence.

This site, in combination with those at Thornylee Quarry, Grieston Quarry and Dob's Linn, helps to illustrate the range of lithologies and fossils present within early Silurian strata of the Southern Uplands area.

Conclusions

This exposure is representative of the late Llandovery Gala Group in eastern Scotland, and is important in studies of Silurian biostratigraphy, graptolite faunas, trace fossil assemblages and environments. The diverse and well-preserved graptolite fauna is one of the best recorded from the Gala Group, allowing dating of the strata as early Telychian, and enabling correlation with other sections in Britain and worldwide.

WOODLAND POINT (NX 169 953)

Introduction

The Girvan district is situated on the western coast of Scotland, north of the Southern Uplands Fault (Figure 3.82). The earliest major work on the area was completed by Lapworth (1882), whose results were largely confirmed by Peach and Horne (1899). The Silurian stratigraphy was revised by Cocks and Toghill (1973), who also provided new maps and an analysis of biostratigraphical data.

Coastal exposures of Silurian strata occur at Craigskelly (NX 1774 9605) and at the GCR site of Woodland Point, which is 1 km to the south-west of Craigskelly and 3 km SSW of the town of Girvan (Figure 3.73). At Woodland Point the rocks exposed on the foreshore belong to the Shalloch Formation of the Ordovician System, overlain by the Craigskelly Conglomerate, the Woodland Formation and the Scart Grits, all of Silurian age (Cocks and Toghill, 1973). Lapworth (1882) considered the junction between these Ordovician and Silurian rocks to be a fault, but Cocks and Toghill (1973) reported an unconformable boundary with lenses of Craigskelly Conglomerate occupying pockets in the top of the Shalloch Formation.

The site is the type locality for the Woodland Formation, which includes the units referred by Lapworth (1882) to the 'Woodland, or Lower *Pentamerus* Limestone', the 'Coralline Limestone' and the 'striped Shales' (Cocks and Toghill, 1973). This formation is rich in fossils, including graptolites, shelly fossils and conodonts, and the Woodland Point site is of considerable importance in studies of early Silurian biostratigraphy, environments and palaeogeography. It is the type locality for the trilobites *Stenopareia acymata* Howells, 1982, and *Acernaspis xynon* Howells, 1982.

Description

At Craigskelly the Craigskelly Conglomerate is about 40 m thick and lies unconformably on shales and greywackes of the Shalloch Formation (Cocks and Toghill, 1973). The conglomerate is clast supported and polymict, with rounded pebbles of acid and basic igneous rocks, greywacke, jasper and metamorphic rocks (Stone, 1996). At Woodland Point, however, the conglomerate occurs only intermittently, occupying lenses rarely more than a metre thick (Cocks and Toghill, 1973).

The succession at Woodland Point is overturned, with an inverted dip of around 70° to the south-east. The Woodland Formation was described by Cocks and Toghill (1973), who gave its thickness as 21.7 m. The lower 10.2 m consists of massive flags, with several of the beds strongly calcareous because of the high content of shells. Above this are 5.5 m of less massive flags with thin shell beds, which become less

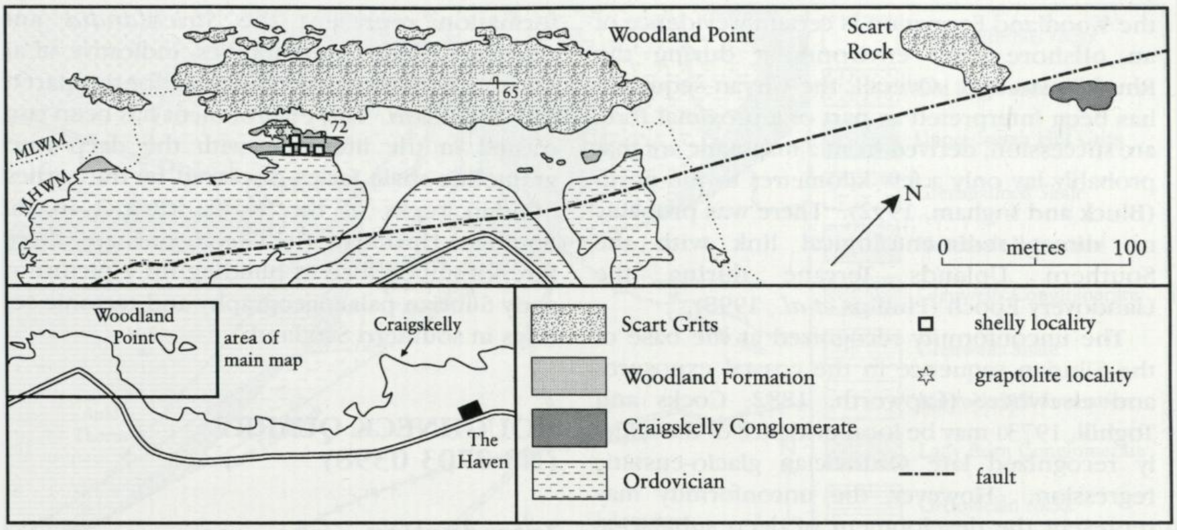

Figure 3.73 Sketch-map of the geology at Woodland Point (after Cocks and Toghill, 1973).

frequent upwards, and the upper 6 m of the formation comprises thinly bedded siltstones and shales. The lower part of the formation has yielded more than 30 species of brachiopod, with *Stricklandia lens lens* dominant; the shells are almost all transported but appear to represent a *Stricklandia* benthic community. In the middle part of the formation, brachiopods of the *Stricklandia* and *Clorinda* benthic communities have been found in life position (Ziegler *et al.*, 1966; Cocks and Toghill, 1973). A graptolitic band occurs 4 m below the top of the formation and has yielded a diverse fauna, including *Coronograptus cyphus*, indicative of the upper part of the *cyphus* Biozone, and of late Rhuddanian age. Conodonts have been recovered from a calcareous band 2 m above the base of the formation and include an early form of *Distomodus* (figured as *D. kentuckyensis* by Aldridge, 1985).

The Scart Grits comprise massive greywacke units, several with conglomeratic bases; they display normal and reverse grading. The formation reaches 45 m in thickness at Woodland Point, but the top is not exposed (Cocks and Toghill, 1973). At Craigskelly, the basal Scart Grits comprise a 14–24 m conglomerate, with clasts of quartz and igneous rock; this unit was separated by Cocks and Toghill (1973) as a Quartz Conglomerate Member. This member is not so well developed at Woodland Point, but may be represented by isolated knolls of conglomerate surrounded by beach shingle.

The Woodland Formation at Woodland Point provides the type locality for several brachiopod taxa, including *Lingula tenax* (Reed, 1917), *Triplesia woodlandensis* (Reed, 1917), *Katastrophomena woodlandensis* (Reed, 1917), *Leptaena? reedi* Cocks, 1968, *Leptaena valentia* Cocks, 1968, *Leptostrophomena jamesoni* (Reed, 1917) and *Fardenia (Saughina) pertinax* (Reed, 1917).

Interpretation

A marine basin occupied the Girvan area during the early Silurian, probably in a back-arc setting (Bluck, 1983). Historically, the Llandovery succession at Girvan has commonly been contrasted with that of the Moffat area (see the Dob's Linn site report), where the succession is thinner and entirely within the deep-water graptolitic facies. Cocks and Toghill (1973), however, considered that although there are shelly faunas at Girvan, most of the deposition did not take place in shallow water. Apart from the basal units, including those exposed at Woodland Point, they attributed the Llandovery strata to relatively deep environments, where turbidites and graptolitic shales accumulated. Cave (in Bassett *et al.*, 1992), in contrast, suggested that the coarse clastic units might represent sub-littoral, storm-generated sand sheets rather than turbidites, and that the water may not have been deep. The presence of faunas of the *Stricklandia* and *Clorinda* benthic communities in life position in the Woodland Formation is certainly evidence of an offshore shelf environment during the Rhuddanian age. Overall, the Girvan sequence has been interpreted as part of a proximal fore-arc succession, derived from a magmatic arc that probably lay only a few kilometres to the north (Bluck and Ingham, 1992). There was probably no direct sedimentological link with the Southern Uplands Terrane during the Llandovery Epoch (Phillips *et al.*, 1998).

The unconformity recognized at the base of the Silurian sequence in the coastal exposures and elsewhere (Lapworth, 1882; Cocks and Toghill, 1973) may be local evidence of the widely recognized late Ordovician glacio-eustatic regression. However, the unconformity may represent the development of deep submarine channels, cutting into the Ordovician strata during the early Silurian, rather than an episode of subaerial erosion (Ingham, 1992a). The Craigskelly Conglomerate lies on higher levels of the Ordovician Shalloch Formation at Craigskelly than at Woodland Point, where the conglomerate is only patchily developed; the exposures therefore demonstrate southward overstep and overlap (Cocks and Toghill, 1973; Harper, 1988). The development of a *Stricklandia* benthic community in the lower part of the Woodland Formation, followed by a *Clorinda* community in the middle part, is evidence of sequential deepening, continuation of which is indicated by the presence of a graptolitic level in the upper beds. A major influx of detritus into the subsiding basin by mass flows is indicated by the conglomeratic proximal turbidites of the Scart Grits.

Biostratigraphical correlations of the different outcrops of Llandovery strata in the Girvan area were detailed by Cocks and Toghill (1973) and are shown in Figure 3.78.

Conclusions

Woodland Point is an important locality for demonstrating the unconformable relationship between the Ordovician and Silurian strata in the classic Girvan area, and provides the best exposures of the early Llandovery (Rhuddanian) succession of the region. It is the type locality of the Woodland Formation, which has rich brachiopod faunas in the lower part and diverse graptolites towards the top. Brachiopod-dominated faunas in life position in the middle of the formation represent the *Stricklandia* and *Clorinda* benthic communities, indicative of an offshore shelf depositional setting for this part of the succession. This environment has been contrasted in the literature with the deep-water graptolitic shale facies displayed by the earliest Silurian rocks of the Moffat district in the Southern Uplands. The Girvan sites are, therefore, of importance in building up a picture of early Silurian palaeogeography and tectonic settings in southern Scotland.

ROUGHNECK QUARRY (NS 2703 0398)

Introduction

The Craighead Inlier (Figure 3.74) lies to the north of the Girvan Valley in the Kyle and Carrick region of south-west Scotland. The stratigraphy was first elucidated by Lapworth (1882) in his classic paper on the Girvan area, and this work was extended by Peach and Horne (1899). Further studies were published by Lamont (1935) and Freshney (1959), the latter showing that the inlier extended farther to the north-east than had been previously appreciated. More recently, Cocks and Toghill (1973) revised the lithostratigraphy and summarized the biostratigraphy of the succession. They recognized the following formations in the Craighead Inlier, in ascending stratigraphical order: the Lady Burn Conglomerate, the Mulloch Hill Formation, the Glenwells Shale, the Glenwells Conglomerate, the Newlands Formation, the Glenshalloch Shale, the Upper Saugh Hill Grits, the Pencleuch Shale and the Lower Camregan Grits.

The quarry at Roughneck (also sometimes termed 'Rough Neuk Quarry' or 'Mulloch Hill Quarry'), in Ladywell Wood, exposes strata in the upper part of the Mulloch Hill Formation, which has a total local thickness of 240 m (Cocks and Toghill 1973). This is the most fossiliferous formation in the Craighead Inlier, and is well displayed in the quarry. The diverse fauna indicates an age in the upper part of the Rhuddanian Stage (Cocks and Toghill 1973), and allows comparisons with other early Llandovery shelly faunas elsewhere in Scotland and in the Welsh Basin. A biostratigraphical correlation of the succession in the Craighead Inlier with those of other outcrops in the Girvan area is shown in Figure 3.78.

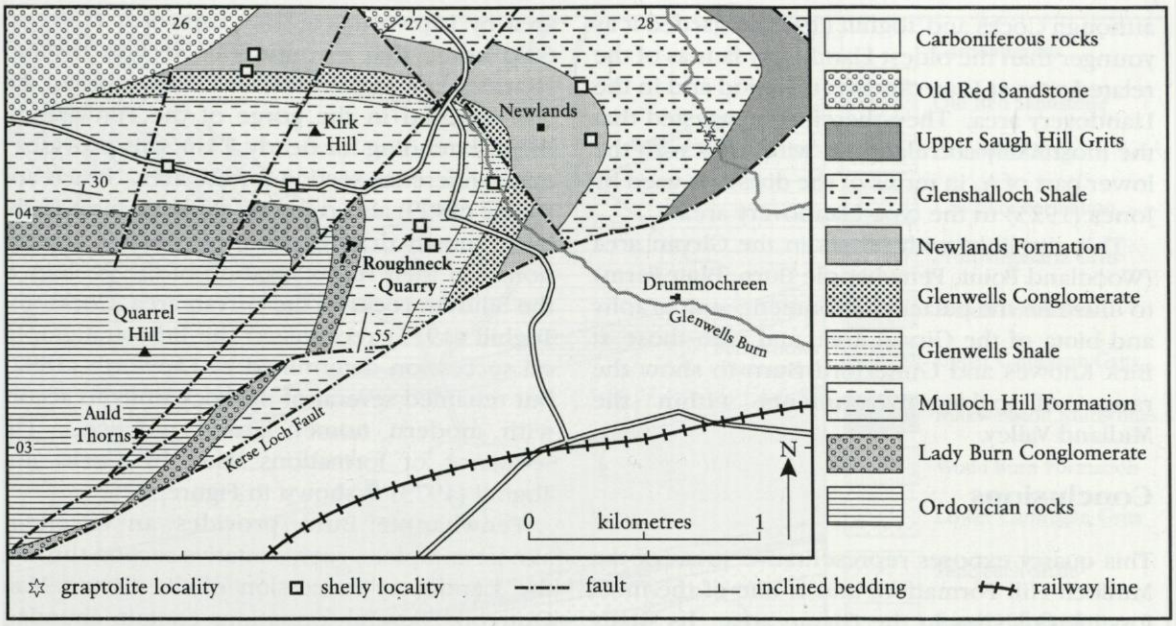

Figure 3.74 Geological map of the Craighead Inlier, showing the location of Roughneck Quarry (after Cocks and Toghill, 1973).

Description

The quarry is situated about 125 m west of the farmhouse of Rough Neuk. The strata comprise sandy shales and thick-bedded sandstones dipping to the east at 40°. The rocks are rich in shelly fossils; a very long list of the fauna was provided by Peach and Horne (1899, p. 530), based on their own collecting and on material collected by Mrs Elizabeth Gray. The assemblage includes calcareous algae, corals (*Aulacophyllum, Favosites, Heliolites* and others), trilobites (*Calymene, Acaste, Encrinurus, Staurocephalus* and others), diverse gastropods, bivalves, conulariids, tentaculitids, bryozoans, asteroids, crinoids, dendroid graptolites, orthocones, and very abundant and varied brachiopods. Cocks and Toghill (1973, p. 213) reported that one sample of 255 specimens from the quarry comprised 69% brachiopods (35% *Dalmanella* sp., 15% *Mendacella mullochiensis*, 14% *Cryptothyrella angustifrons*), 12% corals, plus 15 other species, and referred the collection to a high diversity *Cryptothyrella* benthic community. The quarry is the type locality for a number of fossil taxa, including the brachiopods *Philhedrella mullochensis* (Reed, 1917), *Isorthis prima* Walmsley and Boucot, 1975, *Fardenia (Fardenia) columbana* (Reed, 1917), *Eostropheodonta mullochensis* (Reed, 1917) and *Rostricellula mullochensis* (Reed, 1917).

Interpretation

The Girvan area lies in the Midland Valley, between the Highland Boundary Fault to the north and the Southern Uplands Fault to the south; this region accumulated relatively shallow marine and non-marine sediments during the early Silurian (see Bluck, 1983, and Chapter 1 for regional setting). At Roughneck Quarry, the presence of calcareous algae and a *Cryptothyrella* benthic community indicates that the Mulloch Hill Formation was deposited in a shallow-water environment in which the shelly fossils have been concentrated by bottom currents (Cocks and Toghill, 1973). The shoreline was probably nearby to the north or north-west (Ingham, 1992b). The underlying Lady Burn Conglomerate contains a lower diversity *Cryptothyrella* Community and the overlying Glenwells Shale is graptolitic, indicating a deepening upwards sequence. The graptolites give a *cyphus* Biozone age for the Glenwells Shale, so the Mulloch Hill Formation is Rhuddanian, although Cocks and Toghill (1973) regarded it as younger than the oldest Llandovery faunas of the related sites at Haverfordwest, Meifod and in the Llandovery area. They, therefore, suggested that the most likely correlation is with A_3 or with the lower part of A_4 in terms of the divisions used by Jones (1925) in the type Llandovery area.

This site links with others in the Girvan area (Woodland Point, Penwhapple Burn, Blair Farm) to illustrate the palaeoenvironment, stratigraphy and biota of the Girvan area, and with those at Birk Knowes and Gutterford Burn to show the range of palaeoenvironments within the Midland Valley.

Conclusions

This quarry exposes representative strata of the Mulloch Hill Formation, and is one of the most fossiliferous sites in the Girvan area. Its shelly macrofauna is more diverse than that of almost any other early Llandovery site in Britain, and fossils have been collected from it since the early part of the 19th century. Brachiopods are especially abundant, and the fauna has been referred to a shallow-water *Cryptothyrella* benthic community. The fossils in the formation, together with the constraints placed by the presence of latest, Rhuddanian graptolites in the overlying Glenwells Shale, suggest an age of late, but not latest, Rhuddanian. This is an important locality for regional and comparative investigations of early Silurian marine faunas and environments.

PENWHAPPLE BURN (NX 2327 9769–NX 2262 9892)

Introduction

Penwhapple Burn lies within an outcrop of Silurian rocks to the south of the Girvan Valley, separated from the Craighead Inlier on the north side by a strip of Old Red Sandstone and Carboniferous rocks. This region, termed 'the Main Outcrop' by Cocks and Toghill (1973) in their description of the Silurian strata of the Girvan area (Figure 3.82), displays a succession of formations striking nearly east–west, with the dips nearly all vertical or overturned, so that the rocks dip southwards but young northwards. Along the burn, there are exposures through the complete local Silurian succession (Figure 3.75).

The succession was not fully elucidated until publication of the classic paper on the Girvan area by Lapworth (1882). Lapworth (1882, p. 603) noted that a continuous section through strata of late Ordovician and early Silurian age was exposed in the gorge of the Penwhapple Burn, extending for nearly 5 km; this provides a major reference section for the area. Peach and Horne (1899) also reported the exposures in the burn, mostly drawing from Lapworth's descriptions. In their reinvestigation of the geology of the Silurian rocks of the Girvan area, Cocks and Toghill (1973) recognized the lithostratigraphical succession determined by Lapworth (1882), but renamed several of the rock units to accord with modern nomenclatural practice. The sequence of formations used by Cocks and Toghill (1973) is shown in Figure 3.75.

Penwhapple Burn provides an excellent, almost complete, representative section through the Llandovery succession of the Girvan Main Outcrop. Several formations contain abundant graptolites, allowing accurate local and international correlation of the sequence.

Description

A full description of the succession in and around the burn was given by Cocks and Toghill (1973), whose observations are summarized here. The basal Silurian unit, the Tralorg Formation (the *modestus* Shales of Lapworth), lies unconformably on the Shalloch Formation (the Barren Flagstones of Lapworth), with a gentle overstep westerly onto successively lower levels within this upper Ordovician unit. The contact is exposed in Penwhapple Burn (NX 2327 9769), 360 m north-west of Penwhapple Bridge; the junction here is inverted, with the basal Silurian strata dipping 50° SSE. The lowest beds of the Tralorg Formation consist of 1.5 m of concretionary mudstones with echinoderm fragments and rare brachiopods, identified as *Leangella scissa* and *Clorinda* sp.. The entire thickness of the formation is about 180 m, although estimates are complicated by small faults and folds. Above the basal beds are black pyritic mudstones and thin grey mudstones, which grade up into banded grey and green shales with thin sandstone beds. Graptolites are common in the black mudstones and occur occasionally in the shales of the upper part of the formation. The lower black mudstones have yielded a diverse fauna, including *Atavograptus atavus, A. strachani, Coronograptus cyphus, Monograptus revolutus, Rhaphidograptus*

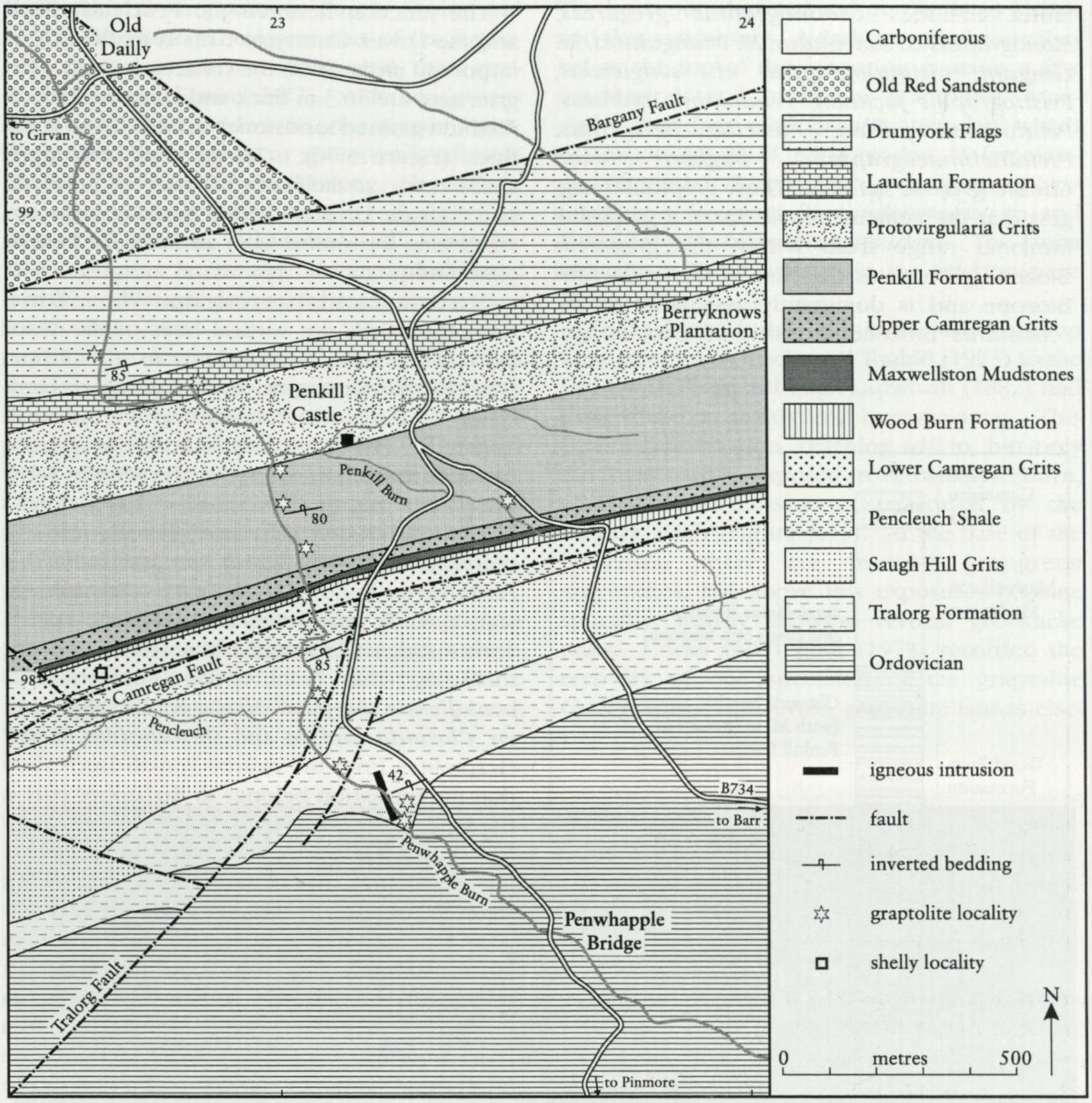

Figure 3.75 Geological map of the Penwhapple Burn area, Main Outrcrop, Girvan (after Cocks and Toghill, 1973).

toernquisti, Climacograptus rectangularis, C. normalis and *C. medius,* with *C. cyphus* and *M. revolutus* persisting into the higher shales. Both of these faunas are indicative of the uppermost Rhuddanian *cyphus* Biozone.

The Tralorg Formation is succeeded abruptly and conformably by the Saugh Hill Grits, which are 180 m thick in Penwhapple Burn. The formation comprises thick greywackes with thin shales and occasional conglomerates. In the middle of the unit is a conspicuous 30 m shale sequence, which contains a few unidentifiable fragments of graptolites.

The Pencleuch Shale (the *M. Sedgwickii* Mudstones of Lapworth) is well exposed in the burn, but is extremely contorted so that bedding is not evident; the estimated thickness is 60 m. Cocks and Toghill (1973) distinguished a lower grey shale subdivision from an upper unit of black shales with large calcareous nodules. The higher unit contains abundant graptolites, sometimes well preserved. The very diverse fauna includes *Coronograptus gregarius*, *Monograptus* cf. *convolutus*, *M. triangulatus*, *M. clingani*, *Stimulograptus* cf. *sedgwickii*, *Pristiograptus jaculum*, *Petalolithus palmeus*, *Petalolithus folium*, *Rastrites peregrinus*, *Pseudoclimacograptus hughesi* and *Climacograptus scalaris*. These graptolites suggest that the Penleuch Shale spans a graptolite biozonal range from within the *gregarius* Biozone perhaps to the base of the *sedgwickii* Biozone and is dominantly assignable to the *convolutus* Biozone. It is thus of Aeronian age.

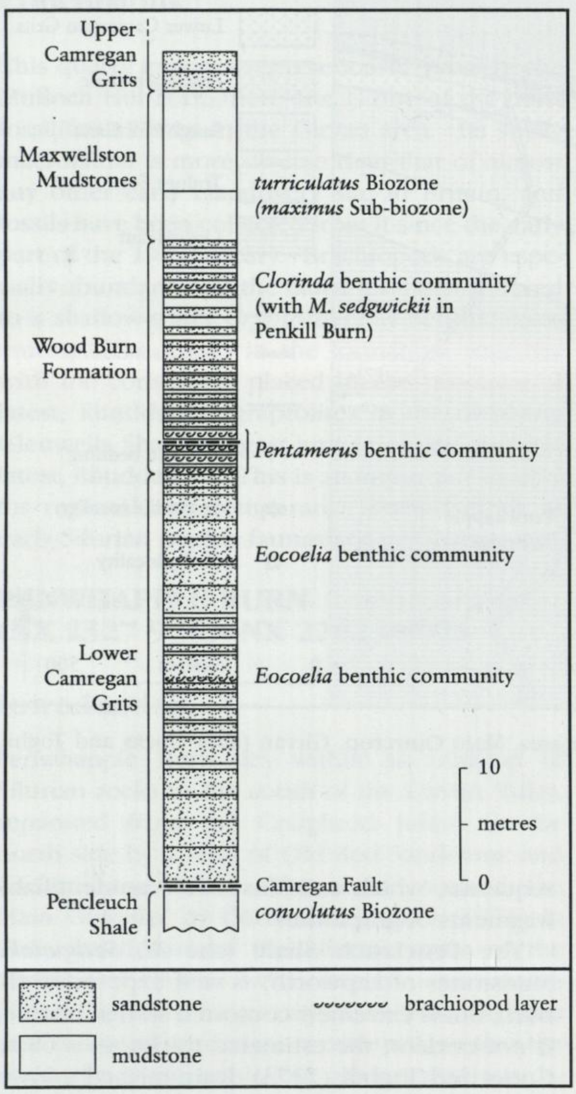

Figure 3.76 Sedimentary log through the Lower Camregan Grits, Wood Burn Formation and Maxwellston Mudstones in Penwhapple Burn (after Cocks and Toghill, 1973).

The junction between the Pencleuch Shale and the Lower Camregan Grits is marked by an important strike fault, the Camregan Fault. The grits here are 36.3 m thick and comprise fine- to medium-grained sandstones in beds 0.1 to 0.6 m thick (Figure 3.76). Transported brachiopod shells occur at the bases of some of the beds, and include rhynchonellids and *Eocoelia* sp., suggesting derivation from an *Eocoelia* benthic community.

Stratigraphically overlying the Lower Camregan Grits are vertical beds of the Wood Burn Formation (equivalent to the Upper *Pentamerus* Limestone and Camregan Limestone of Lapworth), comprising an estimated 19.6 m of siltstones and sandstones grading upwards into siltstones and shales (Figure 3.76). The lower part of the formation has yielded a brachiopod fauna that includes *Pentamerus oblongus* and *Steptalasma* sp., assignable to a *Pentamerus* benthic community. Towards the top, a much more diverse assemblage occurs, constituting a *Clorinda* benthic association, and including the brachiopods *Eoplectodonta penkillensis*, *Atrypa reticularis*, *Coolinia pecten*, *Clorinda undata* and *Skenidioides lewisii*. Graptolites from the nearby Penkill Burn show that the formation belongs to the upper part of the *sedgwickii* Biozone, of uppermost Aeronian age.

The Wood Burn Formation is succeeded abruptly by purple mudstones (the *Rastrites maximus* Mudstones of Lapworth) termed the Maxwellston Mudstones. The formation is 13 m thick, with a 0.3 m bed of dark grey graptolitic mudstone apparent 3.8 m above the base (Figure 3.76). The graptolite fauna includes numerous *Spirograptus turriculatus*, together with *Streptograptus barrandei*, *Torquigraptus planus*, *Stimulograptus halli*, *Pristiograptus nudus*, *P. regularis*, *Rastrites linnaei*, *R.* cf. *maximus* and *Petalolithus altissimus*. This fauna is characteristic of the lowermost *turriculatus* Biozone (*maximus* Sub-biozone), of earliest Telychian age.

Pale greenish-brown greywackes that abruptly follow the Maxwellston Mudstones are referred to the Upper Camregan Grits. These are 33 m thick in Penwhapple Burn, where they have not yielded fossils, but a small quarry in the formation at Camregan Wood (NX 2256 9813) has provided a *turriculatus* Biozone fauna.

Above the Upper Camregan Grits is the 210 m thick Penkill Formation, which is equivalent to

Lapworth's *Crossopodia* or Purple Shales and his Penkill Flags. The lower part of the formation comprises purple shales and thin grey-green shales (Figure 3.77), with sandstones becoming interbedded in the upper part. Graptolitic horizons occur sporadically, all with faunas of the *turriculatus* Biozone. The highest recorded fauna, 15 m below the top of the formation contains *Oktavites* aff. *spiralis, Streptograptus barrandei, Monograptus marri* and *Monoclimacis galaensis*. Meandering trace fossils also occur.

Only the lower 90 m of the 165 m thick Protovirgularia Grits are exposed in Penwhapple Burn, where the formation consists of greywacke units in which shale is subordinate. The trace fossil *Protovirgularia* occurs in the shales. Graptolites are not known from the sequence in the burn, but higher beds elsewhere have yielded faunas assigned to the *crispus* and *griestoniensis* biozones.

The Lachlan Formation (the *Cyrtograptus grayi* Mudstones of Lapworth) reaches a thickness of about 50 m in Penwhapple Burn, although the lowermost beds are not exposed. The unit comprises red and purple flaggy shales and thin sandstones. A dark grey mudstone 9 m below the top of the formation contains a few brachiopods and numerous graptolites, especially abundant *Monograptus priodon* which occurs along with *M. parapriodon, M. knockensis, M. marri, Torquigraptus dextrorsus, Lapworthograptus grayi, Barrandeograptus* sp. and *Retiolites geinitzianus angustidens.* The fauna indicates a Telychian age, in the *griestoniensis* Biozone.

The highest Silurian beds in the Main Outcrop were referred by Cocks and Toghill (1973) to the Drumyork Flags, although Lapworth (1882) had three divisions at this level in some areas. This is a thick formation, reaching 610 m, but only the lower part is exposed in Penwhapple Burn, where the succession is truncated by the Bargany Fault (Figure 3.75). At the base of the formation there are massive grey-green greywackes, but above this exposures become sporadic, mostly showing vertical greywacke units. Cocks and Toghill (1973) recorded the recovery of one specimen of the graptolite *Cyrtograptus? lapworthi*; graptolite faunas else-

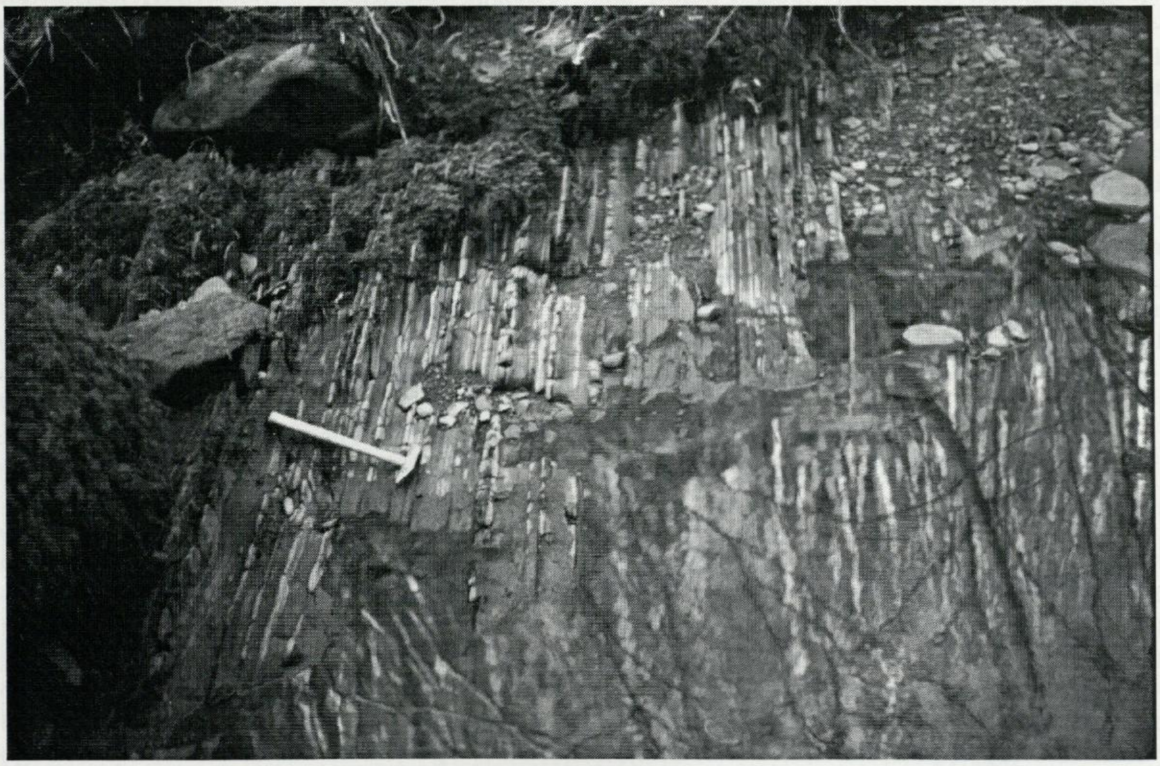

Figure 3.77 Purple mudstones of the Penkill Formation, Penwhapple Burn. (Photo: TS1493, reproduced by kind permission of the Director, British Geological Survey, © NERC.)

where in the main outcrop show that the strata still belong in the *griestoniensis* Biozone.

Interpretation

Much of the sequence at Girvan was considered by Cocks and Toghill (1973) to have been deposited in relatively deep water, characterized by graptolitic shales or by turbidites. Cave (in Bassett *et al.*, 1992), however, suggested that the sea may not have been particularly deep and that the greywackes may represent sub-littoral, storm-generated sands rather than turbidites. A

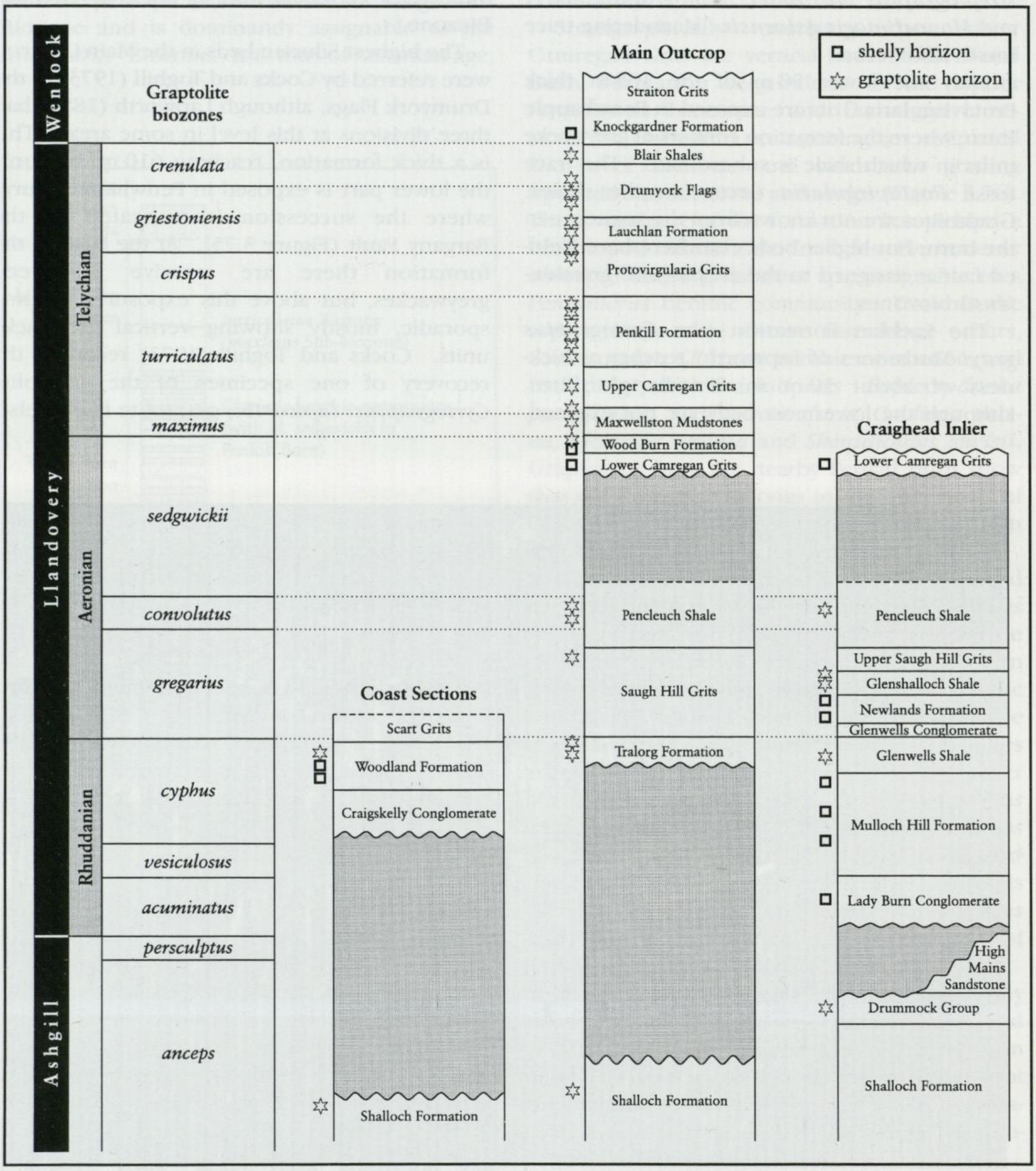

Figure 3.78 Correlation of the Llandovery successions within the various outcrops in the Girvan area (modified after Cocks and Toghill, 1973).

few horizons with shelly fossils certainly indicate a shelf environment, although mostly in the mid and offshore shelf areas.

Lapworth (1882) considered the junction between the Ordovician and Silurian strata in the Main Outcrop to be a fault, but Cocks and Toghill (1973) showed it to be an unconformity both here and in the coastal exposures (see description of the GCR site at Woodland Point). In the Main Outcrop there are no equivalents of the shallow water Craigskelly Conglomerate of the coast sections, nor of the Lady Burn Formation and Mulloch Hill Formation of the Craighead Inlier, so the unconformity incorporates a greater portion of the Rhuddanian in this region. By combining the thickness of the succession in the Craighead Inlier up to the top of the Saugh Hill Grits (1323 m) with that of the Main Outcrop from the Pencleuch Shale to the top of the succession (1514 m), Cocks and Toghill (1973) arrived at a total of 2837 m, nearly three times the figure estimated by Lapworth (1882).

The biostratigraphical data accumulated by Cocks and Toghill (1973) allowed a refinement of the correlations between the outcrops in the Girvan area, and a revision of some of Lapworth's conclusions. Cocks and Toghill's (1973) correlations are shown in Figure 3.78. The recovery of graptolite faunas throughout the succession in the Main Outcrop has demonstrated that the whole sequence is of Llandovery age, in contrast to the suggestion of Walton (1965) that, on lithological grounds, all the formations above the Maxwellston Mudstones might be of Wenlock age. Cocks and Toghill (1973) also postulated a stratigraphical break at the base of the Lower Camregan Grits, equivalent to much of the *sedgwickii* Biozone; their evidence for this comes from the abrupt replacement of euxinic black graptolitic shales of the Pencleuch Shale by shallow-water sandstones with an *Eocoelia* benthic community.

Many of the lithological characteristics of the Girvan sequence were undoubtedly strongly influenced by local factors, particularly at the base and near the top of the succession. However, the effects of more widespread or global changes may also be evident. The very diverse *convolutus* Biozone graptolite fauna of the Pencleuch Shale correlates with a widely recognized episode of diversification in planktonic communities, termed the Jong Primo Episode by Aldridge *et al.* (1993a). The abrupt change to the shelly fauna of the Lower Camregan Grit could, therefore, be attributed to the Sandvika Event, which terminated this episode, or to the onset of the Malmøykalven Secundo Episode. The return of diverse graptolites in the *turriculatus* Biozone would then relate to the beginning of the Snipklint Primo Episode, which persisted for the rest of the Telychian. The oxygenation of deep bottom waters that is characteristic of primo episodes (Jeppsson, 1990) is recognizable in the common development of trace fossils, indicative of a healthy substrate.

The site at Penwhapple Burn combines with those at Woodland Point, Roughneck Quarry and Blair Farm to provide a representative coverage of the early Silurian stratigraphy and palaeoenvironments of the Girvan area. Further sites in the Midland Valley (Birk Knowes, Gutterford Burn) illustrate the wider palaeoenvironmental setting.

Conclusions

In Penwhapple Burn there is an almost complete section through the Llandovery succession of the Main Outcrop in the Girvan area, and this provides an important reference sequence for the whole region. There are numerous graptolitic horizons through the succession, containing abundant specimens, which are often well preserved. This has allowed accurate dating of the sequence, which ranges from the *cyphus* Biozone to the *griestoniensis* Biozone. The graptolites also enable accurate international correlation of the Girvan succession, and provide a basis for recognizing global influences on the local depositional environment. This is, therefore, a site of considerable significance for local, regional and international studies of stratigraphy, palaeontology and palaeoecology.

BLAIR FARM (NS 3248 0233)

Introduction

The area between Blair and Knockgardner, Kyle and Carrick (Figure 3.79), lying to the west of the other Girvan localities, displays the highest part of the Silurian succession in the Girvan district. Throughout the Blair area the strata are vertical or overturned, dipping to SSE but younging northwards. The fourfold stratigraphical division for the local Silurian shown in

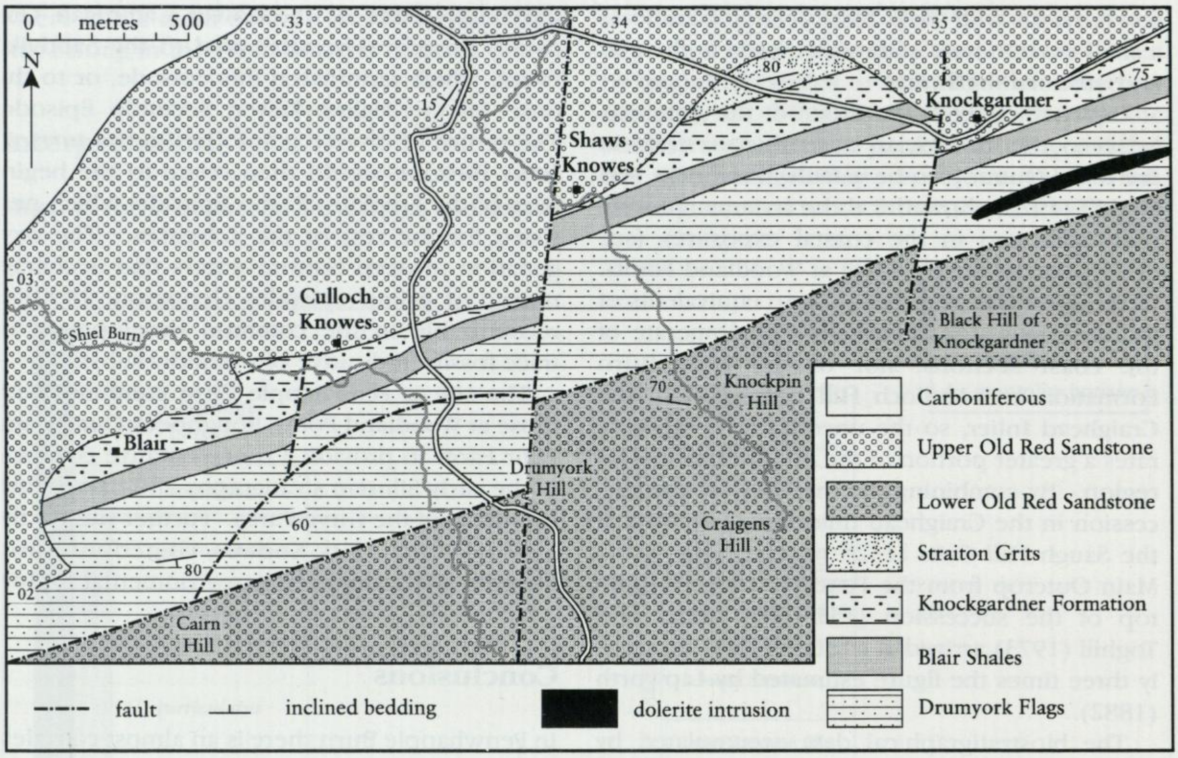

Figure 3.79 Geological map of the Blair–Knockgardner district, Girvan area (after Cocks and Toghill, 1973).

Figure 3.79 was introduced by Lapworth (1882) and followed by Cocks and Toghill (1973).

The section in the gully 70 m SSE of Blair Farm provides the type section for the Blair Formation and also displays the base of the overlying Knockgardner Formation. The Blair Formation is 84 m thick in total (Cocks and Toghill, 1973) and at Blair Farm has yielded a well-preserved graptolite fauna of the upper Telychian *crenulata* Biozone. It also holds high potential for palynological studies.

Description

Cocks and Toghill (1973) described the exposures of the Blair Formation in the gully as comprising 27 m of inverted beds dipping 75° in a direction of 145°. The rocks are soft, thin-bedded yellowish-brown sandstones and shales, in which three graptolitic horizons have been identified. Cocks and Toghill (1973, p. 233) gave the complete graptolite fauna as *Monoclimacis crenulata, Monoclimacis vomerina vomerina, Monoclimacis* sp. nov., *Monograptus tullbergi spiraloides, Monograptus priodon, Monograptus* aff. *spinulosus, Oktavites spiralis* and *Retiolites geinitizianus angustidens*; they assigned this assemblage to the uppermost Telychian *crenulata* Biozone. Spiral graptolites are particularly abundant in the middle horizon, while the lower and upper horizons contain abundant three-dimensionally preserved vomerinids.

The boundary with the overlying Knockgardner Formation is transitional. Three metres are exposed in the gully at Blair Farm, and contain a sparse brachiopod fauna. The brachiopods found locally in the Knockgardner Formation are referred to the *Howellella–Protochonetes* benthic association, which is of Wenlock aspect (Cocks and Toghill, 1973). Hence, the Llandovery–Wenlock boundary approximates to the junction between the Blair and Knockgardner formations.

The thermal maturation of the rocks is low, and they have yielded a well-preserved, but undescribed, acritarch microflora (Dorning, pers. comm.). There is thus clear potential for important palynological research.

Interpretation

The Girvan area lies in the Midland Valley, where marine and non-marine sediments accumulated during the early Silurian (see Bluck, 1983, and Chapter 1 for regional setting). The recognition of a *crenulata* Biozone graptolite fauna in the Blair Formation shows that most of the Silurian succession of the Girvan area is of Llandovery age, with only the highest two formations (the Knockgardner Formation and the Straiton Grits) being assignable to the Wenlock. The presence of a *Howellella–Protochonetes* assemblage in the Knockgardner Formation suggests deposition under fairly shallow water (Cocks and Toghill, 1973), although the shells have clearly been transported, and much of the formation has been interpreted as turbiditic. The Drumyork Flags, which underlie the Blair Formation, were also interpreted by Cocks and Toghill (1973) as turbidites, which would indicate a relatively offshore setting for the whole of the Telychian sequence in this area.

Conclusions

The site at Blair Farm combines with others in the Girvan area (Woodland Point, Roughneck Quarry, Penwhapple Burn) to provide a network of sites representative of the Silurian succession and to enable interpretation of the depositional history. The strata of the Blair Formation contain a well-preserved assemblage of uppermost Llandovery graptolites, and the succeeding Knockgardner Formation, of which the basal 3 m are exposed at this locality, is probably all of Wenlock age. These are, therefore, the highest Llandovery strata in the Girvan area. The locality holds important potential for future palaeontological research, particularly on the graptolites and acritarchs.

GUTTERFORD BURN (NT 1595 5942–NT 1555 5795)

Introduction

This important site encompasses the banks of Gutterford Burn and the northern and eastern margins of the North Esk Reservoir. The locality is situated in the North Esk Inlier (Figure 4.72), which is the largest of three Silurian inliers in the Pentland Hills (Figure 3.82), about 25 km south-west of Edinburgh. The first description of the succession in the area was given by Howell and Geikie (1861), and the first detailed map was produced shortly afterwards (Brown and Henderson, 1867; Henderson and Brown, 1870). Subsequently, numerous geologists have described or commented on the rocks and fossils of the inlier. The area was remapped by Mykura and Smith (1962) and by Tipper (1976), and a palaeoenvironmental interpretation of the Silurian succession has been published by Robertson (1989).

Throughout the inlier the strata dip steeply or vertically with a strike of 030–040°; the succession youngs to WNW. Henderson and Brown (1870) considered the rocks to be of Wenlock and Ludlow age, while Peach and Horne (1899) believed that they extended into the Downton (= Přídolí). Lamont (1947a, b), however, used faunal evidence to show that much of the succession is of Llandovery age, with the youngest beds assignable to the Wenlock Series. Formal stratigraphical names were introduced for the succession by Tipper (1976), who defined a North Esk Group within which he identified four formations: the Reservoir Formation, the Deerhope Formation, the Wether Law Linn Formation and the Henshaw Formation. Robertson (1989) added the Cock Rig Formation between the Deerhope and Wether Law Linn formations, and subdivided the Wether Law Linn Formation into three members. Palaeontological evidence has been used to assign the strata spanning the Reservoir, Deerhope and Cock Rig formations to the Telychian Stage, along with much of the Wether Law Linn Formation (Tipper, 1976; Robertson, 1989). The base of the Wenlock Series has in recent years been regarded as occurring in the vicinity of the base of the Henshaw Formation, although Robertson (1989) considered it likely that the chronostratigraphical boundary lies within the upper member of the Wether Law Linn Formation.

The GCR site at Gutterford Burn (Figure 3.80) lies entirely within the Reservoir Formation, for which it forms part of the type section (Tipper, 1976). The base of the formation is not seen in the inlier, but more than 1000 m of alternating mudstones and siltstones outcrop below the base of the overlying Deerhope Formation. The boundary between the two formations is not exposed, but maps out as conformable (Tipper, 1976). Generally the Reservoir Formation is

Figure 3.80 Gutterford Burn, North Esk Inlier, showing patchy exposures of the Reservoir Formation. (Photo: E.N.K. Clarkson.)

sparsely fossiliferous, but there are a few shelly horizons and Gutterford Burn is famous for the occurrence of eurypterid and starfish beds (e.g. Laurie, 1892, 1899; Peach and Horne, 1899; Spencer, 1914–1940). Exposures of the upper part of the Reservoir Formation and of the Deerhope, Cock Rig, Wether Law Linn and Henshaw formations are available locally in the banks of Deerhope Burn, Wether Law Linn, Henshaw Burn and the North Esk River.

Description

The oldest beds exposed in this section occur at the south-east corner of the reservoir, where sandy bases to siltstone beds contain abundant fragments of the phyllocarid arthropod *Dictyocaris* (Mykura and Smith, 1962). Above this, on the shores of the reservoir and along Gutterford Burn, Mykura and Smith (1962, p. 14) recorded the following succession:

(iv)	grey to olive mudstones with laminae of siltstone and thin beds of flaggy sandstone near the base	200 m +
(iii)	flaggy buff or dark grey grits interbedded with grey mudstones (Gutterford Burn flagstones)	120 m
(ii)	mudstones and silty mudstones with laminae of siltstone and rare beds of flaggy greywacke (Gutterford Burn mudstones)	125 m
(i)	fine-grained grits and siltstones in units up to 20 m thick, alternating with units of interlaminated mudstone and siltstone	seen to 50 m

Strata near the base of the Gutterford Burn mudstones contain trace fossils, orthocones, and the brachiopods *Craniops implicatus* and *Glassia compressa*. Graptolites are mostly recorded from the Gutterford Burn flagstones and from the lower 20 m of the overlying flaggy sandstones; the graptoloid assemblage (Robertson, 1989) is dominated by monoclimacids (referable to *Monoclimacis vomerina sensu lato*) with *Oktavites spiralis*. These indicate a *crenulata* Biozone age (Bull, 1987; Robertson, 1989). Dendroids, which generally outnumber the graptoloids, were described by Bull (1987).

Near the top of the Gutterford Burn flagstones is a 20–25 cm thick impure limestone, the Gutterford Burn limestone, which contains numerous crinoid columnals, together with corals, brachiopods, bryozoans, tentaculitids, trilobites, orthocones, ostracods and graptolites; faunal lists have been given by Peach and Horne (1899, p. 595), by Mykura and Smith (1962, p. 14) and by Robertson (1989, p. 130). Samples of the limestone dissolved in acetic acid have yielded conodont elements, including specimens of *Pterospathodus amorphognathoides*, indicative of a horizon close to the Llandovery–Wenlock boundary (RJA, unpublished collections). The presence of the coral *Palaeocyclus porpita*, reported by Mykura and Smith (1962), is consistent with this age assignment.

Near the top of the Gutterford Burn flagstones there is a 30 cm band that contains abundant remains of well-preserved arthropods, whose skeletons or exuviae are often articulated. Known in the literature as the Eurypterid Bed (Figure 3.81), this has yielded a very diverse arthropod fauna, including many species of eurypterid, a scorpion, phyllocarids and problematical taxa (Laurie, 1892, 1899; Peach and Horne, 1899; Waterston, 1979). Peach and Horne (1899) published a full faunal list for this bed, which also contains calcareous algae, graptolites, corals, tentaculitids, crinoid fragments, brachiopods, gastropods, conulariids and orthocones.

There is a gradual transition from the flagstones into the overlying dominantly argillaceous beds. Within these transitional strata two starfish-bearing horizons have been identified (Peach and Horne, 1899; Mykura and Smith, 1962), from which Spencer (1914–1940) has described a diverse asteroid fauna. Other fossils in this part of the section include sparse brachiopods (especially *Lissatrypa atheroidea*), trilobites and graptolites.

Gutterford Burn is the type locality for numerous fossils, including the dendroid graptolite *Dictyonema pentlandica* Bull, 1987, twelve eurypterid species (Laurie 1892, 1899; Waterston, 1979), the scorpion *Palaeophonus loudonensis* (Laurie, 1899), the crinoids *Macrostylocrinus silurocirrifer* Brower, 1975, *Ptychocrinus longibrachialis* Brower, 1975, *Dimerocrinites pentlandicus* Brower, 1975, *Herpetocrinus parvispinifer* Brower, 1975 and *Dendrocrinus extensidiscus* Brower, 1975, the

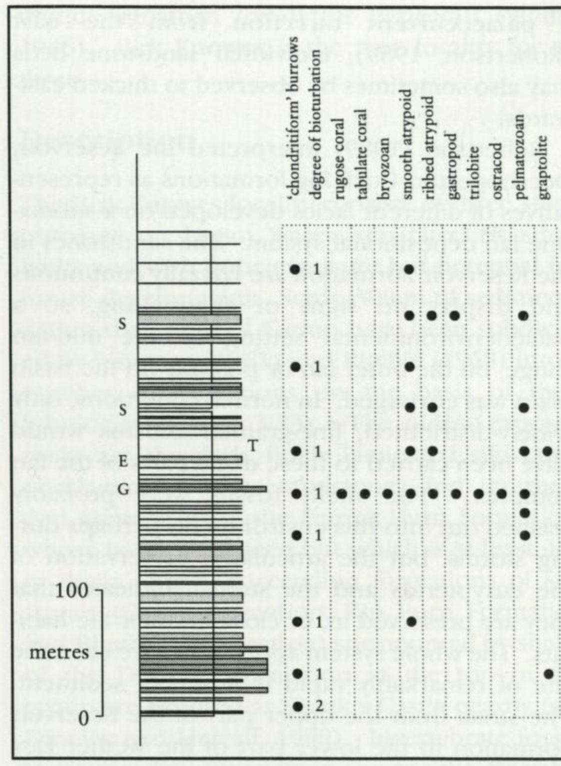

Figure 3.81 Measured section of the Reservoir Formation in Gutterford Burn (after Robertson, 1989). G = Gutterford Burn Limestone, E = Eurypterid Bed, S = Starfish beds.

echinoid *Aptilechinus caledonensis* Kier, 1973, and the starfish species *Urasterella gutterfordensis* Spencer, 1916, *Schuchertia wenlocki* Spencer, 1920, *Protactis wenlockensis* (Spencer, 1922), *Lepyriactis nudus* Spencer, 1925, *Taeniactis wenlocki* Spencer, 1925, and *Crepidosoma wenlocki* Spencer, 1928.

Interpretation

The overall lithology of the Reservoir Formation comprises alternations of homogeneous mudstones and sandy siltstones, with the relative frequency varying considerably (Tipper, 1976). The siltstone beds have sharp lower and upper surfaces, and may show low-angle cross-lamination or convolute lamination. Robertson (1989) suggested that, at least in places, these sequences represent intervals Tbce, Tcde, or Tce of the Bouma turbidite sequence (Figure 3.40). Some of the siltstone and sandstone beds show tool marks on the lower surfaces and these, together with evidence from ripple marks, show a palaeocurrent direction from the east (Robertson, 1989); individual sandstone beds may also sometimes be observed to thicken eastwards.

Robertson (1989) interpreted the Reservoir, Deerhope and Cock Rig formations as representatives of different facies developed on a submarine fan depositional system. The sandstones in the Reservoir Formation are laterally continuous and display no signs of channelling, so a palaeoenvironmental setting on the mid-fan fringe, on the outer fan or possibly on the basin plain was envisaged. In normal conditions, only widely-distributed, fine-grained detritus would have been carried to these distal parts of the fan complex. The shelly fossils were probably washed out into this environment, perhaps during storms, but the articulated preservation of the eurypterids and the starfish indicates that they are preserved in, or close to, their life habitats. The whole system appears to have been the site of remarkably rapid build-up of sediment. The strata from the upper part of the Reservoir Formation to the lower part of the Wether Law Linn Formation are all demonstrably within the *crenulata* Biozone, which may reach a total thickness of 2000 m (Bull, 1987). The presence of the conodont *Pterospathodus amorphognathoides* in the Gutterford Burn Limestone is indicative of a very high Telychian age for this part of the succession and, if the graptolite evidence is secure, this means that this entire thickness was probably deposited within the interval of the *P. amorphognathoides* Conodont Biozone. As a comparison, at the network site at Hughley Brook in Shropshire the *P. amorphognathoides* Biozone is represented by only 0.9 m of strata (Mabillard and Aldridge, 1985).

The Silurian succession in the North Esk Inlier accumulated near the southern margin of the Midland Valley graben, and records a regressive sequence from the offshore marine fan, through a shallow shelf environment (Wether Law Linn Formation) into the terrestrial, alluvial fan environment of the Henshaw Formation (Robertson, 1989). The source of the sediments is somewhat controversial. Leggett *et al.* (1979a) suggested that they originated from an emergent accretionary prism to the south, whereas Bluck (1983, 1984) considered that they were sourced in a volcanic terrane and deposited in an inter-arc basin. This debate is directly linked to the different models for the tectonic evolution of the Southern Uplands, outlined in the interpretation of the GCR site at Dob's Linn (Figure 3.68).

Faunally, the Silurian rocks of the Pentland Hills appear to be distinct from those of the Girvan area and of elsewhere in Britain. For example, the trilobites of the Reservoir and Deerhope formations are endemic, while those of the Wether Law Linn Formation have affinities with East Baltic faunas (Clarkson and Howells, 1981). These faunal similarities suggest there was an open marine connection between eastern Scotland and Balto-Scandia during the latest Llandovery.

Conclusions

Gutterford Burn is an important locality in the Pentland Hills, providing a representative sedimentological sequence and containing characteristic endemic fossils. It is the type section for part of the Reservoir Formation, and the type locality for a large number of fossil species, including many eurypterids and starfish, for which the site is internationally renowned. The Pentlands area was physically or ecologically isolated from other parts of Scotland during the early Silurian, but retained marine connections with Balto-Scandia. This site is therefore of prime importance for studies of early Silurian palaeogeography and for investigations of the tectonic evolution of southern Scotland. It also provides internationally significant evidence of early Silurian faunas and biogeography.

BIRK KNOWES (SO 737 346–SN 738 348)

D. Palmer

Introduction

Birk Knowes on Logan Water in the Lesmahagow area, south of Glasgow, is one of a network of Silurian sites in the Midland Valley of Scotland and has been selected to represent late Llandovery age sediments with unusual and palaeontologically important arthropod and fish faunas. Sediments of similar lithology and age are exposed in the Hagshaw Group of the Hagshaw Hills to the south but the late Llandovery Priesthill Group siltstones of Birk Knowes have provided a greater diversity of fossils.

Lesmahagow is just one of a number of Silurian inliers (Figure 3.82) cropping out north of the Southern Uplands Fault along the southern flank of the Midland Valley from Girvan in the west to Loganlee, south of Edinburgh in the east. The outcrops show a range of sedimentary environments from deep marine (see Blair Farm GCR site description) to shallow water (see Gutterford Burn GCR site description). The stratigraphical relationships of the Lesmahagow sequence were originally thought to indicate a Ludlow age but studies by Robertson (1989), Walton and Oliver (1991), Rolfe (1992a), Wellman and Richardson (1993) and Phillips *et al* (1998) indicate an upper Llandovery, Wenlock and possibly Ludlow age.

The remarkable eurypterid arthropods of the inliers were first discovered in the middle of the nineteenth century (Murchison, 1859), followed by the remains of jawless (agnathan) fish (Powrie, 1870). These palaeontological discoveries established an international importance for a number of the Silurian localities in the Midland Valley and especially that of Birk Knowes, which has yielded the enigmatic arthropod *Ainiktozoon loganense* Scourfield,1937, the thelodont *Loganellia scotica* (Traquair, 1899) and the unique agnathan *Jamoytius kerwoodi* (White, 1946). Birk Knowes is the type locality for all three.

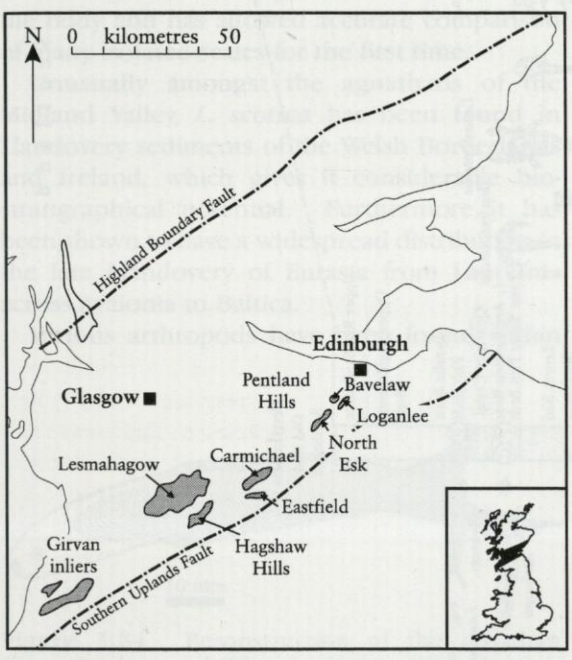

Figure 3.82 Location of the main Silurian inliers of the Midland Valley of Scotland (after Wellman and Richardson, 1993).

Description

The Birk Knowes locality consists of three small outcrops on Logan Water, separated by small faults and with poor exposure but potential for future development. Some 300 m of sediments within the Priesthill Group have been subdivided by Jennings (1961) and Ritchie (1968) into a number of formations on the basis of their lithologies (Figure 3.83). The oldest exposed rocks are the dark, finely laminated siltstones, non-laminated olive mudstones and interbedded greywackes of the Patrick Burn Formation, whose base is not seen but which is at least 400 m thick. Three succeeding formations of siltstones (Castle Formation, Kip Burn Formation and Blueberry Formation) surmounted by shales of the Dunside Formation at the top of the group are exposed at Shank's Castle nearby (see Dineley and Metcalf, 1999). Invertebrate fossils indicate a late Llandovery age for the Priesthill Group (Cocks *et al*., 1992) and this is supported by the presence of the agnathan thelodont *Loganellia scotica*, which is widely distributed in the upper Llandovery of Eurasia (Märss and Ritchie, 1998). Elsewhere in the inlier the succession continues through the Wenlock age shales, sandstones and siltstones of the Waterhead Group, into the conglomerates and sandstones of the Dungavel Group (possibly Ludlow in age) and finally up into Old Red Sandstone conglomerates.

The fauna of the upper Llandovery sediments comprises rare and scattered marine shelly invertebrates and more concentrated remains of arthropods and agnathans. The latter occur in a few horizons of the laminated siltstones, which have consequently been characterized as 'fish beds' and separated (by some 200 m) as a lower *Jamoytius* Horizon in the Patrick Burn Formation and upper *Ceratiocaris* Beds at the base of the Kip Burn Formation.

Although fossils are not common, over the last hundred years or more of collecting, many hundreds of specimens have been found, including some entire but flattened agnathan fish and a variety of arthropods. Many of the fossils have been found in small diagenetic calcareous concretions (< 50 mm in diameter and now largely decalcified). Disarticulated remains, such as

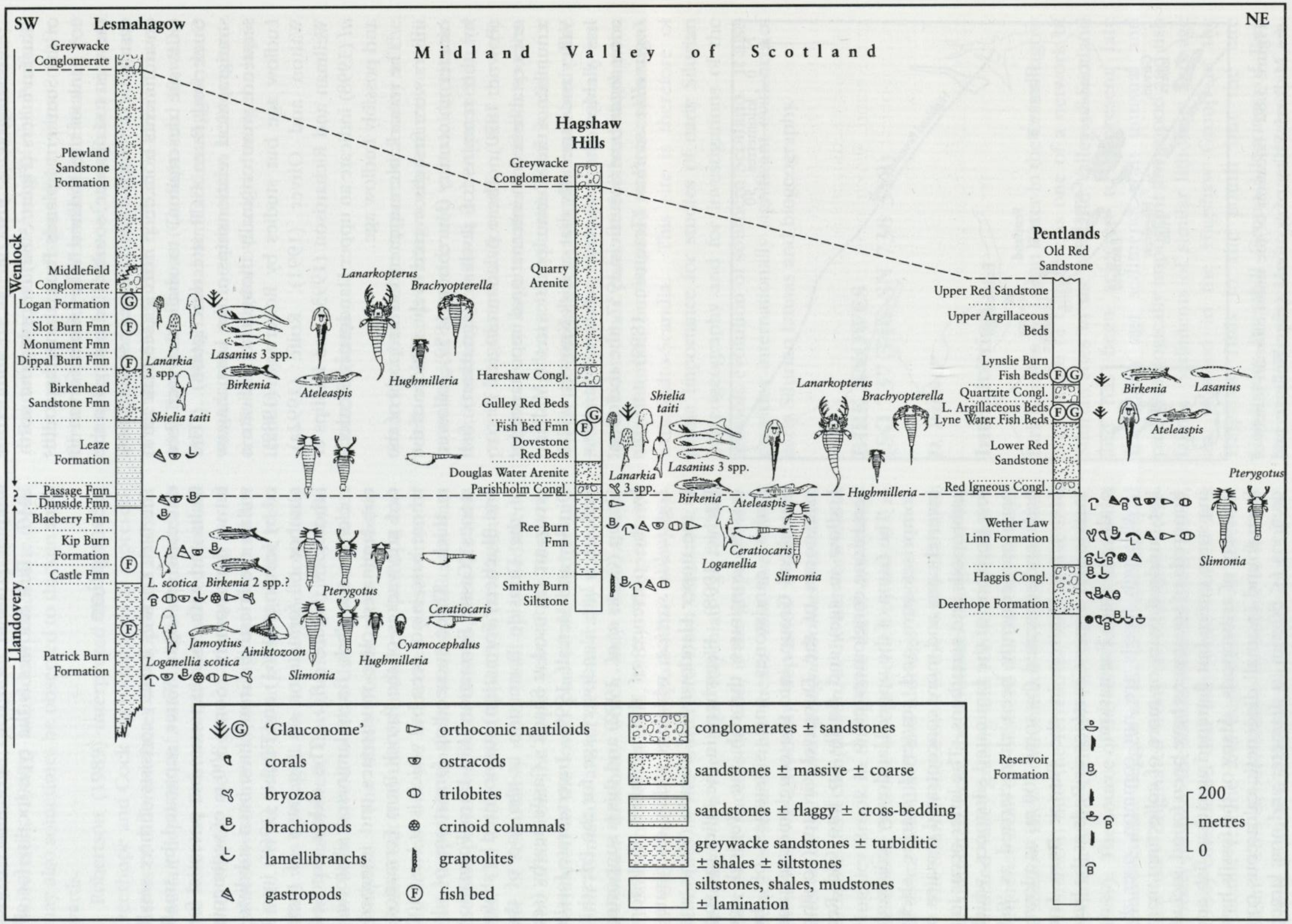

Figure 3.82 Location of the main Silurian inliers of the Midland Valley of Scotland (after Wellman and Richardson, 1993).

patches and coprolitic strings of agnathan skin scales and even individual scales (1–2 mm long) are also found, showing that the animals were originally buried by sediment in varying states of decay.

Palaeontologically, the most interesting member of the fauna is the agnathan *Jamoytius kerwoodi* (180–200 mm long, Figure 3.84), which is unique to the locality and is only found in the *Jamoytius* horizon within the Patrick Burn Formation. It has an elongate 'eel-like' body, simple mouth and gill openings supported by a cartilaginous skeleton, possible hypocercal tail (having a large lower lobe) and very thin skin scales.

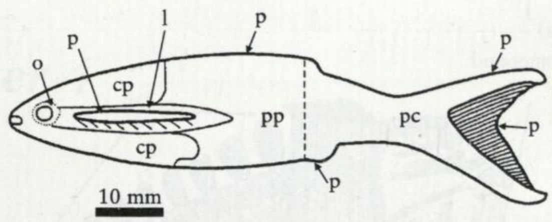

Figure 3.85 The body profile of the agnathan thelodont *Loganellia scotica* (Traquair) and areas with scales of different morphology. Abbreviations: cp, cephalo-pectoral; l, lateral; o, orbital; p, pinnal; pc, precaudal; pp, postpectoral. Magnification × 1 (from Märss and Ritchie, 1998).

The thelodont agnathan *Loganellia scotica* is known by a number of complete flattened specimens and many separate scales (Märss and Ritchie, 1998). This is a medium sized thelodont (generally up to 275 mm in length but some specimens may have reached 400 mm, Figure 3.85) with a dorso-ventrally flattened head and thorax. The front of the head is blunt with a terminal mouth and fairly well-developed eyes. There are paired lateral fin flaps and an asymmetrical hypocercal tail with two prominent lobes of which the lower is slightly larger. Recent detailing of scale morphology for complete specimens by Märss and Ritchie (1998) reveals significant changes in different parts of the body and has allowed accurate comparison of many isolated scales for the first time.

Unusually amongst the agnathans of the Midland Valley, *L. scotica* has been found in Llandovery sediments of the Welsh Borderlands and Ireland, which gives it considerable biostratigraphical potential. Furthermore it has been shown to have a widespread distribution in the late Llandovery of Eurasia from Laurentia across Avalonia to Baltica.

Various arthropods have been found within the *Jamoytius* horizon including the enigmatic *Ainiktozoon*, the eurypterids *Slimonia, Pterygotus* and *Hughmilleria* and ceratiocarids (Figure 3.83).

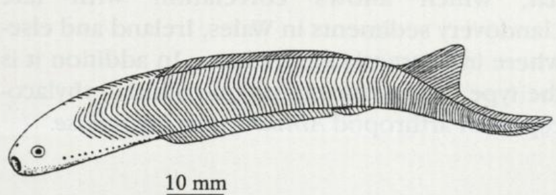

Figure 3.84 Reconstruction of the agnathan *Jamoytius kerwoodi* White by Ritchie, 1968, showing terminal round mouth, elongate body scales, paired lateral fin lobes, single anal and dorsal fins and asymmetrical tail.

Interpretation

The lithology of the late Llandovery sediments at Birk Knowes and their sequential changes up into the Wenlock elsewhere in the Lesmahagow Inlier indicate a marine regression. This interpretation is supported by correlative sequences in the other inliers of the Midland Valley and their changing faunas.

The greywackes of the Patrick Burn Formation are typically marine sediments (Jennings, 1961) and show current depositional movement towards the NNE. The succeeding siltstones and shales are neither diagnostically marine nor freshwater. Indeed there has been continuing debate over interpretation of the environments of deposition of the fish bed horizons. With sediments of this age, when there are few organisms that are known to be characteristically brackish or freshwater in habit, such a diagnosis has depended largely upon an absence of typically marine fossils. But both the sedimentology and occurrence of rare shelly invertebrates in Patrick Burn Formation have supported a marine interpretation. This is further supported by the occurrence of the widespread thelodont *L. scotica*. However, the occurrence of the fish bearing beds of the *Jamoytius* horizon, near the top of the formation with preservation of occasional entire agnathans and very few shelly benthic invertebrates, suggests that bottom conditions were anoxic and that the basin of deposition was becoming increasingly restricted in water circulation. The presence of mobile agnathans and

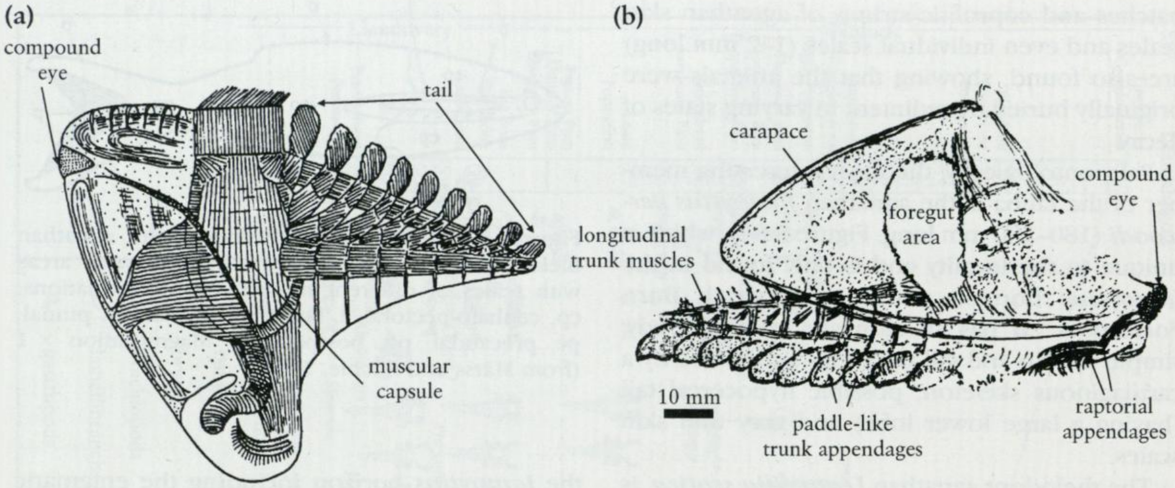

Figure 3.86 *Ainiktozoon loganense* Scourfield. (a) interpreted as a possible chordate by Ritchie, 1985. (b) inverted and reinterpreted as a thylacocephalan arthropod by Brugghen *et al.* 1997 (drawing D. Palmer after Brugghen *et al.*).

arthropods, most of which were scavengers, supports this interpretation.

Palaeontologically, the locality has yielded two unique genera, both of which have generated considerable interest and debate. Most significant has been the discussion over the zoological affinities of *Jamoytius* within the agnathans. Some modern opinion places *Jamoytius* close to the extant lampreys (Forey and Janvier, 1994); if this designation is correct, *Jamoytius* is of considerable significance to the general discussion of relationships between fossil and extant agnathans (see Janvier, 1996 and Dineley and Metcalf, 1999 for reviews).

Ainiktozoon loganense Scourfield (1937) is palaeontologically the most curious member of the Birk Knowes fauna, with little comprehension of its affinities until recently. Its apparently bizarre morphology with an anterior compound eye, deep 'basket-like' body and jointed tail (total length up to 120 mm, Figure 3.86) misled early investigators into considering that it had chordate affinities (Ritchie, 1985). However, the recent realization that the so-called 'branchial basket' is in fact a carapace, that the 'eye' is paired and that the trunk bears paired paddle-like limbs (Brugghen *et al.*, 1997) altered the whole perception of the animal and placed it more reasonably within the thylacocephalan arthropods. There may be some affinity with an as yet undescribed North American thylacocephalan from the Silurian of Waukeshau, Wisconsin.

Conclusion

The conservation value of Birk Knowes is twofold. It has national significance as an excellent example of late Llandovery sediments in the Midland Valley of Scotland. The site has already attained GCR status for its fish fauna, which has elevated it to international significance as a result of its being the type locality for the unique agnathan *Jamoytius kerwoodi* and the biostratigraphically significant thelodont *Loganellia scotica,* which allows correlation with late Llandovery sediments in Wales, Ireland and elsewhere in Laurentia and Baltica. In addition it is the type locality for the unique Silurian thylacocephalan arthropod *Ainiktozoon loganense.*