The Old Red Sandstone of Great Britain

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Chapter 5

The Anglo-Welsh Basin

INTRODUCTION

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The Anglo-Welsh Basin formed on the southern margin of the newly amalgamated Laurussian (Old Red Sandstone) continent and the northern margins of the Rheic Ocean (Figure 1.3, Chapter 1). The basin lay in a distal ('external') setting relative to the main Caledonian Orogen in Late Silurian and Early Devonian times (Allen, 1979). Anglesey may have been the site of a small isolated internal basin within the orogen at the start of Old Red Sandstone deposition, but similar facies in the higher part of the succession point to contiguity with the main basin (Allen, 1965a). The basin lay in sub-tropical latitudes, palaeomagnetic data suggesting a latitude of 17 ± 5°S for the Lower Old Red Sandstone (Channel *et al.*, 1992). The abundance of calcrete palaeosols in the basin-fill points to a warm, semi-arid climate with seasonal rainfall.

Local variations on the regional subsidence pattern were exerted by synsedimentary extensional and transtensional faults. The former were particularly active during deposition of the Late Silurian–Early Devonian Milford Haven Group in south-west Pembrokeshire. The latter may have caused the intermittent emergence of a landmass in the Bristol Channel area in Early and Mid-Devonian times. Previous models of the basin's evolution invoked post-Caledonian flexural subsidence (e.g. King, 1994; Friend *et al.*, 2000; Woodcock, 2000a), but orogen-wide, sinistral pre-Acadian transtension and tectonic subsidence have been proposed recently (Dewey and Strachan, 2003; Soper and Woodcock, 2003).

The Old Red Sandstone is present in a narrow outcrop on Anglesey and in small outliers in Clun Forest and Long Mountain in central Wales. In south and south-central Wales, it is widely distributed in the Carmarthen Fans, Black Mountains and Brecon Beacons, around the northern and eastern rims of the South Wales Coalfield, and in the Welsh Borderland. It also crops out on the limbs of several Variscan folds in south-west Pembrokeshire, where it is magnificently exposed in sea cliffs. The main basin extended south-eastwards into south-east England where the Old Red Sandstone is concealed by younger strata. It may also have extended northwards to the southern Lake District, where a cover of at least 3.5 km of Old Red Sandstone sediments is estimated to have been removed during Acadian inversion (Soper and Woodcock, 2003). The outliers in Anglesey, Long Mountain and Clun Forest are remnants of this former cover.

Old Red Sandstone red-bed sedimentation generally began in Late Silurian Přídolí times, when the Lower Palaeozoic marine Welsh Basin was finally filled, then inverted during the Acadian Orogeny. However, there are earlier occurrences of Old Red Sandstone facies at Marloes Sands, south-west Pembrokeshire, where it is of late Wenlock to early Ludlow age, and in the Llandovery area, where the Trichrûg Formation is of mid-Ludlow (late Gorstian) age. The Old Red Sandstone extends throughout the Devonian and into the Early Carboniferous, with the Mid-Devonian largely unrepresented in the rock record, except perhaps for the southerly derived Ridgeway Conglomerate Formation of south-west Pembrokeshire and the northerly derived Hangman Sandstone Formation of north Devon. For the most part, the southerly advancing Acadian deformation front resulted in uplift and erosion of the Anglo-Welsh Basin in Mid-Devonian times, now represented by a regional unconformity at the base of the Late Devonian Upper Old Red Sandstone.

Přídolí and Lochkovian–Pragian strata are widespread in south-central Wales and the Welsh Borderland, higher (Emsian and Famennian) strata occur mainly as narrow outcrops around the South Wales and Forest of Dean coalfields and as outliers, as for example in the Clee Hills of Shropshire. Good summaries of the Old Red Sandstone succession of the Anglo-Welsh Basin are given by Allen (1974a, 1977) and Hillier and Williams (in press). Bluck *et al.* (1994), Woodcock (2000a) and Soper and Woodcock (2003) presented recent regional overviews. A maximum of about 4.3 km of strata is present north of the Ritec Fault in Pembrokeshire, with up to about 2 km elsewhere. Two major Old Red Sandstone megasequences are recognized, traditionally referred to the Lower Old Red Sandstone and the Upper Old Red Sandstone. The Lower Old Red Sandstone succession is mainly of Late Silurian (Ludlow–Přídolí) to Early Devonian (Emsian) age, the Upper Old Red Sandstone of Late Devonian (late Frasnian–Famennian) to Early Carboniferous age.

Figure 5.1 shows a correlation of the Old Red Sandstone successions and their lithostratigraphical subdivisions. Figure 5.2 shows the location of the GCR sites described in this volume. The basal formation of the Old Red Sandstone (Downton Castle Sandstone/Tilestones/Long Quarry Sandstone) is of early Přídolí Series, Silurian age, and the GCR sites in these formations are described by Lane (2000a) in the companion volume on Silurian stratigraphy (Aldridge *et al.*, 2000). A large part of the Raglan Mudstone Formation and its equivalents are also of Přídolí age. Some of the GCR sites in this formation are also described by Lane (2000a) (Table 1.4, Chapter 1) and only brief descriptions are given in this volume.

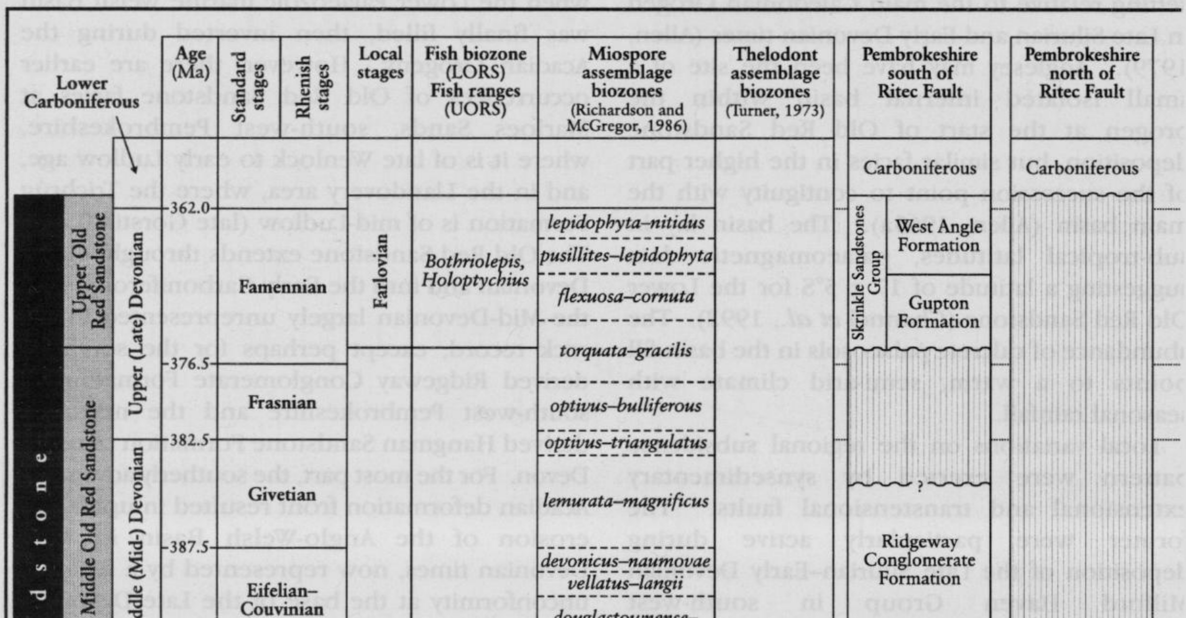
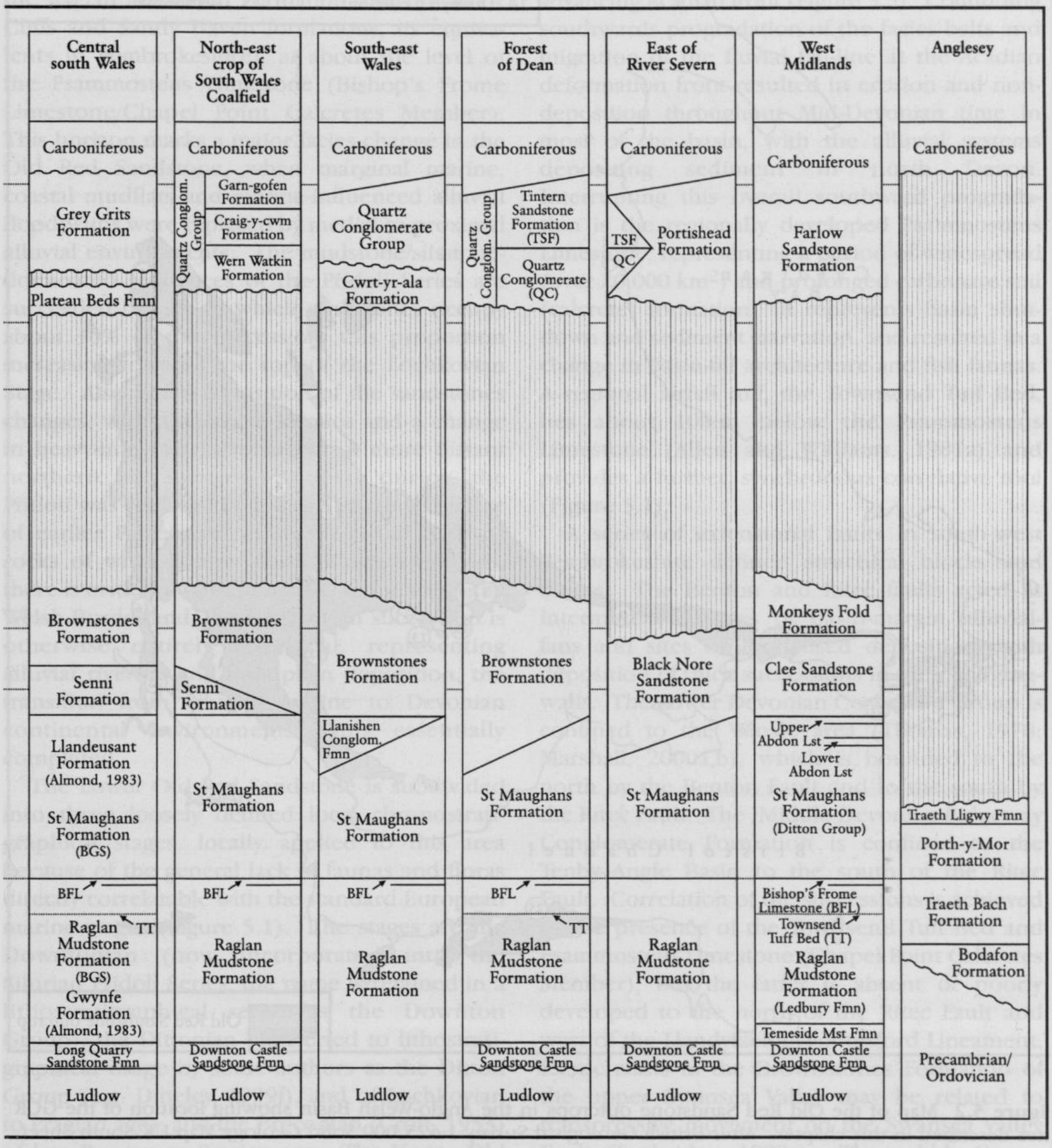


Figure 5.1 Correlation of the successions and biostratigraphical classifications of the Old Red Sandstone in the Anglo-Welsh Basin. Ages in millions of years ago (Ma) are from Williams *et al.* (2000). Broken lines denote imprecisely located boundaries.

The transition from marine, nearshore shelf deposition to continental red-bed Old Red Sandstone deposition was generally regarded as taking place in latest Silurian–Early Devonian time. However, the age of the lowermost Old Red Sandstone beds in the Marloes Peninsula of south-west Pembrokeshire has generated controversy. Sanzen-Baker (1972) suggested that they were Ludlow in age. Allen *et al.* (1976) and Allen and Williams (1978) proposed that an unconformity with no angular discordance separated the underlying Ludlow marine strata from red beds of Přídolí age. Hillier (2000) recorded a transition from Wenlock shallow marine strata (the Gray Sandstone Group) into the Old Red Sandstone Red Cliff Formation, and



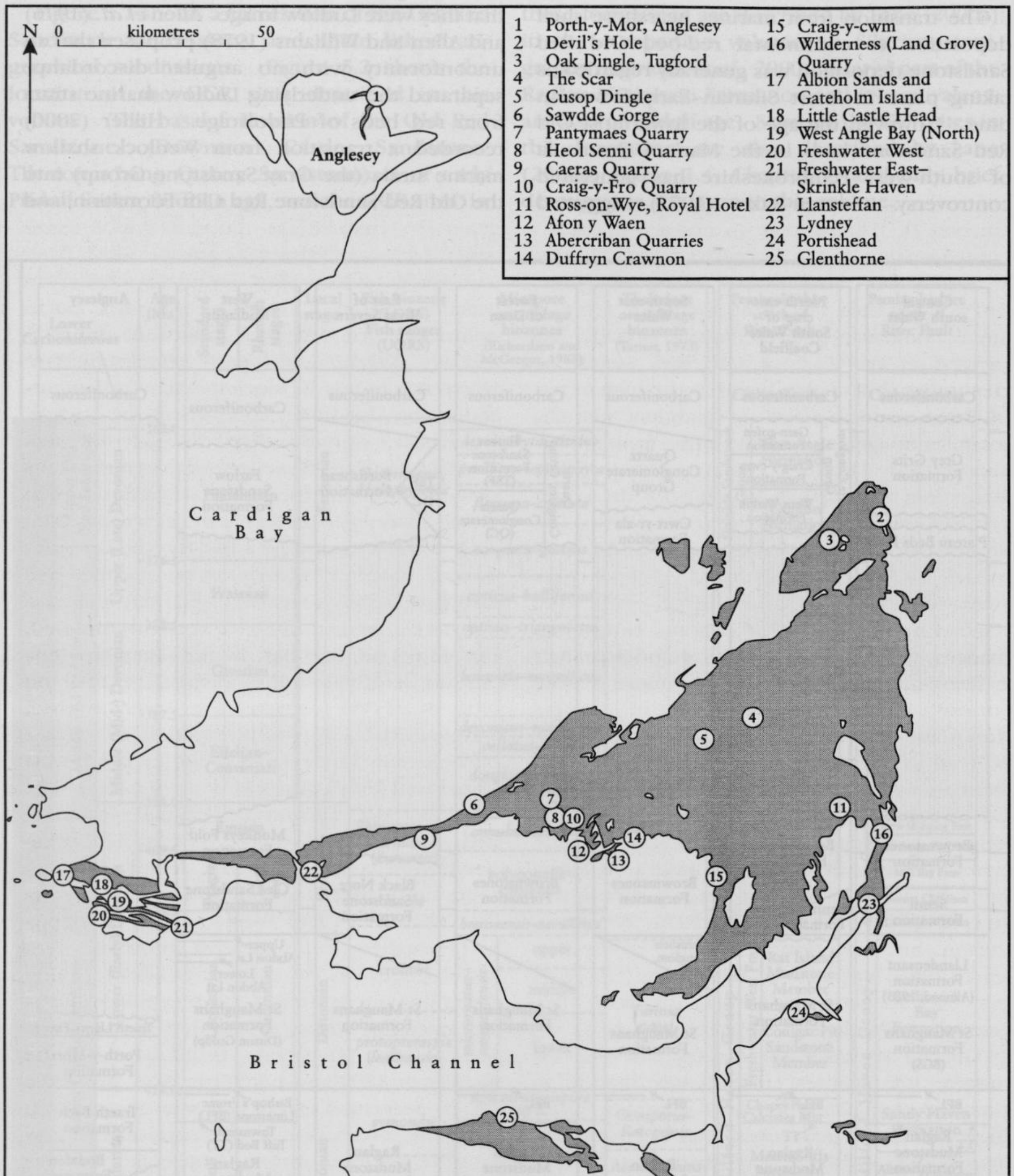


Figure 5.2 Map of the Old Red Sandstone outcrops in the Anglo-Welsh Basin showing location of the GCR sites described in this chapter. After British Geological Survey 1:625 000 Solid Geology Map UK South Sheet, 4th edn (2001).

the recent discovery of Ludfordian spores from the basal beds of the Red Cliff Formation (Hillier and Williams, 2004) confirms a transitional boundary.

The Přídolí–Lochkovian (Silurian–Devonian) boundary remains imprecisely located (see 'Introduction', Chapter 1), but is tentatively placed on the basis of spore assemblages within the uppermost part of the Downton Group (in the Raglan Mudstone Formation and the Moor Cliffs and Sandy Haven formations, its equivalents in Pembrokeshire), at about the level of the Psammosteus Limestone (Bishop's Frome Limestone/Chapel Point Calcretes Member). This horizon marks a major facies change in the Old Red Sandstone, when marginal marine, coastal mudflats and marine-influenced alluvial floodplains were replaced by medial to proximal alluvial environments. The mudstone/siltstone-dominated sequences of the Přídolí Series are succeeded by one in which sandstones occupy about 30% of the succession, this proportion increasing towards the top of the Lochkovian Stage. Also, the composition of the sandstones changes, with a decrease in mica and a change in heavy-mineral assemblages. A more distant northern metamorphic terrane during the Přídolí was replaced by a more proximal source of earlier Palaeozoic sedimentary and igneous rocks of what is now north Wales. Although there is evidence of local marine influence in the Welsh Borderland, the Lochkovian succession is otherwise entirely terrestrial, representing alluvial riverine and floodplain deposition, the transition from Silurian marine to Devonian continental environments being essentially completed.

The Lower Old Red Sandstone is subdivided into three loosely defined local chronostratigraphical stages, locally applied to this area because of the general lack of faunas and floras directly correlatable with the standard European marine stages (Figure 5.1). The stages are the Downtonian (now incorporated into the Silurian Přídolí Series; the name is retained in a lithostratigraphical sense as the Downton Group), the Dittonian (converted to lithostratigraphical usage by some authors as the Ditton Group (e.g. Dineley, 1999f), and of Lochkovian to Pragian age); and the Breconian (Croft, 1953) of late Pragian to Emsian age. The Upper Old Red Sandstone is ascribed to the Farlovian local stage and is of Frasnian–Famennian to early Tournaisian (Carboniferous) age.

The Lower Old Red Sandstone broadly comprises an upward-coarsening offlap succession, consisting, in upward succession, of marginal marine, coastal floodplain, alluvial channel and floodplain and alluvial-fan environments of increasing energy and proximity to the advancing Acadian front (Figure 5.3). Continuing southwards progradation of the facies belts and migration of the fluvial fall-line at the Acadian deformation front resulted in erosion and non-deposition throughout Mid-Devonian time in most of the basin, with the alluvial systems depositing sediment in north Devon. Interrupting this overall southward progradation is the regionally developed Psammosteus Limestone, representing a period of widespread (over 20 000 km^2) and prolonged carbonate soil (calcrete) formation. It represents basin shut-down and sediment starvation, and resulted in a change in basin-fill architecture and fish faunas. A regional airfall tuff, the Townsend Tuff Bed, lies about 100 m below the Psammosteus Limestone (Allen and Williams, 1981a) and provides a further, synchronous correlative tool (Figure 5.1).

A series of extensional faults in south-west Pembrokeshire defined structural blocks and basins. The Benton and Ritec faults acted as intermittent sources of basin-margin alluvial-fans and sites of condensed deposition, with deposition of thick successions in their hanging-walls. The Lower Devonian Cosheston Group is confined to the Winsle area (Thomas, 1978; Marshall, 2000a,b), which is bounded to the north by the Benton Fault and to the south by the Ritec Fault. The ?Middle Devonian Ridgeway Conglomerate Formation is confined to the Tenby–Angle Basin to the south of the Ritec Fault. Correlation of the successions is achieved by the presence of the Townsend Tuff Bed and Psammosteus Limestone (Chapel Point Calcretes Member), but the latter is absent or poorly developed to the north of the Ritec Fault and west of the Llandyfaelog–Pontesford Lineament. Exotic clasts in the Brownstones Formation of the upper Swansea Valley may be related to transpressive movement on the Swansea Valley Fault (Tunbridge, 1980a). The pebbly Caeras

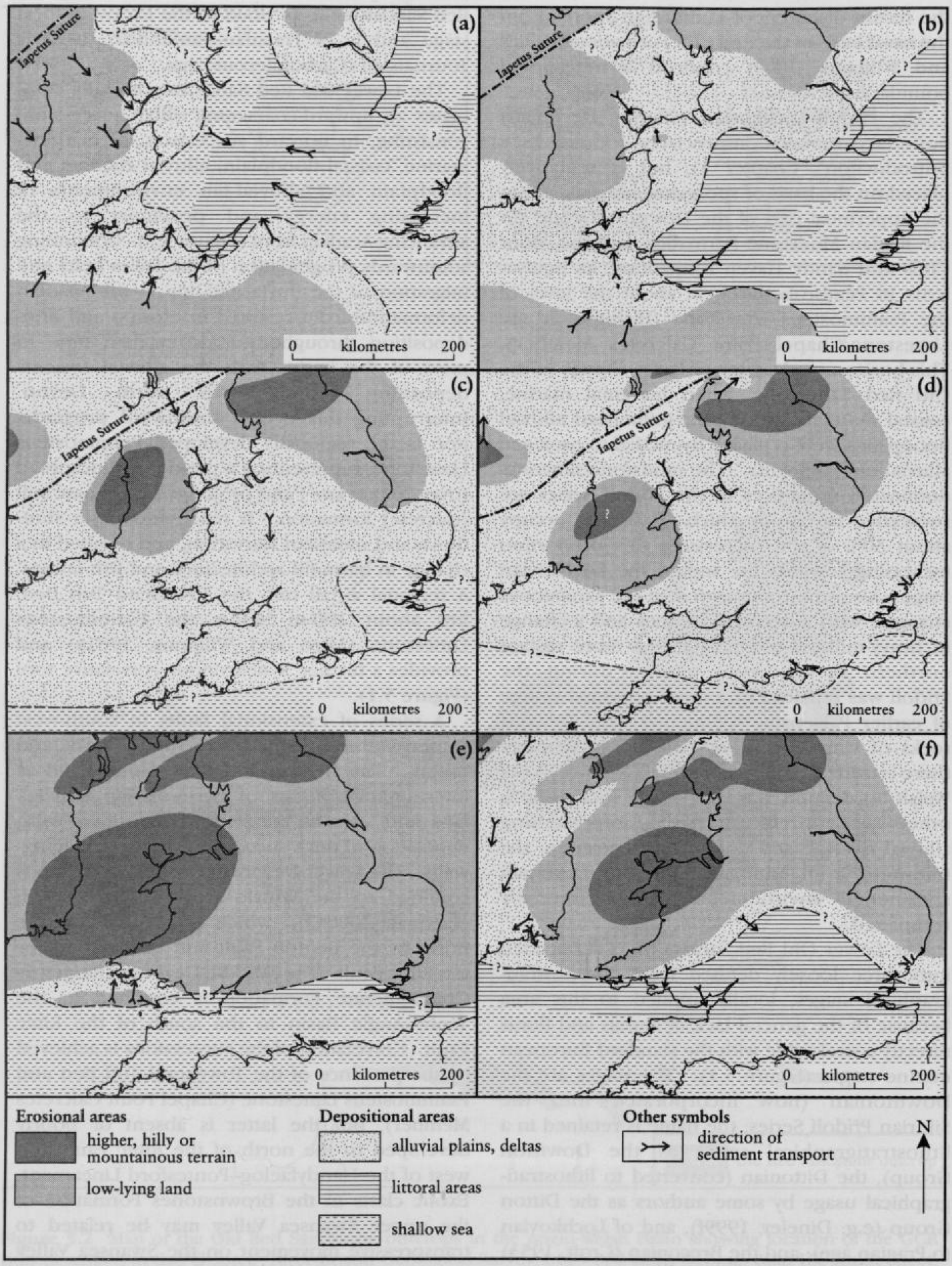


Figure 5.3 Palaeogeographical evolution of the Anglo-Welsh Basin. (a) Earliest Přídolí; (b) mid-Přídolí; (c) Lochkovian; (d) late Pragian–early Emsian; (e) Givetian; (f) Frasnian–early Famennian. (a) and (b) after Bassett *et al.* (1992); (c)–(f) after Bluck *et al.* (1992).

Beds of the Cennen Valley (**Caeras Quarry** GCR site) may have a similar origin in relation to the Carreg Cennen Disturbance.

Most of the early deposits of the Lower Old Red Sandstone succession were derived from the Caledonian uplands north of the Highland Boundary Fault (e.g. Allen and Crowley, 1983). However, the exact nature of the dispersal systems remains controversial. Orogen-parallel drainage from the region of Scandian uplift to the north-east of the UK, through the Midland Valley of Scotland and southwards to the Anglo-Welsh Basin has been proposed (e.g. Simon and Bluck, 1982; Bluck *et al.*, 1992; Sherlock *et al.*, 2002), but Scandian drainage may have terminated in the Midland Valley or Northern Ireland (Friend *et al.*, 2000), with much of the later (post-Psammosteus Limestone) Lower Old Red Sandstone fill of the Anglo-Welsh Basin derived from closer Lower Palaeozoic sources in southern Scotland, southern Ireland and north Wales (Allen, 1974b; Allen and Crowley, 1983; Haughton and Farrow, 1989; Soper and Woodcock, 2003).

The Přídolí Tilestones Formation of south-central Wales (Almond, 1983) was derived from the south. Palaeocurrents in the Ludlow–Přídolí Red Cliff and Lindsway Bay formations of Pembrokeshire also indicate derivation from the south (Hillier, 2000; Hillier and Williams, 2004), although white micas in the former are said to have a Laurentian (Highland) origin (Sherlock *et al.*, 2002). Parts of the Lindsway Bay and the coeval Albion Sands formations were derived from the west, and probably deposited in a fault-controlled axial valley. The southerly source of sediment is thought to have been the remnants of the Early Palaeozoic landmass of Pretannia (Cope and Bassett, 1987; Bluck *et al.*, 1992), which formed the south-east shoulder of the Welsh Basin.

The ?Mid-Devonian Ridgeway Conglomerate Formation of Pembrokeshire, limited to the south (hanging-wall side) of the Ritec Fault, and the Pragian Llanishen Conglomerate Formation of the Cardiff district (Allen, 1975; Waters and Lawrence, 1987) were derived from the south. The Ridgeway Conglomerate Formation forms part of the **West Angle Bay (North)** and **Freshwater East–Skrinkle Haven** GCR sites, as well as part of the **Freshwater West** site. The source of these rocks is believed to have been an emergent area in what is now the Bristol Channel, known as the 'Bristol Channel Landmass' (Mechie and Brooks, 1984; Tunbridge, 1986; Cope and Bassett, 1987; Marshall, 2000a,b). South of the Bristol Channel, the Hangman Sandstone Formation, seen at the **Glenthorne** GCR site, is the only unit of northerly derivation and proven Mid-Devonian age.

The lowermost Přídolí strata, traditionally referred to the Lower Old Red Sandstone, comprise the Downton Castle Sandstone Formation, and the Tilestones (Long Quarry Sandstone) Formation (its lateral equivalent in south-central Wales, seen at the **Sawdde Gorge** GCR site). These are shallow marine, barrier and shore-face deposits, with red-bed Old Red Sandstone deposits overlying them. Locally, a green, lacustrine/back-barrier facies (the Temeside Mudstone Formation) intervenes; the Pont-ar-llechau Member in the Sawdde Gorge is of similar facies, although red (Almond, 1983; Almond *et al.*, 1993). Higher Přídolí strata (Sandy Haven, Moor Cliffs and Raglan Mudstone formations) are predominantly red mudstone/siltstone-dominated successions with common nodular calcretes. Representing marginal marine, coastal mudflat and marine-influenced alluvial-floodplain environments, these strata are represented at the **West Angle Bay (North)**, **Freshwater West**, **Freshwater East–Skrinkle Haven**, **Sawdde Gorge**, **The Scar** and **Cusop Dingle** sites. The **Little Castle Head**, and **Albion Sands and Gateholm Island** GCR sites are described in detail in the Silurian stratigraphy GCR volume (Aldridge *et al.*, 2000) and briefly described in the present volume. The mature calcretes of the Psammosteus Limestone at the top of the Přídolí succession (the Chapel Point Calcretes Member in Pembrokeshire (Williams *et al.*, 1982) and the Bishop's Frome Limestone (Brandon, 1989) in south-east Wales, the Welsh Borderland and south-central Wales) are seen at the **Devil's Hole**, **Freshwater West**, **Freshwater East–Skrinkle Haven**, **Sawdde Gorge**, **Llansteffan**, **Cusop Dingle** and **Lydney** GCR sites.

The Lochkovian–Pragian (Dittonian) rocks (upper part of the Milford Haven Group, Gelliswick Bay, Freshwater West and St Maughans formations; Ditton Group; Figure 5.1) are characterized by the cyclic arrangement of their component facies (mudstone/siltstones, sandstones and intraformational conglomerates) in upward-fining, commonly calcretized alluvial cycles (Allen, 1964a). The thickest development (1000–1500 m) is north of the Ritec Fault in south-west Pembrokeshire. Overall, the succession coarsens upwards, with the sandstones becoming thicker and more dominant. Fish fragments are common in the conglomerates, plant microfossils and megafossils are present locally (e.g. Wellman *et al.*, 2000). There are a few instances of complete fish specimens being discovered, such as in the St Maughans Formation at the Cwm Mill GCR site near Abergavenny (SO 311 156) and the Wayne Herbert Quarry site (SO 335 320) in Herefordshire farther north (Dineley, 1999f). These fish occur in finer lithologies and were probably entombed in overbank deposits during flooding. The swimming and resting traces of fish (*Undichna*) are recorded at Tredomen Quarry near Talgarth (Morrissey *et al.*, 2004). Arthropod traces include the ubiquitous burrow trace *Beaconites barretti* (Morrissey and Braddy, 2004) and crawling traces (*Diplichnites*; Smith *et al.*, 2003; Morrissey *et al.*, 2004).

The intraformational conglomerates, along with some extraformational varieties, are interpreted as channel-lag deposits. The sandstones exhibit a range of architecture (Williams and Hillier, 2004), and although predominantly comprising the in-channel sandbodies of high-sinuosity streams, laterally accreted bodies and sheet-flood deposits also occur. The fine-grained lithologies are thought to represent deposition in floodplain environments that were subjected to frequent desiccation and carbonate soil formation; at least some of the mudrocks may have originated as wind-blown dust, perhaps reworked into lacustrine sediment in floodplain ponds (Marriott and Wright, 2004). Some mudrocks are interbedded with thin point-bar type gravelly lenses of calcrete clasts in low-angle cross-bedded sets and have pelleted fabrics, indicating deposition of pedogenic, pelleted mud aggregates from bedload in small sinuous channels (Ékes, 1993; Marriot and Wright, 1996, 2004). In addition to the immature calcretes, more mature, massive to rubbly calcretes occur sporadically, including the Coldra, Ruperra and Pontypool limestones of south-east Wales (Squirrell and Downing, 1969), the Ffynnon limestones of the Black Mountains and the Abdon limestones of the Clee Hills (Ball and Dineley, 1961; Allen, 1961, 1974c). Some tuffs are present in the Gelliswick Bay Formation in south-west Pembrokeshire and in the St Maughans Formation at Tredomen Quarry (Morrissey *et al.*, 2004).

Sites representing the Dittonian rocks include **Oak Dingle**, **Freshwater West** (potential GCR site), **Freshwater East–Skrinkle Haven**, **Llansteffan**, **Cusop Dingle** (potential GCR site) and **Lydney**. In addition, the disused quarry at Pantymaes near Sennybridge exposes a fine section through a thick channelized sandstone complex and overlying floodplain mudrocks (Owen and Hawley, 2000), as well as a suite of arthropod crawling traces (Smith *et al.*, 2003), and is recommended for GCR status.

Above the St Maughans Formation near Cardiff and Newport in south-east Wales is the Llanishen Conglomerate Formation. Its pebbles include Llandovery quartzites and ?Silurian volcanic rocks, in a suite unlike the northerly derived pebbles of most of the Old Red Sandstone succession, and a nearby southerly source is thus favoured (Allen, 1975; Waters and Lawrence, 1987).

In Anglesey, about 500 m of Old Red Sandstone rocks crop out from the coast between Dulas Bay and Lligwy Bay (see **Porth-y-Mor** GCR site report, this chapter) inland to near Llangefni. The succession records the burial of an already deformed and dissected Anglesey platform by Caledonian molasse shed from the mountain belt to the north. Asymmetric folding and an associated cleavage are attributed to the late Emsian Acadian deformation. The correlation and age of the succession, probably deposited at least initially in a palaeovalley isolated from the main part of the Anglo-Welsh Basin, and with no fossils yet found, are uncertain. Basal conglomerates and pebbly sandstones (the Bodafon Formation) are interpreted as the localized deposits of a series of coalescing alluvial-fans banked against a north-west-facing valley side. The Traeth Bach Formation comprises mainly red-brown siltstones with abundant calcrete nodules which are correlated by Allen (1965a) with the Přídolí Raglan Mudstone Formation of south Wales, although he interprets them as playa-lake deposits, unlike the floodplain alluvial facies of the Raglan Mudstone Formation. The Porth-y-Mor Formation is correlated with the Dittonian succession of south Wales. Thick calcretes at the top of the Traeth Bach Formation invite comparison with the Psammosteus Limestone and support this correlation. The succession of fining-up alluvial cycles and sedimentary structures, including epsilon cross-stratification (first identified by Allen (1963a) in ancient deposits here), is interpreted as the deposits of south-eastward-flowing, meandering streams and their floodplains. The Traeth Lligwy Formation consists of bioturbated sandstones and siltstones and conglomerates, interpreted by Allen (1965a) as the deposits of permanent lakes, a facies not seen in south Wales, except for some minor examples in the Senni Formation at Ferryside (Almond, 1983) and Laughorne (B.P.J. Williams, pers. comm.).

Strata of probable Emsian age are referred to the Breconian local stage. Its type area is the Brecon Beacons, where it comprises the Senni and Brownstones formations (Croft, 1953). The Senni Formation, and the equivalent Cosheston Group in south-west Wales and Clee Sandstone Formation in Shropshire, are characterized by their olive-green colour. The Senni Formation is known particularly for its early vascular plant remains, including *Gosslingia breconensis*, *Hostinella heardii*, *Krithodeophyton croftii*, *Sennicaulis hippocrepiformis*, *Tarella trowenii*, *Uskiella spargens* and *Zosterophyllum llanoveranum* (Cleal and Thomas, 1995). The **Heol Senni Quarry** GCR site provides a characteristic section of the formation, which is interpreted as the deposits of low-sinuosity, seasonally flowing, sandy, braided streams in a mid-fan setting (Owen, 1995). The Cosheston Group (Thomas, 1978; Wellman *et al.*, 1998) is much thicker (1500–1800 m), having been deposited in a zone of active rifting in the hanging-wall of the Benton Fault. The alluvial deposits of braided to meandering, generally southerly flowing stream systems contain, in their lower part, soft-sediment deformation structures that probably reflect seismic activity associated with the rifting of the basin. High water-table conditions are invoked for the preservation of the plant remains and the predominantly green colour of these formations, due to the presence of chloritized micas. A possible climatic cause of the high water-table has yet to be investigated. Only four vertebrate localities are known – the Breconian index fossil fish *Rhinopteraspis dunensis* (= *cornubica*) at Primrose Hill Quarry, Crickhowell (SO 207 200). *R. dunensis* occurs in the Mid-Siegenian of mainland Europe (Dineley, 1999f); *Althaspis senniensis* at Heol Senni Quarry (SN 9145 2210; see GCR site report, this chapter); *Pteraspis dixoni* and *Cephalaspis* sp. at Pengau (Pen-y-gau) Farm (SN 3732 0850) near Ferryside, Pembrokeshire; and *Protopteraspis gosseleti* at Allt ddu near Brecon (SO 027 242) (Habgood, 2000; Edwards and Richardson, 2004).

The Brownstones Formation (the Black Nore Sandstone Formation east of the Severn) is the highest Lower Old Red Sandstone formation in the Anglo-Welsh Basin. It is characterized by red-brown, fine- to coarse-grained, fluvial sandstones, with red-brown, locally green mudstone and siltstone interbeds. Maximum development is in the Forest of Dean, where 1200 m are present; the **Ross-on-Wye, Royal Hotel** GCR site is a typical section. In the type area of the Brecon Beacons and Black Mountains, the sandstones generally form extensive sheets, as seen in the magnificent north-facing scarps of the Brecon Beacons, the succession tending to become more sandstone-dominated in its upper parts (Tunbridge, 1981a). The succession is interpreted as the deposits of a prograding fan system formed in a semi-arid, seasonally wet climate. Channelized sandstones are the product of mid-fan, wet season, flashy deposition, with more distal floodplain environments represented by sheet-flood sandstones and mudstones and siltstones. Gravelly, pebbly and conglomeratic sandstones are locally common, particularly in the upper part of the formation in the Forest of Dean and parts of the north and east crops of the South Wales Coalfield. Pebbly beds at Llyn-y-Fan Fawr (SN 834 216), 4 km west of the Swansea Valley are sourced from the east and perhaps attributable to uplift on the Swansea Valley Fault (Tunbridge, 1980a); similarly, the pebbly Caeras Beds in the Cennen Valley between Llandybie and Kidwelly may have been deposited as a result of uplift on the Carreg Cennen–Llandyfaelog Fault (**Caeras Quarry** GCR site). Pebble suites at Ross-on-Wye and in the Clee Hills comprise igneous, metamorphic and sedimentary rocks of Ordovician to Devonian age thought to have been derived from north Wales (Allen, 1975). The Brownstones Formation of Wales has yet to yield animal body fossils, but the Dittonian index fossil fish *Althaspis leachi* is recorded from the basal Brownstones Formation at the **Wilderness Quarry** GCR site in the Forest of Dean (Allen *et al.*, 1968). East of the Severn Estuary, the Black Nore Sandstone Formation, seen at the **Portishead** GCR site, provides the only occurrence of sandstones of aeolian origin at this level in the basin (Dodd, 1986).

No Middle Devonian strata are yet proved in south Wales, except perhaps for the southerly sourced Ridgeway Conglomerate Formation of south-west Pembrokeshire (see above). Mid- and Early Devonian ages have been suggested, but, bounded by unconformities and lacking in diagnostic fossils (only some crossopterygian fish fragments and plant fragments have been found), the age remains uncertain. It consists of petromict conglomerates, sandstones, and siltstones with calcretes. The clasts in the conglomerates are mainly of quartzite, lithic greywacke, siltstone and vein quartz, with a marked influx of phyllite clasts in the higher beds. The formation is interpreted as the deposits of a braided stream/alluvial-fan complex sourced from a nearby, southerly Lower Palaeozoic–?Precambrian source. A northward-prograding alluvial-fan occupied the area of **Freshwater West**, with more distal braided stream environments at **West Angle Bay (North)** (Williams *et al.*, 1982). Some large-scale, cross-bedded siltstones have been interpreted as bedload-transported pedogenic mud aggregates (Ékes, 1993).

Late Devonian (late Frasnian–Famennian) Upper Old Red Sandstone rocks, referred to the Farlovian local stage, overlie the unconformity that truncates the Breconian and older successions. The **West Angle Bay (North)**, **Freshwater West** (potential), **Freshwater East–Skrinkle Haven** and **Portishead** GCR sites provide sections of the unconformity. The strata are predominantly fluvial, deposited on a southerly facing palaeoslope, but lacustrine, possible aeolian and marginal marine facies occur locally in the Plateau Beds Formation (**Afon y Waen** and **Duffryn Crawnon** potential GCR sites) and aeolian sands are present in the Portishead Formation at the **Portishead** GCR site. The succession is thin in comparison with the Lower Old Red Sandstone, with up to a maximum of about 350 m in south-west Dyfed.

In the Pembroke peninsula, the Skrinkle Sandstones Group (see **Freshwater West**, **West Angle Bay (North)** and **Freshwater East–Skrinkle Haven** GCR site reports, this chapter) accumulated as a synrift succession of alluvial-fan, plain and lacustrine deposits in the hanging-wall of the Ritec Fault. Its distribution is confined to the Tenby–Angle Basin, thickening southwards from 100 m near the Ritec Fault to 330 m at Freshwater West (Marshall, 2000a,b). The beds lie unconformably on the Ridgeway Conglomerate Formation, overstepping it eastwards to rest on the Milford Haven Group, and there is a transition into grey Carboniferous beds at the top of the succession. The group is subdivided into the Gupton Formation and overlying West Angle Formation. The Gupton Formation is interpreted as comprising two axial basin-fill, fluvial, coarsening-upward sequences of mature, clean sandstones. The West Angle Formation is characterized by red sandstones, conglomerates rich in igneous, sandstone and phyllite clasts, and calcretes. The pebbles in the conglomerates were probably derived from the Precambrian Pebidian volcanic complex and associated Ordovician volcanic rocks of the northern south-west Pembrokeshire coast, either directly, or by recycling of the clasts of the Cosheston Group. The upper part of the West Angle Formation (the Red-Grey Member) comprises fining-upward fluvial sequences with mudstone and calcrete tops similar to the meandering channel deposits below, but shows an upward increase in grey beds and grey-green sandstones with plant remains (**West Angle Bay (North)** GCR site). The grey beds contain initially non-marine fossils, but increasing marine influence heralds the main transgression at the start of the Carboniferous Period.

In the Carmarthen Fans, Black Mountains and Brecon Beacons, the Upper Old Red Sandstone is represented by the Plateau Beds Formation, best known for its sporadic vertebrate and marine brachiopod faunas. Fish-bearing conglomerates include the Afon y Waen Fish Bed (see **Afon y Waen** GCR site report, this chapter). The succession represents a broadly transgressive sequence from fluvial (and possibly aeolian) deposition to marginal marine environments (Lovell, 1978a,b; **Duffryn Crawnon** potential GCR site). Fossils recovered include the brachiopods *Cyrtospirifer verneuili*, *Lingula* spp., *Ptychomaletoechia omaliusi*, the bivalves *Leptodesma* cf. *lichas*, *Pterinopecten* sp. and *Sanguinolites* sp. and fragments of the fish *Bothriolepis*, *Coccosteus*, *Holoptychius*, *Pseudosauripterus anglicus*, cf. *Rhinodipterus* and *Sauripterus* (Taylor and Thomas, 1975).

The Plateau Beds Formation is overstepped by the Grey Grits Formation (seen at the **Abercriban Quarries** GCR site), which consists mainly of quartzitic sandstones. Thin, green mudstone interbeds and quartz pebble layers occur sporadically. Fauna is restricted to fish fragments and the bivalve *Sanguinolites*, along with some burrows, including forms resembling *Skolithos* and *Arenicolites*. Cross-bedding indicates a predominant southerly or south-easterly flow, but north-east currents are also recorded, as well as some herring-bone cross-bedding. Braided stream deposition is suggested, although a shallow marine origin for at least part of the formation cannot be discounted (Lovell, 1978a,b).

The Upper Old Red Sandstone is represented by the Quartz Conglomerate Group on the north-east, east and south-east crops of the South Wales Coalfield (see **Craig-y-cwm** potential GCR site report, this chapter). In the Cardiff area, a 114 m-thick succession of thinly bedded quartzitic sandstones, siltstones and mudstones with subordinate thick, commonly pebbly sandstones and calcretes (the Cwrt-yr-ala Formation; Waters and Lawrence, 1987) underlies the Quartz Conglomerate Group. Quartzitic sandstones at the base of the group on the north-east of the coalfield (the Wern Watkin Formation) correlate with the Grey Grits Formation. They are overlain by quartz pebble conglomerates (the Craig-y-cwm Formation) that contain sporadic fish fragments, including *Bothriolepis*. The topmost part of the formation comprises micaceous, feldspathic and garnet-rich sandstones and interbedded red mudstones (the Garn-gofen Formation). Vertebrate remains from these beds include a fragment of *Osteolepis macrolepidotus*. The bivalve *Archanodon jukesi* was collected from the Quartz Conglomerate Group in Monmouthshire, and *Holoptychius nobilissimus* is recorded at Tongwynlais. The group crops out around the Forest of Dean Coalfield in Monmouthshire and Gloucestershire, where it comprises basal quartz conglomerates overlain by the Tintern Sandstone Formation. East of the Severn, the sandstone and conglomerate facies become indistinguishable as the succession thickens southwards and the beds are named the Portishead Formation. In the Clee Hills, the Upper Old Red Sandstone is represented by the Farlow Sandstone Formation, which consists of lower yellow, and upper grey, sandstones.

The uppermost beds of the Quartz Conglomerate Group in south-east Wales locally show a transition into the lower Tournaisian Tongwynlais Formation (Avon Group) of the Carboniferous Limestone, with interbedded marine limestones and red-brown sandstones. Spores from 18 m below the top of the group at Tongwynlais are now regarded as earliest Famennian in age. Elsewhere, there is generally a depositional break between the uppermost beds of the group and the Carboniferous Limestone, but interdigitation of shallow marine beds occurs in Pembrokeshire, as seen at the **West Angle Bay (North)** and **Freshwater East–Skrinkle Haven** GCR sites.

PORTH-Y-MOR, ANGLESEY (SH 490 885–SH 493 876)

J.R. Davies

Introduction

The foreshore sections to the north and south of Porth-y-Mor on the north-east coast of Anglesey (Figure 5.4) afford some of the best and most accessible exposures through Old Red Sandstone fluvial fining-upward cycles in the Anglo-Welsh Basin. The sections occupy an important place in the history of research into fluvial sedimentology, for it was here that Allen (1965a) first recognized ancient examples of epsilon cross-bedding and showed it to be formed by lateral accretion on the point bars of meandering river channels. Also, the sections form part of the only outcrop of Old Red Sandstone strata preserved in north Wales. The GCR site is the type locality of the Porth-y-Mor Formation and, at its southern end near Traeth Lligwy, exposes the overlying Traeth Lligwy Formation. Coastal cliffs at Traeth Bach 800 m north-west of Porth-y-Mor, and 200 m north-west of the GCR site boundary, provide good exposure of the underlying unit of the Old Red Sandstone (the Traeth Bach Formation) and also merit protected status. This folded and cleaved Anglesey succession lies about 110 km north-west of the nearest Devonian outcrop in the Welsh Borderland, providing an important constraint on Devonian palaeogeographical reconstruction, and on the timing and nature of late Caledonian orogenic events.

Description

The Anglesey succession of Devonian red beds was first described in detail by Greenly (1919), who, although recognizing its gross similarities with the Lower Old Red Sandstone of south Wales and the Welsh Borderland, viewed it as the deposits of a separate northern basin. Allen (1965a) subdivided the succession into four formations (which he referred to as 'Beds'). These are, in ascending order, the Bodafon Formation, Traeth Bach Formation, Porth-y-Mor Formation and Traeth Lligwy Formation. Apart from the localized, conglomeratic Bodafon Formation, the formations are exposed in the coastal cliffs between Traeth Dulas (SH 487 888) and Traeth Lligwy (SH 487 877). The Porth-y-

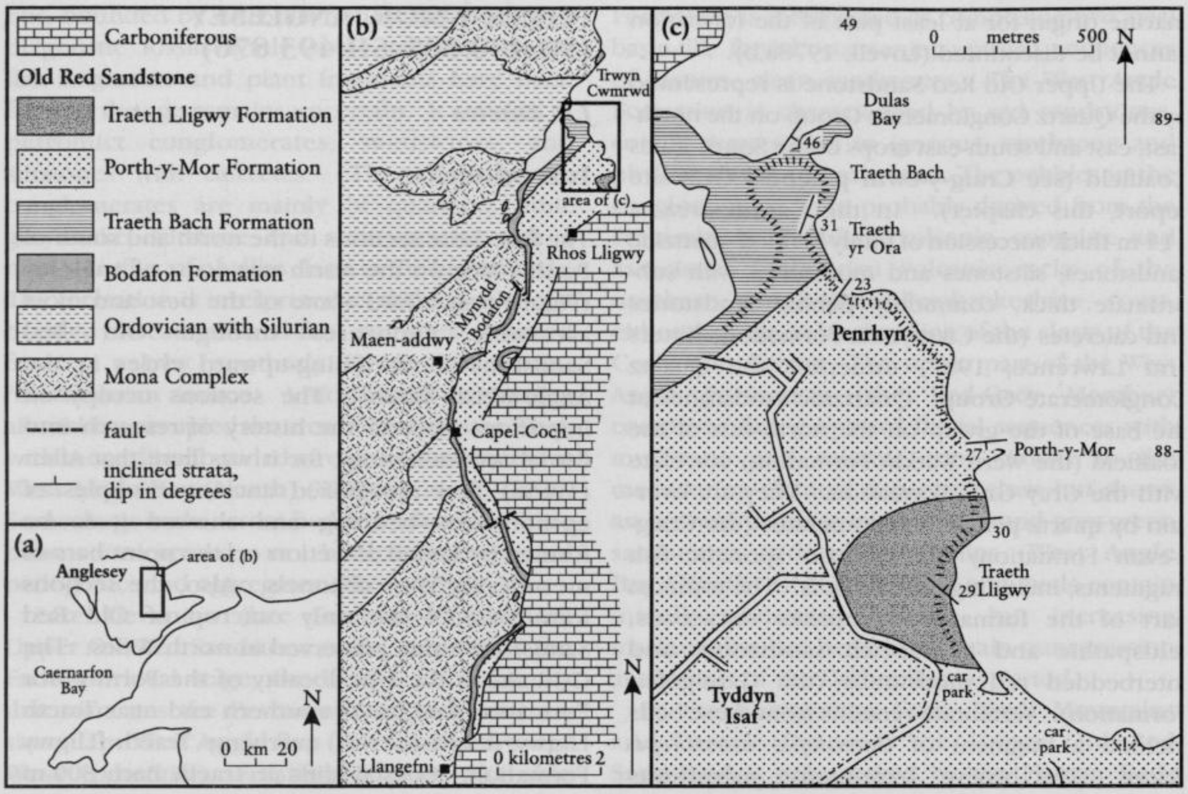


Figure 5.4 Geology of the Porth-y-Mor GCR site, Anglesey. Map (a) shows location of Map (b). Map (b) shows the main outcrop of Old Red Sandstone in Anglesey and location of Map (c). Map (c) shows the geology of the Porth-y-Mor site. Maps (b) and (c) after Allen (1965a).

Mor site lies within this tract, exposing the eponymous Porth-y-Mor Formation and the overlying Traeth Lligwy Formation. Allen gave details of the petrology and sedimentary structures of the rocks, documenting heavy-mineral assemblages, palaeocurrent indicators and the distribution of trace fossils. He also provided palaeoenvironmental and palaeogeographical interpretations, invoking alluvial-fan, fluvial in-channel, alluvial-floodplain and lacustrine depositional environments (see also Allen, 1970).

The Bodafon Formation ranges from 3 m to 45 m in thickness and comprises conglomerates and pebbly sandstones with minor red siltstone lenses. It is exposed on the coast at Trwyn Cwmrwd (SH 492 902), 2 km NNW of the GCR site, where up to 7.6 m of pebbly sandstones and thin conglomerates rest unconformably on vertically foliated gneisses and dip gently seawards. The conglomerates are extraformational ('exotic'), the clasts comprising mainly quartzite, schist, gneiss and vein quartz derived from the local basement and ranging from cobble to pebble grade, with a few boulders.

The Traeth Bach Formation is at least 130 m thick, the lowest 100 m being exposed in the low cliffs at Traeth Bach (SH 487 888–SH 489 887). The formation is dominated by red calcrete-rich siltstones, with minor extraformational conglomerates, pebbly and thin sandstones (Figure 5.5). The calcrete is mainly in the form of nodules, but massive mature dolomite and limestone calcretes occur at several levels, the thickest (5.2 m) lying about 95 m from the base of the section. The pebbles in the conglomerates are mainly of local Precambrian and Ordovician rocks.

The Porth-y-Mor Formation is estimated to be about 347 m thick and is the thickest unit within the local Devonian succession. The section commences on the south side of Traeth yr Ora and dips consistently to the south at about 27°. The contact with the underlying Traeth Bach Formation is concealed beneath the beach to the north. The exposed succession, about 225 m thick, comprises a series of fining-upward cycles. Allen (1965a) recognized 43 cycles, each constructed of a lower conglomerate and sandstone and an upper muddy siltstone. Calcareous nodules (calcrete glaebules) are common throughout the siltstone units and locally form the dominant element, coalescing to form continuous beds of impure limestone and dolomite. In the following description of the section, the cycle numbers are those of Allen (1965a), as shown on his log of the section (Figure 5.5). A 1.4 m-thick calcrete lies at the base of the exposed succession, underlying Cycle 1. There are substantial exposure gaps between cycles 10 and 11 at Porth-y-Mor (SH 4922 8830–SH 4933 8806) and in the cove to the south (SH 4935 8803) between cycles 12 and 13. Apart from the pale grey limestones and brown-weathering dolomites, the lithologies in the Porth-y-Mor Formation are typically red or purple. The siltstones exhibit a northerly dipping cleavage throughout.

Conglomerates are normally present at the base of each cycle, where they rest on an erosion surface cut in the underlying siltstone, ranging from a few centimetres to over 1 m in thickness. Exotic and intraformational types are represented, but the former only occurs at the base of Cycle 1, where a massive 3.4 m-thick unit comprises rounded to angular clasts, ranging up to cobble grade in size, of quartzite, schist, gneiss, vein quartz and cleaved mudstone. These clasts are readily matched with rock types in adjacent Precambrian and Lower Palaeozoic outcrops. In contrast, the intraformational conglomerates, which occur throughout the remaining part of the section, are composed of rounded pebbles and granules of red and green siltstone, fine-grained, red sandstone and limestone, as well as reworked calcrete nodules. They record the reworking of Old Red Sandstone sediments from elsewhere within the basin of deposition.

In every cycle, the basal conglomerate is overlain by, and commonly grades upwards into, a much thicker sandstone unit. Coarse- to fine-grained sandstones are commonly interbedded in the lower parts of these units, but fine- and very fine-grained sandstones with sporadic siltstone partings generally dominate the upper levels. This fining upwards is reflected in the range of tractional sedimentary structures in the sandstones. The coarser lower sandstones and basal conglomerates commonly exhibit large-scale tabular or trough cross-bedding in sets up to 0.45 m thick. In contrast, the overlying finer-grained sandstones are characterized by co-sets of small-scale cross-lamination separated by planar-laminated intervals. This succession of sedimentary structures is seen particulary well in cycles 1 and 2, which contain the thickest sandstone bodies in the succession.

In ten cycles, the basal sandstone and conglomerate unit exhibits a distinctive set of shallow-dipping bedding surfaces. Each surface is tangential with the top of the sandstone, and, in an opposing sense, with the scoured base of the unit, giving a sigmoidal form (Figure 5.6). This pattern of bedding surfaces is epsilon cross-bedding (Allen, 1963a), first recognized in an ancient sedimentary sequence here (Allen, 1965a).

The surfaces cross-cut the vertical lithological changes within the conglomerate and sandstone units, but the upward-fining character, and the upward succession of tractional structures seen in the cycles overall is visible within each cross-bed of the epsilon sets. Critically, palaeocurrent directions indicated by the internal tractional features show that current flow was consistently parallel to the strike of the epsilon cross-bedding surfaces. The latter dip predominantly towards the east, but epsilon cross-sets with either westerly or southerly dipping surfaces are also present.

The upper argillaceous parts of the Porth-y-Mor cycles are typically devoid of tractional sedimentary structures, apart from thin beds of cross-laminated sandstone, which are common at the base and locally present at higher levels. Calcrete nodules, commonly cylindrical in shape and aligned perpendicular to bedding, are scattered throughout. They regularly form part of vertical profiles in which their size and frequency increases upwards until the host siltstone is absent from capping beds of massive limestone or dolomite (Allen, 1965a, 1974d). In thin section, the limestones display a complex range of textures and fabrics (Allen, 1965a). Brecciation is common, with darker masses of inclusion-rich, microcrystalline calcite cross-cut by intersecting veins of clear, coarsely crystalline calcite. Tubular root-related structures (rhizoliths) are also present.

Palaeocurrent indicators in the Porth-y-Mor Formation show that depositing currents largely flowed from the north-east. This is consistent with the orientation of associated linear channel and scour features, and of primary current

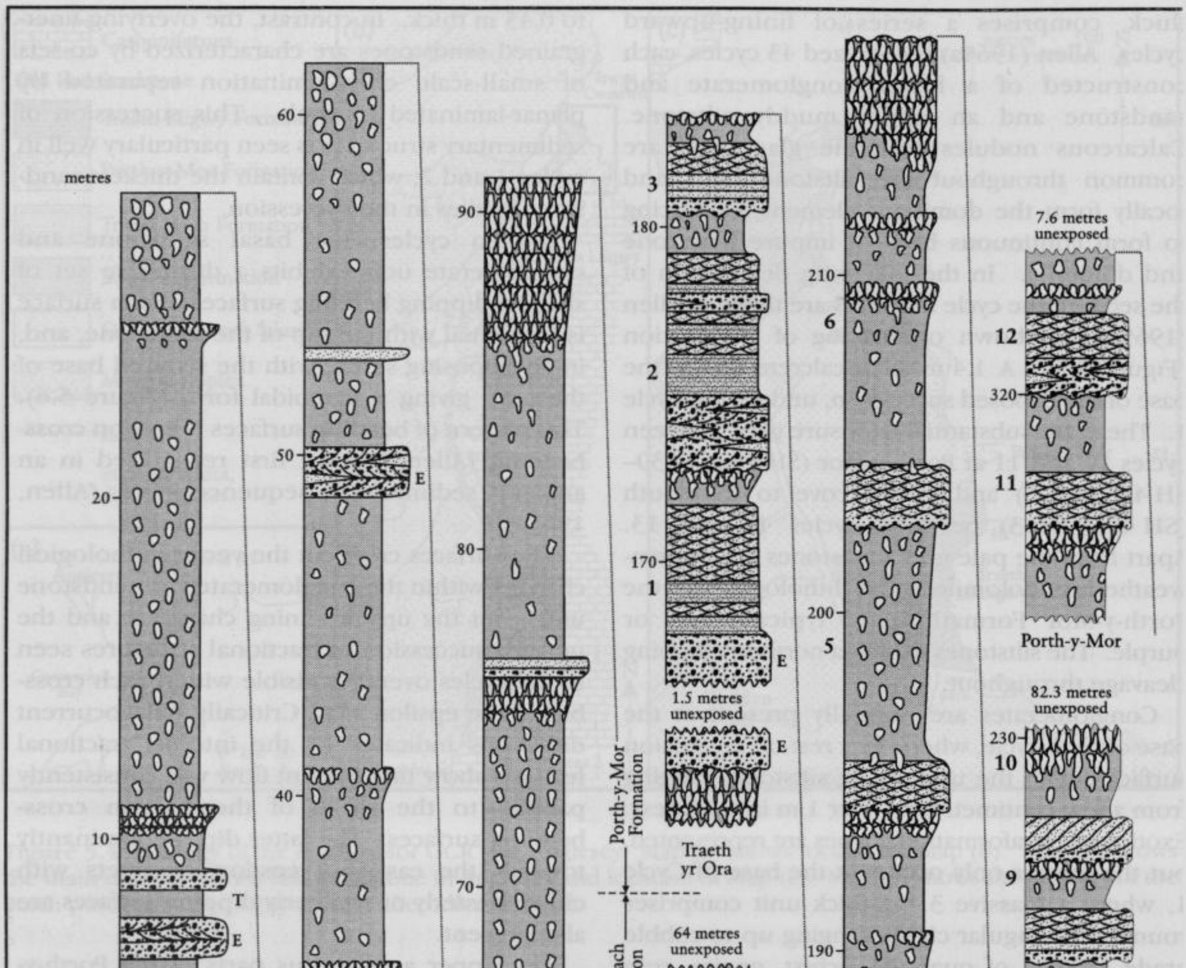
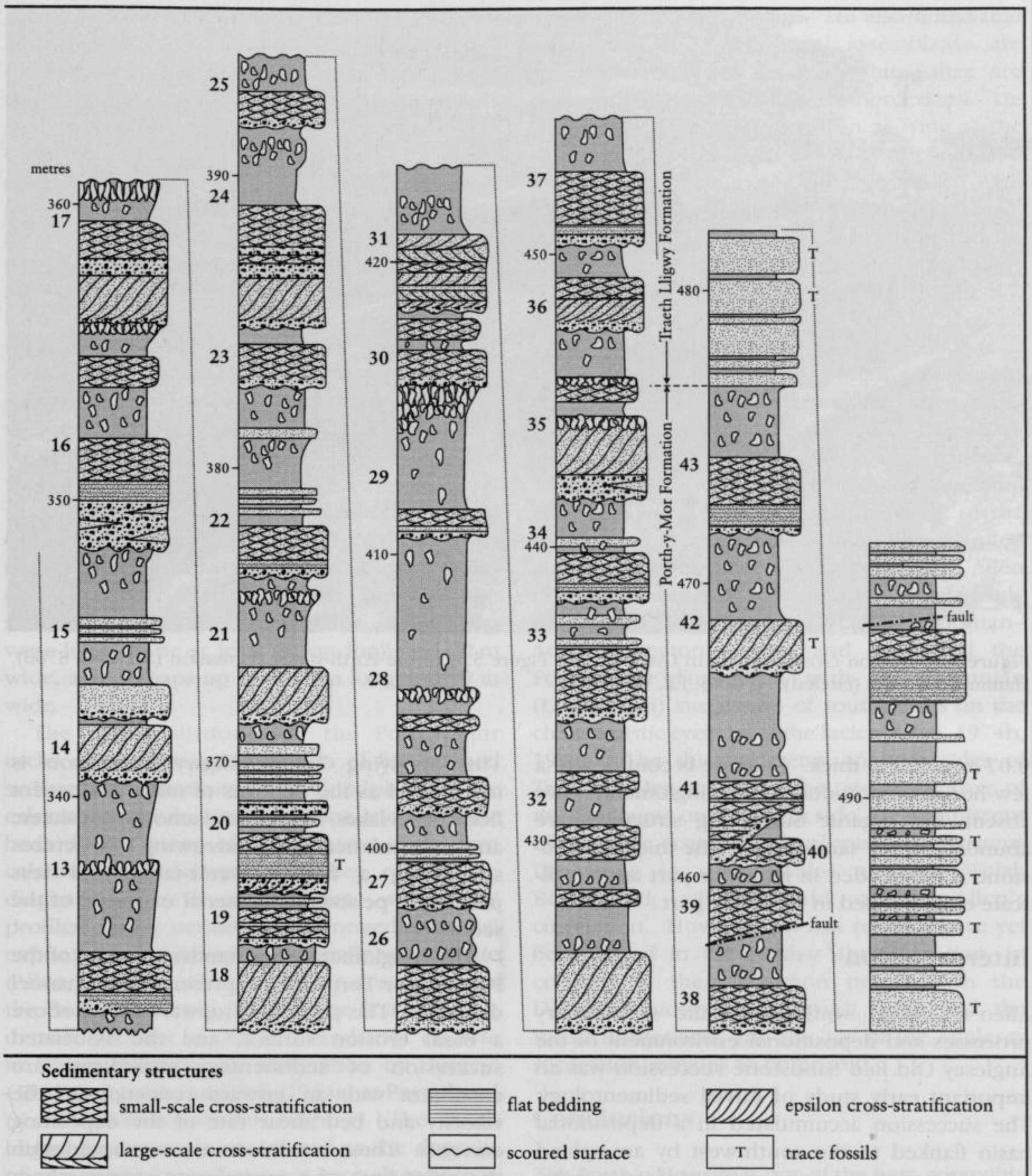


Figure 5.5 Graphic log of section of coastal exposures between Traeth Dulas and Traeth Lligwy measured by Allen (1965a). The Traeth Bach Formation is from 0 m to 129.54 m (425 feet), the Porth-y-Mor Formation is from 129.54 m to 477.01 m (1565 feet) and the Traeth Lligwy Formation is from 477.01 m to 498.96 m (1637 feet). Thicknesses above the base of the section are shown in metres. The numbers in bold are Allen's cycle numbers in the Porth-y-Mor Formation. After Allen (1965a).

lineation present in the plane-bedded sandstones. Trace fossils include a few sporadic burrows throughout, and some arthropod tracks high in the formation (SH 4940 8779), but no body fossils have yet been discovered. The conformable top of the formation is placed at the base of the lowest of the distinctively bioturbated sandstones that characterize the succeeding Traeth Lligwy Formation, in which burrow traces are abundant.



The Traeth Lligwy Formation forms the cliffs on the north side of Traeth Lligwy (SH 494 878–SH 493 875) at the southern end of the GCR site. The basal 24 m of the formation are exposed, preserved in the axial area of an E–W-trending syncline. They are of sandstones and siltstones, in thinner beds than the Porth-y-Mor Formation below. Red, very fine-grained sandstones ranging from 0.15 m to 2.1 m thick, but averaging 0.53 m, are interbedded with red, sandy, siltstones from

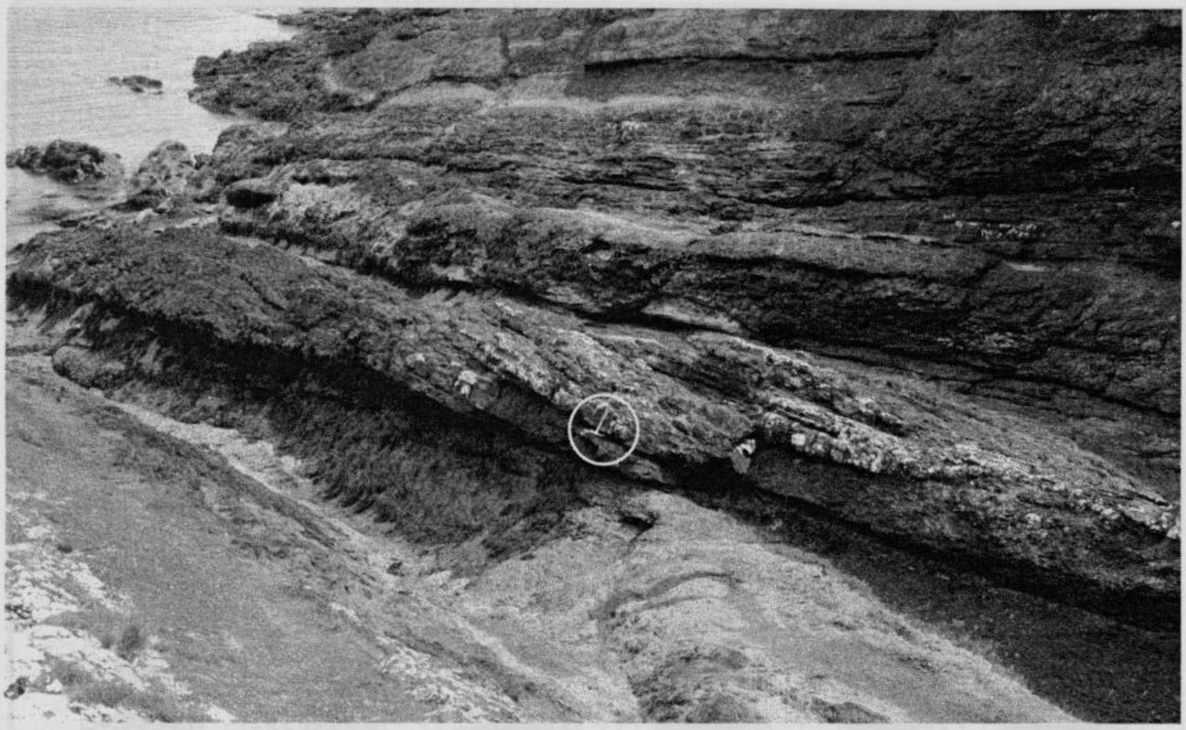


Figure 5.6 Epsilon cross-bedding in Cycle 42 (see Figure 5.5) of the Porth-y-Mor Formation (SH 4940 8780). Hammer for scale (circled). (Photo: J.R. Davies.)

0.07 m to 1.2 m thick. Calcrete is confined to a few horizons of nodules and conglomerates are absent, but organic burrowing structures are abundant in the sandstones. The thickest sandstone is flat-bedded in its lower part and small-scale cross-bedded in its upper part.

Interpretation

Allen's (1965a) synthesis of the sedimentary processes and depositional environment of the Anglesey Old Red Sandstone succession was an important early study of fluvial sedimentology. The succession accumulated in a depositional basin flanked to the south-west by an upland area of Precambrian and Lower Palaeozoic rocks. These older rocks were the source of alluvial-fan gravels (the Bodafon Formation), which accumulated along the basin margin. Away from this margin, these interdigitate with the overlying Traeth Bach and Porth-y-Mor formations. In the GCR site calcareous muddy siltstones of the Traeth Bach Formation were interpreted by Allen as the deposits of ephemeral, non-saline playa lakes. Subsequently, a broad meandering, SE-trending river belt was established, within which the Porth-y-Mor Formation was deposited. The overlying Traeth Lligwy Formation is interpreted as the deposits of more permanent flood basin lakes, the reduced amount of calcrete and abundance of burrowing structures suggesting a higher water-table and less prolonged periods of subaerial exposure of the sediments.

The conglomerate and sandstone units of the Porth-y-Mor Formation represent river channel deposits. The pattern of upward-fining above a basal erosion surface, and the associated succession of sedimentary structures, are consistent with an upward reduction in the velocity and bed shear rate of the depositing currents. These conditions are encountered on the point bars of a meandering stream where the fastest and most-powerful currents are associated with the deepest part of the channel, close to the outer bends of the meanders. Here, the river erodes into its earlier floodplain sediments and deposits its coarsest bedload. In contrast, the currents flowing across the upper parts of point bars formed on the inside bends of the meanders are much slower, and deposit finer-grained sediment. Lateral migration of the river channel and lateral accretion of its point bars generate the upward-fining channel sequence.

The channel conglomerates and sandstones of the Porth-y-Mor Formation are noteworthy in being the first rocks in the stratigraphical record in which epsilon cross-bedding and its significance were recognized. Allen (1965a) demonstrated that the sigmoidal surfaces, dipping perpendicular to the flow direction shown by associated tractional structures, represent the surfaces of meander point-bars, and therefore, that each epsilon cross-set records the process of incremental, sustained lateral accretion. At a time when the understanding of ancient sedimentary, fluvial fining-upwards units was in its infancy, the discovery and interpretation of these features showed that they were the products of laterally migrating, meandering channels of mixed bedload rivers (Allen, 1965a, 1970). On the basis that the thickness of the epsilon cross-sets should correspond to the bankfull depth of the channel in which they were deposited, Allen (1965a) estimated that the rivers that supplied the sediment of the Porth-y-Mor Formation were likely to be at least 60 km long and 20 m wide, and perhaps up to 600 km long and 90 m wide.

The upper siltstones of the Porth-y-Mor cycles record the accumulation of fine-grained sediment on extensive river floodplains. The calcareous nodules and limestone and dolomite beds display many of the features of modern calcretes and dolocretes. They record the diagenetic growth of carbonate within soil profiles during periods of prolonged subaerial exposure in a semi-arid, seasonally wet climate (Allen, 1974d). Allen's (1965a) description of the Porth-y-Mor examples was the first and most detailed account of Old Red Sandstone calcrete in Wales, following its recognition by Burgess (1961) in Ayrshire and Pick (1964a) at **Portishead** (see GCR site report, this chapter). The Traeth Lligwy Formation is interpreted as the deposits of perennial lakes, a facies not seen elsewhere in the Anglo-Welsh Basin.

Early palaeogeographical models envisaged the Anglesey Old Red Sandstone succession as deposited in a narrow gulf opening to the north-east, connected to the Midland Valley of Scotland, and structurally isolated from the sequences of south Wales and the Welsh Borderland (Greenly, 1919; Wills, 1952). Allen (1965a) noted the similarity in lithofacies and cyclicity of the Porth-y-Mor Formation to the Dittonian and Breconian rocks of Pembrokeshire and the Welsh Borderland. He also noted that although the heavy-mineral assemblages are similar to those of Pembrokeshire, they are different to those of the Welsh Borderland. He viewed the Anglesey succession as lying at the margin of a broad depositional tract connected to the main basin to the south, supplied with sediment sourced some distance to the north-west by south-easterly flowing rivers. This remains the favoured palaeogeographical interpretation (Allen, 1974a; Allen and Crowley, 1983; Bluck *et al*., 1992), although the age of the succession remains unproved in the absence of fossil or other direct dating evidence. Structural and stratigraphical constraints provide a time-span only between the Ludlow and Dinantian, inclusive (Allen, 1965a; Allen and Williams, 1979a). A Mid-Devonian age has been suggested (Hurst *et al*., 1978), but the presence of the folding and cleavage makes this unlikely (Allen and Williams, 1979a; Hurst *et al*., 1979). Allen (1965a) attributed the deformation to the widely recognized Mid-Devonian (late Caledonian–Acadian) tectonic event and correlated the Porth-y-Mor Formation with the Dittonian (Lochkovian) succession of south Wales on the characteristic cyclicity of the facies (Allen, 1974b, 1977). The thick calcretes on both sides of Traeth yr Ora, including the one at the base of the exposures on the south side, are reminiscent of the thick, regionally developed Psammosteus Limestone in south Wales and the Welsh Borderland, which would support Allen's correlation. However, no fish remains have yet been found in the Porth-y-Mor Formation, in contrast to their common presence in the Dittonian succession in south Wales and the Welsh Borderland, and the age of the Anglesey succession remains to be proved.

Conclusions

The Porth-y-Mor site is one of the best, accessible sections of Old Red Sandstone alluvial cyclic deposits in the UK. It occupies a unique place in the history of sedimentological research, the excellent exposures including examples of epsilon cross-bedding, first recognized in an ancient sedimentary sequence here. The well-developed profiles of soil carbonate (calcrete) were amongst the first to be described in detail in the Anglo-Welsh Basin. The importance of the site also lies in the presence of the unique lake deposits of the Traeth Lligwy Formation.

The site, set within the cleaved and folded Anglesey Old Red Sandstone succession, provides evidence to suggest that this northern sequence shared the same sediment source as parts of the Lower Old Red Sandstone of south Wales. The two areas may have been part of an extensive, continuous depositional tract prior to Mid-Devonian (Acadian) deformation and uplift. However, the Porth-y-Mor rocks have yet to yield fossils to indicate their precise age, and the site offers opportunities for further palynological and microfossil research.

DEVIL'S HOLE, SHROPSHIRE (SO 672 929)

Potential ORS GCR site

W.J. Barclay

Introduction

The Devil's Hole site in Shropshire (Figure 5.7) is an established GCR site for its fossil fishes (Dineley, 1999f). A brief summary is presented here, along with a geological map of the site. The opportunity is also taken to correct the vertical section (Figure 5.8) given in Dineley's account (fig. 4.8).

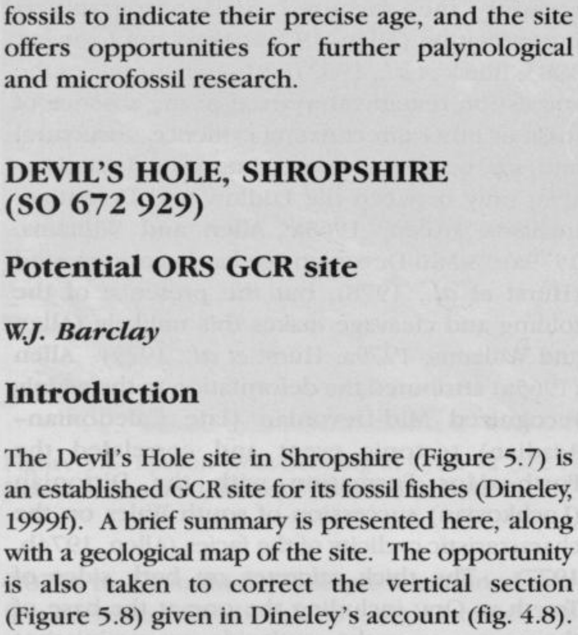


Figure 5.7 Geological map of Devil's Hole GCR site. Based on British Geological Survey 1:10 560 manuscript map Shropshire 58NW (1960) and 1:10 000 manuscript map SO 69SE (2002).

The site provides a stream section across the 'Downtonian'–'Dittonian' boundary, with fish remains recovered from above and below the Bishop's Frome (Psammosteus) Limestone. Excavations by the GCR Unit of the Nature Conservancy Council between 1980 and 1982 enabled a detailed sedimentological and palaeontological analysis by M.A. Rowlands and P. Tarrant (Tarrant, 1991). The section is now poorly exposed and difficult to access.

The section was originally collected by the [British] Geological Survey (Whitehead and Pocock, 1947) and later by Ball and Dineley (1961). Reference to the geology of the site was made by Ball and Dineley (1961), Allen and Tarlo (1963), Banks (1980), Richardson *et al.* (1981), Allen (1985), Blieck (1985), Halstead (1985) and Jenkins (1998). The fish faunas were also referred to by Wills (1948, 1950), White (1950), Denison (1956), Robertson (1957), Turner (1973), Blieck (1981, 1984, 1985), Tarrant (1981) and Vergoossen (2000).

Description

A mature 2.5 m-thick calcrete cropping out in a lichen-coated waterfall (SO 6710 9284) is correlated with the Bishop's Frome (Psammosteus) Limestone and marks the top of the Raglan Mudstone Formation (Jenkins, 1998). The succession below the limestone comprises mainly red mudstones/siltstones with sporadic thin sandstones and several thin calcretes. The St Maughans Formation (Ditton Group of Dineley, 1999f) lies above the Bishop's Frome Limestone and comprises a succession of fining-upward cyclic sandstone–siltstone–mudstone units. The basal coarse members of the cycles include intraformational conglomerate lenses, in which most of the disarticulated fish remains are found. The commonest fish below the limestone is *Traquaraspis* (*Phialaspis*) *symondsi*. Above the limestone, pteraspids dominate, including several species of *Protopteraspis*.

Interpretation

The Raglan Mudstone Formation is interpreted as the deposits of a coastal alluvial-floodplain subject to frequent desiccation and soil carbonate formation and crossed by minor distributary channels. The Bishop's Frome Limestone represents a prolonged period of basin-wide non-deposition and soil carbonate formation. The St

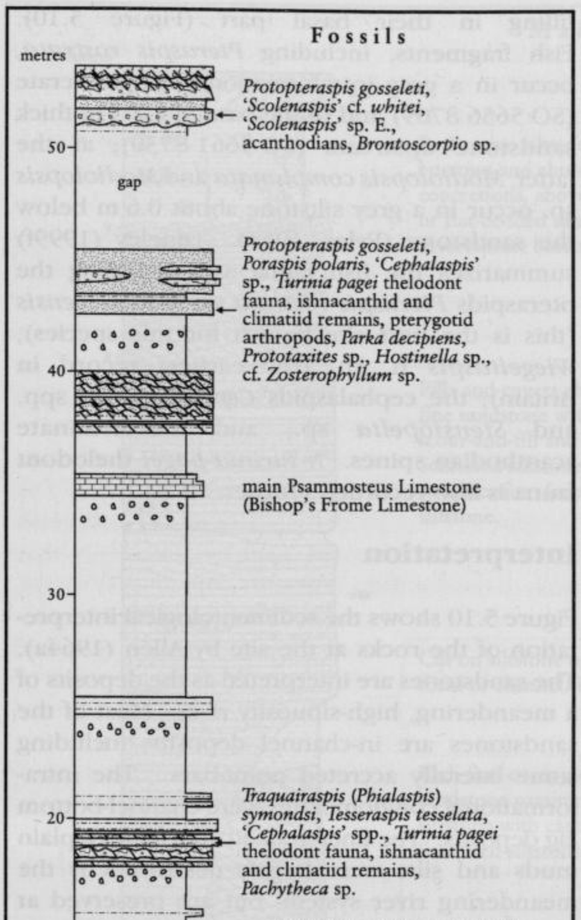


Figure 5.8 Vertical section of the strata at Devil's Hole. Based on Dineley (1999f, fig. 4.8), after M.A. Rowlands (MS).

Maughans Formation represents a medial alluvial environment, with the sandstones being mainly channelized, high-sinuosity stream deposits and the argillaceous lithologies being floodplain deposits.

Conclusions

Historically, this has been an important site for the large amount of fossil fish material it has yielded. The assemblages span the 'Downtonian'–'Dittonian' boundary. Although poorly exposed and difficult to access, the site presents opportunity for further excavation and may help in pinpointing the Silurian–Devonian boundary within the Old Red Sandstone.

OAK DINGLE, TUGFORD, SHROPSHIRE (SO 566 871)

Potential ORS GCR site

W.J. Barclay

Introduction

Oak Dingle near Tugford, Shropshire is already an established GCR site for its fossil fishes (Dineley, 1999f). A brief summary is presented here. The stream section (Figure 5.9) exposes a near-strike section in strata in the lower part of the St Maughans Formation (Ditton Group of Dineley, 1999f). Its main conservation interest is in the rich fossil fish fauna recovered from intraformational conglomerates. Another important feature not discussed by Dineley is the occurrence of modiolopsid bivalves. White (1935) first reported fish from this locality, since when it has been described by Ball and Dineley (1961), Allen (1964a), Greig *et al*. (1968) and Collinson (1978). Turner (1973) collected a thelodont fauna, and other microvertebrate remains from the site are listed by Vergoossen (2000). Greig *et al*. (1968) described modiolopsid bivalves from the site, first reported by Eyles (1953).

Description

Figure 5.10 shows a graphic log of the strata compiled by Allen (1964a). Greig *et al*. (1968) provided details of the section. The strata lie in the lower part of the St Maughans Formation, close above a group of calcretes in about 35 m of

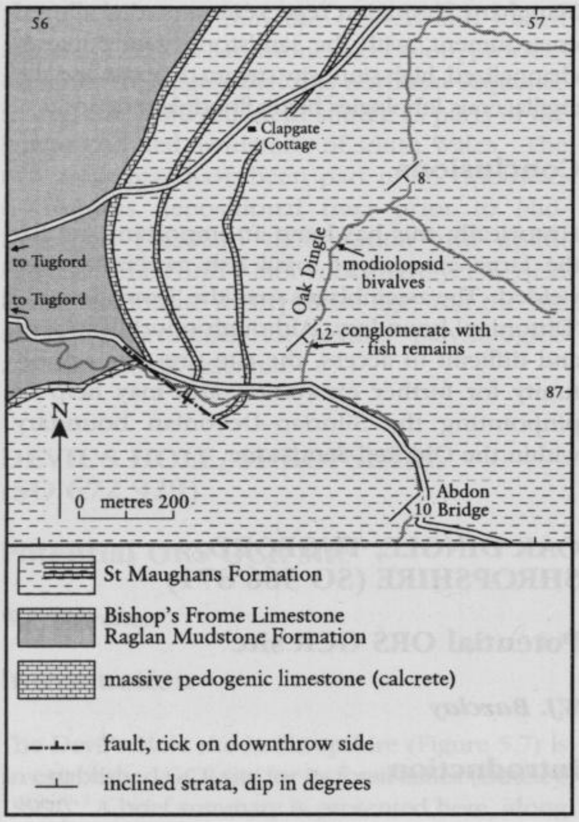


Figure 5.9 Geological map of Oak Dingle, Tugford. After British Geological Survey 1:10 560 manuscript map Shropshire 65NW (1960)

strata named the 'Psammosteus Limestones' by Ball and Dineley (1961) and Greig *et al.* (1968). In this area, there appears to be no single laterally persistent, thick limestone to mark the junction between the underlying Raglan Mudstone Formation and overlying St Maughans Formation. However, a thick (4.3 m) calcrete, the lowest of three, is present to the west of Oak Dingle and can be traced to a 1.3 m calcrete in the stream (SO 563 870) between Oak Dingle and Tugford. Above, it is separated by 0.6 m of mudstone from 0.6 m of mudstone- and calcrete-rich intraformational conglomerate, which is unusual in also containing round quartz pebbles. Greig *et al.* (1968) placed the junction (between their Ledbury Group and Ditton Series) at the base of this bed, which accords with the base of the St Maughans Formation in current lithostratigraphical classification.

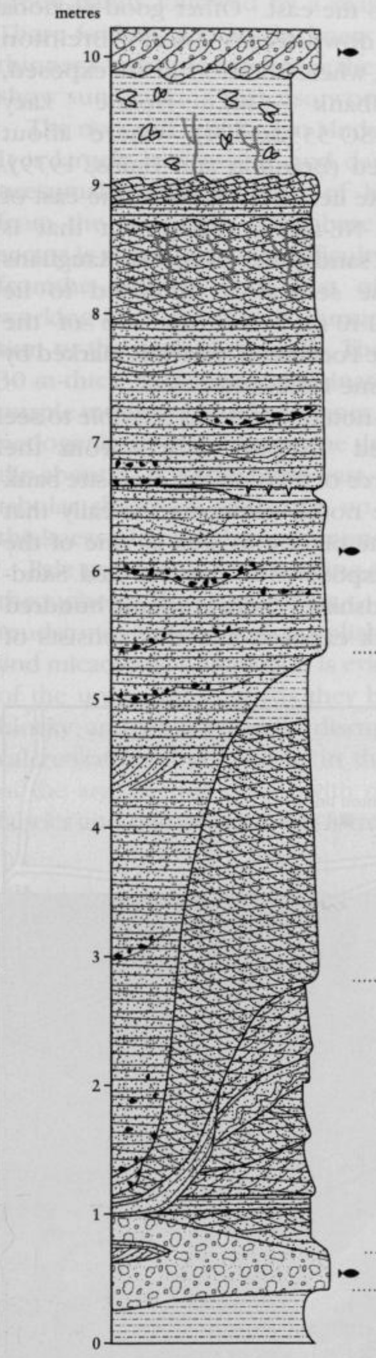
The section mainly comprises sandstones showing evidence of multiple channel incision and filling in their basal part (Figure 5.10). Fish fragments, including *Pteraspis rostrata*, occur in a grey intraformational conglomerate (SO 5656 8709) and in the base of a 2.1 m-thick sandstone upstream (SO 5661 8730); at the latter, *Modiolopsis complanata* and *Modiolopsis* sp. occur in a grey siltstone about 0.6 m below the sandstone (Eyles, 1953). Dineley (1999f) summarizes the fish fauna as comprising the pteraspids *Pteraspis rostrata* var. *trimpleyensis* (this is the best site known for this species), *Wiegeltaspis* n. sp. (the earliest record in Britain); the cephalaspids *Cephalaspis* n. spp. and *Stensiöpelta* sp.; and indeterminate acanthodian spines. A *Turinia pagei* thelodont fauna is also recorded (Turner, 1973).

Interpretation

Figure 5.10 shows the sedimentological interpretation of the rocks at the site by Allen (1964a). The sandstones are interpreted as the deposits of a meandering, high-sinuosity river. Most of the sandstones are in-channel deposits, including some laterally accreted point-bars. The intraformational conglomerates were channel-bottom lag deposits. The finer-grained alluvial-floodplain muds and silts were largely destroyed by the meandering river system, but are preserved at the base and top of the section. Invertebrate burrows and calcrete nodules in the topmost bed point to levee, floodplain and backswamp environments. The presence of modiolopsid bivalves indicates sporadic marine influence, which had largely ceased by this time in the Anglo-Welsh Basin, but is known elsewhere at the same stratigraphical level (Barclay *et al.*, 1994).

Conclusions

The Oak Dingle site allows three-dimensional examination of the sandbodies of an early Devonian fluvial, meandering river complex and its overbank environments. The fish fragments recovered from the site comprise an important early Devonian assemblage and include new species and the earliest examples of some taxa. The site is also one of only a handful in the Anglo-Welsh Basin to have yielded modiolopsid bivalves from a level above the Psammosteus Limestone, providing rare evidence of marine influence in early Devonian times.



Main facts	Interpretation
Red coarse siltstones with invertebrate burrows and abundant calcium carbonate concretions, above red, very fine, ripple- or flat-bedded sandstones with invertebrate burrows.	Vertical accretion deposit from overbank floods. Levee overlain by backswamp deposits. Fluctuating groundwater table during times of exposure.
Fills and covers channel. Red, flat-bedded, fine sandstone with parting lineation, scour-and-fill and local scoured surfaces. Scattered siltstone clasts. Local cross-stratification. Lenticular sun-cracked siltstone.	Channel-fill and lateral accretion deposit. Sand transported as bed-load and reworked over shifting channel floor of flat-topped banks. Exposure of higher banks.
Cut on siltstone or very fine sandstone. In form of channel. Relief ~4.8 m.	Erosion at floor of wandering river channel. Extent of wandering possibly controlled by earlier channel plug.
Red, flat- or ripple-bedded, very fine sandstone passing up into red, coarse siltstone with carbonate concretions. Scattered siltstone clasts at base.	Channel-fill deposit. Overbank floods plug cut-off channel almost to top. Fluctuating groundwater table and periodic exposure.
Cut on very fine sandstones. In form of channel. Relief ~2.2 m.	Attempt to re-open plugged channel.
Repeated graded units overlying scoured surface with small-scale channels. Mostly ripple-bedded, very fine sandstone. Some siltstone.	Channel-fill deposit. Repeated intrusions of suspended sediment down a sloping surface, probably at times of higher stage.
Wedging intraformational conglomerate with sandstone lenticles.	Lag deposit formed at deepest parts of floor of wandering river channel.
Cut on siltstone. Low relief.	Erosion at floor of wandering river channel.

Key: conglomerate; sandstone; siltstone; invertebrate burrows; cross-lamination; cross-bedding; parallel lamination; fossil fish fragments

Figure 5.10 Vertical section of the strata in Oak Dingle, Tugford, showing the sedimentary facies and their interpretation by Allen (1964a). After Dineley (1999f, fig. 4.11).

THE SCAR, HEREFORDSHIRE (SO 354 444)

W.J. Barclay

Introduction

The Scar GCR site is a river cliff on the north bank of a large meander loop of the River Wye 2 km north-west of the village of Monnington-on-Wye, Herefordshire (Figure 5.11). The cliff provides one of the largest vertical and lateral inland sections of the Přídolí Series Raglan Mudstone Formation in the Anglo-Welsh Basin.

Description

Clarke (1952) gave a brief description of the section and later (Clarke, 1955) described the geology of the area immediately to the west of the site on the Merbach Ridge. Brandon and Hains (1979) and Brandon (1989) gave details of the lithologies of the Raglan Mudstone Formation in the Hereford area to the east. Other good sections are present downstream near Breinton (SO 4518 3994), where about 11 m are exposed, and at Redbank Cliff, Holme Lacy (SO 5560 3614–SO 5552 3604), where about 32 m are exposed (Brandon and Hains, 1979). The Scar GCR site lies about 3 km to the east of a NW-trending, NE-facing escarpment that is capped by basal sandstones of the St Maughans Formation. The section is estimated to lie approximately 140 m below the top of the Raglan Mudstone Formation, which is marked by the Bishop's Frome Limestone.

Clarke (1952) noted that it was possible to see the cliff (named 'Brobury Scar') from the Deepwell (a source of tufa) on the opposite bank of the Wye. He noted somewhat lyrically that 'this is one of the biggest as well as one of the most beautiful exposures of the Old Red Sandstone in Herefordshire. There are some hundred feet of solid rock exposed and this consists of

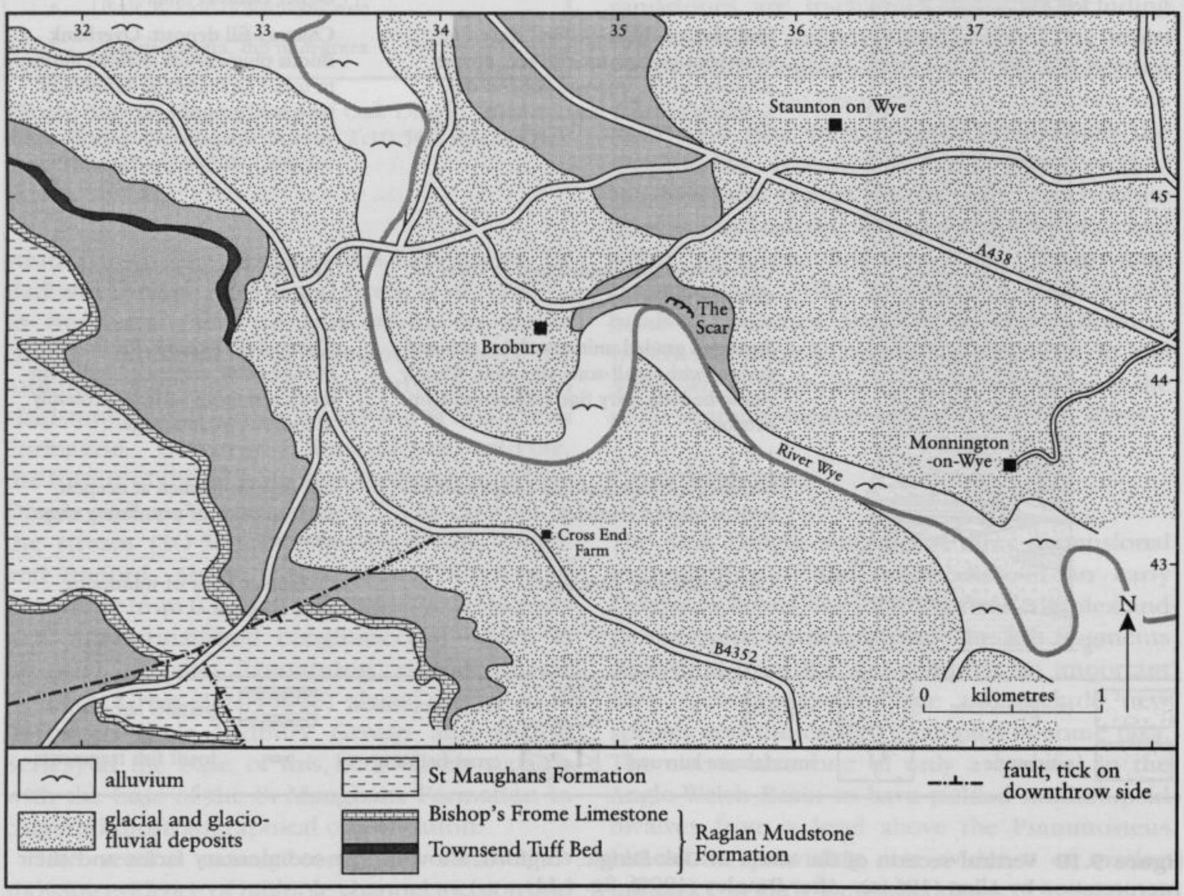


Figure 5.11 Geological map showing location of The Scar GCR site. After British Geological Survey 1:50 000 Sheet 197 (England and Wales), Hay-on-Wye (in press).

purple shales at the river level with two persistent green bands followed by a massive sandstone. There is then a great thickness of marl with a thinner sandstone band near the top. The shales show sun cracking and also worm casts.'

The river cliff is of Raglan Mudstone Formation. It is largely inaccessible and dangerous, Clarke presumably making most of his observations from the Deepwell. The base of the eastern sector is accessible with difficulty by descending fromthe cliff-top path east of the cliff and working back westwards through thick vegetation to the base of the cliff. The cliff exposes a 30 m-thick succession dominated by red and purple mudstones and siltstones, all of which are pedogenically altered to some degree. The beds dip about 5°–6° to the north-east. Thin lenses and tabular sheets of sandstone up to a maximum thickness of about 1 m occur sporadically.

Pale green, leached mottling and layers occur throughout the succession. The siltstones/mudstones are dull red, purplish and red-brown and micaceous. Lamination is evident at the bases of the units, but upwards they become massive, blocky and pedogenically disrupted. Incipient calcretization is ubiquitous in the topmost parts of the argillaceous layers, with prismatic vertisol fabrics and calcrete glaebule formation. All of the mudstones are distinctly calcareous. Locally, the calcrete nodules attain walnut-size. The most pedogenically altered horizons are clearly distinguished by their purple colour and pale green, prismatic vertisol mottling.

The sandstones are largely confined to the basal part of the section (Figure 5.12). The highest sandstone seen lies about 10 m above the base of the section. The sandstones are red-brown and purple, fine- to medium-grained and highly micaceous. They have gradational tops and sharp bases resting on erosion surfaces on the underlying mudstones. Some intraformational mudstone clasts are present in the bases of the sandstones. Cross-bedding seen is mostly planar, with minor synsedimentary deformation of the foresets seen at one point. One set of foresets indicates currents from the NNE. One bedding plane of a fallen block is littered with burrow traces.

Interpretation

The succession of strata of the Přídolí Raglan Mudstone Formation exposed at Monnington (or Brobury) Scar is interpreted as the deposits of an alluvial floodplain, formed under semi-arid tropical conditions and subject to seasonal

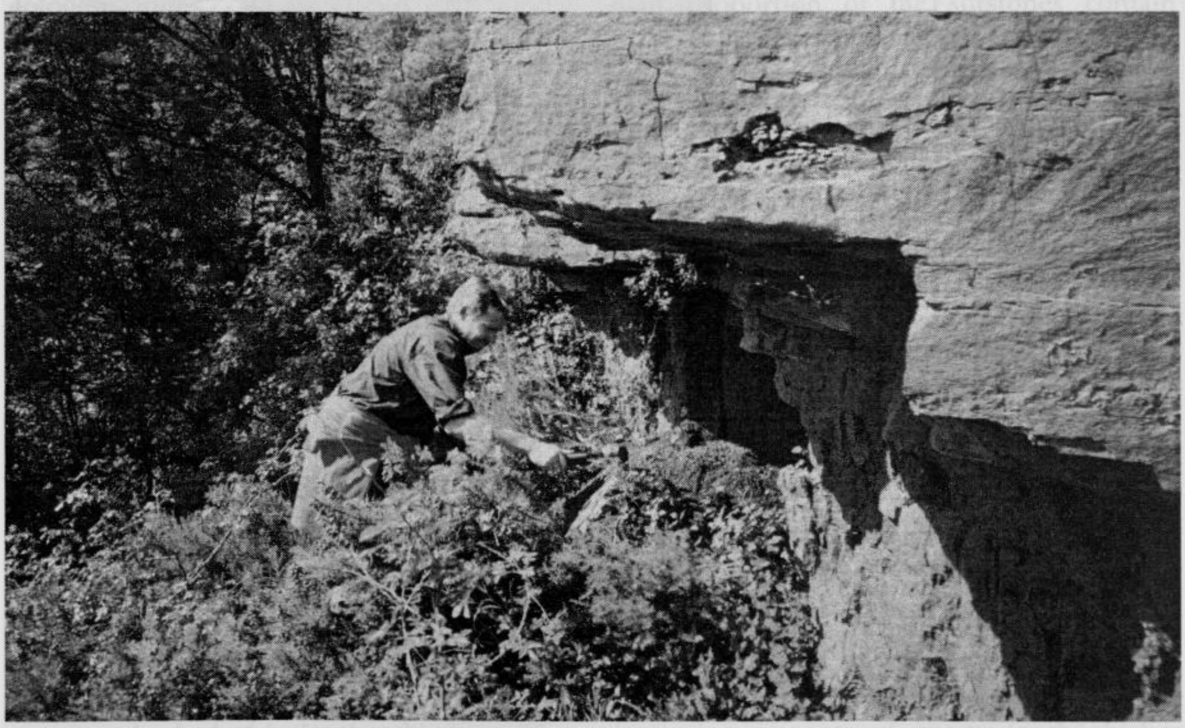


Figure 5.12 Sandstone overlying mudstone at the base of The Scar. (Photo: W.J. Barclay.)

wetting (e.g. Allen, 1974d; 1986; Brandon, 1989). Purple horizons are interpreted as cyclic pedogenic soil horizons, with incipient vertisol and calcrete formation. The deposits show a cyclicity typical of alluvial-floodplain deposits. The sandstones were either the channel-fills of shallow braided streams, perhaps subject to sporadic crevassing, or sheet-flood deposits. Detailed examination will refine the sedimentological interpretation. The environment was not entirely hostile to animal life, burrow traces being preserved locally.

Conclusions

The Scar GCR site provides one of the best inland exposures of Přídolí red-bed strata in the Anglo-Welsh Basin. About 30 m of beds mainly comprise a stacked succession of cyclic mudstone/siltstone-dominated units, which show evidence of soil formation in a semi-arid, seasonally wet climate.

CUSOP DINGLE, HEREFORDSHIRE–POWYS (SO 233 421–SO 257 384)

Potential GCR site

D.J. Hawley

Introduction

Cusop Dingle (Figure 5.13) is a prominent deep valley that cuts into the foot-slopes of the Black Mountains, immediately south-east of Hay-on-Wye, Powys. For much of its length it forms the border between England and Wales. The stream sections exposed by the Dulas Brook and its tributaries, the Crigiau Stream and Esgryn Brook, provide approximately 215 m of vertical succession, making up one of the two most continuously exposed inland sections of late Přídolí–early Devonian Old Red Sandstone succession in the Welsh Borderland–Black

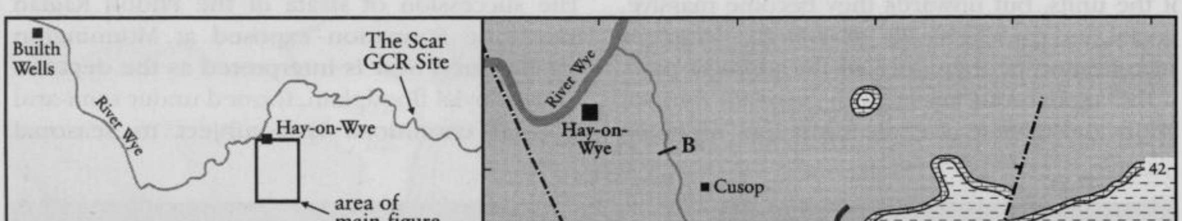


Figure 5.13 Geological map of Cusop Dingle. Based on British Geological Survey 1:50 000 Sheet 214 (England and Wales), Talgarth (2004).

Mountains area. The **Sawdde Gorge** section (see GCR site report, this chapter) provides the other (Almond, 1983). The section exposes the upper part of the Raglan Mudstone Formation (late Downtonian–Přídolí) and the lower part of the St Maughans Formation (Dittonian) (Figure 5.14), the top of the former marked by a thick pedogenic limestone (the main 'Psammosteus' (Bishop's Frome) Limestone). The lower part of the succession is dominated by red siltstones, commonly showing pedogenic characteristics, and punctuated by grey, green and red sandstone bodies. It includes the volcanogenic Townsend Tuff Bed (Allen and Williams, 1981a). The upper part of the succession is dominated by green and grey fluvial sandstones with subordinate green and red siltstones. The lithologies illustrate a facies change in the Lower Old Red Sandstone from distal (marginal marine) mudflats to fluvial-dominated alluvial plains. Descriptions of geological localities in Cusop Dingle and the adjacent areas have featured in literature and other records, but the following account presents the first comprehensive description of the succession.

Murchison (1834) provided the first geological sections and notes on the area. King (1934) summarized the geology and stratigraphy of the area, allocating the succession to lithostratigraphical zones. M'Caw (1936) gave a brief description of the geology of the Black Mountains area based on King's work, together with a rudimentary geological map. From the 1930s to the 1950s, Cusop Dingle was visited by palaeontologists, including H.A. Toombs, W.N. Croft and R.H. Denison from the British Museum (Natural History), in search of early vertebrate remains. Brief lithological descriptions of the localities collected were recorded in their field notebooks. White (1946) provided outline descriptions of two localities in Cusop Dingle, together with lists of the fauna found. Turner (1973) noted a thelodont assemblage 9 m below the 'Psammosteus' Limestone in Cusop Dingle. The geology and stratigraphical succession of Merbach Ridge and Merbach Brook, immediately east of the Black Mountains and Cusop Dingle, was described by Clarke (1955). Clarke described and named two lithologically distinct marker units within the Downtonian Red Marls, the Newton Marlstone and the Middlewood Sandstone. He also mentioned a bed of 'volcanic ash' about 95 m below the main 'Psammosteus' Limestone, later correlated by Allen and Williams (1981a) with the Townsend Tuff Bed.

The geology of the Black Mountains area to the south of Cusop Dingle is not well documented, but Turner *et al.* (1995) described the microvertebrate fauna from a section exposed at Pwll-y-Wrach, near Talgarth, first recorded by Hawley (1991). Barclay and Wilby (2003) provide a brief description of the geology of the Talgarth 1:50 000 geological map.

Description

The lower part of the succession (Figure 5.13), below the Bishop's Frome Limestone, exposes about 160 m of strata dominated by packages of siltstones (65–75%), with the remaining 25–35% consisting of two types of sandstone bodies. The siltstones are red-brown, micaceous and generally poorly sorted. They contain some primary sedimentary structures and many secondary features, including palaeosols. The most abundant primary structures are parallel bedding planes, parallel lamination, low-angle ripple cross-lamination, wrinkle marks on bedding planes, desiccation cracks and a range of trace fossils, including surface trackways, shallow horizontal burrows, vertical lobate burrows and vertical *Skolithos*-type burrows. A high proportion of the siltstones contain pedogenic (vertisol) structures, including concentrations of pale subspherical carbonate (calcrete) nodules, most common in the upper part of some siltstone units, where they are locally concentrated and form horizons that are more resistant to erosion. Below horizons of carbonate nodules, or where concentrations are low or absent, many siltstones display large bowl-shaped, curved, slickensided fracture planes (pseudo-anticlines), blue-grey drab haloes, prismatic ped structures and wedge-shaped ped forms. Desiccation cracks occur in the tops of some beds with weak carbonate nodule development. The vertical profile of pedogenic features is truncated and repeated in many siltstone units.

The sandstones (Figure 5.15) are mainly green or grey, although purple varieties also occur and the finer-grained sandstones are commonly red. Many sandstones in the lowest part of the succession contain high proportions of mica, giving them a grey or silver colour, but increasing amounts of quartz in the higher sandstones result in them being dominantly

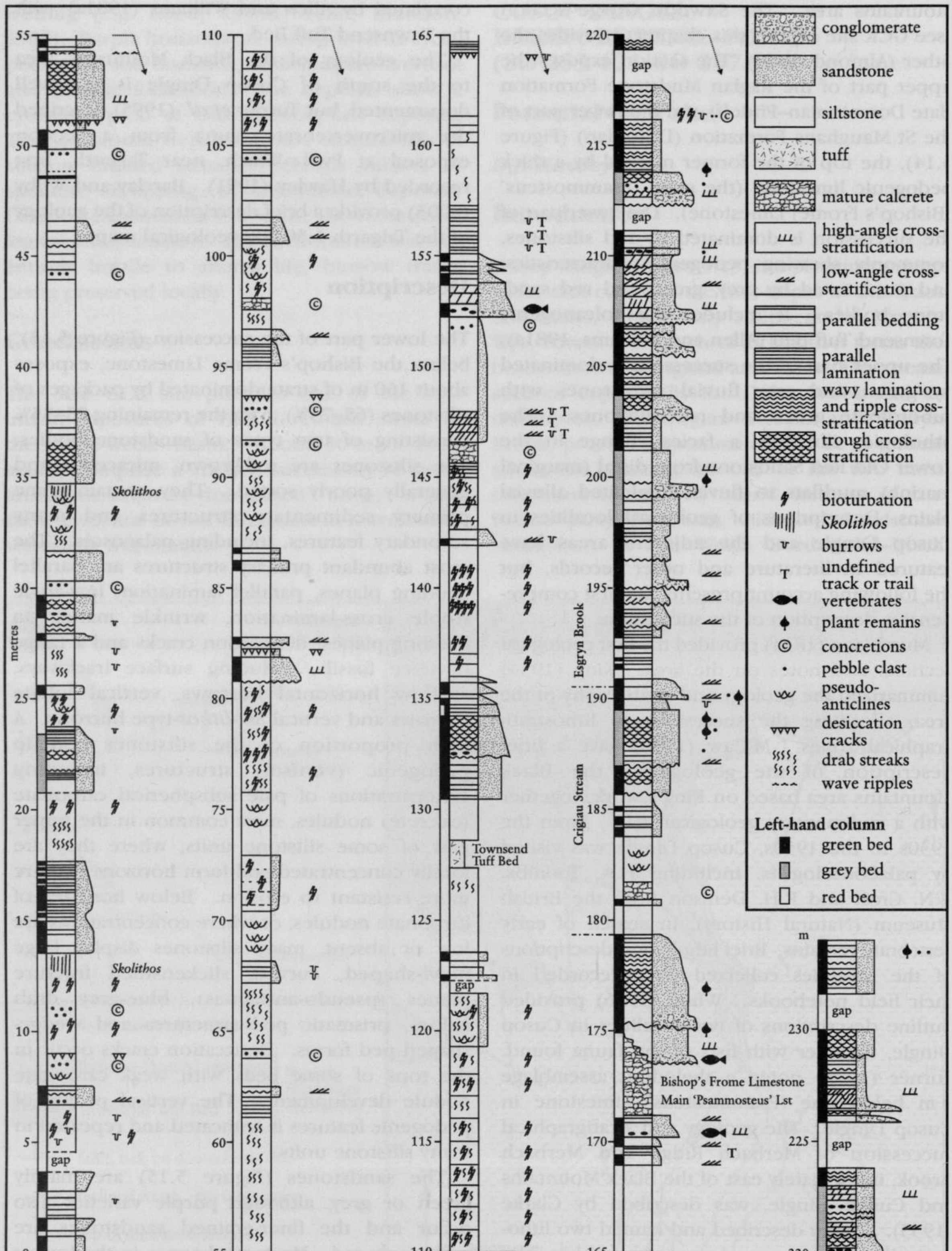


Figure 5.14 Graphic log of the section in Cusop Dingle.

Figure 5.15 Distributary channel sandstone body in the Raglan Mudstone Formation at Cusop Mill fall (SO 239 413). Fining-upward tabular and trough-cross-stratified beds overlie a scoured surface cut in parallel-bedded fine-grained sandstones that conformably overlie siltstones. The coarser sandstones are more resistant and cap a waterfall. (Photo: D.J. Hawley.)

green or grey. Two distinct sandstone bodies can be recognized. Coarse- to fine-grained, fining-upward sandbodies are 3 m to 5 m thick. Their basal parts consist typically of fine- to medium-grained sandstone sets with parallel bedding, low-angle cross-stratification or ripple cross-lamination, capped by a thin, bioturbated siltstone with desiccation cracks. The succeeding main sandstone unit overlies a sharp, mild erosion surface with strings of siltstone clasts or laterally impersistent lenses of poorly sorted conglomerate containing clasts of red and green siltstone, calcrete pebbles and poorly preserved fish fragments. The sandstone is coarse grained and well-sorted, and comprises tabular and/or trough cross-stratified units. The trough cross-sets are thinly laminated where there is a high mica content. At the top of the sandbodies are fine-grained, tabular, parallel-laminated or ripple-laminated, fining-upward sandstone sets, capped by thin red siltstones or truncated by a scour surface. Palaeocurrent directions are variable, but predominantly to the south-east.

Medium- to fine-grained, well-sorted, red and green interbedded sandstone bodies overlie siltstone units. They range between 0.4 m and 0.8 m in thickness, and typically have a very low-relief, undulating base or one comprising interdigitating lenses of siltstone and sandstone. The beds commonly comprise low-angle cross-stratified beds or decimetre-thick tabular sheets with alternately coloured lamination. Some of the beds are bioturbated and contain shallow cylindrical burrows and trails on the upper surfaces.

The 'Psammosteus' Limestones Group (Squirrell and Downing, 1969) includes three mature calcretes and is the correlative of the Chapel Point Calcretes Member of Pembrokeshire, where there are up to eight profiles in 50 m of mudrock. The main 'Psammosteus' Limestone of Ball and Dineley (1961) and the Bishop's Frome Limestone of Brandon (1989) is 1.5 m to 4 m thick (its base is not exposed in the Esgryn Brook), with less well-developed calcretes 11.5 m above and about 20 m below.

A fine-grained, green, splintery tuff about 1.5 m thick with a distinctive jointing/fracture pattern (SO 250 400) occurs 40 m stratigraphically below the base of the main 'Psammosteus' Limestone, at 190 m above OD, and is overlain by two thinner beds of hard, pale purple rock, both with some green mottling and separated by a thin, red, coarse-grained sandstone. The lowest bed is very fine-grained, whereas the upper one is coarser grained and contains glassy fragments. These beds are correlated with the Townsend Tuff Bed (Allen and Williams, 1981a), which crops out at similar stratigraphical levels in the Digedi Brook and River Enig to the west, and in Scotland Dingle and Merbach Brook to the east.

The upper part of the succession (above the main 'Psammosteus' Limestone) exposes about 55 m of strata correlated with the St Maughans Formation. These are dominated by green and grey, coarse- to fine-grained sandstones and conglomerates comprising 65% of the succession, with the remainder being siltstones. In addition to the stream section, exposures also occur in small outcrops and old quarries scattered across the upper slopes of the valley.

The sandstones are multi-storey bodies up to 9 m thick made up of discrete channel-fill and fining-upward units of variable thickness. The base of each unit lies on an erosion surface of varying relief, overlain by lenses and thin beds of poorly sorted conglomerate with planar or low-angle cross-stratification. A scatter or string of disc-shaped siltstone clasts is common where conglomerate is absent. The overlying sandstones are generally well-sorted and preserve an upward progression of sedimentary bed types reflected in the decrease in grain size, from planar and trough cross-stratification through low-angle cross-beds to horizontally bedded and laminated beds with parting lineation, passing up into ripple cross-lamination showing common re-activation surfaces. This sequence is rarely found in full and is commonly truncated by an erosion surface and overlain by a succession of units displaying one or more of the bed types.

Poorly preserved plant fragments commonly occur in the coarser-grained sandstones, scattered along the bases of troughs. Concentrations of more comminuted plant debris are found at the tops of laminated beds. Similarly, fish fragments occur in basal conglomerates and coarse-grained sandstones, with better-preserved specimens occurring in the laminated beds. Burrows occur in the troughs of ripples. Palaeocurrents are variable, but have a predominantly southerly drainage direction.

The sandbodies grade up into fine-grained, micaceous beds up to 4.5 m thick. These are dominated by green, very fine-grained sandstones and green siltstones with subordinate thinner beds of intercalated green and red siltstones. In thicker developments, these pass up into red siltstone beds. Strong parallel lamination is dominant, with coarser-grained layers displaying low-relief undulations or low-amplitude ripple-lamination, sporadically disturbed by bioturbation. Some thicker red siltstones contain weakly developed pedogenic features.

Interpretation

The lithologies and facies displayed in the lower part of the succession in Cusop Dingle represent the distal component of an extensive fluvial system, deposited in a semi-arid climate. The environment is interpreted as a broad, low-relief aggradational alluvial-floodplain, largely composed of silt and crossed by shallow, through-flowing, sandy river channel systems. Mica-rich sediments and distinctive suites of heavy minerals suggest that the source of sediments was the metamorphic terrane of north-west Britain (Allen, 1974c).

The two types of sandstone bodies correspond to different types of fluvial drainage across the area. The thicker sandbodies represent channels of the main distributary systems. These were high-sinuosity, laterally migrating rivers that deposited broad bar forms and low-relief dunes and were subject to highly variable discharge rates, with channels drying completely at some times. Frequent flooding caused water to spill on to low-gradient interfluve areas, resulting in shallow outbreak channels and poorly channelized or unconfined ephemeral flows from which the thinner, sheet-like sandstone bodies were deposited (e.g. Williams and Hillier, 2004). The vertical distribution of the sandstone bodies and the development of pedogenic horizons suggest regular avulsion of the main channels, over distances of several kilometres (Love and Williams, 2000).

The packages of siltstones record episodes of subaqueous deposition interspersed with significant periods of subaerial exposure and pedogenesis. Thick sequences of well-laminated siltstones indicate frequently repeated and rapid inundation of the floodplain by shallow sheets of water followed by very short intervals of subaerial exposure. In some instances the sediment remained damp enough for colonization by burrowing invertebrates, although the bioturbation density is generally low, suggesting that residence time was limited by relatively rapid sedimentation rates. Marriott and Wright (2004) suggest that burrowed laminated facies in stratigraphically equivalent beds in Pembrokeshire may indicate more prolonged periods of subaqueous deposition in semi-permanent lakes formed in depressions in the floodplain. Long interruptions to these aggradational periods are recorded by desiccation cracks and other pedogenic features, which show that sedimentation rates slowed or stopped and the floodplain frequently dried out. Variation in the maturity of the pedogenic features and calcrete palaeosols indicates non-depositional periods of the order of between 500 and 30 000 years (Retallack, 1990). The main 'Psammosteus' Limestone represents the longest hiatus in sedimentation, for which Allen (1985) proposed a maximum period of 30 000 years. He postulated that the 'Psammosteus' Limestone facies records the commencement of final uplift of the former Welsh Basin and Irish Sea Ridge, producing a change in sediment provenance and depositional style. During this time, the Anglo-Welsh Basin was sediment-starved and effectively shut down. The Townsend Tuff Bed is evidence of a Plinian-type eruption that deposited volcanic ash across the floodplain. It is widespread throughout Pembrokeshire, central south Wales and the Welsh Borderland, providing a valuable stratigraphical marker horizon across the Anglo-Welsh Basin (Allen and Williams, 1981a). Its source is not known, although Allen and Williams (1981a) suggested it might have been either to the west or east along the strike line of the developing Rheic Ocean, with dispersal by winds from one of these directions.

The succession above the main 'Psammosteus' Limestone shows the change in depositional style consequent on the uplift to the north-west (Allen, 1985). This resulted in the establishment of predominantly fluvial conditions on a more proximal floodplain characterized in part by laterally accreting, sinuous, meandering rivers draining southwards (cf. Williams and Hillier, 2004). The overall climate may have become wetter, the region experiencing sub-tropical monsoonal conditions.

The sandstone bodies display the fining-upward features of point-bar deposits, arranged in (incomplete) multi-storey packages with common erosion surfaces and repetition of bedsets, which would be expected from lateral, downstream meander migration during aggradation (Bridge and Diemer, 1983). The prevalence of parallel-laminated beds suggests currents of relatively large stream power. Cross-cutting re-activation surfaces within ripple cross-laminated beds point to frequent fluctuations in water-levels. Individual bedsets were probably deposited during individual, major, flood events, but the rivers were perennially charged. The regularity of siltstone clasts in basal conglomerates and cross-beds and the low proportion of siltstone to sandstone indicate regular reworking of the floodplain. The increased amounts of plant material suggests more favourable conditions for plant growth, with stands of vegetation growing on the flood-plain marginal to the channels. The dominance of the green and grey colour of the lithologies suggests that the area experienced relatively high water-tables during this period.

Conclusions

The stream sections in the Dulas Brook and its tributaries, the Crigiau Stream and Esgryn Brook, expose approximately 215 m of vertical succession, making up the most continuous and representative section of the late Přídolí–early Devonian Old Red Sandstone succession in the Welsh Borderland and Black Mountains area. The sections provide evidence of the changing conditions in the Lower Old Red Sandstone Anglo-Welsh Basin, illustrating a shift in environment from low-lying mudflats created by ephemeral distributary channels at the distal end of a river system, through a hiatus in sedimentation to alluvial plains dominated by perennially charged meandering rivers. The section includes exposure of two important stratigraphical marker beds in the Lower Old Red Sandstone, the volcanic Townsend Tuff Bed and the main 'Psammosteus' Limestone, which allow correlation and comparison with other Lower Old Red Sandstone outcrops in the Anglo-Welsh Basin.

SAWDDE GORGE, POWYS (SN 729 245–SN 733 237)

P.R. Wilby

Introduction

The section described here lies in the Afon Sawdde gorge in Powys, south-central Wales, and is an extension to the 2 km-long section of strata of Llandovery to Ludlow age described in the companion GCR volume on Silurian stratigraphy (Aldridge *et al.*, 2000). It commences at Pont-ar-llechau bridge (SN 7285 2448) and extends for approximately 1 km upstream (Figure 5.16). Almost complete exposure in the bed and banks of the Afon Sawdde provides one of the most continuous sections in Wales and the Welsh Borderland through the upper part of the Ludlow Series, all of the Přídolí Series and the basal part of the lower Devonian (Lochkovian) succession. Crucially, it includes a complete section through the early Přídolí Tilestones Formation (the Long Quarry (Sandstone) Formation of Potter and Price, 1965), a probable lateral equivalent of the Downton Castle Sandstone Formation of the Welsh Borderland. The southern boundary of the original GCR site extended 150 m upstream of Pont-ar-llechau bridge, but it is recommended that it should be extended southwards to beyond Turkey Cottage (SN 7331 2365) to include the basal part of the St Maughans (Llanddeusant) Formation. It is a key section in the study of the nature and the

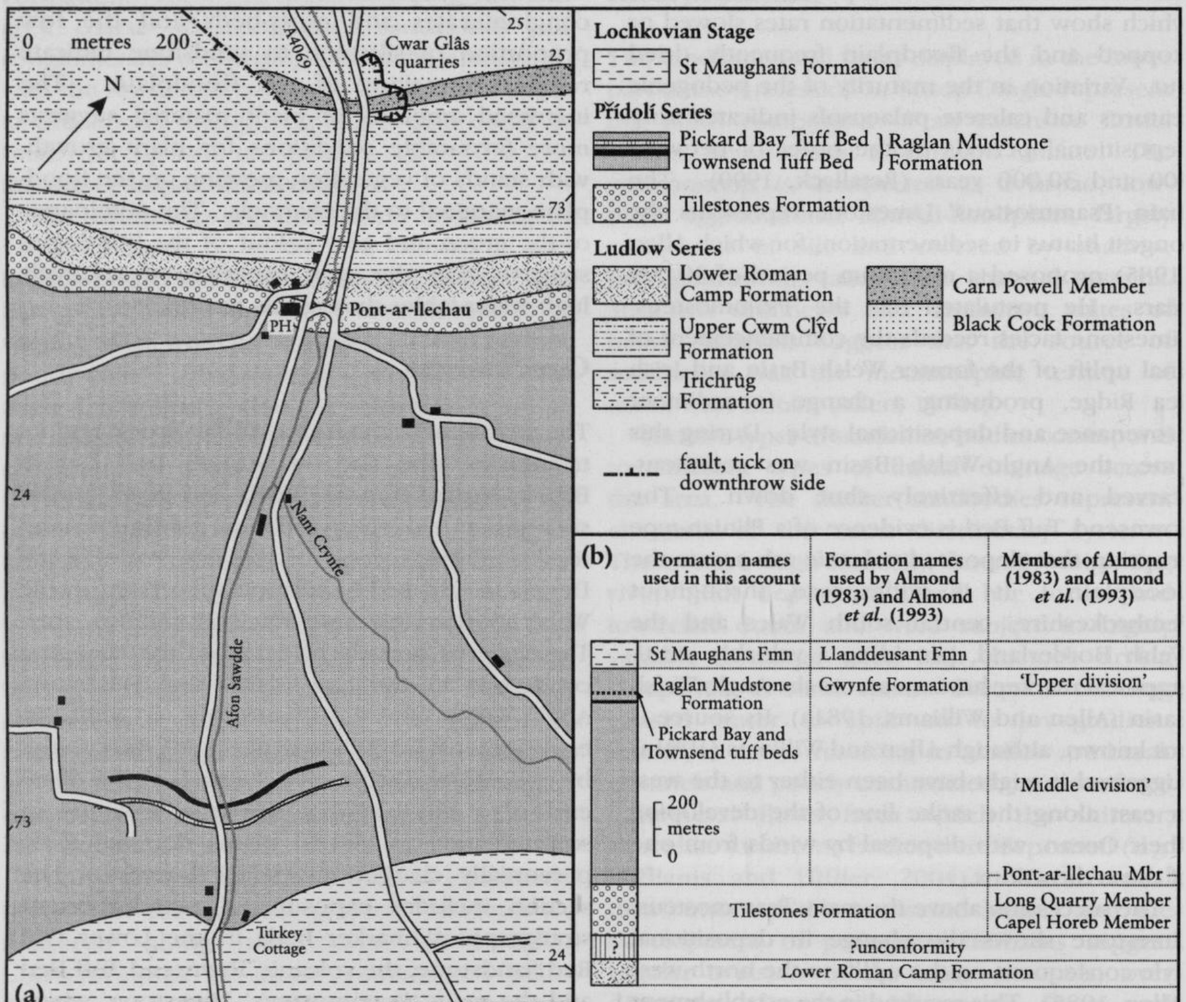


Figure 5.16 Geology of the upper part of the Sawdde Gorge: (a) – geological sketch map (north-west part after Derek J. Siveter, 2000); (b) – lithostratigraphical classification of the succession.

timing of the late Silurian marine to terrestrial transition. In addition, it is important for the interpretation of the depositional environments of the rocks exposed. It also provides one of the few inland exposures of the stratigraphically important Townsend Tuff Bed (Allen and Williams, 1981a), as well as the younger Pickard Bay Tuff Bed and a number of other lesser tuffs.

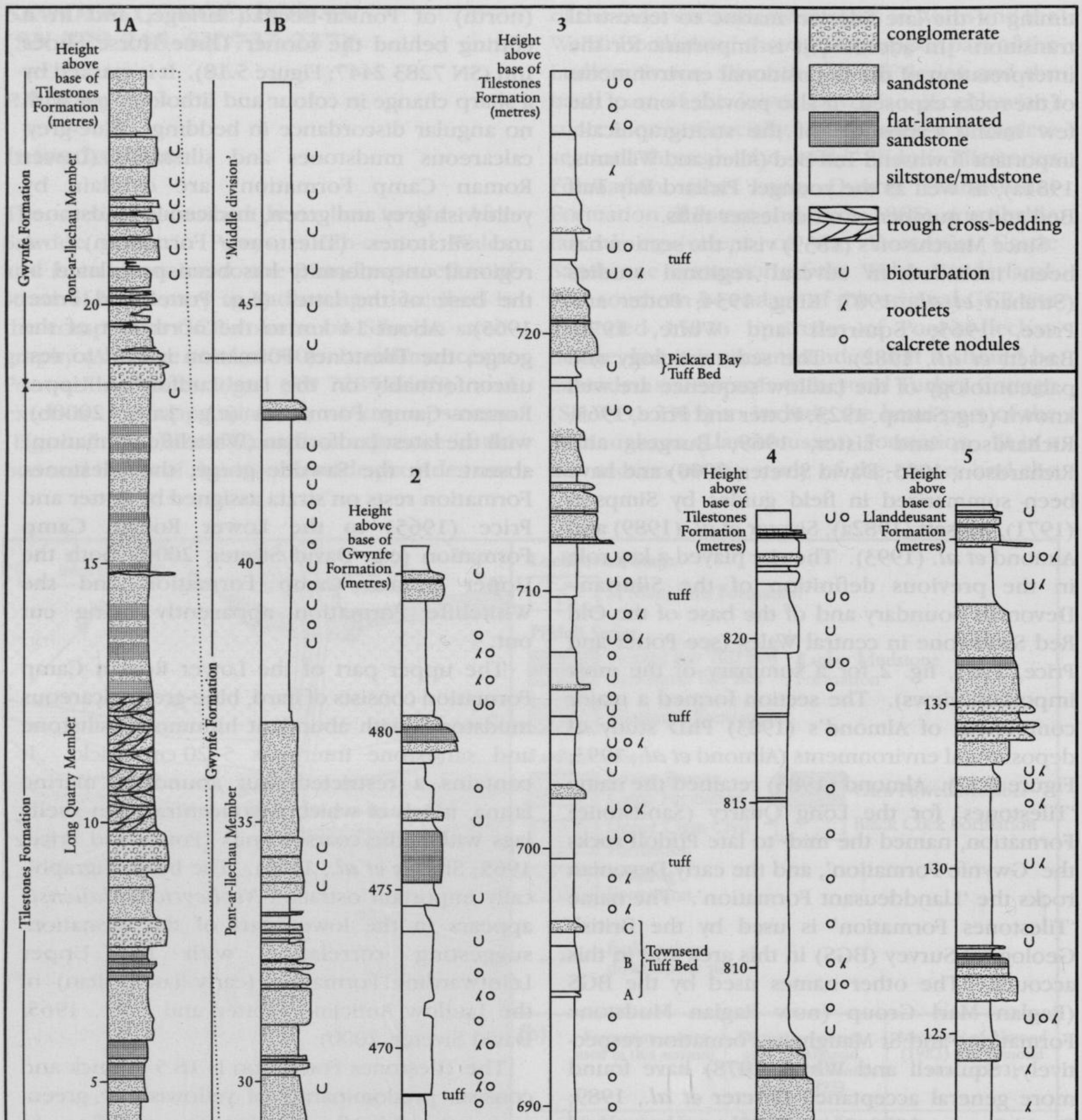
Since Murchison's (1839) visit, the section has been included in several regional studies (Strahan *et al.*, 1907; King, 1934; Potter and Price, 1965; Squirrell and White, 1978; Bassett *et al.*, 1982). The sedimentology and palaeontology of the Ludlow sequence are well known (e.g. Stamp, 1923; Potter and Price, 1965; Richardson and Lister, 1969; Burgess and Richardson, 1995; David Siveter, 2000) and have been summarized in field guides by Simpson (1971), Bassett (1982a), Siveter *et al.* (1989) and Almond *et al.* (1993). The site played a key role in the previous definition of the Silurian–Devonian boundary and of the base of the Old Red Sandstone in central Wales (see Potter and Price, 1965, fig. 2 for a summary of the most important views). The section formed a major component of Almond's (1983) PhD study of depositional environments (Almond *et al.*, 1993; Figure 5.17). Almond (1983) retained the name 'Tilestones' for the Long Quarry (Sandstone) Formation, named the mid- to late Přídolí rocks the 'Gwynfe Formation', and the early Devonian rocks the 'Llanddeusant Formation'. The name 'Tilestones Formation' is used by the British Geological Survey (BGS) in this area and in this account. The other names used by the BGS (Raglan Marl Group (now Raglan Mudstone Formation) and St Maughans Formation respectively; Squirrell and White, 1978) have found more general acceptance (Siveter *et al.*, 1989; David Siveter, 2000; Lane, 2000b) and are used in this account. Figure 5.16 shows these and the names erected by Almond. Most recently, Jenkins (1998) examined the uppermost part of the section in an attempt to establish the extent of marine influence on Old Red Sandstone deposition around the Silurian–Devonian boundary in the Anglo-Welsh Basin.

Description

The strata in the gorge dip steeply (up to 70°) towards the SSE. The base of the Old Red Sandstone (and of the Tilestones Formation) is exposed in the river bed 4 m downstream (north) of Pont-ar-llechau bridge, and in a cutting behind the former Three Horse Shoes Inn (SN 7283 2447; Figure 5.18). It is marked by a sharp change in colour and lithology, but with no angular discordance in bedding. Blue-grey, calcareous mudstones and siltstones (Lower Roman Camp Formation) are overlain by yellowish grey and green, micaceous sandstones and siltstones (Tilestones Formation). A regional unconformity has been postulated at the base of the latter (e.g. Potter and Price, 1965). About 14 km to the north-east of the gorge, the Tilestones Formation is said to rest unconformably on the late Ludfordian Upper Roman Camp Formation (e.g. Lane, 2000b), with the latest Ludfordian (Whitcliffe Formation) absent. In the Sawdde gorge, the Tilestones Formation rests on strata assigned by Potter and Price (1965) to the Lower Roman Camp Formation (e.g. David Siveter, 2000), both the Upper Roman Camp Formation and the Whitcliffe Formation apparently being cut out.

The upper part of the Lower Roman Camp Formation consists of hard, blue-grey, calcareous mudstones with abundant hummocky siltstone and sandstone interbeds 5–20 cm thick. It contains a restricted, but abundant, marine fauna, much of which is concentrated in shelly lags within the coarser units (Potter and Price, 1965; Siveter *et al.*, 1989). The biostratigraphically important ostracod *Neobeyrichia lauensis* appears in the lower part of the formation, suggesting correlation with the Upper Leintwardine Formation (early Ludfordian) of the Ludlow Anticline (Potter and Price, 1965; David Siveter, 2000).

The Tilestones Formation is 18.5 m thick and consists predominantly of yellowish or green-grey, mica-rich, flaggy siltstones and fine- to medium-grained sandstones. A 0.5 m-thick mudstone occurs near the base. Bedding is conspicuously thicker (0.15–0.5 m) than that in the Lower Roman Camp Formation. A limited faunal assemblage includes brachiopods (e.g. *Lingula minima*, *Protochonetes ludloviensis* and *Microsphaeridiorhynchus nucula*) (Potter and Price, 1965; Almond, 1983), bivalves (e.g. *Modiolopsis complanata*), gastropods (e.g. *Turbochelius helicites*, *Loxonema gregaria*), crinoid ossicles, nautiloids (*Orthoceras* sp.), carbonaceous plant fragments and an assemblage of kloedinine beyrichiacean ostracods (Siveter *et al.*, 1989; David Siveter, 2000). Most


1A
1B
3
2
4
5
Height above base of Tilestones Formation (metres)
Height above base of Gwynfe Formation (metres)
Height above base of Landdeusant Formation (metres)
Gwynfe Formation
Pont-ar-llechau Member
Long Quarry Member
Tilestones Formation
Capel Horeb Member
Lower Roman Camp Formation
Middle division
Gwynfe Formation
Pont-ar-llechau Member
gap
tuff
Pickard Bay Tuff Bed
Townsend Tuff Bed
A
B
silt
sand
conglomerate
conglomerate
sandstone
flat-laminated sandstone
siltstone/mudstone
trough cross-bedding
bioturbation
rootlets
calcrete nodules

◂**Figure 5.17** Graphic logs of parts of the Old Red Sandstone succession in the Afon Sawdde. 1A,1B – continuous section of the Tilestones Formation and basal part (Pont-ar-llechau Member) of the Gwynfe (Raglan Mudstone) Formation (SN 7282 2452–SN 7286 2449); 2 – part of the 'Middle Division'of the Raglan Mudstone Formation (SN 7308 2400); 3 – part of the 'Middle Division' containing the Townsend Tuff Bed and Pickard Bay Tuff Bed (SN 7325 2385); 4 – section typical of the 'Upper Division' of the Raglan Mudstone Formation (SN 7330 2381–SN 7332 2372); 5 – section typical of the St Maughans Formation (SN 7340 2364). After Almond *et al.* (1993). Note that the logs have different scales.

of the sandstones are planar laminated or low-angle cross-laminated, some have bases resting on erosion surfaces. Many contain concentrations of shell fragments, green intraformational mudstone clasts (up to 3 cm) and faecal pellets; rare acid igneous clasts also occur. Locally, particularly near the top of the formation, communities of bivalves are preserved in life position and, in some of the thinner beds, burrowing (*Skolithos* sp.) destroyed all of the original sedimentary structures.

To the south-west of the Afon Sawdde, the Tilestones Formation is overstepped by the 'Green Beds' (the Capel Berach Beds of Potter and Price, 1965), the local basal unit of the overlying Raglan Mudstone Formation (Squirrell and White, 1978). In the Afon Sawdde, approximately 7 m upstream (south) of Pont-ar-llechau bridge, the formation is conformably overlain by the Raglan Mudstone Formation (Figure 5.17). The basal 26 m (the Pont-ar-llechau Member of Almond, 1983) are distinguished by very fine- to medium-grained, highly quartzitic sandstones with thin green siltstones and mudstones. The lowest 5 m of these comprise an upward-coarsening sequence of stacked, grey and green-grey, micaceous sandstones, which preserve horizontal to low-angle cross-lamination where not homogenized by bioturbation. *Skolithos* burrows are preserved locally and a bedding plane near the top exposes large *Fucusopsis*-type burrows. Some of the sandstones are composite bodies. Many of them rest on erosion surfaces, their bases containing scattered quartz granules, intraformational mudstone clasts

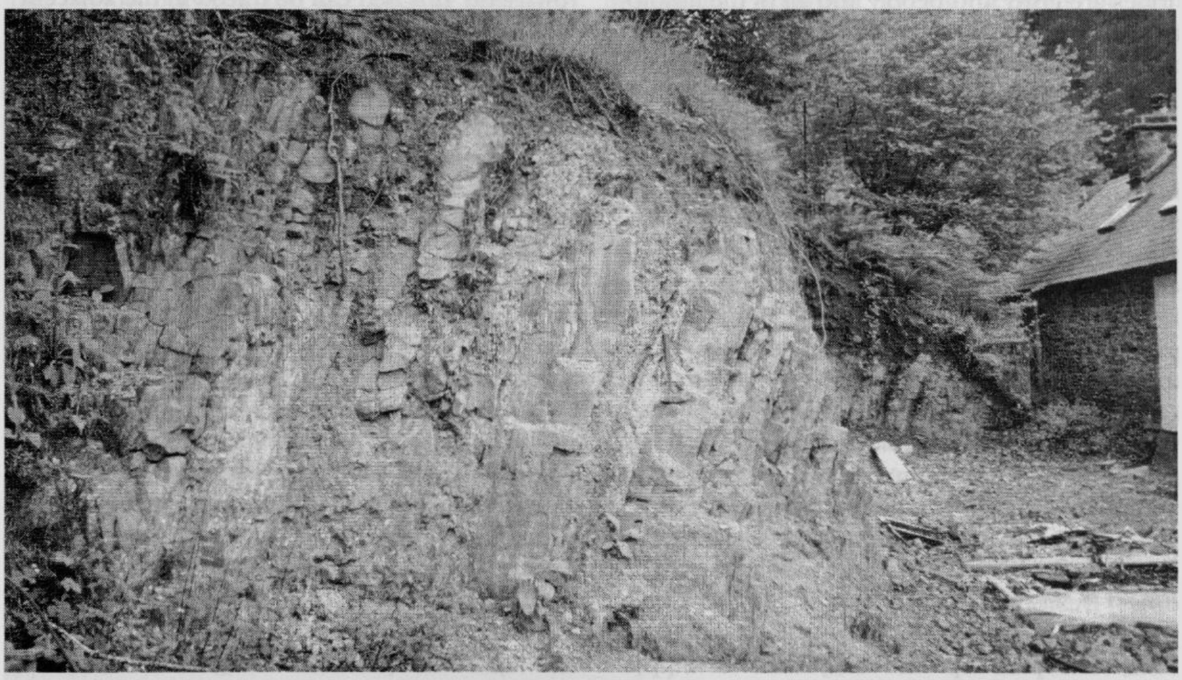


Figure 5.18 Section behind the former Three Horse Shoes Inn (SN 7283 2447) exposing the junction of the basal beds (Capel Horeb Member of Almond *et al.*, 1993) of the Tilestones Formation and the underlying topmost beds of the Lower Roman Camp Formation. The hammer marks the junction. (Photo: R.A. Waters.)

and/or shell fragments; one shows excellent soft-sediment deformation structures. Interbedded with the sandstones are dull green and yellowish green lenticular siltstones and mudstones.

Above are 15 m of red, micaceous, ripple cross-laminated and wavy bedded, very fine-grained sandstones and homogeneous siltstones and mudstones, some arranged in fining-upward packages. Bioturbation is widespread and the beds have yielded a poor, low-diversity, nearshore, shallow marine fauna, including the brachiopod *Lingula cornea*, the gastropod *Cymbularia carina*, the ostracod *Leperditia* sp., and a range of forms also present in the Tilestones Formation (e.g. *Modiolopsis complanata*, *Turbochelius helicites*, *Lingula minima*) and older strata (*Loxonema conicum*) (Potter and Price, 1965). Almond (1983) recovered a cornua of *Cyathaspis banksi*, an ostracoderm known from the Downton Castle Sandstone Formation (Bassett *et al.*, 1982).

The topmost 6 m of Almond's Pont-ar-llechau Member consists of dull red, massive mudstones and very fine-grained, ripple cross-laminated sandstones interbedded with wavy, flaser and lenticular bedded siltstones. Some of the sandstones are gritty and pebbly and all of the lithologies are commonly intensely bioturbated, with modiolopsids and lingulids seen in life position.

The succeeding 750 m of strata (the 'Middle division' and 'Upper division' of Almond's Gwynfe Formation) are typical of much of the Raglan Mudstone Formation in south and central Wales and the Welsh Borderland. They consist predominantly of massive, bright red, silty mudstones/siltstones with moderately well-developed calcrete profiles, and minor purple, grey and pink, fine- to medium-grained, lithic sandstones. The sandstones are typically 1 m to 3 m thick, locally pebbly, and have sharp bases resting on erosion surfaces. Internally, they generally show a fining-upward trend, with planar cross-bedding at the base passing up into horizontal lamination and ripple cross-lamination with lenticles of siltstone and mudstone at the top. Desiccation cracks and Skolithoform burrows are common at their tops, and some sandstones pass up into thin units of ripple cross-laminated silty mudstone.

Except for trace fossils, particularly *Beaconites antarcticus*, the 'Middle division' and 'Upper division' of the Raglan Mudstone Formation are poorly fossiliferous and have yielded only a few specimens of *Modiolopsis* sp., *Pachytheca* sp. and disseminated plant debris. Airfall tuffs are common (Almond, 1983; Almond *et al.*, 1993), the thickest of nine recorded being the Townsend Tuff Bed (2.9 m). As at **Little Castle Head** (see GCR site report, this chapter; Lane, 2000c), and at most localities in south-central Wales (Allen and Williams, 1981a), the Townsend Tuff Bed comprises three closely spaced airfall tuffs (A, B and C), which are sheared here. Fall A (0.25 m) is a muddy dust tuff with its upper surface characteristically strewn with faecal pellets. Fall B comprises fine-grained, cream, purple and yellow, crystal- and crystal-lithic tuff passing up into a siliceous dust tuff. It is truncated by an erosion surface overlain by Fall C, which consists of coarse- to medium-grained crystal-lithic tuff grading up into dull red and green mottled dust tuff. A tuff 23 m above is correlated by Almond (1983) with the Pickard Bay Tuff Bed of south Pembrokeshire. It is 0.75 m thick and consists of two superimposed tuffs, the lower fine-grained and crystal-lithic, the upper a muddy dust tuff. Both the Townsend and Pickard Bay Tuff beds outcrop in weathered recesses on the west bank of the river (*c.* SN 7325 2385) and the outcrop of the Townsend Tuff Bed can be traced in the adjacent field in a waterlogged gully.

Although still dominated by mudstones, the overlying 100 m of strata (the 'Upper division' of Almond, 1983) show a general coarsening-upward trend, through an increase in the thickness and the frequency of the sandstones, until the base of the St Maughans Formation is reached about 20 m south of Turkey Cottage. Almond (1983) and Jenkins (1998) identified two types of cyclic facies sequences in these beds. The first (5–8 m thick) comprises sandstones above a basal erosion surface, fining upwards through trough- and low-angle cross-bedded, fine- to medium-grained sandstones into micaceous, planar-laminated siltstones (up to 1.5 m thick) and then blocky siltstone with calcrete nodules. The second (4.4–8.7 m thick) is characterized by a coarsening- and then fining-upward trend. Typically, it consists of ripple cross-laminated siltstone (0.3–1 m thick) overlain by low-angle and trough cross-bedded sandstones (2.5–3 m thick) that fine upwards into thin (up to 1 m), planar-laminated and ripple cross-laminated siltstones. These are in turn overlain by a micaceous, blocky siltstone unit (up to 4.6 m thick), commonly containing calcrete nodules.

There are numerous moderately mature calcrete horizons in the uppermost beds of the Raglan Mudstone Formation, although the thick limestone development of the Psammosteus (Bishop's Frome) Limestone as seen elsewhere is absent. A 10.2 m-thick horizon of siltstone with calcrete nodules (Stage I–II calcrete of Machette, 1985) 10–20 m south of Turkey Cottage (SN 733 238) marks the top of the formation (Jenkins, 1998).

The basal 36 m of the St Maughans (Llanddeusant) Formation consists of interbedded sandstones and siltstones with minor conglomerates arranged in three fining-upward sequences (Jenkins, 1998). The sandstones include some laterally accreted units. The conglomerates rest on erosion surfaces and are intraformational, except for four thin (2–7 cm) extraformational beds near the base of the formation, which have small (up to 5 mm) quartz pebbles in addition to intrabasinal mudstone and siltstone clasts (Jenkins, 1998).

Interpretation

The period between the late Ludlow and late Přídolí was one of dramatic palaeogeographical and environmental change within the Welsh Basin (Woodcock, 2000b). The differentiation between basin and shelf that had existed throughout Ordovician and Silurian times (Holland and Lawson, 1963; Cherns, 1988) broke down as Avalonia finally docked with Laurentia, initiating basin inversion (Allen, 1985; Woodcock and Gibbons, 1988). The Sawdde Gorge is situated on the south-east flank of the Tywi Anticline, a major Caledonian lineament which formed part of a fault system that defined the southern margin of the basinal area (Woodcock and Gibbons, 1988). To the south of the fault system, the strata of the Ludlow Series formed mainly in shallow shelf and nearshore marine environments and show an overall shallowing trend that culminated in a regional hiatus at the base of the Přídolí Series (Bassett, 1982a; David Siveter, 2000).

This unconformity (Straw, 1930; Walmsley, 1962; Squirrell and White, 1978; Bassett *et al.*, 1982) is placed at the base of the Tilestones Formation in the Sawdde Gorge (Potter and Price, 1965; David Siveter, 2000), although there is no angular discordance and no basal lag deposit, as reported elsewhere at this level.

The Tilestones Formation is interpreted as the product of shallow marine deposition, probably sourced in part from volcanic rocks to the south-west (Allen, 1985; cf. Almond, 1983). Sedimentation occurred in a range of nearshore to marginal marine and lagoonal settings against the NW–SE-trending shore of the 'Pretannia' landmass to the south (Potter and Price, 1965; Squirrell and White, 1978; Cope and Bassett, 1987). Almond (1983) interpreted the basal 3 m (the Capel Horeb Member) as the deposits of a brackish-water lagoon or protected shallow marine embayment, the sandstones representing washover storm events.

The upward increase in grain size and frequency of higher-energy bedforms were interpreted by Almond (1983) to be caused by increased wave action, or by encroachment of a tidal-flat complex into the area. Above is a transgressive sequence of lower to middle shoreface sediments (the Long Quarry Member of Almond, 1983) that were deposited on a high-energy coastline periodically affected by storm waves. The shelly sandstones were possibly the deposits of tidal channels.

Almond (1983) interpreted much of the Raglan Mudstone Formation as the deposits of the lower reaches of a muddy, low-lying coastal plain (cf. Allen, 1985). However, the basal 5 m (of the Pont-ar-llechau Member) are interpreted by her as the infilling of a shallow lagoon by washover sheet sands. The succeeding 15 m-thick, heterolithic sequence is interpreted as the deposits of small tidal channels. The uppermost 6 m of the Pont-ar-llechau Member are interpreted as a stacked, generally regressive sequence of subtidal to supratidal deposits, the latter containing evidence of pedogenesis in the form of small calcrete nodules.

The sandstones in the succeeding mudrock-dominated, calcrete-prone 'Middle division' and 'Upper division' are interpreted by Almond (1983) as the deposits of low- to moderately sinuous river channels, perhaps subjected to tidal influence. The calcretes point to carbonate soil formation on the alluvial floodplain. Jenkins (1998) distinguished fining- and coarsening-upward sequences in the uppermost 100 m of the Raglan Mudstone Formation, emphasizing the importance of rapid run-off, variable discharge and the flashy nature of sedimentation in the Old Red Sandstone. The fining-upward sequences are interpreted as the bars and fills of wide, shallow channels prone to overtopping, the overlying sediments probably being deposited during one discharge event. Siltstone-based, coarsening-upward sequences may have been the products of flood events, with initial deposition of silt from dense hyper-concentrated sediment- and soil-rich flood waters followed by sand deposition from streams derived from the upper catchment.

The absence of a thick, mature calcrete at the top of the Raglan Mudstone Formation equivalent to the Psammosteus Limestone was ascribed by Almond *et al.* (1993) to more continuous subsidence and sedimentation in this area, perhaps controlled by movement on the nearby Carreg Cennen Disturbance (Cope, 1979).

The St Maughans Formation represents a range of fluvial channel, overbank and floodplain facies similar to those at the top of the Raglan Mudstone Formation, but with channelized sandstones becoming thicker and more common at the expense of both finer-grained overbank and sheet-flood sandstones and argillaceous calcretized floodplain mudrocks. A thin, siltstone-based, coarsening-upward unit at the base of the formation may have been the deposit of a two-peak, single discharge event similar to those in the Raglan Mudstone Formation.

Conclusions

The Sawdde Gorge site provides a unique transect through the Silurian and Early Devonian rocks of south-central Wales. Together with the sections through earlier Silurian rocks described in the GCR volume on Silurian stratigraphy (Aldridge *et al.*, 2000), the site and recommended extension present one of the most complete successions through the Silurian strata of the Welsh Basin and succeeding Old Red Sandstone of the Anglo-Welsh Basin. The part described here is a key section in the understanding of the transition from late Silurian offshore marine to littoral and terrestrial environments. The nature of the junction between the rocks representing the offshore and littoral environments warrants further examination. The site is one of only a handful of inland exposures of the stratigraphically important Townsend Tuff Bed. The recommended extension to the GCR site provides a complete section through the late Silurian (Přídolí Series) Raglan Mudstone Formation into the early Devonian St Maughans Formation, and provides an opportunity for further investigation of the Silurian–Devonian boundary.

PANTYMAES QUARRY, POWYS (SN 914 265)

Potential GCR site

W.J. Barclay

Introduction

Pantymaes Quarry, 3 km south of Sennybridge, Powys (Figure 5.19) is an important site in providing a superb inland exposure of a fluvial sandstone complex within the St Maughans Formation of the Lower Old Red Sandstone. The level of exposure has allowed a detailed analysis of the facies and sedimentology of the sandstone unit (Owen and Hawley, 2000). The quarry is also internationally known for its early arthropod trackways (Smith *et al.*, 2003).

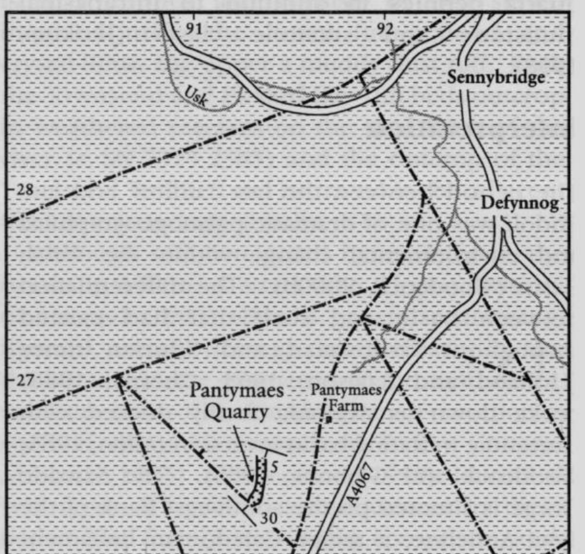


Figure 5.19 Geological map and location of Pantymaes Quarry. After British Geological Survey 1:50 000 Sheet 213 (England and Wales), Brecon (in press).

Description

The long-abandoned Pantymaes Quarry (Figure 5.20) exposes a main face 25 m high and 275 m long in strata belonging to the Lower Old Red Sandstone. It has been described in detail and interpreted by Owen and Hawley (2000). These authors referred the section to the upper (Dittonian) Red Marl Group; more recent mapping by the British Geological Survey (Barclay *et al.*, in press) assigns it to the St Maughans Formation, of Lochkovian age. A description of arthropod myriapod trackways at the quarry has been given by Smith *et al.* (2003), who also provide sedimentological logs of eight vertical transects along the quarry face. Hassan (1982) carried out a palynological study.

The strata dip gently southwards in most of the quarry, but are horizontal along a synclinal axis in the southern part, with north-easterly dips to its south in the hanging-wall of a small NW-trending fault at the southern end of the quarry (cf. Owen and Hawley, 2000). The succession comprises a lower sandstone unit (the Sandstone Facies Association of Owen and Hawley, 2000) up to about 15 m thick (its base is not exposed) and an overlying red mudstone about 15 m thick (the Mudstone Facies Association of Owen and Hawley) (Figure 5.21). An erosion surface separates these units. Thin sandstone beds overlie the mudstone unit at the top of the quarry face.

The following account summarizes that of Owen and Hawley (2000). The sandstone unit consists predominantly of grey-green, micaceous, fine- to coarse-grained sandstone (Facies S2 of Owen and Hawley). Bedding is mostly planar, horizontal to gently inclined parallel lamination, with some trough cross-bedding. Erosive bounding surfaces of individual sandstone bodies define a complex of nested channels. Some bodies fine upwards, with intraformational calcrete clast conglomerate lenses (Facies S1 of Owen and Hawley) at the

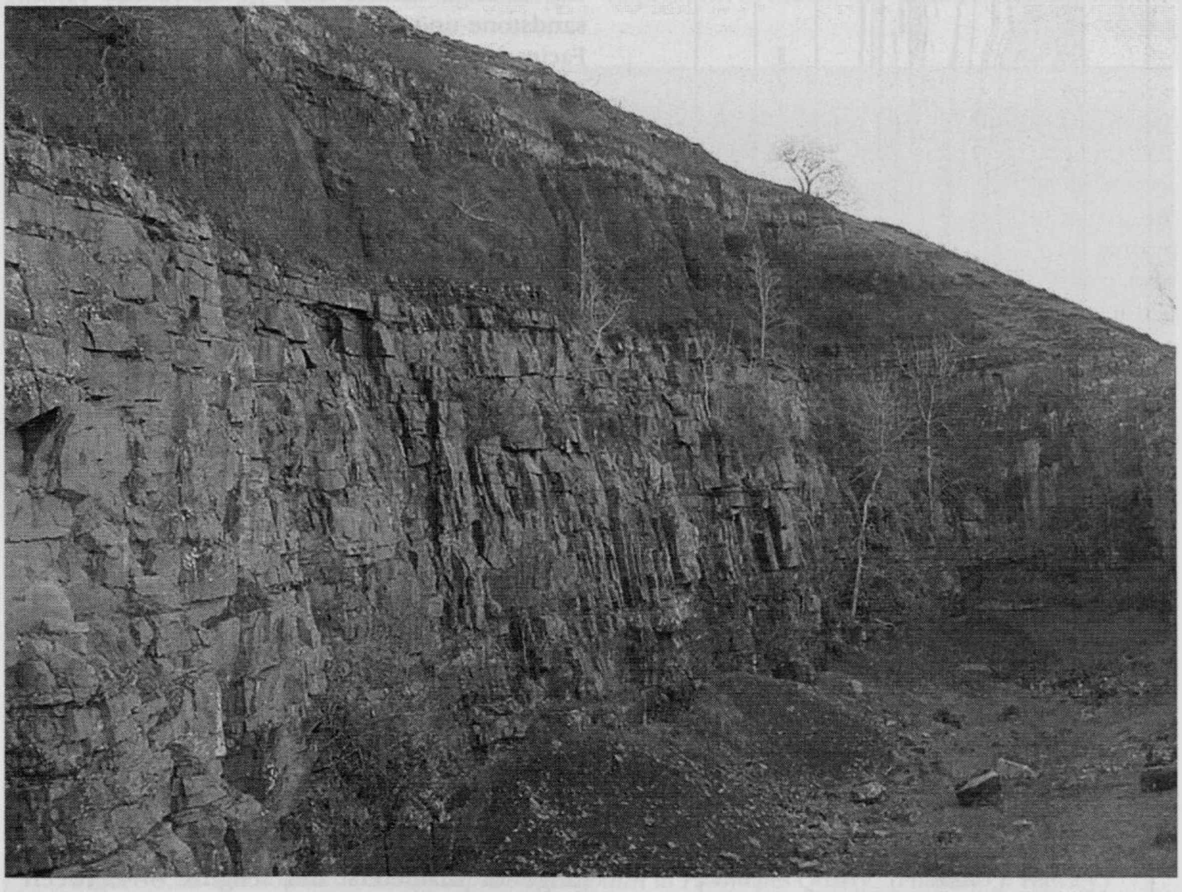
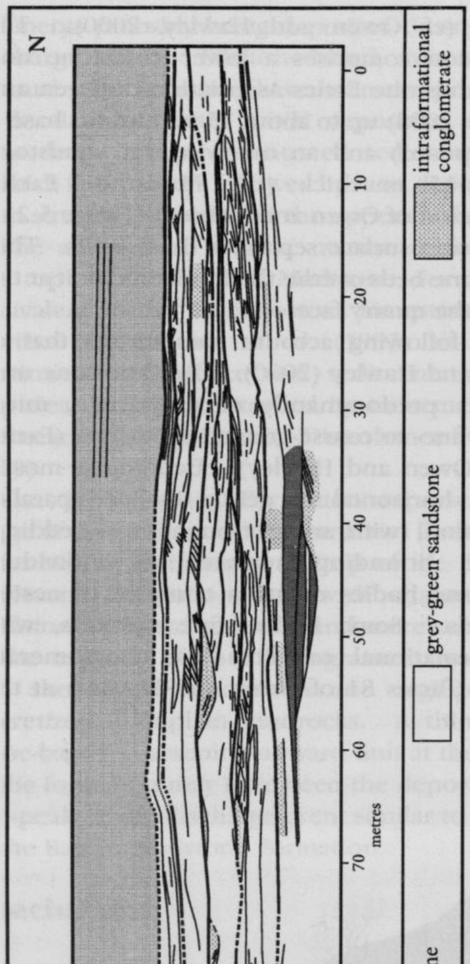


Figure 5.20 Main face of Pantymaes Quarry. Lower sandstones are overlain by mudstones with thin sandstone beds at their top. The lower sandstones are 15 m thick. (Photo: D.J. Hawley.)



◄**Figure 5.21** Main face at Pantymaes Quarry showing the main sedimentary bounding surfaces in the Sandstone Facies Association. After Owen and Hawley (2000).

base and cross-lamination at the top. Plant debris, including *Parka decipiens*, occurs in flaggy, micaceous sandstones and at the bases of fining-upward units. Arthropod tracks are recorded from the finer sandstones. Grey siltstone (Facies S3 of Owen and Hawley) occurs as clasts in intraformational conglomerate and as interbeds up to 1.5 m thick.

The sandstone body is traversed by a series of erosion surfaces, the most extensive of which can be traced for over 100 m. These are major (first-order) bounding surfaces that separate discrete channelized complexes, within which are less extensive second-order erosion surfaces. Five channel complexes (A to D) are recognized and described in detail by Owen and Hawley (2000).

The 15 m-thick red mudstone unit overlying the erosion surface that truncates the lower sandstone unit comprises, in detail, three facies. Facies M1 is a finely laminated mudstone with repeated horizons of bioturbation in the form of vertical burrows and horizons of calcrete nodules. Desiccation cracks are also present and seen best in fallen blocks. Facies M2 is predominant and comprises red, purple and blue, massive, friable mudstone with scattered calcrete nodules and a prismatic to blocky ped structure. There are some shallow, curved, slickensided slip surfaces and bioturbation by *Skolithos*-type vertical burrows. Facies M3 is a succession of upward-fining, red, micaceous siltstone–mudstone units, each about 0.55–0.7 m thick and consisting of a basal centimetre-thick sandstone, weakly cross-laminated, burrowed siltstone, and an upper 0.25–0.35 m-thick bed of upward-fining, intensely bioturbated siltstone–mudstone with thin blue-grey vein-like structures and desiccation cracks. *Skolithos*-type vertical burrows occur in the cross-laminated siltstones, as well as some ovate, horizontal burrows packed with pellets. Lobate sub-horizontal burrows are present at the top of some of the siltstones and arthropod trackways are present on parting surfaces. The topmost units have vertical burrows with a range of diameters and lengths of between

0.25 m and 0.35 m. Arthropod trackways are seen in fallen blocks of facies similar to these units.

The majority of arthropod trackways described in the quarry are seen in an isolated west-facing outcrop in the floor of the quarry. The outcrop is 5 m long and 3 m high and surrounds a pool in the centre of the quarry (Smith *et al.*, 2003). It consists of grey planar-laminated and ripple-laminated, micaceous, fine-grained sandstones and siltstones. The trackways (Figure 5.22) occur in 0.5 m of siltstones, which are overlain by cross-bedded, medium- to coarse-grained sandstones. They are assigned to two types (A and B) of *Diplichnites gouldi*, Type A probably being a kampecarid myriapod and Type B a coarthropleurid myriapod.

Interpretation

The intraformational conglomerate (Facies S1) lenses and beds are interpreted by Owen and Hawley (2000) as the deposits of high-energy channel-fills and bars. The sandstones (Facies S2) are interpreted as the fluvial deposits of braided river channelized flows with variable discharge, the dominance of planar lamination over cross-bedding suggesting a high-energy, perhaps flash-flow regime. Owen and Hawley interpret the grey siltstones (Facies S3) as wet, alluvial-floodplain deposits, high water-table allowing preservation of plant debris. It also allowed preservation of the trackways of the arthropods that inhabited and crawled over the floodplain.

The red mudstone with calcretized horizons (Facies M1) is interpreted as an overbank deposit, its occurrence above the erosion surface that truncates the underlying Sandstone Facies Association suggesting accumulation in an abandoned channel. The limestone nodules are Stage II calcrete soils (Machette, 1985), indicating prolonged carbonate soil formation and a semi-arid, seasonally wet climate. The red, purple and blue calcretized mudstone (Facies M2) represents flood basin overbank deposition of muds, the sediments being subject

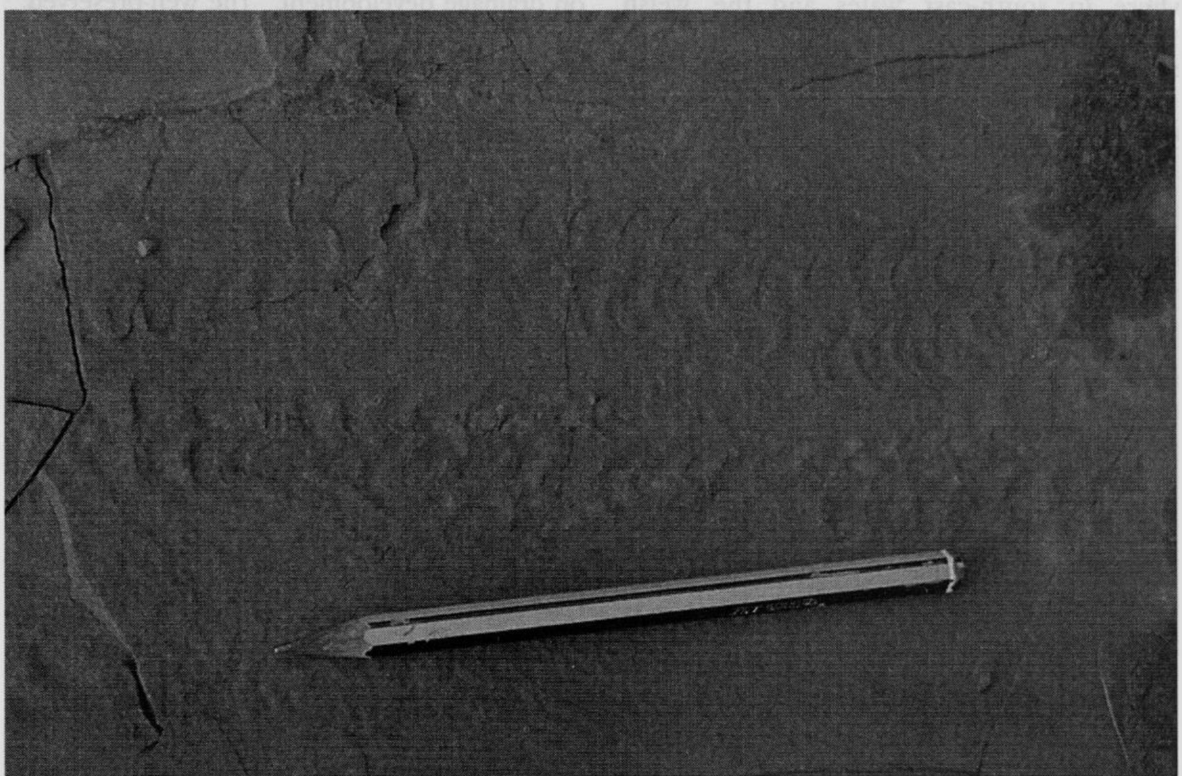


Figure 5.22 Arthropod trackways *Diplichnites gouldi* in Pantymaes Quarry. (Photo: D.J. Hawley.)

to repeated wetting and drying and carbonate soil formation. The upward-fining red siltstone units (Facies M3) are interpreted by Owen and Hawley as flood basin overbank deposits. Marriott and Wright (2004) suggest rapid deposition from crevassing events for similar heterolithic, fining-upward sequences in the Moor Cliffs Formation of Pembrokeshire. These authors stress the importance of deposition of pedogenic mud aggregate bedload-transported sediment in the accumulation of mudrock sequences in the Old Red Sandstone, and a similar origin for some of the mudrocks at Pantymaes is possible. They also suggest the presence of semi-permanent depressions on the floodplain in which ephemeral lakes formed after floods and which trapped dust from frequent dust storms. It is possible that some of the laminated mudstones (Facies M3) may have had a similar origin.

The quarry is important in exposing a sequence of facies that is markedly different from the fining-upward, autochthonous sandstone–mudstone alluvial cycles that characterize the St Maughans Formation elsewhere in south-east Wales and the Welsh Borderland (e.g. Allen, 1963b, 1970) and equivalent successions in Pembrokeshire (Conigar Pit Sandstone Member (Williams *et al.*, 1982) and Gelliswick Bay Formation (Allen and Williams, 1978)). Owen and Hawley (2000) suggest an allocthonous, external, tectonic trigger for the change from the Sandstone Facies Association to the Mudstone Facies Association and the intervening erosion surface.

The channel complexes of the Sandstone Facies Association show major differences in fluvial style, suggesting to Owen and Hawley (2000) that it is not a multi-storey channel sandbody representing the punctuated infilling of a single channel, but that it represents distinct phases of fluvial development. Northward-stepping of successive erosion surfaces in several channel complexes further suggests tectonic control, each complex representing a response of the fluvial system to a pulse of tectonic movement. Owen and Hawley (2000) suggest that the sporadic movements on the Carreg Cennen Disturbance about 2 km to the north-west may have disrupted the general southerly drainage, producing an increase in stream gradient across the fault zone, braiding of the drainage to the south of the fault, and input of coarser intraformational bedload. Dextral strike-slip movement along the fault may have caused the migration of successive channels towards the north. Recent mapping by the British Geological Survey (in press) suggests the presence of several faults of north-east trend between Pantymaes and the Carreg Cennen Disturbance, and these may also have exerted control on sedimentation.

Conclusions

Pantymaes Quarry is a site of national and international importance, and worthy of consideration for protected status. Its conservation value lies in it being almost unique in the Anglo-Welsh Basin in providing a large, accessible inland section of the St Maughans Formation where lateral facies variations in a sandstone complex can be demonstrated. It also shows a style of facies architecture quite different from that seen elsewhere at this level in the basin, perhaps indicating pulsed movement on the nearby Carreg Cennen Fault and local tectonic control on drainage development. The well-preserved, internationally known arthropod traces also merit protection, providing valuable information on our understanding of the earliest known land animals that colonized the alluvial plains of the Early Devonian.

HEOL SENNI QUARRY, POWYS (SN 915 221)

W.J. Barclay

Introduction

Heol Senni Quarry lies on the north-east face of Fan Bwlch Chwyth (Figure 5.23), Powys, 1.8 km south-west of the village of Heol Senni. The quarry provides a fine section of the Lower Devonian Senni Formation, exposing about 40 m of a succession dominated by grey-green sandstones (Figure 5.24). In addition to the site's lithological and sedimentological value, it is the type locality of *Althaspis senniensis*, which is known only from this site, providing unique dating evidence of the Senni Formation. A wide range of fossil plant remains and miospores adds to the site's importance.

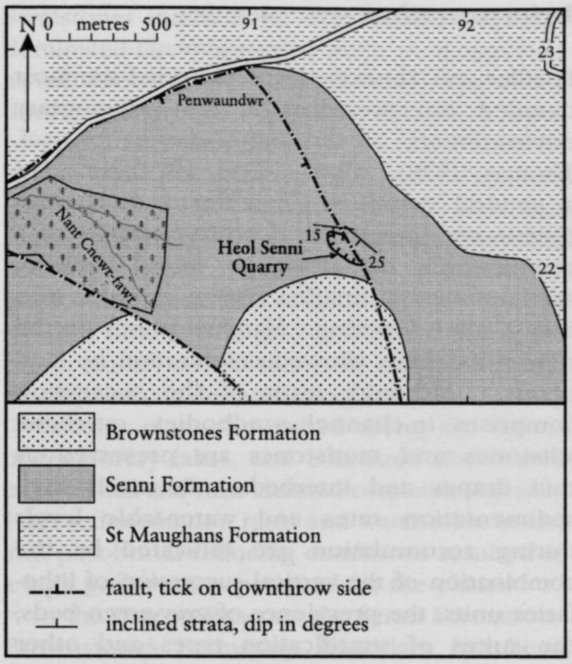


Figure 5.23 Geological sketch map and location of Heol Senni Quarry. After British Geological Survey 1:50 000 Sheet 213 (England and Wales), Brecon (in press).

Description

The quarry was first described by Edwards *et al.* (1978) for a field guide produced for a symposium on the Devonian System. These authors summarized the lithologies, palaeobotany and palynology. During the symposium field visit to the quarry, fossil fish remains (*Althaspis senniensis*) were discovered (Loeffler and Thomas, 1980). Almond *et al.* (1993) gave a brief description of the quarry. The site's importance as a fossil fish locality is detailed in the GCR fossil fishes volume (Dineley and Metcalf, 1999).

The succession comprises grey-green sandstones, with minor siltstones, mudstones and intraformational conglomerates. The beds dip generally about 5° to the SSW. A NW-trending fault, which throws down to the west, cuts the south-east corner of the quarry, producing a steeper (*c.* 25°) south-west dip in its footwall, with dips of 5° in a minor hanging-wall anticline. There is no obvious cyclicity to the arrangement of the facies. The sandstones are fine- to medium-grained, lithic arenites and are generally

Figure 5.24 View looking into the north-west corner of Heol Senni Quarry. (Photo: W.J. Barclay.)

massive, but have low-angle cross-bedding and parallel lamination. The latter is defined by grain size, and mica and carbonaceous concentrations. Some large-scale planar and trough cross-bedding is also evident. The finer-grained sandstones are ripple cross-laminated and linguoid ripple marks are present on some bedding surfaces. The sandbodies overlie erosion surfaces, with lenses of intraformational conglomerates at their base. The conglomerates, most of which are calcitic, contain grey-green siltstone intraclasts up to 450 mm in length and rolled calcrete nodules. No exotic pebbles are recorded. Some sandstone beds are rich in mica and show primary current lineation. Shredded plant debris is also common. Soft-sediment deformation structures are prominent and include a laterally persistent ball-and-pillow unit and large-scale slump folds. The thin mudstone interbeds are mostly grey-green and blue-grey, but red-brown siltstones, some containing calcrete nodules, are present towards the top of the exposed succession. Some of the mudstones have sandstone-filled desiccation cracks.

The quarry is one of only four localities to have yielded fossil fish remains in the Senni Formation discovered to date. The species (*Althaspis senniensis*) is unique to this site (Loeffler and Thomas, 1980; Dineley, 1999f). The other three localities are Primrose Hill Quarry, Crickhowell (White, 1938; Barclay, 1989), which yielded *Rhinopteraspis dunensis* (= *cornubica*), Ferryside, Carmarthenshire, which yielded *Pteraspis dixoni* and *Cephalaspis* sp., and Allt ddu, Brecon (SO 027 242), which yielded *Protopteraspis gosseleti* (Habgood, 2000; Edwards and Richardson, 2004). Dineley (1999f) gave a detailed account of the faunal significance of the Heol Senni site and it is not repeated here.

Plant fragments are common (Edwards *et al.*, 1978). Vascular plant axes several centimetres long, cf. *Sawdonia* and cf. *Cooksonia* are recorded. Edwards *et al.* (1978) recorded well-preserved miospore assemblages from blue-grey siltstone beds. One assemblage from a fissile bed near the top of the succession contains large numbers of distally sculptured *Emphanisporites* specimens and numerous examples of *Apiculiretusispora*. Thomas (1978) recognized over fifty taxa of dispersed miospores. The important constituents of the assemblages are listed by Edwards *et al.* (1978).

Interpretation

Loeffler and Thomas (1980) provided the most detailed interpretation of the sedimentary environments of the Senni Formation (cf. Thomas, 1978). Allen (1974a, 1979) provided a general overview. Loeffler and Thomas (1980) interpreted the deposits as those of a comparatively high-discharge, mixed bedload, sand-dominated, braided stream complex in a medial alluvial setting. Marginal ponds on the river floodplains allowed colonization by land plants. Although most of the succession comprises in-channel sandbodies, overbank siltstones and mudstones are preserved as thin drapes and interbeds. Relatively high sedimentation rates and water-table levels during accumulation are indicated by the combination of the vertical succession of lithofacies units, the prevalence of grey-green beds, the suites of stratification types and other sedimentary structures, and the preservation of the vascular plant remains and miospores.

The in-channel facies recognized include channel lags, channel-fill deposits, units formed by the migration of linguoid, transverse, lateral and rhomboid mid-channel bars and low-amplitude sand waves, bar delta wedges and bar top sequences. Thick, multi-storey sandbodies containing interbeds and/or lenses of intraformational conglomerate that overlie basal erosion surfaces imply repeated channel superposition, filling and excavation. Many channel units are draped by thin mudstones deposited from suspension during waning flood stages. Local, rapid, channel shifting and complete or partial channel abandonment was common. Ponding of flood waters occurred in channel cut-offs and (between stages) in parts of the secondary and tertiary distributaries of the active channel network. This local ponding, combined with decomposition of plant material (with the subsequent lowering of redox potentials), and the presence of reworked calcrete glaebules and calcitized plant fragments, giving high pH and bicarbonate ion concentrations, resulted in the calcification of many channel-lag intraformational conglomerates.

The extra-channel and floodplain sediments comprise proximal and distal crevasse-splay deposits, some possible levee sediments, and thin, fine-grained, fluvio-lacustrine units laid down in temporary floodplain lakes.

Sandstones interbedded with these mudstone-dominated fluvio-lacustrine units are interpreted as incursions of crevasse-splay sands deposited during river-avulsion episodes. The Heol Senni pteraspid may well have been carried from its habitat in the main channel system and deposited within a floodplain lake or channel-fill mud unit during one such flood event. Strongly reducing post-depositional conditions are indicated for most of the fluvio-lacustrine sediments by their typically blue-grey to grey-green colour, and the preservation within them of pyrite nodules, macroplant cuticles and miospores.

Vascular plants flourished along the shores of temporary lakes, and colonized abandoned channel-fills and near-channel overbank deposits. High sedimentation rates and water-table levels, and post-burial reducing conditions resulted in a high preservation potential for the plants.

In the Brecon Beacons the Senni Formation–Brownstones Formation boundary has been drawn at the junction between the predominantly grey-green sequence and the overlying red-brown succession, even though there are apparently no major sedimentological differences between the lithofacies immediately below and above the colour change. The facies also inter-finger locally (Barclay, 1989) and Owen and Hawley (2000) note a similar interfingering of green and red facies in the underlying St Maughans Formation. However, the Brownstones higher in the succession were laid down by sandy braided streams of a more shallow and ephemeral nature than those which deposited the sediments of the Senni Formation (Tunbridge, 1981a).

The Senni Formation is the lithostratigraphical and chronostratigraphical equivalent of the lower and middle portions of the 560–600 m-thick Mill Bay Formation of the Cosheston Group of south-west Wales, which Thomas (1978; Loeffler and Thomas, 1980) and Wellman *et al*. (1998) interpreted as the deposits of a braided–meandering river system. Owen (1995) proposed a similar interpretation for the Senni Formation of the Llansteffan peninsula, suggesting low-sinuosity channels with seasonal flow in a seasonally wet, semi-arid climate.

Loeffler and Thomas (1980) and Dineley (1999f) provided the most comprehensive stratigraphical reviews. The palynomorphs indicate a late Lochkovian to Pragian age and the pteraspid *Althaspis senniensis* is a late Dittonian to Breconian form. The Primrose Hill pteraspid *Rhinopteraspis dunensis* occurs in the type area of the Siegenian (Pragian) stage. This, combined with the Heol Senni pteraspid and the palynomorphs, indicates that the Lochkovian–Pragian boundary lies within the Senni Formation. *Rhinopteraspis dunensis* is taken as the index fossil of the poorly defined, local Old Red Sandstone Breconian stage.

Conclusions

Heol Senni Quarry is of great importance for the sedimentological and stratigraphical information it provides. It has the thickest exposed inland vertical succession of Senni Formation in south Wales. The architecture of the stacked sand-dominated units and the relationship and types of the lithofacies present allow the anatomy of the contemporaneous floodplain and river channel environments to be modelled. Rapid sedimentation and a high water-table subsequent to burial of plant fossils provided high preservation potential and the site has yielded early vascular plant remains, as well as a rich miospore assemblage. The latter is particularly important in strati-graphical correlation in view of the lack of body fossils, except for the discovery at the quarry of the only specimen (the holotype) of the ostracoderm fish *Althaspis senniensis*. This is one of only four localities in the Senni Formation to yield fossil vertebrates, and together with its miospore assemblage, makes the site of great importance, fully justifying its protected status.

CAERAS QUARRY, CARMARTHENSHIRE (SN 607 167)

W.J. Barclay

Introduction

Caeras Quarry, 2 km north-west of the village of Llandybie (Figure 5.25), exposes conglomeratic sandstones at the top of the Brownstones Formation of the Lower Old Red Sandstone. Quartz pebbles predominate in the beds, but some larger pebbles are locally derived and provide evidence of tectonic movements

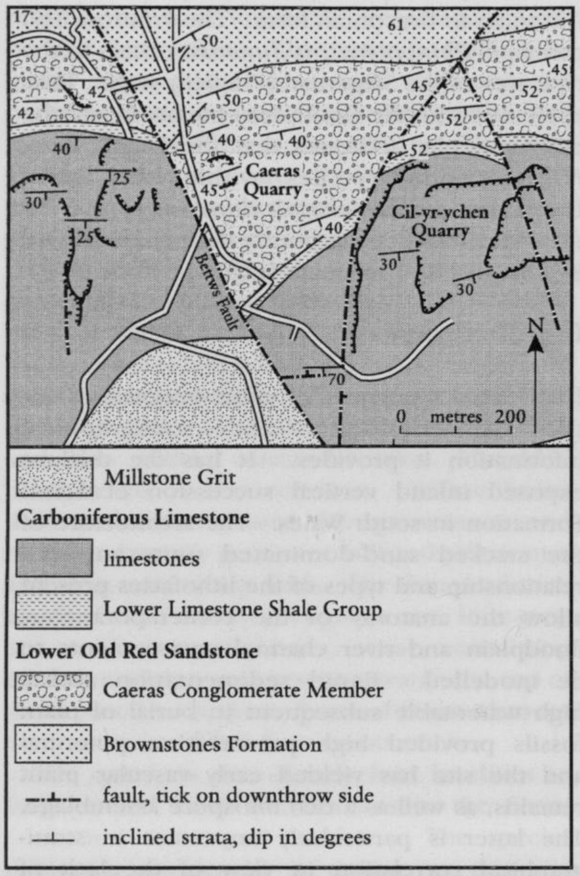


Figure 5.25 Geological map of the area of Caeras Quarry. After British Geological Survey 1:10 560 Sheet SN 61NW (1973).

causing local basement uplift and erosion. This contrasts with most of the Brownstones, which had a source area far to the north. This pebbly facies is only locally developed on the north crop of the South Wales Coalfield at this level, and this quarry provides the best exposure in the area. Similar pebbly sandstones and conglomerates are present to the east around Llyn-y-Fan Fawr (SN 834 216) in the Carmarthen Fans (Tunbridge, 1980a).

Description

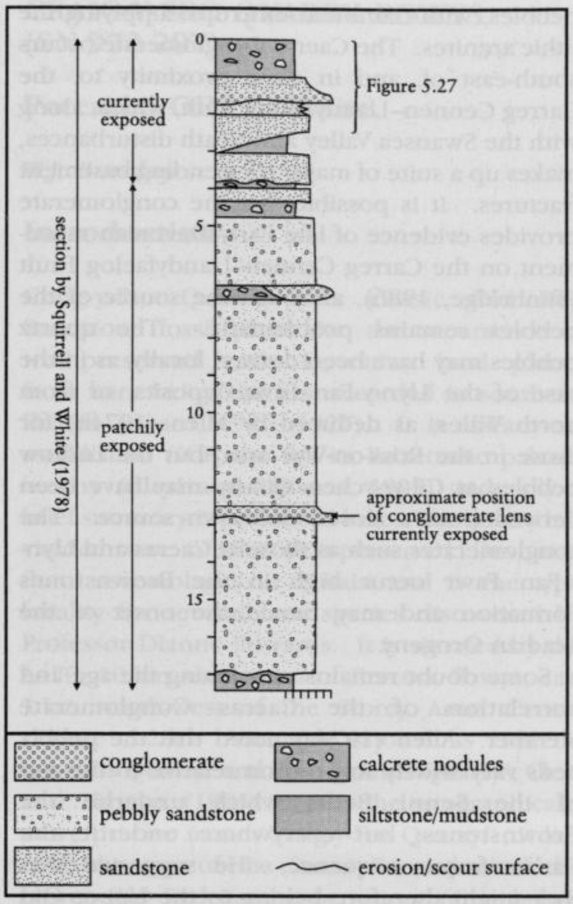
Caeras Quarry provides the best exposures of conglomeratic sandstones that occur at the top of the Brownstones Formation in the west of the Cennen Valley, between Llandybie and Kidwelly, south-east Carmarthenshire (Strahan *et al.*, 1907; Squirrell and White, 1978). The conglomerates were formerly termed the 'Pebbly Beds' (Institute of Geological Sciences, 1977; Squirrell and White, 1978), but are here named the 'Caeras Conglomerate Member' to distinguish them from pebbly beds that occur at different levels elsewhere in the Brownstones. The quarry illustrates the variable nature of the succession, although overgrown at the time of writing, with the highest beds in the south wall providing the best exposures.

The Brownstones Formation in the area has been described by Squirrell and White (1978). It comprises a succession of interbedded red-brown sandstones and siltstones/mudstones, with rare, intraformational, calcrete-clast conglomerates. A few of the siltstone/mudstone beds contain calcrete nodules. Conglomerates are common in the west of the Cennen Valley area, and at Caeras Quarry they are interbedded with siltstone/mudstone beds containing abundant calcrete nodules. The overall proportion of sandstones and conglomerates in the succession is generally 50–65%, although ranging from 40% to 75%.

The Brownstones Formation forms the highest beds of the Early Devonian Lower Old Red Sandstone. Although unfossiliferous, it is assigned a late Pragian to Emsian age. It also belongs to the local Breconian stage, and is unconformably overlain by the Lower Carboniferous Lower Limestone Shale Group at Caeras. In the region of Caeras Quarry, the Brownstones are thickest in the east, reaching 610 m in the Sawdde Fechan and Clydach valleys, but attenuating markedly westwards to about 210 m south of Carreg Cennen Castle. To the west of there, they thicken again to about 370 m in the vicinity of Caeras Quarry. The Caeras Conglomerate thickens markedly from its feather edge at Blaengweche Farm about 3.5 km east of Caeras Quarry to its maximum development of 170 m at Caeras. It then thins from Caeras westwards to 90 m at Carmel (SN 5865 1660) and to about 50 m west of the Afon Dulais.

Squirrell and White (1978) recorded the section at Caeras Quarry. Figure 5.26 shows the section graphically, modified in the light of a recent site visit, where only the topmost beds (Figure 5.27) remain well exposed. The beds dip about 45° SSE. Harrison (in Squirrell and White, 1978, their Appendix 1) gave details of some of the lithologies present.

About 13 m from the top of the section, within 5.2 m of sandstones noted by Squirrell



◂**Figure 5.26** Graphic section of part of Caeras Quarry. After Squirrell and White (1978).

and White, a grey-green, brown-weathered, quartzitic sandstone has a conglomeratic, pebbly base. A lens of grey mudstone with enclosed quartz pebbles occurs near the base of the sandstone, but it is not clear from the limited exposure whether it is a large reworked clast or the remains of an in-situ bed. Palynological analysis of the mudstone produced no dateable spores (M. Stephenson, pers. comm.).

The highest strata of the Caeras Conglomerate Member were formerly exposed at the nearby Cil-yr-ychen Quarry (SN 6165 1686), where basal olive-green sandstones of the Carboniferous Lower Limestone Shale Group rest on:

	Thickness (m)
Sandstone, red, massive, fine- to coarse-grained, commonly conglomeratic (quartz pebbles)	17.0
Siltstone, red, with many calcrete nodules up to 5 cm long	0.6
Sandstone, red, massive, medium- to coarse-grained, with quartz pebbles	4.0

Cantrill (in Strahan *et al.*, 1907, p. 63) recorded a conglomerate ('conglomeratic cornstone') in this quarry 8.2 m below the base of the Lower Limestone Shale Group. It contained a few pebbles of 'earthy limestone' containing what are probably *Camarotoechia nucula*, *Chonetes striatella*? and *Orthis* (*Dalmanella*) *elegantula*. Cantrill noted that the pebbles are from the Ludlow Series. Squirrell and White (1978) noted that the quarry is now partially filled and that no conglomerate is visible.

Interpretation

The Brownstones of south Wales and the Welsh Borderland are broadly interpreted as the proximal fluvial deposits of a piedmont plain on the southern margin of the evolving Caledonian mountain chain. They represent the culmination of a Lower Devonian coarsening-upward off-lap succession (Allen, 1979; Allen and Williams, 1979b). Continuing uplift and southerly migration of the facies belts led to non-deposition and erosion in the Anglo-Welsh basin in Mid-Devonian times. Allen (1974a) provided a general interpretation of the sedimentation of the Brownstones. Allen and Crowley (1983) demonstrated that the source of the sediments was the outcrop of Lower Palaeozoic rocks in the Irish Sea–north Wales area. Tunbridge (1980a, 1981a) interpreted the sheet sandstones of the Brecon Beacons area as semi-arid sheet-flood deposits, deposited on extensive alluvial-fans. The mudstones and siltstones are interpreted as floodplain deposits, either deposited from flash-floods, or from slow-moving or still water bodies, although an aeolian origin for some is also possible (Tunbridge, 1981a). The carbonate nodules in the finer lithologies are interpreted as pedogenic calcrete formed on the alluvial floodplains and are indicative of a tropical, seasonally wet, semi-arid climate (e.g. Marriott and Wright, 2004).

Local pebbly facies similar to the Caeras Conglomerate Member occur elsewhere in the higher parts of the Brownstones Formation in south Wales and the Welsh Borderland. Allen (1974b) described the clasts in the Ross-on-Wye area. The pebble suite there comprises a range

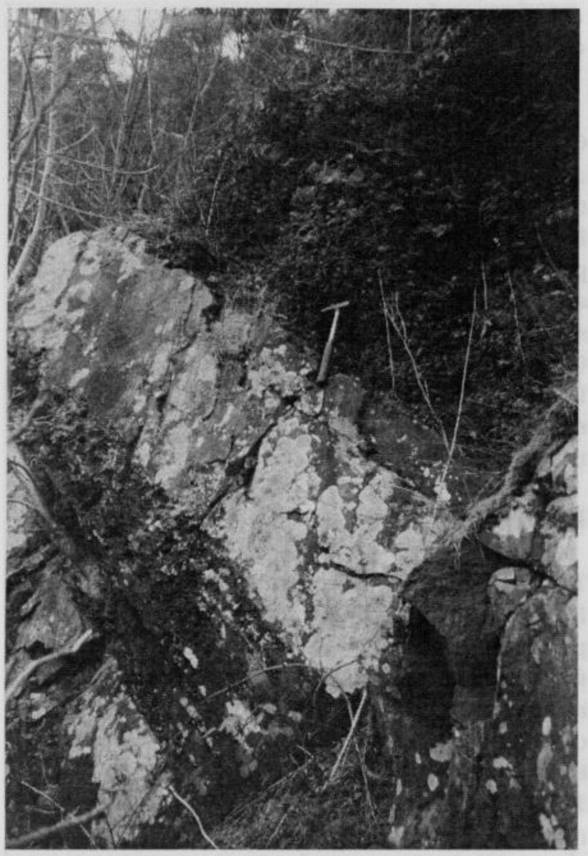


Figure 5.27 Topmost beds exposed in Caeras Quarry; red mudstone/siltstone with calcrete nodules rests on sandstone. The hammer is 0.3 m in length. (Photo: W.J. Barclay.)

of igneous, sedimentary and igneous rocks ranging from Ordovician to early Devonian in age, with perhaps some Precambrian, and concluded that they were derived from north Wales. A similar pebble suite occurs in the Woodbank Series of Shropshire (Allen, 1974b), which is the stratigraphical equivalent of the Brownstones. The pebbles in the conglomeratic facies in the topmost 100 m of the Brownstones around Llyn-y-Fan Fawr (SN 834 216) about 24 km north-east of Caeras Quarry (Tunbridge, 1980a) are angular, and hence of local derivation. They include acid volcanic rocks, lithic arenites and vein quartz derived from the east, suggesting relatively short-lived uplift of older Lower Palaeozoic rocks. Tunbridge concluded that this is evidence of uplift caused by strike-slip movement along the Swansea Valley Fault 4 km to the south. Cope (1981) suggested that a Precambrian source lay in the vicinity, and may have supplied the volcanic and vein quartz pebbles, with Cambrian outcrops supplying the lithic arenites. The Caeras Conglomerate occurs south-east of, and in close proximity to, the Carreg Cennen–Llandyfaelog Fault, which, along with the Swansea Valley and Neath disturbances, makes up a suite of major NE-trending basement fractures. It is possible that the conglomerate provides evidence of late Early Devonian movement on the Carreg Cennen–Llandyfaelog Fault (Tunbridge, 1986), although the source of the pebbles remains problematic. The quartz pebbles may have been derived locally, as in the case of the Llyn-y-Fan Fawr deposits, or from north Wales, as deduced by Allen (1974b) for those in the Ross-on-Wye area, but the Ludlow pebbles at Cil-yr-ychen Quarry may have been derived from a closer, unknown source. The conglomerates such as those at Caeras and Llyn-y-Fan Fawr occur high in the Brownstones Formation and may herald the onset of the Acadian Orogeny.

Some doubt remains concerning the age and correlation of the Caeras Conglomerate Member. Allen (1974a) noted that the pebbly beds vary widely in position relative to the top of the Senni Beds, which underlie the Brownstones, but everywhere underlie the Carboniferous sequence. He suggested that they might therefore belong to the Upper Old Red Sandstone and to be of late Devonian to early Carboniferous age. Squirrell and White (1978), however, retain the beds as part of the Brownstones Formation.

Conclusions

Caeras Quarry provides the best exposure of locally developed pebbly beds (the Caeras Conglomerate Member) lying at the top of the Brownstones Formation. There is some debate as to whether the beds belong to the topmost Brownstones or the overlying Upper Old Red Sandstone, and the site merits palynological examination to resolve this, as well as a detailed sedimentological study. The section illustrates the variable nature of the beds, comprising interbedded sandstones, pebbly and conglomeratic sandstones and siltstones/mudstones with calcrete nodules. Some of the pebbles may have been of local derivation, providing evidence of late Early Devonian movement on the major NE-trending lineaments and erosion of Precambrian and older Lower Palaeozoic basement outcrops.

CRAIG-Y-FRO QUARRY, POWYS (SN 972 207)

Potential ORS GCR site

W.J. Barclay

Introduction

Craig-y-Fro Quarry is a classic Old Red Sandstone fossil plant site, the occurrence of well-preserved early Devonian land plants from here being the first recorded in southern Britain (Heard, 1926, 1927). It is already an established GCR site for its Palaeozoic palaeobotany (Cleal and Thomas, 1995) and only a brief summary is presented here. The quarry has yielded one of the best-preserved Devonian floral assemblages in Britain and is the type locality for several new species discovered by Professor Dianne Edwards. It is situated by the A470, 10 km south-west of Brecon, Powys, and 1 km north-west of the Storey Arms Centre (Figure 5.28). Variously known as 'Brecon Beacons Quarry' and 'Storey Arms Quarry', Cleal and Thomas (1995) gave it the geographically more precise name 'Craig-y-Fro Quarry'. It lies near the top of the Senni Formation of the Lower Old Red Sandstone, about 60 m below the junction with the overlying Brownstones Formation. A brief geological description was given by Robertson (1932). Edwards and Richardson (1978) provided a detailed description of the section (Figure 5.29) and its plant and miospore assemblages. Hassan (1982) also reported on the miospore assemblages from the site.

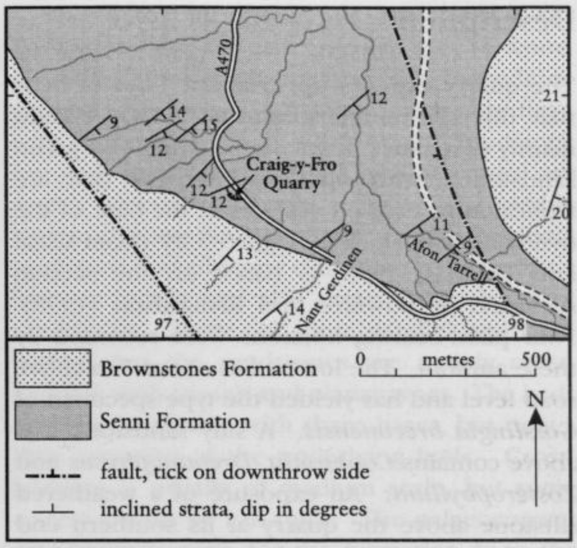


Figure 5.28 Geological map of the area around Craig-y-Fro Quarry. After British Geological Survey Scale Sheet SN 92SE (1973).

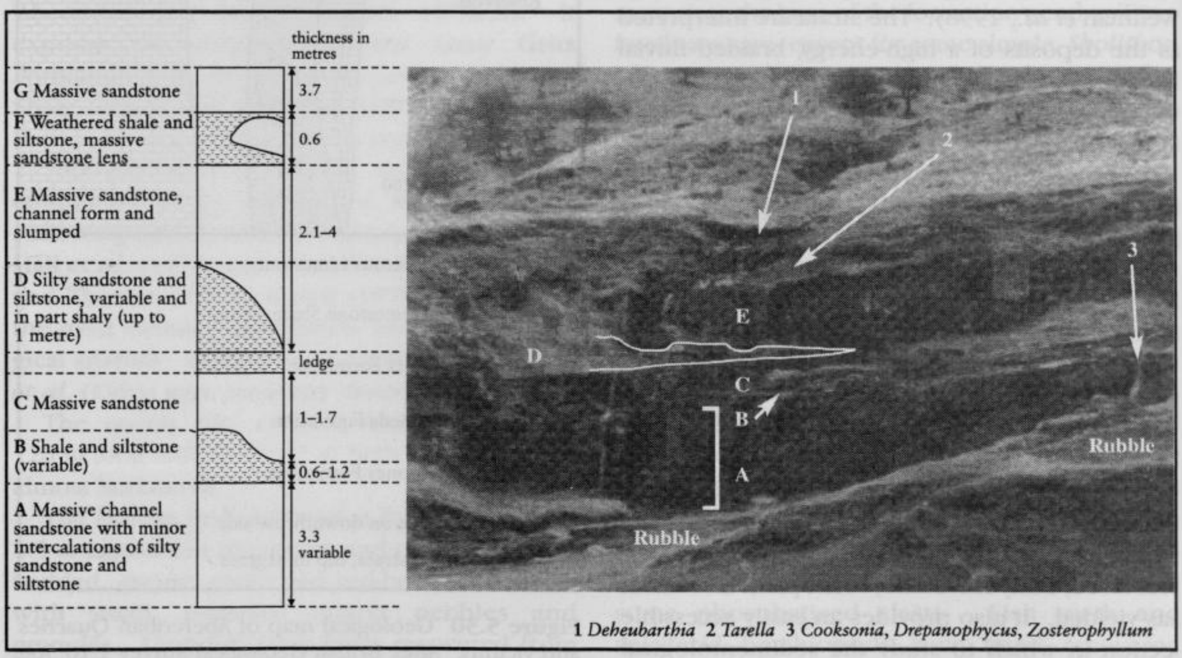


Figure 5.29 Graphic log and view of Craig-y-Fro Quarry. After Cleal and Thomas (1995, fig. 4.16). Numbers (1), (2), and (3) are three of the main plant beds. (Photo: D. Edwards.)

Description

The quarry exposes up to about 14 m of beds that dip 12° to the south-east. They consist mainly of massive, lenticular, channelized green sandstones, with siltstone interbeds that are truncated by erosion surfaces at the base of the overlying sandstones. Figure 5.29 (from Cleal and Thomas, 1995) is based on the section recorded by Edwards and Richardson (1978). Four plant-bearing horizons were recorded by these authors. The lowest lies about 7 m above road level and has yielded the type specimen of *Gosslingia breconensis*. A silty sandstone 2 m above contains *Cooksonia*, *Drepanophycus* and *Zosterophyllum*. An exposure of a weathered siltstone above the quarry at its southern end has yielded a new possible zosterophyll, *Tarella trowenii*. The overlying sandstone has yielded another new zosterophyll, *Deheubarthia splendens*. The macroplant taxa obtained from the quarry are detailed by Cleal and Thomas (1995) and summarized by Wellman *et al.* (1998).

Interpretation

Cleal and Thomas (1995) discuss the significance and importance of the macroplant assemblages. Miospore assemblages belong to the *polygonalis–emsiensis* biozone, providing a Pragian age (e.g. Wellman *et al.*, 1998). The strata are interpreted as the deposits of a high-energy, braided fluvial system, with most of the fine-grained floodplain sediments being reworked during subsequent fluvial incision and channel migration (Thomas, 1978; Owen, 1995). The green colour of the rocks and the preservation of the plants points to relatively high water-table levels and perhaps a more humid, wetter climate. Red-brown mudstones with calcrete nodules and intra-formational conglomerates with calcrete clasts above the section point to re-establishment of more arid conditions.

Conclusions

Craig-y-Fro Quarry is a site of national importance, its conservation value lying in the well-preserved, Early Devonian, fossil-plant remains it has yielded. It also provides an easily accessible section in which to study the sedimentological features of the Senni Formation.

ABERCRIBAN QUARRIES, POWYS (SO 064 123; SO 064 127)

W.J. Barclay

Introduction

These quarries on the slope east of the Taf Fechan Reservoir, 5 km north of Merthyr Tydfil (Figure 5.30), provide sections typical of the Grey Grits Formation of the Upper Old Red Sandstone. The formation ranges from Late Devonian to early Carboniferous in age, and marks the regional change from continental,

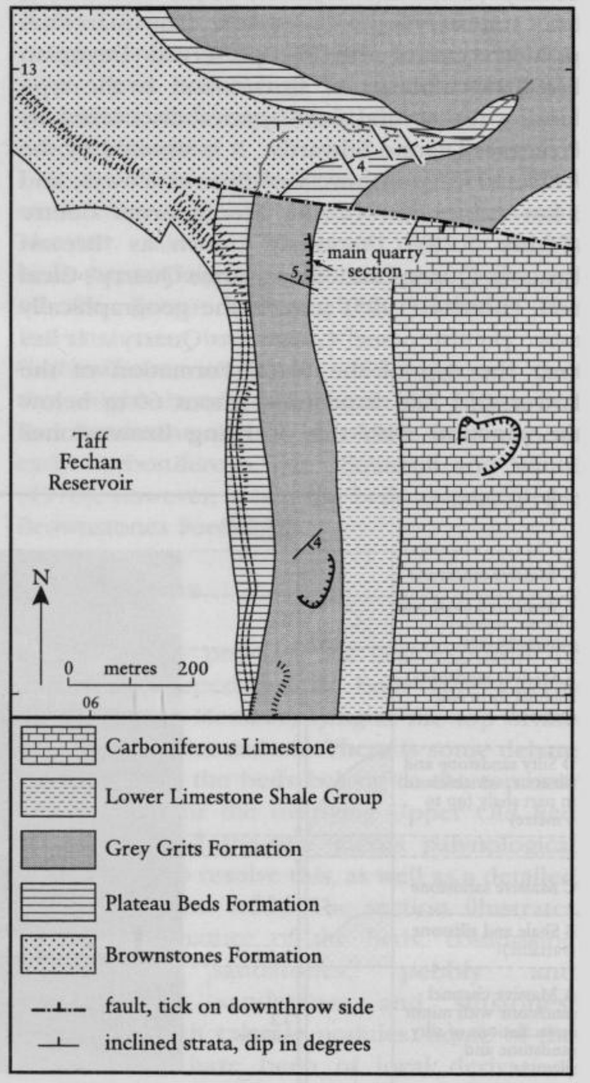


Figure 5.30 Geological map of Abercriban Quarries and vicinity. After British Geological Survey 1:10 560 Sheet SO 01SE (1980).

mainly fluvial, red-bed deposition of Late Devonian times to the shallow marine carbonate shelf environment of the early Carboniferous. The more northerly quarry (SO 0635 1272) shows a complete section of the formation, along with its contacts with the underlying Plateau Beds Formation and overlying Lower Limestone Shale Group. The more southerly quarry (SO 0635 1225) exposes about 8 m of the formation. The quarries are important in providing exposures revealing the nature of the basal and upper boundaries of the formation; in providing sedimentological evidence for the depositional environments of the Grey Grits Formation; and for allowing comparison of the Upper Old Red Sandstone of the north crop of the South Wales Coalfield with the thicker successions of Pembrokeshire. A third quarry (SO 066 124), also known as 'Abercriban Quarry', is higher in the succession and entirely in the overlying Carboniferous Limestone (the type locality of the Abercriban Oolite; Barclay *et al.*, 1988).

Description

The more northerly quarry (SO 0635 1272) (Figure 5.31) is the best-known Grey Grits Formation locality and is referred to variously as 'Abercriban Grit Quarry' (Robertson, 1932), 'Abercriban Quarry' (Hall *et al.*, 1973; Taylor and Thomas, 1975; Barclay *et al.*, 1988) and 'Abercriban grit quarry' (Lovell, 1978a,b). It exposes the junction of the Grey Grits Formation with the overlying Lower Limestone Shale Group and with the underlying Plateau Beds Formation (Taylor and Thomas, 1975; Lovell, 1978b; Barclay *et al.*, 1988), thus providing a complete (11 m) section of the formation. Following descriptions by Robertson (1932) and Hall *et al.* (1973) and a brief mention by Taylor and Thomas (1975), Lovell (1978a,b) provided the most detailed description and sedimentological analysis. Barclay *et al.* (1988) and Almond *et al.* (1993) gave summary descriptions.

The quarry has a north–south face about 120 m long and about 12 m high. The beds are almost horizontal.

The Plateau Beds Formation forms the lowest 1.5 m exposed in the quarry and comprise thinly bedded, greyish green and red-brown siltstones with small, rounded quartz pebbles and granules. Lingulids have been recovered from the red-brown siltstones (Hall *et al.*, 1973).

The main lithologies of the Grey Grits Formation here are pale greenish grey to white, quartzitic, lithologically uniform, fine- to medium-grained sandstones (mainly quartz arenites), with lesser amounts of siltstone and mudstone forming thin interbeds. Conglomerates are mainly absent, with only a few quartz pebble lenses at some levels. Some intraformational mudstone and siltstone clasts line cross-bedding foresets locally and also occur at the bases of sandbodies. There are some parallel-laminated bodies, but the sandstones are mainly cross-bedded, with trough and planar types. The beds are mainly tabular, with sharp bases, but only a little scouring of the underlying beds. Cross-bedding is usually of medium scale, but some co-sets are up to 1 m thick. The palaeocurrent grand vector-mean for the formation is to the south-east, but both SSE and NNE palaeocurrents have been recorded in beds at different, discrete levels. The best example of this is seen at the northern end of the quarry where a 1.15 m-thick bed (3.85 m above the base of the formation) shows ENE-directed cross-bedding and is overlain by a bed with SE-directed cross-beds. The intervening erosion surface can be traced through most of the quarry (Lovell, 1978a,b).

No body fossils have been recovered from the formation here, although Taylor and Thomas (1975) recorded a calcareous brachiopod fragment near the base of the formation nearby. Trace fossils are rare, except for some simple, *Skolithos*-like, vertical burrows at some levels, and a few slightly sinuous simple burrows (epichnial casts) on one surface near the base of the formation. Elsewhere, a thin basal intraformational conglomerate has yielded fish fragments and the bivalve *Sanguinolites* sp. (Hall *et al.*, 1973; Taylor and Thomas, 1974; Lovell, 1978a,b).

The basal bed of the Castell Coch Limestone Formation, which is the basal formation of the Lower Limestone Shale Group, overlies an erosion surface that truncates the Grey Grits Formation. A green, 0.9 m-thick siltstone bed at the north end of the quarry is absent to the south. The Lower Limestone Shale Group begins with a thin (0.2 m) lag conglomerate containing quartz pebbles, some altered acid-lava pebbles (including jasper), intraformational clasts and some phosphatized clasts. Fish teeth and spiriferid brachiopods have been recovered (Lovell, 1978a).

Interpretation

There were formerly differing interpretations of the relationship of the Grey Grits Formation and the underlying Plateau Beds Formation. Robertson (1932) thought that the two formations interfinger, but Allen (1965b) suggested that there is evidence of uplift and erosion between the two formations. Taylor and Thomas (1975) confirmed Allen's interpretation, noting that the Grey Grits form a wedge resting unconformably on various levels of the Plateau Beds throughout their outcrop, depending on the amount of pre-Grey Grits erosion. The nature of the boundary between the Grey Grits Formation and the overlying Lower Limestone Shale Group has also been the subject of different interpretation. Allen (1965b) and Hall *et al.* (1973) suggested a transitional contact. Taylor and Thomas (1975) noted a lack of discordance and no apparent break between the formations, and lent support to the suggestion of Cantrill (in Strahan *et al.*, 1904) that the Grey Grits represent commencement of Carboniferous sedimentation in the region. However, the widespread lag conglomerate at the base of the Lower Limestone Shale Group indicates at least a disconformity, with erosion having preceded deposition of the conglomerate (Burchette, 1981; Lovell, 1978a,b; Barclay *et al.*, 1988). The truncation of the topmost siltstone bed of the Grey Grits at the main Abercriban quarry (see above) confirms this interpretation.

The depositional environment of the Grey Grits has been interpreted variously as shallow marine to fluvial. Allen (1965b) proposed a dominantly fluvial origin. Regionally, Taylor and Thomas (1975) noted the presence of conglomerate layers at the bases of sandbodies resting on erosion surfaces, and small channels cut in calcareous sandstones and infilled with discoidal pebbles. They suggested depositional environments that varied from fluvial to marginal marine. Lovell (1978a,b) supported Allen's (1965b) fluvial interpretation, proposing deposition in shallow, sandy braided streams. It is possible, however, that the fluvial channels were tidally influenced (B.P.J. Williams, pers. comm.).

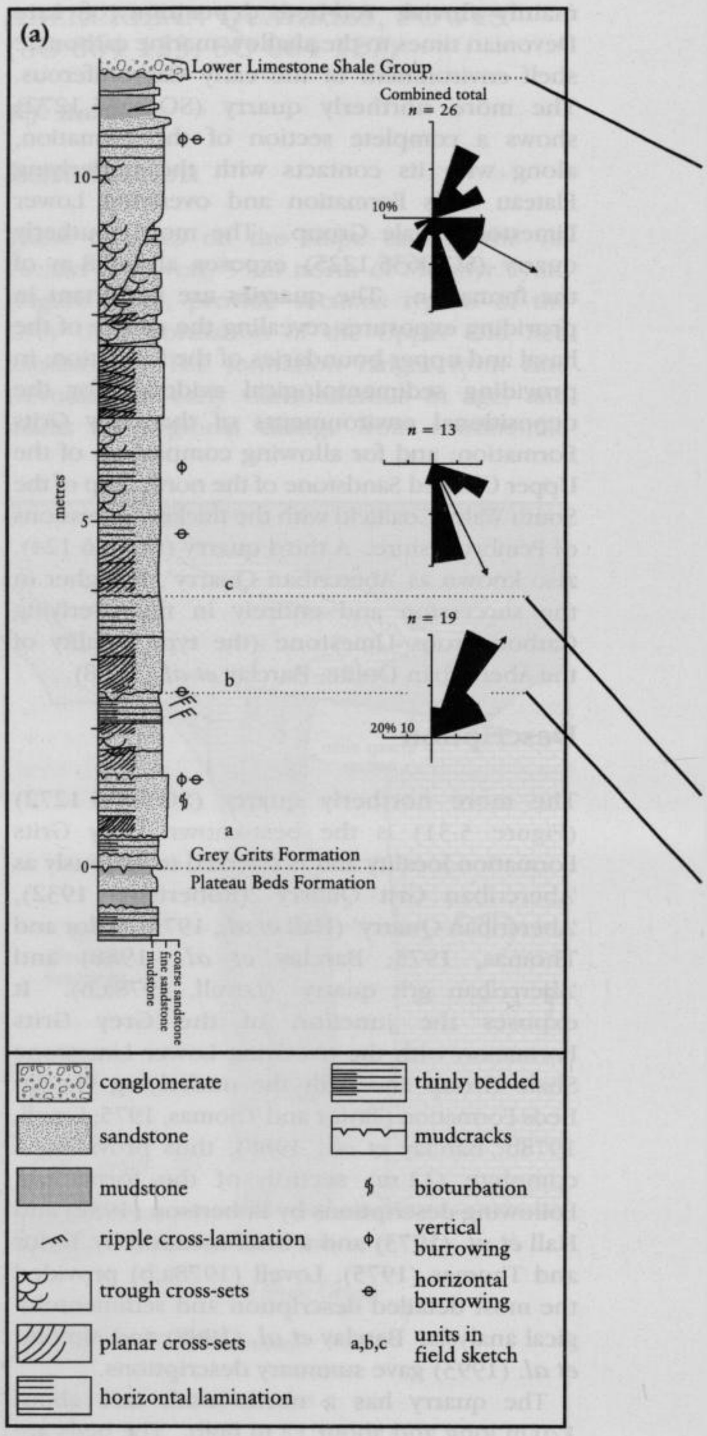


Figure 5.31 Northern Abercriban quarry. (a) composite log from the north and south ends of the quarry showing palaeocurrent directions. After Lovell (1978a,b). Continued on page 261.

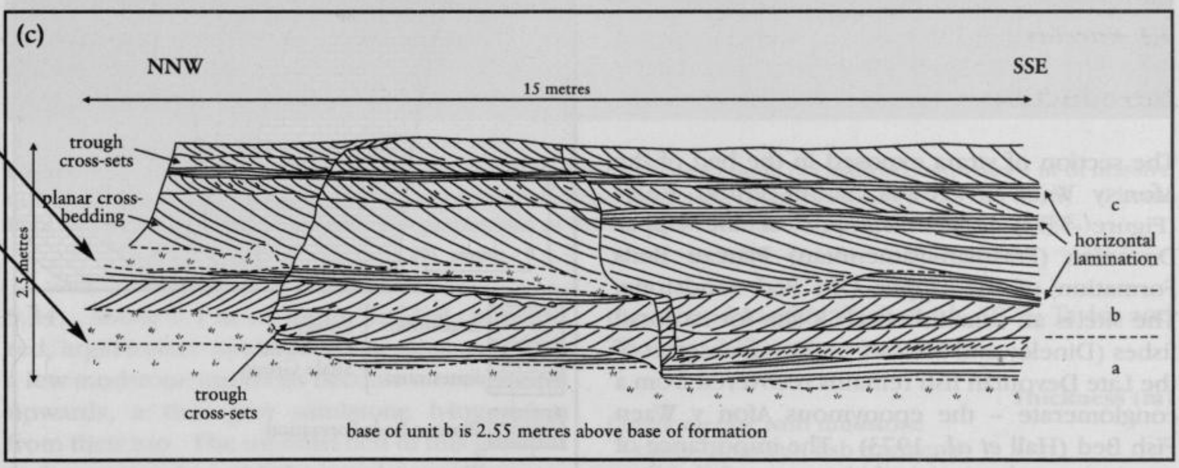


Figure 5.31 – *continued*. Northern Abercriban quarry. (b) – view of part of the northern Abercriban quarry showing the basal beds of the Lower Limestone Shale Group and the upper part of Grey Grits Formation; (c) – sketch section of lower part of quarry (after Lovell, 1978a,b). (Photo: BGS No. A11993, reproduced with the permission of the Director, British Geological Survey, © NERC.)

The exact age of the Grey Grits remains unknown, but a Late Devonian to Early Carboniferous age is likely (Lovell, 1978a,b). The underlying Plateau Beds are thought to be late Frasnian to early Famennian in age and the base of the Lower Limestone Shale Group here appears to be of Early Carboniferous (Tournaisian (Tn) 2a) age (Lovell, 1978a,b).

Conclusions

The larger of the two quarries in the Grey Grits Formation (SO 0635 1272) provides a complete section through the formation, exposing its upper and lower boundaries. The quarry is thus important in providing evidence of the nature of these boundaries. It is also important in the detailed sedimentological evidence it provides for a fluvial, shallow braided stream origin for the Grey Grits Formation, thereby putting the formation into the regional context of Late Devonian to Early Carboniferous sedimentation when compared with, for example, the broadly coeval Skrinkle Sandstones Group of Pembrokeshire.

AFON Y WAEN, POWYS (SN 976 147)

Potential ORS GCR site

W.J. Barclay

Introduction

The section of strata exposed in the bed of the Afon y Waen in Powys, south-central Wales (Figure 5.32) is characteristic of the Upper Devonian (Frasnian–Famennian) Plateau Beds Formation of the Upper Old Red Sandstone. The site is an established GCR site for its fossil fishes (Dineley and Metcalf, 1999) on account of the Late Devonian fish remains recovered from a conglomerate – the eponymous Afon y Waen Fish Bed (Hall *et al.*, 1973). The importance of the site is enhanced in being one of the best sections of the Plateau Beds Formation, which elsewhere contains a shallow marine fauna that is unique in the predominantly continental Late Devonian Old Red Sandstone facies. The formation is also important in containing an aeolian sandstone facies, not known elsewhere in the Anglo-Welsh Basin, and seen, for example, in a key section at **Duffryn Crawnon** (SO 095 150) (see GCR site report, this chapter; Lovell, 1978a,b).

Description

Hall *et al.* (1973) provided a detailed description of the section, following the discovery of fish remains by Taylor (1972). In the Afon y Waen valley to the north of the site, the Plateau Beds are repeated by a NE-trending fault. The basal part of the Plateau Beds is exposed north of the fault (SN 972 172–SN 973 174), where a variable succession comprises 0.9–1.8 m of purplish red, flaggy sandstones and red mudstones, truncated by an erosion surface and overlain by 0.6–2.7 m of quartz pebble conglomerate (Figure 5.33). The section south of the fault is shown in Figure

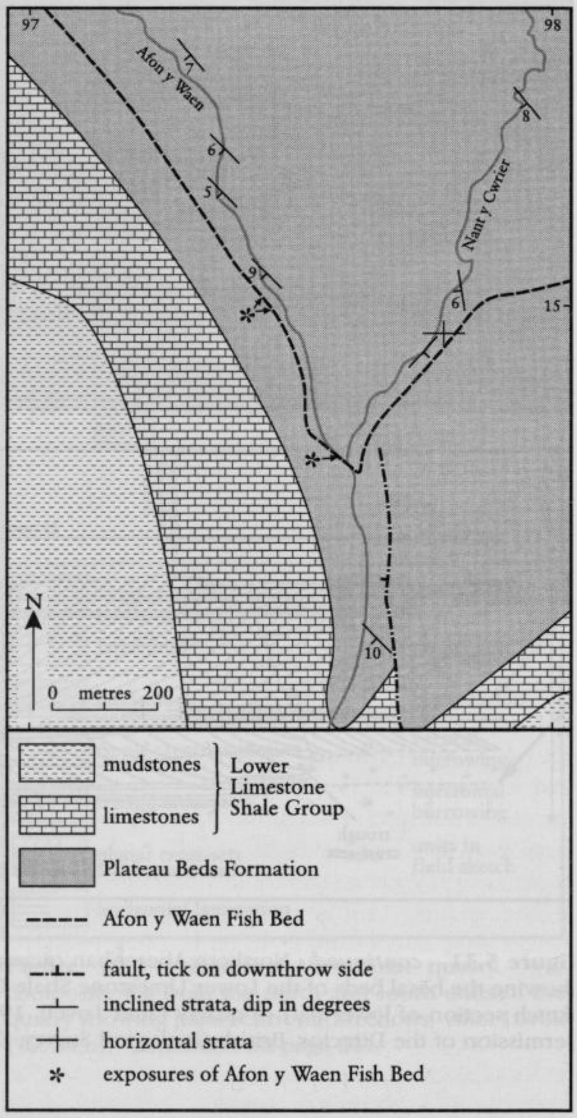


Figure 5.32 Geological map of Afon y Waen potential GCR site. After British Geological Survey 1:10 560 manuscript maps SN 91NE and SN 91SE (both 1973).

Figure 5.33 Cwar Llwyd, Afon y Waen. The basal bed of the Plateau Beds Formation comprises 3 m of massive quartz pebble conglomerate above 1.5 m of thinly bedded sandstones and siltstones (SO 9720 1730). (Photo: BGS No. A12010, reproduced with the permission of the Director, British Geological Survey, © NERC.)

5.34. About 6.1 m of thinly bedded, purplish red, argillaceous sandstones and siltstones with a few mudstone interbeds become more massive upwards, a thin grey sandstone lying 4.5 m from their top. The topmost bed of this group is a fine-grained, reddish purple, argillaceous sandstone with buff sandstone-filled burrows. It is overlain by the Afon y Waen Fish Bed, which is exposed at two localities in cliffs on the west bank of the stream (SN 9747 1500; SN 9761 1476). At the first, a 1.52 m-thick, purplish grey, trough cross-bedded, quartzitic sandstone has lenses of quartz conglomerate at its base containing fish fragments. These also occur in the bases of the cross-bedded sets. At the second locality (Hall *et al.*, 1973; Taylor and Thomas, 1974), the section is:

	Thickness (m)
Conglomerate with mudstone clasts, abundant fish fragments and a few quartz pebbles in a purple, fine-grained sandstone matrix	0.1
Sandstone, fine-grained, purple to grey, with a layer of pebbles and fish fragments at the base, which is channelled down into the underlying unit	0.6–1.0
Sandstone, fine-grained, purple to grey, trough cross-bedded	0.7
Conglomerate, friable, with quartz pebbles, red-brown mudstone clasts and abundant fish fragments	0.15

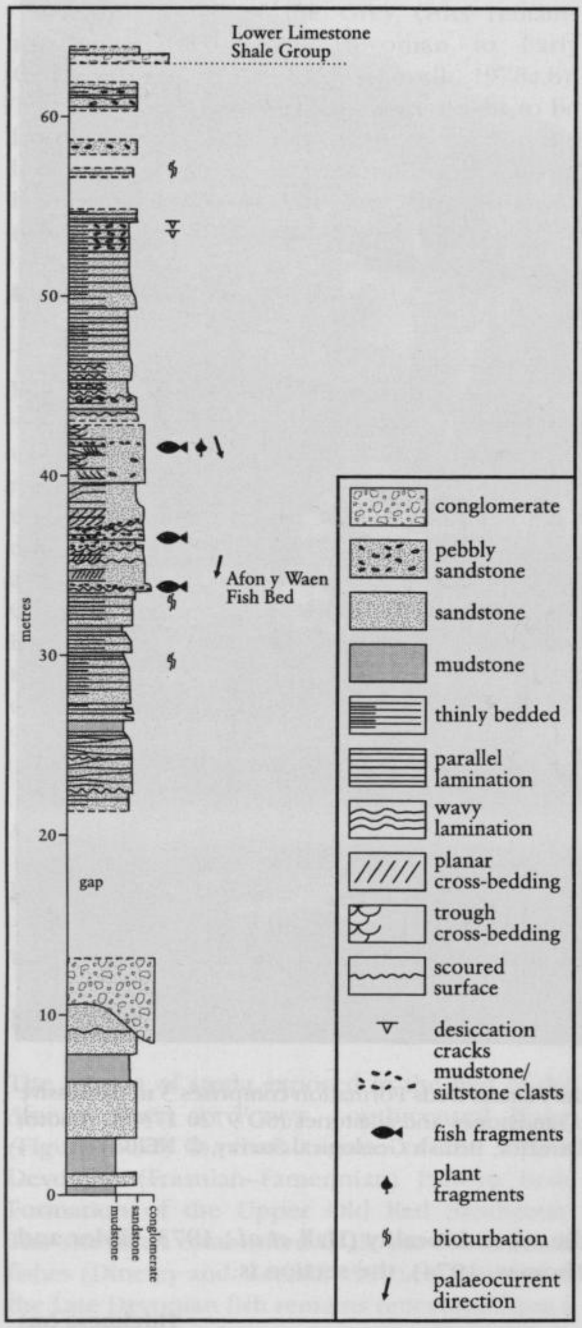


Figure 5.34 Vertical section of the strata in the Afon y Waen. Basal 13 m after Hall *et al.* (1973), upper part after Lovell (1978a).

Holoptychius sp. and *Bothriolepis* sp. have been found at these localities (Taylor, 1972; Hall *et al.*, 1973). No marine fossils have been found in the section, but lingulids occur above the level of the Afon y Waen Fish Bed in the nearby Cefn Esgair South Borehole (SN 9845 1353) and in Nant Mawr (SN 9519 1572) 2.5 km to the north-west. The fish bed was taken by Hall *et al.* (1973), Taylor and Thomas (1974, 1975) as a marker bed, subdividing the Plateau Beds into Lower and Upper units, and these units are shown on the Institute of Geological Sciences (1979) map of the area.

Above the fish bed, 4.57 m of fine- to medium-grained quartzitic sandstone are overlain by thinly bedded, deep purple, fine-grained, argillaceous sandstones and red-brown mudstones. Blue-grey, fine-grained, ripple cross-laminated sandstones close above were correlated with the Grey Grits Formation by Hall *et al.* (1973), but included in the Plateau Beds by Lovell (1978a).

Brachiopods recovered elsewhere from the Plateau Beds include *Lingula* sp., *Cyrtospirifer verneuili*, cf. *Ptychomaletoechia omaliusi*, *Leptodesma* cf. *lichas* and ?*Pterinopecten* sp.. In addition to *Bothriolepis* sp. and *Holoptychius* sp., fish remains include cf. *Pseudosauripterus anglicus* and cf. *Sauripterus* sp.. Trace fossils include cf. *Planolites* and *Rusophycus*. All of the brachiopods were recovered from the topmost part of the formation.

Interpretation

In a detailed sedimentological analysis of the Plateau Beds, Lovell (1978a) recognized three subdivisions (A, B and C). Division A is present only to the west of Afon y Waen, where it comprises a laterally variable succession of trough cross-bedded, pebbly sandstone and conglomerate with red mudstone interbeds. It was tentatively interpreted by Lovell (1978a) as the deposits of a southerly flowing braided stream system. Division B consists mainly of thin- and medium-bedded, red-brown sandstones, with local planar cross-bedded sandstones indicating southerly derivation. Lovell (1978a,b) suggested an aeolian origin for the latter, with the former being fluvial, possibly wadi sediments. The Afon y Waen section lies entirely within Division C. This is a heterolithic unit of interbedded, channelized, pebbly and conglomeratic sandstones, fine-grained sheet sandstones and mudstones. Cross-bedding indicates SE-directed palaeocurrents. A marginal marine environment is suggested (Allen, 1965b; Taylor and Thomas, 1975; Lovell, 1978a,b), with evidence of supratidal, tidal-flat and possibly subtidal environments (Lovell, 1978b). All of the marine fauna recovered from the Plateau Beds comes from this uppermost division. Lovell (1978a) noted that the Afon y Waen Fish Bed is a lenticular horizon of limited lateral extent. Similar channel-bottom lag deposits elsewhere, of which there are several, probably occur at slightly different stratigraphical levels, and the bed is not a continuous marker bed as envisaged by Hall *et al.* (1973) and Taylor and Thomas (1974, 1975). Similar facies occur above and below the Afon y Waen Fish Bed. The brachiopods and fish remains recovered from the formation suggest a Frasnian to Famennian age for the Plateau Beds.

Conclusions

The Afon y Waen section exposes beds characteristic of the upper part of the Plateau Beds Formation of the Upper Old Red Sandstone. The section is the type locality of the Afon y Waen Fish Bed, a lenticular conglomerate that has yielded fragments of the Late Devonian fish *Bothriolepis* and *Holoptychius*. The strata are of continental, Old Red Sandstone red-bed facies, but at nearby localities include marginal marine deposits that presage the marine transgression which led to the establishment of marine environments in Early Carboniferous time. Future research at the site will include the search for marine fossils known to occur at this level elsewhere.

DUFFRYN CRAWNON, POWYS (SO 095 150)

Potential GCR site

W.J. Barclay

Introduction

Accessible cliff exposures at the head of the Duffryn Crawnon Valley, Powys (Figure 5.35) between the headwaters of Nant ddu and the Afon Crawnon provide a complete transect through the Late Devonian Plateau Beds Formation. These strata are unique in the Anglo-Welsh Basin in containing shallow marine deposits and possible aeolian sandstones, both facies being present here. Following the discovery of fish remains during mapping by the [British] Geological Survey (Hall *et al.*, 1973; Taylor and Thomas, 1974, 1975), a detailed sedimentological analysis was carried out by Lovell (1978a,b). The site's importance is enhanced in it being the type locality for the Plateau Beds (Lovell, 1978a).

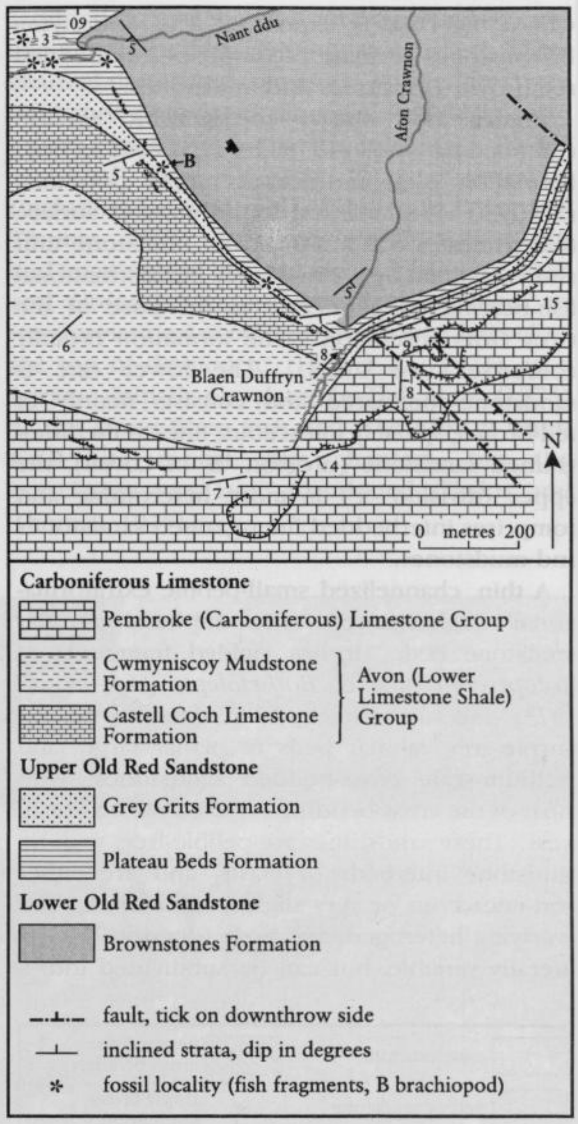


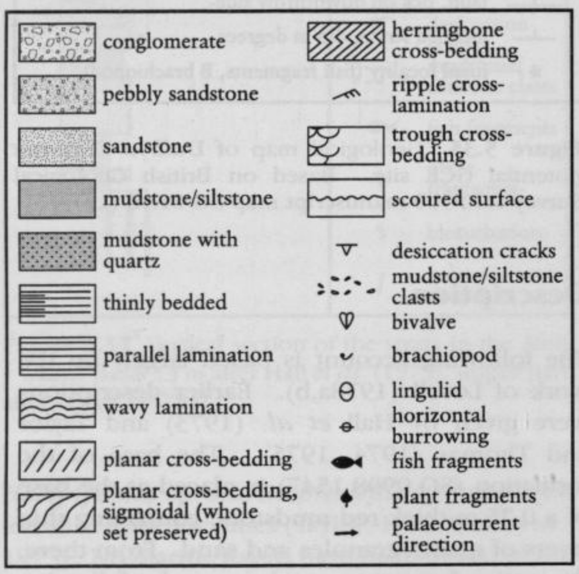
Figure 5.35 Geological map of Duffryn Crawnon potential GCR site. Based on British Geological Survey 1:10 560 manuscript map SO 01NE (1973).

Description

The following account is based largely on the work of Lovell (1978a,b). Earlier descriptions were given by Hall *et al.* (1973) and Taylor and Thomas (1974, 1975). The base of the formation (SO 0908 1547) is placed at the base of a 0.75 m-thick red mudstone containing thin layers of quartz granules and sand. From there, the entire formation can be seen by following the public footpath that contours round the bottom of the steepest part of the cliffs, or by climbing a grassy slope about 80 m south of where the base is exposed. The underlying Brownstones Formation comprises interbedded red-brown sandstones and mudstones.

Figure 5.36 shows the graphic section compiled by Lovell (1978a,b). The Plateau Beds Formation is 36 m thick, its upper boundary (SO 0930 1518) marked by an erosion surface that truncates a 2.5 m-thick red mudstone unit and is overlain by 0.2 m of grey intraformational fish-bearing conglomerate at the base of the Grey Grits Formation. The formation broadly comprises two units. The lower one is sandstone-dominated and consists mainly of red-brown, sparsely micaceous, fine- to medium-grained sandstone (division 'B' of Lovell), the upper (division 'c') is more heterolithic and comprises interbedded finer-grained sandstones and mudstones.

A thin, channelized small-pebble extraformational conglomerate overlies the basal granular mudstone bed. It has yielded fragments of *Holoptychius* and cf. *Bothriolepis* (Hall *et al.*, 1973). It is succeeded by 18 m of red-brown and purple-grey, tabular beds of planar large- and medium-scale cross-bedded sandstones, with most of the cross-bedding directed to the north-west. These sandstones are pebble-free, with no mudstone interbeds or clasts, and are either non-micaceous or very slightly micaceous. The overlying heterogeneous beds (division 'c') are laterally variable, but can be subdivided into a



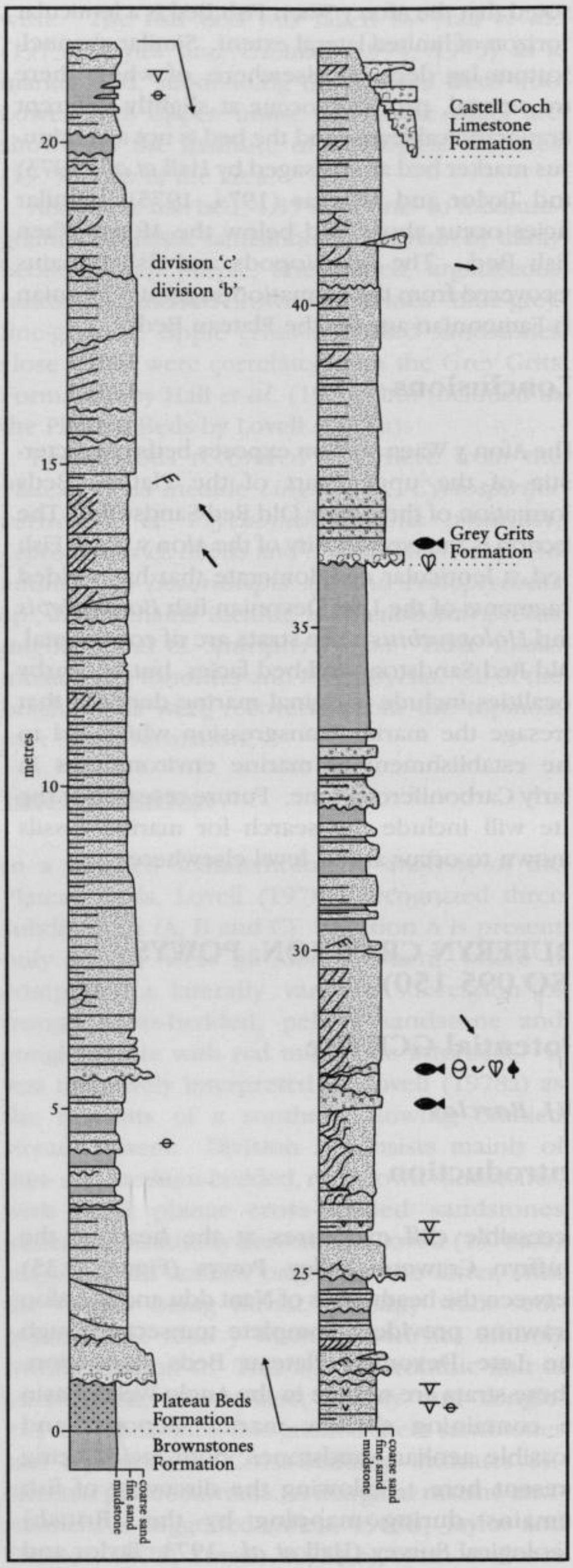


Figure 5.36 Vertical section of the strata at Duffryn Crawnon. After Lovell (1978a,b).

lowermost part of 9 m consisting mainly of small, fining-upward, fine-grained sandstone–mudstone cycles 0.75 m to 1.75 m thick. The unit bases are slightly erosional or sharp, and parallel lamination is present in a number of beds. Some channelling is seen locally (Figure 5.37). A few beds have rippled surfaces, and desiccation cracks occur at some levels. Bioturbation is present in some beds in the form of horizontal hypichnial casts. Sediment dispersal in both these beds and the overlying 9 m was towards the south. The upper 9 m commence with a siderite clast and fish-bearing sandstone that passes up into cross-bedded sandstones or is overlain (and laterally cut out) by a channel-fill, cross-bedded sandstone. There are several superimposed and cross-cutting channelized sandbodies, and the bases of two channels contain brachiopod-bearing mudstone clasts. This channel-dominated sequence is overlain by a mudstone-dominated sequence, which, in turn, passes into the uppermost sandstones. Fossils recorded from division 'c' are lingulids (including Lingulid sp. B of Butler, in Taylor and Thomas, 1975), *Ptychomaletoechia omaliusi*, and fragments of fish and plant. Cf. *Bothriolepis* and *Holoptychius* sp. are recorded from an intraformational conglomerate about 12 m below the top of division 'c' (Hall *et al.*, 1973), in a horizon initially correlated by Hall *et al.* (1973) as the Afon-y-Waen Fish Bed (see **Afon y Waen** GCR site report, this chapter), but the correlation was later abandoned (Taylor and Thomas, 1975).

Figure 5.37 South face of Blaen Duffryn Crawnon (SO 0936 1507). Sandstones and siltstones fill a channel in the upper part of the Plateau Beds Formation. Brachiopods are present in the channel-fill. (Photo: BGS No. A12015, reproduced with the permission of the Director, British Geological Survey, © NERC.)

The Grey Grits Formation is up to 10 m thick and consists predominantly of grey-green, cross-bedded quartzitic sandstones showing SE-directed palaeocurrents. A siderite- and green mudstone-clast conglomerate marks the base of the formation and has yielded fish fragments and the bivalve *Sanguinolites*. Small channel-fill and scour features characterize the immediately overlying beds and are lined with discoidal quartz pebbles.

Interpretation

The Brownstones Formation is interpreted to be of sheet-flood and braided river origin (Tunbridge, 1981a). It is truncated by a regional unconformity marking basin inversion and erosion during the culmination of the Acadian Orogeny. Although no angular discordance is discernible at Duffryn Crawnon, the unconformity marks a major hiatus in which the Mid-Devonian succession is unrepresented.

The granule-rich mudstone at the base of the Plateau Beds is recognized widely (Hall *et al.*, 1973; Lovell, 1978a,b) and is interpreted by Lovell (1978a) as an alluvial mudflow deposit. Hall *et al.* (1973) subdivided the Plateau Beds into lower and upper units at the level of the Afon-y-Waen Fish Bed, but Lovell (1978a) concluded that fish-bearing conglomerates such as this are lenticular and not laterally persistent, and probably occur at different levels. The main differentiation of the succession is lithological, with a lower sandstone-dominated unit (division 'b') and an upper heterolithic unit (division 'c').

Some cross-bedded sandstones of division 'b' show NW-directed palaeocurrents, opposite to the regional drainage direction. Lovell (1978a,b) considered that these may represent wind-blown dune sets, either interbedded with unconfined waterlain (?wadi) sands or forming part of a coastal dune sequence. Lovell (1978a) noted, however, that if an aeolian environment is represented, dune formation appears to have been relatively limited. If Lovell's aeolian interpretation is correct, this is the first recorded occurrence of wind-blown sand deposition in the Anglo-Welsh Basin (but see also **Portishead** GCR site report, this chapter). The more heterogeneous deposits of division 'c' were interpreted as marginal marine sediments, with evidence of supratidal, tidal-flat and possibly subtidal deposition (Allen, 1965b; Lovell, 1978a,b). The fish fragments and brachiopods recovered from here and elsewhere constrain the age of the Plateau Beds to the late Frasnian–Famennian. The Grey Grits were interpreted by Allen (1965b) and Lovell (1978a) as fluvial deposits, although Taylor and Thomas (1975) suggested marginal marine deposition. At least some of the fluvial channels may have been affected by the influx of shallow marine waters (B.P.J. Williams, pers. comm.).

Conclusions

Duffryn Crawnon is the type locality of the Late Devonian Plateau Beds Formation and provides an excellent, complete transect through the entire formation. These strata are unique in the Anglo-Welsh Basin in containing shallow marine deposits and aeolian sandstones, and the site's importance lies in the presence of both of these facies. The site also exposes the lower and upper boundaries of the Plateau Beds, thereby providing evidence on the inter-relationships of the formations present. Fossil fish fragments from the site have provided information on the age of the Plateau Beds, and the sporadic presence of shallow marine fossils adds further importance.

CRAIG-Y-CWM, TORFAEN (SO 283 089)

Potential GCR site

W.J. Barclay

Introduction

Craig-y-cwm lies on the east-facing escarpment of the South Wales Coalfield 3.5 km south-east of Blaenavon (Figure 5.38). It provides the most complete section of the Upper Devonian (Upper Old Red Sandstone) Quartz Conglomerate Group of the eastern part of the South Wales Coalfield. It is also the type locality for the Craig-y-cwm and Garn-gofen formations of the Quartz Conglomerate Group (Barclay, 1989; Lovell, 1978a). Although these formations are not completely exposed, the Wern Watkin Formation, the basal formation of the group, is exposed in its entirety. A similar succession is exposed to the north at Craig-yr-Hafod (SO 2780 0994).

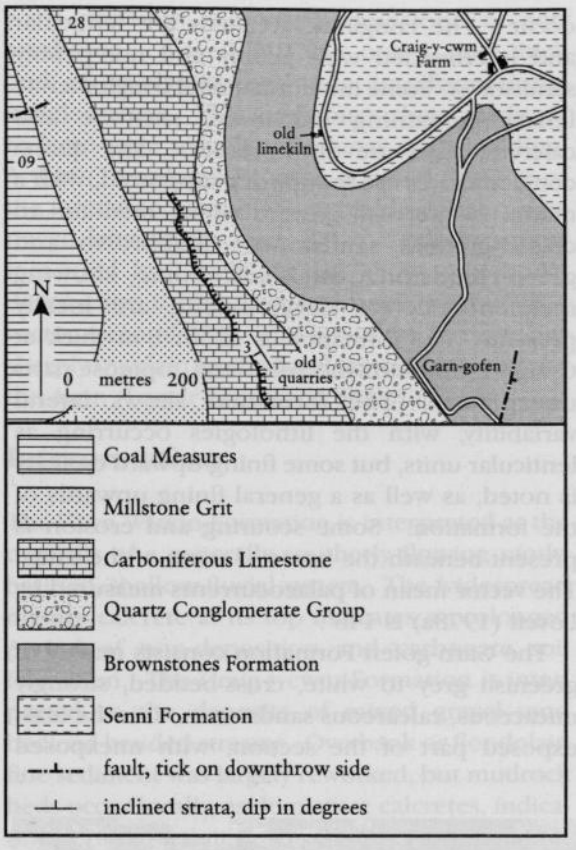


Figure 5.38 Geological map of Craig-y-cwm potential GCR site. After British Geological Survey 1:10 560 manuscript map SO 20NE (1984).

Description

The Quartz Conglomerate Group is 42 m thick at Craig-y-cwm (Figure 5.39). Strahan and Gibson (1900) first gave details of the succession at the site (repeated by Robertson, 1927). Barclay (1975) recognized three units within the group, later formalized as formations by Lovell (1978a), who gave a detailed description of the site and sedimentological interpretations of its constituent formations (summarized by Barclay, 1989). The following account is based largely on Lovell (1978a).

The base of the Wern Watkin Formation rests with no obvious discordance on the Lower Old Red Sandstone Brownstones Formation. The junction is placed where very fine- to fine-grained, ripple cross-laminated, thinly bedded, non-micaceous, non-calcareous, pale greenish sandstones of the Wern Watkin Formation rest on the pinkish brown, micaceous, fine- to medium-grained, friable sandstones of the Brownstones Formation. The latter is leached and weathered to pale green sand immediately below the junction. The Wern Watkin Formation is 19 m thick and comprises mainly pale green-grey to yellow-white, non-micaceous, fine-grained, flat-bedded, quartzitic sandstones (Lovell, 1978a). The sandstones are mainly in tabular sheets ranging from 0.2 m to 0.4 m in thickness, although one bed is 1.2 m thick. Mudstones are uncommon, but two thin beds are present, and intraformational green siltstone

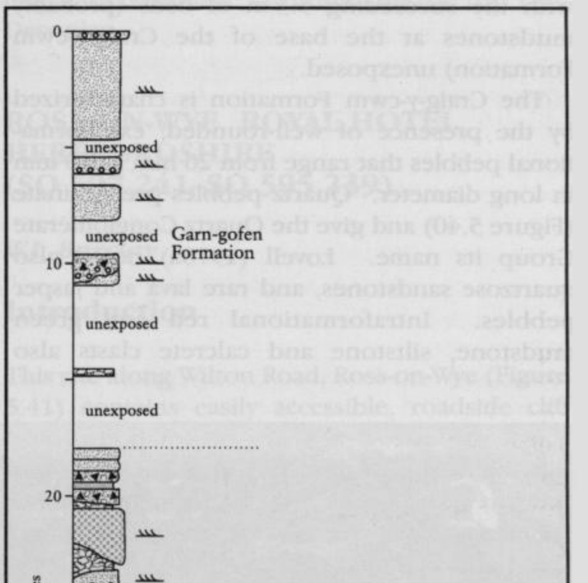


Figure 5.39 Graphic log of strata at Craig-y-cwm. After Barclay (1989).

clasts occur at some levels. The sandstone sheets show equal amounts of parallel lamination and cross-bedding. Both planar and trough cross-bedding occur. The 1.2 m-thick sandstone can be traced for over 300 m and its bedding characteristics change from a single, planar cross-bed set to a series of superimposed trough cross-beds. Measurements of the cross-bedding give a vector mean towards the north-west, which contrasts with southerly current directions measured at other localities. The top of the formation is marked by a massive calcrete, with the succeeding 5.3 m of beds (probably mudstones at the base of the Craig-y-cwm Formation) unexposed.

The Craig-y-cwm Formation is characterized by the presence of well-rounded, extraformational pebbles that range from 20 mm to 50 mm in long diameter. Quartz pebbles predominate (Figure 5.40) and give the Quartz Conglomerate Group its name. Lovell (1978a) noted also quartzose sandstones, and rare lava and jasper pebbles. Intraformational red and green mudstone, siltstone and calcrete clasts also occur. The conglomerate beds are lenticular and interbedded with pebbly and non-pebbly sandstones. Some intraformational conglomerate lenses containing mudstone, siltstone and calcrete clasts are also present. The quartz conglomerates are framework-supported, with a matrix of greenish grey to white, medium- to coarse-grained sandstone. Red-brown and green mudstone interbeds, some showing incipient calcrete development, are locally present. The formation is about 8 m thick at Craig-y-cwm, with the basal and topmost parts unexposed. The formation shows lateral variability, with the lithologies occurring as lenticular units, but some fining-upward cyclicity is noted, as well as a general fining upwards of the formation. Some scouring and erosion is present beneath the bases of some of the units. The vector mean of palaeocurrents measured by Lovell (1978a) is 148°.

The Garn-gofen Formation consists mainly of greenish grey to white, cross-bedded, strongly micaceous, calcareous sandstones. It is the least exposed part of the section, with unexposed

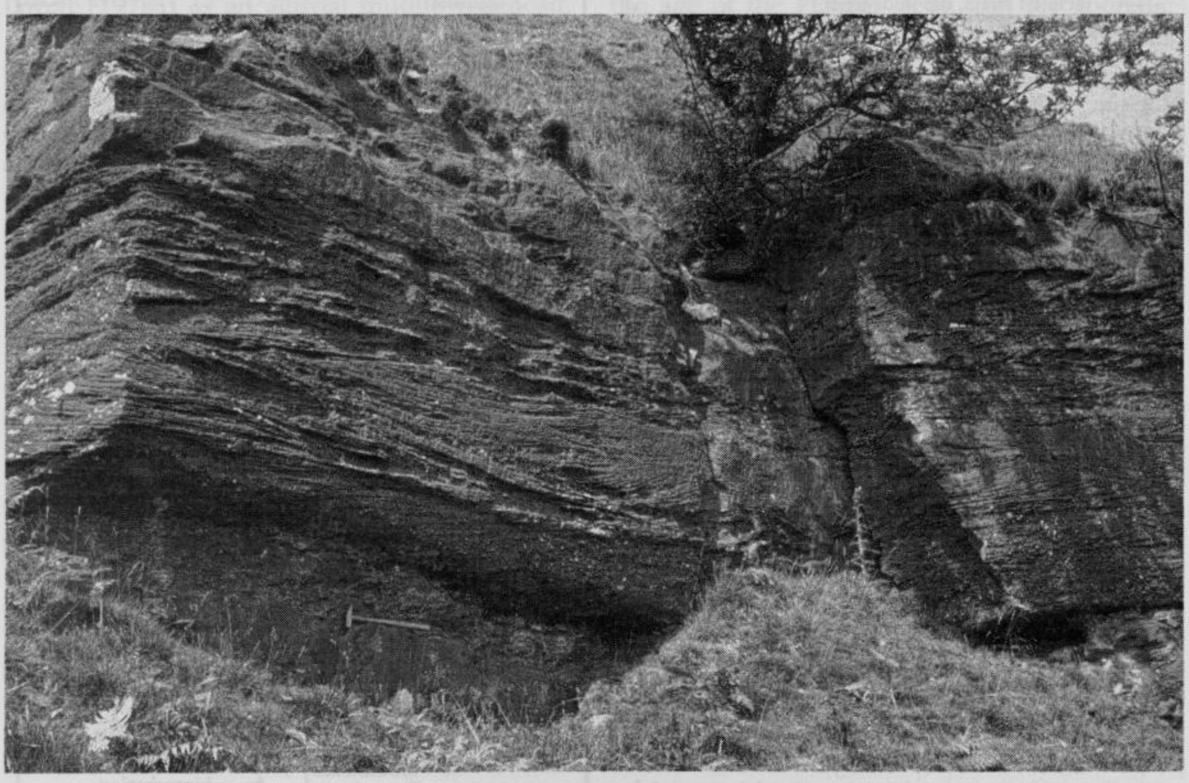


Figure 5.40 Cross-bedded pebbly sandstones above calcrete, Craig-y-cwm Formation, Craig-y-cwm. Hammer for scale. (Photo: BGS No. 13449, reproduced with the permission of the Director, British Geological Survey, © NERC.)

parts probably comprising mudstone or soft sandstone. Lovell (1978a) noted one thick bed of mudstone and one intraformational conglomerate. The sandstones show medium- to large-scale trough and planar cross-bedding. A thin (10 cm) sandstone 3 m below the top of the formation has convolute bedding that can be traced laterally for over 100 m. Palaeocurrents measured by Lovell (1978a) show a bi-modal distribution to the west and north-west, with a vector mean of 254°. The top of the formation is sharply overlain by the basal lag conglomerate of the Avon (Lower Limestone Shale) Group.

Interpretation

The Wern Watkin Formation is interpreted as the deposits of a generally southerly flowing sandy, braided, shallow fluvial system. The widespread mature calcrete at its top indicates a prolonged period of non-deposition and carbonate soil formation. The Craig-y-cwm Formation is interpreted as the deposits of mixed gravel–sand bedload braided streams. Overbank or floodplain fine sediment was largely reworked, but mudrock beds occur locally, as do mature calcretes, indicating periodic stability. The Garn-gofen Formation is interpreted as the deposits of meandering streams flowing from the north-east, with the abundance of clastic mica, garnet and feldspar indicating a metamorphic rock source.

Regionally, the Quartz Conglomerate Group crops out on the eastern rim of the South Wales Coalfield, extending from about Daren Cilau on the north crop eastwards to the Blorenge, and from there southwards to the Newport area. It also crops out on Pen-Cerrig-Calch and the Sugar Loaf to the north of the coalfield. To the west of Daren Cilau, the basal formation (Wern Watkin Formation) is correlated with the Grey Grits Formation (see **Duffryn Crawnon** GCR site report, this chapter), the upper two formations being absent. In the Forest of Dean, the Upper Old Red Sandstone is represented by basal quartz conglomerates (the Quartz Conglomerate, probably equivalent to the Craig-y-cwm Formation) and the overlying Tintern Sandstone Formation (probably equivalent to the Garn-gofen Formation). No fish remains have yet been recovered at the site, but fragments such as *Bothriolepis* sp. recovered elsewhere indicate a Late Devonian to Early Carboniferous age (Barclay, 1989).

Conclusions

Craig-y-cwm provides an excellent opportunity to examine easily the facies and formations that comprise the Upper Old Red Sandstone Quartz Conglomerate Group of the South Wales Coalfield. It is the type locality for the Craig-y-cwm and Garn-gofen formations, and a reference section for the Wern Watkin Formation. The detailed sedimentological analysis carried out at this site, among others, has led to an increased understanding of the fluvial depositional environments of the Late Devonian.

ROSS-ON-WYE, ROYAL HOTEL, HEREFORDSHIRE (SO 597 241–SO 595 239)

W.J. Barclay

Introduction

This site along Wilton Road, Ross-on-Wye (Figure 5.41) contains easily accessible, roadside cliff exposures of the Brownstones Formation, which forms the highest part of the Lower Old Red Sandstone magnafacies of south Wales and the Welsh Borderland. There are more extensive, but less accessible sections in nearby road cut-

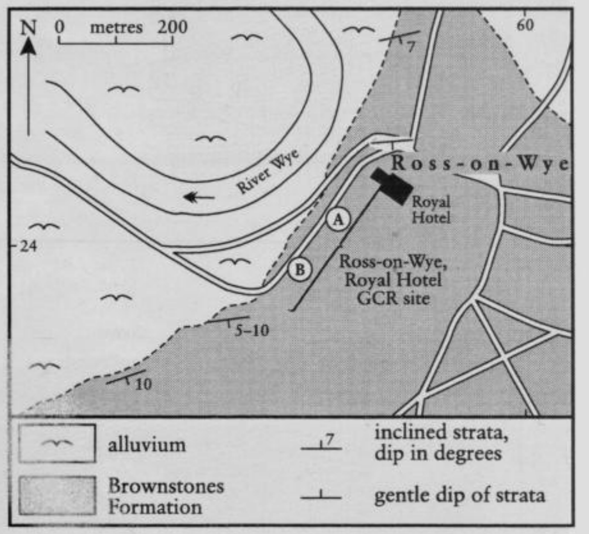


Figure 5.41 Location of Ross-on-Wye, Royal Hotel GCR site. After British Geological Survey Ross-on-Wye Special 1:10 000 Sheet (1980).

tings on the A40 at Glewstone (SO 567 223) and the A449 (SO 598 252); this site comprises an almost continuously exposed, 300 m-long section in which the architecture of the sandbodies can be easily seen. The Brownstones here are pebbly, cross-bedded sandstones, which formed in an alluvial, low-sinuosity, braided river system. The section has facilitated a reconstruction of bar morphologies, river channel sizes and palaeocurrent directions, and demonstrates the vertical stacking of the facies. The architecture of the stacked sand-bodies, representing in-channel bars and dunes, is typical of the eastern outcrops of the Brownstones Formation and contrasts with those farther west in south-central Wales, in which unconfined sheet sandstones are more typical. The sedimentological study of this site and the nearby road cuttings by J.R.L. Allen (1983a), and that of the beds between the Townsend and Pickard Bay Tuff beds in Pembrokeshire by Allen and Williams (1982) are the most detailed analyses of fluvial architecture carried out in the Anglo-Welsh Basin.

Description

Allen (1971, 1974b, 1978a, 1980, 1983a,b) provided detailed descriptions and illustrations of the section (Figure 5.42a,b). Smith (1980) provided a summary. The following description is based largely on Allen's work. The cliff section exposes about 25 m of beds over a distance of about 300 m. They lie in the upper part of the Brownstones Formation and dip gently to the SSE. The beds comprise mainly red-brown, fine- to coarse-grained, locally gravelly, cross-bedded, lenticular sandbodies, grouped into multi-storey complexes in which a hierarchical structure is defined by erosion surfaces. At the north-east end of the site, near the entrance to the Royal Hotel, a near-dip section shows cross-bedded, coarse-grained sandstones and pebbly, conglomeratic sandstones arranged in sets about 0.3–0.5 m thick, with foresets directed consistently to the south-west. There are also some parallel-laminated, fine- to medium-grained sandstones, many being the topsets of the cross-bedding foresets. Towards the south-west of the site, a

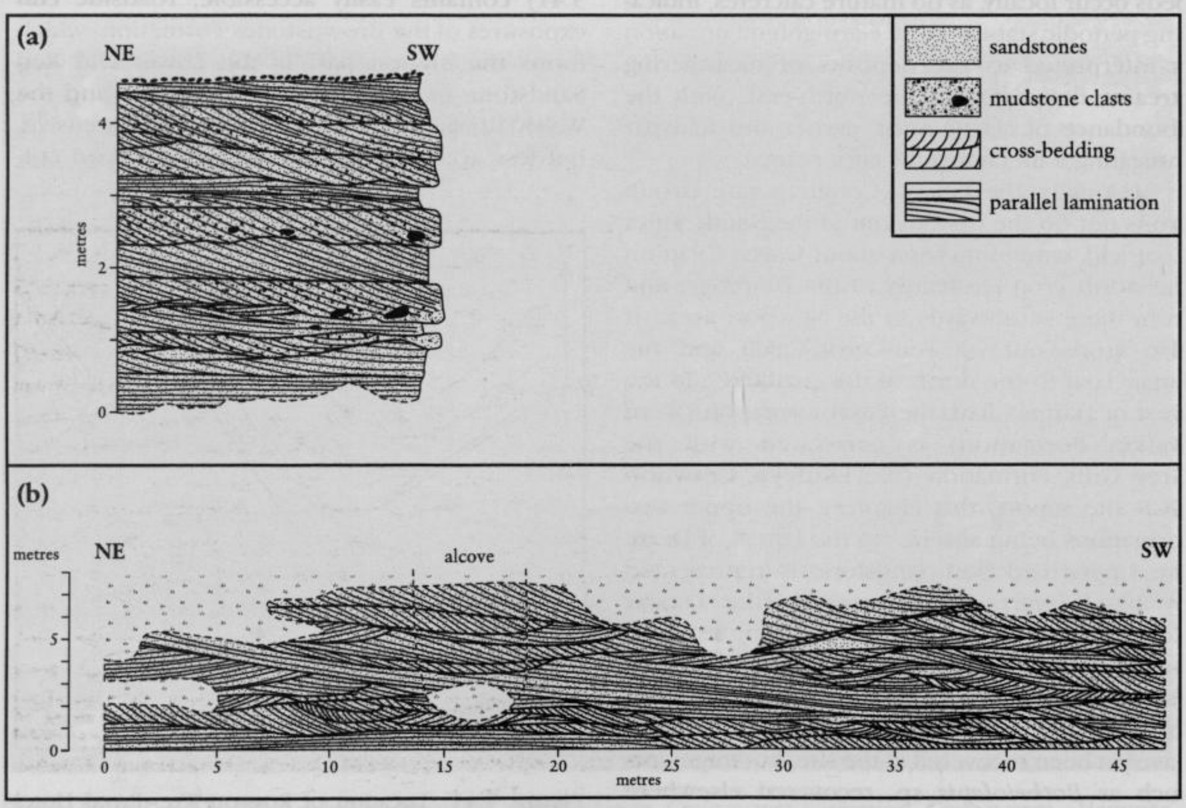


Figure 5.42 Graphic logs of the Brownstones Formation at the Ross-on-Wye Royal Hotel GCR site. (a) – vertical section at Point A on Figure 5.41; (b) – elevation showing sedimentary structures at Point B on Figure 5.41. After Allen (1971, 1978a).

near-strike section shows similar cross-bedded, pebbly sandstones and parallel-laminated sandstone bodies that have less consistent palaeocurrent directions (Figure 5.43). Parallel-laminated units extend laterally for up to 45 m. Most of the sandbodies rest on erosion surfaces and the pebbles include exotic types, as well as intraformational calcrete, mudstone and siltstone clasts, some of which are calcified, and a few of which are up to cobble or boulder size.

The exotic pebbles are mainly vein quartz, quartzite, cataclasite, jasper, acid lava, fine-grained green to red and yellow sandstones (?Lower Old Red Sandstone), a few with ?Silurian brachiopods, fine- to coarse-grained ?Silurian greywackes, pink sandstones with a Llandovery fauna and dark grey to black, fine-grained, acid lavas and tuffs with a mid-Ordovician shelly fauna, chert and 'oolite'. A detailed analysis of the pebbles is given by Allen (1974b).

Interpretation

Allen (1971) compared the rocks to those of modern sand-bed streams. He later (Allen, 1974b, 1983a,b) gave a detailed sedimentological interpretation of the section, as well as interpreting dune morphologies in exposures nearby as having formed by differentiation of a mixed bedload by gravel overpassing of hump-back bars (Allen, 1983b). The cross-bedded units originated as channel dunes or bars that migrated downstream with accompanying scouring. The absence of argillaceous flood-plain deposits, other than as reworked clasts in the conglomeratic and pebbly layers, suggests low-sinuosity, high-energy streams with steep gradients (Allen, 1974b, 1983a). The prevalence of siltstone clasts, but absence of siltstone interbeds points to deposition of silt drapes on floodplains and in abandoned channels, but constant channel switching led to their destruction. This, plus the low variance in cross-bedding directions, points to braided streams, with flashy behaviour suggested by the scoured surfaces at the bases of the sandbodies and the laterally impersistent fining-upward units. In addition, Allen (1983a) noted some epsilon cross-bedding in most of the complexes, indicating the presence of laterally accreted bars as well as the predominant, larger, downstream-migrating forms.

Allen (1971, 1974b) noted that except for the acid-lava pebbles, the pebble suite resembles that of the stratigraphically equivalent Monkeys Fold Formation of Brown Clee Hill in Shropshire and concluded that the pebbles were derived from Ordovician, Silurian, early Lower Old Red

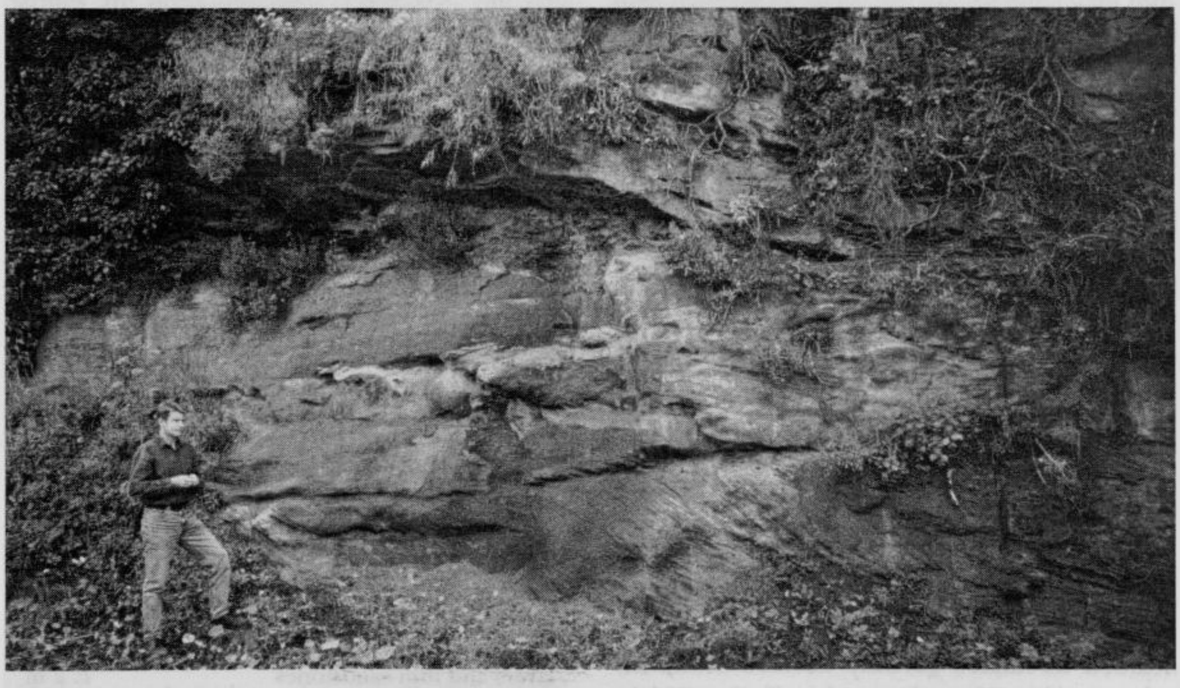


Figure 5.43 Cross-bedded sandstones of the Brownstones Formation at the Ross-on-Wye, Royal Hotel GCR site. (Photo: W.J. Barclay.)

Sandstone and perhaps Precambrian outcrops in north Wales and Anglesey.

The markedly lenticular, channelized sandstones present in this section, typical of the Brownstones Formation of the Welsh Borderland and south-east Wales, contrast with the more heterogeneous Brownstone successions farther west in the Brecon Beacons, where, in addition to the braided channel facies seen in the Ross-on-Wye section, interbedded sheet-like sandstone bodies and floodplain siltstones were interpreted by Tunbridge (1981a) as representing deposition in a more distal setting on an extensive alluvial plain.

Conclusions

The site comprises easily accessible roadside cliff exposures of the Brownstones Formation. The section has been the subject of a detailed sedimentological analysis and interpreted as the deposits of braided, steep, flashy rivers. Its study has allowed reconstruction of bar morphologies, river channel sizes and palaeocurrent directions. The far-travelled pebbles in the sandstones and conglomerates were derived from a northerly Welsh source, consistent with the general southerly flow of the streams that carried them.

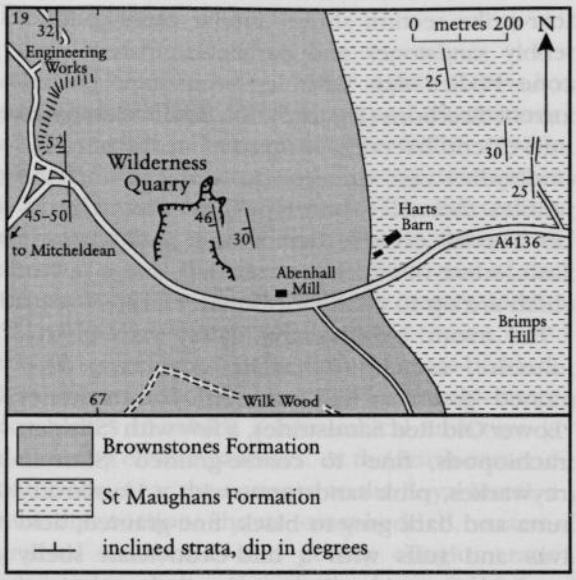


Figure 5.44 Geological map of the area around Wilderness Quarry. After British Geological Survey 1:10 560 manuscript map Gloucs. 23SE (1956).

WILDERNESS (LAND GROVE) QUARRY, GLOUCESTERSHIRE (SO 672 185)

W.J. Barclay

Introduction

This site near Mitcheldean, Gloucestershire is a working building stone quarry in the Early Devonian Brownstones Formation of the Lower Old Red Sandstone (Figure 5.44). The site is important in displaying a fine section of alluvial facies that represent deposition in an environment that was intermediate between the more distal environments of the underlying Dittonian St Maughans Formation and the more proximal, sand-dominated environments of the higher parts of the Brownstones. The vertical arrangement of the facies in the quarry were included in Allen's (1964a) detailed study of cycles in the Dittonian rocks of the Welsh Borderland, and thus instrumental in the modelling of Early Devonian Old Red Sandstone alluvial environments. The site is of national and international importance in being the only locality in the Brownstones Formation to have yielded remains of the late Dittonian index fish *Althaspis leachi*.

Description

The quarry exposes beds dipping steeply (*c.* 30°) westwards (Figure 5.45). They lie about 150 m above the base of the Brownstones Formation of the Forest of Dean (Welch and Trotter, 1961). Allen (1962, 1964a,b, 1971) and Allen *et al.* (1968) gave detailed descriptions of this quarry. Currently, about 23 m of beds are exposed, the section summarized as:

	Thicknesses (m)
Thinly bedded, red-brown sandstones and mudstones	*c.* 10 m
Red-brown sandstones in large channels, some sandstone beds up to 1 m thick; thin red-brown mudstone interbeds	*c.* 6 m
Mudstone, red-brown; prominent persistent bed	*c.* 1 m
Sandstone, red-brown, in beds of about 1 m average thickness	*c.* 4 m
Mudstone, red-brown, with pale green layers and thin sandstones	*c.* 2 m
Sandstone; top forms prominent bedding plane at eastern limit of workings	

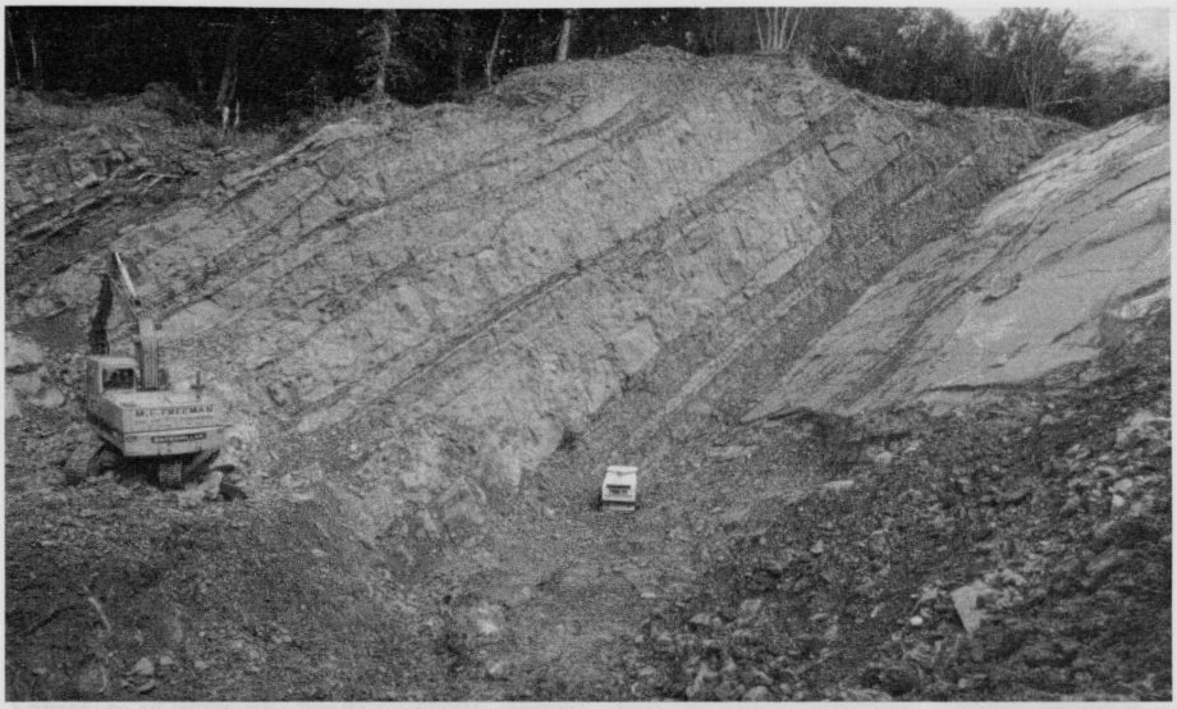


Figure 5.45 Wilderness Quarry. Main face showing major channelized sandstone bodies and intervening thin mudstones: (Photo: R.T. Mogridge.)

The following account of the succession (Figure 5.46) is based largely on the descriptions of Allen (in Allen *et al.*, 1968; Allen, 1971). The sandstones are predominantly red-brown, but pale green reduced zones occur at the bases of beds and in local random patches. Some red/green colour layering is present locally. Fine- to medium-grained, red-brown sandstones predominate, with some very fine-grained sandstones. Minor lithologies include coarse-grained, red-brown siltstones, intraformational conglomerate and red-brown siltstones/mudstones with calcrete nodules. The sandstones are mainly parallel-laminated, but cross-bedding occurs at some levels. The finer-grained sandstones are commonly cross-laminated and have rippled bedding surfaces. The siltstones are poorly bedded, although some are cross-laminated and most are strongly bioturbated. The intraformational conglomerates consist of rounded to angular clasts of siltstone and mudstone, very fine-grained sandstone and calcrete set in a sandy matrix. Intraformational mudstone/ siltstone clasts are common, mainly occurring as concentrations at the bases of channel-fill sandstones, but they also occur sporadically throughout the sandstones.

The beds are arranged in fining-upward cycles. Each has a basal scoured surface overlain by sandstones, and locally conglomerates, in turn overlain by siltstones interbedded with thin sandstones. Fine-grained sandstone-filled desiccation cracks are present locally towards the tops of the siltstones. The scoured surfaces locally cut steeply down into the siltstones and thin sandstones of the underlying cycle. Broad, shallow channels are common in the siltstones, locally extending down to the underlying thick sandstones.

Wilderness Quarry is noted also for yielding one of the highest ostracoderm faunas known from the Lower Old Red Sandstone of south Wales and the Welsh Borderland (Allen *et al.*, 1968). The assorted, disarticulated remains of the ostracoderm *Althaspis leachi* (White) and, very rarely, the articulated remains of the thelodont *Turinia pagei* (Powrie) were collected from a distinctive bed of purplish to greenish white sandstone within siltstones 29 m above the base of the section recorded in 1968. This bed occurs high up on the western face of the quarry, but was formerly exposed by the entrance to the quarry 2 m above the quarry floor. In addition, the quarry yields several

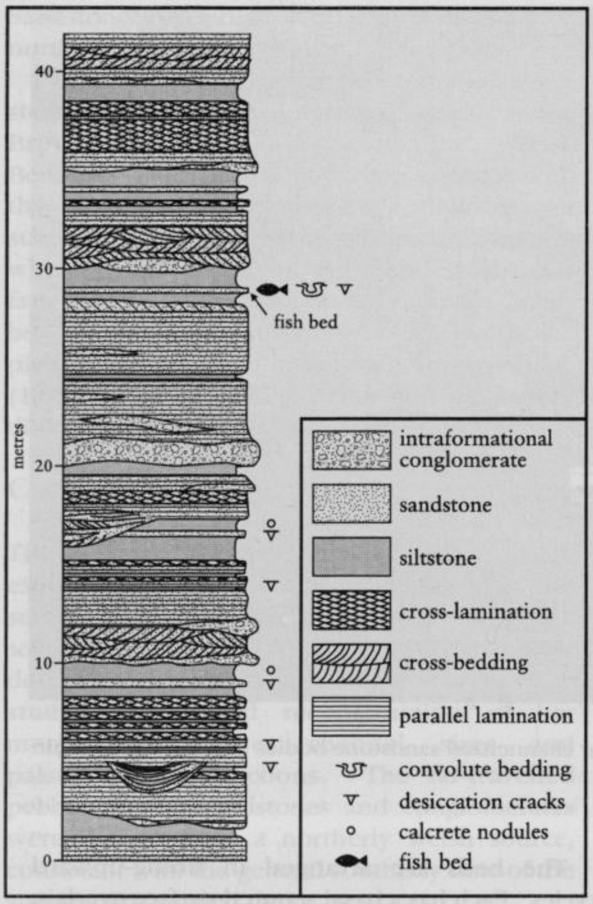


Figure 5.46 Generalized section of the Brownstones Formation at Wilderness Quarry. After Allen (1971).

different types of trace fossil, which are particularly abundant in the siltstones. The traces include irregularly, randomly orientated, branching tubes with longitudinally crinkled walls and less common smooth, sinuous tubes on bedding planes. *Planolites* occurs in the fish-bearing sandstone.

The fish-bearing sandstone ranges between 14 cm and 25 cm thick and overlies a red siltstone that fills and extends beyond a shallow depression in the top of the underlying sandstone. At its thickest, the bed is a tough, green, fine-grained, parallel-laminated sandstone with scattered siltstone clasts at its base. Over most of its outcrop in the quarry, the bed is a distinctive, fine- to very fine-grained, pinkish to mauve-brown sandstone that is parallel laminated at its base and cross-laminated in its finer-grained upper part. Convolute bedding is widespread.

Interpretation

The succession is interpreted as one that accumulated on an alluvial floodplain (e.g. Allen, 1964a, 1971; Allen *et al.*, 1968). The scoured surfaces at the bases of the cycles were cut by stream channels migrating laterally across the floodplain. The channel-fill sandstones were deposited in high-energy streams, with planar sandstone beds being more common than dune forms. The fine-grained, argillaceous lithologies are interpreted as overbank, extra-channel floodplain deposits, as indicated by their desiccation cracks and pedogenic carbonate (calcrete) nodules. The fish bed, occurring within fine-grade, floodplain facies, probably originated as a flash-flood deposit, either as a crevasse-splay sheet-flood or levee.

Fossil fish remains collected by Sibly in 1915 were first identified as *Pteraspis* cf. *dunensis* (Trotter, 1942) and later as the Breconian index fossil *Rhinopteraspis dunensis* (Welch and Trotter, 1961). These, as well as a large collection of pteraspid fragments obtained in 1965 were assigned to *Althaspis leachi* (Allen *et al.*, 1968). The presence of this late Dittonian index fossil in beds previously assumed to be Breconian in age emphasizes the need for more accurate definition of the local Anglo-Welsh stages, but may also demonstrate the diachronism of the Brownstones Formation.

Conclusions

Wilderness Quarry provides the best exposure in the Welsh Borderland at which to examine a facies of the Brownstones Formation that is transitional between those of the underlying St Maughans Formation and the overlying, more typical, Brownstones. Although sandstones dominate, mudstone interbeds are common and divide the succession into typical cycles comprising alluvial meandering channel deposits and overbank floodplain facies.

The site is internationally important in yielding the only fossil vertebrate remains from the Brownstones Formation. The occurrence of abundant disarticulated fragments of the late Dittonian index fossil *Althaspis leachi* in a floodplain deposit is one of a few such occurrences in the Anglo-Welsh Basin, and provides an insight into the contemporaneous habitats and sedimentary environments of the Anglo-Welsh Basin during Early Devonian times.

LYDNEY, GLOUCESTERSHIRE (SO 652 015–SO 655 023)

P.R. Wilby

Introduction

This site is situated on the north-west bank of the River Severn in Gloucestershire and extends northwards from Lydney Harbour (SO 652 015) to a point mid-way between Fairtide Rock (SO 655 021) and Cliff Farm (SO 656 025) (Figure 5.47). It consists of laterally extensive cliff and foreshore sections in the uppermost part of the Raglan Mudstone Formation and the lowermost few metres of the St Maughans Formation. The Raglan Mudstone Formation is mostly of Přídolí (Silurian) age and the St Maughans Formation is Early Devonian (Lochkovian–Dittonian stage), with the Silurian–Devonian boundary thought to lie within the uppermost part of the Raglan Mudstone Formation. The locality has played a key role in establishing the extent of both fluvial and marine influences in the deposition of the Lower Old Red Sandstone, and includes a regionally important fish fauna, for which it is independently selected as a GCR site (Dineley and Metcalf, 1999). It is also one of only a few sites in the Anglo-Welsh Basin that has yielded modiolopsid bivalves at this stratigraphical level. In addition, the site contains several mature fossil soil carbonate (calcrete) profiles, including the regionally important Psammosteus Limestone (the Bishop's Frome Limestone of the Welsh Borderland and the Chapel Point Calcretes Member of Pembrokeshire).

Description

The section was initially documented by Welch and Trotter (1961), who described its geological context and identified the Psammosteus Limestone. Subsequently, Allen (1964a) examined the locality in greater detail and recognized the palaeoenvironmental significance of a complex cyclothem, which contributed to the establishment of a fluvial, meandering stream model for the deposition of large parts of the Lower Old Red Sandstone. The limestones at the site were among those used to develop a model for soil carbonate (calcrete) formation in the Old Red Sandstone of the Anglo-Welsh Basin (Allen, 1974d).

Allen (1964a, 1971) placed the cyclothem he described, and thus a large part of the sequence at Lydney, in the St Maughans Formation. Later, however (Allen, 1974d, 1978b), he recognized that the cyclothem actually lies beneath the Psammosteus Limestone, which forms the topmost bed of the underlying Raglan Mudstone Formation. Confusion over the stratigraphical position of the cyclothem, and that of the associated fish faunas, has since been compounded by Dineley (1999e, fig. 3.19). He produced an erroneous composite section by combining two different versions (Allen, 1964a, fig. 5 and Allen, 1978b, fig. 34) of the same cyclothem, one of which he placed above the Psammosteus Limestone and the other beneath it.

The sequence is gently folded and cut by several NW-trending faults. Between two prominent faults (SO 652 016; SO 655 023), the first about 200 m north of the harbour wall, the topmost mudstones of the Raglan Mudstone Formation are downthrown to the level of the foreshore and can be examined in laterally continuous exposures over several hundred metres (Figure 5.47). The Psammosteus Limestone and a few metres of the overlying St Maughans Formation are well exposed above about halfway up the cliff face just to the north of Fairtide Rock.

The section in the Raglan Mudstone Formation is typical of the unit elsewhere in Wales and the Welsh Borderlands. It consists predominantly of thick, red, micaceous, calcretized mudstones and siltstones, interbedded with thin, very fine-grained sandstones. It is, however, notable at this site in containing bivalve molluscs, one of only a few occurrences known at this level (Barclay *et al.*, 1994). The bivalves (*Modiolopsis complanata* Sowerby var. *trimpleyensis* Reed) are preserved in abundance and in life position, most with their valves tightly closed, in two thin layers within a 5 m-thick interval of red, well-bedded, coarse siltstones on the foreshore not far beneath the Psammosteus Limestone (Allen, 1973a). Scattered fish debris and abundant sub-vertical burrows are also present. The bivalves were examined by Allen and a British Geological Survey party in 1980, but were not located during a visit to the site in 2000 and are now probably concealed beneath estuarine mud. Among the fish remains recovered from intraformational conglomerate layers, Dineley (1999e) lists the heterostracan *Tesseraspis tessellata* Wills and the unusual acanthodian *Sabrinacanthus arcuatus* Miles.

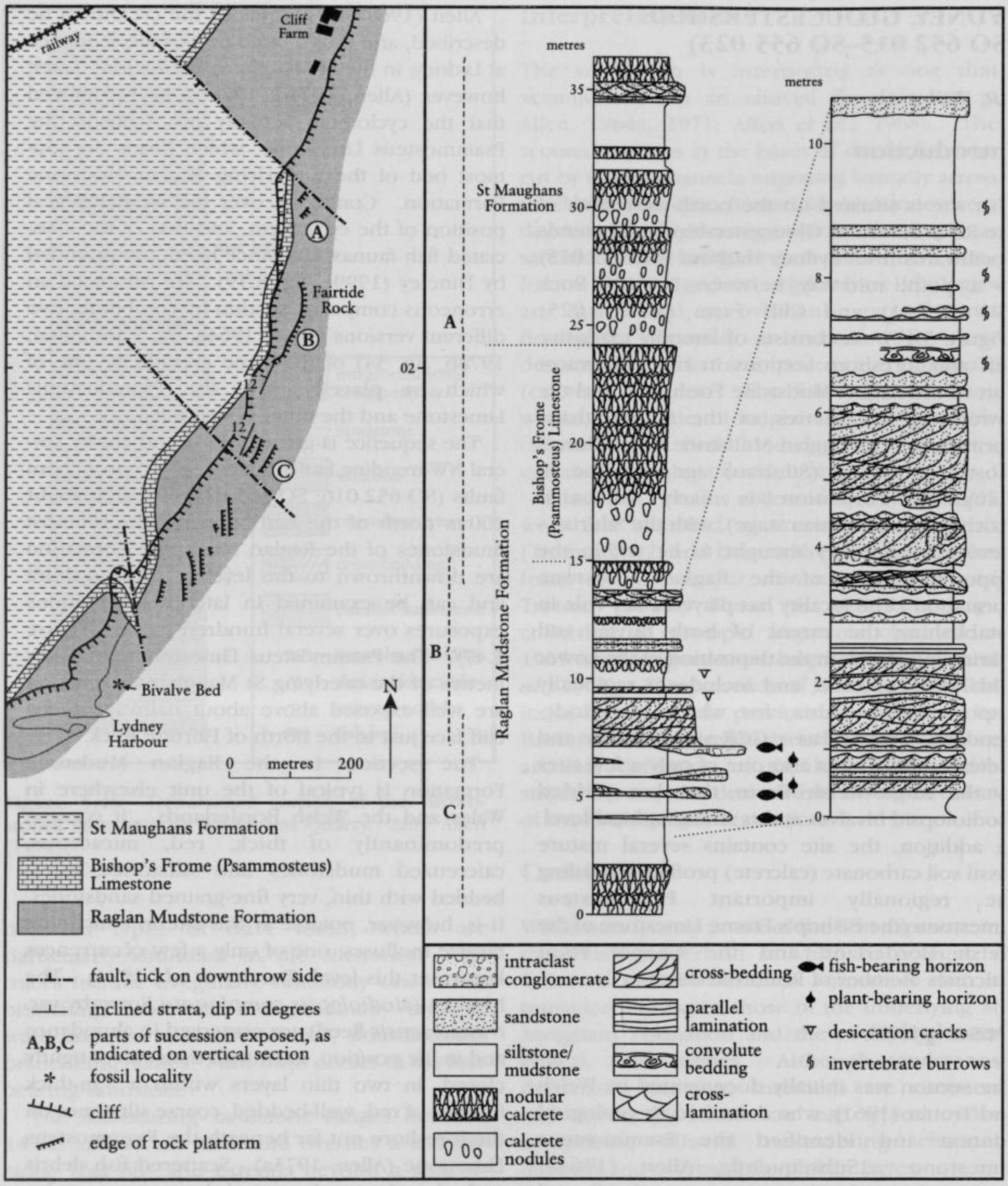


Figure 5.47 Geological sketch map of Lydney GCR site (inset) and composite vertical section of the strata exposed. Map after British Geological Survey 1:10 560 manuscript map SO 60SE (1973). Section based on Allen (1978b) and Dineley (1999e, fig. 3.19).

The cyclothem immediately below the Psammosteus Limestone consists of three facies arranged in a fining-upward sequence, and is best exposed on and around Fairtide Rock. The lowermost facies rests on a scoured surface of red silty mudstones with abundant calcrete nodules. It consists of finely interbedded pale green siltstones, some of which yield plant fragments, and white to green, fine- to coarse-grained lenticular sandstones. The sandstones have sharp bases, locally resting on erosion surfaces. They contain mudstone rip-up clasts, are cross-stratified, and have sharp, rippled or smooth tops. They are generally 5–25 cm thick and locally contain fish debris, *Pachytheca* and other carbonized plant fragments. These beds are sharply overlain by red, green and purple, micaceous, cross-bedded, fine- to medium-grained sandstones of the second facies. Most of the sets in this facies are planar, but some are contorted owing to extensive de-watering. This facies everywhere lies on a scoured surface, and locally, a 20 cm-thick intraformational conglomerate. The topmost facies comprises red, coarse-grained, micaceous siltstones inter-bedded with thin (less than 16 cm), red, mauve and white, ripple-bedded sandstones. The sandstones range from clayey and fine-grained to clean and medium-grained. Some of their tops are gradational, but all of their bases are sharp and some overlie surfaces with desiccation cracks. The top few metres of the cyclothem consist of red, clayey siltstones and sandy siltstones with abundant calcrete nodules, faint ripple-bedding and rare invertebrate burrows. The cyclothem terminates at the base of a thin sandstone, 10.5 m beneath the base of the St Maughans Formation. Directional structures throughout the cyclothem consistently indicate palaeoflow from the north.

Above the cyclothem are 20 m of red mudstone containing six calcrete profiles, the first three of which are particularly mature. The first and third profiles comprise massive limestone beds, and the second profile (the Psammosteus Limestone) is especially thick (9 m). It shows a gradual upward increase in the size and density of calcrete nodules from small, sporadic nodules at the base to a persistent horizon of closely packed, crudely prismatic nodules at the top. The Psammosteus Limestone and several other calcrete profiles show superb examples of pseudo-anticlines and nodule fans (Figure 5.48). The most prominent forms have a regularly undulose top in which cuspate or sharply rounded crests are separated by broadly rounded troughs on a scale of several metres. Within these 'folds', the calcrete nodules are arranged in fan-like arrays.

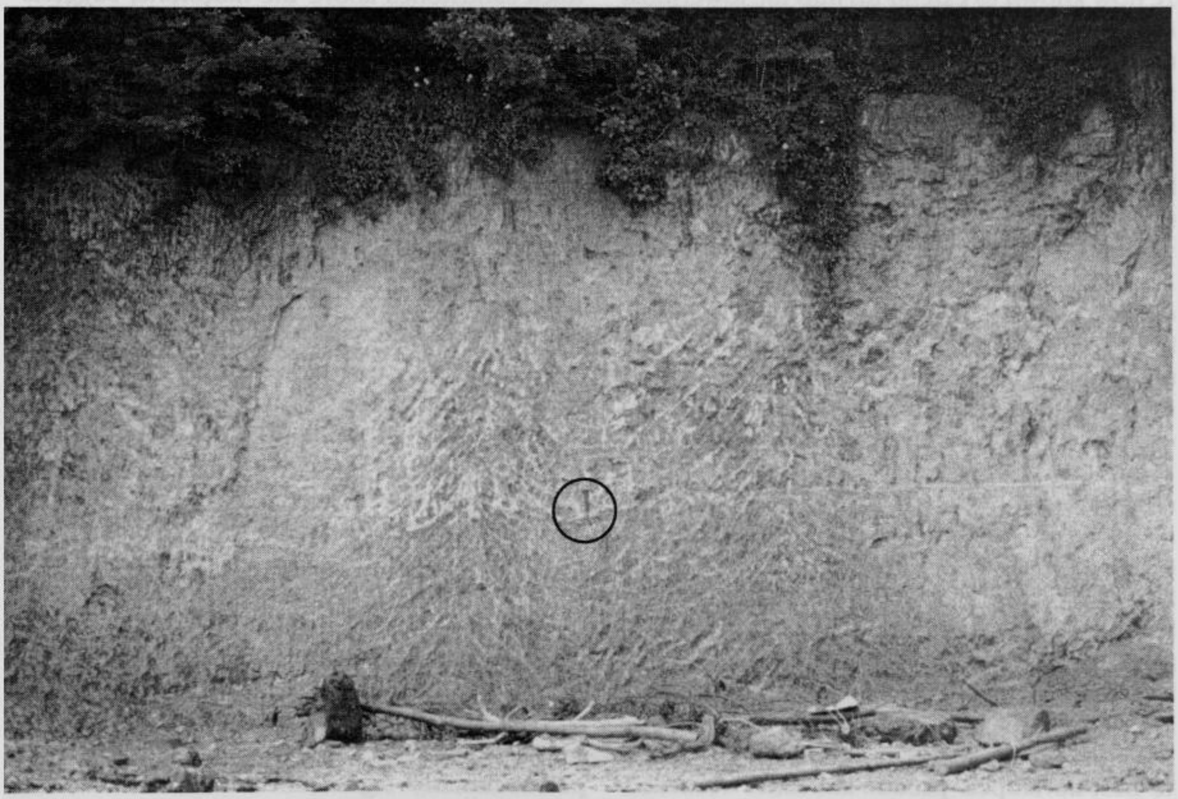


Figure 5.48 Calcrete profile in the Psammosteus Limestone at Lydney showing pseudo-anticlinal structure. Hammer (circled) for scale. (Photo: P.R. Wilby.)

Interpretation

The locality provides an excellent section of the strata at the boundary between the Raglan Mudstone Formation (Downtonian) and the St Maughans Formation (Dittonian). The boundary corresponds to an important tectonically induced diastem, represented by basin shut-down and major pedogenic carbonate development, and which more-or-less coincides with a major faunal and facies change (Allen and Tarlo, 1963; Allen, 1985; Dineley, 1999e). The Raglan Mudstone Formation was deposited on extensive coastal mudflats traversed by sparse channels (Allen, 1985). The section at Lydney has played an important part in assessing the nature, extent and timing of marine influence on these mudflats, and the nature of the transition from the marine environments of late Silurian times to the terrestrial, continental environments of early Devonian times (Allen, 1985). It is one of a handful of occurrences in the Welsh Borderland that has yielded a low-diversity, brackish to marine bivalve mollusc fauna (Allen, 1973a; King, 1934) at this level. These faunas, which are now known to extend up into the lowermost part of the St Maughans Formation (Barclay *et al.*, 1994), record short-lived, but probably quite extensive, brackish-water incursions on to the coastal mudflats (Allen, 1973a).

Further evidence for marine influence in the deposition of the Raglan Mudstone Formation is afforded by the lowermost facies of the cyclothem at Lydney. It consists of rapid alternations of siltstone and lenticular sandstone, which, based on modern analogues, suggests deposition in a tidal river channel in which the freshwater was periodically backed up by advancing tides (Allen, 1964a). The overlying part of the cyclothem was probably deposited in a non-tidal, meandering river that migrated across, and incised into, the deposits of an earlier channel system, with the finer topmost beds representing overbank facies. This non-tidal part is typical of cyclothems elsewhere in the Lower Old Red Sandstone and provides strong evidence for a fluvial origin of much of the sequence in the Anglo-Welsh Basin (Allen, 1964a).

The overlying calcrete profiles exhibit some of the best-developed pseudo-anticlines recorded from the Old Red Sandstone of Britain, comparable to those in Pembrokeshire. Lydney was one of five localities at which Allen (1974d) demonstrated a pedogenic origin for the limestones in the Old Red Sandstone of the Anglo-Welsh Basin. By comparison with modern examples, he concluded that they formed by replacive and displacive development of calcite in alluvial, floodplain muds. Pseudo-anticlines and related structures develop due to the swelling of the clay-rich sediment and the displacive growth of the calcite in response to seasonal wetting and drying (Allen, 1973b; 1974d, 1986). Allen (1974d, 1985) deduced that the climate in the Anglo-Welsh region during deposition of the Lower Old Red Sandstone was relatively warm (mean annual temperature of 16°–20°C), with low, seasonal rainfall averaging 100 mm to 500 mm per annum. He estimated that each calcrete profile records a period (and depositional break) of the general order of 10^4 years. Marriott and Wright (2004) provide a more recent discussion of calcrete formation, which may have taken tens of thousands to millions of years. The Psammosteus Limestone at Lydney, as at other localities, is particularly mature and is notable for its considerable thickness. This, together with the incoming of thick sandstones above the limestone, suggests that it records a regional, tectonically controlled event that resulted in changes to the source and rate of sediment supply to the basin (Allen, 1985).

Conclusions

The riverside cliffs at Lydney provide one of the best and most accessible sections in the uppermost part of the Přídolí–Lower Devonian (Downtonian) Raglan Mudstone Formation. The beds comprise a basal complex sandstone body of intertidal origin, and pass up through fluvial sediments into a stacked series of calcrete profiles, including the regionally important Psammosteus Limestone. The site is important because of its role in helping to model the depositional environments of the Lower Old Red Sandstone, and in determining the degree of marine influence during the transition into the overlying, wholly terrestrial Old Red Sandstone facies. In addition, it has played a key role in understanding the genesis of fossil calcretes and their palaeoenvironmental and palaeoclimatic significance. It is a site of continuing research, particularly into the composition of its fish faunas.

ALBION SANDS AND GATEHOLM ISLAND, PEMBROKESHIRE (SM 771 074)

Potential ORS GCR site

W.J. Barclay

Introduction

This site was described in detail in the companion Silurian stratigraphy GCR volume (by Lane in Aldridge *et al.*, 2000) on account of the late Silurian (Ludlow–Přídolí) age of the lowermost beds of Old Red Sandstone red-bed facies. Only a brief summary is given here, with an updated interpretation based on recent work on the marine Silurian–Old Red Sandstone junction by Hillier (2000) and Hillier and Williams (2004). The site comprises the cliffs and foreshore at Albion Sands and on the adjacent Gateholm Island (Figure 5.49). It provides a magnificent section of almost 250 m of strata dipping steeply on the southern limb of the Marloes Anticline (Figure 5.50). Following early accounts by the [British]

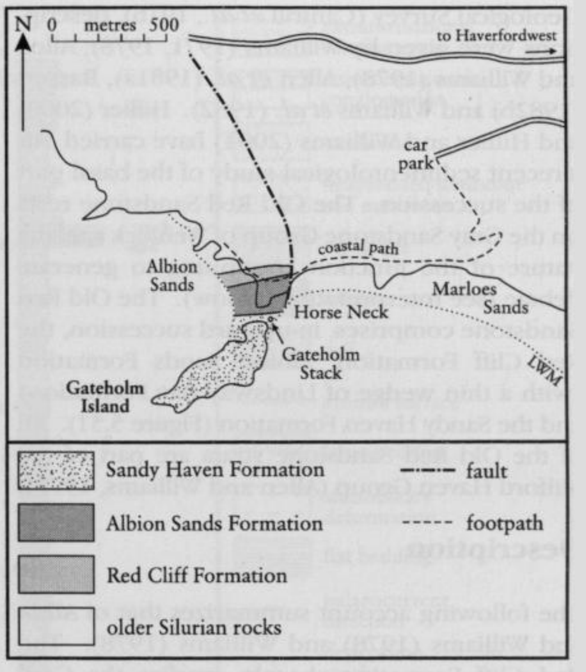


Figure 5.49 Location and simplified geology of Albion Sands and Gateholm Island. Based on Williams (1978) and Lane (2000c, fig. 6.20).

Figure 5.50 Oblique aerial view looking ENE to Albion Sands, the promontory of Horse Neck connecting with Gateholm Island, and Marloes Sands. (Photo: S. Howells.)

Geological Survey (Cantrill *et al.*, 1916), descriptions were given by Williams (1971, 1978), Allen and Williams (1978), Allen *et al.* (1981a), Bassett (1982b) and Williams *et al.* (1982). Hillier (2000) and Hillier and Williams (2004) have carried out a recent sedimentological study of the basal part of the succession. The Old Red Sandstone rests on the Gray Sandstone Group of Wenlock age, the nature of the junction continuing to generate debate (see Interpretation, below). The Old Red Sandstone comprises, in upward succession, the Red Cliff Formation, Albion Sands Formation (with a thin wedge of Lindsway Bay Formation) and the Sandy Haven Formation (Figure 5.51). All of the Old Red Sandstone strata are part of the Milford Haven Group (Allen and Williams, 1978).

Description

The following account summarizes that of Allen and Williams (1978) and Williams (1978). The Red Cliff Formation sharply overlies the Gray Sandstone Group at the northern end of the section. It comprises 51.6 m of interbedded red-brown mudstones and very fine- to fine-grained, bioturbated sandstones. Calcrete nodule horizons are present in a few of the mudstones. A Ludlow (late Ludfordian) spore assemblage has recently been recovered from the formation (Hillier and Williams, 2004). The Albion Sands Formation is named from this locality. It is over 100 m thick and consists mainly of thick, pale yellow to buff, multi-storey sandstones. Thin red-brown laminated mudstone interbeds occur throughout, with 11 m of mudstones with calcrete nodules lying at the top of the formation, as defined by Allen and Williams (1978). Calcrete nodules appear to be absent in the mudstone interbeds below, prompting Lane (in Aldridge *et al.*, 2000) to note that the topmost 11 m are much more like the calcrete-bearing mudstones in the overlying Sandy Haven Formation. Mudcracks in the laminated mudstones are desiccation cracks, and not synaeresis cracks as stated by Lane (in Aldridge *et al.*, 2000). The sandstones comprise individual bodies over 2 m thick and common multi-storey bodies up to 5 m thick. They have sharp tops and bases, the latter resting on erosion surfaces and commonly containing lenses of intraformational conglomerate with mudstone clasts up to cobble size. The sandstones also contain much igneous debris, and extraformational conglomerates also occur locally. The petrography of the sandstones and conglomerates indicates a westerly provenance. Thin airfall dust- and crystal-lithic tuffs occur sporadically, including a distinctive 1 m-thick, lilac, purple, red and yellow mottled dust tuff. A thin (7.42 m) wedge of conglomerates in the upper part of the formation outcrops on Horse Neck (SM 7718 0751) is correlated with the Lindsway Bay Formation. Here, it comprises petromictic conglomerates with exotic igneous pebbles interbedded with ill-sorted, granule-rich mudstones. The conglomerates have the greatest assortment of clasts of any petromict in the Old Red Sandstone of southern Britain.

The base of the Sandy Haven Formation is placed on Gateholm Stack (SM 7725 0746), where there is a conformable transition with the underlying Albion Sands Formation. About 85 m of beds comprise mainly bright red mudstones and thin pebbly sandstones. The mudstones are heavily calcretized, with mature soil carbonates and pseudo-anticlinal structures. The pebbly sandstones have yielded *?Onchus wheathillensis*, *Pachytheca* and lingulids. Large-scale synsedimentary faults were recorded at Horse Neck by Hillier (2000).

Interpretation

The nature of the base of the Old Red Sandstone has generated much debate. A conformable contact with the underlying Wenlock Gray Sandstone Group was advocated by Cantrill *et al.* (1916), Sanzen-Baker (1972), Walmsley and Bassett (1976) and Hurst *et al.* (1978) and assigned a late Wenlock, or, at the latest, early Ludlow age. Allen and Williams (1978) preferred a disconformable contact, with the basal Old Red Sandstone being Downtonian (Přídolí) in age. Recent spore analysis has confirmed a late Wenlock (Homerian) age for the Gray Sandstone Group (Hillier and Williams, 2004). Hillier (2000) re-affirmed a conformable junction, with terrestrial red-bed sedimentation commencing here in the Ludlow. This is confirmed by the presence of late Ludfordian spores in the Red Cliff Formation (Hillier and Williams, 2004). Hillier (2000) and Hillier and Williams (2004) attribute the succession to the final of five episodes of incision and valley-fill in a structurally controlled basin. Transtensional movement on a series of NE-trending faults produced rifting on the southern margins of the Lower Palaeozoic Welsh Basin, producing local basins (the Skomer Basin in this case) fed with

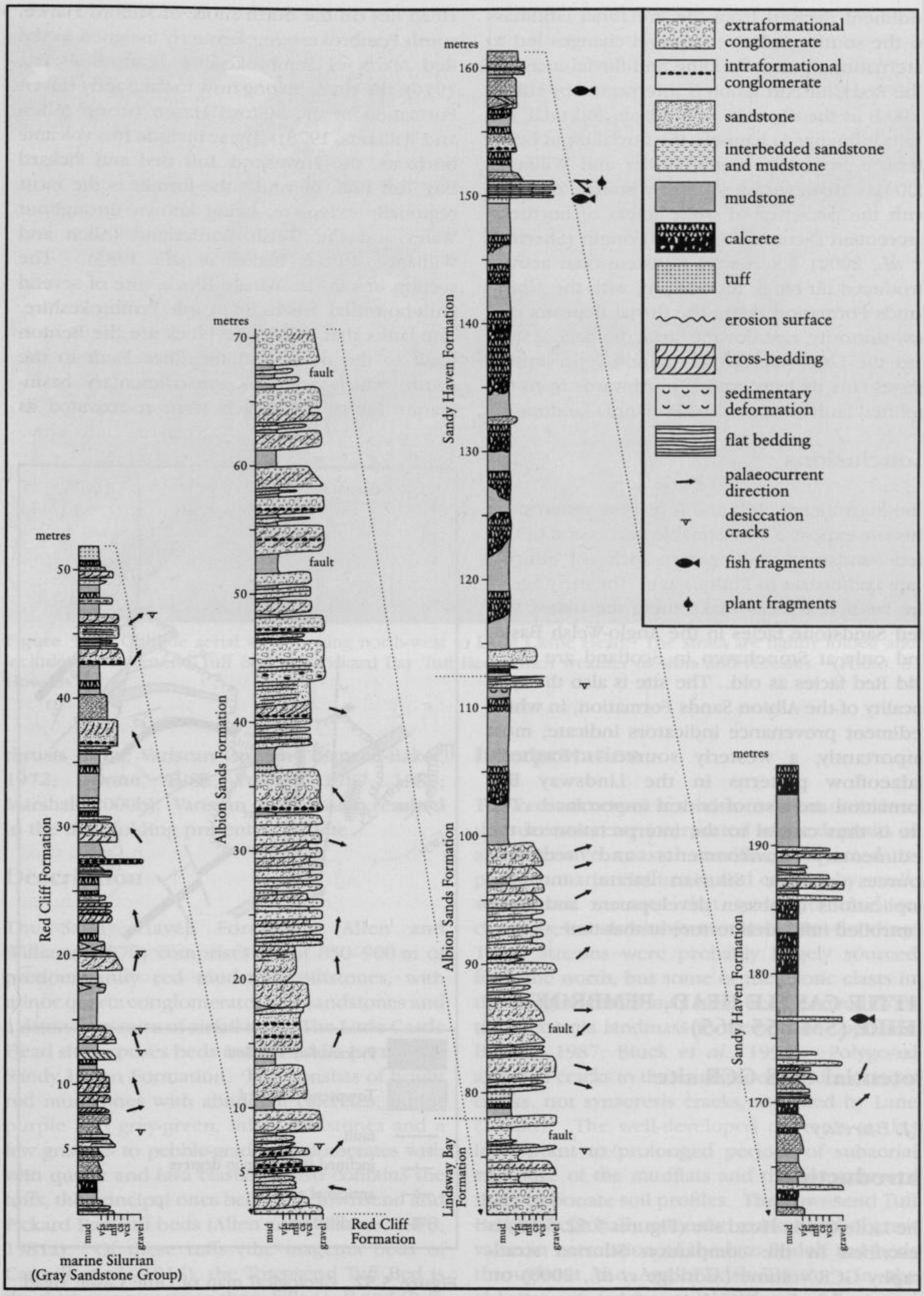


Figure 5.51 Vertical section of the strata at Albion Sands and Gateholm Island. After Williams (1978).

sediment derived from the Pretannia landmass to the south. Relative sea-level changes led to alternating marine flooding and fluvial incision. The Red Cliff Formation is interpreted by Hillier (2000) as the deposits of mudflats and tidal, fluvially influenced channels, the fluvial input being derived from the south (Hillier and Williams, 2004). However, a southerly source conflicts with the presence of white micas of northerly Laurentian (Scottish Highland) origin (Sherlock *et al.*, 2002). Renewed transtensional activity produced tilt block topography, with the Albion Sands Formation being the fluvial deposits of a low-sinuosity, east-flowing, axial drainage system and the Lindsway Bay Formation representing gravel fans that prograded northwards from the uplifted fault scarps of the Pretannia landmass.

Conclusions

The magnificent cliffs and foreshore outcrops at this site expose a conformable succession of Old Red Sandstone sedimentary rocks of Silurian (late Ludfordian to Přídolí) age. The early age of the basal red rocks make them the oldest Old Red Sandstone facies in the Anglo-Welsh Basin, and only at Stonehaven in Scotland are there Old Red facies as old. The site is also the type locality of the Albion Sands Formation, in which sediment provenance indicators indicate, most importantly, a westerly source. Northerly palaeoflow patterns in the Lindsway Bay Formation are also of critical importance. The site is thus crucial to the interpretation of the sedimentary environments and sediment sources of late Silurian strata, and the implications for basin development and fault-controlled infill architecture at that time.

LITTLE CASTLE HEAD, PEMBROKESHIRE (SM 855 065)

Potential ORS GCR site

W.J. Barclay

Introduction

The Little Castle Head site (Figures 5.52, 5.53) is described in the companion Silurian stratigraphy GCR volume (Aldridge *et al.*, 2000) on account of the late Přídolí age of the strata. Only a brief account is presented here. Little Castle Head lies on the north shore of Milford Haven, south Pembrokeshire. Formerly assigned to the Red Marls of Pembrokeshire (Cantrill *et al.*, 1916), the strata belong now to the Sandy Haven Formation of the Milford Haven Group (Allen and Williams, 1978). These include two volcanic horizons, the Townsend Tuff Bed and Pickard Bay Tuff Bed, of which the former is the most regionally extensive, being known throughout Wales and the Welsh Borderland (Allen and Williams, 1981a; Parker *et al.*, 1983). The section lies in the Winsle Block, one of several fault-bounded basins in south Pembrokeshire. The faults that define the block are the Benton Fault to the north and the Ritec Fault to the south, which acted as synsedimentary basin-margin faults and which were re-activated as

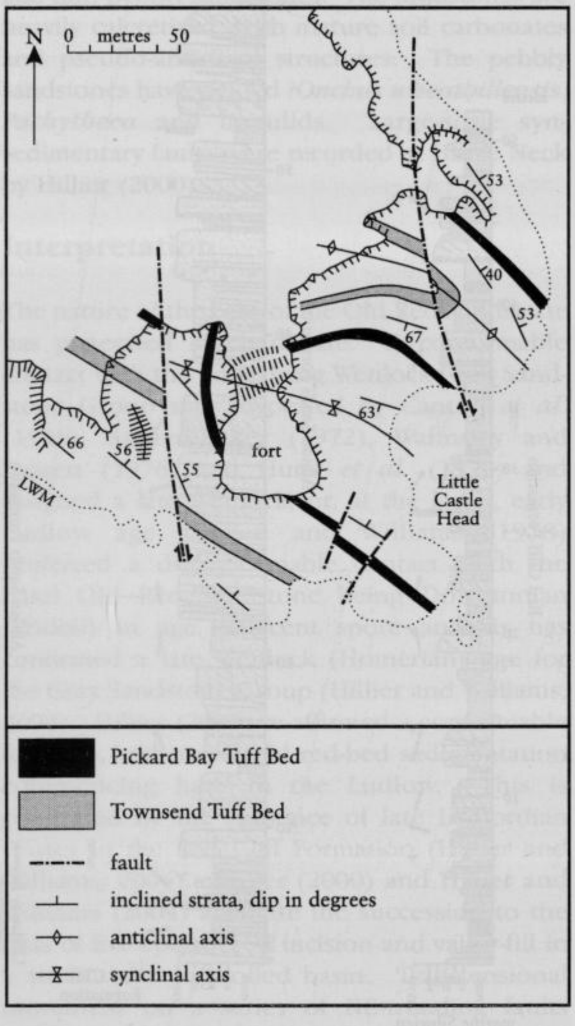


Figure 5.52 Geological map of Little Castle Head. Based on Allen (1980), Hancock *et al.* (1982) and Parker *et al.* (1983).

Figure 5.53 Oblique aerial view looking north-west to Little Castle Head. The strata are tightly folded and include the Townsend Tuff Bed and Pickard Bay Tuff Bed, which weather to slots and recesses. (Photo: S. Howells.)

thrusts in the Variscan Orogeny (Sanzen-Baker, 1972; Dunne, 1983; Powell, 1987, 1989; Marshall, 2000b). Variscan compression resulted in the tight folding present at the site.

Description

The Sandy Haven Formation (Allen and Williams, 1978) comprises about 850–900 m of predominantly red mudstones/siltstones, with minor quartz conglomerates and sandstones and a distinctive suite of airfall tuffs. The Little Castle Head site exposes beds in the middle part of the Sandy Haven Formation. This consists of bright red mudstones with abundant calcretes, minor purple and grey-green, lithic sandstones and a few granule- to pebble-grade conglomerates with vein quartz and lava clasts. It also contains the tuffs, the principal ones being the Townsend and Pickard Bay Tuff beds (Allen and Williams, 1978; 1981a). Of these tuffs (the magenta beds of Cantrill *et al.*, 1916), the Townsend Tuff Bed is the thicker, comprising three falls (A, B and C) in 2–4 m of beds (Figure 5.54).

Interpretation

The red calcrete-rich mudstones that dominate the succession are interpreted as the deposits of an extensive coastal mudflat, subjected to periodic marine influence and crossed by small, wet-season streams that were confined to channels, but also subject to flash sheet-flooding. These streams were probably largely sourced from the north, but some of the exotic clasts in the conglomerates may have been derived from the Pretannia landmass to the south (Cope and Bassett, 1987; Bluck *et al.*, 1992). Polygonal arrays of cracks in the mudstones are desiccation cracks, not synaeresis cracks, as stated by Lane (2000d). The well-developed calcretes at this level point to prolonged periods of subaerial exposure of the mudflats and the formation of thick carbonate soil profiles. The Townsend Tuff Bed is a regionally extensive marker bed of great value in correlation of the late Přídolí red beds throughout the Anglo-Welsh Basin. In the absence of faunas at this level, Allen and Williams (1981a) suggested that it could be used

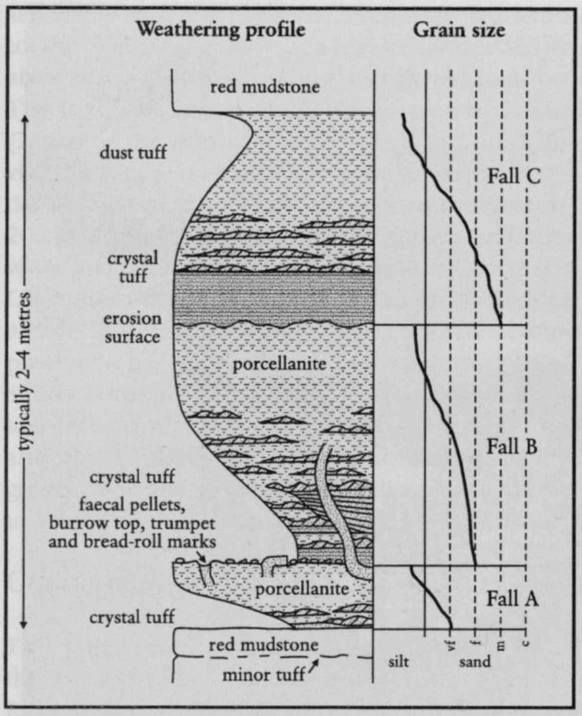


Figure 5.54 Schematic profile of the Townsend Tuff Bed illustrating its main sedimentological features. After Allen and Williams (1981a).

as the local Silurian–Devonian boundary. Palynomorph and thelodont assemblages suggest that this lies at a higher level (e.g. Richardson *et al*., 2000), but sampling so far has been of suitable facies at a level when early Devonian species were already established. Radiometric dating of the tuffs may provide some degree of age precision. Allen and Williams (1981a) speculated that the tuffs were the products of Plinian eruptions. The thinnest of the Townsend tuffs (Fall A) was deposited by strong east–west winds from a centre 100–200 km away, but its location is unknown (Bevins in Stephenson *et al*., 1999).

Conclusions

Little Castle Head provides a reference section for the Sandy Haven Formation of late Přídolí age. Red mudstones rich in soil carbonate (calcrete) horizons point to a coastal alluvial mudflat subjected to prolonged periods of emergence. The site also provides a reference section for the Townsend Tuff Bed, an important volcanic ashfall marker bed in the region, here in a succession tightly folded by Variscan compressive forces.

WEST ANGLE BAY (NORTH), PEMBROKESHIRE (SM 852 034)

P.R. Wilby

Introduction

The low cliffs at West Angle Bay (North), south Pembrokeshire, expose a continuous section from the Ridgeway Conglomerate Formation at the base, through the Skrinkle Sandstones Group, up into the Lower Limestone Shale Group (Figure 5.55). The age of the Ridgeway Conglomerate is uncertain, lacking diagnostic fossils, bounded by unconformities and lying in a fault-bounded block; late Early Devonian and Mid-Devonian ages have been suggested. The formation is one of only three in south Wales to have been sourced from the south. The age of the overlying Skrinkle Sandstones Group is well constrained, extending from the Late Devonian to the lowermost Carboniferous (Tournaisian).

The section is regionally important because it demonstrates the transitional nature of the boundary between the non-marine Old Red Sandstone facies and the marine deposits of the Lower Carboniferous strata in this part of the Anglo-Welsh Basin. It is also important in providing evidence with which to correlate the local Upper Old Red Sandstone succession with international biostratigraphical schemes based on spores and conodonts, and in allowing the location of the Devonian–Carboniferous boundary. In addition, the site is the stratotype for the West Angle Formation of the Skrinkle Sandstones Group, and was the first locality at which bedload-transported pedogenic mud aggregates were recognized in the Lower Old Red Sandstone of the Anglo-Welsh Basin (Ékes, 1993).

Description

Dixon (1921) was the first person to examine and log the succession at West Angle Bay in detail, following early work by De la Beche (1846). Williams (1964), Hassan (1966) and Marshall (1977, 2000a,b) have refined the lithostratigraphy of the section and studied its sedimentology. The section is described in several field guides (Williams, 1971; Marshall, 1978; Williams *et al*., 1982). The nature and age of the transitional boundary between the Old

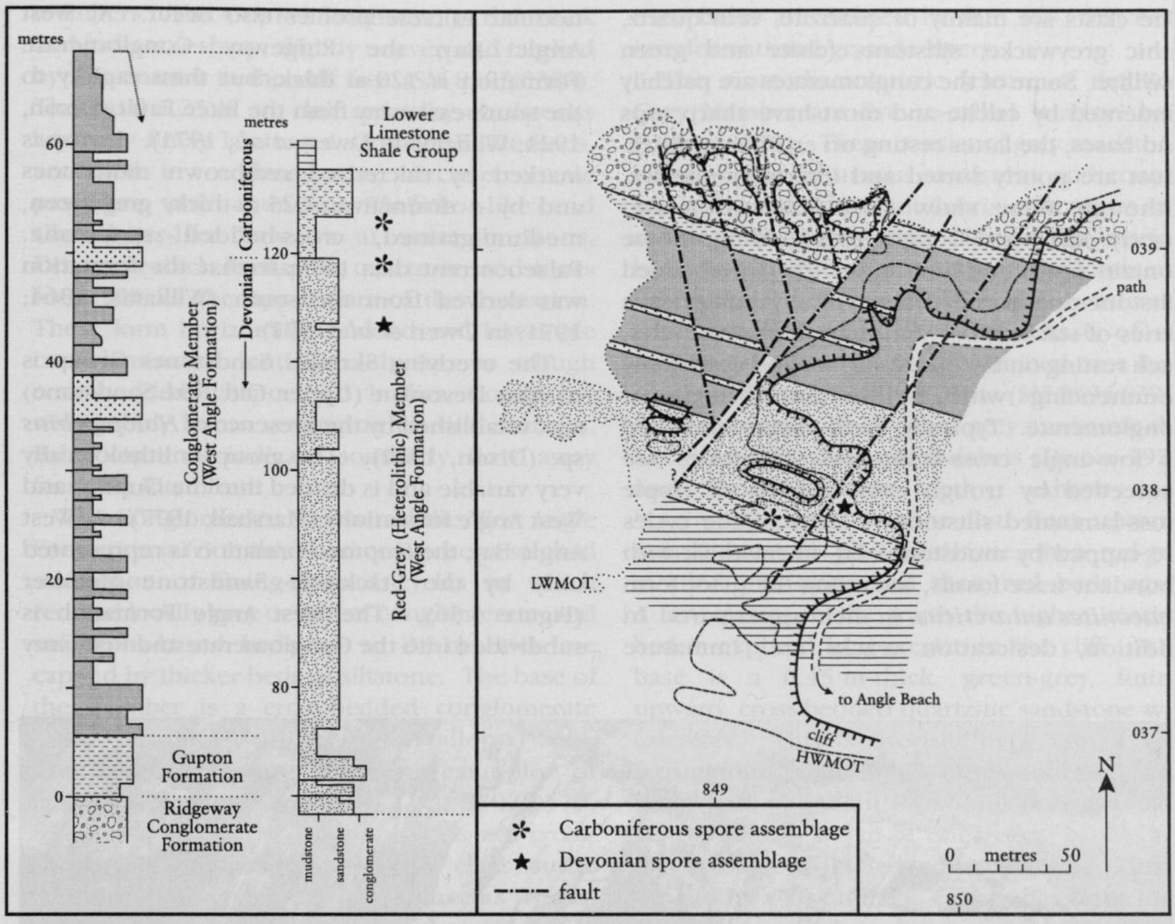


Figure 5.55 Geological sketch map of the north side of West Angle Bay and log of the Skrinkle Sandstones Group. After Williams *et al.* (1982).

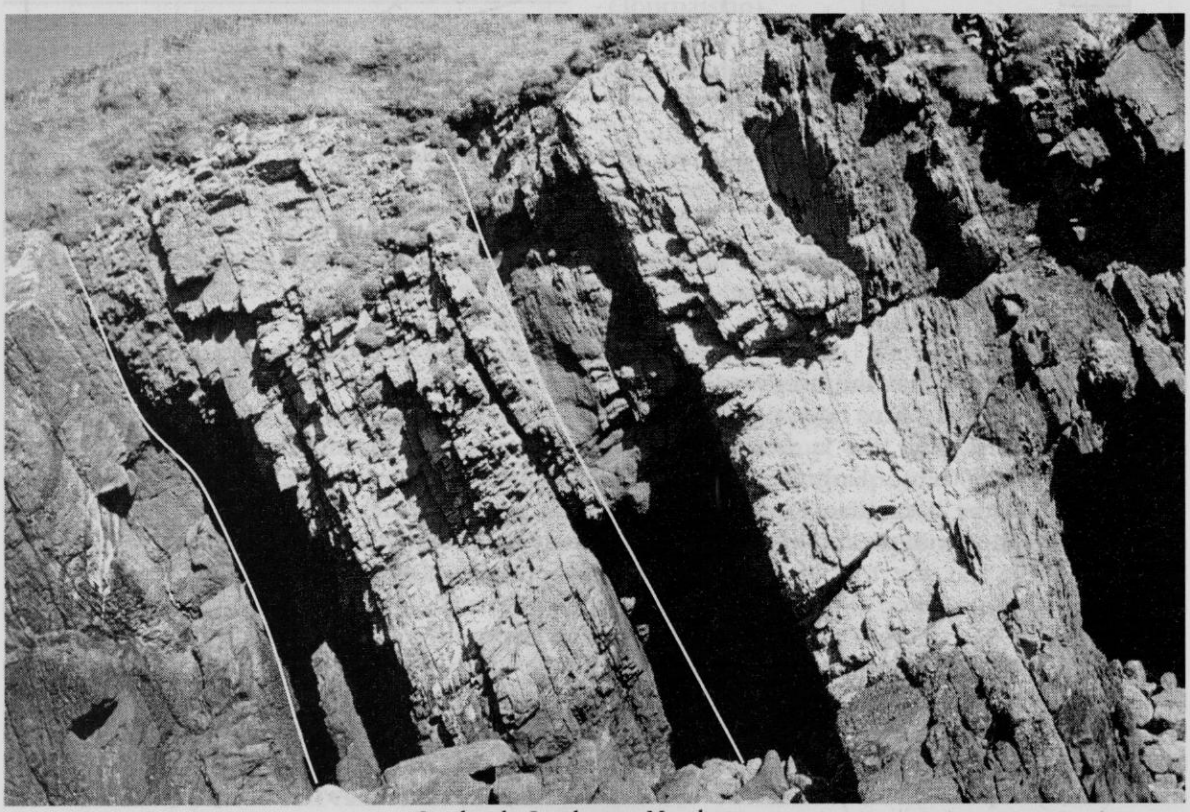
Red Sandstone facies and the overlying Lower Limestone Shale Group have been discussed by numerous workers (e.g. De la Beche, 1846; Marshall, 1977, 2000a,b). Early faunal studies suggested that the Devonian–Carboniferous boundary coincided with the top of the Old Red Sandstone facies (at the top of the Skrinkle Sandstones Group) (Salter, 1863; Cantrill *et al.*, 1916; Dixon, 1921; George, 1970). However, spore and conodont studies (Dolby, 1971; Bassett and Jenkins, 1977) demonstrated that the Devonian–Carboniferous boundary lies at a lower level, within the top part of the Skrinkle Sandstones Group.

The faulted succession forms part of the northern limb of the Angle Syncline, a WNW-trending Variscan structure, the axis of which passes through the centre of the bay. The strata dip steeply (typically between 55° and 70°) and are repeated, but with some important lithological differences, on the south side of the bay (Dixon, 1921; Marshall, 2000b). The strata were deposited on the southern margin of the Wales–Brabant Massif, immediately to the south of the Ritec Fault, in the small (30 × 10 km) Tenby–Angle Basin that developed by intermittent subsidence during Devonian and Early Carboniferous times (Powell, 1987, 1989; Marshall, 2000a,b). The exposed succession is divided into three major lithostratigraphical units – Ridgeway Conglomerate Formation, Skrinkle Sandstones Group and Lower Limestone Shale Group.

The Ridgeway Conglomerate Formation consists of red-brown and purple, coarse, polymict, extraformational conglomerates 1–3 m thick, interbedded with thicker (1–25 m) red-brown siltstone-dominated units. The conglomerates contain subangular to well-rounded clasts, generally 1–5 cm in diameter, with some up to 20 cm, in a sandstone matrix.

The clasts are mainly of quartzite, vein quartz, lithic greywacke, siltstone, felsite and green phyllite. Some of the conglomerates are patchily cemented by calcite and most have sharp tops and bases, the latter resting on erosion surfaces. Most are poorly sorted and internally massive, although some show clast imbrication and poorly developed trough cross-bedding. Some contain sandstone interbeds. The interbedded siltstone-dominated units typically comprise a series of stacked, 0.5–2 m-thick fining-up cycles, each resting on a scoured surface and commonly commencing with a thin intraformational conglomerate. Typically, basal planar laminated or low-angle cross-laminated sandstones are succeeded by trough cross-bedded or ripple cross-laminated siltstones. Many of the cycles are capped by mudstones 20–40 cm thick with abundant trace fossils, including the giant form *Beaconites antarcticus*, in their upper parts. In addition, desiccation cracks and immature nodular calcrete profiles also occur. At West Angle Bay, the Ridgeway Conglomerate Formation is 120 m thick, but thins rapidly to the south-east away from the Ritec Fault (Dixon, 1921; Williams in Owen *et al*., 1971). Its top is marked by calcretized red-brown mudstones and by a distinctive, 1.25 m-thick, grey-green, medium-grained, cross-bedded sandstone. Palaeocurrent data indicate that the formation was derived from the south (Williams, 1964; 1971; in Owen *et al*., 1971).

The overlying Skrinkle Sandstones Group is of Late Devonian (Upper Old Red Sandstone) age, established by the presence of *Holoptychius* sp. (Dixon, 1921). The group is lithologically very variable and is divided into the Gupton and West Angle formations (Marshall, 1977). At West Angle Bay, the Gupton Formation is represented only by the Stackpole Sandstone Member (Figure 5.56). The West Angle Formation is subdivided into the Conglomerate and Red-Grey



Ridgeway Conglomerate Formation — Stackpole Sandstone Member (Gupton Formation) — Conglomerate Member (West Angle Formation)

Figure 5.56 Strata in West Angle Bay; view looking east (SM 8503 0380). The beds dip steeply and young southwards (left to right). The Ridgeway Conglomerate Formation is succeeded by the Stackpole Sandstone Member of the Gupton Formation, which in turn is overlain by the basal beds of the Conglomerate Member of the West Angle Formation. (Photo: P.R. Wilby.)

members. The Gupton Formation is 6 m thick and its base is sharp, slightly uneven and marked by a re-entrant in the cliff face (SM 8503 0380). The basal 1.25 m are dull red, silty mudstones and very finely laminated sandstone interbeds, arranged in centimetre- to decimetre-scale packages with abundant *Skolithos*-like and *Chondrites*-like burrows at some horizons. Decimetre-thick, hard, pink, quartzose sandstones form 90% of the upper part of the formation. These form horizontally bedded and low-angle cross-laminated lenticular sheets, or trough cross-bedded, channelized bodies, commonly with pebbly layers, resting on erosion surfaces. Palaeocurrents indicate southerly flow away from the Ritec Fault.

The Conglomerate Member of the West Angle Formation is 63 m thick and comprises a stacked succession of fining-upward cycles in which red and locally grey or green, conglomerate- and sandstone-based beds up to 2.5 m thick are capped by thicker beds of siltstone. The base of the member is a cross-bedded conglomerate about 1 m thick, with a sharp, scalloped base. Three beds preserve excellent examples of lateral accretion sets (e.g. SM 8502 0379, SM 8498 0373). The conglomerates are cross-bedded and contain a varied clast suite, including vein quartz, acid igneous rocks, mylonite, purple quartzite and intraformational fragments. They are generally of pebble grade and moderately well-rounded to subangular. The bases of the conglomerates and sandstones are sharp, but not obviously erosion surfaces. Most of the siltstones are red and structureless, and several contain immature, nodular calcrete horizons. Disturbed, dark grey mudstone laminae are preserved in a grey-green siltstone approximately 20 m above the base (SM 8498 0373). Palaeoflow data indicate south-westerly sediment dispersal.

The base of the overlying Red-Grey Member (Heterolithic Member of Marshall, 2000a) of the West Angle Formation coincides with a malachitic horizon (SM 8494 0375) first noted by Dixon (1921). The member is 59 m thick and dominated by red, mauve and green-grey, decimetre-scale beds of quartzitic sandstone and silty mudstone, commonly in fining-upward units capped by mottled mudstones and nodular calcretes. The sandstones are fine- to coarse-grained, commonly cross-bedded and sharp based. Some rest on erosion surfaces, particularly those towards the top of the member, where their bases are defined by thin (6–7 cm) basal intraformational granule layers.

The most characteristic feature of the Red-Grey Member are five so-called 'marine' beds (Dixon, 1921). These consist of grey mudstone, limestone or calcareous sandstone and contain bivalves, ostracods, plant debris, root traces and, at one level, a thin coal. Two of the 'marine' beds are particularly distinctive. The lower one lies above a 0.4 m-thick nodular calcrete, approximately 33 m above the base of the member and is most easily examined on a large southward-facing bedding plane (SM 8494 0370). Its base consists of 15 cm of grey mudstone that has yielded bivalves, plant debris (Dixon, 1921) and abundant fish teeth. Above is a burrowed, grey sandstone that fines upwards over 0.4 m into grey mudstone, then red-grey mottled mudstone and then red beds again. A few metres to the south the higher 'marine' bed is exposed in a crevice in the cliff. At its base is a 0.45 m-thick, green-grey, fining-upward, cross-bedded quartzitic sandstone with calcretes. This is overlain by 0.3 m of grey, ferruginous interbedded mudstone and sandstone with abundant *Planolites* burrows, overlain in turn by 0.5 m of calcareous, brown and grey, trough cross-bedded sandstone. This is capped by a 10 cm-thick, rubbly, bioclastic limestone.

The top of the Red-Grey Member is best exposed on the foreshore (*c.* SM 8492 0369). Here, the characteristic red-grey interbedding is replaced about 7 m beneath the top of the member by the abrupt appearance of interbedded grey shales and thin (generally less than 15 cm), yellow-weathering, dolomitic sandstones. Dixon (1921) recorded fish fragments, bivalves (*Modiola lata*), crinoid ossicles and brachiopods (*Lingula* sp.) from these beds and an orthocone nautiloid (*Orthoceras* sp.) from the red siltstone immediately beneath. These beds are succeeded by about 3 m of cross-bedded sandstone containing bryozoa and ooliths, which mark the top of the Skrinkle Sandstones Group. At West Angle Bay the total thickness of the Skrinkle Sandstones Group is 130 m, but it thickens dramatically to the south (Marshall, 1977). It is succeeded by grey mudstones and calcareous sandstones of the Lower Limestone Shale Group, which contains abundant sedimentary slump folds near its base (SM 8491 0362) (Kelling and Williams, 1966).

Interpretation

During Early and Late Devonian times, sedimentation in south Pembrokeshire was strongly influenced by a series of southerly dipping, NW-trending growth faults that controlled the formation of a series of small, fault-bounded basins, each with its own distinct lithostratigraphy (Allen and Williams, 1978; Powell, 1989). The rocks exposed along the foreshore of West Angle Bay were deposited in the southernmost of these basins. The succession is confined immediately to the north of the GCR site by the Ritec Fault, and to the south by a series of major faults on the northern margin of the former so-called 'Bristol Channel Landmass' (Dunne, 1983; Tunbridge, 1986; Brooks *et al.*, 1988). Syndepositional movement on the faults resulted in considerable lateral facies and thickness variations in the succession across the basin (Powell, 1989).

The succession is dominated by continental deposits. The Ridgeway Conglomerate Formation has been interpreted as a proximal alluvial-fan with braided stream deposits (Williams, 1971; Williams *et al.*, 1982; Cope and Bassett, 1987). Braided stream deposition is suggested by the upward-fining cyclothems at West Angle Bay, as well as the presence of *Beaconites antarcticus*, which is believed to be the trace of an animal that inhabited the banks of active river channels (Allen and Williams, 1981b). At least some of the siltstones may have been transported as pedogenic aggregates of mud pellets and deposited from stream bedload (Ékes, 1993). Based on palaeocurrent trends, structural data and the predominance of exotic Lower Palaeozoic sedimentary/metasedimentary clasts, the Ridgeway Conglomerate Formation is widely believed to have been sourced from the 'Bristol Channel Landmass' to the south (Dixon, 1921; Williams, 1964; Williams *et al.*, 1982; Tunbridge, 1986; Cope and Bassett, 1987). This is consistent with the northwards decrease in the average particle size of the unit and with its dramatic thickening towards the Ritec Fault. Lacking diagnostic fossils and bounded by unconformities, the age of the Ridgeway Conglomerate is uncertain. It has generally been assigned to the late Early Devonian (Lower Old Red Sandstone) (Dixon, 1921; Thomas, 1978; Williams, 1978; Allen, 1979; Powell, 1987, 1989; Ékes, 1993) on tectonic (post-Acadian deformation) and lithological grounds, although it may extend into the Mid-Devonian (Middle Old Red Sandstone) (Williams, 1964, 1971; Allen, 1965b, 1977; Allen *et al.*, 1967; Tunbridge, 1986).

The Skrinkle Sandstones Group was deposited following major tectonic inversion in Mid-Devonian times. This event completely changed the palaeogeography of the region (Allen, 1974a) and switched the sediment source of the Tenby–Angle Basin from the south to the north (Allen, 1965b). Continued movement on the basin-bounding faults during Late Devonian time (Powell, 1989) imparted a southerly tilt on the basin and a reversal in the sense of thickening of the sequence. Allen (1965b, 1974a) interpreted the Skrinkle Sandstones Group as a large-scale, fining-upward system comprising lower braided stream deposits and upper heterolithic coastline barrier deposits. Allen (1986) suggested that the Gupton Formation may be of shallow marine origin. More recently, however, Marshall (1977, 2000a,b) interpreted the lower, laminated part of the Stackpole Sandstone Member of the Gupton Formation as the lacustrine deposits of a lake that may have drained to the south or east, and the overlying quartzose sandstones as high-energy, sandy braidplain ephemeral stream and sheet-flood deposits.

SE-directed palaeocurrents and the textural maturity of the Gupton Formation indicate axial basin-fill, parallel to the bounding faults (Marshall 2000a,b). In contrast, the succeeding Conglomerate Member of the West Angle Formation records the influx of immature, locally derived fluvial sediments sourced from the north-east, across the Ritec Fault (Marshall, 1978). Once established, this sediment transport path persisted throughout the deposition of the remainder of the West Angle Formation. The varied suite of clasts in the conglomerates, which is very different to those in the Ridgeway Conglomerate Formation, suggests a source in Carmarthen or north Pembrokeshire (Marshall, 1977) and confirms the presence of a major depositional break between the Ridgeway Conglomerate Formation and Skrinkle Sandstones Group.

The overlying Red-Grey Member of the West Angle Formation is interpreted as the deposits of a coastal barrier/lagoon complex (Allen, 1965b; Marshall, 1978; 2000a,b). Marshall (2000b) recognized a complex of tidal-flat, lagoonal and washover fan deposits, culminating in the topmost barrier sandstone. The Red-Grey Member is laterally equivalent to the Shirehampton Beds of the Bristol district (see **Portishead** GCR site report, this chapter). Both record the start of the northward marine transgression of the Lower Carboniferous sea on to the Wales–Brabant Massif ('St George's Land'), culminating in deposition of the fully marine Lower Limestone Shale Group. Spore and conodont data from West Angle Bay indicate that the Devonian–Carboniferous boundary is located 8–15 m below the top of the Skrinkle Sandstones Group (Dolby, 1971; Bassett and Jenkins, 1977).

Conclusions

The low cliffs at West Angle Bay (North) expose a continuous section encompassing the Ridgeway Conglomerate Formation of possible Mid-Devonian age, the Late Devonian to Early Carboniferous Skrinkle Sandstones Group, and the succeeding Lower Limestone Shale Group. The section exhibits a wide range of lithologies, representing depositional environments in a small, fault-bounded basin.

The site is important because:

- it shows the transition from the non-marine Upper Old Red Sandstone facies, through a number of marginal marine grey beds at the top of the Skrinkle Sandstones Group, to the fully marine Lower Limestone Shale Group.
- microfossil evidence indicates that the Devonian–Carboniferous boundary lies within Old Red Sandstone facies, 8–15 m below the top of the Skrinkle Sandstones Group.
- it provides evidence to show that deposition during Devonian times in this region was tectonically controlled and confined to fault-bounded sub-basins. Correlation between these sub-basins is difficult, but detailed spore analysis at West Angle Bay has enabled the Upper Old Red Sandstone lithostratigraphy of the Tenby–Angle area to be correlated with an international biostratigraphical scheme based principally on marine sequences.
- in addition to being the stratotype for the West Angle Formation, the locality is critical to the understanding of the palaeoenvironmental setting of the Skrinkle Sandstones Group. The site offers continued opportunities to collect Late Devonian fish material.

FRESHWATER WEST, PEMBROKESHIRE (SR 884 996–SR 887 988)

Potential ORS GCR site

W.J. Barclay and B.P.J. Williams

Introduction

Foreshore and cliff exposures at Freshwater West (Figure 5.57) in the Pembroke peninsula south of Milford Haven provide a magnificent, continuously exposed, easily accessible section (depending on tides) of the entire Old Red Sandstone succession. The basal Lower Old Red Sandstone rocks rest unconformably on marine rocks of Wenlock age at the north end of the section, the strata dipping steeply and younging southwards. At the southern end of the section, Upper Old Red Sandstone rocks are conformably overlain by the Dinantian Lower Limestone Shale Group. The section was first mapped in detail and described by the [British] Geological Survey (Dixon, 1921, 1933a,b). Field guides by Williams (1971, 1978), Allen *et al.* (1981b) and Williams *et al.* (1982), and detailed study by Marshall (1977, 2000a,b) have highlighted the importance of the section. Together with the presence of the Townsend Tuff Bed and the Chapel Point Calcretes Member, the recent discoveries of an early Devonian microflora (Higgs, 2004) and of exceptionally well-preserved burrowing traces (*Beaconites barretti*; Morrissey and Braddy, 2004) have added to that importance. This is the Old Red Sandstone section most visited by geologists and students in southern Britain because of its completeness and the superb exposure of all of the formations. Varied sedimentary structures and trace fossils can be studied in detail on wave-polished surfaces. The site provides an easily demonstrable picture of the evolving nature of sandbody architecture in the Lower Old Red Sandstone (Williams and Hillier, 2004). It also provides the most proximal, complete and accessible section through the unconformity-bounded Ridgeway Conglomerate Formation, and is important in having yielded fragments of the late Devonian fish *Holoptychius* from the basal beds of the Skrinkle Sandstones Group (Dixon, 1921). Furthermore, the Flimston Bay Fault, which transects the entire rock sequence with increasing amount of throw to the south, provides an additional, spectacular feature.

Figure 5.57 Aerial oblique view of Freshwater West looking south to Great Furzenip headland. Steep, south-dipping beds of the Freshwater West Formation are cut by the Flimston Bay Fault. The Skrinkle Sandstones Group crops out on Great Furzenip. (Photo: S. Howells.)

Description

Descriptions of the section have been given by Dixon (1921, 1933a,b), Williams (1971, 1978), Allen *et al.* (1981b) and Williams *et al.* (1982). Marshall (2000a,b) described the Upper Old Red Sandstone in detail. Freshwater West lies in the Pembroke peninsula south of Milford Haven and south of the Ritec Fault (Figure 5.58). The strata at Freshwater West occupy the southern limb of the Castlemartin Corse Anticline (Hancock, 1973), dip steeply (50°–80°) southwards and are locally overturned. The southern third of the section, in the Upper Old Red Sandstone, lies within the Castlemartin Tank Range, and permission to visit must be obtained in advance from the Commandant, Merrion Camp, Castlemartin.

The section can be reached from the B4319. From this road above Little Furzenip (SR 885 994) there is a magnificent view of the steeply dipping succession, exposed in a rock platform between high-tide and low-tide levels. The Old Red Sandstone comprises most of the section (Figure 5.59), outcrops being confined in the north to the foreshore between Little Furzenip and the main beach of Freshwater West (SR 8872 9900). To the south, the Ridgeway Conglomerate Formation and Skrinkle Sandstones Group crop out in cliffs about 35 m high. The north-trending Flimston Bay Fault, a Variscan dextral wrench fault, bisects the entire section, displacing the strata about 120 m in the middle of the outcrop. This fault also isolates the Little Furzenip stack from the headland and is marked by a shatter zone on Great Furzenip headland (SR 887 987). It dies out through a myriad of small splay faults immediately north of Little Furzenip and does not affect the rock sequence on the northern limb of the Castlemartin Corse Anticline (Hancock, 1973).

At the northern (Little Furzenip) end of the section, the basal Old Red Sandstone rests unconformably on marine Silurian rocks of Wenlock age, the Gray Sandstone Group (Williams, 1971, 1978; Bassett, 1974; Allen and Williams, 1979b; Allen *et al.*, 1981b;

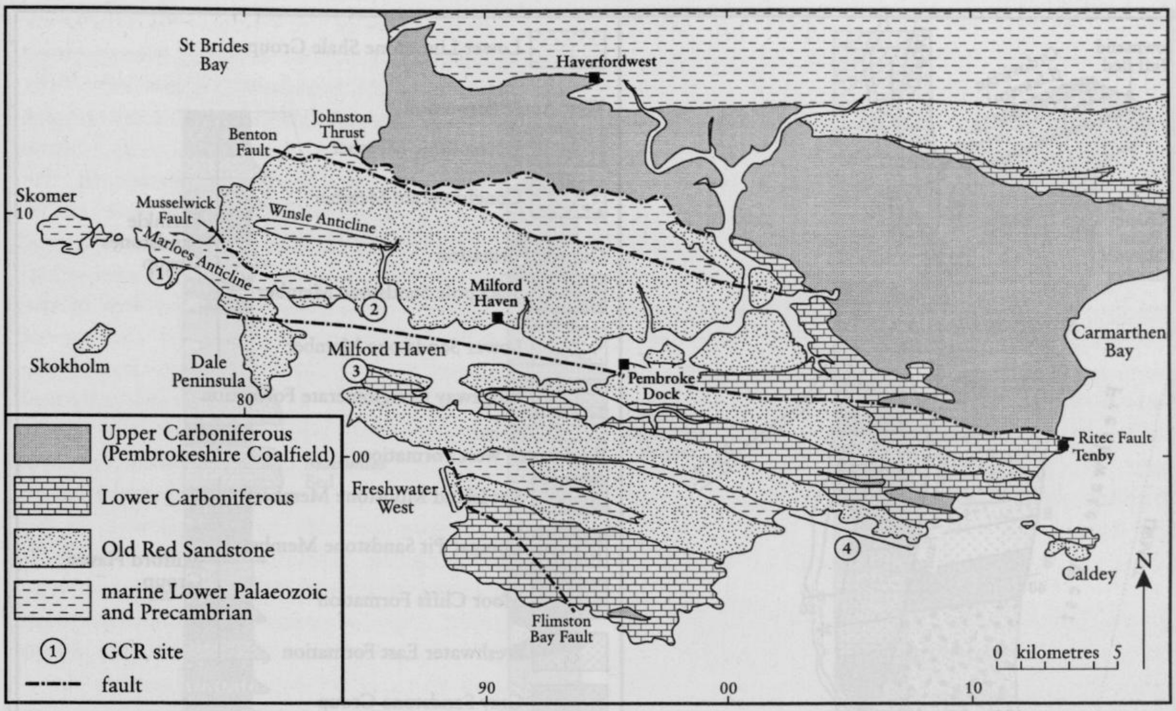


Figure 5.58 Geological map of the Pembroke peninsula and location of the potential GCR site at Freshwater West. Locations of GCR Old Red Sandstone sites on the peninsula are also shown. (1 – Albion Sands and Gateholm Island; 2 – Little Castle Head; 3 – West Angle Bay (North); 4 – Freshwater East–Skrinkle Haven.)

Williams *et al.*, 1982). The Gray Sandstone Group consists of conglomerates, green fine- to medium-grained sandstones, thin limestones and dark grey mudstones. The group is truncated by an irregular scoured, channelled surface that is overlain by the basal Old Red Sandstone rocks, the Freshwater East Formation. This is 18.45 m thick and comprises conglomerates in its lower part, with finer-grained sandstones above. The conglomerates are green to dark grey, of cobble- and pebble-grade, and are interbedded with fine- to medium-grained sandstones and green-grey mudstones. They are framework supported and include clasts up to 450 mm of quartzitic and lithic sandstones, vein quartz and olive-green mudstone in a coarse-grained sandstone matrix, some of the clasts matching lithologies in the underlying Silurian strata. The conglomerates are massive or cross-bedded with internal scour surfaces and overlie erosion surfaces. The upper, finer-grained beds contain lingulids, plant remains, arthropod tracks, *Pachytheca* and ostracoderm fragments (Dixon, 1921; Richardson and Lister, 1969; Williams, 1978).

The Freshwater East Formation is succeeded by the Moor Cliffs Formation. This is 119.56 m thick and consists predominantly of red and green mudstones in which calcrete glaebules and tubules are abundant, commonly arranged in pseudo-anticlinal structures. Subordinate lithologies include very fine- to fine-grained sandstones, exotic and intraformational conglomerates and airfall tuffs. The Townsend Tuff Bed is the thickest (2.81 m) of the tuffs. It crops out on the foreshore immediately north of Little Furzenip (SR 8847 9946) and is visible when the sand cover is removed. It lies 37.89 m above the base of the Moor Cliffs Formation (in contrast to 300 m on the northern limb of the same fold) and is succeeded by 13.53 m of beds in which there are five thin (0.01–0.11 m), pink-purple dust tuffs (markers B, C, E, F and G of Allen and Williams, 1982; Marker D is apparently absent here because of erosion). These are overlain by the Pickard Bay Tuff Bed, which is 1.25 m thick (Allen and Williams, 1982). A medium- to coarse-grained, cross-bedded litharenite lies 56 m above the Townsend Tuff Bed and forms a prominent rib on the foreshore and Little Furzenip headland. The sandstone rests on an erosion surface and the cross-bedding is in four to six tabular sets. The highest beds of the

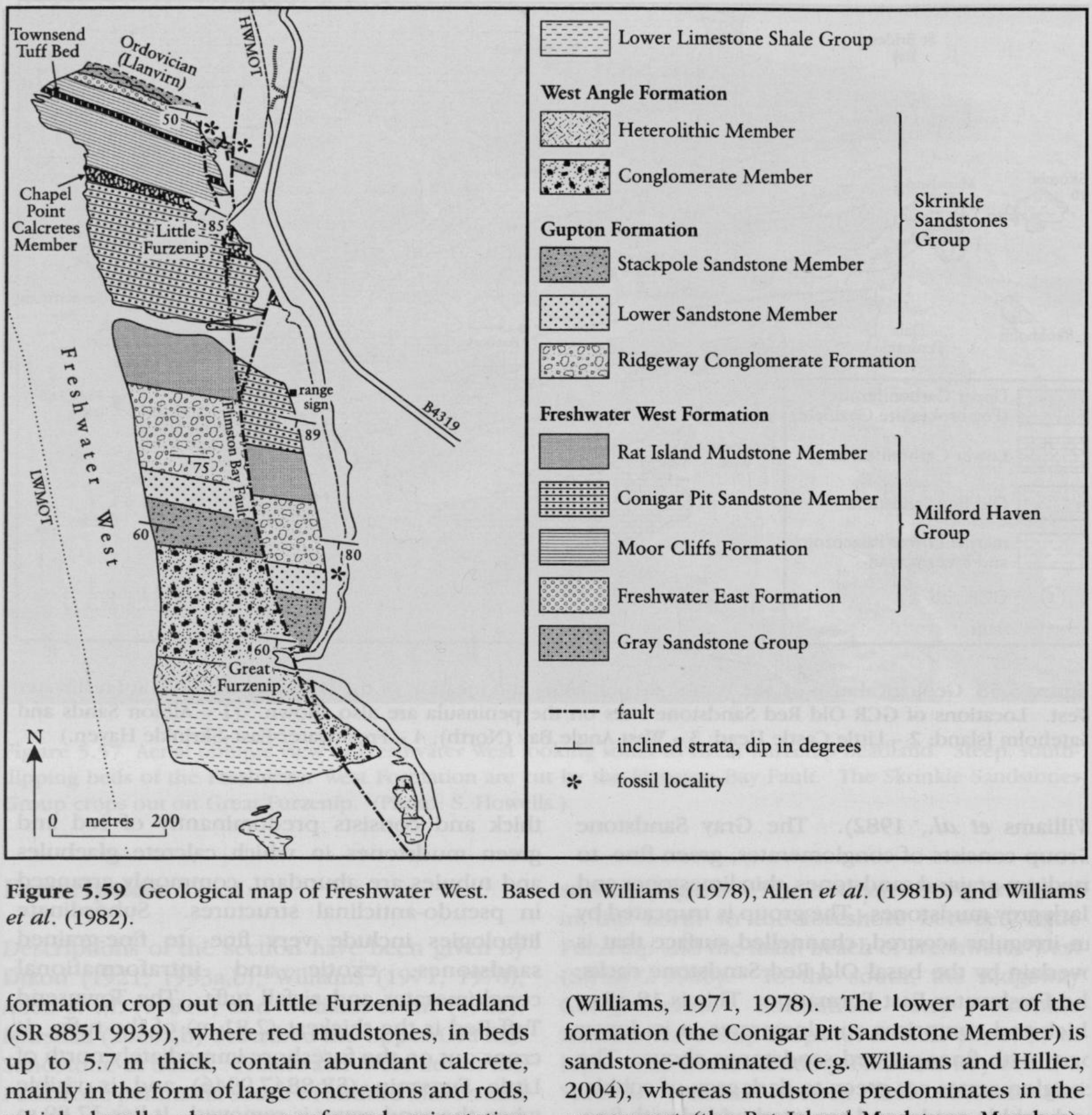


Figure 5.59 Geological map of Freshwater West. Based on Williams (1978), Allen *et al.* (1981b) and Williams *et al.* (1982).

formation crop out on Little Furzenip headland (SR 8851 9939), where red mudstones, in beds up to 5.7 m thick, contain abundant calcrete, mainly in the form of large concretions and rods, which locally show a preferred orientation parallel to cleavage or are arranged in pseudo-anticlinal festoons. The calcretes are arranged in stacked profiles and are correlated with the Chapel Point Calcretes Member of Pembrokeshire and the Psammosteus Limestone (Bishop's Frome Limestone) of the Anglo-Welsh Basin.

The abrupt junction between the Moor Cliffs Formation and the overlying Freshwater West Formation is well exposed on the southern side of Little Furzenip headland. The latter is 345.78 m thick and can be examined in great detail on the wave-polished foreshore section between the headland and the base of the Ridgeway Conglomerate Formation to the south (Williams, 1971, 1978). The lower part of the formation (the Conigar Pit Sandstone Member) is sandstone-dominated (e.g. Williams and Hillier, 2004), whereas mudstone predominates in the upper part (the Rat Island Mudstone Member). The Conigar Pit Sandstone comprises intraformational conglomerates, very fine- to medium-grained sandstones and calcrete-bearing mudstones, commonly arranged in upward-fining cycles (Figure 5.60). The conglomerates contain calcrete and mudstone clasts, mainly of pebble grade, and overlie low-relief erosion surfaces. They and the coarser sandstones contain fish fragments at four horizons, including plates, spines and scales of pteraspids, onchids and traquairaspids. The member can be examined in detail near the range warning sign (SR 8857 9917). The sandstones are mainly fine grained, red and green, parallel or cross-bedded

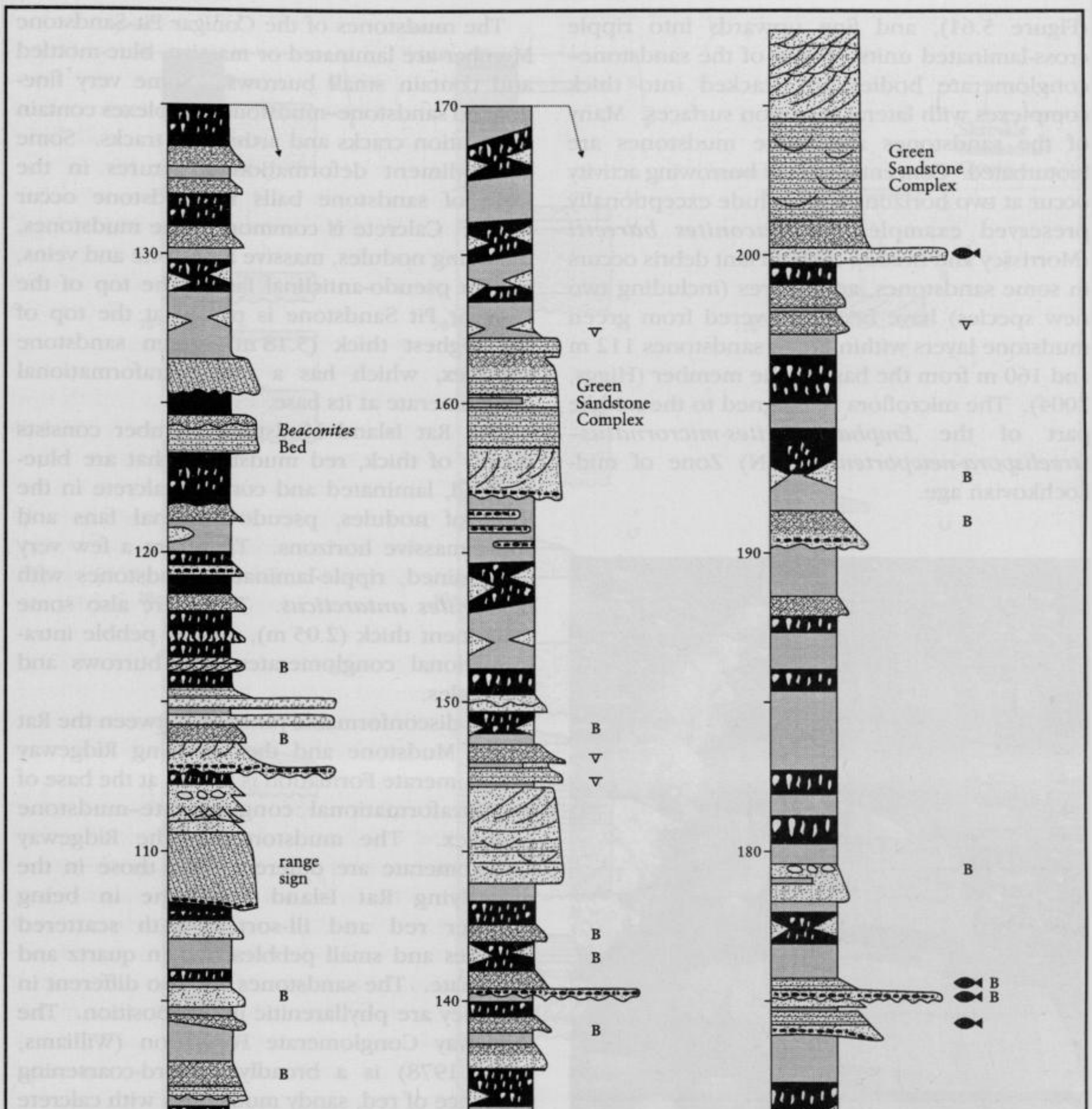


Figure 5.60 Sedimentary log through part of the Conigar Pit Sandstone Member, Freshwater West Formation at Freshwater West. Thicknesses are in metres from the base of the member. Based on Allen *et al.* (1981b) and Williams *et al.* (1982).

(Figure 5.61), and fine upwards into ripple cross-laminated units. Some of the sandstone–conglomerate bodies are stacked into thick complexes with lateral accretion surfaces. Many of the sandstones and some mudstones are bioturbated. Concentrations of burrowing activity occur at two horizons and include exceptionally preserved examples of *Beaconites barretti* (Morrissey and Braddy, 2004). Plant debris occurs in some sandstones, and spores (including two new species) have been recovered from green mudstone layers within green sandstones 112 m and 160 m from the base of the member (Higgs, 2004). The microflora is assigned to the middle part of the *Emphanisporites-micrornatus–Streelispora-newportensis* (MN) Zone of mid-Lochkovian age.

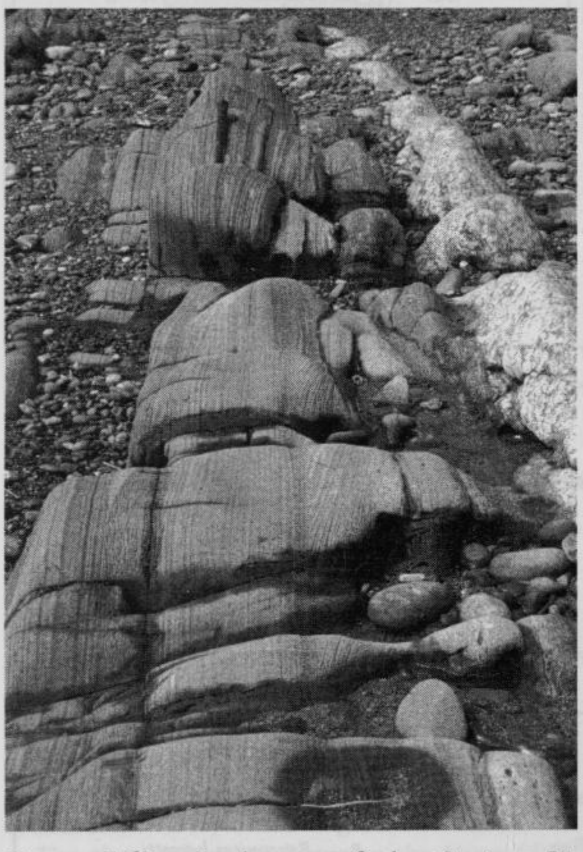


Figure 5.61 Sandstones of the Conigar Pit Sandstone Member, Freshwater West, 114 m above the base of the member. The sequence youngs from left to right. Planar cross-bedded sandstone overlies flat-bedded sandstone and is overlain by sandstone/mudstone and massive calcrete. The sandstones are interpreted as sheet-flood deposits. (Photo: B.P.J. Williams.)

The mudstones of the Conigar Pit Sandstone Member are laminated or massive, blue-mottled and contain small burrows. Some very fine-grained sandstone–mudstone complexes contain desiccation cracks and arthropod tracks. Some soft-sediment deformation structures in the form of sandstone balls in mudstone occur locally. Calcrete is common in the mudstones, including nodules, massive limestone and veins, and in pseudo-anticlinal fans. The top of the Conigar Pit Sandstone is placed at the top of the highest thick (5.18 m), green sandstone complex, which has a rare extraformational conglomerate at its base.

The Rat Island Mudstone Member consists mainly of thick, red mudstones that are blue-mottled, laminated and contain calcrete in the form of nodules, pseudo-anticlinal fans and some massive horizons. There are a few very fine-grained, ripple-laminated sandstones with *Beaconites antarcticus*. There are also some prominent thick (2.05 m), coarse, pebble intra-formational conglomerates with burrows and fish scales.

The disconformable junction between the Rat Island Mudstone and the overlying Ridgeway Conglomerate Formation is placed at the base of an intraformational conglomerate–mudstone complex. The mudstones in the Ridgeway Conglomerate are different from those in the underlying Rat Island Mudstone in being brighter red and ill-sorted, with scattered granules and small pebbles of vein quartz and carbonate. The sandstones are also different in that they are phyllarenitic in composition. The Ridgeway Conglomerate Formation (Williams, 1971, 1978) is a broadly upward-coarsening sequence of red, sandy mudstones with calcrete and ill-sorted mudrocks, fine- to coarse-grained litharenites rich in metamorphic and sedimentary rocks, and exotic, mainly clast-supported, petromict conglomerates (Figure 5.62). The formation is 115 m thick and contains eleven conglomerate bodies ranging from 0.6 m to 9 m thick, which make up 30 m of the formation. These overlie erosion surfaces and are massive or have weak internal cross-bedding or horizontal bedding, with some clast imbrication. The conglomerates are mainly framework-supported, with clasts ranging from 4 mm to 64 mm (Figure 5.63), but a 9 m-thick unit 14 m below the top of the formation contains vein quartz boulders up to

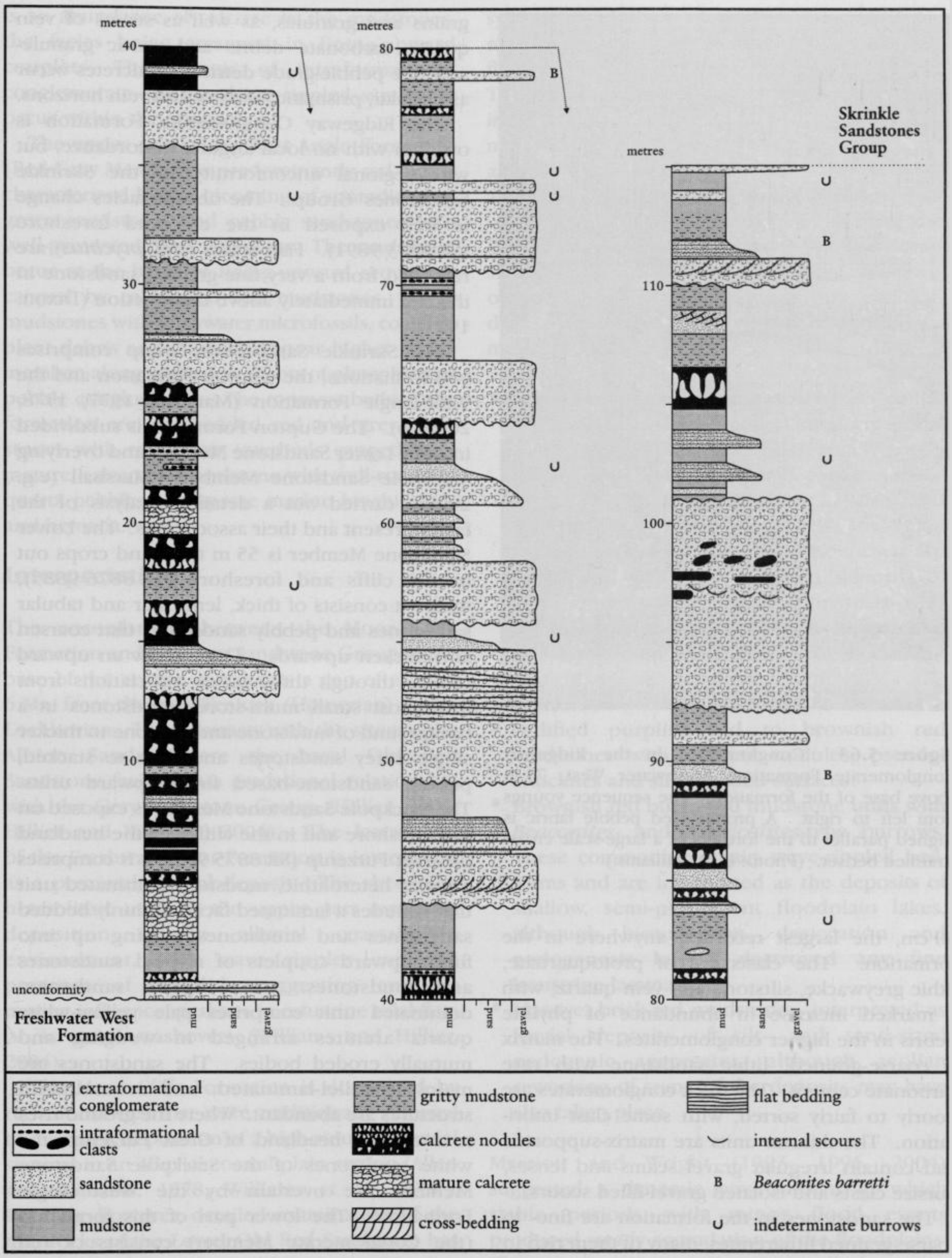


Figure 5.62 Sedimentary log of the Ridgeway Conglomerate Formation at Freshwater West. Based on Williams *et al.* (1982) and Allen *et al.* (1981b).

Figure 5.63 Conglomerate in the Ridgeway Conglomerate Formation, Freshwater West, 73 m above base of the formation. The sequence youngs from left to right. A pronounced pebble fabric is aligned parallel to the foresets of a large-scale cross-stratified bedset. (Photo: B.P.J. Williams.)

30 cm, the largest recorded anywhere in the formation. The clasts are of protoquartzite, lithic greywacke, siltstone and vein quartz, with a marked increase in abundance of phyllite debris in the higher conglomerates. The matrix is coarse-grained, lithic sandstone with rare carbonate cement. The thick conglomerates are poorly to fairly sorted, with some clast imbrication. The thinner units are matrix-supported and contain irregular gravel seams and lenses, outsize clasts and isolated gravel-filled scours.

The sandstones in the formation are fine- to coarse-grained litharenites, many of them rich in phyllite fragments. They are massive or graded, parallel bedded or cross-bedded and locally burrowed. The mudstones are mainly thick and bright red and are ill-sorted, with quartz grains and granules, as well as seams of vein quartz, carbonate debris and exotic granule- and fine pebble-grade detritus. Calcretes occur as nodular, prismatic, massive and vein horizons.

The Ridgeway Conglomerate Formation is overlain with no local angular discordance, but with regional unconformity, by the Skrinkle Sandstones Group. The abrupt facies change is well exposed in the cliff and foreshore (SR 8873 9891). Fish scales (*Holoptychius*) are recorded from a very fine-grained sandstone in the cliff immediately above the junction (Dixon, 1921).

The Skrinkle Sandstones Group comprises two formations, the Gupton Formation and the West Angle Formation (Marshall, 1977, 1978, 2000a,b). The Gupton Formation is subdivided into the Lower Sandstone Member and overlying Stackpole Sandstone Member. Marshall (e.g. 2000a) carried out a detailed analysis of the facies present and their associations. The Lower Sandstone Member is 55 m thick and crops out in the cliffs and foreshore (SR 8876 9885), where it consists of thick, lenticular and tabular sandstones and pebbly sandstones that coarsen and thicken upwards. These show an upward change through three facies associations from lowermost small multi-storey sandstones in a background of mudstone and siltstone to thicker single-storey sandstones and then to stacked, pebbly, sandstone-based fining-upward units. The Stackpole Sandstone Member is exposed on the foreshore and in the cliff near the headland of Great Furzenip (SR 8875 9878). It comprises a lower heterolithic, mudstone-dominated unit that includes a laminated facies of thinly bedded sandstones and mudstones passing up into fining-upward couplets of rippled sandstones and mudstones. An upper sandstone-dominated unit comprises pale yellow-white quartz arenites arranged in wedging and mutually eroded bodies. The sandstones are mainly parallel-laminated, and scour-and-fill structures are abundant. Where the ground rises to meet the headland of Great Furzenip, the white sandstones of the Stackpole Sandstone Member are overlain by the West Angle Formation. The lower part of this formation (the Conglomerate Member) consists of red sandstones, conglomerates and mudstones, and is markedly different in texture and composition from the underlying beds. The sandstones and conglomerates are rich in lithic debris and there is an abundance of calcrete in the mudstones, the facies being arranged in fining-upward couplets. Thin sheets of intraformational conglomerate and overlying rippled sandstone occur within the mudstones.

The upper part of the West Angle Formation (Red-Grey Member) is predominantly red, but is characterized by the incoming of sporadic grey-green sandstones and pebbly sandstones with well-preserved plant fragments. The sandstones occur at the bases of fining-upward sequences capped by calcretized red mudstones. Grey mudstones with freshwater microfossils, coalified plant debris and lingulids appear higher in the member, along with a few sheets of phosphatized pebble conglomerate. The topmost beds of the formation are interbedded red and grey sandstones with mudstone interbeds capped by a mature, calcareous sandstone with well-rounded quartz pebbles and sparse marine brachiopods and bryozoa.

Interpretation

The unconformity between the Moor Cliffs Formation and the Gray Sandstone Group at the base of the section represents a gap of at least 6 Ma, from the late Wenlock (Homerian) to the Lochkovian. This contrasts with the situation at Albion Sands, where the basal Old Red Sandstone facies has a gradational relationship with the Gray Sandstone Group (Hillier, 2000; Hillier and Williams, 2004). The lower part of the Freshwater East Formation is interpreted as a proximal alluvial deposit. The sheet-like, heterolithic units in the upper part represent deposition in an alluvial coastal-plain environment, with wave ripples and the presence of lingulids suggesting episodic marine influence, perhaps in estuarine tidal-flats or as storm washovers (Williams and Hillier, 2004).

The Moor Cliffs Formation is dominated by red mudstones that were traditionally referred to overbank deposition of a high-sinuosity fluvial systems in an alluvial coastal-plain setting (Allen and Williams, 1978; Williams *et al.*, 1982). Recently, however, detailed examination of the mudrocks of the Lower Old Red Sandstone has revealed a range of possible origins (Marriott and Wright, 1996, 2004; Marriott *et al.*, 2005). These authors propose a depositional environment similar to a modern tropical dryland river system in which moderately sinuous, anastomosing ephemeral rivers reworked muddy floodplain sediment during seasonal flooding. The floodplain sediments were pedified to varying degrees as calcic vertisols (calcretes) and mud soil aggregates that were reworked by wind and/or water as sand- or silt-sized pelleted aggregates. Infrequent major flood events caused extensive stripping of sediment from the floodplain surface and the deposition of sand sheets. Ephemeral lakes formed in depressions on the floodplain after floods, trapping aeolian dust. Marriott and Wright (2004) recognize four mudrock facies:

- Heterolithic facies dominated by red mudstone with minor interbedded intraformational conglomerates (Type B of Allen and Williams, 1979b) and extraformational conglomerates (Type A of Allen and Williams, 1979b) and sandstones. These occur as low-angle inclined or horizontal units. The former are interpreted as lateral accretion deposits of the point bars of meandering channels, with the mudstone deposited from bedload as pedogenic mud aggregates. The horizontal units may be the products of rapid, crevassing events.
- Pedified purplish red to brownish red mudstones with calcrete nodules, pseudo-anticlines and slickensided surfaces.
- Brownish red burrowed mudstone units with *Beaconites*- and *Arenicolites*-type burrows. These commonly contain wave-rippled bedforms and are interpreted as the deposits of shallow, semi-permanent floodplain lakes, although bioturbation, desiccation and pedogenesis largely destroyed any fine lacustrine lamination.
- Massive, brick-red mudstones, interpreted as fluvial deposits of silt- and sand-sized pedogenic aggregates, although aeolian reworking of some of the deposits may have also taken place.

Marriott and Wright (1993, 1996, 2004) suggested a dynamic environment in which stable periods with minor flood events produced steady aggradation of the floodplains. These were interrupted occasionally by major flood events when vast amounts of sediment were stripped and deposition in river channels took place.

The alluvial architecture of the sandstones of the Moor Cliffs Formation has been intensively studied (e.g. Williams and Hillier, 2004), particularly in the interval immediately above the Townsend Tuff Bed (Allen and Williams, 1982; Love, 1993; Love and Williams, 2000; Love *et al.*, 2004). The sheet-like finer-grained sandstones were probably the products of unconfined sheet flooding over the floodplain. The coarser, cross-bedded sandstone 56 m above the Townsend Tuff Bed is an amalgamation of units produced by sheet-flood events, its erosive incision reflecting a drop in sea level that was possibly induced tectonically (Williams and Hillier, 2004).

The common presence of calcrete nodules in the formation is evidence of repeated, seasonal wetting and drying of the floodplain in a semi-arid climate. The thick succession of stacked, mature calcretes (Stage III of Machette, 1985) of the Chapel Point Calcretes Member points to a prolonged period of non-deposition, sediment starvation and basin shut-down. Each mature profile is estimated to have taken 10 000 years (e.g. Allen, 1974d, 1986), although Marriott and Wright (2004) note that rates of carbonate formation are highly variable, depending on factors including the porosity of the parent sediment and the carbonate content of the percolating water. Hundreds of thousands to millions of years may have been required for Stage III calcrete formation. The regional extent of these calcretes demonstrates 'shut-down' of the Anglo-Welsh Basin, after which sediment provenance, fish fauna and ichnofacies all changed.

The change in basin architecture instigated deposition of the more proximal Freshwater West Formation. The common cyclic arrangement of the facies in fining-upward sequences in the lower part (the Conigar Pit Sandstone Member) points locally to a fluvial origin in high-sinuosity meandering streams, as evidenced by common lateral accretion surfaces (Williams, 1978; Allen *et al.*, 1982). However, the basin infill architecture is variable, with unconfined sheet-flood facies also being abundant (Williams and Hillier, 2004). The basal part of the member here is more mud-rich than elsewhere in Pembrokeshire, perhaps due to its elevated position in the hanging-wall of the Ritec/Benton Fault (Williams and Hillier, 2004). A northerly provenance is indicated by palaeocurrent directions, in contrast to the southerly derived Ridgeway Conglomerate Formation above. The Rat Island Mudstone Formation is of muddy floodplain origin similar to that of the Moor Cliffs Formation (Marriott and Wright, 1993, 1996, 2004; Marriott *et al.*, 2005).

The Ridgeway Conglomerate Formation is interpreted as the deposits of an alluvial-fan system that prograded northwards over fringing alluvial mudflats or playas from an emergent southern source (Williams, 1971; Williams *et al.*, 1982; Tunbridge, 1986; Ékes, 1993). The source area may have formed as a result of uplift in the footwall of a fault in what is now the Bristol Channel during Acadian deformation (Marshall, 2000a). At least some of the red mudrock interbeds in the formation owe their origin to deposition from bedload of pedogenic mud aggregates reworked from muddy floodplains (Ékes, 1993). Other mudrock facies represent mudflows on the fan surface (Williams *et al.*, 1982).

The Skrinkle Sandstones Group is interpreted as the fill of a post-Acadian synrift, fault-bounded basin in which alluvial-fan, lacustrine, braidplain delta and high-energy braidplain deposition took place successively in two superimposed sequences, the first an axial basin-fill, the second transverse fill (Marshall, 2000a,b). The Ritec Fault bounded the basin to the north, the succession thickening southwards in the hanging-wall of a fault in the present-day Bristol Channel. The first phase of the axial basin filling commenced with deposition of the Lower Sandstone Member of the Gupton Formation. Marshall (2000a,b) interpreted the three facies associations of the member respectively as small sheet-flood systems in a lacustrine or floodplain setting; isolated channel-fills; and meandering channel deposits. The coarsening- and thickening-upward nature of the succession suggested to Marshall a distal to proximal change and a SE-prograding terminal fan system. The lower part of the Stackpole Sandstone Member (mudstone-rich heterolithic association) is interpreted as lacustrine and lake-delta deposition, the upper (quartz arenite association) as high-energy, fluvial braidplain deposition. The textural maturity of the sandstones suggests long axial transport paths rather than local sourcing from the footwall of the Ritec Fault.

The West Angle Formation represents the second, transverse, basin-fill succession. Palaeocurrent directions in the lower part (the Conglomerate Member) indicate south and south-west drainage. Lateral accretion sets indicate point-bar formation and meandering river channels, with thin sheets of intraformational conglomerate and overlying rippled sandstone in the mudstone floodplain facies probably representing sheet-flood events. The upper part of the West Angle Formation (Red-Grey Member) is interpreted by Marshall (2000b) as recording the start of the Carboniferous transgression. The sporadic green beds and plant fragments point to a higher water-table on the alluvial floodplain. The progressive incoming of grey mudstones with freshwater microfossils, coalified plant debris and lingulids higher in the member suggests lacustrine deposition. The sheets of phosphatized pebble conglomerate contain bryozoa and sharks' teeth and indicate sporadic marine inundation prior to the main Carboniferous transgression. The calcareous sandstone at the top of the sequence has north-directed palaeocurrents and is interpreted by Marshall as a coastal barrier sand, with the underlying beds being lagoonal and washover fan deposits.

Conclusions

The importance of this site lies in the magnificent exposure of the entire Old Red Sandstone succession and the ease of accessibility of most of the rocks, which attracts large numbers of students and researchers. It is the classic section of the Lower Old Red Sandstone in southern Britain. The site has played a crucial role in the understanding of Old Red Sandstone–basement relationships in the Anglo-Welsh Basin, and of the tectonic and sedimentary history of the basin. The detailed sedimentological studies carried out here have vastly increased our knowledge of the terrestrial depositional environments of the Devonian. Also of prime importance is the part the site has played in the elucidation of the effects of contemporaneous faulting in controlling deposition. Along with the **West Angle Bay (North)** and **Freshwater East–Skrinkle Haven** sites, this site provides a complete picture of the transition into the overlying Carboniferous marine succession. Recent palynological study has added to the stratigraphical importance of the site by yielding an Early Devonian plant spore assemblage. Exceptionally well-preserved trace fossils provide an insight into the early animals that inhabited dry land for the first time.

FRESHWATER EAST–SKRINKLE HAVEN, PEMBROKESHIRE (SS 021 981–SS 082 974)

W.J. Barclay

Introduction

The sea cliffs and foreshore of south Pembrokeshire, south Wales offer the best exposures of the Old Red Sandstone in southern Britain. This 8 km-long, well-exposed along-strike section, also known as 'Tenby Cliffs', extends from Freshwater East in the west to Skrinkle Haven in the east (Figure 5.64). It gives a complete transect through the Old Red Sandstone, from the junction with the Silurian Gray Sandstone Group at Freshwater East, through the Lower Devonian Red Marls, the ?Middle Devonian Ridgeway Conglomerate Formation, the Upper Devonian Skrinkle Sandstones Group and the junction of the Skrinkle Sandstones Group with the overlying Carboniferous Lower Limestone Shale Group at Skrinkle Haven. The strata lie on the southern limb of the Pembroke Syncline (or northern limb of the Freshwater East Anticline), dipping very steeply to the NNE or being almost vertical. With the strata striking almost parallel to the coast, individual beds can be traced laterally for long distances, allowing detailed measurement of sandbody sizes and confirmation of the lateral persistence of marker beds such as calcretes and ash-fall tuffs. It should be noted, however, that large parts of the cliffs are inaccessible and dangerous.

Of particular interest is the group of eight closely spaced marker tuff beds within the Moor Cliffs Formation, the most distinctive of which are the Townsend Tuff Bed, Pickard Bay Tuff Bed and Rook's Cave Tuff. Their identification, combined with the extensive exposures, has allowed a detailed analysis of the alluvial architecture and sedimentary environments of parts of the succession, notably of that between the Townsend and the Pickard Bay Tuff beds (Allen and Williams, 1982) and of the Moor Cliffs Formation as a whole (Love, 1993; Love and Williams, 2000). The Townsend Tuff Bed and Rook's Cave Tuff between Manorbier Bay and Presipe preserve a unique set of trace fossils at their junctions with the underlying floodplain mudstones (Allen and Williams, 1981a; Morrissey and Braddy, 2004). The Ridgeway Conglomerate is important because of its

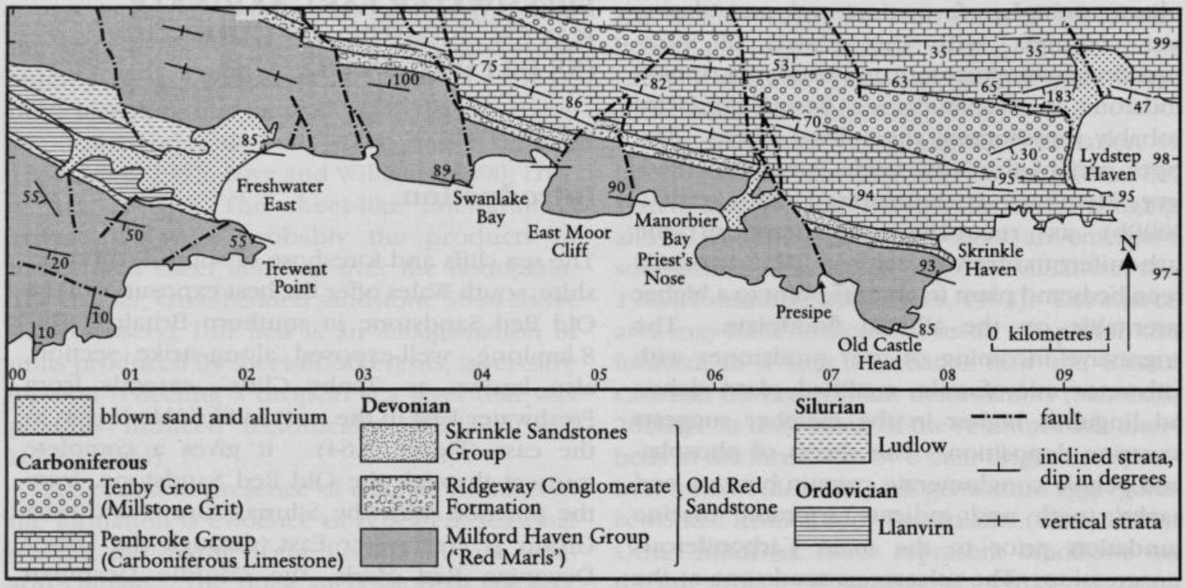


Figure 5.64 Geological map of the Freshwater East–Skrinkle Haven coast section. After British Geological Survey 1:50 000 sheets 244 and 245 (England and Wales), Pembroke and Linney Head (1983).

derivation from a local southerly source and the implications for Mid-Devonian tectonics and palaeogeography. The site also includes the type locality of the Upper Devonian Skrinkle Sandstones Group. The section east of Manorbier was included in a field guide by Williams *et al.* (1982).

Description

The foreshore (depending on extent of sand cover) and cliffs on the north-east side of Freshwater East bay expose the Basement Group (of Dixon, 1921) and the lower part of the Moor Cliffs Formation (the Lower Marl Group of Dixon). The Basement Group lies disconformably on fossiliferous sandstones and mudstones of the Gray Sandstone Group of Wenlock age. Dixon (1921, p. 41) gave a section and Bassett (1982b) described the succession. A basal conglomerate–sandstone 1.4 m thick is overlain by the lower part of the mudstone-dominated Moor Cliffs Formation, in which there are four complexes of green mudstones and green or pale grey, micaceous sandstones. The lowest green beds yielded a spore assemblage (Richardson and Lister, 1969). These green beds contain sporadic lingulids and ostracoderm fragments, together with the vascular plants *Cooksonia*, *Hostinella*, and *Tautilicaulis* (Edwards, 1979b). Malachite occurs on joint faces. There are fine examples of calcretes in the intervening red mudstones, as well as some airfall tuffs. Hancock *et al.* (1982) gave details of the structures.

West Moor Cliff provides exposures of the lower part of the Moor Cliffs Formation, Swanlake Bay exposes the upper part. Allen and Williams (1982) included the Swanlake Bay section in their detailed sedimentological analysis of the section between the Townsend Tuff Bed and the overlying Pickard Bay Tuff Bed. Allen (1974e) analysed cycles in the overlying Freshwater West Formation at Manorbier Bay (SS 057 976; SS 059 973) and at Swanlake Bay (SS 043 981). Marriott and Wright (1993, 2004) gave a detailed description of the mudrocks of the Moor Cliffs Formation.

Love and Williams (2000, fig. 4) and Love *et al.* (2004) gave detailed lithofacies profiles of part of the Moor Cliffs Formation at its type locality of East Moor Cliff and from Priest's Nose to Rook's Cave in the cliff east of Manorbier Bay (Figure 5.65). The section analysed extends from about 25 m below to 50–60 m above the Rook's Cave Tuff, which lies about 90 m below the Townsend Tuff Bed. Marriott and Wright (1993) examined 17 m of strata below, and 69 m above the Rook's Cave Tuff, 40 m west of Rook's Cave.

The cliffs to the east of Priest's Nose expose a magnificent strike section of the Moor Cliffs

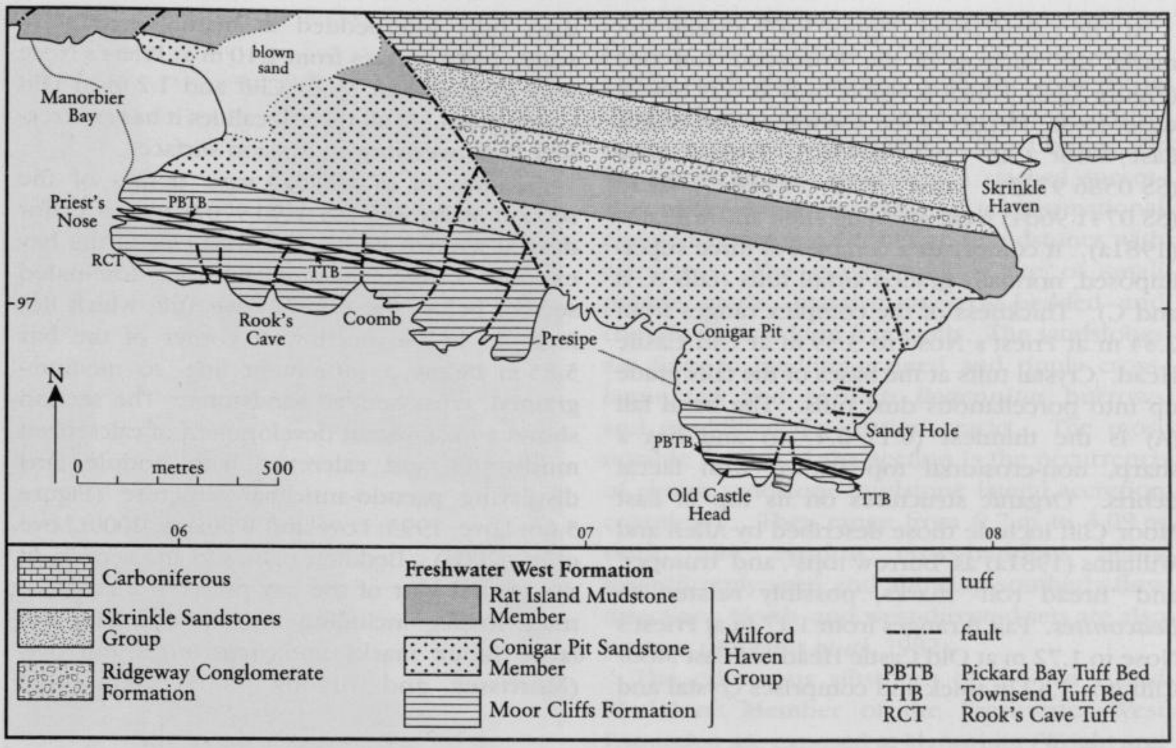


Figure 5.65 Geological map of the Manorbier–Skrinkle Haven coast section. After Williams *et al.* (1982).

Formation (e.g. Marriott and Wright, 2004). The sequence is dominated by calcretized, red mudstones/siltstones, many showing pseudo-anticlinal structures (Figure 5.66). There are a few, thin, fine- to medium-grained sandstones, as well as some thin lenses and lenticular sheets of intraformational conglomerate (Allen and Williams, 1979b) and a very few thin, extraformational conglomerate lenses. Conspicuous, laterally persistent slots occur where softer airfall tuffs have been weathered out. The Rook's Cave Tuff buried an irregular surface with shallow depressions and channels, probably occupied by water, separated by inter-pond, slightly eroded tracts of mud (Williams *et al.*, 1982). Organic burrow structures ('trumpet marks' of Allen and Williams, 1981a) and arthropod tracks (Morrissey and Braddy, 2004) occur at the base of the tuff (Allen and Williams, 1981a). Love and Williams (2000) record six tuffs in the 60 m of beds above the Rook's Cave Tuff.

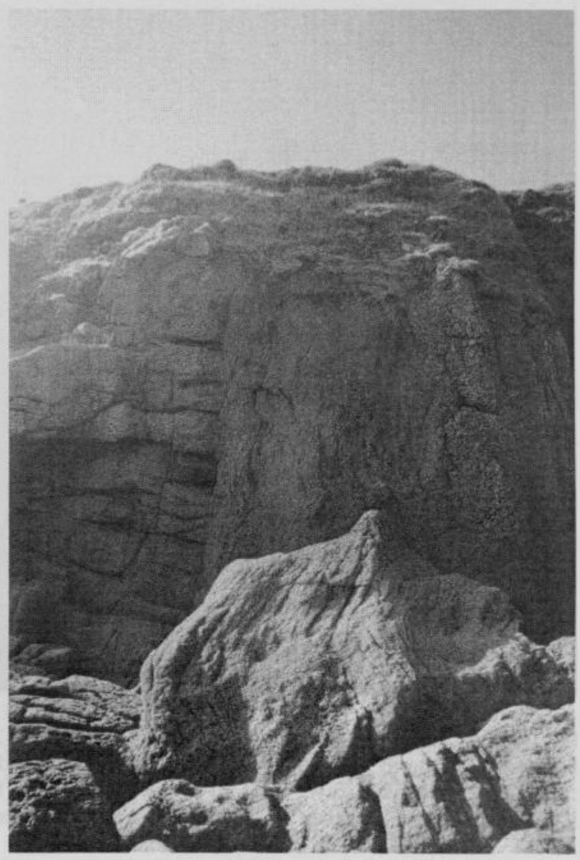


Figure 5.66▸ Calcrete forming pseudo-anticlinal structure, Moor Cliffs Formation, Presipe. View looking west, near-vertical sequence younging left to right. (Photo: W.J. Barclay.)

At Old Castle Head (Figure 5.67) a deep slot marks the outcrop of the Townsend Tuff Bed (Figure 5.68), which is visible only at very lowest water-level. Details of the Townsend Tuff Bed at East Moor Cliff (SS 0456 9762), Priest's Nose (SS 0586 9723) and Old Castle Head (SS 0741 9664) were given by Allen and Williams (1981a). It comprises a complex of three superimposed, normally graded airfall tuffs (falls A, B and C). Thickness of the complex ranges from 2.44 m at Priest's Nose to 3.39 m at Old Castle Head. Crystal tuffs at the bases of the falls grade up into porcellanous dust tuffs. The basal fall (A) is the thinnest (0.17–0.47 m) and has a sharp, non-erosional top strewn with faecal debris. Organic structures on its top at East Moor Cliff include those described by Allen and Williams (1981a) as 'burrow tops', and 'trumpet' and 'bread roll' marks, possibly related to *Beaconites*. Fall B ranges from 1.17 m at Priest's Nose to 1.72 m at Old Castle Head. At East Moor Cliff it is 1.42 m thick and comprises crystal and dust tuffs interbedded at mainly centimetre scale. Fall C ranges from 1.10 m at Priest's Nose to 1.15 m at East Moor Cliff and 1.2 m at Old Castle Head. At all three localities it has an irregular base overlying an erosion surface.

Williams *et al.* (1982) gave details of the section at Presipe (SS 0690 9707) near a major dextral wrench fault. The west cliff of the bay exposes a fine mudstone/siltstone-dominated section below the Rook's Cave Tuff, which lies high up in the north-west corner of the bay 5.85 m below a prominent fine- to medium-grained, cross-bedded sandstone. The section shows a magnificent development of calcretized mudstones and calcretes, with nodule fans displaying pseudo-anticlinal structure (Figure 5.66; Love, 1993; Love and Williams, 2000; Love *et al.*, 2004). Bedding planes in the section in the central part of the bay preserve a range of trace fossils, including arthropod tracks and large scour marks and *Beaconites* burrows (Morrissey and Braddy, 2004). Mud-filled

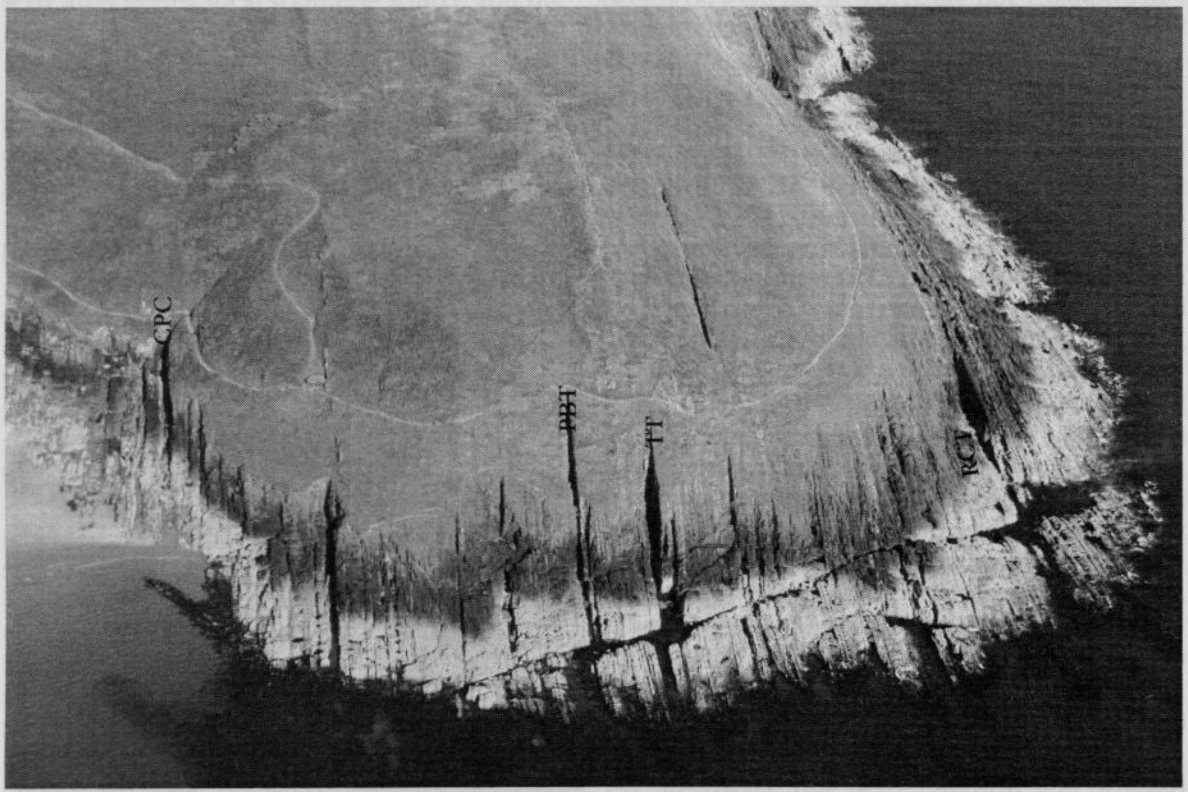


Figure 5.67 Oblique aerial view looking east of Old Castle Head. Vertical strata of the Moor Cliffs Formation. The strata young to the north (right to left) and a fault displaces them dextrally. Tuffs are marked by slots in the cliffs (RCT – Rook's Cave Tuff; TT – Townsend Tuff Bed; PBT – Pickard Bay Tuff Bed; CPC– Chapel Point Calcretes Member). Other slots probably mark unnamed tuffs. (Photo: S. Howells.)

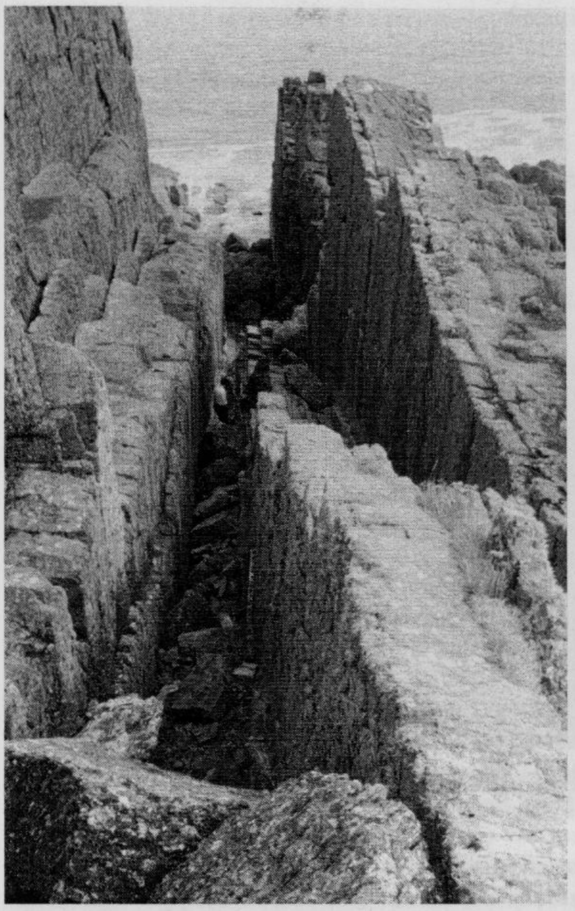


Figure 5.68 The Townsend Tuff Bed, Old Castle Head. View looking east, sequence younging right to left. (Photo: B.P.J. Williams.)

desiccation polygons and rippled surfaces are also seen. The beds are arranged in upward-fining cycles and some of the sandstones contain fine examples of soft-sediment deformation.

The Chapel Point Calcretes Member, the local name for the regionally developed Psammosteus Limestone, forms the top of the Moor Cliffs Formation. It crops out near King's Quoit (SS 0596 9733) and comprises 10–15 m of massive, purple careously weathered calcrete, which form a pronounced notch on the foreshore (Figure 5.69) and alcove in the cliff. Immediately overlying it is a very distinctive conglomerate 1.5–2.2 m thick and containing angular quartz pebbles (Williams and Hillier, 2004). The calcrete is at least 11.2 m thick at Conigar Pit to the east (Williams *et al.*, 1982).

The overlying beds comprise the Conigar Pit Sandstone Member at the base of the Freshwater West Formation. Conigar Pit (SS 0724 9696) provides a magnificent type section of the Conigar Pit Sandstone Member (Williams *et al.*, 1982), with the junction with the underlying Chapel Point Calcretes Member exposed at low-water mark (SS 0722 9680). The Conigar Pit Sandstone mainly comprises a stacked succession of upward-fining cycles of intraformational conglomerates, sandstones and mudstones with calcretes. The conglomerates are of small pebble grade, massive or cross-bedded and contain ostracoderm fragments. The sandstones are fine- to medium-grained and ripple cross-laminated and contain *Beaconites* burrows and mud-filled desiccation cracks. The most notable feature of the section is the occurrence of eleven sandstone-mudstone lateral accretion complexes. They range from 0.7 m to 3.09 m thick, the epsilon cross-bedding being magnificently seen and showing southerly flow direction. North- and west-directed sets are also present (Williams *et al.* 1982).

The calcareous siltstones of the Rat Island Mudstone Member of the Freshwater West Formation are exposed at Manorbier (Wright and Marriott, 1996) and on the headland south of Skrinkle Haven (Marriott and Wright, 1993, 1996, 2004). Their junction with the vertical Ridgeway Conglomerate Formation (SS 0800 9718) is erosional, although the basal conglomerate appears to pass laterally into red and green siltstones high in the face. However, a small fault at this point may complicate the relationship (Williams, 1971).

Williams (1971) described the Ridgeway Conglomerate. It is attenuated to 47 m at Skrinkle Haven and consists of interbedded siltstones, sandstones and extraformational conglomerates (Williams, 1971, fig. 5). Four conglomerate beds comprise 9 m of the formation. One 4.5 m-thick, green conglomerate lies 24 m above the base of the formation. Imbricated pebbles are set in a coarse-grained sandstone matrix with a carbonate cement. A thick (4 m) mature, massive calcrete overlies the conglomerate. Ékes (1993) noted abundant, metre-thick, massive calcretes showing pseudo-anticlinal 'gilgai'-type structures. The pebbles of the Ridgeway Conglomerate have not yet been matched with older formations (Allen, 1974a), but palaeocurrent evidence and decreasing pebble size northwards indicate a southerly derivation (Williams, 1971; Allen, 1974a; Cope and Bassett, 1987; Powell, 1989; Ékes, 1993).

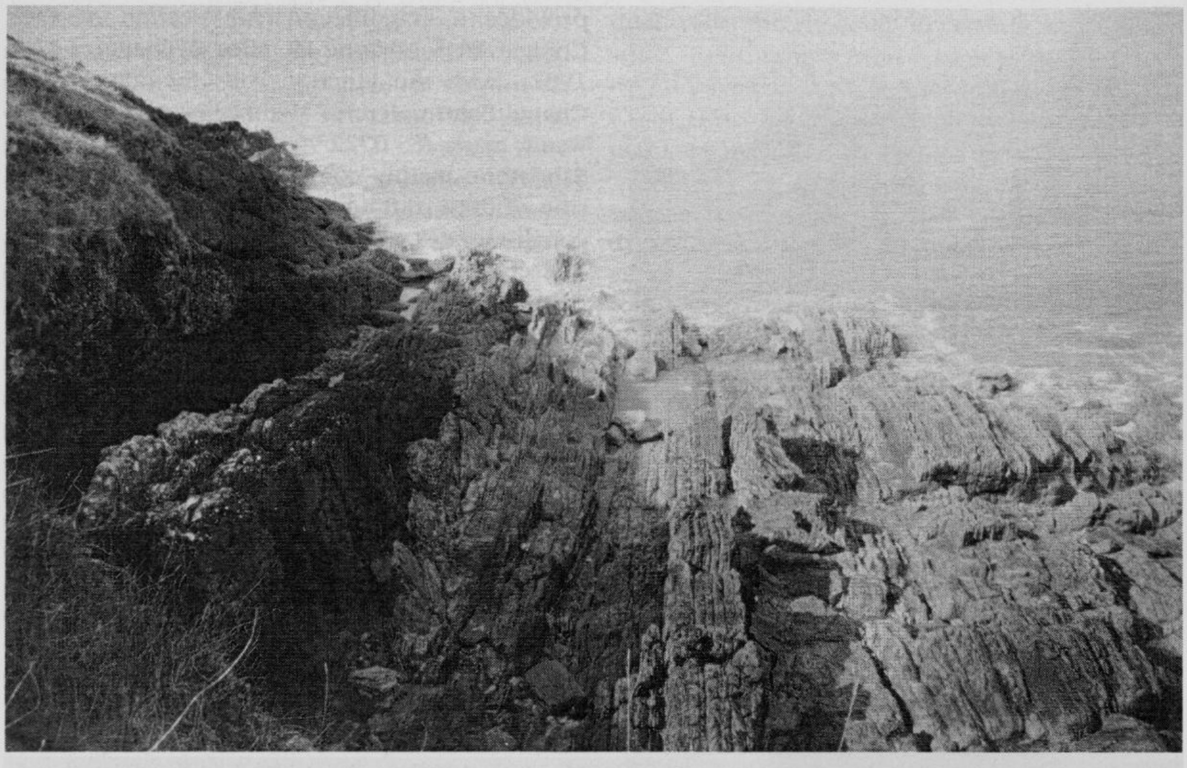


Figure 5.69 Near-vertical basal beds of the Freshwater West Formation. View looking WSW at southern end of Manorbier Bay. The Chapel Point Calcretes Member forms the notch on the left, the sequence younging left to right. (Photo: W.J. Barclay.)

Skrinkle Haven is the type locality of the Skrinkle Sandstones Group, which unconformably overlies the Ridgeway Conglomerate. Williams (1971) provided a description. It is 91 m thick and includes a lower quartzite unit (15.5 m) and upper conglomerate unit 54 m thick. The upper unit contains a 0.35 m-thick, grey and red mottled siltstone containing *Lingula* sp. and bivalves including *Modiola* sp.. The top of the Skrinkle Sandstones Group is sharp, where green sandstones are overlain by grey shales of the Lower Limestone Shale Group.

Interpretation

Allen and Williams (1982) interpreted the succession between the Townsend and Pickard Bay Tuff beds as having been deposited in an extensive mudflat environment, with sporadic fluvial channels. Widespread calcretes point to periodic subaerial exposure of the mudflats and precipitation of carbonate in the vadose zone. The ubiquitous destruction of sedimentary lamination is attributed to organic bioturbation. Allen and Williams (1982) were unclear as to whether the mudflats were subjected to tidal influence (an interpretation that they favoured), as suggested by the strong currents that affected the ashfall tuffs, although the evidence of variability of palaeocurrents is lacking. Marriott and Wright (1993, 1996) ruled out tidal influence during deposition of the Moor Cliffs Formation, favouring an unstable, flashy alluvial-floodplain system with ephemeral stream channels subject to common erosional events that reworked earlier soil horizons and the floodplain sediments. Love and Williams (2000) also discounted any marine influence. The alluvial-floodplain facies associations indicate prolonged periods of stability, non-deposition and soil formation. The calcretes indicate a seasonally wet, monsoonal, sub-tropical climate. Love and Williams (2000) and Marriott and Wright (1996) favoured an active, channelized depositional floodplain setting for much of the mudstones and siltstones, rather than a strictly overbank model favoured by earlier workers (e.g. Allen and Williams, 1981b). The floodplain channels were ephemeral, extremely broad and with low relief and flow, depositing mud and silt as bedload aggregates. Love (1993) and Love and Williams (2000) emphasize the role of land-plant colonization, with the primitive, shallow-rooted vegetation being unable to protect the floodplain from the rapid removal of sediments and calcrete soils during wet-season flooding.

Love and Williams (2000) and Love *et al.* (2004) interpret the sedimentary architecture of the Moor Cliffs Formation as the product of deposition by sporadic, large, broad, sandy channel systems with highly variable discharges and ephemeral flow, and by ephemeral, flashy, shallow streams on extensive interfluvial areas. Marriott and Wright (2004) envisage an environment analogous to a modern dryland system in which mud-dominated, moderately sinuous ephemeral rivers reworked floodplain muds during seasonal flooding. There is little evidence to support the conventional view that the mudstones/siltstones were deposited by suspension from standing water. For the heterolithic mudstone, sandstone–conglomerate mudrock facies and the massive brick-red mudrocks, Marriott and Wright (1996, 2004) favour active deposition of mud/silt aggregates from bedload. Rippled bodies and laminated sheets were deposited in through-draining larger channels and lumps of silt/mud aggregates and calcrete clasts were transported as coarse sand and gravel bedload in the shallow inter-distributary channels and deposited as bar forms. Units of burrowed mudrocks are attributed to lacustrine deposition in floodplain lakes, the pedified and desiccation-cracked, calcrete-prone mudrocks to steady aggradation on the floodplain during relatively stable periods, occasionally interrupted by flood events (see **Freshwater West** GCR site report, this chapter, for a fuller account of Marriott and Wright's important work). The strong cyclicity of the succession and of the calcrete palaeosols, which show increasing upward maturity, is attributed by Love and Williams (2000) to autocyclic processes of fluvial avulsion and aggradation.

The Conigar Pit Sandstone is interpreted by Hillier and Williams (2004) to represent a range of fluvial environments. Multi-storey sandstone bodies occupied the main channel belts and were mainly laterally accreted channel sandbodies. Also present are heterolithic sandstone/mudstone beds representing ephemeral channel deposition and sheet sands deposited from unconfined sheet floods. The Rat Island Mudstone comprises four facies, as detailed by Marriott *et al.* (2005) at a section (SS 0580 9775) on the west side of Manorbier Bay. These authors compare the environment to the Channel Country of central Australia, where mud sheet-flood deposits on a muddy braidplain border anastomosing fluvial systems. Intraformational conglomerates with mudstone and calcrete clasts were deposited as gravels in slightly sinuous, ephemeral channels, and heterolithic mudstone/sandstone units were deposited as accretionery benches in the channels. Pedified, purplish red mudstones with carbonate nodules are palaeo-vertisols (Stage II or III calcretes of Machette, 1985). Brick-red, pelleted mudstones were probably deposited as fine sand-sized aggregates in bedload during sheet-flood events. Subaerial exposure between flows was sufficiently long to allow pedogenic processes to form immature calcrete vertisols. Alternatively, the upper parts of the beds of pelleted mudrocks may have been deposited as aeolian dust. The facies are stacked in fining-upward units, 2.5m–5 m thick, representing ephemeral channel-zone deposition in which fluvial reworking of the palaeo-vertisols as clay pellet bedload took place.

The age of the Ridgeway Conglomerate Formation remains unknown. Unconformities at its base and top constrain it to between late Early and Mid-Devonian age (Marshall, 2000a,b). Allen (1974a) suggested that its base marks an important depositional break that extended into Mid-Devonian, and perhaps even into Late Devonian, times. Williams (1971) favoured a Mid-Devonian age, but later (Williams, 1978) suggested a late Early Devonian age. Powell (1989) gave a Siegenian (Early Devonian) age, but provided no evidence on which this is based. It is now clear that the formation post-dates the Acadian deformation (B.P.J. Williams, pers. comm.).

Allen (1974a) compared the Ridgeway Conglomerate Formation to the sediments of modern semi-arid playa-basins and alluvial-fans, with the conglomerates probably being of local origin; an alluvial-fan–braided river setting has also been suggested by several authors (e.g. Williams, 1971; Williams *et al.*, 1982; Powell, 1989; Ékes, 1993). The sediments were probably sourced from Lower Palaeozoic or

?Precambrian outcrops in the Bristol Channel Landmass to the south. Tunbridge (1986) and Cope and Bassett (1987) suggested that Mid-Devonian tectonics in the Bristol Channel area produced this positive area.

The Skrinkle Sandstones Group is of Late Devonian to Early Carboniferous age. It was deposited in a fault-bounded basin (the Tenby–Angle Basin), of which the Ritec Fault marked the northern limit (Powell, 1989; Marshall, 2000a,b). No detailed sedimentological work has been carried out at Skrinkle Haven, but Marshall interpreted the succession in **West Angle Bay (North)** to the west (see GCR site report, this chapter) as the product of alluvial-fan, alluvial-plain and lacustrine deposition. This was controlled by movements of the basin-bounding faults, within an overall transgressive regime as subsidence on the southern margin of the Wales–Brabant Massif was matched by rising sea level in early Carboniferous times.

Conclusions

The magnificent, cliff exposures along this 6 km-long section of coast reveal the entire succession of Old Red Sandstone strata in south Pembrokeshire. The high quality and lateral persistence of the extensive exposures of near-vertical strata allow detailed analyses of facies and their architecture. The modern sedimentological research of the section has been instrumental in the elucidation of the alluvial environments of the Old Red Sandstone, ranging from the distal floodplains of Late Silurian and Early Devonian times to the more proximal alluvial-fan deposition of the southerly sourced Early–Mid-Devonian Ridgeway Conglomerate Formation and the Upper Devonian Skrinkle Sandstones Group. Of special interest are the marker ashfall tuffs, of which the Townsend Tuff Bed, Rook's Cave Tuff and Pickard Bay Tuff Bed are the principal ones. These preserve a unique set of trace fossils, including faecal pellets, burrow-fills and arthropod tracks at their junctions with the floodplain mudstones. The magnificent exposures of calcretes, showing varying stages of maturity and gilgai-type pseudo-anticlinal structures, as well as the facies and architecture of the sandbodies and mudrocks, have been utilized to model the contemporaneous sub-tropical, semi-arid, seasonally wet climate of Late Silurian and Devonian times.

LLANSTEFFAN, CARMARTHENSHIRE (SN 350 100)

W.J. Barclay

Introduction

The site is a coastal section exposing beds traditionally referred to the Red Marl Group (Lower Old Red Sandstone) of Pembrokeshire (Strahan *et al.*, 1909). The presence of the Chapel Point Calcretes Member (Psammosteus Limestone) at the site, in a magnificent development of stacked, mature, pedogenic calcrete profiles, allows subdivision of the succession, with the beds above the limestones correlated with the lowermost part of the Freshwater West Formation of south Pembrokeshire (Allen, 1978c; Allen *et al.*, 1981b; Williams *et al.*, 1982). These beds include large, fluvial, sandbodies deposited in large rivers, as well as the deposits of small, muddy, interfluvial distributaries with little sand, but much intraclast gravel. This site has provided important evidence towards the understanding of Early Devonian alluvial-plain geomorphology and drainage patterns. Apart from the type locality of the Chapel Point Calcretes Member on Caldey Island, the limestones here are some of the best examples of mature Old Red Sandstone calcrete profiles seen in the Anglo-Welsh Basin, all completely exposed in extensive cliffs. The site has been instrumental in the understanding, interpretation and significance of these calcretes.

Description

The GCR site lies immediately south of the village of Llansteffan and extends along the coast of the Towy estuary from 100 m north-east of Llansteffan Castle (SN 3526 1026) south-westwards to near St Anthony's Cottage (SN 3470 0085) in Scott's Bay (Figure 5.70). Murchison (1839) noted that the section exposed 'the finest example of a limestone of the Old Red Sandstone System in Carmarthenshire'. Strahan (in Strahan *et al.*, 1909) was the first to describe the section. More recently, Allen (1978c, 1986), Allen *et al.* (1981b), Cope (1982), Marriott and Wright (1996), Wright and Marriott (1996) and Jenkins (1998) examined the section, providing details and sedimentological analyses. Morrissey and Braddy (2004) describe animal burrows and trails in the Freshwater West Formation.

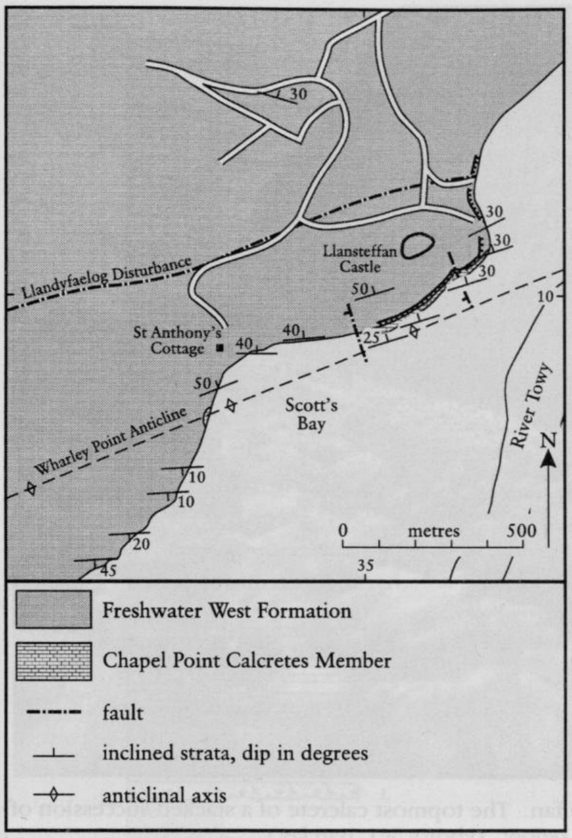


Figure 5.70 Geological sketch map of the Llansteffan area. After British Geological Survey 1:10 560 manuscript map Carmarthenshire 45SE (1906).

The site lies on the northern limb of the Wharley Point (or St Anthony's) Anticline, a NE-trending anticline, which lies in the hanging-wall of the Llandyfaelog Disturbance (Strahan in Strahan *et al.*, 1909). This major structure has a similar trend to the anticline and crops out close to the northern end of the site. The axis of the anticline crosses the coast south-west of the western end of the site, 230 m south of St Anthony's Cottage, the Llansteffan succession being repeated and higher strata exposed towards Wharley Point.

The Chapel Point Calcretes Member is the lowest bed exposed in the site, cropping out along the axis of the anticline (Figure 5.71) and being continuously exposed from east of Llansteffan Castle (SN 353 101) to south-west of the castle (SN 350 099). Correlated with the regionally developed Psammosteus Limestone, it forms the uppermost part of the Moor Cliffs Formation of the Pembroke peninsula. Figure 5.72 is a graphic log of the near-strike succession exposed in the section, on the northern limb of the Wharley Point Anticline. The following description is based largely on that given by Strahan (in Strahan *et al.*, 1909), Allen (1978c) and Allen *et al.* (1981b). The succession comprises three parts, in ascending order: thick calcretes (the Chapel Point Calcretes Member); interbedded calcretes, mudstones and intraformational conglomerates; and sandstones and mudstones in upward-fining sequences. The cliffs from below the castle for 350 m south-westwards expose 15 m comprising six closely spaced calcrete profiles. Strahan (in Strahan *et al.*, 1909) referred to the beds as massive limestone composed of concretions perpendicular to bedding. The calcretes are grey to green and rubbly to massive, and show an upward increase of maturity, with increasing carbonate content and a gradation from discrete nodules, which increase upwards in size and coalesce into rubbly and massive limestones. Irregular, horizontally laminated limestones are present locally, but the profiles have a mainly prismatic, bedding-perpendicular fabric (Allen, 1974d, 1978c, 1986; Allen *et al.*, 1981b). Allen (1974d, 1986) differentiated the calcretes on the basis of their maturity into three types. Type A profiles comprise scattered nodules (glaebules) with locally more intense concentrations (Stage I of Machette, 1985); in Type B, the glaebules are larger and closely packed at intermediate to upper levels, giving a crude prismatic fabric (Stage II of Machette). Type C profiles represent the most mature profiles in which closely packed glaebules coalesce (Stage III of Machette) and contain laminated carbonate layers (Stage IV of Machette). Most of the calcretes in this section are of Type B (stages II to III).

Overlying the calcretes is a mudstone-dominated succession, which marks the base of the Freshwater West Formation. It contains some calcretes and three types of sandstone bodies (Allen, 1980):

- thin, mainly very fine-grained sandstones with lateral accretion structures;
- thick, mainly fine-grained, cross-bedded or parallel-laminated sandstones; and
- lenticular intraformational conglomerates.

The conglomerates are bounded above and below by mudstones, locally cross-bedded and preserve dune or bar forms and internal channelling (Allen, 1978c; Allen and Williams, 1979b). The conglomerates occur at the base of

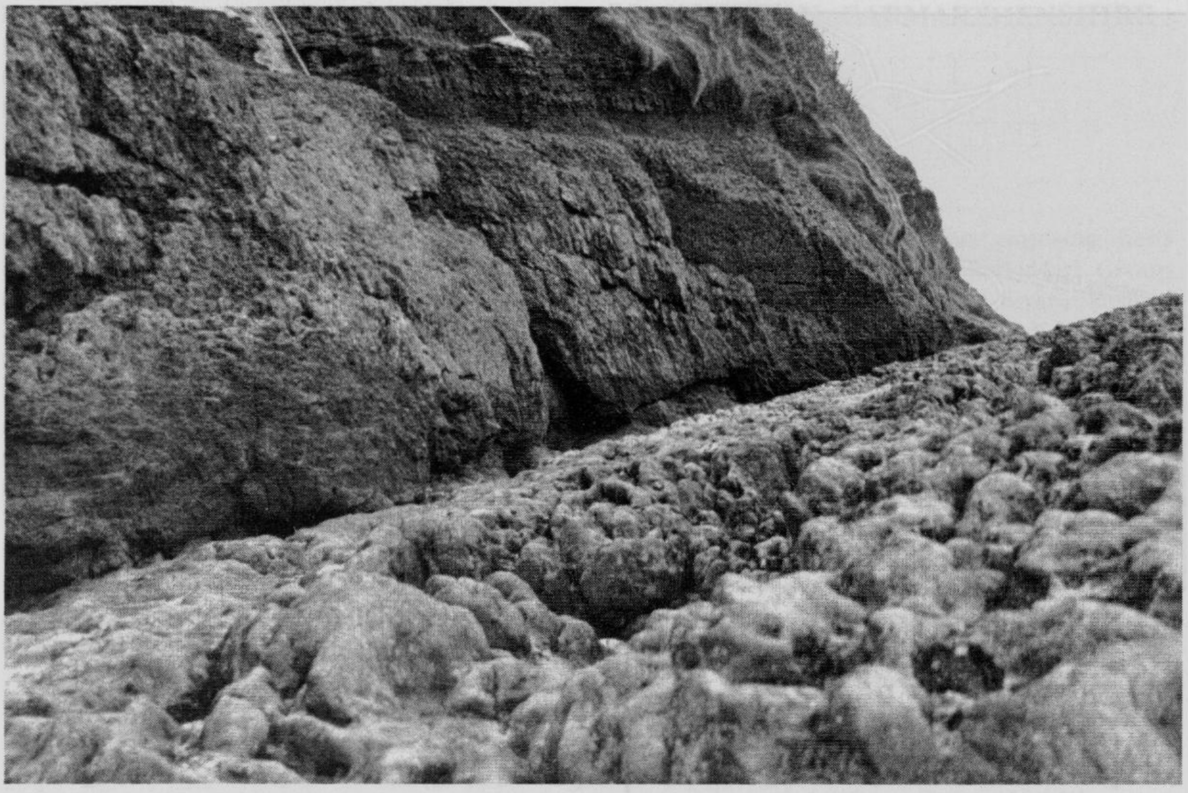


Figure 5.71 The Chapel Point Calcretes Member, Llansteffan. The topmost calcrete of a stacked succession of calcretes overlies the careously weathered top of the one below. (Photo: W.J. Barclay.)

the succession and overlie erosion surfaces (Allen, 1978c; Allen *et al.*, 1981b). The calcretes, which lie within the mudstones exposed in and to the south-west of a slight embayment south-west of the Chapel Point Calcretes Member cliff, show varying degrees of maturity (but are mostly Type A) and well-developed pseudo-anticlines (Allen, 1973b).

Marriott and Wright (1996) described a section of 6 m of strata lying 10 m above the base of the Freshwater West Formation. They interpreted some of the red mudstones in the succession as originating as sand-sized mud aggregates or pellets produced in soils and deposited from bedload in small, sinuous channels, similar to the aggregates described by Ékes (1993) in the Ridgeway Conglomerate Formation of West Angle Bay.

There are several metre-scale, mainly cross-laminated, very fine-grained sandstones with lateral accretion surfaces. Between 29 m and 35 m above the base of the section is a complex of upward-fining and upward-thinning intraformational conglomerates interbedded with mudstones. The conglomerate bodies have sharp bases resting on downcutting erosion surfaces and are either cross-bedded or horizontally bedded. The higher conglomerates are thin, of granule grade and lack quartz sand (Type B of Allen and Williams, 1979b). A conglomerate near the top of this part of the section contains plant fragments and *Pachytheca*.

The upper (third) part of the succession is exposed in the cliff that extends towards St Anthony's Cottage (SN 346 099–SN 347 099). Two thick, green sandstone bodies lie 80 m and 95 m above the base of the section. They are coarser and thicker than the underlying laterally accreted sandstones and contain no lateral accretion structures. The lower one is 5.2 m thick, has a thin, fish-bearing intraformational conglomerate resting on a scoured surface, and comprises parallel-laminated sandstones overlain by cross-bedded, fine-grained sandstones. At the top, 0.8 m of cross-laminated, very fine-grained sandstone passes up into calcretized mudstone. Internal erosion surfaces at the bases of sets are strewn with intraformational clasts. The higher sandstone is 7.2 m thick and comprises a complex of trough cross-bedded,

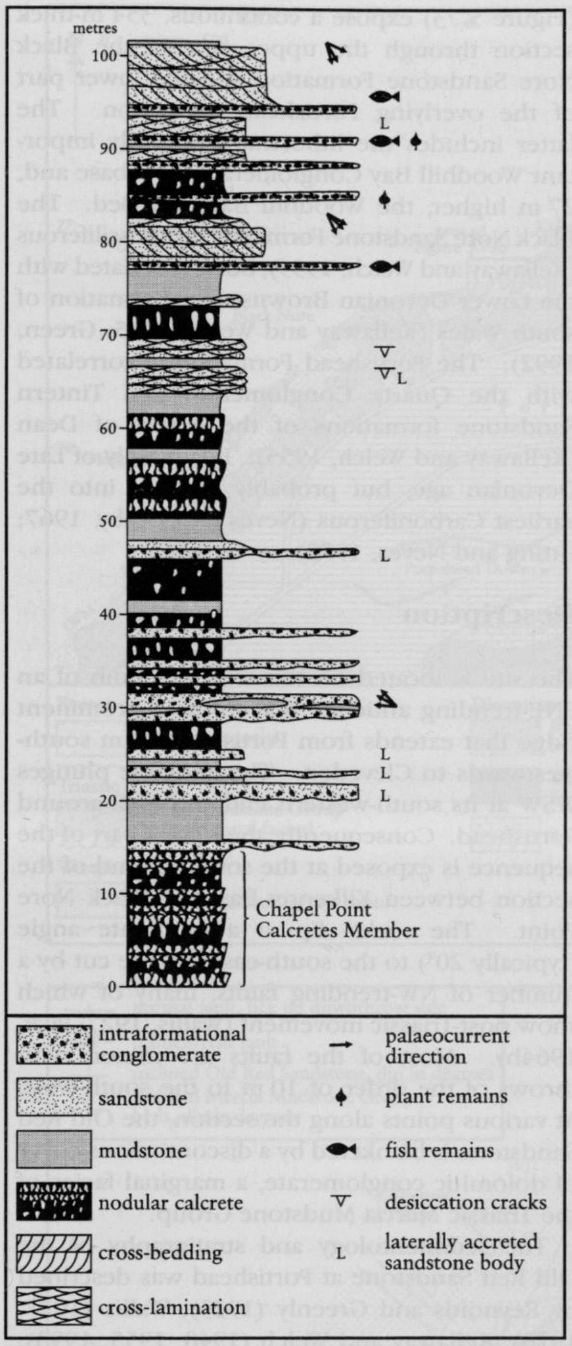


Figure 5.72 Vertical section of the strata exposed at Llansteffan. Based on Allen (1978c) and Allen *et al*. (1981b).

parallel-laminated and cross-laminated sandstones resting on a thick basal intraformational conglomerate containing ostracoderm fragments. The burrow trace fossil *Beaconites* is very common towards the top. Allen *et al.* (1981b) referred it to *Beaconites antarcticus*, Morrissey and Braddy (2004) to *Beaconites barretti*. Arthropod trackways and foraging traces occur in mudstones near Wharley Point (Morrissey and Braddy, 2004).

Interpretation

The succession of six stacked calcrete profiles comprising the Chapel Point Calcretes Member at the base of the section correlates with the regionally developed Psammosteus Limestone. It represents a prolonged period of geomorphological stability, with little subsidence of the alluvial floodplain or fluvial incision, allowing subaerial exposure and pedogenic carbonate formation, each profile representing periods that may have ranged between tens of thousands to millions of years (Allen, 1974d, 1986; Allen and Williams, 1979b; Marriott and Wright, 1993, 2004). Some of the mudstones/siltstones have been interpreted as originating as sand-sized pedogenic mud aggregates (pellets) produced in floodplain soils and deposited from bedload in small, sinuous channels (Marriott and Wright, 1996, 2004).

The cross-bedded, intraformational conglomerates in the overlying beds suggest deposition in broad, shallow channels. Their distribution, many as bar and dune forms within mudstones, may represent ephemeral drainage systems in interfluvial areas between the main distributary channels (Allen and Williams, 1979b; Allen *et al.*, 1981b). The cross-laminated, very fine-grained sandstones with lateral accretion surfaces may represent high-sinuosity channels with sluggish water flows. The higher conglomerates are thin sheets, also lacking in quartz sand, and suggesting deposition of reworked muds (including pedogenic mud aggregates) and calcretes in ephemeral streams and sheet floods (Marriott and Wright, 1996). The green, coarser-grained, thicker sandstones 80 m and 95 m above the base of the section are interpreted as the deposits of larger, higher-energy, low-sinuosity streams, suggesting the establishment of major rivers in the area (Allen, 1978c; Allen *et al*. 1981b). The inception of major fluvial sedimentation above the Chapel Point Calcretes Member was a regional event recognized throughout the Anglo-Welsh Basin, marking the establishment of generally south-flowing rivers from a source nearer than that of the streams which deposited the strata below the limestone (Allen and Crowley, 1983).

Conclusions

The site is of regional and national importance in providing the best onshore and most easily accessible exposure of a condensed succession of stacked Old Red Sandstone mature fossil soil carbonate (calcrete) profiles, representing the best development of the Chapel Point Calcretes Member (Psammosteus Limestone) in the Anglo-Welsh Basin. It provides important information on the contemporaneous climate, which, by analogy with the occurrence of modern calcretes, was semi-arid, seasonally wet and tropical.

Detailed sedimentological analyses at the site have been instrumental in building models of Old Red Sandstone alluvial sedimentation. Analyses of the sandstone and intraformational conglomerate bodies have provided an insight into a range of fluvial environments, including major, sand-filled distributary channels in the higher parts of the section, and more localized shallow, ephemeral flashy streams in the lower parts. A further point of interest lies in some of the mudstones above the Chapel Point Calcretes Member, which may have originated as pedogenic mud aggregates deposited from stream bedload or sheet floods.

PORTISHEAD, NORTH SOMERSET (ST 461 770)

P.R. Wilby

Introduction

The Portishead GCR site exposes Lower and Upper Old Red Sandstone beds and provides the best exposure on the southern side of the Bristol Channel of the Lower–Upper Devonian boundary as preserved in continental red-bed facies. It also exposes the biostratigraphically important Woodhill Bay Fish Bed. The site has played an important role in identifying the provenance of the Old Red Sandstone in southern Britain, and in demonstrating its thickening southwards across the Anglo-Welsh Basin. The importance of the site also lies in its unique fish fauna, for which it is described separately in the fossil fishes GCR volume (Dineley and Metcalf, 1999).

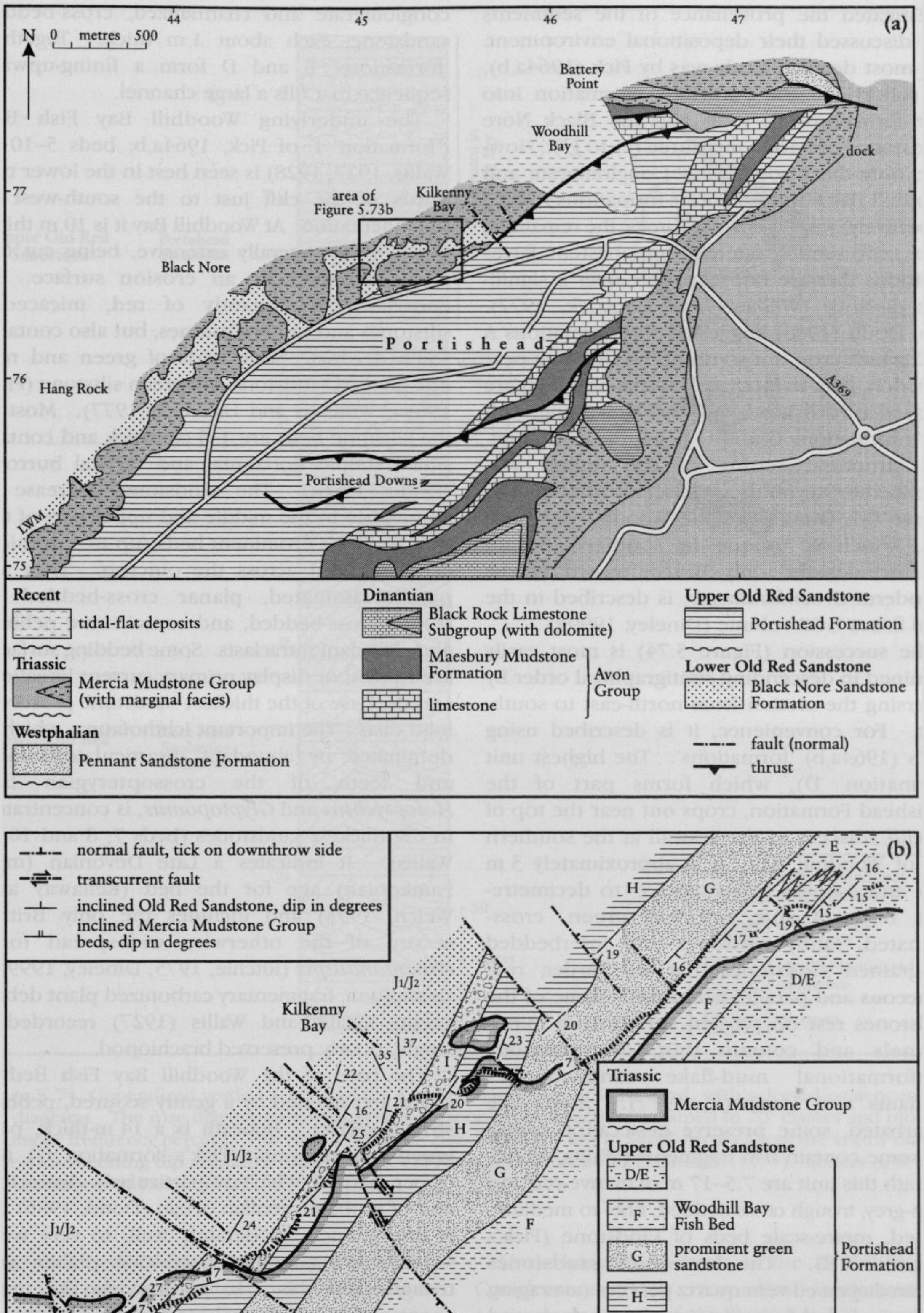
The low cliffs of Woodhill Bay, Kilkenny Bay and Black Nore Point to the south of Portishead (Figure 5.73) expose a continuous, 354 m-thick section through the upper part of the Black Nore Sandstone Formation and the lower part of the overlying Portishead Formation. The latter includes the lithostratigraphically important Woodhill Bay Conglomerate at its base and, 27 m higher, the Woodhill Bay Fish Bed. The Black Nore Sandstone Formation is unfossiliferous (Kellaway and Welch, 1955), but is correlated with the Lower Devonian Brownstones Formation of south Wales (Kellaway and Welch, 1955; Green, 1992). The Portishead Formation is correlated with the Quartz Conglomerate and Tintern Sandstone formations of the Forest of Dean (Kellaway and Welch, 1955). It is mainly of Late Devonian age, but probably extends into the earliest Carboniferous (Neves and Dolby, 1967; Utting and Neves, 1970).

Description

The site is located on the southern limb of an ENE-trending anticline that forms a prominent ridge that extends from Portishead 5 km south-westwards to Clevedon. The anticline plunges WSW at its south-western end and ENE around Portishead. Consequently, the lowest part of the sequence is exposed at the southern end of the section between Kilkenny Bay and Black Nore Point. The rocks dip at a moderate angle (typically 20°) to the south-east and are cut by a number of NW-trending faults, many of which show post-Triassic movement (Wallis, 1927; Pick, 1964b). Most of the faults are minor, with throws of the order of 10 m to the south-west. At various points along the section, the Old Red Sandstone is blanketed by a discontinuous cover of dolomitic conglomerate, a marginal facies of the Triassic Mercia Mudstone Group.

The sedimentology and stratigraphy of the Old Red Sandstone at Portishead was described by Reynolds and Greenly (1923), Wallis (1927, 1928), Kellaway and Welch (1948, 1955, 1993), Butler *et al.* (1972) and Dodd (1986). The site is included in two field guides (Reynolds, 1921; Williams and Hancock, 1977). Wallis (1927)

Figure 5.73▸ Location and geology of the Portishead GCR site. (a) Geological map (after British Geological Survey 1:50 000 Sheet 264 (England and Wales), Bristol (2003)); (b) detailed map of section in southern Kilkenny Bay (based on Pick (1964a) and Williams and Hancock (1977)). Letters in (b) are 'formations' of Pick (1964a).


(a)
N
0 metres 500
44
45
46
47
-77
-76
-75
Battery Point
Woodhill Bay
dock
Kilkenny Bay
area of Figure 5.73b
Black Nore
Portishead
Hang Rock
A369
Portishead Downs
LWM
Recent
tidal-flat deposits
Triassic
Mercia Mudstone Group (with marginal facies)
Westphalian
Pennant Sandstone Formation
Dinantian
Black Rock Limestone Subgroup (with dolomite)
Maesbury Mudstone Formation
limestone
Avon Group
Upper Old Red Sandstone
Portishead Formation
Lower Old Red Sandstone
Black Nore Sandstone Formation
fault (normal)
thrust
(b)
normal fault, tick on downthrow side
transcurrent fault
inclined Old Red Sandstone, dip in degrees
inclined Mercia Mudstone Group beds, dip in degrees
Kilkenny Bay
J1/J2
E
D/E
F
G
H
I
N
0 metres 100
Triassic
Mercia Mudstone Group
Upper Old Red Sandstone
D/E
F Woodhill Bay Fish Bed
G prominent green sandstone
H
I Woodhill Bay Conglomerate
Portishead Formation
Lower Old Red Sandstone
J1/J2 Black Nore Sandstone Formation

investigated the provenance of the sediments and discussed their depositional environment. The most detailed study was by Pick (1964a,b). He subdivided the Portishead Formation into nine formations (A to I) and the Black Nore Sandstone Formation into three (J1 to J3). However, only the Woodhill Bay Conglomerate and Woodhill Bay Fish Bed (Pick's formations I and F respectively) justify separate names, the remaining units representing laterally impersistent facies variations that are not mappable over a significant distance (Williams and Hancock, 1977). Also, Dodd (1986) suggested that formations A to C, which crop out south of the GCR site near Clevedon, may, in fact, be the same beds that are exposed at Portishead, repeated by faulting, with Pick's formations C and G being the same unit. The structural setting of the region was described by Reynolds and Greenly (1924). The diverse fish fauna from the Woodhill Bay Fish Bed, which is unique in southern Britain and includes the only British record of the placoderm *Groenlandaspis*, is described in the fossil fishes GCR volume (Dineley, 1999g).

The succession (Figure 5.74) is most easily examined in descending stratigraphical order by traversing the section from north-east to south-west. For convenience, it is described using Pick's (1964a,b) 'formations'. The highest unit ('formation' D), which forms part of the Portishead Formation, crops out near the top of the cliff adjacent to the seawall at the southern end of Woodhill Bay. It is approximately 3 m thick and consists of centimetre- to decimetre-scale beds of soft, red and green, cross-laminated, sandy siltstones and interbedded fine-grained sandstones that are harder, red, micaceous and parallel-laminated. Some of the sandstones rest on erosion surfaces, fill minor channels and contain thin, discontinuous intraformational mud-flake conglomerates (Williams and Hancock, 1977). Some are bioturbated, some preserve desiccation cracks and some contain fish fragments (Wallis, 1928). Beneath this unit are 7.5–17 m of mauve-red and green-grey, trough cross-bedded, fine- to medium-grained, metre-scale beds of sandstone (Pick's 'formation' E). The lowermost sandstones contain dispersed vein quartz pebbles (averaging 1.3 cm in length), mudstone rip-up clasts and rare eurypterid remains (Simpson, 1951). The base of this unit is marked just to the north-east of an indentation in the cliff (ST 4602 7695) by an erosion surface above which lies a conglomerate and channelized, cross-bedded sandstone, each about 1 m thick. Together, 'formations' E and D form a fining-upward sequence that fills a large channel.

The underlying Woodhill Bay Fish Bed ('formation' F of Pick, 1964a,b; beds 5–10 of Wallis, 1927, 1928) is seen best in the lower two thirds of the cliff just to the south-west of the indentation. At Woodhill Bay it is 10 m thick, but it is not laterally extensive, being cut out north-eastwards by an erosion surface. It consists predominantly of red, micaceous siltstones and sandy siltstones, but also contains some decimetre-scale beds of green and red, fine-grained sandstone and green siltstone (Pick, 1964a; Williams and Hancock, 1977). Most of the siltstone beds are 1–5 cm thick and contain small, simple horizontal and vertical burrows (Dodd, 1986). The sandstones increase in abundance in the middle and upper part of the unit and four prominent beds (up to 1 m thick) can be traced across the outcrop. They are parallel-laminated, planar cross-bedded or trough cross-bedded, and contain rare pebbles and abundant intraclasts. Some bedding surfaces are rippled or display primary current lineation, and the base of the thickest sandstone preserves load casts. The important ichthofauna, which is dominated by abundant disarticulated scales and teeth of the crossopterygian fish *Holoptychius* and *Glyptopomus*, is concentrated in the thickest sandstones (beds 7, 8 and 10 of Wallis). It indicates a Late Devonian (mid-Famennian) age for the bed (Kellaway and Welch, 1993) and includes the only British record of the otherwise widespread form *Groenlandaspis* (Ritchie, 1975; Dineley, 1999g). In addition, fragmentary carbonized plant debris occurs locally and Wallis (1927) recorded a single, poorly preserved brachiopod.

The base of the Woodhill Bay Fish Bed is sharp and defined by a gently scoured, pebble-strewn surface. Beneath is a 14 m-thick, pale green sandstone unit (Pick's 'formation' G), the upper part of which is particularly distinctive and of probable aeolian origin (Dodd, 1986). It is fine grained, moderately well- to very well-sorted, and contains large-scale planar and trough cross-sets. In contrast to the units above and below, intraclasts and quartz pebbles are absent, and the cross-bedding indicates transport predominantly from the south-east.

'Formation' H consists of 13.5 m of red and green-grey, cross-laminated and cross-bedded,

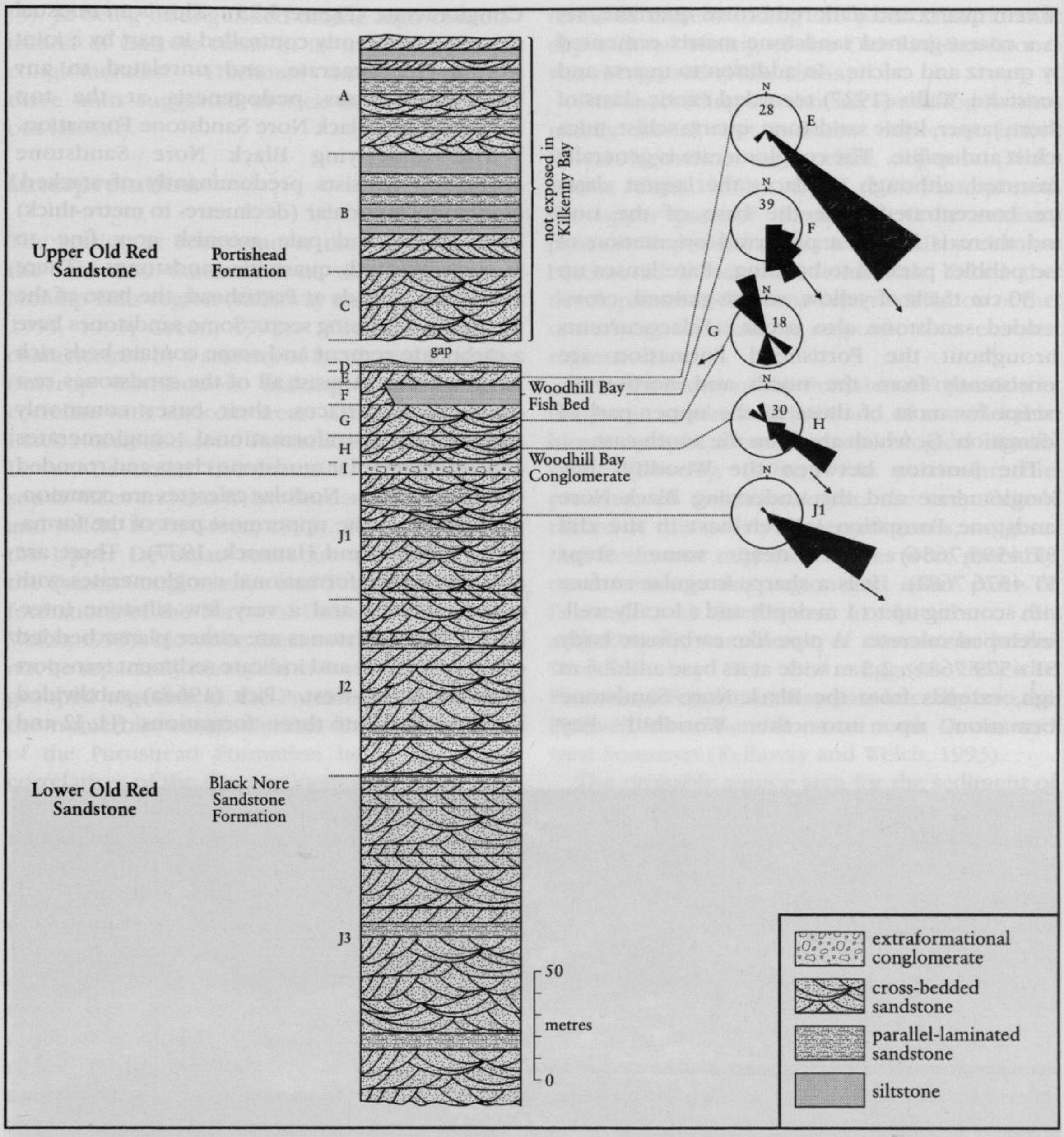


Figure 5.74 Generalized vertical section of the Old Red Sandstone at Portishead, with selected palaeocurrent rose diagrams. The rose diagrams show preferred palaeocurrent directions grouped in 20° classes and plotted as number frequency percent. The circles mark the 20% frequency level. Small arrows show the vector means of the cross-bedding dip azimuths. Based on Pick (1964a) and Williams and Hancock (1977). Letters A, B, etc. are 'formations' of Pick (1964a).

metre-scale beds of fine- to coarse-grained sandstone and pebbly sandstone with subordinate thin siltstones (up to 1.2 m thick) and minor (15–25 cm thick) conglomerates. Many of the sandstones are channelized, an excellent example of which occurs just above the base of the unit at the bottom of the cliff (ST 4585 7688).

Underlying these beds is the Woodhill Bay Conglomerate (Pick's 'formation' I), designated as the lowest unit of the Portishead Formation. Although thin (4–4.5 m), the bed is laterally extensive (Kellaway and Welch, 1955). It consists of well-rounded pebbles (averaging 2 cm) and cobbles (up to 15 cm), predominantly of vein quartz and dark red-brown quartzite, set in a coarse-grained sandstone matrix cemented by quartz and calcite. In addition to quartz and quartzite, Wallis (1927) recorded exotic clasts of chert, jasper, lithic sandstone, quartz schist, mica schist and spilite. The conglomerate is generally unsorted, although in places the largest clasts are concentrated near the base of the unit and there is locally a preferred orientation of the pebbles parallel to bedding. Rare lenses up to 30 cm thick of yellow, coarse-grained, cross-bedded sandstone also occur. Palaeocurrents throughout the Portishead Formation are consistently from the north and north-west, except for most of those in the upper part of 'formation' G, which are from the south-east.

The junction between the Woodhill Bay Conglomerate and the underlying Black Nore Sandstone Formation is seen best in the cliff (ST 4585 7686) and near some steps (ST 4576 7681). It is a sharp, irregular surface with scouring up to 1 m depth and a locally well-developed calcrete. A pipe-like carbonate body (ST 4579 7681), 2.5 m wide at its base and 2.5 m high, extends from the Black Nore Sandstone Formation up into the Woodhill Bay Conglomerate (Figure 5.75). This is an unusual calcrete, apparently controlled in part by a joint in the conglomerate, and unrelated to any contemporaneous pedogenesis at the top surface of the Black Nore Sandstone Formation.

The underlying Black Nore Sandstone Formation consists predominantly of stacked, commonly lenticular (decimetre- to metre-thick) beds of red and pale greenish grey, fine- to medium-grained, quartzitic sandstones. There are 292 m of beds at Portishead, the base of the formation not being seen. Some sandstones have a carbonate cement and some contain beds rich in muscovite. Almost all of the sandstones rest on erosion surfaces, their bases commonly marked by intraformational conglomerates containing angular mudstone clasts and rounded calcrete pebbles. Nodular calcretes are common, particularly in the uppermost part of the formation (Williams and Hancock, 1977). There are also a few extraformational conglomerates with quartz pebbles and a very few siltstone interbeds. The sandstones are either planar bedded or cross-bedded and indicate sediment transport from the north-west. Pick (1964a) subdivided the formation into three 'formations' (J1, J2 and

Figure 5.75 Conglomerates of the Woodhill Bay Conglomerate above sandstones of the Black Nore Sandstone Formation, Kilkenny Bay (ST 4579 7681). A pipe-like carbonate body extends across the junction and carbonate nodules occur in the Black Nore Sandstone Formation. (Photo: BGS No. A10737, reproduced with the permission of the Director, British Geological Survey, © NERC.)

J3), J2 being distinguished on the high concentration of calcrete clasts in its intraformational conglomerates. Thickness variations of the three units suggested to Pick that they wedge out laterally.

Interpretation

The section at Portishead is the stratotype for the Old Red Sandstone in the Bristol and Mendip Hills region (Kellaway and Welch, 1948, 1955, 1993; Green, 1992). The succession is characterized by a scarcity of fossils and a patchy outcrop distribution, making it difficult to correlate with adjacent areas. Lithologically, the Black Nore Sandstone Formation resembles the Lower Devonian Brownstones Formation of south Wales and the Welsh Borderland (Kellaway and Welch, 1955; Green, 1992). North of Bristol, the Upper Devonian strata are correlated with the Quartz Conglomerate and Tintern Sandstone formations of the Forest of Dean (Kellaway and Welch, 1993). However, these two formations cannot be separately identified at Portishead and are grouped together as the Portishead Formation, the numerous conglomerates and pebbly beds of the Portishead Formation being the distal correlatives of the Quartz Conglomerate.

The Black Nore Sandstone Formation and the Portishead Formation were deposited during two periods of sedimentation separated by a major (Mid-Devonian) orogenic phase. Most workers (e.g. Kellaway and Welch, 1955, 1993; Pick, 1964a; Allen, 1965b) placed the break at the base of the Woodhill Bay Conglomerate, although there is no angular discordance. Tunbridge (1986) suggested that the conglomerate may be of late Early or early Mid-Devonian age. Williams and Hancock (1977) questioned the significance of the Woodhill Bay Conglomerate–Black Nore Sandstone Formation junction, suggesting that the main unconformity may lie a few metres higher, at the top of the Woodhill Bay Conglomerate.

The Black Nore Sandstone Formation consists predominantly of alluvial channel-fill facies (Pick, 1964a; Williams and Hancock, 1977). Aeolian sandstones have been reported at Clevedon (Dodd, 1986), just to the south of the GCR site, the only occurrence of such facies at this level in the Anglo-Welsh Basin. The formation was one of the first in which the limestones of the Old Red Sandstone were interpreted as calcretes, and their significance in terms of understanding the palaeoclimatic and depositional setting of the Old Red Sandstone was recognized (Pick, 1964a).

The succeeding Portishead Formation is also mainly fluvial, but includes important inter-fluvial lacustrine or mudflat deposits (Pick, 1964a; Allen, 1965b). Dodd (1986) interpreted the upper part of 'formation' G as aeolian, probably deposited as relatively small barchan or barchanoid dunes. He tentatively linked the development of the dune field to deflation of the underlying sandflats in response to a eustatic regression.

The fish fauna of the Portishead Formation is unique in southern Britain and of considerable biostratigraphical and palaeoecological significance (Dineley, 1999g). In particular, the presence of *Groenlandaspis*, the only British record of this widely dispersed genus, suggests that freshwater migration routes were probably open between this region and other parts of Laurasia and Gondwana at that time. In addition, the occurrence of *Coccosteus* in the Woodhill Bay Fish Bed suggests that the Portishead Formation may pass laterally into the Pickwell Down Sandstone of north Devon and west Somerset (Kellaway and Welch, 1993).

The probable source area for the sediment of the Portishead Formation can be suggested from its petrology (Reynolds and Greenly, 1924; Wallis, 1927; Allen, 1965b) and palaeocurrent data (Wallis, 1927; Pick, 1964a; Allen, 1965b). Most workers (e.g. Reynolds and Greenly, 1924; Wallis, 1927; Allen, 1965b) concluded that the source was a Precambrian massif lying to the north-west, with a similar composition to the green schists of the Gwna Melange in the Mona Complex of Anglesey. However, based on tectonic criteria and on the regional distribution of similar conglomerates, Tunbridge (1986) and Cope and Bassett (1987) suggested that the Woodhill Bay Conglomerate may have been sourced from a periodically exposed landmass to the west in the area of the present Bristol Channel.

In the Bristol area, the continental Portishead Formation passes up through a transitional sequence into fully marine Carboniferous rocks. At Portishead, the transitional sequence (the Shirehampton Formation) is concealed beneath Recent tidal-flat sediments. It was logged nearby by Reynolds and Greenly (1923) at Portishead Pier station, and by Butler *et al.* (1972) in a temporary exposure at Woodhill (ST 4689 7733). At these localities it consists of intercalated red fluvial sandstones and mudstones, and grey, marine limestones and mudstones (Butler *et al.*, 1972; Kellaway and Welch, 1993) with a 'mixed' Devonian–Carboniferous fauna. Traditionally, the Devonian–Carboniferous boundary was placed at the base of the Shirehampton Formation in this region (see Kellaway and Welch, 1955). However, palynological evidence suggests that the boundary may lie in the upper part of the Portishead Formation (Neves and Dolby, 1967; Utting and Neves, 1970).

Conclusions

The cliffs to the south of Portishead between Woodhill Bay and Black Nore Point are the type locality for the Lower Devonian Black Nore Sandstone Formation and the overlying Upper Devonian to Lower Carboniferous Portishead Formation. The Portishead Formation includes important stratigraphical marker beds – the Woodhill Bay Conglomerate and the Woodhill Bay Fish Bed, the latter containing a diverse fauna that is unique in southern Britain and which provides a valuable insight into the palaeoecology of Devonian fish and their migration routes across the Old Red Sandstone continent. The site has been the subject of sustained research. It is regularly visited by undergraduate parties, and its eurypterid fauna is currently being studied. The nature of the Lower–Upper Old Red Sandstone junction, in particular the unusual calcrete development, requires detailed study to resolve conflicting interpretations. Aeolian sandstones reported in both the Black Nore Sandstone Formation and Portishead Formation also require further investigation, those in the former being unknown elsewhere in the Anglo-Welsh Basin at that stratigraphical level.

GLENTHORNE, DEVON (SS 795 499–SS 805 495)

P.R. Wilby

Introduction

The coastal outcrops at Glenthorne (Figure 5.76), which extend from Giant's Rib (SS 795 499) to The Caves (SS 805 495), provide the most representative section of the Hangman Sandstone Formation (*sensu* Edwards, 1999), the only substantial continental deposit of northerly derivation and proved Mid-Devonian age in southern Britain. The site is nationally important because it provides evidence of the southerly progradation of continental facies into the mainly marine area of north Devon and west Somerset when most of the Wales–Brabant Massif to the north was being eroded. It includes abundant examples of unconfined sheet-flood sandstones, which have not been widely recognized elsewhere in the Old Red Sandstone of Britain until recently

Description

The Hangman Sandstone Formation conformably overlies the shallow marine Lynton Formation (Simpson, 1964; Evans, 1983; Edmonds *et al.*, 1985) and is succeeded by the fully marine Ilfracombe Slates (Holwill, 1962; Edmonds *et al.*, 1985). Although largely unfossiliferous (see summary by Edwards, 1999), it is believed to be of mid-Eifelian age (Goldring *et al.*, 1978; Edmonds *et al.*, 1985), perhaps extending into early Givetian times (Evans, 1922; Knight, 1990; Edwards, 1999). A formal lithostratigraphical subdivision of the Hangman Sandstone proposed by Tunbridge (1978) broadly follows that of earlier workers (e.g. Lane, 1965), but the units are difficult to trace inland away from the well-exposed coast. The modified classification proposed by Edwards (1999) is therefore adopted in the following account. Estimates of the thickness of the Hangman Sandstone Formation vary considerably, principally because of structural complexities (Evans, 1922), ranging between 1097 m and 1658 m (Lane, 1965; Tunbridge, 1980b, 1981b, 1984, 1986). The Trentishoe Member makes up most of the formation (perhaps over 80%) and forms the entire section at Glenthorne. Its sedimentology has been studied in some detail, the most important contributions being by Tunbridge (1978, 1980b, 1981b, 1983a, 1984), Jones (1995) and Edwards (1999). The source of the sediments was discussed by Tunbridge (1983b, 1986) and Cope and Bassett (1987), and the nature of the upper and lower boundaries of the formation were described by Webby (1965a, 1966a) and Tunbridge (1983a). Descriptions of the sections at Glenthorne and nearby exposures were given by Tunbridge (1978), Jones (1995) and Edwards (1996, 1999). Details of the sequences preserved in the nearby inliers

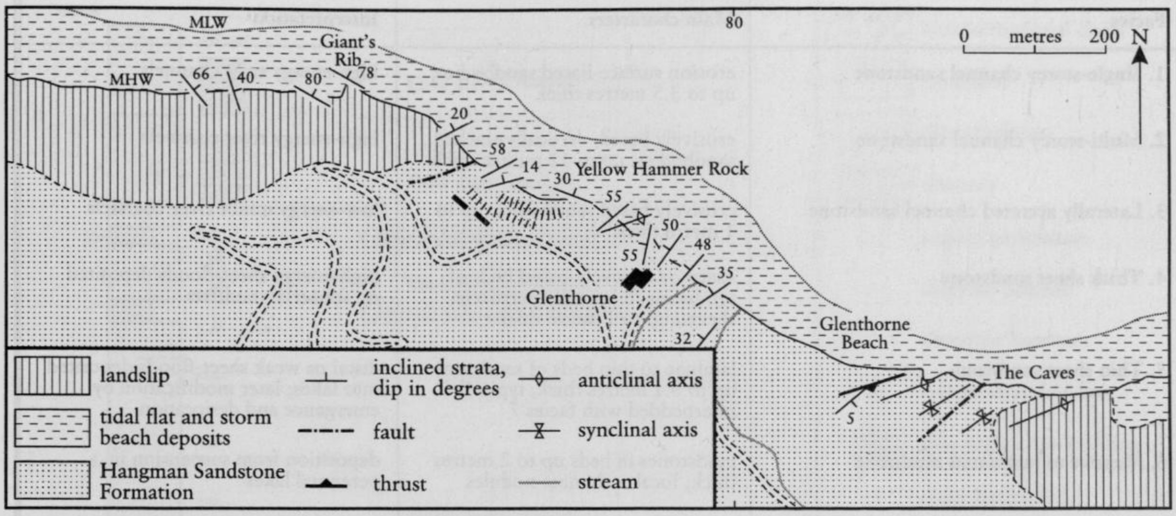


Figure 5.76 Geological map of the Glenthorne area, north Devon. Based on British Geological Survey 1:10 560 Sheet SS 74NE (1983) and 1:10 000 manuscript map 84NW (1993).

forming the Brendon Hills and Quantock Hills were given by Webby (1965b, 1966b).

Glenthorne is situated in a complex structural zone on the northern limb of the Lynton Anticline (Shearman, 1967; Sanderson and Dearman, 1973; Edwards, 1999). The exposed sequence is intensely folded and cut by numerous sub-vertical faults striking north-west or ENE. Most of the folds are open, plunge to the north-east and ENE at 10° to 30° and have axial surfaces dipping about 40° to the south-east. Locally, an axial planar fracture cleavage is developed in the more argillaceous units, and some of the sandstones are affected by bedding-parallel shear. Because of the structural complexity, it is not possible to examine a continuous sequence through the Trentishoe Member at the site, or to assess major vertical facies variations. However, the locality exposes the most important constituent facies of the unit (Tunbridge, 1984; Jones, 1995; Edwards, 1999) (Figure 5.77). Estimates of the abundance of each of these facies in the Minehead district by Jones (1995) appear to be representative of the sequence exposed at Glenthorne and are quoted below.

About 75% of the succession at Glenthorne comprises a variable suite of grey, purple and red, fine- to medium-grained, metre-scale beds of well-sorted, hard, lithic, quartzose sandstones and subordinate siltstones (Tunbridge, 1986; Strong, 1995). Approximately 40% of the succession consists of distinctive sheet-like sandstones, in which two facies are distinguished by differences in sandstone thickness (Tunbridge, 1984; Jones, 1995; Edwards, 1999). The thicker sheet sandstones (facies 4 of Edwards, 1999) form laterally persistent, 0.1–1.0 m-thick beds that are traceable over tens of metres with no obvious thinning. They have sharp, planar bases that rest on erosion surfaces and locally contain intraformational mudstone and siltstone clasts. Internally, they are dominated by low-angle planar or trough cross-bedding that commonly passes up into cross-lamination. Current- and wave-ripple sets occur in the topmost parts of some of the beds, and convolute lamination, climbing ripples and primary current lineation occur locally. In places, these thick sheet sandstones are stacked to form composite units, particularly good examples of which are exposed at Giant's Rib and Yellow Hammer Rock (Figure 5.78), and in the cliffs between the eastern end of Glenthorne Beach and The Caves.

The thinner sheet sandstone facies (facies 5 of Edwards, 1999) consists of laminae and thin beds (up to 0.1 m thick) of very fine- to fine-grained sandstone with sharp bases not characterized by erosion surfaces. Most of these sheets persist laterally for only a few metres. Many of them exhibit unidirectional cross-lamination and a fining-upward trend, or more rarely, wave ripple cross-lamination. Typically, this facies is interbedded with mudstones containing abundant desiccation cracks. It is best exposed on the foreshore at the base of the cliff approximately

Facies	Main characters	Interpretation
1. Single-storey channel sandstone	erosion surface-based sandbodies, up to 3.5 metres thick	high-energy river channels
2. Multi-storey channel sandstone	erosively based, vertically stacked sandbodies, up to 12 metres thick	high-energy river channels
3. Laterally accreted channel sandstone	erosively based sandbodies, up to 1 metre thick	low-energy minor river channels
4. Thick sheet sandstone	sharp or erosively based beds of sandstone in laterally persistent sheets, up to 1 metre thick	high-energy sheet-floods deposited on subaerial mudflats
5. Thin sheet sandstone	laminae to thin beds of sandstone up to 0.1 metres thick, typically interbedded with facies 7	distal or weak sheet-floods deposited into lakes; later modification by emergence and desiccation
6. Massive to laminated mudstone	mudstones in beds up to 2 metres thick; local carbonate nodules	deposition from suspension in perennial lakes
7. Desiccated and remobilized mudstone	mudstones, with common desiccation cracks; typically interbedded with facies 5; abundant bioturbation and local carbonate nodules	deposition from suspension in ephemeral lakes; emergence caused drying of sediment surface; folded and convoluted laminae caused by water escape
8. Mudstone with extraformational pebbles	mudstones with scattered quartz pebbles	cohesive, subaerial debris flows

Figure 5.77 Summary of the sedimentary facies of the Hangman Sandstone Formation and their interpretation. After Edwards (1999).

midway between Giant's Rib and Yellow Hammer Rock.

Interbedded with the sheet sandstone facies, or separated from them by thin mudstone- and siltstone-dominated units, are single-storey, channelized sandstones, each up to 3.5 m thick (facies 1 of Edwards, 1999). Most of these sandstones rest on erosion surfaces and their bases are commonly marked by laterally impersistent intraformational conglomerates. Internally, they are dominated by low-angle, unidirectional, planar or trough cross-bedding, and their upper surfaces are generally sharp and locally preserve asymmetrical ripple forms. Convolute bedding is also common and thin mudstone beds are present locally. This facies comprises approximately 20% of the sequence and is best exposed on the eastern side of Yellow Hammer Rock just above a modern storm beach ridge (Figures 5.78, 5.79). At several points, the channelized sandstones are stacked to form composite, multi-storey units (facies 2 of Edwards, 1999). These comprise approximately 15% of the succession and some are over 5 m thick. Some (e.g. SS 7963 4980) display convolute bedding and de-watering pipes.

In addition to the sandstone facies described above, Tunbridge (1984, fig. 17b) logged a 1.75 m-thick laterally accreted channel sandstone at the site (facies 3 of Edwards, 1999). Such sandstones are volumetrically unimportant at Glenthorne and only form about 1% of the sequence in the Minehead district. All of the sandstone facies show a consistent southerly palaeocurrent flow.

Interbedded with the sandstone facies, in units generally 0.1–2.5 m thick, are two finer-grained, mudstone-dominated facies. The first (facies 6 of Edwards, 1999) comprises approximately 9% of the succession and consists of red, purple and grey-green mudstones, silty mudstones and siltstones, some in interbeds mainly less than 5 cm thick. Some siltstones are internally cross-laminated. The mudstones are massive or laminated, and some contain simple, vertical burrows. The second facies (facies 7 of Edwards, 1999) comprises about 15% of the sequence and is characterized by an abundance of desiccation and remobilization structures. These include folds, diapirs, pipes, upcurled mudstone laminae and sand-filled desiccation cracks up to 6 cm deep, many of which penetrate multiple laminae.

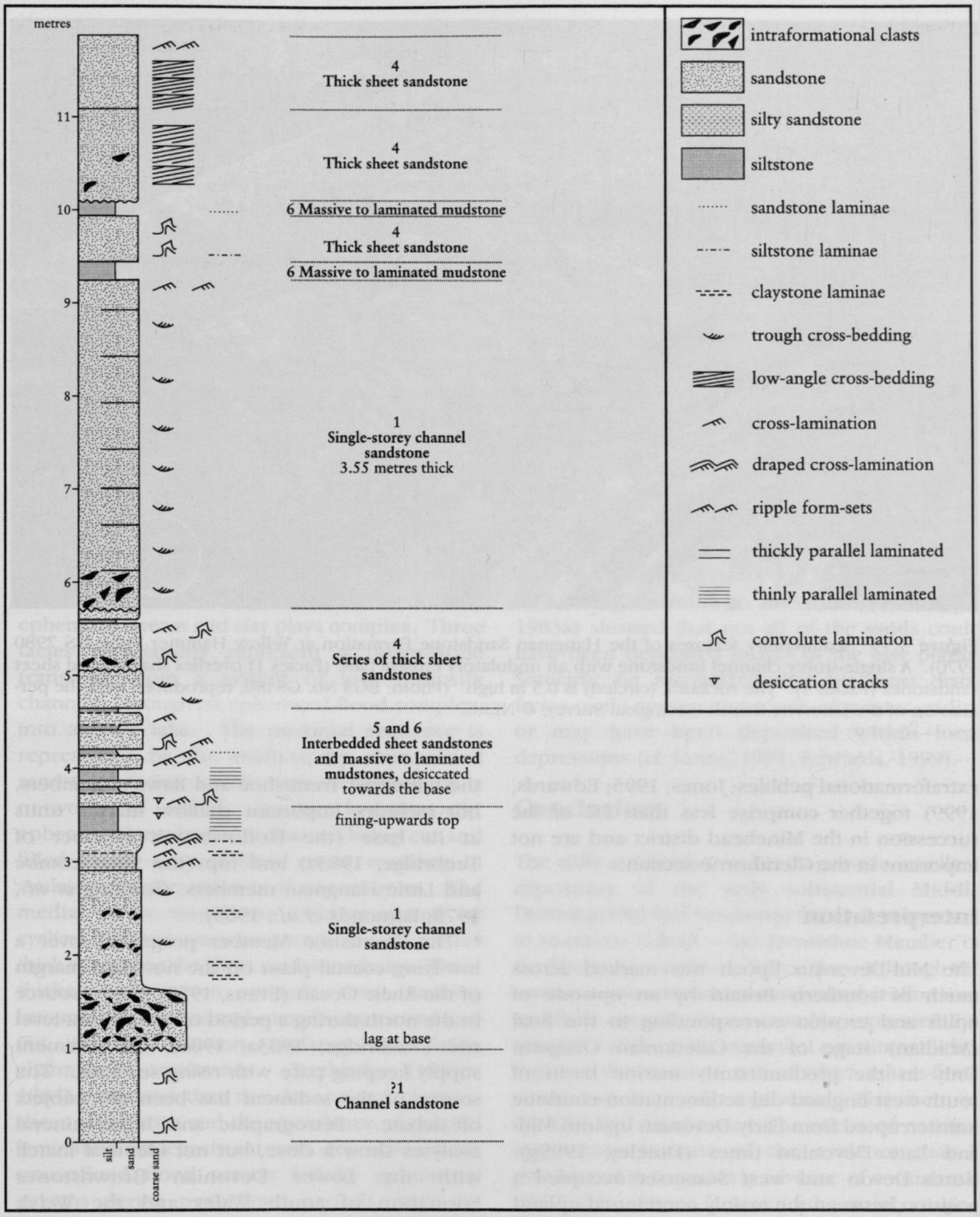


Figure 5.78 Graphic sedimentary log and interpretation of the Hangman Sandstone Formation at Yellow Hammer Rock (SS 7980 4975). After Edwards (1999).

Locally, these structures are so common that the sediment appears comprehensively brecciated or even homogenized. Sand- and mud-filled burrows, probably attributable to *Beaconites* and *Planolites*, are also common at certain levels.

Two other fine-grained facies (mudstones with pedogenic calcretes and mudstones with

Figure 5.79 Sedimentary features of the Hangman Sandstone Formation at Yellow Hammer Rock (SS 7980 4970). A single-storey channel sandstone with an undulatory erosive base (Facies 1) overlies sharp-based sheet sandstones (Facies 4). The rucksack (circled) is 0.5 m high. (Photo: BGS No. GS480, reproduced with the permission of the Director, British Geological Survey, © NERC.

extraformational pebbles; Jones, 1995; Edwards, 1999) together comprise less than 2% of the succession in the Minehead district and are not important in the Glenthorne section.

Interpretation

The Mid-Devonian Epoch was marked across much of southern Britain by an episode of uplift and erosion corresponding to the final (Acadian) stage of the Caledonian Orogeny. Only in the predominantly marine basin of south-west England did sedimentation continue uninterrupted from Early Devonian up into Mid- and Late Devonian times (Dineley, 1999g). North Devon and west Somerset occupied a position between the mainly continental upland area of the Wales–Brabant Massif to the north and the wave-dominated shoreline to the south (Webby, 1965a, 1966a; Edmonds *et al.*, 1975). Shifts in the position of the shoreline in response to fluctuations in sea level (House, 1975) are recorded by the alternation of shallow marine and terrestrial facies. The Hangman Sandstone Formation is dominated by the terrestrial Trentishoe and Rawn's members, but includes important shallow marine units at its base (the Hollowbrook Member of Tunbridge, 1983a) and top (the Sherrycombe and Little Hangman members; Goldring *et al.*, 1978; Edmonds *et al.*, 1985).

The Trentishoe Member prograded over a low-lying coastal plain on the northern margin of the Rheic Ocean (Evans, 1922) from a source to the north during a period of eustatic sea-level rise (Tunbridge, 1983a, 1986), the sediment supply keeping pace with rising sea level. The source of the sediment has been the subject of debate. Petrographic and heavy-mineral analyses show a close, but not identical match with the Lower Devonian Brownstones Formation of south Wales and the Welsh Borderlands. This unit, having then been recently deposited, is likely to have been poorly consolidated and particularly susceptible to rapid erosion during Acadian uplift (Tunbridge, 1984). However, garnet, which is the dominant heavy mineral in the Brownstones Formation, is rare and generally highly etched in the Trentishoe Member. This led investigators to discount south Wales as the source of the Trentishoe Member in favour of a landmass, either in the Bristol Channel area (Dewey, 1982) or in some other, as yet, unidentified lateral source (Hallam, 1934). The rarity of garnet in the Trentishoe Member has been interpreted more recently as a diagenetic phenomenon and the Brownstones Formation has been re-instated as the most likely source (Tunbridge, 1981b, 1984, 1986; Edwards, 1999), which is entirely consistent with the palaeocurrent evidence. In marked contrast, the overlying Rawn's Member consists of much coarser and more immature facies, including abundant conglomerates, that contain exotic, angular clasts which do not match any possible source rocks in south Wales. It records a dramatic switch in sediment source and is widely believed to have been derived from the intermittently exposed Bristol Channel landmass (Tunbridge, 1984; Cope and Bassett, 1987).

Tunbridge (1984), following Evans (1922), but contrary to Holwill *et al.* (1969), interpreted the Trentishoe Member as an extensive sandy ephemeral stream and clay playa complex. Three facies associations represent a down-slope transition from a system of low sinuosity channels, through an ephemeral flood complex, into a playa lake. The proximal sequence is represented by the multi-storey channelized sandstone facies which were deposited by a network of small, sandy, low-sinuosity, ephemeral streams, each channel being cut and filled during a single flood event, resulting in avulsion and the incision of new courses. The medial facies association is represented by cyclical, upward-coarsening units several metres thick containing the sheet sandstone facies. These thicken and coarsen upwards, some stacking into multiple bodies and some being incised and cut out by erosion surfaces underlying channelized sandstones. Tunbridge (1981b, 1984) proposed that the dimensions of these sheet sandstones and the abundance of parallel lamination are consistent with deposition from unconfined flood waters fed by ephemeral streams during peak flood periods, with the cyclicity being a response to progradation of lobes during consecutive floods. The distal facies association comprises mainly the desiccated mudstone and sandstone facies, but also contains rare thin sheet sandstones. It represents the final stage in the down-slope decline in flow velocity and the main site of muddy flood deposition.

Jones (1995) and Edwards (1999) supported Tunbridge's (1981b, 1984) tripartite division of the facies, but suggested that it does not necessarily reflect down-slope changes. Instead, they proposed that it may be due to variations in channel flux, fan retrogradation, and/or lateral shifts in fan position. Consequently, they interpreted the entire sequence as having been deposited on the distal part of an alluvial-fan complex, with periodic development of ephemeral mudflats. This, they suggested, is more consistent with the relative abundance of both sheet and channel sandstones, which imply continual proximity to a sediment source. In this model, periods of high and frequent discharge resulted in the formation of sandflats, whereas mudflat–playa-lake environments formed during periods of low discharge. Ephemeral lakes may also have formed after sheet flooding.

Tunbridge (1984) recognized some problems with his model and conceded that the presence of a sandy coastline to the south (Tunbridge, 1983a) showed that not all of the sands could have been deposited inland of the clay playas. Similarly, he recognized that his most distal facies could represent periods of greater aridity, or may have been deposited within local depressions (cf. Jones, 1995; Edwards, 1999).

Conclusions

The cliffs at Glenthorne Beach provide excellent exposures of the only substantial Middle Devonian Old Red Sandstone facies development in southern Britain – the Trentishoe Member of the Hangman Sandstone Formation. Although the section is intensely folded and faulted, it affords an excellent opportunity to examine representative examples of the most important constituent lithologies of the member, one of which (sheet-flood sandstone) is poorly represented elsewhere in the Old Red Sandstone. The site is of national importance because of the evidence that it provides of the southerly advance of continental Old Red Sandstone facies into the mainly marine area of north Devon and west Somerset at a time when the rest of the Anglo-Welsh Basin to the north was undergoing erosion. This has important implications for the palaeogeography of the basin, and for the relationship between sea-level changes and the rates of source erosion and sediment transport during Mid-Devonian times.