British Cambrian to Ordovician Stratigraphy

A.W.A. Rushton
Palaeontology Department, Natural History Museum,
London, UK

A.W. Owen
Division of Earth Sciences, University of Glasgow, UK

R.M. Owens
Department of Geology, National Museum of Wales, Cardiff, UK

and

J.K. Prigmore
Equipoise Solutions Ltd, Croydon, UK

GCR Editor: **L.P. Thomas**

JOINT NATURE CONSERVATION COMMITTEE

Chapter 3

Cambrian of North Wales

A. W. A. Rushton and J. K. Prigmore

HARLECH DOME

The Harlech Dome (see Figure 3.2) exposes the largest area of Cambrian rocks in Wales and, together with the small but well-exposed inlier at St Tudwal's Peninsula, shows the most complete and informative stratigraphical succession. The Harlech Dome is also the least controversial of the Cambrian areas studied during the late 19th century, its original assignment by Sedgwick to the Cambrian System (Sedgwick and Murchison, 1835) never having been seriously challenged; for although Hicks (1881a, 1891) claimed to have recognized pre-Cambrian rocks in the core of the Harlech Dome, his findings have never been accepted. It accordingly remains the best exemplar of Sedgwick's Cambrian concept.

Early workers distinguished a lower group of Harlech Grits, overlain by 'Lingula Flags'; these correspond broadly to the 'Harlech Grits Group' and 'Mawddach Group' of present usage (Allen and Jackson, 1985). Having studied the 'Lingula Flags', Belt (1867b, 1868) accepted Salter's (1866a) exclusion of the equivalents of the newly characterized Menevian Beds of St David's in South Wales, and he subdivided the main part of the 'Lingula Flags' into formations, namely the Maentwrog, Festiniog and Dolgelly, which have since been generally adopted. The Harlech Grits proved intractible until Lapworth observed that certain manganiferous strata (the Hafotty Formation) could be used as a stratigraphical marker, enabling a lithostratigraphy to be developed. The formational divisions were described by Andrew in 1910, but mapping of their out-

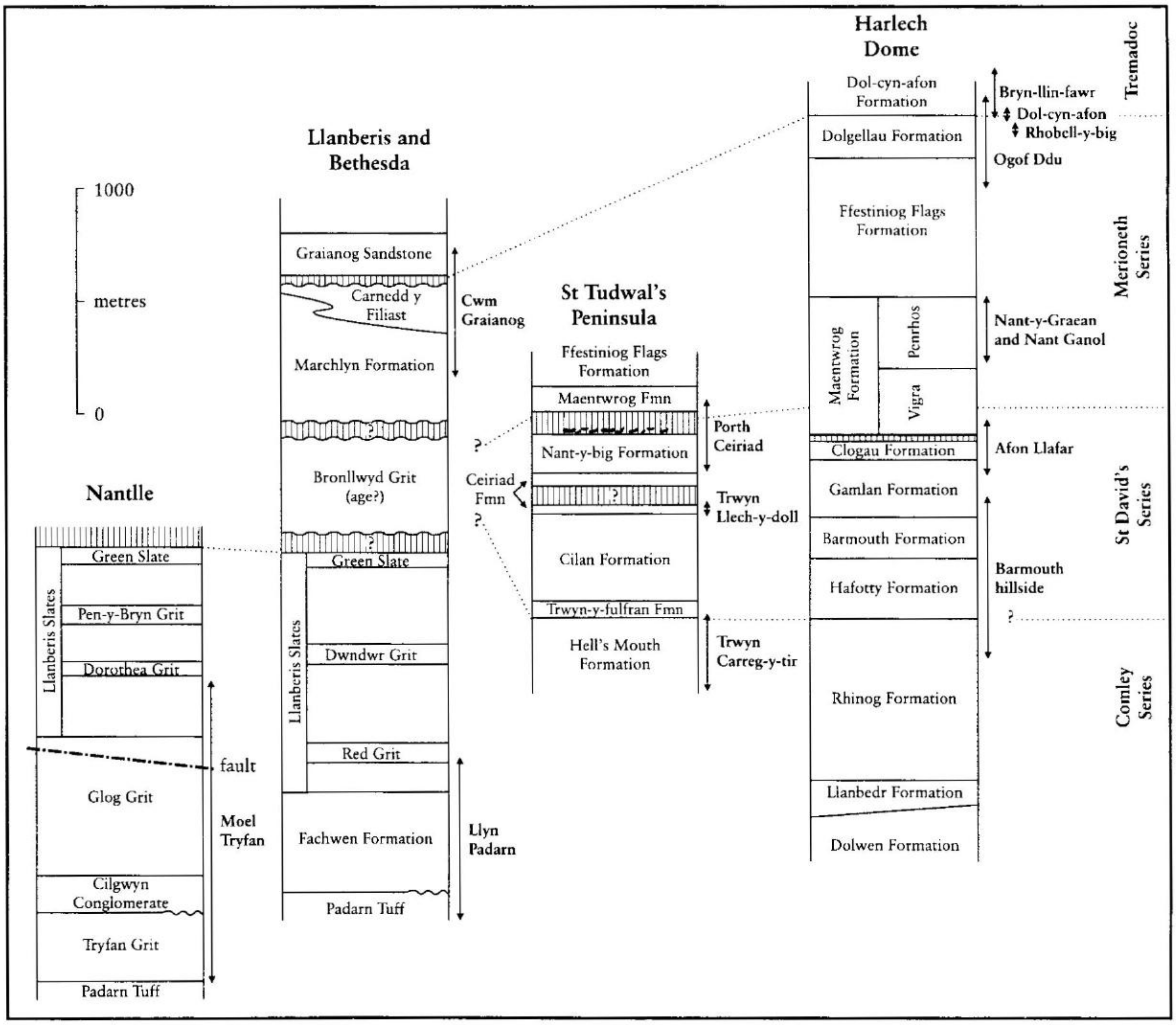

Figure 3.1 Correlation of the principal Cambrian sequences in North Wales, modified from Rushton (1974, fig. 2). The arrows in this and succeeding figures indicate the stratigraphical ranges of individual GCR sites.

crops was not completed until 1946 (Matley and Wilson, 1946). The stratigraphy of the Harlech Dome was revised and the nomenclature formalized by Allen and Jackson (1985).

Nicholas (1915) gave an excellent account of the St Tudwal's Inlier, his results being confirmed, with additions but only slight modification, by Young *et al.* (1994). Recognition of the manganiferous beds and other features of the Harlech Grits Group in the St Tudwal's succession enables a secure correlation with the Harlech Dome, whilst additional faunal information enhances the utility of the stratigraphical succession.

The formations recognized and their approximate correlation are shown in Figure 3.1 and their general stratigraphical distribution in Figures 3.2 and 3.3. These successions are correlated at the manganiferous base of the Hafotty and Trwyn y Fulfran formations and in the Merioneth Series, but between these levels the formations are not correlated one-for-one (Young *et al.*, 1994); thus, for example, the base of the Nant-y-big Formation appears to correlate with a level within the upper part of the Gamlan Formation. Allen and Jackson (1985) assigned all the formations from Dolwen to Gamlan to the Harlech Grits Group, and took the base of the Mawddach Group as the base of the Clogau Formation, but Young *et al.* (1994) assigned only the succession from the Hell's Mouth to Cilan formations to the Harlech Grits Group and did not refer any of the Nant-y-big Formation to the Mawddach Group.

The base of the Harlech Grits Group has been seen only in the Bryn-teg Borehole (Allen and Jackson, 1978), where it rests without strong angular unconformity, but with a probable hiatus in deposition, upon the Bryn-teg Volcanic Formation of possible Precambrian age. The Harlech Grits Group is interpreted as deltaic and prodeltaic deposits overlain by a sequence mainly comprising turbidites (Allen and Jackson, 1985, p. 5), together amounting to about 2 km of thickness. They represent the filling of a rapidly subsiding basin (Prigmore *et al.*, 1997). The Harlech Grits are biostratigraphically constrained at wide intervals: the Dolwen Formation contains a *Platysolenites* of possible Tommotian (early Cambrian) age (Rushton, in Allen and Jackson, 1978), the Hell's Mouth Formation has late Comley (Branchian Series) trilobites, and the Clogau and Nant-y-big formations have faunas of middle and late St David's

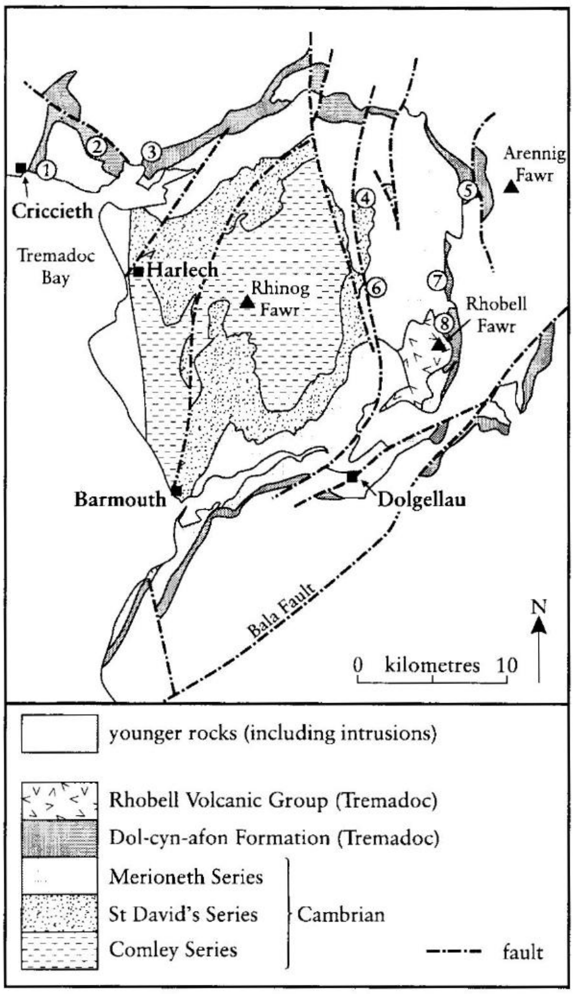

Figure 3.2 Geological sketch-map of the Harlech Dome, after the British Geological Survey (1994b). Cambrian and Tremadoc GCR sites are as follows: 1, Ogof Ddû; 2, Tyn-llan and Wern; 3, Y Garth; 4, Afon Llafar; 5, Amnodd Bwll; 6, Nant-y-graean; 7, Bryn-llin-fawr; 8, Rhobell-y-big and Dol-cyn-afon.

age, as detailed below.

The Mawddach Group represents a further phase of subsidence characterized by clastic deposits about 2 km or more in thickness. This was followed by a period of sediment-starvation, giving rise to the thin, condensed Dolgellau Formation, with somewhat coarser clastic deposition in the succeeding Dol-cyn-afon Formation. These formations are fossiliferous at many levels and represent a fairly complete succession of Merioneth and Tremadoc rocks, only the basal zone of the Merioneth remaining unproved in North Wales.

The proximal turbidites and silty mudstones that make up the greater part of the Harlech Grits Group and the manganese ore bed are all

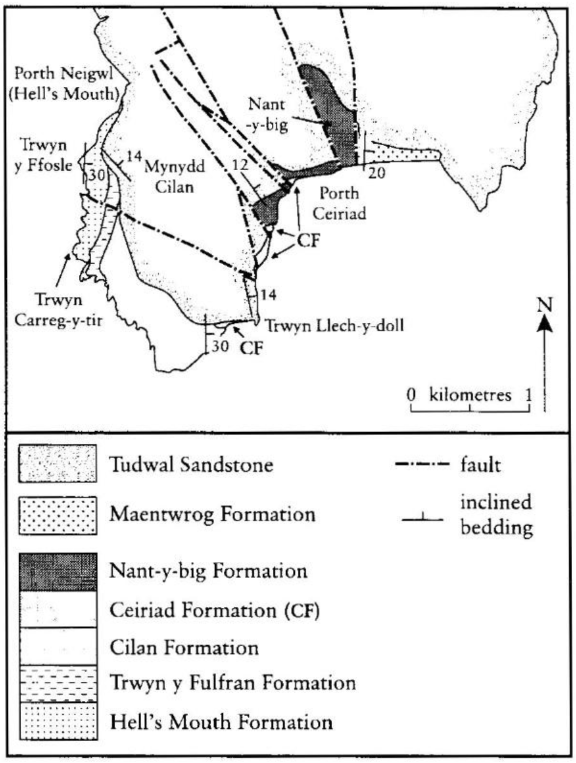

Figure 3.3 Geological map of St Tudwal's Peninsula, after Nicholas (1915) and Young *et al.* (1994).

exemplified by the site on Barmouth Hillside, whereas details of the sedimentology and the important fossil-bearing horizon at the top of the Hell's Mouth Formation are seen at Trwyn Carreg-y-tir. At the Afon Llafar section the faunal succession in the mid St David's Series (Middle Cambrian) is seen and the hiatus of one zone at the base of the Maentwrog Formation is inferred, whilst at Porth Ceiriad the correspon-ding hiatus is more extensive but includes derived material illustrative of the horizon that is absent at Afon Llafar; Middle Cambrian metaben-tonites are also well exposed there.

The faunal succession of the Maentwrog Formation is exemplified at Nant y Graean and Nant Ganol, and the whole succession from the top of the Ffestiniog Formation into the Dol-cyn-afon Formation (Tremadoc) is well-seen in the important Cambrian–Ordovician Boundary section at Ogof Ddû. Although the rocks at Ogof Ddû are fossiliferous, faunas of the *Peltura scarabaeoides* Zone are better preserved at Moel Gron, and latest Merioneth faunas of the *Acerocare* Zone are known from Bryn-llin-fawr, discussed in Chapter 7 (on the Tremadoc Series).

BARMOUTH HILLSIDE (SH 615 162)

Introduction

The Barmouth Hillside (Figure 3.4) exposes an almost continuous section through the upper part of the Harlech Grits Group, from the higher part of the Rhinog Formation, through the Hafotty and Barmouth formations, into the Gamlan Formation (Figure 3.1). These exemplify a considerable part of the Cambrian succession in a part of Wales where the Cambrian System was conceived.

The rocks of the area were assigned by Sedgwick (in Sedgwick and Murchison, 1835) to the Middle Cambrian division of his newly defined Cambrian System. He subsequently named the Harlech Grits as part of a redefined Lower Cambrian (Sedgwick, 1852). The work of the Geological Survey (Jukes and Selwyn, 1848) led to the publication in 1854 of maps in which the Harlech Grits were distinguished from the overlying 'Lingula Flags'. The recognition by Lapworth and Wilson that the manganese ore mined in the area forms a stratigraphical marker enabled the Rhinog and Barmouth grits to be distinguished as separate formations (Andrew, 1910) and led to elucidation of the stratigraphy, culminating in Matley and Wilson's (1946) map and description of the Harlech Grits.

Keunen's (1953) early recognition that many of the coarse grits were deposited by turbidity currents led to descriptions of the sedimentary structures by Kopstein (1954) and facies analysis by Crimes (1970a). The manganese ore was studied petrographically by Woodland (1938, 1939) and geochemically by Mohr (1964) and Glasby (1974). Allen and Jackson (1985) described the Harlech Dome area and gave formal definition to Andrew's (1910) formational nomenclature, which had been used on their British Geological Survey map of 1982. The account of Allen and Jackson is followed here.

Description

The Barmouth Hillside site is a large area of moorland with a good deal of craggy exposure, such that the various formations and even individual beds can be traced along-strike for considerable distances (Figure 3.4). The rocks generally dip north-east or east at about 50–60°, though strikes and dips vary. The general features of these beds have been described by

Figure 3.4 Barmouth, viewed from the west. To the left, greywackes of the Rhinog Formation (Lower Cambrian) form wooded outcrops above the town. The smoother terrain beyond is occupied by the Hafotty Formation (St David's Series), the manganiferous basal beds lying approximately along the line of the track that extends from the church (centre right, arrowed) obliquely up the hill to the left. The rougher highest ground consists of Barmouth Formation greywackes, with the Gamlan, Clogau and Maentwrog formations beyond. The far side of the Mawddach Estuary is made up of upper Cambrian and lower Ordovician rocks. (Photo: Cambridge University Collection of Air Photographs, BST 038: copyright reserved.)

Matley and Wilson (1946) and Allen and Jackson (1985); they have not proved fossiliferous. The exposures are described from north to south, in ascending succession.

The upper part of the Rhinog Formation generally consists of greywacke sandstones with thin intercalations of siltstone and mudstone that give a 'scarp and slack' topography. The greywackes are medium- to coarse-grained and are generally about 50 cm (but occasionally up to 4 m) in thickness. Intercalated siltstones are usually 5–30 cm thick but can reach 3 m. Compositionally, quartz predominates and is often pink or blue (Woodland, in Matley and Wilson, 1946), but feldspar clasts and lithic fragments are also common. Most beds show elements of Bouma (1962) turbidite sequences, as described by Allen and Jackson (1985).

Amalgamated units are common. Sole marks include flute- and groove-casts and load structures (Crimes, 1970a). Mudstone rip-up clasts also occur, and burrows can sometimes be seen on the bases of sandstones or in intercalated mudstones. Beds up to 1–2 m thick of well-sorted coarse sandstone and quartz-pebble conglomerate occur throughout the sequence and include washouts with pebbly fills. The formation is 780 m thick, the upper 100 m or so being exposed here.

The Hafotty Formation overlies the Rhinog Formation conformably. It is predominantly of blue- or green-grey striped mudstones and siltstones with occasional beds of sandstone. Matley and Wilson (1946) divided the formation into three members:

Upper or Manganese Shales	100–200 m
Manganese Grit	2–60 m
Lower (or Ore Bed) Shales	15–20 m

The lower member was further subdivided by Woodland (1939) and near the middle includes the Manganese Ore Bed itself. This is a hard, fine-grained, flinty bed about 0.3 m thick, showing red-brown, yellow and occasional blue-black bands when fresh, the manganese-bearing minerals being rhodochrosite and spessartine. The petrology was described by Allen and Jackson (1985) and Woodland (1939). Although the ore itself is not easy to examine *in situ*, its outcrop can be traced across the hillside by following the old mine workings. Above the ore bed are finely laminated manganiferous mudstones, followed by banded mudstones, siltstones and fine sandstones with a distinctive ribbed appearance when weathered. Graded beds of greywacke sandstone occur, of which the Manganese Grit is the most persistent, though here it is only about 2 m thick. The mudstones forming the bulk of the formation are grey, green or purple, and they show cleavage dipping north at about 80°.

The stratotype base for the Barmouth Formation (Allen and Jackson, 1985) is on the hillside path above Barmouth (6160 1580). It rests abruptly but conformably on the Hafotty Formation and is marked by the abrupt appearance of coarse, pebbly greywacke sandstones, the lowermost showing a complete Bouma sequence (*a* to *e* divisions). However, the quartz pebbles are usually white in colour, the pink and blue varieties of the Rhinog Formation being absent. The characteristics of this formation, described by Allen and Jackson (1985), are very similar to those of the Rhinog Formation, although the beds are generally coarser, with fewer and thinner mudstone intercalations.

The Barmouth Formation is abruptly succeeded by the Gamlan Formation, which consists of green-grey and blue-grey silty mudstones, with thin beds of fine- to medium-grained sandstone. The boundary forms a topographical slack that can be traced along strike, and the transition is exposed north of the footpath across the top of the hill (6178 1584) (Allen and Jackson, 1985). The strata are well and thinly bedded, and prominently striped. Siltstone and fine sandstone beds, from a few millimetres to 10 cm thick, occur; they often show parallel, convolute or cross-lamination (Bouma *bcd* or *cd* sequences). Sediment-filled *Planolites* burrows are common parallel to bedding. Some 50 m of the lower part of this unit are exposed here.

Interpretation

The sandstones of the Rhinog Formation are interpreted as proximal turbidites (Kuenen, 1953) deposited under conditions of a high-flow regime, transported by south-flowing currents (Crimes, 1970a; Allen and Jackson, 1985). The better-sorted cross-bedded sandstones represent reworking; washouts at their bases show an east–west orientation perpendicular to that given by the sole marks in the turbidites, and the cross-bedding implies westerly transport. Thus, although turbidity current flow was from the north, an easterly source was also operating. The abrupt appearance of the Rhinog turbidites over mudstones of the underlying Llanbedr Formation indicates the advance of a prograding turbidite fan, the Rhinog Grits representing the mid- to inner fan. The overlying banded mudstones, siltstones and sandstones of the Hafotty Formation exhibit sedimentary structures and grain-size variations that indicate they were deposited by distal turbidites.

Woodland (1939) considered that the manganese ore was deposited by precipitation as a colloidal gel, in very quiet water conditions, probably in an enclosed basin. Both he and Mohr (1956) favoured a gneissic landmass as the source of the manganese. Glasby (1974) favoured a diagenetic origin for the ore bed, ruling out the need for a manganese-rich source, and suggested that the ore formed in a shallow marine basin where reducing conditions had developed. However, the coarse greywacke sandstones of the Manganese Grit resemble those of the Rhinog Grits above and are difficult to reconcile with a shallow basin (Allen and Jackson, 1985); and Binstock (1977) considered the managanese-bearing beds to be part of a deep-water sequence, the manganese enrichment being related to an interval of pelagic deposition.

The Barmouth Formation represents a renewed influx of proximal turbidites. Sole marks and washouts indicate a general NW–SE alignment (Crimes, 1970a), while directional sole marks indicate currents flowing to the north-west. These sediments were presumably derived from a source to the south-east of the Harlech Dome. The overlying Gamlan Formation siltstones and mudstones were deposited from turbidity currents also flowing towards the north or north-west, but represent more distal, lower energy deposits.

The Barmouth Hillside site thus displays a stratigraphical succession through the principal formations of the Harlech Grits Group, with examples of the contacts between the formations and including the basal stratotypes of the Barmouth and Gamlan formations. It also illustrates the filling of the basin by two cycles of turbidite deposition, though whether the quiescent period in between represented a period of shallowing is debated.

The general similarity of the sequence exposed on Barmouth Hillside with that in St Tudwal's Peninsula, and in particular the presence of manganiferous beds (Nicholas, 1915), allows correlation of the Harlech Grits Group in the two areas. This is important stratigraphically because of the presence of fossils in the St Tudwal's succession (see the Trwyn Carreg-y-tir site report). Correlation by manganese has been extended to Newfoundland (Mohr and Allen, 1965), where a manganese-rich horizon occurs at the base of the Chamberlain's Brook Formation, which is assumed to be early Middle Cambrian in age.

Conclusions

The site on Barmouth Hillside displays a thick Lower to Middle Cambrian sequence typical of the Harlech Grits Group. These are coarse sandstones and mudstones, deposited in a deep marine basin by strong flows of sediment-laden water, that typify a major part of the Cambrian of the historical type area. Particularly important is a manganese-rich horizon that can be used as a marker band and which allows correlation, in the absence of fossils, with similar, locally fossiliferous, rocks in St Tudwal's Peninsula.

TRWYN CARREG-Y-TIR (SH 2876 2402)

Introduction

Trwyn Carreg-y-tir and the adjacent cliffs form the best accessible section through any part of the Harlech Grits Group. Excellent exposure of the Hell's Mouth Formation allows study of their sedimentology. The higher beds yield the only Lower Cambrian (late Comley Series) trilobites known from the Harlech Grits Group, making this a key section for regional correlation.

Nicholas (1915) described the geology of St Tudwal's Peninsula (Figure 3.3). He termed the oldest strata, exposed in the cliffs on the west of the peninsula, the 'Hell's Mouth Grits'. Bassett and Walton (1960) described the sedimentology and provenance, and Young *et al.* (1994) redescribed the rocks and formalized the formational names. The Hell's Mouth Formation is correlated lithologically with the upper part of the Rhinog Formation of the Harlech Dome, in particular because each is overlain by a formation with dark manganiferous siltstones. However, whereas the Rhinog Formation is unfossiliferous and poorly constrained as to age, the occurrence of fossils in the Hell's Mouth Formation indicates a level near the top of the Comley Series and provides an important biostratigraphical datum for the Cambrian of North Wales.

Description

The cliffs around Trwyn Carreg-y-tir, including the coast to Trwyn y Ffosle 800 m to the north (2868 2482), expose about 190 m of Hell's Mouth Formation dipping eastwards at 30–40° (Figure 3.5). The formation is composed mainly of coarse- to medium-grained sandstone, commonly in beds 0.3–1 m thick but occasionally approaching 4 m in thickness, interbedded with thinner siltstone units usually not more than 0.5 m thick. Bassett and Walton (1960) described sedimentary structures typical of Bouma cycles and showed that the sandstones are turbidites. The orientation of bottom struc-

Figure 3.5 Cliffs on the west side of St Tudwal's Peninsula, looking north-east, showing the type development of the Hell's Mouth Formation. The headland on the right is Trwyn Carreg-y-tir, and the beds with trilobites lie near the top of the cliff. The Trwyn y Fulfran Formation underlies the smoother ground beyond and the trial-pits for manganese ore show dark. The cultivated ground behind is underlain by the Tudwal Sandstone Formation of Arenig age. (Photo: Cambridge University Collection of Air Photographs, 70K EH5: copyright reserved.)

tures such as groove and flute casts shows that depositional currents flowed from the north-east (Bassett and Walton, 1960, p. 98).

Young *et al.* (1994) took the exposures at Trwyn y Ffosle as the type-section of the Hell's Mouth Formation, but the upper part is best seen at Trwyn Carreg-y-tir (2876 2402), where units I to K of Bassett and Walton (1960, p. 88) are exposed. The base of the overlying Trwyn y Fulfran Formation of Young *et al.* (1994), broadly equivalent to the base of Nicholas' Mulfran Beds, is marked by the disappearance of thick sandstone beds and the appearance of manganiferous siltstone (Young *et al.*, 1994).

Bassett and Walton (1960, p. 103) collected a fauna of trilobites and sponge spicules from three levels in the upper 23 m of the Hell's Mouth Formation. These were described by Bassett *et al.* (1976), who considered that the trilobites *Hamatolenus (Myopsolenus) douglasi* Bassett, Owens and Rushton, *Kerberodiscus succinctus* Bassett, Owens and Rushton and possibly *Serrodiscus ctenoa* Rushton indicate a late Comley Series age (late Lower Cambrian in traditional terms). Martin (in Young *et al.*, 1994) recorded acritarch floras from several levels in the Hell's Mouth Formation. Most of the taxa she recorded have long stratigraphical ranges, but a few, including *Skiagia scottica* Downie, are restricted to strata that elsewhere are assigned to the Lower Cambrian.

Interpretation

Bassett and Walton (1960) showed that the Hell's Mouth Formation is composed of turbidites deposited from currents flowing from the north-east, much like the Rhinog Formation (see the Barmouth Hillside site report). The fossils that they discovered in the top of the formation are significant because biostratigraphical control of the Harlech Grits Group is so scanty. The next younger faunal horizon lies well up in the Middle Cambrian at Porth Ceiriad (see site report below), and the only older fossils are a *Platysolenites* from the Dolwen Formation (Rushton, in Allen and Jackson, 1978) and an indeterminate brachiopod from the Llanbedr Formation (Lockley and Wilcox, 1979), both from the centre of the Harlech Dome.

Assessment of the trilobites from Trwyn Carreg-y-tir gives conflicting ages. *Kerberodiscus*, though endemic, is related to *Leptochilodiscus,* which is associated with *Olenellus* in eastern North America, implying an early Cambrian age, as recognized in North America (Bassett *et al.*, 1976). The species of *Hamatolenus (Myopsolenus)* is related to species associated with early Paradoxididae in Morocco, implying a mid-Cambrian age (Geyer, 1990). It is clear that the level taken as the Lower–Middle Cambrian boundary in North America is not the same as in Morocco, but evidently the Hell's Mouth fauna lies near the Lower–Middle Cambrian boundary. Here it is assigned to the Lower Cambrian, following Young *et al.* (1994). Reference to a high level in the Comley Series of Cowie *et al.* (1972) is independent of the ambiguities of 'Lower' and 'Middle' Cambrian.

The fauna from Trwyn Carreg-y-tir is also of value in showing the relative ages of the Harlech Dome sequence and the Llanberis Slates belt of Arfon; this question troubled discussants of Bassett and Walton's paper (1960, pp. 106, 109). Rushton (1974, p. 80) and Bassett *et al.* (1976, p. 641) showed that the level in the Llanberis Slates that yielded *Pseudatops viola* (Woodward) is lower than the Hell's Mouth fauna and indicates that the Llanberis Slates as a whole can be regarded as older than the Hell's Mouth and Rhinog formations.

Conclusions

Trwyn Carreg-y-tir and the adjoining cliffs form a key site, important in understanding the geological history of the whole region. It shows better than elsewhere the conditions of deep-water sedimentation in the Welsh Basin during the latest Lower Cambrian period, when the Hell's Mouth Formation was deposited. Their age is inferred from fossil-bearing layers that are the only such beds of this age known in North Wales.

PORTH CEIRIAD (SH 3056 2469–SH 3106 2482)

Introduction

Porth Ceiriad displays a good succession of the higher St David's and lowest Merioneth series (Middle Cambrian and Upper Cambrian) and exposes more clearly than elsewhere in Britain the nature of the St David's–Merioneth contact. It is a key site for interpreting Cambrian stratigraphy in North Wales.

Nicholas (1915) described the geology of the area and included references to earlier work. He named the main stratigraphical divisions and identified the presence of a non-sequence at the Middle–Upper Cambrian contact. In the next year he gave a detailed account of the trilobite fauna (Nicholas, 1916), some species of which were revised by Lake (1906–1946). Young *et al.* (1994) revised the whole succession, reviewed the faunas and provided new sedimentological and microfloral information.

The stratigraphical units are as follows:

Nicholas (1915)	**Young *et al.* (1994)**
Maentwrog Beds	Maentwrog Formation
Nant-pig Mudstones Upper Caered Mudstones	Nant-y-big Formation
Caered Flags	Ceiriad Formation (restricted)

Description

At the western end of the section the basal beds of the Nant-y-big Formation conformably overlie green siltstones of the Ceiriad Formation, dipping south-east at 30°. Nicholas (1915) described the section and Young *et al.* (1994, fig. 4) logged the basal part. The lower part of the formation consists of crudely graded or massive siltstone interbedded with laminated siltstone; it contains several interbeds of metabentonite (Roberts and Merriman, 1990). The thicker siltstone beds are interpreted as turbidites. Fossiliferous levels near the base and 50–60 m above the base contain trilobites of the *fissus* Zone.

Nicholas (1915) recorded a transition from blue-grey and greenish-grey mudstones to dark-grey laminated mudstone, which he assigned to his 'Nant-pig Mudstones'. Young *et al.* (1994) considered that the sedimentary facies of silty turbidites linked the darker beds with the underlying division and referred both to the same formation, their 'Nant-y-big Formation'. The lower part of the darker mudstones yields trilobites of the *fissus* Zone.

Towards the top of the formation silty turbidites are less dominant, giving way to dark-coloured laminated mudstone with coarse-grained layers. The upper 15 m of the formation contain thicker (>20 cm) sandstones, locally very pyritous and containing carbonate concretions. Trilobite faunas from the upper beds are referred to the *parvifrons* Zone. The top 20 cm of the Nant-y-big Formation consists of hard siltstone cemented with carbonate (Figure 3.6); this is the lower part of Nicholas' (1915) 'Calcareous Grit' unit, and was recorded by Young *et al.* (1994) as consisting of two beds (their Beds 1 and 2) overlain by a surface of disconformity.

Overlying the Nant-y-big Formation are beds of coarse conglomeratic sandstone regarded by Young *et al.* (1994, p. 344) as the local base of the Maentwrog Formation. Young (in Young *et al.*, 1994, p. 342) recognized four beds above the surface of disconformity: Bed 3 consists of coarse sandstone with clasts of Bed 2, possibly the source of Nicholas' trilobite fauna, which Young *et al.* (1994) assigned to the *brachymetopa* Zone. Bed 4 is possibly a bentonite, Bed 5 a sandstone that has yielded a sparse acritarch flora supposedly of Upper Cambrian age, and Bed 6 is an eroded bioclastic limestone.

Above the calcareous base are seen 34 m of typical Maentwrog Formation, consisting of fine sandstone in thick beds (up to 40 cm), interbedded with thinner layers of dark-coloured mudstone (Figure 3.6). These beds show bioturbation and sedimentary structures (Crimes, 1970a) and early diagenetic concretions (Crimes, 1966). Bose (1983) interpreted the sediments as having been deposited in a shallow sea through the action of storms, and Crimes (1970a) reported that the current action flowed from a southerly quarter. The Maentwrog Formation contains acritarchs of early Upper Cambrian age and poorly preserved trilobites compared with *Olenus* and *Homagnostus obesus* (Belt), consistent with the fauna of the *Olenus* Zone (Young *et al.*, 1994, p. 345; see site report for Nant y Graean).

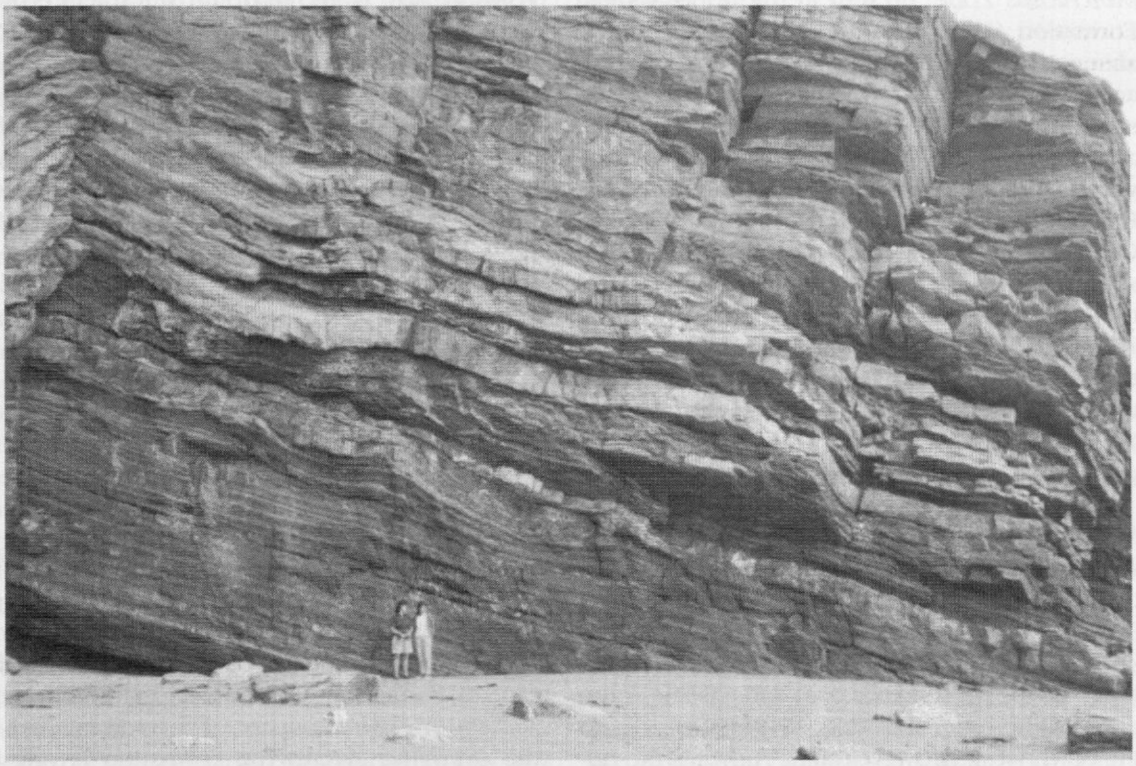

Figure 3.6 Middle–Upper Cambrian boundary at Porth Ceiriad, St Tudwal's Peninsula. The figures are standing in front of dark mudstones of the upper part of the Nant-y-big Formation. The composite calcareous unit at the boundary of the Nant-y-big and Maentwrog formations reaches beach level at the right of the photograph, and is overlain by sandstone beds of the Maentwrog Formation. (Photo: A.W.A. Rushton.)

Interpretation

Porth Ceiriad is one of the few places in Britain where the Middle–Upper Cambrian boundary is identifiable with faunal control, and it has yielded the best Middle–Upper Cambrian succession of acritarch floras. In the English Midlands the Middle–Upper Cambrian boundary is well constrained in the Merevale No. 3 Borehole by trilobites and bradoriids (Rushton, 1978) but is not exposed. In the Harlech Dome there are good exposures (e.g. Pratt *et al.*, 1995), but faunal control is poor except in Afon Llafar (see site report, below).

The succession shows progressive shallowing from turbidites deposited in relatively deep water to dark, condensed muds with concretions, accompanied by pauses in deposition and disconformity, followed by storm sediments in the Maentwrog.

The faunal and lithological characteristics allow correlation of the Nant-y-big Formation with the upper Gamlan and lower Clogau formations of the Harlech Dome (see site description below); these represent the *fissus* and *parvifrons* trilobite zones, but the overlying *punctuosus* Zone, present in the upper Clogau Formation (Allen and Jackson, 1985, p. 12), is absent from the Nant-y-big Formation on account of the non-sequence in the calcareous sandstone beds. The Maentwrog Formation can also be correlated lithologically and biostratigraphically between Porth Ceiriad and the Harlech Dome. However, whereas at Porth Ceiriad *Olenus* and *Homagnostus obesus* occur about 30 m above the base of the Maentwrog, in the Harlech Dome they appear 140 m or more above the base and are underlain by agnostoid trilobites, occurring near the base of the formation, that are thought to represent a highest Middle Cambrian horizon (Allen *et al.*, 1981, p. 307).

A regressive phase, recognizable across Avalonia and Baltica, caused a break that represents four trilobite zones in the St Tudwal's area, whereas the corresponding break in the Harlech Dome is of only one zone, the *brachymetopa* Zone (cf. Figure 2.2). The more pronounced break in the St Tudwal's area reflects the influence of the Anglesey–Wexford positive area to the north-west. However, at St Tudwal's the calcareous sandstone beds that bound the Middle–Upper Cambrian non-sequence contain clasts with fragmentary trilobites of that same zone, the *brachymetopa* Zone (Young *et al.*, 1994, p. 345). The clasts were presumably derived from a late Middle Cambrian shallow-water calcareous unit, not known *in situ* but of fairly local origin, that was formed during the regressive *brachymetopa* phase (Conway Morris and Rushton, 1988, p. 101) and soon afterwards derived into a transgressive early Upper Cambrian deposit (Young *et al.*, 1994). They are the only definite representative of the *brachymetopa* Zone in Britain, for although Cobbold and Pocock (1934) assigned the *forchhammeri* Grit, in the upper part of the Upper Comley Sandstone of the Wrekin area, to this zone, Rushton (1974) questioned the zonal assignment of their fauna.

The acritarch floras recorded by Martin (in Young *et al.*, 1994, fig. 7) show considerable turnover between the Nant-y-big and Maentwrog formations and are potentially valuable for correlation with successions of acritarch floras in other parts of the world (Molyneux *et al.*, 1996).

Conclusions

Porth Ceiriad is an important site for interpreting Cambrian history in North Wales in that it contains evidence of the conditions around the Middle–Upper Cambrian boundary. Overlying mid-Middle Cambrian beds there is evidence for shallowing, uplift and erosion, followed by early Upper Cambrian strata. Fragments of fossiliferous limestone that had been formed during the time of shallowing are the only evidence in Britain for the late Middle Cambrian '*brachymetopa* fauna', which is known principally from Scandinavia.

AFON LLAFAR (SH 7357 3644–SH 7329 3687)

Introduction

The Afon Llafar site exposes the basal stratotype of the Clogau Formation and is the only section in which the three zones recognized in the Clogau Formation are proved in stratigraphical succession. An exposure of the lowest part of the overlying Maentwrog Formation is one of only two that have yielded Middle Cambrian fossils.

The Clogau Formation was originally taken as the basal part of the 'Lingula Flags' (Salter, 1864a, pl. 10, p. 4), but with the detection of *Paradoxides* and other fossils in the unit, Belt (1867b, p. 494) excluded it from the 'Maentwrog Group', the lowest division of the 'Lingula Flags' as restricted by him, and he employed the South Welsh term 'Menevian Group'. The name 'Clogau Shales' was introduced by Andrew (1910) as a local name for the lowest unit of dark-grey laminated mudstones in the Dolgellau district, and the unit was described fully and its outcrop mapped by Matley and Wilson (1946). Allen *et al.* (1981) formalized the term 'Clogau Formation' and defined a basal stratotype in the Afon Llafar. Subsequently Pratt *et al.* (1995) described a clearer and much larger (though less fossiliferous) exposure on the coast at Llwyngwril (SH 602 114).

Description

Allen *et al.* (1981, p. 301) described the transitional contact (at 7357 3644) between the sandstones of the Gamlan Formation and the dark-grey laminated mudstones of the Clogau Formation, marking the basal stratotype of the latter (Figure 3.7). The strata dip north at 12–15° and sparse faunas of the *fissus* Zone, including *Plutonides hicksii* (Salter), have been collected from both the transitional beds at the top of the Gamlan and the lower beds of the Clogau Formation. About 17 m stratigraphically above the base of the Clogau Formation are fossils, including *Hartshillina spinata* (Illing), referred to the *parvifrons* Zone.

A further 50 m upstream and about 15 m higher stratigraphically, sparse representatives of the *punctuosus* Zone appear (Figure 3.8), whilst richer and more representative faunas (listed in Allen *et al.*, 1981, p. 303) occur for the next 300 m upstream. These include the trilobites *Paradoxides davidis* Salter and *Meneviella venulosa* (Salter), plus solenopleurids and agnostids, and are identical with typical Menevian faunas from South Wales (see the Porth-y-rhaw site report).

Alluvium covers the contact between the Clogau and Maentwrog formations, but a mudstone bed estimated to occur about 25 m above the base of the Maentwrog (7329 3687) has yielded poorly preserved agnostid trilobites that appear to represent a late Middle Cambrian horizon (Allen *et al.*, 1981, p. 307). Above this, a considerable thickness of the lower part of the

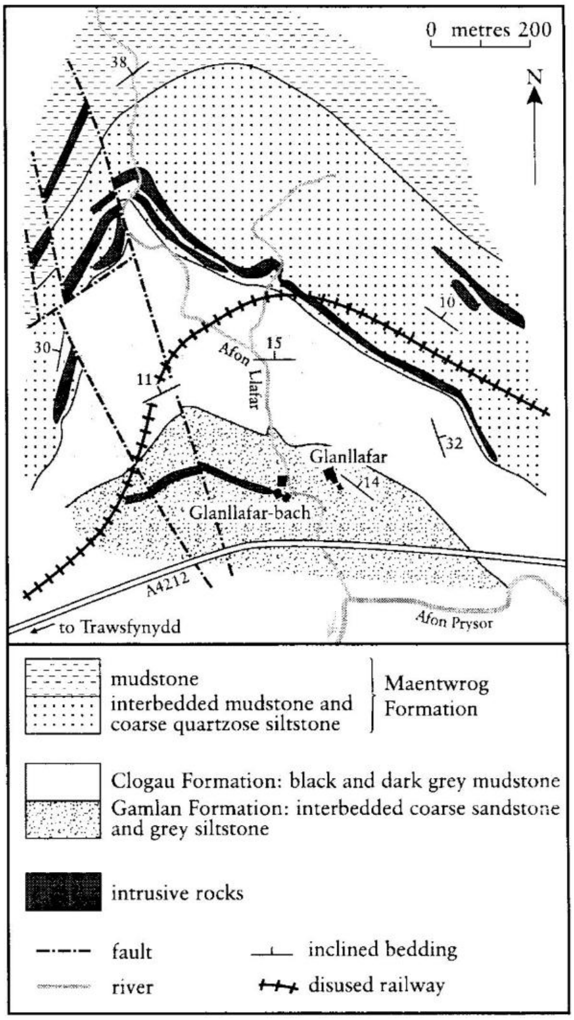

Figure 3.7 Geological map of Afon Llafar, after Allen *et al.* (1981, fig. 3).

Maentwrog Formation is unfossiliferous, but father upstream, north of Dolddinas (7376 3822), the middle part of the Maentwrog Formation contains a fauna of *Homagnostus obesus* (Belt) and *Olenus* sp., both typical of the *Olenus* Zone.

Interpretation

The Afon Llafar includes the basal stratotype for the Clogau Formation and shows the faunal succession from *fissus* to *punctuosus* zones better than anywhere else in North Wales. The choice of a basal stratotype for the Clogau Formation is arbitrary on account of the generally transitional nature of the basal contact, but also because of regional variation in both the Gamlan and

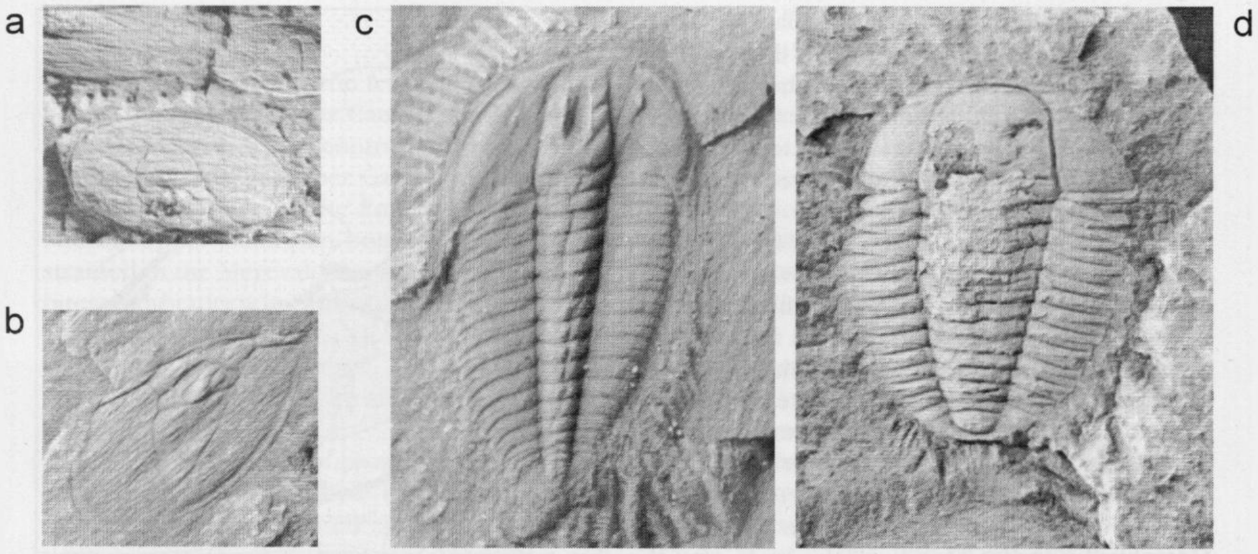

Figure 3.8 Cambrian trilobites from North Wales. (a, b) *Ptychagnostus punctuosus*, cephalon and pygidium, ×4, from the Clogau Formation (St David's Series) in Afon Llafar. (c) *Olenus micrurus* Salter, ×4, from Maentwrog Formation (Merioneth) of Nant Ganol. (d) *Peltura scarabaeoides* (Wahlenberg), ×3, from Dolgellau Formation of Rhobell-y-big.

Clogau formations. At Afon Llafar the Gamlan includes a coarse sandstone, with the Cefn Coch Grit of Matley and Wilson (1946) as its topmost division, and the Clogau Formation is dominantly of dark-grey laminated mudstone. At the contact at Llwyngwril, described in detail by Pratt *et al.* (1995), the Cefn Coch Grit is absent and the Clogau Formation, though marked by the appearance of laminated hemipelagite, contains a higher proportion of sandstone and siltstone. The Llafar section is much clearer biostratigraphically. At Llwyngwril the only useful fossil is a *Plutonides hicksii*, indicating the *fissus* Zone, found about 40 m above the base of the formation (Pratt *et al.*, 1995). In the Llafar section the *fissus* Zone is confined to the lowest 15 m of the section and is overlain by the *parvifrons* Zone, also about 15 m thick, followed by the *punctuosus* Zone, which appears to be more than 60 m thick (Allen *et al.*, 1981).

The occurrence of Middle Cambrian fossils near the base of the Maentwrog Formation and the *Olenus* Zone higher up shows that the base of the Upper Cambrian lies within the formation. Allen *et al.* (1981, p. 306) suggest that a non-sequence corresponding to the *brachymetopa* Zone separates the Maentwrog and Clogau formations and that the *pisiformis* Zone may be represented by strata that have not yet yielded diagnostic fossils. A comparable situation is inferred at Porth Ceiriad (see site description), where the basal non-sequence is more pronounced, but the Middle Cambrian fossils may be largely derived, and the strata representing the *pisiformis* Zone are not proved (Young *et al.*, 1994). In contrast, Pratt *et al.* (1995) described the contact between the Clogau and Maentwrog formations at Llwyngwril as conformable; however, there is insufficient biostratigraphical control (none for the Maentwrog) from which to infer this, and from the evidence elsewhere a non-sequence may be suspected.

Conclusions

Afon Llafar is the only place in North Wales to show the full succession of trilobite faunas, from the *fissus* to *punctuosus* zones, that inhabited the Welsh Basin during mid-Middle Cambrian times. These faunas allow correlation with the lithologically similar Menevian Beds of South Wales. It is one of only two places where one can identify the time in the late Middle Cambrian at which the pyritic mid-Middle Cambrian deposits were replaced by influxes of the sandy Maentwrog Formation.

NANT Y GRAEAN (SH 7356 3043) AND NANT GANOL (SH 7659 3285)

Introduction

Nant y Graean displays a section in the Maentwrog Formation from which the biostratigraphy of three subzones of the *Olenus* Zone can be inferred more readily than from anywhere else around the Harlech Dome. The area of Nant Ganol shows the upper of these subzones, including both *Olenus micrurus* and the more widely distributed *O. cataractes*. The sites are of importance in the regional correlation of the Maentwrog Formation.

The Maentwrog Formation, mainly of early Upper Cambrian (Merioneth) age, is present around the Harlech Dome and the outcrop extends to the core of the Ynyscynhaiarn Anticline (Tremadog) and to St Tudwal's Peninsula. The base is discomformable on the Clogau Formation and, according to Crimes (1970a), marks the onset of a new cycle of sedimentation in the North Wales area. The formation consists of alternations of quartzitic sandstone beds, some of turbiditic origin, and dark-coloured mudstone. Allen *et al.* (1981) defined the basal stratotype and described the formation in detail. In places the Maentwrog Formation can be divided into a lower, dominantly arenaceous, Vigra Member, and an upper, argillaceous, Penrhos Member (e.g. Pratt *et al.*, 1995), but it is evident that the lithological succession varies locally (Allen *et al.*, 1981, p. 304). Crimes (1970a) suggested that the deposition of the Maentwrog Formation was in general below wave base, but Bose's (1983) study of correlative strata at Porth Ceiriad (see site description) showed that shallower-water conditions obtained there.

The base of the Maentwrog Formation is considered to be of late Middle Cambrian age (see site reports for Afon Llafar and Porth Ceiriad), but the bulk of the formation is known to be of late Cambrian age by the occurrence of diagnostic trilobites: Belt (1867a) described *Olenus gibbosus* (Wahlenberg), *Homagnostus obesus* (Belt) and *Glyptagnostus reticulatus* (Angelin) (as '*Agnostus nodosus*') from near Dolmelynllyn (SH 7295 2373), and Salter (1866b, p. 246) gave the distribution of some other species. However, although the Maentwrog Formation is well exposed along the Mawddach Estuary, the biostratigraphy is poorly known there because there are few fossil localities. Around Maentwrog fossils are locally abundant, but preservation is generally very poor (Salter, 1864a, pl. 1, fig. 2), on account of the strong cleavage. The best area for biostratigraphical interpretation of the Maentwrog Formation is east of Trawsfynydd, where there are several fossil localities and the cleavage is not so intense.

Description

Nant y Graean

Nant y Graean is a minor tributary of Afon Gain, 6 km SSE of Transwfynydd. Between about 400 m and 1000 m upstream from the confluence with Afon Gain the stream reveals extensive exposures of sandstone and mudstone typical of the Maentwrog Formation, generally dipping gently upstream but locally showing folding. The area was mapped by Matley and Wilson (1946), whose results were incorporated in the British Geological Survey (1982) map of the Harlech district. At the downstream end of the exposure (7356 3043), *Olenus gibbosus* (Wahlenberg) is associated with *Glyptagnostus reticulatus* (Angelin); these indicate the *gibbosus* Subzone of the *Olenus* Zone (Allen *et al.*, 1981, p. 307). Near the upper end of the exposure *Homagnostus obesus* is associated with poorly preserved *Olenus truncatus* (Brünnich), indicating the *truncatus* Subzone. Directly down dip, a roadside exposure (745 301) yielded *Olenus micrurus* Salter which is taken to indicate the overlying *cataractes* Subzone.

Nant Ganol

About 6 km south-east of Trawsfynydd this stream crosses the axes of a syncline–anticline pair, creating large exposures of gently dipping Maentwrog Formation (7659 3285). *Homagnostus obesus* and *Olenus micrurus* (Figure 3.8c) are relatively common locally, both here and along strike by the road (7648 3298); the latter locality also yielded a specimen of *Olentella? rara* (Orłowski), figured by Allen and Jackson (1985, pl. 4, fig. 2). Farther east (7727 3326), but at a similar stratigraphical level, *Olenus cataractes* Salter and *H. obesus* were collected, whilst a specimen of *H. obesus* collected still farther east (7786 3336) represents the only trilobite yet known from the base of the Ffestiniog Flags Formation.

Interpretation

Many collections of *Olenus* from the Maentwrog Formation are from isolated exposures or are not well localized. In the absence of a consistent lithostratigraphy one cannot place such collections into a reliable stratigraphical succession. Nant y Graean is therefore important in providing a section in which superposition of the subzones of the *Olenus* Zone can be assessed. A similar superposition of *Olenus truncatus* above the *gibbosus* Subzone is seen in Nant Braich-y-Ceunant (SH 7572 3627), but the fossils thence are poorly preserved and the *cataractes* Subzone is not proved there.

In the Nant y Graean evidence for the *truncatus* Subzone is estimated to appear 100–140 m above the *gibbosus* Subzone, the corresponding figure in Nant Braich-y-Ceunant being about 50 m (Allen *et al.*, 1981, p. 308). At Nant y Graean the specimen indicative of the *cataractes* Subzone occurred about 150 m above the locality with *O. truncatus*.

Although the *cataractes* Subzone is well shown in the area of Nant Ganol, folding makes it difficult to estimate its thickness. It is the area from which the type and other good specimens of *O. micrurus* were collected (Allen and Jackson, 1985, pl. 4, fig. 1).

Conclusions

Nant y Graean is the best place in North Wales to observe the succession of trilobite faunas during the earlier Late Cambrian. The three successive faunas allow correlation of the Maentwrog Formation and comparison of events in other parts of Britain and elsewhere. The upper fauna is, however, better seen at Nant Ganol than at Nant y Graean.

RHOBELL-Y-BIG–FOEL GRON (NY 7859 2845 AND NY 7882 2827)

Introduction

Localities in the Dolgellau Formation between Rhobell-y-big and Foel Gron yield the best faunas of the *Peltura scarabaeoides* Zone in Wales. These are of value for correlation with those from the measured section at Ogof Ddû and the Scandinavian standard succession.

The *Peltura scarabaeoides* Zone is recognized on both east and west sides of the Harlech Dome, but whereas the material collected to the west (from Penmorfa and Garreg-wen (Salter, 1866b, p. 250) and from Ogof Ddû (see site report)) is commonly strongly deformed, the localities between Foel Gron and Rhobell-y-big yield relatively well-preserved specimens. Various localities hereabouts were evidently known to early collectors and appear to include the type localities of some trilobite species described by Belt (1868), but the present localities were described more exactly by Wells (1925, p. 467) and Allen *et al.* (1981).

Description

Two main streams drain the moorland between Rhobell-y-big and Foel Gron. The lower reaches of the western stream (7869 2907 to 7880 2921) cross the lower part of the Dolgellau Formation (*spinulosa* Zone), but the upper part reveals sporadic exposures of the upper Dolgellau Formation, which consists of soft, black, pyritous mudstone that is finely laminated and weakly cleaved. Exposures are not extensive and the folding and faulting preclude assessment of the superposition or thickness of these beds. Locally (7859 2845) trilobites occur plentifully. Allen *et al.* (1981, p. 314) recorded a fauna representing the *bisulcata* Subzone of the *scarabaeoides* Zone: *Ctenopyge (Ct.) bisulcata* (Phillips), *Ct. (Ct.) directa* Lake, *Ct.* (*Ct.*) *falcifera* Lake, *Ct. (Ct.) pecten* (Salter), *Lotagnostus trisectus* (Salter), *Parabolinella* aff. *caesa* Lake, *Parabolinites? williamsonii* (Belt), *Peltura scarabaeoides scarabaeoides* (Wahlenberg) (Figure 3.8d) and *Sphaerophthalmus humilis* (Phillips). They are flattened but fairly well preserved (Allen *et al.*, 1981, pl. 2, figs 1, 2, 4, text-fig. 5). The next stream to the east yields a different assemblage representing a slightly higher horizon, possibly the *linnarssoni* or *lobata* Subzone, including *L. trisectus, Micragnostus* sp., *Parabolinites? longispinus* (Belt), *P. scarabaeoides westergardi* Henningsmoen, *Plicatolina* cf. *quadrata* Pokrovskaya and *Sphaerophthalmus major* Lake (7882 2823 and

7882 2827). Earlier collectors also found *Parabolinites longispinus* (Belt) and *Hedinaspis? expansa* (Salter) hereabouts. The lower stretch of the eastern stream crosses higher beds of the Dolgellau Formation and yields good faunas of the *Acerocare* Zone (locality A of Rushton, 1982, p. 44).

Interpretation

The faunas consist entirely of trilobites and include only agnostids and olenids, forms that were adapted to dysaerobic environments typical of the Dolgellau Formation, also evinced here by the lack of bioturbation. The species of *Ctenopyge* reported from the *bisulcata* Subzone allow correlation with the *bisulcata* Subzone of the Scandinavian sequences (Henningsmoen, 1957) and are the same as those recorded from the White-leaved Oak Shale of the Malvern area (Worssam *et al.*, 1989). None of the *Ctenopyge* species is known from the measured section at Ogof Ddû, and the *bisulcata* Subzone has not yet been identified there with certainty. The fauna of the *linnarssoni–lobata* Subzone has species in common with the corresponding fauna from Ogof Ddû (Howells and Smith, 1997), but at Rhobell it includes the olenid *Plicatolina* (known from a single specimen) and lacks both brachiopods and the remopleuroid trilobite *Richardsonella? invita* (Salter) known from Ogof Ddû.

Belt's specimens are generally poorly localized and his publications state only that various of his species, such as *Parabolinites? longispinus, P.? williamsonii* and *Pseudagnostus obtusus,* are from 'near Rhiw-felyn' (SH 781 292) (Belt, 1868, pp. 9–11); but the Geological Survey investigations (Allen and Jackson, 1985) suggest that the streams draining Rhobell-y-big and Foel Gron are probably the type localities of some of Belt's species.

Conclusions

These localities reveal good faunas of trilobites of the *Peltura scarabaeoides* Zone, that were adapted to living in poorly oxygenated sea water such as characterized many areas during the later Cambrian. These faunas compare closely with others from parts of England, Wales and Scandinavia and allow an exact correlation.

OGOF DDÛ (RHIW-FOR-FAWR) (SH 512 381–SH 515 379)

Introduction

The section at Ogof Ddû is a site of international stratigraphical and historical importance. It exposes a section from the Ffestiniog Flags Formation, through the Dolgellau Formation (both Merioneth Series), into the Lower Sandstone and Lower Mudstone members of the Dol-cyn-afon Formation (Tremadoc Series) and

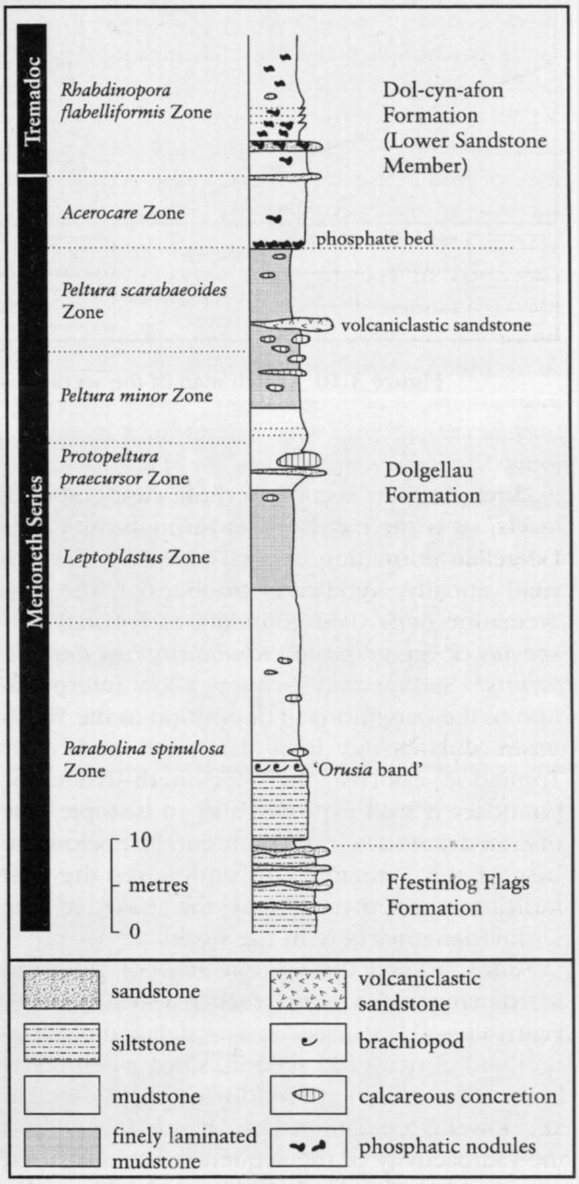

Figure 3.9 Stratigraphical succession east of Ogof Ddû, Criccieth, measured by D.R.A. Ponsford (unpublished), with zonal stratigraphy from Howells and Smith (1997, fig. 5).

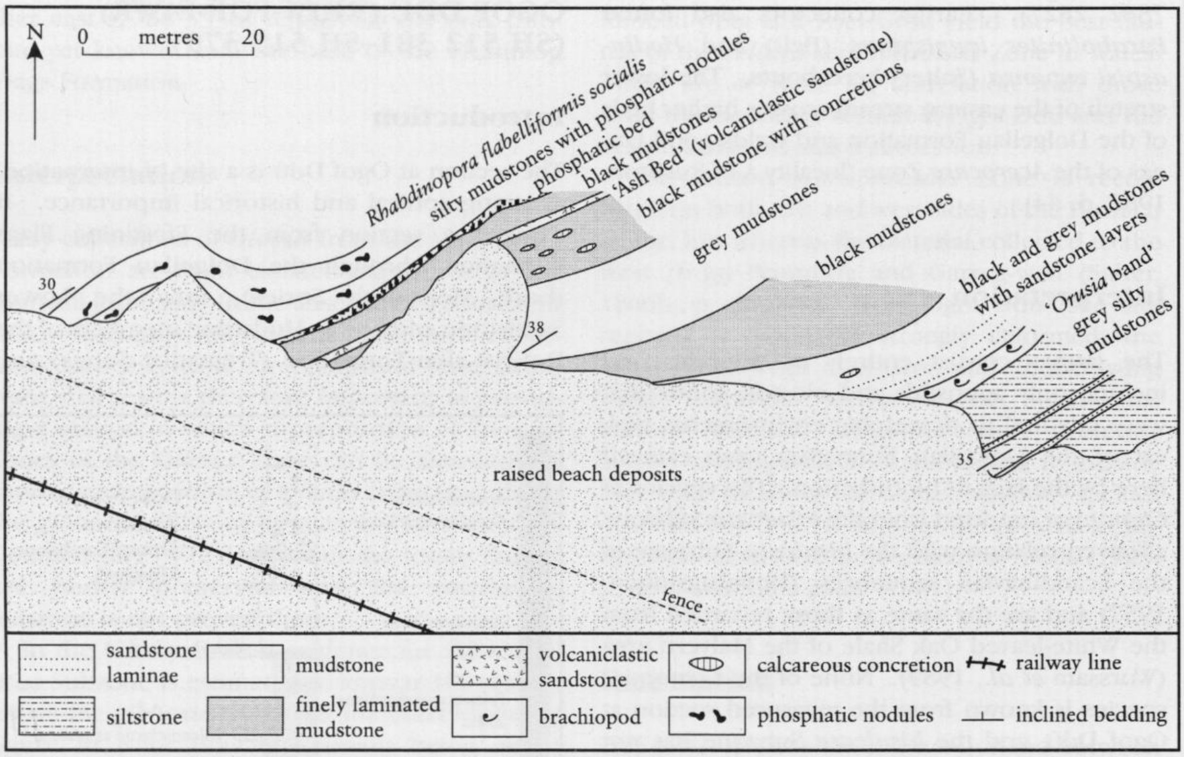

Figure 3.10 Sketch map of the section east of Ogof Ddû, after Ponsford (unpublished).

is much the best section at these stratigraphical levels. It is the only section through the entire Dolgellau Formation, several horizons of which yield zonally significant trilobites. The low Tremadoc Beds yield abundant early-zonal subspecies of the graptolite *Rhabdinopora flabelliformis*. Sedimentary features allow interpretation of the conditions of deposition in the Welsh Basin during the late Merioneth and early Tremadoc epochs: the Merioneth–Tremadoc boundary is well exposed, and an isotopic date obtained from a volcaniclastic bed just below the base of the Tremadoc currently gives the best indication of the age of the base of the Ordovician anywhere in the world.

Salter studied the section at Ogof Ddû and listed many fossils thence (Salter, 1866b, p. 250). Fearnsides (1910) gave a more detailed description and a measured section, since when it has become a reference section for the Dolgellau and lower Tremadoc rocks. It was logged and the radioactivity of the sequence was measured (summary in Ponsford, 1955), and it proved a key locality in the sedimentological study of Prigmore (1994). The site is easily accessible and accounts have been included in geological guides to the Ynyscynhaiarn area (Roberts, 1979; Cattermole and Romano, 1981). Following detailed mapping, Howells and Smith (1997) rationalized the lithostratigraphy and gave details of the biostratigraphy, and their account is followed here.

Description

The section at Ogof Ddû (Figures 3.9 and 3.10) is an old sea-cliff cut into the side of the small hill Rhiw-for-fawr, on the western limb of the northward-plunging Ynyscynhaiarn (Tremadog) Anticline. Bedding dips north-west or WNW at about 35–40°, and cleavage dips steeply at about 80° in a similar direction. The section is described here working up the sequence from east to west.

Merioneth Series

The section (Figure 3.9) begins in the upper part of the Ffestiniog Flags Formation, which consists of alternations of dark-grey, poorly laminated silty mudstones with pale-grey, fine- to medium-grained massive sandstones. The sandstones are

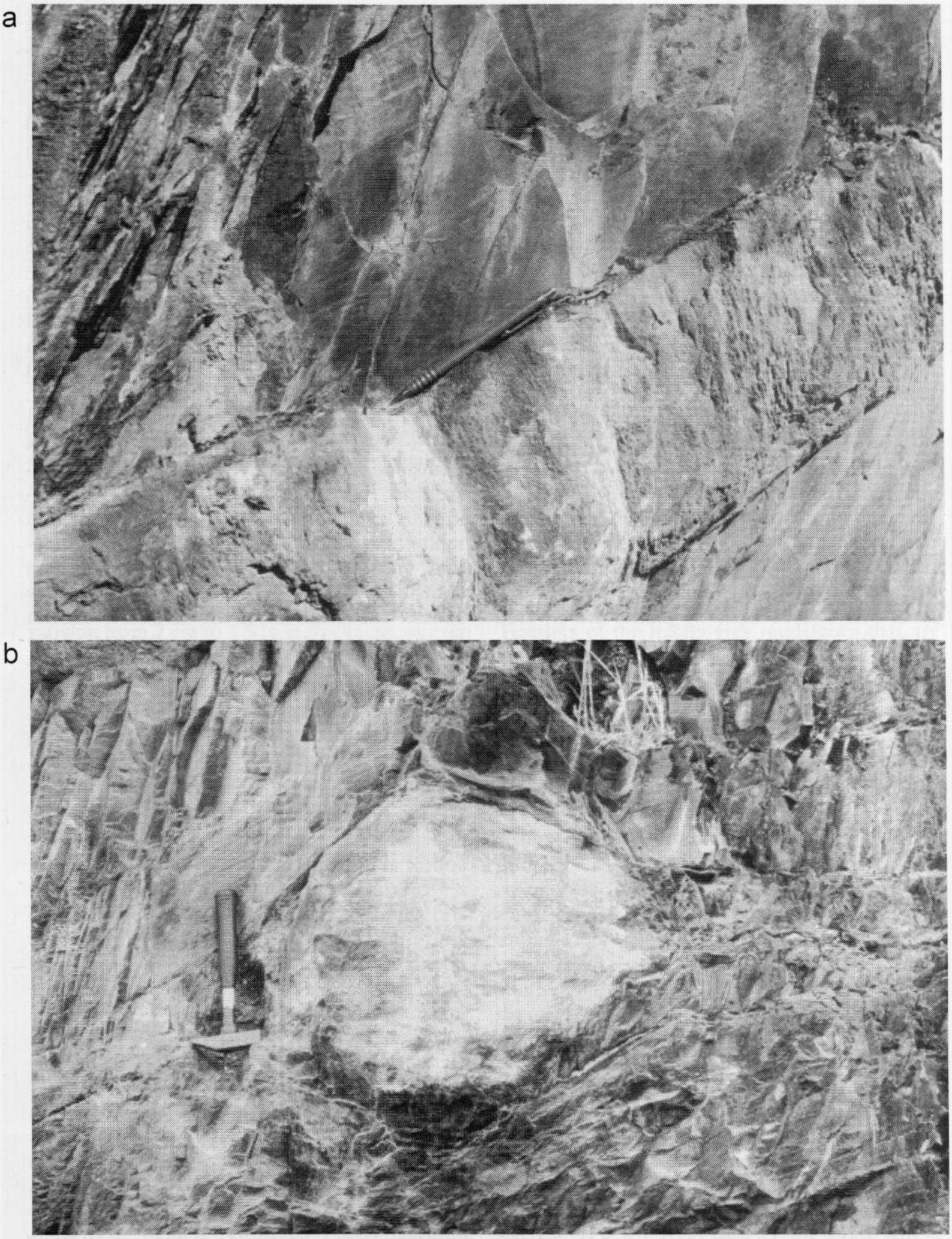

Figure 3.11 The Dolgellau Formation exposed at Ogof Ddû. (a) The thickest of the beds of volcaniclastic sandstone in the *scarabaeoides* Zone. Zircon crystals from this bed yielded an age of 491 ± 1 Ma. (b) A large calcareous concretion in the *scarabaeoides* Zone, lying about 1 m below the sandstone in (a). Bedding lamination is visible dipping to the left just above the hammer handle; cleavage dips more steeply to the left. (Photos: J.K. Prigmore.)

around 5–40 cm thick but show changes of thickness laterally; they have sharp contacts and show climbing ripple cross-lamination, scour and fill structures, loaded bases and convolute lamination. Trace fossils include *Rusophycus*, *Cruziana* and *Skolithos*. The brachiopod *Lingulella davisii* (M'Coy) is common at several horizons, occurring as disarticulated valves in a current-stable orientation. The top of the Ffestiniog Flags Formation is taken where sandstone beds die out. The overlying 6 m of strata are transitional between the Ffestiniog and Dolgellau formations and consist of finely laminated dark-grey silty mudstones and structureless silty mudstones, with pale-grey pyritous siltstone laminae occurring every few centimetres.

West of a small break in exposure at a slack in the cliff face, the rocks are more typical of the Dolgellau Formation and consist of dark-grey and black laminated carbonaceous silty mudstones, with two or three laminae per millimetre. Organic carbon content is high and bioturbation is completely absent. Siltstone laminae occur throughout, and are common near the base, where some bedding planes are covered with the brachiopod *Orusia lenticularis* (Wahlenberg). The trilobite *Parabolina spinulosa* (Wahlenberg) is reported, and these beds yielded the types of the non-olenid trilobites *Cermatops discoidalis* (Salter) and *Maladioidella abdita* (Salter), respectively redescribed by Hughes and Rushton (1990) and Rushton and Hughes (1996).

The overlying 40 m of strata are of similar black mudstones, with rare siltstones and mudstones from low-concentration turbidity flows. Ponsford (1955) found that the black mudstones of the Dolgellau Formation were more radioactive than the adjacent formations, the radioactive source being uranium concentrated in phosphate nodules and in some of the darker mudstone bands. The mudstones are fossiliferous at several levels, and the zones of *Parabolina spinulosa*, *Leptoplastus*, *Protopeltura praecursor*, *Peltura minor* and *P. scarabaeoides* have all been recognized (Rushton in Howells and Smith, 1997, fig.5), mostly by means of olenid trilobites that are considered to have been adapted to dysaerobic environments.

Just above the *Orusia* beds are several pale-grey, pyritous, fine-grained, micaceous sandstones, up to 5 cm thick, which consist of recrystallized argillaceous material. They probably represent volcanic ash deposits. Towards the middle of the formation there are fewer black laminae and more lighter-grey mudstones, possibly introduced by waning-flow events. Some of the lighter-grey laminae show disruption, possibly due to bioturbation. Study of polished slabs shows a few pale-grey event beds, 7 mm thick, which fine upwards from quartz-rich siltstone to clays (Prigmore, 1994). Towards the top of the Dolgellau Formation (5142 3795) a thicker, medium- to coarse-grained volcaniclastic sandstone occurs low down in the cliff-face (Figure 3.11a). This thins rapidly from 30 cm to 3 cm thick across 10 m of outcrop. It consists of sub-angular grains of quartz and feldspar in a matrix of recrystallized argillaceous material and is presumably a reworked volcanic ash deposit. Zircon crystals from it have been dated at 491 ± 1 Ma (Davidek *et al.*, 1998). Below this sandstone are several levels with calcareous concretions up to 100 × 60 cm across (Figure 3.11b) that tend to be nucleated on thin sandy beds. They show a cone-in-cone structure, and some contain trilobites representing subzones of the *minor* and *scarabaeoides* zones. The shales above the sandstone contain the brachiopod *Eoorthis* and trilobites of the *scarabaeoides* Zone, including *Richardsonella? invita* (Salter).

At the top of the Dolgellau Formation the black shales pass into dark-grey mudstones of the Dol-cyn-afon Formation. Howells and Smith (1997) followed Ponsford in placing the boundary between the Dolgellau and Dol-cyn-afon formations at the level where phosphates first appear abundantly in the section. They occur in a 5 cm thick band, with a few sandstone lenses and laminae, forming a distinctive horizon 6 m above the 30 cm volcaniclastic sandstone. The possible occurrence of *Parabolina acanthura* (Angelin) there is consistent with, but not diagnostic of, the *Acerocare* Zone.

Tremadoc Series

The lower part of the Dol-cyn-afon Formation (the 'Tremadoc Slates' of early writers) consists of dark-grey silty mudstones that coarsen upwards into massively bedded silty sandstones that are about 100 m thick. These beds are the informal 'Lower Sandstone Member' of Howells and Smith (1997), equivalent to the 'Tynllan Beds' of Fearnsides (1910). The basal beds are well laminated but with signs of disruption and contain white-weathering phosphate nodules lying along the bedding at intervals of a few centimetres. Above the base the dark- and light-grey lamination becomes increasingly disrupted, producing an indistinct mottled texture. Bioturbation becomes increasingly important upwards, with small mudstone-filled *Chondrites* burrows cutting across the lamination. Beds of pale-grey mudstone up to 10 cm thick occur occasionally. They have sharp bases, become gradually darker-coloured upwards and may show synsedimentary microfaulting; phosphate nodules often occur towards their tops. Fine- to medium-grained sandstone laminae occur throughout the sequence, but especially near the base of the Lower Sandstone Member, where they form three or four upwardly coarsening cycles every 10 cm. Brachiopods and phosphate nodules are abundant, and *Rhabdinopora flabelliformis socialis* (Salter) covers the bedding planes of intervening mudstones, the lowest being some 8.5 m above the basal phosphatic horizon (Figure 3.9).

Up section, the sandstone laminae increase in thickness and frequency and pass into massive, pale-grey, fine- to medium-grained sandstones, ranging from 2 cm to 1.5 m in thickness, or even thicker towards the top of the member. They are mostly structureless and contain numerous rhyolitic clasts. Fining-upwards sequences about 10 cm thick also occur. The commonest fossils are brachiopods, including *Broeggeria,* with a few trilobites.

West of the Lower Sandstone Member is a grassy depression through which Fearnsides (1910) mapped the outcrop of his '*Dictyonema* Band', though the graptolite has never been found *in situ* there. To the west, the lower part of the Lower Mudstone Member (equivalent to the 'Moelygest Beds' of Fearnsides (1910)) consists of a monotonous sequence of strongly cleaved dark-grey silty mudstones, structureless and thoroughly disrupted by bioturbation. Phosphate nodules are common, and thin siltstone laminae occur sporadically. No fossils are known.

Interpretation

The Ffestiniog Flags Formation is considered to represent deposition in shallow near-shore environments with regular current activity. Sedimentary structures seen at Ogof Ddû and in correlative strata at localities nearby (Crimes, 1970a) imply that deposition occurred in a storm-dominated, sub-tidal or littoral environment. The *Skolithos* burrows and other traces indicate fairly energetic conditions and well-oxygenated water. Crimes (1970a) reported that currents acted from the south or south-west. Mud-cracks reported by Fearnsides (1912) suggest shallow to emergent conditions. The great thickness of these shallow-water deposits, some 650 m in the Ynyscynhaiarn Anticline but up to 1050 m elsewhere in the Harlech Dome (Allen and Jackson, 1985), indicates that sedimentation kept pace with subsidence for a considerable period. The beds transitional to the Dolgellau Formation may represent more distal deposits generated from storm currents similar to those that gave rise to the coarser sandstones of the Ffestiniog Flags Formation, though the undisturbed lamination in these beds implies lower levels of oxygenation.

The black shales of the Dolgellau Formation accumulated under predominantly anoxic conditions and represent a combination of fallout of organic matter and hemipelagic sediment from the water column, with rare siltstones and mudstones from low-concentration turbidity flows. Features of the lighter-grey mudstones that are conspicuous towards the middle of the Dolgellau Formation indicate a slight increase in oxygenation. As similar phenomena are recognized at a corresponding level elsewhere in the Harlech Dome (Prigmore, 1994), they may reflect a basin-wide increase in oxygenation at that level. The section at Ogof Ddû thus shows a rapid environmental change, from high-energy, shallow near-shore conditions for the Ffestiniog Flags Formation, to quiet, restricted and sediment-starved environments with low oxygen levels for the Dolgellau Formation. The development of Palaeozoic black mudstones such as the Dolgellau Formation has been related to periods of sea-level rise (e.g. Leggett, 1980; Leggett *et al.*, 1981), and the abrupt facies change from Ffestiniog to Dolgellau certainly suggests a relative rise in sea level at this time, though whether eustatic or caused by regional subsidence is not yet clear.

Ogof Ddû is much the best section through the Dolgellau Formation; however, the succession differs from the thicker correlative beds on the south and east of the Harlech Dome (e.g. Foel Gron) in evincing more current activity and bioturbation and in yielding certain non-olenid trilobites (*Maladioidella, Richardsonella?*). This may reflect stronger current activity and oxygenation in relative proximity to the Irish Sea positive area. The volcaniclastic sandstone in the *scarabaeoides* Zone has given the best radiometric date for late Merioneth rocks and currently (1999) provides the best available constraint on the base of the Ordovician anywhere in the world (Davidek *et al.*, 1998).

The transition from black to dark-grey mudstones across the Dolgellau to Dol-cyn-afon formational boundary, better exposed at Ogof Ddû than elsewhere, is due to the reduced preservation of organic carbon in Tremadoc rocks and is correlated with the upward trend towards increased oxygenation and more rapid sedimentation through the Tremadoc succession. The transition differs from that on the south and east of the Harlech Dome (see the Dol-cyn-afon and Bryn-llin-fawr site reports) in showing a relatively condensed succession at a phosphate-rich bed, with a possible non-sequence above or below it and a much reduced development of the *Acerocare* Zone. The well-laminated mudstones at the base of the Lower Mudstone Member presumably remained largely anoxic, with the gradual upward increase in disruption and bioturbation indicating increased oxygenation, leading to the development of structureless and thoroughly bioturbated mudstones by mid-Tremadoc times, when normal well-oxygenated conditions existed at the sea floor. The Dolgellau to Dol-cyn-afon boundary at Ogof Ddû is recognized at the appearance of abundant phosphate nodules such as characterize Tremadoc sequences throughout the Harlech Dome. Current theory for precipitation of phosphate as nodules (Smith, 1988) requires that some thickness of sediment must have been oxic (although oxygen levels were low at times, judging from the record of bioturbation). It is considered that the increase of waning-flow events introduced sufficient oxygenation to provide a mechanism for the precipitation of phosphate nodules (see discussion in Prigmore, 1994).

The majority of Dol-cyn-afon lithologies indicate deposition from waning-flow events, such as turbidite or storm events. The laminated and mottled mudstones characteristic of the Lower Mudstone and Lower Sandstone members formed from low-concentration turbidity currents or bottom currents, along with pelagic fall-out of organic material. The thick- to medium-bedded sandstones high in the Lower Sandstone Member were presumably produced by high-concentration turbidity currents, whilst the numerous rhyolitic clasts imply a strong volcanic component. Thinner but otherwise similar sandstones occur elsewhere in the Harlech Dome (Prigmore, 1994), but the absence of thick volcanogenic sandstones in those areas suggests that Ogof Ddû lay in a more proximal position, indicating a possible volcanic source to the west or north-west.

The Ogof Ddû section gives the best exposure of the lithological and sedimentological succession through the Lower Sandstone Member of the Dol-cyn-afon Formation, though because of the strong cleavage the faunas are better seen at Tyn-llan and Wern Road (see site reports, Chapter 7).

Conclusions

The section at Ogof Ddû is of international importance, both stratigraphically and historically. It shows better than elsewhere a full sequence of higher Upper Cambrian rocks and is the type locality for several species of trilobite. The rocks show evidence for changes in marine environments, from sandstones deposited in a shallow sea to black muds deposited in quiet waters away from the influence of land areas; this change may be due to rapid foundering of the sea floor. The succession of faunas enables correlation across Britain to other parts of the world. Around the Cambrian–Ordovician boundary the black mudstones pass upwards into grey mudstones, the colour change being related to increasing levels of oxygenation in the water and possibly to a global sea-level rise. A volcanic bed just below the boundary is 491 million years old and gives the best available indication of the age of the Cambrian–Ordovician Boundary.

ARFON AREA

The Cambrian rocks of the Arfon area, lying between the Harlech Dome and Anglesey (Figure 2.1), are strongly faulted and tectonized, such that the mudrocks are cleaved into good roofing-slates, which have been exploited in large quarries that mark the 'Carnarvonshire Slate Belt'. The stratigraphical succession in Arfon is less complete and less well dated than that of the Harlech Dome, but the base of the succession is of particular interest historically and stratigraphically for showing a debated conformable or paraconformable contact between

Table 3.1 General stratigraphical successions proposed for the Arfon area

	Llanberis	**Nantlle**
	Wood, 1969; Reedman *et al.*, 1984	Morris and Fearnsides, 1926
(Arenig	Graianog Sandstone)	
Merioneth	Marchlyn Formation (with Carnedd y Filiast Grit at top)	
age uncertain	Bronllwyd Grit	Cwmffyrch Grit
Comley	Llanberis Slates	Llanberis Slates
	Fachwen Formation	Glog Grits Cilgwyn Conglomerate Tryfan Grits
Cambrian or Precambrian	Padarn Tuff	Padarn Tuff

Cambrian sedimentary rocks and underlying volcanic rocks, supposedly of Precambrian age. In his original description of the Cambrian System, Sedgwick (in Sedgwick and Murchison, 1835) included the roofing-slates of Llanberis in the system, and it remained as part of the Cambrian in all later re-classifications of the Lower Palaeozoic rocks (Sedgwick, 1852; Cowie *et al.*, 1972, fig. 1).

Underlying the Llanberis Slates is a sequence of conglomerates, sandstones and tuffs, and quite apart from the problems in establishing their stratigraphy in such strongly folded and faulted ground, it has also proved difficult to map a satisfactory boundary between that sedimentary sequence and the volcanic rocks on which it rests (see site report for Llyn Padarn). When the downward extent of the Cambrian was being debated in the late 19th century (Blake, 1892), the very difficulty of interpreting the successions in Arfon added force to the protagonists' views (see Wood, 1969).

The stratigraphical succession is marked by lateral and vertical facies changes, but the general successions shown in Table 3.1 have been proposed.

The Padarn Tuff was formerly regarded as Precambrian, in the sense that it underlies the historical type Cambrian, part of which, the Llanberis Slates Formation, is dated palaeontologically. The nature of the contact between the Padarn Tuff and the overlying Cambrian was not clearly established, so the tuff was appropriately mapped as 'Cambrian or Precambrian' by the British Geological Survey (1988a). The Padarn Tuff has since yielded an isotopic date of 614 ± 2 Ma (Tucker and Pharaoh, 1991) and is now considered to be well within the Precambrian.

The sequence from the Fachwen Formation to the Llanberis Slates Formation records deposition in a deepening sea, and trilobites from the top of the Llanberis Slates indicate a mid-Comley age. The St David's Series is unproved in the Arfon area, and the Bronllwyd Grit Formation remains of uncertain age, though Wood (1969) correlated part of it with the Gamlan Formation in the Harlech Dome, which is of St David's age.

The Marchlyn Formation has yielded fossils of the lower parts of the Merioneth Series and is overlain locally by the lower part of the Dolgellau Formation (Shackleton, 1959), but over the remainder of its outcrop pre-Arenig erosion has removed all later Merioneth strata.

The lower part of the succession at Llanberis is shown at Llyn Padarn, where the problems of the basal contact of the Fachwen Formation and lateral variations in the conglomerate units are evident. Parts of the succession up through the Llanberis Slates Formation are exposed around Moel Tryfan, though the overlying Bronllwyd

Grit Formation is not represented in the GCR. The Marchlyn Formation and its contact with the Graianog Sandstone are well shown at Cwm Graianog.

LLYN PADARN (SH 569 616–SH 574 614)

Introduction

The north-west side of Llyn Padarn exposes the basal Cambrian succession in the historical type area of the Cambrian System and is one of the few localities in the Arfon area where the relationship between the Precambrian Arvonian volcanic rocks and the Cambrian can be adequately demonstrated. The Cambrian succession displays complex interdigitation of volcanic and sedimentary facies.

Early workers found the general geological succession difficult to interpret, as shown by the sometimes heated controversy surrounding the study of these rocks, the history of which is outlined by Wood (1969). In brief, Ramsay (1866) considered the 'felsite' of the Padarn Ridge to have been intruded into Cambrian conglomerates but found it difficult to delineate a precise boundary between them, whereas Hicks (1878) claimed that, as the conglomerates overlie the volcanic rocks unconformably, the latter should be referred to his newly recognized Pebidian and Dimetian 'series' of Precambrian age. The opinions of later workers (Blake, 1888, 1892; Geikie, 1891) differed as to the number of conglomerate beds, their structural relationships and whether or not they represent a major marine transgression following a stratigraphical break.

Later, Morris and Fearnsides (1926) described the Cambrian rocks in the area and established the stratigraphical succession used here; in keeping with the concept prevalent at that time of a general sub-Cambrian hiatus, they assumed that their 'Cilgwyn Conglomerate' formed the local transgressive base to the Cambrian.

Wood (1969) made a detailed map of the area north of Llyn Padarn and named the basal Cambrian rocks the 'Fachwen Formation'; it consists of conglomerates, sandstones and thin ignimbrites. He demonstrated that the Arvonian volcanic rocks and the overlying Fachwen Formation are folded together into a faulted syncline–anticline pair but show no significant unconformity.

Reedman *et al.* (1984) mapped a wider area of Arfon and named the Arvonian volcanic rocks the 'Padarn Tuff'. Locally they identified both unconformable and disconformable relationships between the Padarn Tuff and the Fachwen Formation and, by regional interpretation of the Bouger Gravity Anomaly, showed that the Padarn Tuff was deposited in a fault-controlled basin.

Description

The site extends along the north-east shore of Llyn Padarn by the Llanberis Lake Miniature Railway (Figure 3.12). Exposures at the north-west end are highly siliceous welded Padarn Tuff, showing little or no structure. They pass upwards into the sedimentary-volcanic sequence of the Fachwen Formation, but the actual boundary, and hence the base of the Cambrian

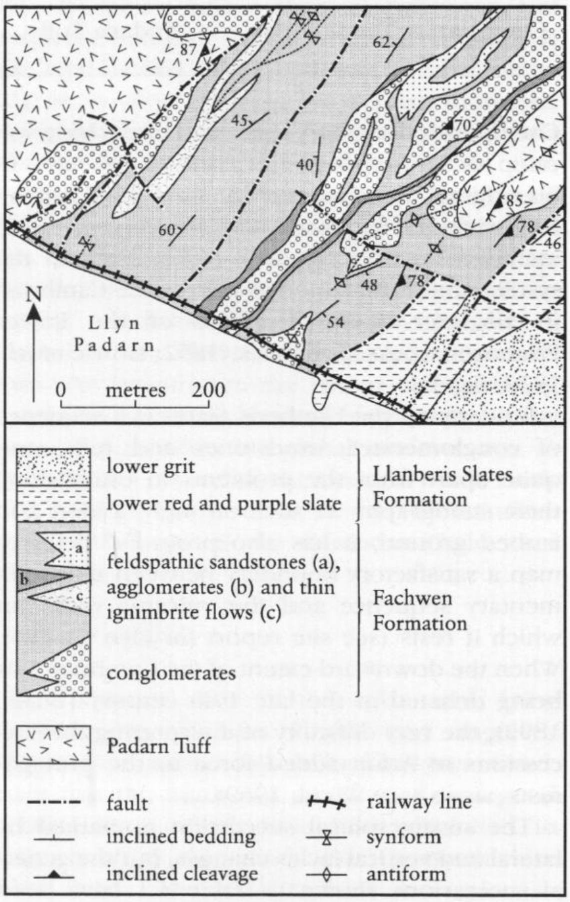

Figure 3.12 Geology of the section along the north side of Llyn Padarn through the Fachwen Syncline and Gallt-y-foel Anticline, after Wood (1969), with stratigraphical terminology modified by Reedman *et al.* (1984).

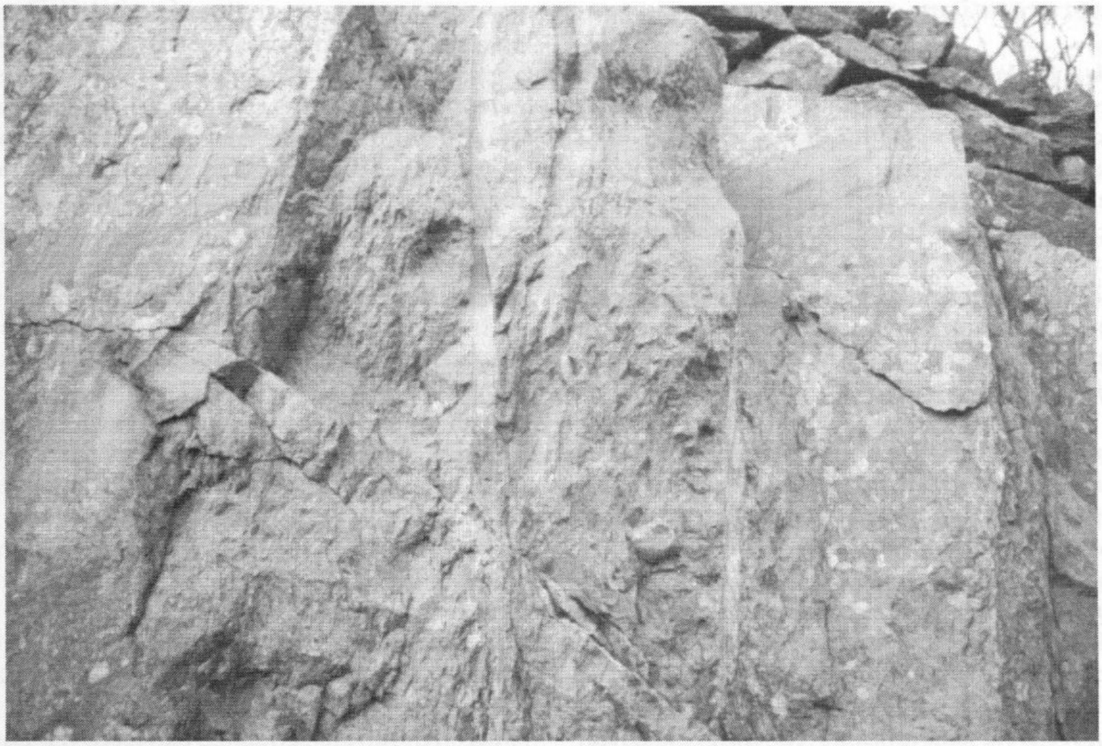

Figure 3.13 Conglomerate and sandstone of the Fachwen Formation (Lower Cambrian), dipping to the left and cleaved almost vertically. Railway cutting, north side of Llyn Padarn, Snowdonia. (Photo: J.K. Prigmore.)

sought by earlier workers, is difficult to identify. Wood (1969) mapped the boundary at the lowest horizon at which pebbles may be recognized (approximately 5689 6169). South-eastwards the sequences exposed in the Fachwen Syncline and Gallt-y-Foel Anticline are mainly sedimentary in origin.

The basal conglomerate dips steeply to the south, and though of variable thickness, it is the thickest of several conglomerates (Figure 3.13). Most of the pebbles are of volcanic rock, but a few are sedimentary, and the matrix gradually becomes more clearly sedimentary upwards. To the south-east, beyond a dolerite dyke, is a 50 m sequence of the Fachwen Formation consisting of fine- to medium-grained sandstones with fine parallel lamination and cross-lamination. Some beds are quite coarse, with grains up to 1 mm in size. These pass up into red and green fine-grained tuffaceous silts, very finely laminated and resembling the overlying Llanberis Slates; they generally dip south-east at about 70°, although minor folding is present close to the major synclinal axis. Towards the core of the Fachwen Syncline are green-coloured, coarse, medium and fine sandstones and siltstones, often parallel-laminated and occasionally cross-bedded.

To the south-east, after a break in exposure, is a bed of conglomerate dipping north-west at about 40°, the basal contact of which rests on an agglomerate bed that shows a strong fabric dipping north-west at about 70°. This passes down into welded tuffs identical in lithology to the Padarn Tuff. Below this, after another break in exposure, are beds of cross-bedded sandstone interbedded with a number of conglomerate horizons, which may reach several metres in thickness. Some are clast-supported and pebble-rich, with clasts of siliceous tuffs, red sandstones, green tuffaceous mudstones, basalts, jasper, quartzites and quartz schists; the variety of clast types contrasts with the relative uniformity of the pebbles in the conglomerates seen at the base of the Fachwen Formation. Other beds are matrix-supported and have few clasts, with a matrix of recrystallized material.

Crossing the faulted axis of the Gallt-y-Foel Anticline, beds of coarse to medium sandstones by the railway station dip south-east and pass upwards into red, green and purple slates of the Llanberis Slates Formation. The whole Fachwen Formation is about 400 m thick.

Interpretation

This site displays the relationship between the Precambrian Arvonian rocks and the overlying Cambrian sediments and demonstrates marked facies variations within a small area. For example, whereas in the south-east limb of the Fachwen Syncline there are conglomerate horizons both above and below volcanic rocks, including a vitric tuff and an agglomerate, in the north-west limb only one bed of conglomerate is present and there are no volcanic rocks.

The Padarn Tuff Formation represents a welded ignimbrite flow deposited under subaerial conditions. The base of the Fachwen Formation is recognized by the appearance of pebbles, which constitute the first indication of aqueous reworking of the Padarn Tuff. However, the recognition of this boundary is difficult, as the matrix of the lowest pebble-bearing horizon is indistinguishable from the underlying ignimbrite. The presence of glass shards and feldspar crystals in this matrix suggests that the pebbles were incorporated contemporaneously in the ignimbrite, or very shortly after emplacement of the flow (Wood, 1969). The basal conglomerate also appears to lie conformably on the eutaxitic texture of the Precambrian welded tuffs at this locality.

The complex facies variations within the Fachwen Formation and the interdigitation of volcanic and sedimentary facies are significant. The conglomerates and cross-bedded sandstones are waterlain but are associated with welded tuffs, similar to those of the Padarn Tuff, which suggests subaerial emplacement and indicates that there was at least local temporary reversion to subaerial conditions. Furthermore, the siltstones of the Fachwen Formation closely resemble the overlying Llanberis Slates Formation, which is indisputably of marine origin. The Fachwen Formation thus shows strong similarities to both the underlying and overlying divisions.

Wood (1969) concluded that there was no important break in deposition at the base of the Cambrian conglomerates and that the Cambrian is essentially conformable on the Arvonian. However, Reedman *et al.* (1984) record that at some other localities there is major discordance between the underlying welding fabric in the tuffs and the base of the overlying sedimentary rocks. This they took to indicate that erosion and tilting of the Precambrian volcanic deposits occurred prior to sedimentary deposition. Where the relationship between the welding fabric in the tuffs and the basal conglomerates is concordant, as in the Llyn Padarn section, they found that the tuffs were intensely welded right up to the basal contact and suggested that any non-welded tuff was removed prior to deposition. Reedman *et al.* (1984) proposed that the lenses of conglomerates and sandstones represent alluvial fans and fluvial deposits close to fault scarps. They found variation in angular relationships across faults, suggesting rotation of fault-blocks prior to and during sedimentation. The conglomerates of Bangor and Anglesey, considered coeval with those of Llyn Padarn, rest with slight unconformity on the Arvonian, and so this contact must represent a period of significant upheaval, rather belied by the sequence exposed at Llyn Padarn. This view supported Tucker and Pharaoh's (1991) determination of an isotopic age of 614 ± 2 Ma for the Padarn Tuff – much older than the base of the Cambrian, which is about 543 Ma.

Throughout the sequence exposed, the energy of deposition appears to have diminished upwards and may indicate general deepening. Conglomerates deposited in high-energy environments give way to sandstones and then to siltstones, albeit with local reversals when shallow-water conglomerates and subaerial welded tuffs were deposited. The trend towards deeper-water sedimentation culminated in the marine deposition of the thick and uniform Llanberis Slates Formation. Contemporaneous subsidence is invoked to effect the change from subaerial to submarine conditions over the interval of deposition of the Fachwen Formation, and to accommodate its thickness.

Conclusions

This site is of historical importance, being the subject of controversy among Victorian geologists as to the nature of the base of the Cambrian in the type area. It exposes sequences that, in the light of modern interpretations, show affinities with both the Precambrian volcanic rocks below and the Cambrian slates above, and provides evidence for the nature of the local base of the Cambrian. The rocks were laid down in shallow water, are underlain by volcanic rocks emplaced on land and overlain by finer-grained, deeper-water sediments. Abrupt variations in rock type occur over a small area. The evidence regionally indicates that a break in sedimentation probably occurred across this boundary, although this is not evinced by the sequence at Llyn Padarn.

MOEL TRYFAN (SH 517 560)

Introduction

The summit of Moel Tryfan and the adjacent quarry offer important exposures of the lower part of the Cambrian succession of the Nantlle area, namely the Tryfan Grit Group, the Cilgwyn Conglomerate and members of the Llanberis Slates Formation (the Purple Slates, Dorothea Grit and Striped Blue Slates), forming the base of the Cambrian as recognized by Sedgwick (1852) in the historical type area.

Morris and Fearnsides (1926) summarized early research in the area. Critical for understanding the geology was a tunnel (now closed) driven in 1876 north-westwards from Alexandra Quarry through Moel Tryfan. It became a focus for controversy over the base of the Cambrian when Hicks (1878, p. 152) recognized 'Pebidian' rocks of his 'Pre-Cambrian System' there. The full sequence in the tunnel was described by Blake (1893). Hughes (1917) studied the conglomerates and grits in neighbouring areas, but the most detailed account was given by Morris and Fearnsides (1926), and this forms the basis of the present stratigraphy for the region. The area of Moel Tryfan was mapped by the British Geological Survey (1988a), and new information was given by Webb (1983).

Description

Parts of the lower units of the succession are well displayed around the summit of Moel Tryfan, while the higher divisions are superbly exposed in Moel Tryfan (or Alexandra) quarry. North-north-west of the summit, the lowest Cambrian sediments in the area (the Tryfan Grits 'Group') are exposed locally, but as this division is in general rather poorly exposed Morris and Fearnsides (1926) took the type section in Moel Tryfan tunnel. The exposures show thinly bedded grey-green siltstones, fine sandstones and quartzose feldspathic tuffaceous sediments, dipping south-east at about 55°. They are extensively recrystallized, but in places structures resembling wavy bedding can be discerned.

The main exposure of the Cilgwyn Conglomerate on the summit of Moel Tryfan shows thickly bedded pebble and cobble conglomerates, dipping south-east at about 60°. Its contact with the Tryfan Grits below is not exposed but is described in the tunnel section as erosive, indicating slight disconformity (Morris and Fearnsides, 1926). The thickness of the conglomerate unit here is estimated at 150 m but is variable. The conglomerates are clast-supported and contain rounded pebbles up to 15 cm across but elongated in the direction of cleavage (Morris and Fearnsides, 1926). Clasts are mainly of Arvonian ignimbrites, with pink quartzites and jasper.

A large fault that is unexposed but which was observed in the tunnel section is assumed to cut out the Glog Grit 'Group', which elsewhere overlies the Cilgwyn Conglomerate.

Moel Tryfan Quarry (Figure 3.14) exploited an anticlinal fold of the lowest member of the Llanberis Slates Formation – the 'Purple Slates' of Morris and Fearnsides (1926). The fold is bounded on the north-west and south-east by faults and is affected by numerous smaller faults and minor folds. The main body of the quarry exposes red, purple and green fine-grained slates, formerly quarried for durable good quality roofing-slates. Green reduction spots are common in the red slates. The cleavage is strong, dipping vertically or north-east at 80°. Bedding can be discerned only where there are thin sandstones: siltstones and sandstones occur regularly in the sequences exposed, with beds 1–2 cm thick being common and thicker (5–10 cm) beds occurring occasionally. They show an abundance of sedimentary structures, such as graded bedding, climbing ripple cross-lamination and, especially, convolute lamination. Some beds show parallel lamination both above and below a ripple cross-laminated division (Crimes, 1970a). Bases are sharp and erosive and may show flute casts and load structures. Some sandstones fine upwards into mudstones indistinguishable from the background slates.

Higher in the inferred succession, sandstones become thicker and more massive, forming the 'Dorothea Grit' of Morris and Fearnsides (1926), which they found useful as a marker horizon in deciphering the structure. The Dorothea Grit, seen on the north-west side of the quarry (Figure 3.14), consists of thick- to medium-bedded coarse greywacke sandstones, generally 10–50 cm thick, but occasionally reaching 1 m in

Figure 3.14 Alexandra Quarry, Moel Tryfan, looking south-west, showing vertically cleaved Llanberis Slate dipping at about 45° to the left. The Dorothea Grit to the right does not show the cleavage conspicuously. (Photo: British Geological Survey photographic collection, L2333.)

thickness. Some beds have pebbly bases, with grains 2–3 mm in size, and most beds show upward fining. Fine parallel-laminated and cross-laminated sandstones occur occasionally at the tops of these beds. Higher, the sandstones become thinner and fewer and appear to pass upwards into the 'Striped Blue Slates' of Morris and Fearnsides (1926), seen on the south-east side of the quarry. Thin siltstones and sandstones are common, giving the rock a striped appearance. These beds are the highest exposed and dip south-east at about 50°.

Interpretation

The Tryfan Grit 'Group', which was best seen in the tunnel and was estimated by Morris and Fearnsides (1926) to be 300 m thick, consists of a lower division of coarse sandstones and an upper division of sandstones and finely laminated siltstones. Poorly welded quartzose-feldspathic tuffs occur within the sandstones. The Tryfan Grits are underlain by the Arvonian volcanic rocks (locally known as the 'Clogwyn Volcanics') of Precambrian age. In the tunnel the contact was not faulted, so, as at Llyn Padarn, the tuffs in the sedimentary Cambrian sequence indicate a genetic link between the highest Precambrian and lowest Cambrian rocks. No strong unconformity is seen at this horizon, but the Tryfan Grits are of variable thickness and either pinch out laterally or are absent laterally on account of strike-faulting. The nature of the contact between the Arvonian Volcanic Group and the Cambrian sediments remains uncertain. Cattermole and Jones (1970) suggest that there was not a large time-break between these horizons, but that deposition of the Tryfan Grits occurred on an irregular surface formed in Arvonian times.

The Cilgwyn Conglomerate above contains rounded pebbles that can be matched with the local Clogwyn volcanic rocks and with the Mona Complex now exposed on Anglesey (Crimes, 1970a), suggesting derivation from a source in that direction. The overlying Glog Grits (not seen at Moel Tryfan) were deposited in shallow water, according to Morris and Fearnsides

(1926). The top of this unit and base of the Llanberis Slates Formation are generally faulted, but the character of the Llanberis Slates which are dominantly fine-grained sediments, with packets of graded greywacke sandstones, suggests that the sandstones were deposited by turbidity currents in fairly deep marine conditions. The thicker sandstones of the Dorothea Grits Group show Bouma (1962) sequences of *a* or *ab* type and are proximal turbidites deposited under conditions of high-flow regime. The thinner sandstones within the finer-grained parts of the succession show *bcd* or *cd* Bouma sequences. They were deposited from low- to medium-density flows from a more distal source. Thickness variations within the Dorothea Grit and the complicated structures it shows indicate fault control during deposition (Morris and Fearnsides, 1926; Webb, 1983).

Sandstones of the Llanberis Slates have not yielded useful palaeocurrent information, so the source area for those beds remains problematical. The few pebble horizons include fragments of quartzite, jasper and green schist, which could all have been derived from the Mona Complex of Anglesey. However, in some sandstones, blue quartz grains are abundant, as in the Rhinog Formation (see site report for Barmouth Hillside). Blue quartz is not present in local Precambrian rocks, but it has been discovered in southern Leinster (Crimes, 1970a), although this is not necessarily the source area.

The lower sandstones and conglomerates represent shallow-water deposition, and the higher mudstones with intercalated sandstones represent turbidity-current sedimentation in deeper water. Thus, as at Llyn Padarn, subsidence of the area must have occurred throughout this interval to accommodate a thick sequence in a deepening marine basin.

Conclusions

This site exposes rocks of the lower part of the Cambrian in the Arfon area, a classic area in which the Cambrian concept was conceived. The succession of conglomerates and coarse sandstones overlying the Padarn Tuff and succeeded by deeper-water mudstones with occasional sandstones (Llanberis Slates Formation) exemplifies the Lower Cambrian transgression in the Welsh Basin.

CWM GRAIANOG (SH 625 630)

Introduction

This site displays magnificent exposures of the Upper Cambrian Marchlyn Formation, including near its top the Carnedd y Filiast Member, overlain unconformably by the Graianog Sandstone of Ordovician (Arenig) age. The Marchlyn Formation is correlated with the Upper Cambrian Maentwrog and Ffestiniog Flags formations of the Harlech Dome but exemplifies much coarser facies. Trace fossils are abundant, and this is the type locality for the trilobite trace *Cruziana semiplicata*.

The stratigraphy of the region was studied by H. Williams (1927) and D. Williams (1930), the latter work describing Cwm Graianog in detail. Crimes described the trace fossils (Crimes, 1970b) and analysed depositional environments and palaeogeographical information (Crimes, 1970a). The Geological Survey mapped the area around Cwm Graianog (British Geological Survey, 1985), and the results are reported in Howells *et al.* (1985). The position and nature of the Cambrian–Ordovician unconformity at Cwm Graianog is considered in detail by Reedman *et al.* (1983).

Description

This site is on either side of the corrie known as Cwm Graianog, the best exposures of Upper Cambrian strata occurring on the northern wall of the cwm. The Marchlyn Formation exposed near the bottom of the hillside consists of dark-grey mudstones with regularly spaced laminae, a few millimetres thick, of pale-grey fine sandstone and siltstone, which give the rock a striped appearance. These rocks dip east at about 40°. Up-sequence sandstones become commoner, with beds a few centimetres thick every 30 cm or so. They show parallel lamination and occasionally cross- and convolute lamination and become more frequent upwards. Well-sorted fine- to medium-grained sandstones up to 10 cm thick also occur.

The grain-size coarsens upwards into the Carnedd y Filiast Grit Member near the top of the Marchlyn Formation. Thickly bedded, massive, medium to coarse sandstones, 10–50 cm thick, occur in packets 5 m thick and overlie thinly bedded, fine- to medium-grained sandstones and siltstones. There are several of these

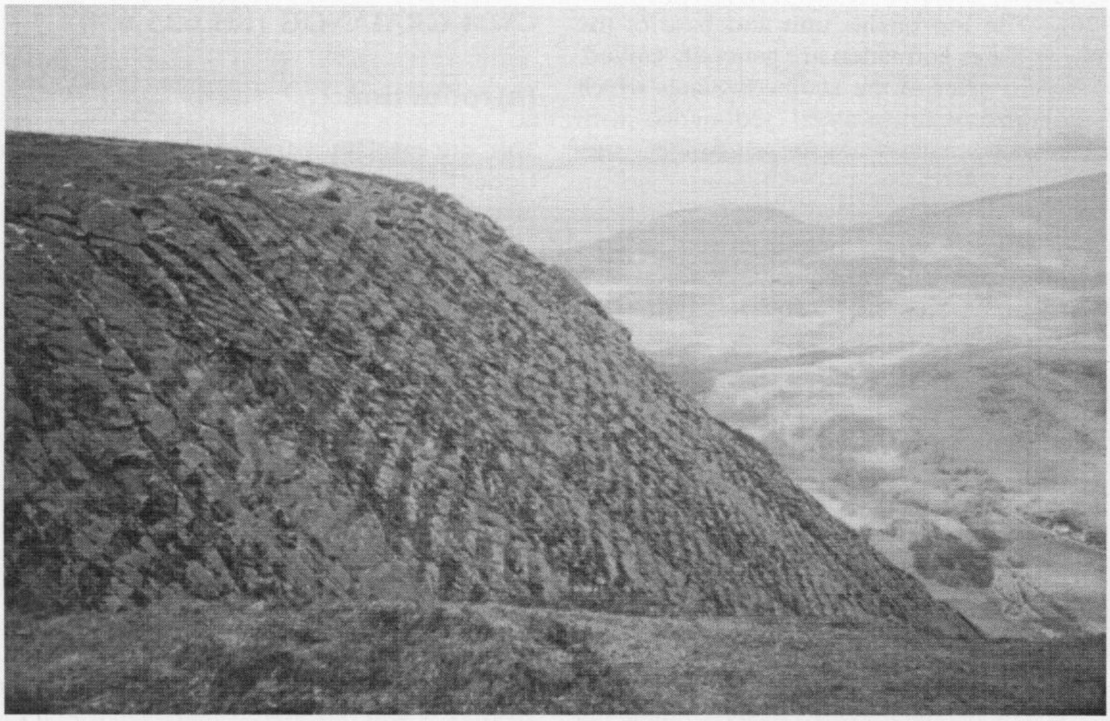

Figure 3.15 Cwm Graianog, Nant Ffrancon, looking north-west. Large ripples on the upper surface of a bed of quartzose sandstone in the Upper Cambrian Carnedd y Filiast Grit. (Photo: J.K. Prigmore.)

upwardly-coarsening sequences, and they give a distinctive scarp and slack topography. Beds of granule and pebble conglomerate also occur, with quartz and feldspar pebbles that reach 2 cm across. Some beds pinch and swell laterally and may be lenticular, and many are well sorted throughout, but graded bedding is uncommon. Large-scale cross-bedding is common in the coarse sandstones and conglomerates; in places, bi-directional cross-bedding can be seen. Flute and groove casts occur on the bases of the finer sandstones. The tops of the coarser beds show ripple marks, of which Crimes (1970a, figs 21–25) illustrated several types. Some bedding planes are covered with mega-ripples with wavelengths of 60 cm (Figure 3.15).

This is the type locality for *Cruziana semiplicata* Salter (Crimes, 1970b), and it and other trace fossils abound: *Rusophycus*, *Phycodes*, *Planolites*, *Diplichnites* and *Dimorphichnus*. *Skolithos* occurs at the top of the succession, and Crimes (1970a) recorded a few blocks of mud-cracked sediment there. Interbedded mudstones yield the brachiopod *Lingulella davisii* (M'Coy).

Above the Carnedd y Filiast Grit is a 50 m thickness of flaggy mudstones and thin sandstones that have been correlated with the '*Lingulella* Band' at the top of the Ffestiniog Formation in the Harlech Dome. A diverse acritarch assemblage from here is indicative of a late Cambrian age (Reedman *et al.*, 1983).

In Cwm Graianog the Carnedd y Filiast Grit is overlain with slight angular unconformity (Figure 3.16) by the Graianog Sandstone – a dark-grey argillaceous sandstone, bioturbated and containing the trace fossils *Phycodes* and *Teichichnus,* with the oncolitic structure known as '*Bolopora undosa*' at its base; it yields an assemblage of acritarchs of Arenig age or younger (Reedman *et al.*, 1983).

Interpretation

The lower parts of the Marchlyn Formation are coarser-grained than the contemporaneous Maentwrog and Ffestiniog formations, as developed in the Harlech Dome (Howells and Smith, 1997). The thin sandstones presumably represent deposition from waning-turbidity flows, such as turbidity currents or storm surges, and become thicker and more common upwards.

The coarser beds of the Carnedd y Filiast Grit Member, although interpreted as turbidites by

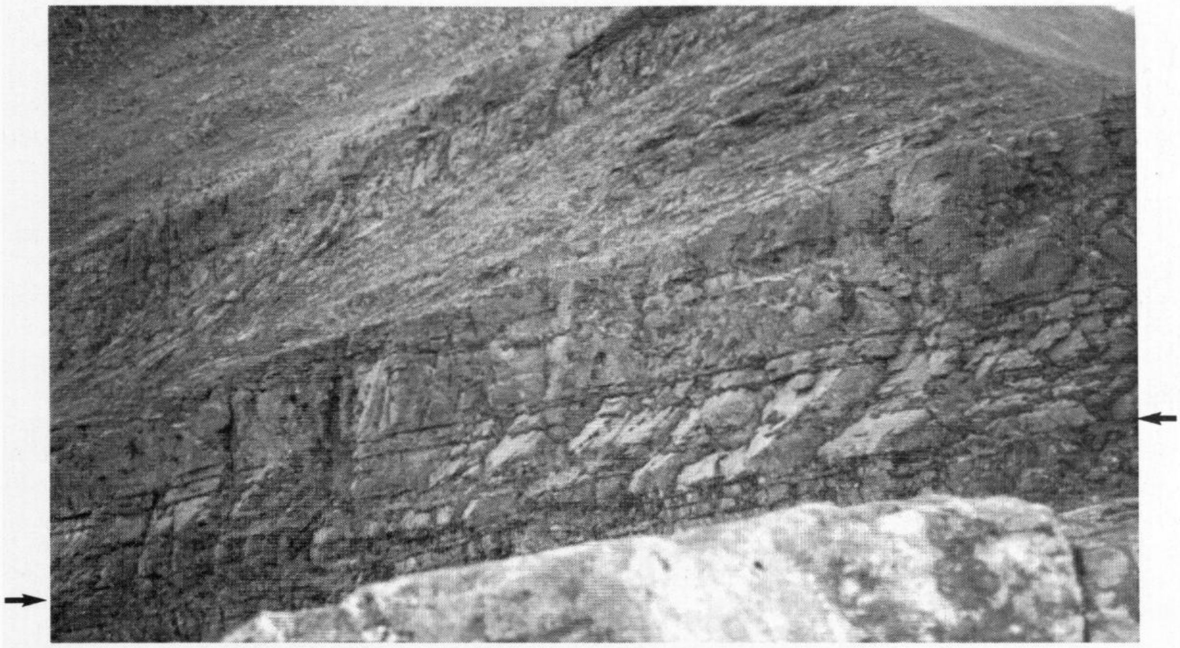

Figure 3.16 The Cambrian–Ordovician unconformity at Cwm Graianog (arrowed). Overlying the Carnedd y Filiast Grit (close foreground, pale) are thinner bedded flags of the Marchlyn Formation (Merioneth Series) that are overstepped uphill by the base of the Graianog Sandstone of Arenig age. (Photo: J.K. Prigmore.)

Evans *et al.* (1966), generally lack graded bedding and do not show a typical event-bed sequence of sedimentary structures. On the contrary, analysis of the sedimentary structures and trace fossils indicate deposition under tidal influence in a sublittoral environment (Crimes, 1970a, b). Deposition of most of the sediments occurred at depths between wave base and low water, but the presence of mud-cracks at the top of the sequence implies periodic drying out, and the *Skolithos* ichnofauna is consistent with intertidal conditions (Droser, 1991).

The shallow-water features and coarse nature of the sediments suggest a local source for these rocks, and the restriction of this facies to the north-west part of North Wales suggests a source area to the north-west. Palaeocurrent indicators created by a variety of flow regimes indicated to Crimes (1970a, p. 152) that the source area probably lay to the north-west with a south-east-facing palaeoslope, with tidal flow from north-west to south-east. In contrast, the correlative Ffestiniog Flags Formation are finer-grained and were deposited from north-flowing currents.

The Marchlyn Formation thus records the upward transition from basinal deposition to shallow-water, storm and tidally dominated environments, even to intertidal conditions at the top of the formation, followed by temporary emergence, erosion and tilting before deposition of the unconformably overlying Graianog Sandstone of Arenig age. Although the unconformity between the Cambrian and Ordovician had long been inferred from considerations of the regional geology (for example the presence of the Dolgellau Formation, discovered by Shackleton (1959) at the head of Cwm Pennant, but absent at Cwm Graianog), angular unconformity proved elusive until identified at Cwm Graianog by Reedman *et al.* (1983).

Conclusions

Cwm Graianog shows the best Upper Cambrian succession in the Arfon area. The lower part of the Marchlyn Formation is fairly fine grained, but the overlying Carnedd y Ffiliast Grit is coarse and was deposited in shallow, high-energy environments with a source area to the north or north-west. This is the type stratum for the trace fossil *Cruziana semiplicata*. The unconfomity of the Ordovician on the Cambrian is more clearly visible at this locality than elsewhere in Snowdonia.