British Lower Jurassic Stratigraphy

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GCR Editor: R. Gallois

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Chapter 3

The Mendip and South Wales massifs

M.J. Simms

INTRODUCTION

The Mendip Hills of Somerset form a major Palaeozoic inlier separating the predominantly Mesozoic rocks of the Severn Basin to the north and the Wessex Basin to the south. They comprise an en-echelon series of four asymmetric periclines developed in Carboniferous and older rocks, these periclines being markedly steeper, or even overturned, on their northern flanks and in several instances underlain by low-angle thrust planes (Williams and Chapman, 1986). Intensive subaerial erosion in Permo–Triassic times stripped away the Upper Carboniferous, and in places the Lower Carboniferous and underlying Devonian, rocks across the fold crests. Rising sea level during the Jurassic Period then saw the progressive submergence of the Palaeozoic inlier and its complete burial by late Jurassic times (Simms, 1997). Roughly along-strike to the WNW, Triassic and Lias Group strata similarly onlap onto the Carboniferous basement of the Welsh Massif and thicken southwards into the Bristol Channel Basin, a north-westward extension of the Wessex Basin (Figure 2.1, Chapter 2). The precise effect of proximity to these Palaeozoic massifs varies from locality to locality. The most widely observed effect is the development of carbonate-dominated, often bioclastic, marginal facies such as are seen at the **Pant y Slade to Witches Point** and **Viaduct Quarry** GCR sites of south Wales and the southern Mendips respectively. In contrast the sequence to the north-east of the Mendips, on the Radstock Shelf, is highly condensed but not necessarily of marginal facies. It is clear that, just as for the main Wessex Basin, the Palaeozoic rocks of the Mendip Hills experienced significant extension during the Mesozoic Era. The most graphic and spectacular evidence for this is the late Triassic and early Jurassic sediment-filled fissures that cut through the Carboniferous Limestone at the GCR sites of **Cloford Quarry** and **Holwell Quarries**.

The general lithostratigraphy of the sites discussed in this chapter is summarized in Figure 2.3 (Chapter 2).

THE LIAS GROUP OF SOUTH WALES

The Lias Group successions exposed at the two GCR sites in south Wales exemplify the relationship between facies and proximity to Palaeozoic basement rocks. The succession at the **Pant y Slade to Witches Point** GCR site shows clear lateral and vertical facies changes close to the underlying basement, whereas the succession at the **Lavernock to St Mary's Well Bay** GCR site is typical of more distal facies farther into the Bristol Channel Basin. The Welsh succession was documented by Trueman (1920, 1922b, 1930), who provided the basis for later sedimentological and palaeoecological investigations by Hallam (1960a, 1964a) and by Wobber (1965, 1966, 1968a,b). More recent accounts covering these sites are those of Waters and Lawrence (1987), Wilson *et al.* (1990) and Warrington and Ivimey Cook (1995).

LAVERNOCK TO ST MARY'S WELL BAY, GLAMORGAN (ST 174 676–ST 187 682)

Introduction

The Lavernock to St Mary's Well Bay coastal section, covering a 2 km stretch of coastline (Figure 3.1), provides the best offshore Blue Lias Formation section of South Wales, exposing about 35 m of marine Hettangian strata. The section from the Hettangian strata passes down through a continuous succession into the quasi-marine Penarth Group and the non-marine Mercia Mudstone Group of the Triassic System.

The Blue Lias Formation at this site is of typical facies, in contrast to the marginal facies of equivalent age exposed at the **Pant y Slade to Witches Point** GCR site farther west, and the site is therefore of key importance for revealing the nature of lateral facies changes through comparison both with the marginal facies at the Pant y Slade to Witches Point GCR, and with the correlative succession exposed on the south coast of the Bristol Channel at the **Blue Anchor–Lilstock Coast** GCR site.

The Blue Lias Formation strata in the Lavernock to St Mary's Well Bay section are folded into a gentle syncline, with the youngest strata exposed in the cliffs in the central part of the GCR site (Figure 3.2). The lower part of the Blue Lias Formation, exposed at the western and eastern ends of the site, has been named the 'St Mary's Well Bay Member'. It comprises typical Blue Lias Formation facies of alternating limestones and mudstones on a decimetre scale (Waters and Lawrence, 1987). It is succeeded by

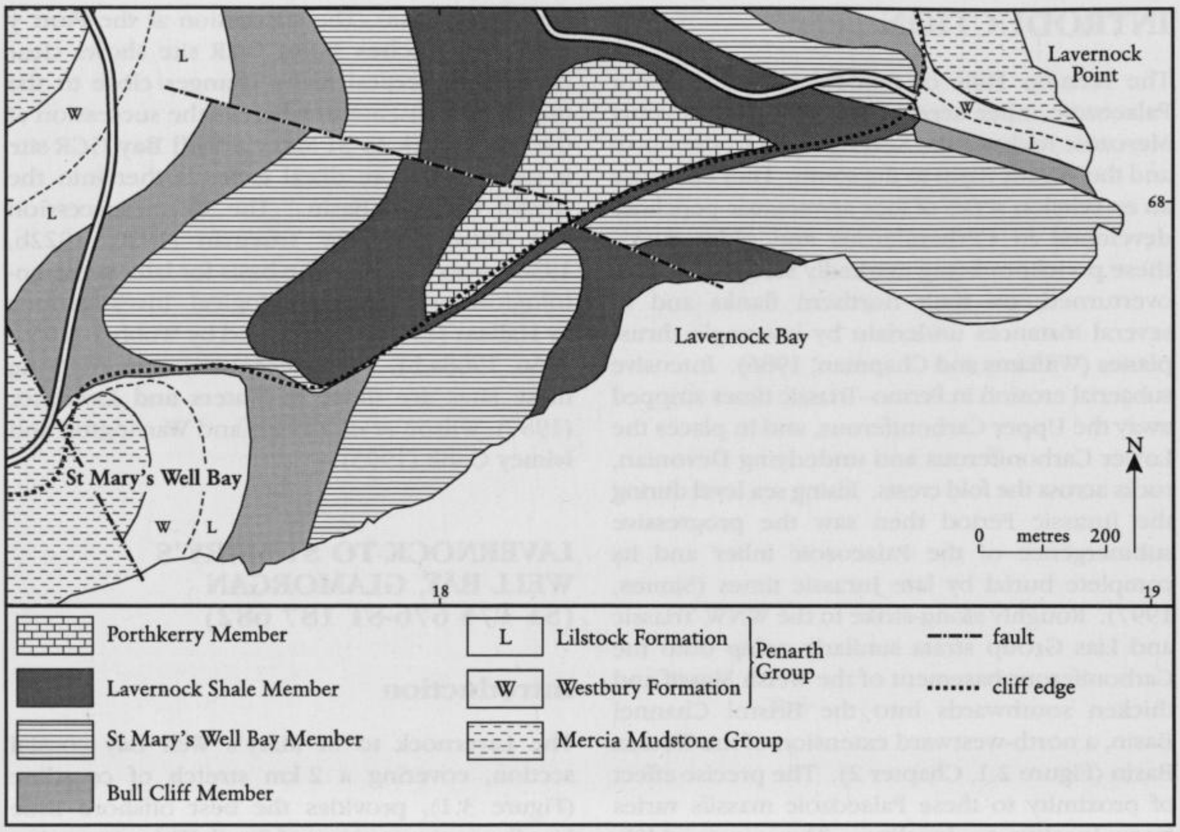


Figure 3.1 Geological sketch map of the Lavernock to St Mary's Well Bay area. After Trueman (1920).

a mudstone-dominated sequence, called the 'Lavernock Shale Member' (Strahan and Cantrill, 1902), which forms part of the cliffs in the centre of the bay (Figure 3.2). This in turn is overlain by further Blue Lias Formation limestone–mudstone alternations representing the lower part of the Porthkerry Member (Waters and Lawrence, 1987). The site is the type locality for the St Mary's Well Bay Member and the Lavernock Shale Member.

The Lavernock to St Mary's Well Bay GCR site is the only site in south Wales at which the transition from the Triassic Penarth Group to the early Jurassic Blue Lias Formation is exposed and, as such, has attracted the attention of palaeontologists and stratigraphers for more than a century. Bristow and Etheridge (1873) provided vertical sections through the Penarth Group and Blue Lias Formation and Woodward (1893) gave a brief description. Further details were published by Strahan and Cantrill (1902, 1912). Richardson (1905) published a stratigraphical account of the lower part of the succession, but did not provide any detail of the succession above the Planorbis Zone. Trueman (1920) published a detailed account of the biostratigraphy and lithostratigraphy of the Lias here, which included an outcrop map and sketch section of the strata exposed in the cliff and foreshore. Hallam (1960a, 1964a) and Wobber (1965, 1966, 1968a,b) included the Lavernock to St Mary's Well Bay GCR section in their sedimentological and palaeoecological investigations of the south Wales Lias, and Wobber (1968a,b) provided a simplified graphic log for the entire section. Micropalaeontological investigations have been undertaken at this site (Wall, 1965; Copestake, 1989; Lord and Boomer, 1990) and elements of the bivalve fauna have been described from here (Hodges, 2000). Detailed accounts of the sections have been published by Waters and Lawrence (1987) and by Warrington and Ivimey-Cook (1995). Hodges (1994) published a detailed section through the basal Lias and described the biostratigraphy of ammonites and bivalves through this part of the succession. Bessa and Hesselbo (1997) have published gamma-ray logs for the site.

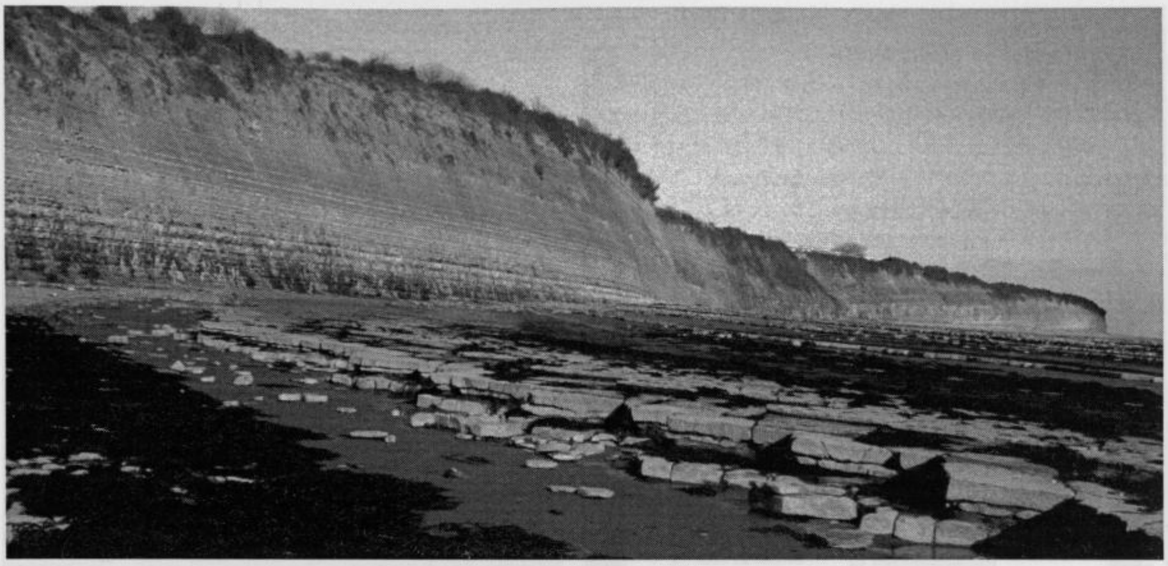
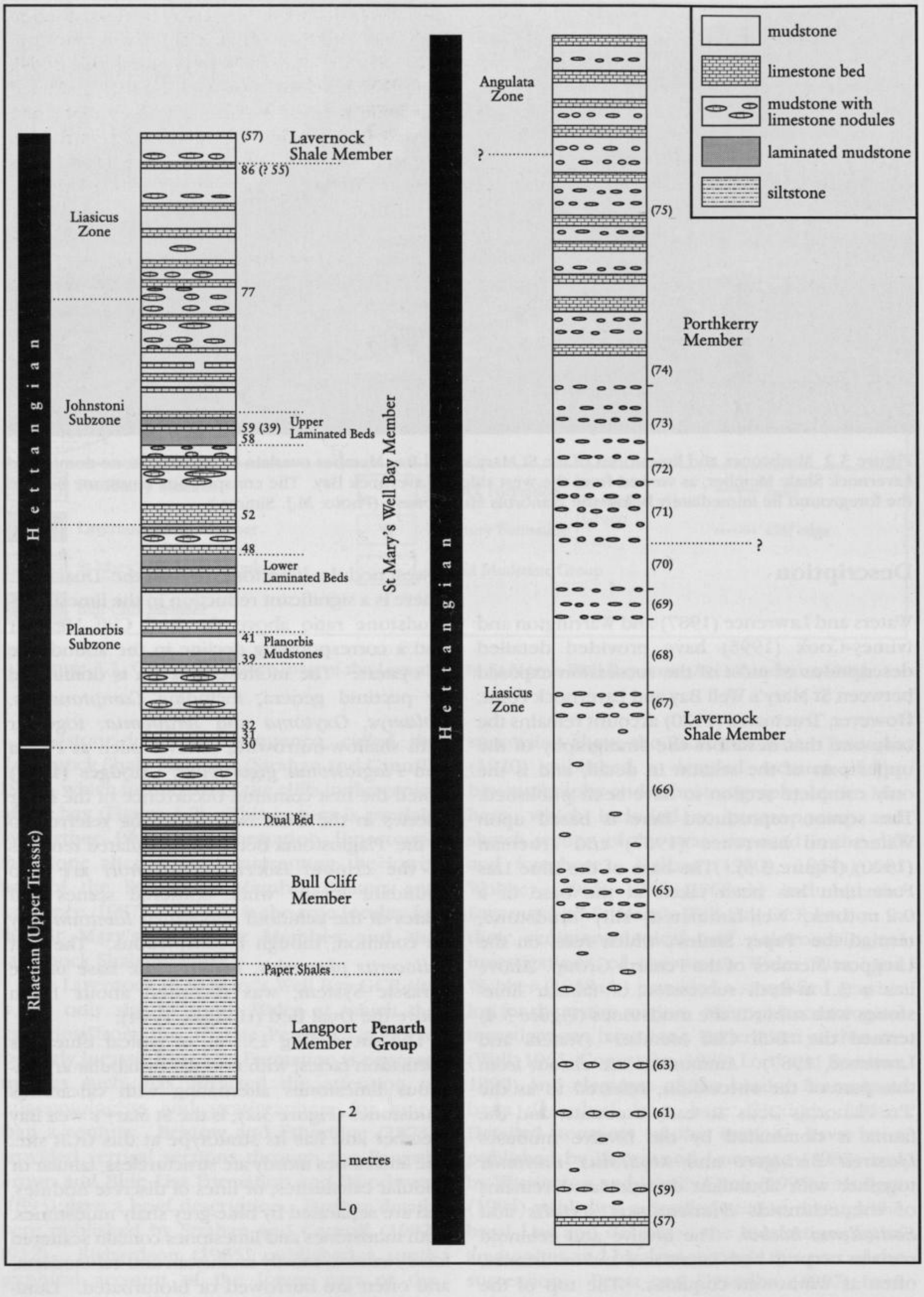


Figure 3.2 Mudstones and limestones of the St Mary's Well Bay Member overlain by the mudstone-dominated Lavernock Shale Member, as viewed from the west side of Lavernock Bay. The conspicuous limestone beds in the foreground lie immediately below the Planorbis Mudstones. (Photo: M.J. Simms.)

Description

Waters and Lawrence (1987) and Warrington and Ivimey-Cook (1995) have provided detailed descriptions of most of the succession exposed between St Mary's Well Bay and Lavernock Point. However, Trueman's (1920) account remains the only one that describes the stratigraphy of the upper part of the section in detail, and is the only complete section to have been published. The section reproduced here is based upon Waters and Lawrence (1987) and Trueman (1920) (Figure 3.3). The base of the Blue Lias Formation has been taken at the base of a 0.2 m-thick, well-laminated, silty mudstone, termed the 'Paper Shales', which rests on the Langport Member of the Penarth Group. Above lies a 3.1 m-thick succession of tabular limestones with subordinate mudstones (Figure 3.4) termed the 'Bull Cliff Member' (Waters and Lawrence, 1987). Ammonites are absent from this part of the succession, referred to as the 'Pre-Planorbis Beds' in early accounts, and the fauna is dominated by the bivalve molluscs *Liostrea hisingeri* and *Modiolus minimus* together with abundant disarticulated remains of the echinoids *Diademopsis serialis* and *Eodiadema bechei*. The bivalve and echinoid remains occur in both limestones and mudstones, often as winnowed coquinas. The top of the Bull Cliff Member is taken at the base of the lowest nodular limestone, termed the 'Dual Bed'. There is a significant reduction in the limestone–mudstone ratio above the Bull Cliff Member and a corresponding decline in the abundance of oysters. The molluscan fauna is dominated by pectinid genera, including *Camptonectes*, *Chlamys*, *Oxytoma* and *Terquemia*, together with shallow-burrowing bivalves such as *Pinna* and *Plagiostoma giganteum*. Hodges (1994) noted the first common occurrence of the latter species in the Dual Bed, which he referred to as the 'Plagiostoma Bed'. Disarticulated remains of the crinoid *Isocrinus psilonoti* are also abundant locally while scattered spines and plates of the echinoid *Miocidaris lobatum* may be common, though inconspicuous. The first *Psiloceras planorbis*, marking the base of the Jurassic System, was recorded about 1.4 m above the Dual Bed (Hodges, 1994).

The succeeding 13.1 m, of typical Blue Lias Formation facies, with nodular or tabular argillaceous limestones alternating with calcareous mudstones (Figure 3.2), is the St Mary's Well Bay Member and has its stratotype at this GCR site. The limestones mostly are structureless, tabular or nodular calcilutites, or lines of discrete nodules, and are separated by blue-grey shaly mudstones. Both mudstones and limestones contain scattered fossil remains, mostly molluscan and echinoderm, and often are burrowed or bioturbated. Laminated mudstones and limestones occur at only


mudstone
limestone bed
mudstone with limestone nodules
laminated mudstone
siltstone
Rhaetian (Upper Triassic)
Hettangian
Liasicus Zone
Johnstoni Subzone
Planorbis Subzone
Lavernock Shale Member
Upper Laminated Beds
Lower Laminated Beds
Planorbis Mudstones
Dual Bed
Bull Cliff Member
Paper Shales
Langport Member
Penarth Group
St Mary's Well Bay Member
Angulata Zone
Porthkerry Member
metres

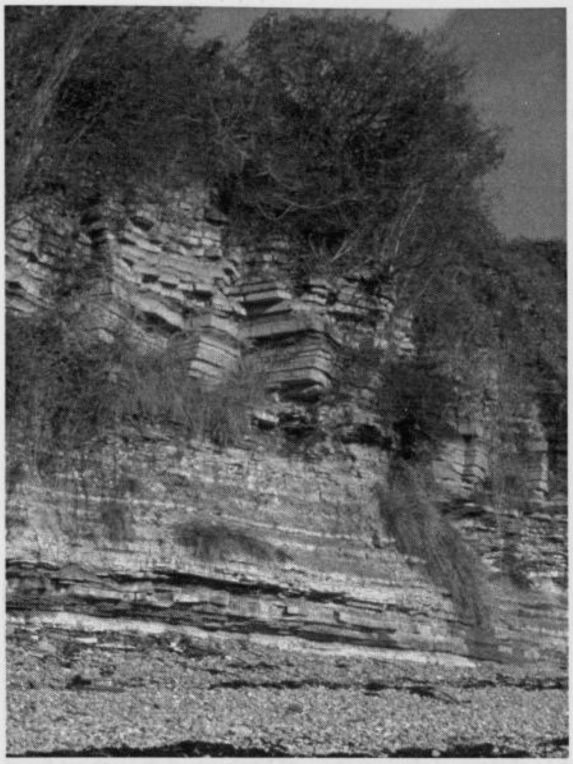


Figure 3.4 The section at St Mary's Well Bay, showing the conspicuous tabular limestones of the Bull Cliff Member in the upper part of the cliff overlying the silty mudstones of the Langport Member of the Penarth Group, with prominent sandstones in the Cotham Member visible near the base of the cliff. (Photo: M.J. Simms.)

three levels in the St Mary's Well Bay Member and form important marker bands. The lowest of these, termed the 'Planorbis Mudstones' by Waters and Lawrence (1987), lie about 7 m above the base of the bed and comprise 0.65 m of dark-grey fissile mudstone with abundant poorly preserved *Psiloceras planorbis*. The 'Lower Laminated Beds' lie about 1 m higher in the section, towards the top of the Planorbis Subzone, and comprise 0.7 m of fissile mudstone

◂**Figure 3.3** Section through the Blue Lias Formation in Lavernock Bay, based on Waters and Lawrence (1987) and Trueman (1920). The sequence through the Lavernock Shale and Porthkerry members has been compiled from Trueman's (1920) description and should be considered only provisional (see comments in main text). Bed numbers are those of Waters and Lawrence (1987), and Trueman (1920) in brackets.

with a thin laminated limestone. Almost 2.5 m higher still, towards the middle of the Johnstoni Subzone, are the 'Upper Laminated Beds', comprising a distinctive 0.08 m-thick laminated limestone within a 0.9 m-thick fissile mudstone capped by a further thin laminated limestone. These laminated limestones and mudstones typically are organic-rich and lack evidence of burrowing or shelly benthos.

The uppermost 2.7 m of the St Mary's Well Bay Member has been assigned to the Liasicus Zone and is dominated by mudstones with only a few tabular or nodular limestones. The boundary with the overlying Lavernock Shale Member is arbitrary, and has been placed at the top of a tabular limestone bed, Bed 86 of Waters and Lawrence (1987). Here, at the stratotype section, the member is some 12 m thick but largely inaccessible (Figure 3.2). This part of the succession was recorded by Trueman (1920) on the basis of a log compiled from small exposures inland rather than from the cliff section itself. However, Waters and Lawrence (1987) considered Trueman's record of this part of the section to be unreliable and to contain errors of correlation and/or identification. It remains otherwise undocumented in any detail to the present day. The Lavernock Shale Member is dominated by grey calcareous mudstones with only a few thin nodular limestones. The sediments are fossiliferous and bioturbated, with a varied fauna of benthic molluscs, particularly bivalves such as *Cardinia listeri*, echinoderm debris and a few ammonites. The ammonites include *Waehneroceras portlocki* and *Psilophyllites hagenowi*, indicative of the Liasicus Zone. The top of the member is taken at the base of Bed 87 of Waters and Lawrence (1987), within about 2 m of where the dominantly mudstone sequence passes up into strata in which mudstones and nodular limestones occur in roughly equal proportions.

About 10 m of alternating limestone and shale of the Porthkerry Member is poorly exposed in the upper part of the cliff in St Mary's Well Bay. Much of this lies within the upper part of the Liasicus Zone, but Trueman (1920) reported a specimen of *Schlotheimia* aff. *thalassica* from near the top of the section, indicative of the Angulata Zone.

Fossil preservation throughout the Blue Lias Formation at this GCR site almost invariably is calcitic or pyritic.

Interpretation

Although the succession exposed at this site is fossiliferous and contains ammonites in much greater abundance than the marginal facies farther to the west, at the **Pant y Slade to Witches Point** GCR site, details of the biostratigraphy of parts of the section have only recently been clarified. Trueman (1920) assigned much of the Lavernock Shale Member to the Angulata Zone on the basis of numerous fragments of supposed *Schlotheimia* spp. (presumably *Saxoceras* or immature *Waehneroceras*), and *Alsatites liasicus* from the uppermost part of the succession. However, the rationalization of the zonal stratigraphy of the Lias by Dean *et al.* (1961) resulted in the lower part of what had been the Angulata Zone becoming the Liasicus Zone. Wobber (1968a,b) continued to use Trueman's (1920) zonal divisions and considered the Liasicus Zone to be only 1.2 m thick at this GCR site. In addition, he claimed to have found *Vermiceras scylla* near the top of the section, indicative of the Rotiforme Subzone (Page, 1992), but this probably arose through mis-identification of *Alsatites*. The Lavernock Shale Member lies entirely within the Liasicus Zone and the strata preserved in the Lavernock outlier range no higher than the Angulata Zone (Waters and Lawrence, 1987).

The mudstone-dominated facies of the Lavernock Shale Member can be correlated with the St Audrie's Shales of the **Blue Anchor–Lilstock Coast** GCR site (Palmer, 1972; Warrington and Ivimey-Cook, 1995), the Saltford Shale Member of the Bristol district (Donovan, 1956; Donovan and Kellaway, 1984) and a more argillaceous part of the succession on the Dorset coast (Hesselbo and Jenkyns, 1995) (see Figure 2.6, Chapter 2). This has been interpreted as evidence for a eustatic sea-level rise in Liasicus Zone times (Hallam, 1981). Bessa and Hesselbo (1997) noted that the gamma-ray logs for the Blue Lias Formation of the Somerset and south Wales coasts were similar, except close to the Planorbis–Liasicus zonal boundary where they inferred the St Mary's Well Bay section to be the more complete. Individual limestone beds can, in many cases, be traced for kilometres along the south Wales coast while the distinctive Lower Laminated Beds and Upper Laminated Beds were traced across to the **Pinhay Bay to Fault Corner** GCR site by Hallam (1960a, 1964a). The Paper Shales, taken as the base of the Blue Lias Formation here, have also been correlated with similar shales which comprise most of the Watchet Beds (Richardson, 1911) of the **Blue Anchor–Lilstock Coast** GCR site (Whittaker, 1978).

Wobber (1968b) recognized five offshore biofacies in the Blue Lias Formation of the south Wales coast on the basis of a broad range of sedimentological features. These included carbonate content, benthic oxygen levels, sedimentation rates and bioclastic content. He used these to identify marginal and offshore lithofacies and biofacies and to relate them to relative depths of deposition. Benthic oxygen levels seem rarely to have fallen sufficiently to exclude burrowing organisms, and there is a diverse shelly benthos at many levels. Wobber (1968b) noted that the faunas of the limestones and mudstones were similar. Disarticulation of echinoderms and the fragmentation of much molluscan shell material indicates moderate- to high-energy conditions at times. Wobber (1968b) also considered burrowing and scavenging organisms to be critical for disrupting stratification and reducing bioclastic debris size. Laminated benthos-free sediments are present at only three levels, all in the Planorbis Zone, but since at least two have been correlated across to the **Pinhay Bay to Fault Corner** GCR site they probably relate to climatic or sea-level changes rather than to local sedimentological factors.

The benthic fauna throughout the Blue Lias Formation exposed at this site, as elsewhere in the offshore facies of the south Wales Lias, is dominated by bivalve molluscs. Strongly ribbed bivalves are rare or fragmentary in the Lias at this site, suggesting that such remains are allochthonous here, whereas in the more marginal facies around Witches Point they are common and almost certainly autochthonous. Within the Lavernock section there is a clear ecological succession reflecting water depth and/or sedimentation rate. The abundance of the cemented *Liostrea hisingeri*, the byssate *Modiolus minimus*, and the algal-grazing echinoids *Diademopsis* and *Eodiadema*, in the limestone-dominated Bull Cliff Member suggests slow sedimentation and a firm substrate, perhaps with incipient hardgrounds. These epifaunal bivalves are largely replaced in the St Mary's Well Bay Member by shallow burrowers, such as *Plagiostoma*, and pectinids, indicating an increased sedimentation rate and a stable, well-oxygenated sea floor with gentle currents.

Pinna hartmanni occurs at a few levels and indicates more constant sedimentation rates during these intervals. The presence of deeper burrowing forms, notably *Cardinia listeri*, in the Lavernock Shale Member indicates a softer sea floor associated with a rise in sea level.

Conclusions

The Lavernock to St Mary's Well Bay GCR site exposes the most complete and representative section through the lower part of the Blue Lias Formation in south Wales from its boundary with the underlying Penarth Group. It records particularly clearly the gradual change from the limestone-dominated Bull Cliff Member through to the mudstone-dominated Lavernock Shale Member, with corresponding faunal changes from a firm substrate epifauna to a soft substrate shallow infauna. Biostratigraphical correlation with the marginal facies of the **Pant y Slade to Witches Point** GCR site farther west, and correlative GCR successions on the Dorset and north Somerset coasts, provides a valuable insight into the nature of early Jurassic sedimentation on this basin margin.

PANT Y SLADE TO WITCHES POINT, GLAMORGAN (SS 870 741–SS 890 726)

Introduction

The Pant y Slade to Witches Point GCR site is a coastal section, some 2 km in length (Figures 3.5 and 3.6) that exposes, better than any other site, the lateral and vertical transitions from 'marginal' facies unconformable on Carboniferous Limestone in the west through to more 'offshore' Blue Lias Formation facies in the east. As such it is one of the classic British examples of lateral facies changes in ancient sediments. Three distinct sedimentary units, the Sutton Stone Member, the Southerndown Member and the Blue Lias Formation (Porthkerry Member), can be recognized along the section although precise boundaries between them are diachronous and difficult to define. A gentle easterly dip brings the marginal facies, exposed in the upper part of the cliff above the Carboniferous Limestone at Pant y Slade, down to beach level at Southerndown. Between there and Witches Point (Trwyn y Witch) the cliffs are formed in alternating limestones and mudstones of Blue Lias Formation facies. Faults on the western side of Witches Point bring the Carboniferous Limestone into the lower part of the cliff, with the marginal facies forming the cliffs above and descending to beach level a short distance to the east. This site is a key locality for demonstrating, through faunal evidence, the diachronous relationships of facies.

The oldest Jurassic rocks, termed the 'Sutton Stone' by Henry De la Beche (1846), comprise coarse bioclastic calcarenites with reworked limestone lithoclasts and rest on an irregular surface of Carboniferous Limestone. This passes up gradationally into more thinly bedded bioclastic calcarenites with fewer and smaller limestone lithoclasts, and a higher clay content. These were termed the 'Southerndown Beds' by Tawney (1866). In turn this passes up into offshore Blue Lias Formation facies of the Porthkerry Member. The succession fines upwards from the coarsely conglomeratic base of the Sutton Stone Member to the mudstones and argillaceous limestones of the Blue Lias Formation. There is a corresponding increase in faunal diversity upward through the succession. The striking transition from marginal facies to offshore Blue Lias Formation sediments has been the focus of considerable discussion since it was first noted by De la Beche (1846). Publications that have been concerned with the age of the sediments and their fossil content included Tawney (1866), Bristow (1867), Duncan (1867a,b, 1886), Moore (1867a), Tate (1867), Tomes (1878, 1884) and Hodges (1986). One of the most comprehensive descriptions of the section is that of Trueman (1922b): useful summaries were provided by Woodward (1888a, 1893), Strahan and Cantrill (1904), Arkell (1933), Thomas (1970), Wilson *et al.* (1990) and Warrington and Ivimey-Cook (1995). Accounts by Hallam (1960a), Wobber (1965, 1966, 1968a,b), Ager (1986a,b), Fletcher (1988) and Johnson and McKerrow (1995) have focused on the palaeoenvironments deduced from the sedimentology and palaeoecology.

Description

The Lias succession exposed along the coast between Pant y Slade and Witches Point shows vertical and lateral changes that demonstrate the transgressive nature of the basal Lias in this area. The unconformity between the Lias marginal

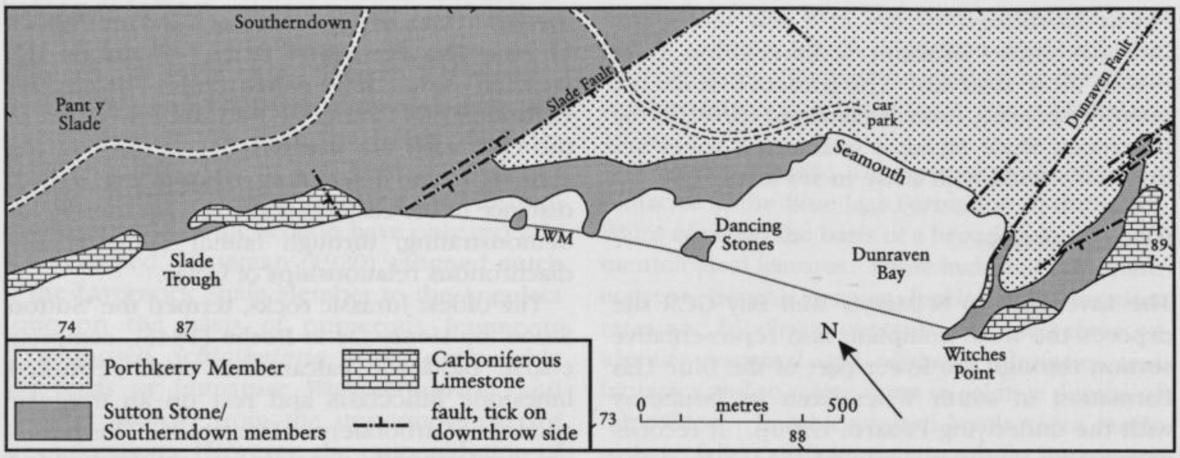


Figure 3.5 Sketch map of the Pant y Slade to Witches Point GCR site. After Wilson *et al.* (1990).

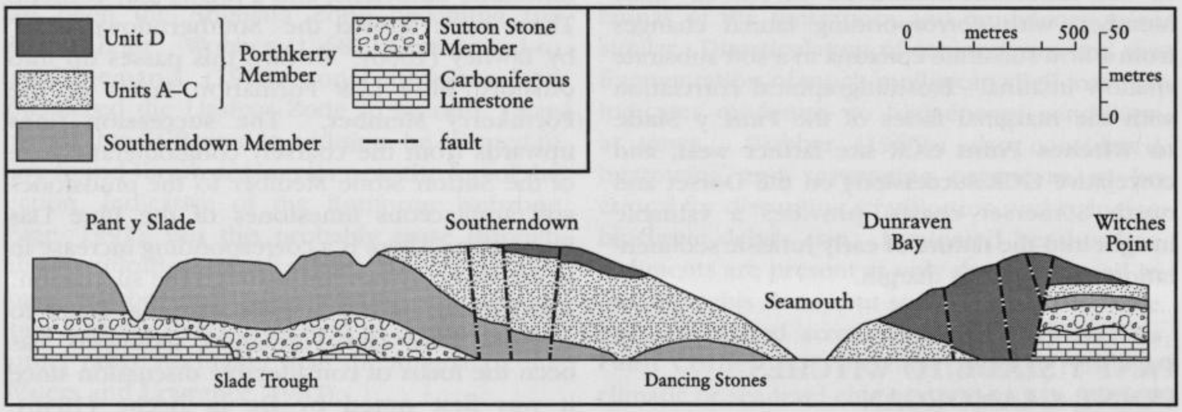


Figure 3.6 Coastal section from Pant y Slade to Witches Point, showing lateral facies changes in the Lias Group. After Trueman (1922b).

facies and the Carboniferous Limestone is best exposed at Pant y Slade (Figure 3.7) but can also be seen at Witches Point. The two lithofacies divisions of the marginal facies, the Sutton Stone Member and the Southerndown Member, also are most accessible at Pant y Slade since their outcrop farther east is tidally restricted. The transition from marginal facies to the offshore facies of the Porthkerry Member is most easily examined in the cliffs below Southerndown whereas the progressive increase in the proportion of mudstone to limestone upwards through the succession can be seen in Dunraven Bay.

The surface on the Carboniferous Limestone beneath the marginal facies of the Lias is mostly smooth or gently undulating. The unconformity is particularly striking below Southerndown, where it truncates a steep monocline in the Carboniferous Limestone. At Pant y Slade the unconformity forms a broad trough, approximately 150 m wide and more than 10 m deep, cut into the limestone (Figure 3.6). It was termed the 'Slade Trough' by Fletcher (1988). The margins of the trough are steep and terraced, particularly on its western margin where the unconformity surface ascends steeply from beach level (Figure 3.7). On the platform just to the north-west of the Slade Trough, Fletcher (1988) described a low, irregularly scalloped scarp beneath which a series of broad channels and ridges descend the dip of the unconformity surface for several metres before becoming more subdued as the unconformity surface levels out. The surfaces of the ridges and troughs are intensively bored, as are the roof and walls of occasional crevices; most of the borings are narrow and elongate (*Trypanites*) but flask-shaped lithophagid bivalve crypts also occur. Johnson and McKerrow (1995) also

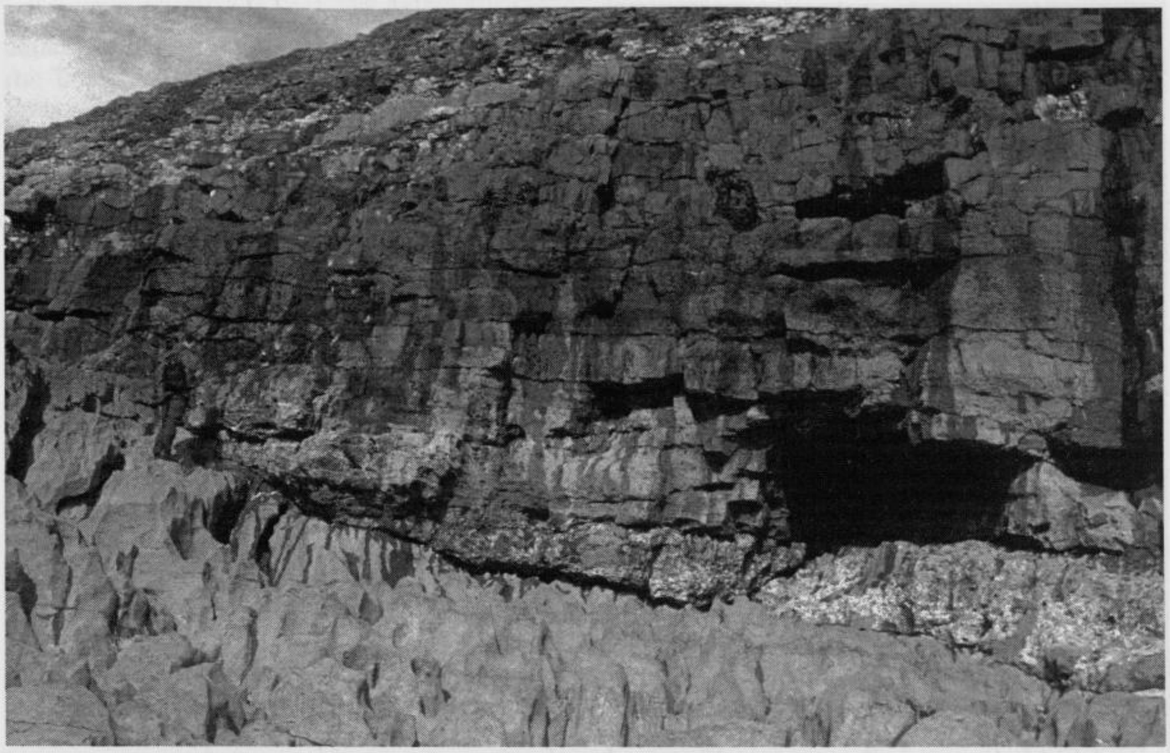


Figure 3.7 Coarsely bedded marginal facies of the Lias Group resting unconformably on Carboniferous Limestone at the western edge of the Slade Trough. The paler bed immediately above the unconformity, and wedging-out rapidly westwards, is the heavily mineralized boulder bed unique to the Slade Trough. The person, for scale, is standing on the unconformity surface immediately west of the boulder bed (Photo: M.J. Simms.)

described corals and oysters encrusting the unconformity surface at this locality.

Resting directly upon this irregular unconformity surface is the Sutton Stone Member, which may be formally assigned member status (Cox *et al.*, 1999), and comprises thickly bedded, coarsely bioclastic calcarenites and conglomerates. The Sutton Stone Member is 10–13.5 m in thickness, being greatest where banked against the western margin of the Slade Trough (Hallam, 1960a). Hallam (1960a) recognized two subdivisions within the Sutton Stone Member which he claimed were separated by an irregular bored surface. The lower unit, up to 10 m thick, is markedly conglomeratic towards the base with abundant pebbles of Carboniferous Limestone (Figure 3.8). Coarse breccias are restricted to the lower part of the Slade Trough, where irregular Carboniferous Limestone lithoclasts, up to 2 m across, are encrusted and bored by fossil marine organisms and set in a matrix of smaller clasts and shell debris (Bed 1 in Figure 3.8). An impersistent calcarenite unit (Bed 2) lies between this and an overlying breccia (Bed 3) in which the clasts, generally smaller than those in the lower breccia, are supported in a coarse bioclastic matrix. Irregular colonial coral masses up to 0.5 m across occur in the lower part of Bed 3. Massive- to thinly bedded polymictic framework-supported conglomerates with a sparry calcite cement are conspicuous a little higher in the succession (Bed 8). Above this, fragments of limestone and chert are rarely more than 0.03 m across and tend to be confined to discrete layers above irregular partings. Within the conglomerates the sphericity of limestone clasts (up to 0.90) consistently is higher than that of chert clasts (0.40–0.70). Many elongate or discoidal clasts have a preferred orientation, with some exhibiting imbrication. Hallam (1960a) described the upper unit as about 4 m of thinly bedded calcarenites with abundant gravel-grade lithoclasts of limestone and chert. Wobber (1965) considered that this division could be recognized only locally and that east of Pant y Slade Hallam's upper division could not be distinguished from the overlying Southerndown Member. Bands of pseudo-oolite, sand-sized

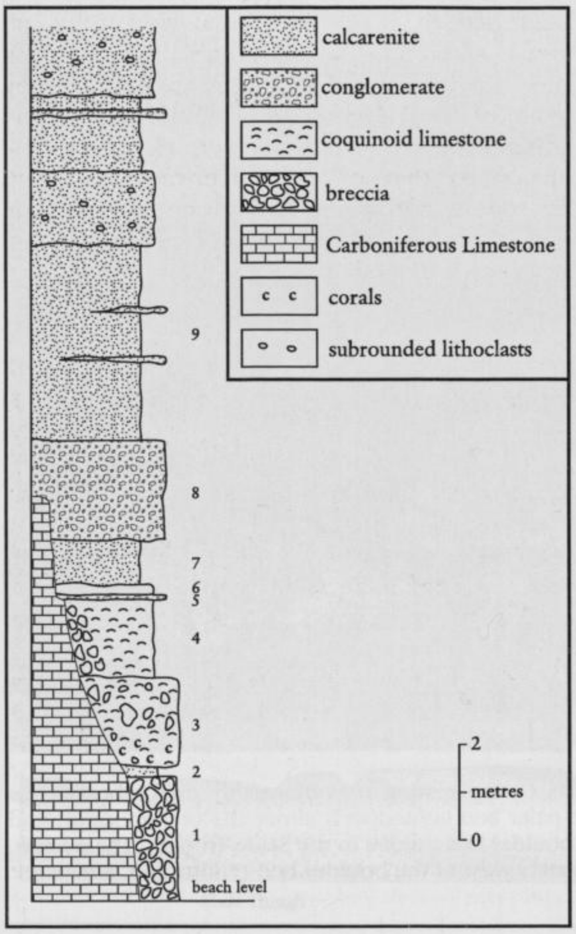


Figure 3.8 Lithological log of the lower part of the marginal facies of the Lias Group within and adjacent to the Slade Trough. After Fletcher (1988).

lithoclasts with semi-opaque rims of microcrystalline calcite, are common throughout the Sutton Stone Member (Hallam, 1960a; Wobber, 1965).

The Sutton Stone Member passes vertically and laterally into the succeeding Southerndown Member but the transition is gradational and, locally, there is no distinct boundary between the two units. The Southerndown Member, like the Sutton Stone Member, comprises lithoclastic and bioclastic sands and gravel-grade conglomerates but these contain a lower proportion of limestone lithoclasts, a higher clay content and are more thinly bedded. The succession includes occasional thin (less than 0.03 m) argillaceous units separating the limestone beds. Locally the upper part of the Southerndown Member contains bands of oolitic limestone which are associated with, and gradational from, underlying conglomerates. Ooid nuclei are formed of calcarenite grains, shell fragments and quartz grains.

There is a gradation, both vertically and laterally, from thinly bedded conglomeratic limestones of the Southerndown Member into shales and nodular limestones of the typical offshore facies of the Porthkerry Member. The lateral changes, although visible, are inaccessible in the sheer cliffs between Pant y Slade and Seamouth but the vertical transition can be examined at some localities. At Seamouth (SS 883 733) an oolite bed at the top of the Southerndown Member has a hummocky surface overlain by shale in which occur abundant boulders of this same oolite, often encrusted by fossil oysters. About 400 m west of this point the 'boulder bed' is absent and there is a transition between facies, with an increase in mean chert lithoclast size followed by a sharp decrease in lithoclast abundance in passing into the shale and limestone of the more offshore facies of the Porthkerry Member. There is a corresponding upward increase in pyrite abundance.

The Porthkerry Member is of typical Blue Lias Formation facies, with centimetre- to decimetre-scale alternations of mudstone and argillaceous limestone. Argillaceous micritic limestones, from 0.04 m to 0.76 m thick, comprise from 45% to 75% of rock volume in different parts of the Porthkerry Member exposed at the eastern end of the GCR site. The limestone–mudstone ratio is useful as a broad lithostratigraphical indicator and enabled Wilson *et al.* (1990) to recognize four distinct lithostratigraphical units in the Porthkerry Member. Units A to C are limestone-dominated while Unit D has a significantly higher proportion of mudstone. Limestones vary from bands of isolated ellipsoidal nodules through to continuous semi-nodular or tabular beds. A few of the tabular limestones are laminated, as are some of the ellipsoidal nodules. Some distinctive limestone beds or groups of beds can be traced for several kilometres along the main coastal exposures of the Porthkerry Member to the east of this GCR site, but Wilson *et al.* (1990) found it difficult to correlate any of these with the succession exposed at Dunraven Bay. A few of the limestone beds can be recognized by their distinctive fossil content, for instance corals or brachiopods (Wobber, 1968a). A limestone exposed on the foreshore in Dunraven Bay contains abundant *Montlivaltia haimei* (Trueman, 1922b), and this same coral occurs in lower abundance in several of the adjacent limestone beds. The fossil content of the limestones varies from rare to more than 50%, mostly as bioclastic debris. Based on this Wobber (1965) recognized four dominant limestone types; micrite, pelmicrite, fossiliferous micrite and biomicrite. Most of the bioclastic debris is randomly distributed and orientated, and highly fragmented. Winnowed accumulations commonly occur on the top of limestone bands. Fossils within the limestone typically are uncrushed.

Most of the mudstone units within the Porthkerry Member are bioturbated calcareous shales containing a moderate to abundant benthic fauna. Fossils are commonly fragmentary or, where intact, distorted by compaction around irregular limestone nodules beneath them. Thin lenses of fibrous calcite, or 'beef', occur locally and they too may be distorted around fossils or nodules. Organic-rich laminated shales occur throughout the succession but are rare; they are characterized by pyritized ammonites, fish debris and an impoverished bivalve fauna.

The striking facies changes which occur upwards through the Lias Group succession at this GCR site are reflected in substantial faunal differences between the Sutton Stone Member, Southerndown Member and Porthkerry Member. Fossil material is common in the Sutton Stone Member, but is mostly fragmentary or poorly preserved. The finer-grained units of the Sutton Stone Member are characterized by a great abundance of the bivalves *Chlamys valoniensis* and *Terquemia arietis*, both of which are minor elements of the offshore facies. Other common taxa in the Sutton Stone Member are *Lima succincta*, *Pseudolimea hettangiensis*, *Cardinia* sp. and the patellid gastropod *Acmaea schmidti*. Large poorly preserved colonial corals occur in the lower part of the Sutton Stone Member, especially in the Slade Trough, and include *Heterastraea latimeandroides*, *Isastraea globosa* and *Stylophyllopsis murchisoniae*. Several large thecosmiliid colonies at the base of the Sutton Stone Member immediately west of the Slade Trough have been replaced by barite. Their poor preservation has led to their mis-identification as serpulid reefs (Cope, 1971; Ager, 1986a; Johnson and McKerrow, 1995; Simms *et al.*, 2002). The coastal exposures of the Sutton Stone Member do not preserve the rich and diverse fauna of corals, bivalves, gastropods, serpulids and bryozoa which was described from 19th century collections at inland quarries near Brocastle (SS 93 77) and Ewenny (SS 91 77) (Duncan, 1867b; Beauvais, 1976; Negus, 1983). The fauna of the Southerndown Member has a closer resemblance to that of the offshore facies, but gastropods are more common and larger with several genera represented, among them *Coelostylina*, *Katosira*, *Procerithium* and *Pseudomelania*.

The succeeding offshore facies of the Porthkerry Member contains a fairly rich and diverse fauna similar to that of the Blue Lias Formation elsewhere. Bivalves are especially common. *Gryphaea arcuata* occurs profusely at some stratigraphical levels and specimens from Dunraven Bay formed the basis for part of the classic investigation into the evolution of this bivalve by Trueman (1922a), and more recent studies by Jones and Gould (1999). Large examples of *Pinna* in life position also form a conspicuous element of the fauna. Ammonites are common in the Porthkerry Member and provide good biostratigraphical control.

Ammonites are rare in the Sutton Stone and Southerndown members and seldom well-preserved, and precise biostratigraphical correlation with the offshore facies of the Blue Lias Formation has proved difficult. Tawney (1866) assigned both the Sutton Stone and the Southerndown members to the Rhaetic (= Upper Triassic, Penarth Group) despite recording *Ammonites suttonensis* and *A. dunravenensis* (subsequently re-identified by Tate, 1867), which demonstrably were Jurassic taxa, from the Sutton Stone Member. Hodges (1986) and Wilson *et al.* (1990) have summarized the known ammonite records recovered from the marginal facies. Within the GCR site the oldest dated marginal deposits are of Johnstoni Subzone age. On the south side of Witches Point the youngest marginal facies is of Portlocki Subzone age and is succeeded by offshore facies of proven Laqueus Subzone age at the base of the Porthkerry Member. However, on the northern side of Dunraven Bay, at Dancing Stones, the youngest marginal facies is of Angulata Zone age and the base of the overlying Porthkerry Member lies within the Conybeari Subzone. Trueman (1922b), Hallam (1960a) and Hodges (1986) established that inland from this GCR site the marginal facies extends up into the Bucklandi Zone and possibly even into the Semicostatum Zone.

Mineralization occurs to an unusual extent in the Lower Jurassic succession of this area. Silicification is widespread, both in the marginal and offshore facies and particularly in the upper part of the Porthkerry Member. Primary chert nodules are not uncommon and fossil material frequently is beekitized, although preservation is often poor. Septal chambers of ammonites and other cavities may be lined with drusy quartz crystals, occasionally amethystine. A striking feature of the marginal facies is the widespread occurrence of barite in the conglomerates and breccias. The barite occurs either as a micro-crystalline buff-coloured replacement of fossils and geopetal sediments or as a white, more coarsely crystalline, interstitial cement or cavity fill, which often is associated with white, coarsely crystalline calcite. Galena crystals up to 15 mm across are common and concentrated particularly at the barite–calcite boundary. This barite–calcite–galena mineralization is particularly evident at the western margin of the Slade Trough where it fills cavities dissolved in the bioclastic matrix of the basal breccia as well as many of the biogenic borings in the Carboniferous Limestone clasts (Fletcher, 1988). Shell coquinas and corals in this area also have experienced extensive replacive mineralization (Simms *et al.*, 2002). There is a clear relationship between barite–calcite–galena mineralization in the base of the marginal facies and the presence of mineral veins in the Carboniferous Limestone beneath (Fletcher, 1988). Although little sulphide mineralization is evident in the offshore facies of the Porthkerry Member, there is a frequent and conspicuous association between small crystals of galena and pieces of coalified drift-wood.

Interpretation

The vertical and lateral (diachronous) changes exposed within this GCR site, from the conglomeratic Sutton Stone Member, through the Southerndown Member into typical Blue Lias Formation mudstones and limestones of the Porthkerry Member, confirm the observation of Trueman (1922b) that wherever the Lias of this region is in contact with the underlying Carboniferous rocks it is of Sutton Stone Member facies, regardless of age. Hence it is impossible to assign any biostratigraphical significance to a particular marginal facies. The Sutton Stone Member passes laterally and vertically into Southerndown Member-type facies which, in turn, passes into typical offshore Blue Lias Formation facies. Clearly the boundaries between these units are diachronous and were determined by the interplay between local topography and the transgression of the early Jurassic sea over the irregular surface of the Palaeozoic rocks beneath. The Sutton Stone and Southerndown members should be regarded as no more than local names given to distinctive types of marginal facies (Hodges, 1986). Even at this site, the type locality, the two units inter-digitate in a complex manner and often do not show a clear relationship to each other; Wobber (1965) noted the difficulty at Dunraven of applying Hallam's (1960a) two-fold division of the Sutton Stone Member. Diachronous changes from Sutton Stone Member marginal facies through the Southerndown Member to fairly typical offshore facies of the Porthkerry Member occur over quite short distances. For instance at Black Rocks Quarry, just beyond the north-west limit of the site, the Laqueus Subzone is in Sutton Stone Member facies with the onset of offshore facies not occurring until early in the Bucklandi Zone; yet less than 2 km to the south-east, on the south side of Trwyn-y-Witch, the Laqueus Subzone is in offshore facies (Hodges, 1986). The vertical and lateral changes seen in the Blue Lias Formation at this site therefore represent an exceptionally clear example of Walther's Law, in which facies occurring in a conformable vertical sequence were deposited in laterally adjacent environments.

The depositional environment of the marginal facies has long been the subject of discussion. Trueman (1922b) considered that the marginal facies of the Sutton Stone and Southerndown members were littoral deposits that accumulated close to the shore of an island archipelago which gradually was submerged by the transgression of the early Jurassic sea. These 'islands' of Carboniferous Limestone represent parts of the breached and eroded Cardiff–Cowbridge Anticline against which the marginal facies are, in general, banked. However, elsewhere in south Wales the marginal facies may overlie Triassic rocks or be interbedded with typical offshore facies of the Porthkerry Member, as was found in the St Fagans Borehole farther east, near Cardiff (Waters and Lawrence, 1987). Wilson *et al.* (1990) observed that facies boundaries appeared broadly to parallel several major faults, among them the Slade and Dunraven faults, which define the margins of the narrow Dunraven Graben extending ENE towards Cowbridge. It would appear that periodic movement on these faults in early Jurassic times had a major influence on sedimentation in this area. Not only did it maintain the high-energy shorelines that sustained the marginal facies but it probably exerted an influence on sedimentation patterns within the offshore facies of the Porthkerry Member sufficient to disrupt attempts at bed-by-bed correlation of limestones between the Dunraven Graben and the main coastal exposures. Significantly, the NW-trending coastline in this area lies virtually on the strike of the Napton and Nash faults that Kamerling (1979), Miliorizos and Ruffell (1998) and Chadwick (in Peacock and Sanderson, 1999) have proposed as the northward extension of the Watchet–Cothelstone–Hatch Fault System (see Figure 2.1, Chapter 2). This has been interpreted as a major transfer fault between southern and northern areas of extension in Mesozoic times. Its obvious proximity to the Slade Trough, which also parallels the trend of the Bristol Channel Basin as a whole, suggests that movement on the Watchet–Cothelstone–Hatch Fault System would have had a profound influence both on sedimentation immediately adjacent to it as well as in the Slade Trough. The evidence seen in the Slade Trough would seem to support this.

Hallam (1960a) considered the Sutton Stone Member to have been deposited in very shallow, clear water subject to strong current or wave action and experiencing periodic emergence. He ascribed the change to Southerndown Member facies to a marked deepening, with the localized oolite boulder bed at the transition to the offshore facies providing clear evidence for a further episode of emergence immediately prior to this. The poorly sorted conglomerate bands elsewhere in the Southerndown Member he attributed to rapid deposition from density currents, though graded bedding is absent. Wobber (1965) considered the Sutton Stone Member sediments to derive from the mechanical and biological abrasion of shell debris and Carboniferous Limestone, with seaward winnowing of any terrigenous silt or clay. The environment clearly was a high-energy one, with rock slivers indicating that impacts sometimes were sufficient to shatter clasts. Wobber ascribed the presence of the coarse breccias in the Slade Trough to subaqueous slides and the undercutting of the Carboniferous Limestone. Some of the minor erosion surfaces and associated textural and sorting anomalies seen elsewhere in the marginal facies he attributed to slumping of debris off the flanks of the islands as well as to tidal and wave scour. He interpreted the Southerndown Member as merely a more seaward correlative of the Sutton Stone Member, with the increased representation of chert lithoclasts reflecting preferential destruction of limestone clasts. Wobber (1968b) identified three subdivisions of his marginal biofacies, along with five offshore biofacies. He attempted to correlate these with marginal and offshore lithofacies, linking them all to relative water depth.

Ager (1986a,b) compared the Sutton Stone Member at Pant y Slade with coarse breccias, of presumed Triassic age, at Ogmore-by-Sea, little more than 1 km farther to the north-west. These latter breccias rest upon a highly irregular unconformity surface, with fissures, steps and steep faces cut into the Carboniferous Limestone. They are absent to the east, where the marginal Sutton Stone Member facies is developed. Furthermore, the unconformity surface on the Carboniferous Limestone beneath the Sutton Stone Member has a more subdued relief. Ager (1986a) interpreted these differences as due to the contrast between debris flows emplaced subaerially onto a karstified limestone surface, in the case of the Ogmore breccias, and those emplaced onto a marine planation surface following the onset of the early Jurassic transgression. On this basis he considered the lower, breccia-rich, part of the Sutton Stone Member to have been deposited catastrophically as a single debris-flow generated by a major storm, with succeeding units in the Sutton Stone and Southerndown members representing subsequent lesser events. This interpretation was challenged by Fletcher *et al.* (1986) who considered storms to be just one of several factors involved in deposition of the Sutton Stone Member over a prolonged time period. In a subsequent paper, Fletcher (1988) attributed the morphology of the unconformity surface beneath the Sutton Stone Member, with its stepped series of low scalloped scarps and dip-parallel ridges and troughs, to tidal erosion and cliff-line retreat associated with still-stands during the early Jurassic transgression. He considered that the collapse of overhangs led to the accumulation of coarse angular debris which now lies adjacent to the low scarps, this being buried beneath bioclastic debris and calcarenites as the transgression progressed. Hesselbo and Jenkyns (1998) broadly supported Ager's (1986a) debris-flow model and suggested a deeper-water origin for these marginal facies. In contrast, Johnson and McKerrow (1995) considered the Sutton Stone Member to have been deposited during transgression across a rocky shore, on which a range of encrusting and boring organisms were preserved, and they did not support Ager's (1986a) contention that it was a mass-flow deposit. However, the restriction of *Trypanites* borings to only the underside of the large blocks would seem to favour Ager's (1986a) debris-flow theory for the basal breccia. It indicates that the blocks reached their present position within the breccia in an unbored state, as would be the case for material transported into a shallow marine environment by a debris flow originating subaerially, and only then did boring organisms commence to colonize their undersurfaces. If, as Fletcher (1988) maintained, these large blocks originated from collapse of overhangs in a marine environment then we might expect to find at least a moderate proportion of the blocks to have overturned before reaching their final position and hence have a significant number of borings on their present upper surfaces, relics from when they were actually on the underside of these overhangs. This seems not to be the case.

The Dunraven Bay section is particularly important since the offshore facies at the **Lavernock to St Mary's Well Bay** GCR site, the only other Lower Jurassic GCR site in south Wales, does not extend above the Angulata Zone. Both Hallam (1960a) and Wobber (1965) considered the environment of deposition of the offshore facies in some detail. Hallam (1960a) noted the apparent independence from terrigenous influence of the calcareous 'mud' component of both marginal and offshore facies, from which he concluded that much of the calcium carbonate in the limestones was inorganically precipitated rather than derived from bioclastic debris swept offshore. However, Wobber (1965) maintained that fine bioclastic debris was a significant component of these same limestones and contributed to substrate firmness, a significant factor in his biofacies subdivisions. Hallam (1964a) considered initially that the limestones were, to a large extent, primary in origin but more recently (Hallam, 1986) suggested that many could originate solely from early diagenetic segregation of calcium carbonate, citing the south Wales succession in evidence. This view has since been contested by Weedon (1987) who maintained that the limestones were, to a significant extent, primary in origin. The difficulty of correlating limestone 'marker bands' from the main coastal exposures into the Dunraven Graben is further evidence for the predominantly primary origin of the limestones, indicating that local subsidence rates exerted a significant influence. Lenses of fibrous calcite, or 'beef', are only a minor component of the Porthkerry Member by comparison with correlative strata in the Dorset Lias, suggesting that sedimentation rates did not increase markedly in the latter part of early Jurassic times.

The limestone–mudstone rhythms described by Hallam (1964a) from the Blue Lias Formation of Dorset are, on the whole, rather poorly developed in the Porthkerry Member. Most of the mudstone units are bioturbated and contain a benthic fauna; laminated, organic-rich shales are comparatively rare and this suggests that the Porthkerry Member was deposited in shallower water than correlative strata in Dorset, thereby preventing the development of significant sea-floor anoxia. Bivalves are the most abundant element of the fauna in the Porthkerry Member. *Gryphaea* is more common in the mudstones than in the limestones and may constitute up to 60% by volume of some mudstone units at Seamouth (SS 883 733), with 60–95% of these in life position. Strongly ribbed bivalves are more common than in the more offshore facies of the Blue Lias Formation, such as the Lavernock Shale Member. *Pinna* in life position is conspicuous at certain levels in Dunraven Bay and indicates periods of stable sedimentation rate. The presence of the coral *Montlivaltia haimei* indicates very slow sedimentation rates, reaching a minimum in the limestone band in which this species occurs in profusion. Considerable bioturbation of this limestone band, as of others, is indicated by many specimens lying at a considerable angle from the horizontal. Wobber (1968a) analysed several gastropod taxa and found that, in general, they were more common and grew to a larger size on fine sand than on the finer sediments of the offshore facies. While some species are very facies restricted, others have a eurytopic distribution.

Poorly preserved patellids (*Scurriopsis*) are associated with cobbles and shelly sand in the Sutton Stone Member facies whereas *Pleurotomaria* is widespread in both offshore and marginal facies. *Coelostylina*, *Zygopleura* and *Pseudomelania* were more common where shale partings, indicating slight deepening, were present in the Southerndown Member.

Hallam (1960a) compared the offshore facies at this site with correlative successions on the Dorset coast, at Tolcis Quarry near Axminster, and with the Saltford Railway Cutting near Bristol. Palmer (1972) made a similar comparison of the Dorset and Glamorgan successions with that of the north Somerset coast. The Porthkerry Member is substantially thicker than the correlative strata in Dorset, though slightly thinner than the north Somerset coast succession. In the offshore facies exposed between Pant y Slade and Witches Point this is attributable to an increase in the limestone–mudstone ratio compared with Dorset and Somerset. Hallam (1960a), Palmer (1972) and Whittaker and Green (1983) have all commented on the correlation of distinctive limestone or mudstone units along considerable stretches of coastline, with some being broadly traceable from south Wales through Somerset to Dorset, implying that controls on offshore facies were not merely regional in their extent. The limestone–mudstone diagrams of both Hallam (1960a) and Palmer (1972), in which they correlate the successions in south Wales, Somerset and Dorset, imply that the Bucklandi Zone in both Dorset and Somerset is substantially thicker than in south Wales. However, it is well established (Cope *et al.*, 1980a) that the Bucklandi Zone in Dorset is significantly thinner than that of either Somerset or south Wales, a fact more in keeping with the generally more attenuated succession in Dorset.

No precise correlation is possible between the marginal facies of south Wales and those of other regions, such as the Mendip–Radstock area or the western Scottish sites. The broad similarity of facies found in these marginal environments reflects the influence of local factors rather than the broader-scale influences which are evident in the offshore facies. Most marginal facies share a common prevalence of massive bioclastic carbonate units with only minor mudstone development. The fauna of such facies typically is dominated by corals and molluscs adapted to high-energy environments; ammonites invariably are rare or absent. Nonetheless, attempts have been made to correlate the marginal facies of the Pant y Slade to Witches Point GCR site with the offshore facies of the Lavernock section farther east. The earliest proven age for the marginal facies is Johnstoni Subzone, thereby correlating with the upper part of the St Mary's Well Bay Member. On the north side of Witches Point the overlying Liasicus Zone, largely equivalent to the Lavernock Shale Member, is entirely in marginal facies that extends up into the Angulata Zone. However, to the south of Witches Point only the lower part of the Liasicus Zone, the Portlocki Subzone, is in marginal facies and passes up into more offshore facies in the succeeding Laqueus Subzone. However, this 'offshore' facies of alternating limestones and mudstones is still strikingly different from the mudstone-dominated Lavernock Shale Member. The only attempt at lithostratigraphical correlation between the marginal facies at Pant y Slade and the offshore facies of the Lavernock outlier was by Wobber (1968b) who suggested that the degree of lithoclast rounding and sorting in the marginal facies was, in some way, analogous to the limestone–mudstone ratio of the offshore facies. More specifically, he suggested that the decrease in lithoclast percentage and sparite cement, and the presence of clay partings in part of the marginal facies, could be correlated with the general increase in dominance of mudstone during the Liasicus Zone at Lavernock and elsewhere.

The calcite–barite–galena mineralization which pervades the marginal facies at Pant y Slade is one of the most intriguing features of this site. The association of more intensively mineralized areas of marginal facies with mineral veins cutting the Carboniferous Limestone directly beneath, described by Fletcher (1988), suggests that 'cold seeps' may have existed in this area in early Jurassic times. Fletcher (1988) noted that this mineralization was particularly evident in the Slade Trough, and elsewhere along the outcrop it is clear that there was a direct association between active faulting and mineralization. The close proximity of these marginal sediments to the north-westward extension of the Watchet–Cothelstone–Hatch Fault System, which lies just offshore and virtually parallel to the coast, may well account for the presence of fairly extensive mineralization along this stretch of coast. The barite–

calcite mineralization appears to have favoured open framework sediments and cavities, being particularly evident where it replaces fossil material in shell coquinas and corals, and in the *Trypanites* borings. The association of galena with driftwood in the Porthkerry Member is clear evidence that the mineralizing fluids pervaded the sediment pile for some distance above the unconformity, precipitating sulphides in the reducing environment represented by the wood. The sulphide mineralization in the marginal facies has been considered, on isotopic evidence, to be early Jurassic in age (Jenkins *et al.*, 1990) although field relationships indicate only a post-Hettangian date. Fletcher *et al.* (1993) obtained isotopic evidence for at least two phases of lead mineralization in the Mendip and south Wales orefield, with the later of these being of early Jurassic age. The existence of cold seeps here seems quite plausible, therefore, if the sea floor was breached by faults or fractures along which mineralizing fluids were migrating. However, Haggerty *et al.* (1996) favoured a single mineralizing episode, probably of Middle Jurassic age (see also Simms, 1997), for the Mississippi Valley-type deposits in the Mendip Hills. They attribute this to fluid expulsion from adjacent Mesozoic sedimentary basins, which in the case of Ogmore would be the Bristol Channel Basin to the south, as a result of over-pressuring associated with rapid subsidence in Triassic and Jurassic times. A post-early Jurassic age for the mineralization would seem to preclude the existence of cold seeps in the Ogmore area although different rates and timing of subsidence in the Bristol Channel, as compared with the Somerset and Wessex basins which border the Mendip Hills, may have led to the earlier onset of mineralization in south Wales.

Conclusions

The coastal cliffs between Pant y Slade and Witches Point expose the finest sections anywhere in Britain that show the transition from coarse marginal facies to much finer offshore facies of the Hettangian Stage. The succession is of crucial importance for demonstrating the early Jurassic transgression and for the interpretation of both marginal and offshore Lower Jurassic sediments in the Bristol Channel and Mendip region. The site also provides evidence of mineralization.

MARGINAL AND FISSURE FACIES OF SOUTH MENDIP

The Mendip Massif clearly exerted an enormous influence on early Jurassic sedimentation, with its flanks supporting a range of distinctive palaeoenvironments and facies unrepresented in the basinal settings to the north and south. However, the nature of this depositional influence was far from uniform across the Mendip Massif, with particularly striking differences between those on the north and south flanks. Sedimentation on the northern flank was exemplified by the highly condensed successions of the Radstock area, with the entire Sinemurian Stage represented by 1 m or less of sediment, and individual ammonite zones locally by no more than a few centimetres. Even within the Radstock area the Lower Jurassic succession shows considerable thickness variations over short distances, with the three GCR sites of **Bowldish Quarry**, **Kilmersdon Road Quarry** and **Huish Colliery Quarry**, being selected to show the style of lateral variation characteristic of this area.

In contrast to the succession at Radstock, sections through the Lower Lias in the Shepton Mallet area, on the south side of the massif, are developed in a richly bioclastic limestone facies with subordinate bands of quartzose conglomerate. Unlike the highly condensed Radstock Lias, this 'marginal' facies is slightly thicker than correlative offshore units farther into the Wessex Basin. The contact of the marginal facies with the underlying Carboniferous Limestone is clearly displayed at **Hobbs Quarry**, whereas a thicker sequence with hardgrounds and pebble beds is exposed at **Viaduct Quarry**.

A third distinctive facies type is developed on slightly higher parts of the massif, where Middle Jurassic rocks typically rest unconformably on the planed-off surface of the Carboniferous Limestone with no intervening Lower Jurassic strata. The Lower Jurassic facies found here are predominantly a fine, yellowish or pinkish micritic limestone which usually is confined to fissures within the Carboniferous Limestone. Excellent examples are seen at **Cloford Quarry** and **Holwell Quarries**. Exceptionally, this same facies is seen as part of a normal-bedded sequence, exposed at **Leighton Road Cutting**.

The precise controls on these strikingly different facies remain unclear. The highly condensed Radstock succession suggests considerable stability of the massif, exceptionally low subsidence rates, and prolonged sediment starvation. However, the evidence from the fissure deposits and the marginal facies indicates that the area was far from tectonically quiet. This apparent conflict has yet to be resolved and much work still needs to be undertaken on the remarkable Lower Jurassic deposits of the Mendip Hills.

VIADUCT QUARRY, SOMERSET (ST 621 443)

Introduction

The Viaduct Quarry GCR site is a disused quarry that lies 50 m east of the abandoned railway viaduct where it crosses the Shepton Mallet–Downside road, on the northern outskirts of Shepton Mallet (Figure 3.9). This site provides the best-exposed and thickest section seen in the Downside Stone marginal facies of the Mendip region. A succession of coarsely bioclastic, and often conglomeratic, limestones contrasts markedly with the contemporaneous mudstone-dominated 'offshore' facies which is developed away from the Palaeozoic outcrop. Only a few brief descriptions of this or nearby exposures, such as Beacon Farm (ST 635 448) or road cuttings to the north of Shepton Mallet, which exposed very similar successions, have been published (Moore, 1867a; Woodward, 1893; Richardson, 1909; Reynolds, 1912, 1921; Donovan, 1958a; Green and Welch, 1965; Savage, 1977; Copp in Duff *et al*., 1985).

Description

The vertical face of Viaduct Quarry (Figure 3.10) exposes about 9 m of Downside Stone, a series of coarsely bioclastic limestones which represent the marginal facies of the Lower Lias in this area. The strata here dip gently southwards such that the lowest beds, estimated to lie about 4.5 m

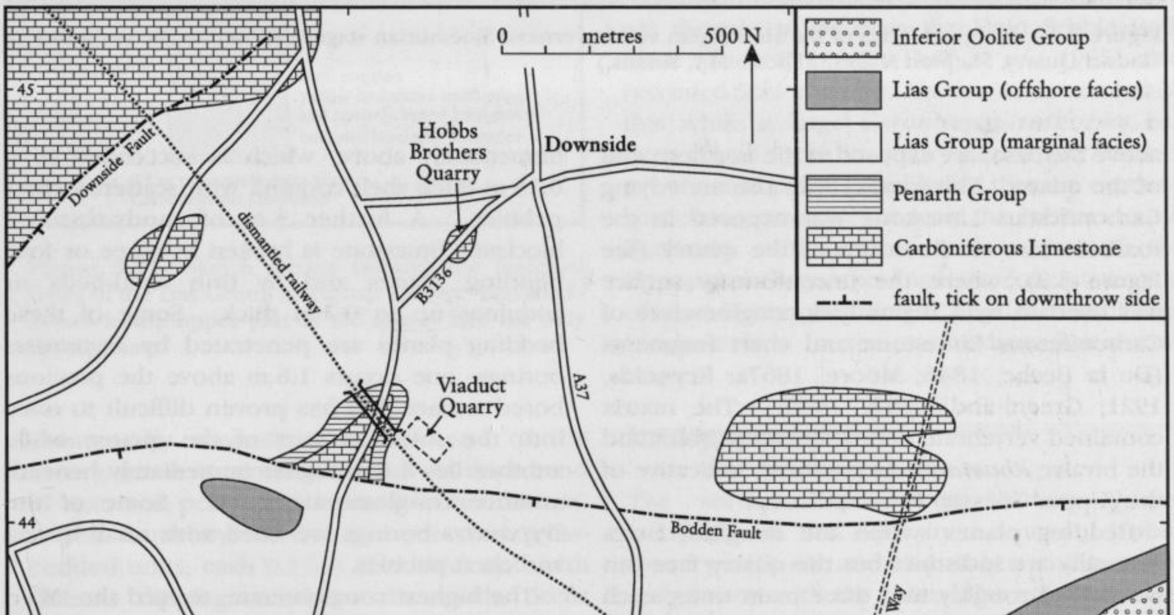


Figure 3.9 Sketch map of the geology in the area around Viaduct Quarry and Hobbs Quarry.

Figure 3.10 Marginal facies of the Hettangian and lowermost Sinemurian stages exposed in the main face of Viaduct Quarry, Shepton Mallet. (Photo: M.J. Simms.)

above the base, are exposed at the northern end of the quarry. The contact with the underlying Carboniferous Limestone was exposed in the roadside just to the south of the quarry (see Figure 3.9), where the unconformity surface was overlain by a 0.3 m-thick conglomerate of Carboniferous Limestone and chert fragments (De la Beche, 1846; Moore, 1867a; Reynolds, 1921; Green and Welch, 1965). The matrix contained vertebrate debris, quartz pebbles and the bivalve *Rhaetavicula contorta*, indicative of the (Upper Triassic) Penarth Group.

Bedding planes within the marginal facies generally are indistinct but the quarry face can be divided roughly into three main units, each about 3 m thick. The lower two units, rather massive and sandy-textured, are divided by a conspicuous notch at the level of a thin conglomerate. The upper third of the face is more thinly bedded, on a 0.1–0.3 m scale, and somewhat ferruginous (Figure 3.11).

The lowest bed exposed is a compact, pale-brown, sandy-textured bioclastic limestone with a gently undulating top penetrated by scattered, indistinct borings. It is sharply demarcated from a thin breccio-conglomerate of small chert clasts immediately above, which is succeeded by a 0.15 m-thick shell coquina with scattered chert pebbles. A further 3 m of sandy-textured bioclastic limestone is broken by three or four bedding planes and by thin shell-beds or coquinas up to 0.2 m thick. Some of these bedding planes are penetrated by *Trypanites* borings; one occurs 1.6 m above the previous bored surface, but has proven difficult to trace into the southern part of the quarry, while another lies 1.6 m higher immediately beneath another conglomerate band. Some of the *Trypanites* borings are filled with small quartz and chert pebbles.

The highest conglomerate, termed the 'Main Pebble Bed' can be traced throughout the quarry and was mentioned specifically by Woodward (1893), Donovan (1958a) and Copp (in Duff *et al.*, 1985). At the south end of the quarry it forms a poorly sorted, clast-supported conglomerate up to 0.25 m thick showing crude stratification and with a fairly sharp top and base. Most clasts are of angular to subrounded chert fragments, up to 8 cm across and often highly fractured, but poorly to well-rounded quartz pebbles are also common. The Main Pebble Bed thins

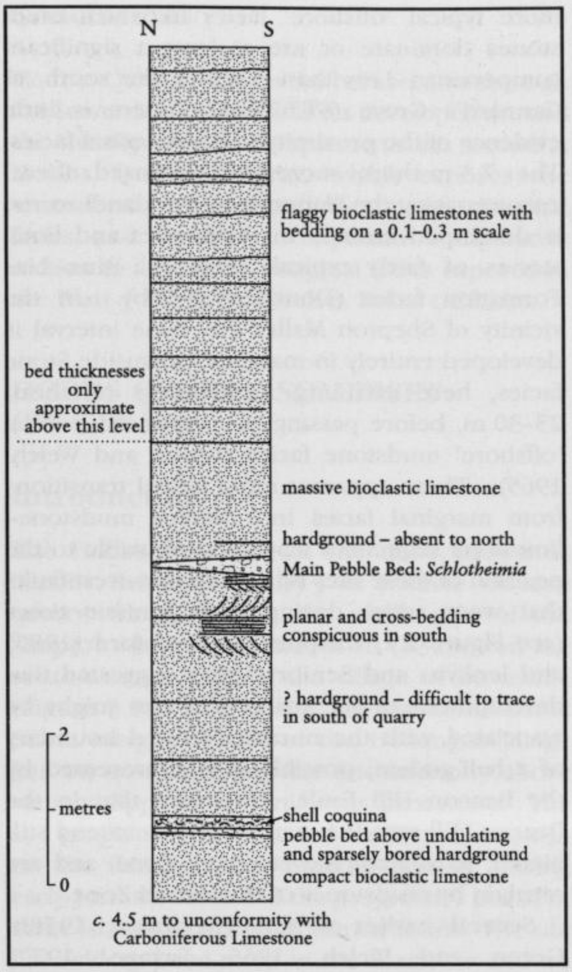


Figure 3.11 Sketch section through the marginal facies of the Lias Group at Viaduct Quarry. Bed thicknesses in the upper part of the quarry face are only approximate.

dramatically towards the north end of the quarry, where it consists of a 2–3 cm thick band of scattered pebbles in a poorly sorted matrix. At the south end of the quarry several cross-bedded units, each 0.15–0.25 m thick and with foresets dipping mostly to the south, occur above and below the Main Pebble Bed and are associated with shell beds containing scattered intact bivalve moulds. The cross-bedded units cannot be identified in the central and northern parts of the quarry, where the Main Pebble Bed is succeeded by a particularly massive limestone bed about 1.5 m thick. Above are four to five thinner beds, each 0.3–0.5 m thick, passing up into still more thinly bedded limestones, each 0.1–0.3 m thick, which comprise the top third of the quarry face.

Comminuted bioclastic debris forms a significant component of the Downside Stone but intact material occurs more sparsely. Fossils tend to occur concentrated into thin shell-bands or 'coquinas', sometimes containing scattered pebbles, but the shells are usually disarticulated and broken. The tops of these shelly layers often show traces of boring; Moore (1867a) noted that some of the chert pebbles were encrusted with the bivalve *Atreta intusstriata*. In the intervening beds the shells are still articulated. The fauna is dominated by bivalves, typically epifaunal taxa, but also includes gastropods and montlivaltiid corals (Moore, 1867a; Copp in Duff *et al.*, 1985). At this site, as elsewhere in the Downside Stone, many of the fossils are preserved as moulds. Only those with originally calcitic shells, such as *Ctenostreon tuberculatus* and *Liostrea laevis*, have survived dissolution. *Pseudopecten* and *Plagiostoma* are the main taxa, with *Liostrea* also present in the lower beds. Ammonites are rare in the Downside Stone but several taxa have been found at this site. Specimens of *Alsatites* and *Waehneroceras* are thought to be from the Main Pebble Bed, from which Copp (in Duff *et al.*, 1985) also recorded *Schlotheimia*. *Caloceras* occurs below this while a large *Coroniceras rotiforme* has been found loose in quarry debris (N. Morton, pers. comm.). This establishes that the exposed section encompasses at least the Johnstoni and Portlocki subzones near the base of the Hettangian Stage, the Angulata Zone at the top of the Hettangian Stage, and the Rotiforme Subzone low in the succeeding Sinemurian Stage.

Interpretation

The section exposed at Viaduct Quarry complements that seen in the nearby **Hobbs Quarry** GCR site and also makes an interesting comparison with the Lower Lias marginal facies exposed far more extensively on the south Wales coast at the **Pant y Slade to Witches Point** GCR site. Although the contact with the underlying Carboniferous Limestone (well exposed at the nearby Hobbs Quarry GCR site) is no longer exposed in the vicinity of Viaduct Quarry, the presence of pebbles of Carboniferous Limestone, chert and quartz up to 8 m above the junction indicate continued erosion of the nearby Palaeozoic outcrop during early Jurassic times. A similar conglomeratic unit was described by Donovan (1958a) from Beacon Farm Quarry (ST 635 448), just over 1 km to the north-east, and was correlated by him with the Main Pebble Bed at Viaduct Quarry. This would imply that a fairly widespread event transported pebbles from the Palaeozoic outcrop and into the early Jurassic marginal deposits. The limestone and chert clasts were derived from the Carboniferous Limestone while the quartz pebbles were considered by Woodward (1893) to originate in the Old Red Sandstone, which today crops out about 2 km to the north, demonstrating that the Carboniferous Limestone across the anticline crest had already been breached by Early Jurassic times. Similar discrete layers of limestone and chert pebbles also occur some distance above the base of the marginal facies of the Lower Lias at the Pant y Slade to Witches Point GCR site. The presence of pebbles and the greater disarticulation and fragmentation of fossil material in the shell beds when compared with the intervening sediments suggests occasional brief periods of increased turbulence or current activity, perhaps associated with storms. The presence of bored surfaces beneath the conglomerates, and also at the top of some of the shelly units, demonstrates sufficiently long pauses in sedimentation for hardgrounds to develop although some of these hardgrounds appear to of very local extent. Records of both Liasicus- and Angulata-zone ammonites associated with the main hardground and conglomerate unit suggest that this hiatus may encompass at least the upper part of the Liasicus Zone.

The upward lithological change at this site, from massive sandy textured beds into more thinly bedded units, is reflected in some elements of the fauna, with the cemented bivalve *Liostrea* being confined to the lower beds. The upward lithological change parallels that seen at the **Pant y Slade to Witches Point** GCR site in south Wales. By analogy with the latter site, this facies change probably records the increasing distance, both vertically and laterally, from the unconformable contact with underlying Palaeozoic rocks. It implies that here, as in the similar situation in south Wales, this boundary is diachronous, although biostratigraphical resolution within the marginal facies of the Mendip region is inadequate to demonstrate this. However, correlation with other Lower Lias successions in the area shows the strongly diachronous nature of the boundary between the marginal Downside Stone facies and the more typical 'offshore' facies in which mudstones dominate or are at least a significant component. Less than 3 km to the south, at Cannard's Grave (ST 629 414), there is little evidence of the proximity of the marginal facies. The 7.3 m-thick succession exposed there, encompassing the Planorbis to Bucklandi zones, is developed entirely in mudstones and limestones of fairly typical 'offshore' Blue Lias Formation facies (Donovan, 1958b). In the vicinity of Shepton Mallet this same interval is developed entirely in marginal Downside Stone facies, here attaining a thickness of about 25–30 m, before passing up into more normal 'offshore' mudstone facies (Green and Welch, 1965). These apparent rapid lateral transitions from marginal facies into basinal mudstone–limestone sequences may be attributable to the position of these sites relative to east–west faults that were active during early Jurassic times (see Figure 2.1, Chapter 2). Cornford (1986) and Jenkyns and Senior (1991) suggested that development of the marginal facies might be associated with the northern-faulted boundary of a half-graben, possibly now represented by the Beacon Hill Fault, and noted that in the Beacon Hill area the marginal facies extend still higher, to at least the Jamesoni Zone, and are overlain by mudstones of the Davoei Zone.

Several earlier writers (Donovan, 1958b; Green and Welch, 1965; Savage, 1977) commented on the apparent greater thickness of the Planorbis to Bucklandi zone succession when developed in marginal facies rather than the more basinal, or 'offshore', facies, attributing this to banking up of these marginal sediments by offshore currents. However, the discovery of *Coroniceras rotiforme* at Viaduct Quarry indicates that the marginal facies is not substantially thicker than the oft-cited correlative section at Cannard's Grave (Donovan, 1958b).

The composition of the fauna at the Viaduct Quarry GCR site bears considerable similarities to that seen in the analogous marginal facies of the **Pant y Slade to Witches Point** GCR site, as commented on by Moore (1867a), and clearly is facies controlled. At both sites the fauna is dominated by thick-shelled bivalves and a relative abundance of gastropods, and ammonites are very rare. However, whereas the south Wales site has yielded a rich and fairly diverse fauna of colonial and solitary corals, only occasional solitary montlivaltiids have been recovered from the Downside Stone in the Mendip region.

Conclusions

Viaduct Quarry exposes the best section through the Lower Lias marginal facies developed around the Mendip Hills. It complements the section at **Hobbs Quarry** nearby, which exposes the unconformable contact beneath the marginal facies, and provides an important comparative section to analogous marginal facies exposed in the **Pant y Slade to Witches Point** GCR site.

HOBBS QUARRY, SOMERSET (ST 622 446)

Introduction

The Hobbs Quarry GCR site (also known as 'Hobbs Brothers Quarry') is a small disused quarry, which lies on the north side of the Shepton Mallet–Downside road (B3136) on the south-western edge of the village of Downside (Figure 3.9). At this site, the basal Downside Stone marginal facies of the Hettangian Stage lies on a striking angular unconformity above steeply dipping Carboniferous Limestone. The site graphically illustrates the effects of erosion on the flanks of the 'Mendip Islands' during early Jurassic times and the progressive burial of these islands by marginal marine facies. The site has seldom been cited in the literature and no detailed account has been published. A brief description was given in Donovan (1958a) with even more cursory mentions in Richardson (1911) and Green and Welch (1965).

Description

Hobbs Quarry is located just to the north of a small inlier of (Dinantian) Black Rock Limestone that lies within an extensive outcrop of Lower Jurassic marginal facies. The Black Rock Limestone is exposed throughout the quarry to a height of about 3 m and dips at 65° to the south (160°). The northern face formerly exposed about 5 m of Lower Jurassic marginal facies, but the top 3–4 m at the time of writing was heavily overgrown (Figure 3.12). The Black Rock Limestone is well bedded on a decimetre- to metre-scale with a few thin (centimetre-scale) shale partings. Irregular to sheet-like chert bands 5–20 cm thick are common within the richly bioclastic limestones. A N–S-orientated face at the western end of the quarry, immediately adjacent to the studied section, exposes a minor fault with a downthrow of about 1.5 m to the east.

The unconformity surface on which the marginal Lias rests was reported by Donovan (1958a) as irregular, with a relief of several decimetres, though this was not evident in 1999. The overlying Downside Stone marginal facies is a coarse, bioclastic, cream-coloured limestone, crudely bedded on a decimetre- to half-metre-scale. It is very porous and packed with shell debris towards the base, where elongate angular lathes of reworked Carboniferous chert also occur. These chert lathes are distinct from the irregular, pale grey-brown chert bands which also occur near the base of the Jurassic marginal facies here. The Downside Stone here is very fossiliferous, in places packed with thick-shelled, coarse-ribbed bivalves including *Cercomya deshayesi*, *Ctenostreon tuberculatus*, *Atreta intusstriata*, *Liostrea* cf. *laevis*, *Plagiostoma valoniensis* and *Terquemia arietis* (Donovan, 1958a; Green and Welch, 1965). Donovan

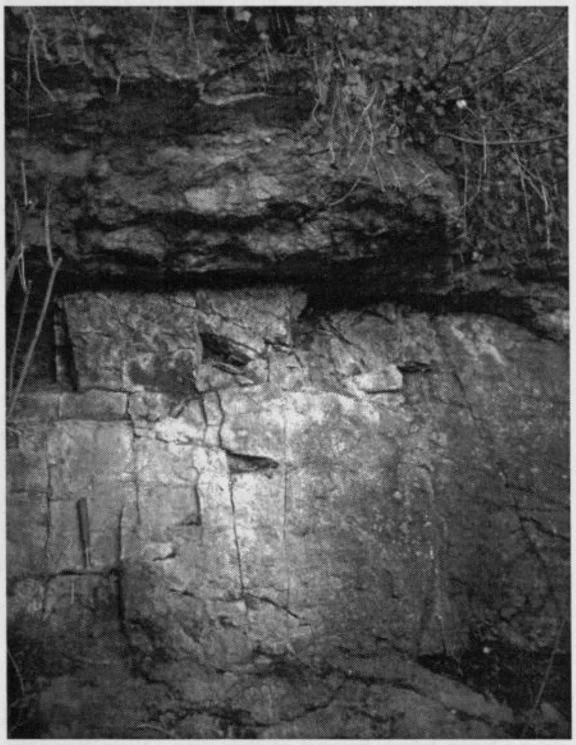


Figure 3.12 Near-horizontal marginal facies of the Lias Group resting unconformably on Carboniferous Limestone dipping steeply southwards (towards the camera) at Hobbs Quarry, Shepton Mallet. The hammer, for scale, is in the lower left of the picture. (Photo: M.J. Simms.)

(1958a) noted that gastropods and belemnites were also abundant at the site, but this was not confirmed in 1999. No ammonites have yet been recorded from the site.

Interpretation

The irregular nature of the unconformity surface on the Black Rock Limestone was attributed by Donovan (1958a) to differential erosion of the steeply dipping strata beneath, much as is found in modern sublittoral settings. However, observations in 1999 could not confirm this and there were indications that the apparent irregularity of the unconformity was due to the effects of recent weathering and the relationship of the studied section to the minor fault immediately to the west. Nonetheless, such small-scale relief is evident in parts of the **Pant y Slade to Witches Point** GCR site in south Wales, where horizontal to steeply dipping Carboniferous Limestone also is overlain by Lower Jurassic marginal facies, and hence its development here would not be unexpected. Significant marine erosion must have preceded the deposition of the overlying Downside Stone marginal facies, which represent the first sediments to have entered the area after the transition from an erosional to a depositional regime. It is evident from the angular nature of the reworked chert lathes that the eroded Carboniferous material experienced relatively little transportation.

Some details of the facies at this site differ significantly from that at the nearby **Viaduct Quarry** GCR site. The irregular chert bands near the base of the marginal facies here have not been recorded at Viaduct Quarry, while the angularity of the derived Carboniferous chert fragments here contrasts with the generally more rounded Carboniferous pebbles which occur in the Viaduct Quarry succession. In addition, intact fossil material at this site appears to be more common and more evenly distributed than at Viaduct Quarry where it tends to be concentrated at particular horizons.

The age of the Downside Stone at Hobbs Quarry is uncertain. As with the south Wales marginal facies, ammonites are rare in the marginal facies around the Mendip Hills and none have been found at this site. Significantly, the Penarth Group conglomerate seen at the base of the Downside Stone near **Viaduct Quarry** is absent here. Similarly, it was not seen at Bowlish Quarry, 1 km to the south-west, although Penarth Group material was present in fissures in the Carboniferous Limestone at that locality (Richardson, 1911). These observations suggest that the base of the marginal facies in the Mendip Hills is diachronous and may commence above the base of the Hettangian Stage at Hobbs Quarry. Green and Welch (1965) concluded that the age of the Downside Stone ranges from the Planorbis Zone to the Bucklandi Zone in the immediate area of Downside and Shepton Mallet, although to the north it apparently may extend as high as the Jamesoni Zone. None of the bivalve taxa present at Hobbs Quarry are biostratigraphically diagnostic but together they suggest a Hettangian age for the deposit.

Conclusions

The succession at the Hobb Quarry GCR site exposes the best-remaining section through the unconformity between steeply dipping Carboniferous Limestone and the near-horizontal marginal facies of the Lower Jurassic Series. It complements the thicker and lithologically more diverse section through the marginal facies found at the nearby **Viaduct Quarry** GCR site, where the contact with the underlying Carboniferous Limestone is not exposed. Together these two sites provide invaluable information on the nature of the Lower Jurassic marginal facies of the Mendip High, which can be further enhanced by comparison with the much more extensively exposed marginal Lias in the **Pant y Slade to Witches Point** GCR site of south Wales.

CONDENSED FACIES OF THE RADSTOCK SHELF

GENERAL INTRODUCTION

The Radstock Shelf lies to the north-east of the Mendip periclines and is underlain at shallow depth by the Coal Measures. A thin sequence of arenaceous Mercia Mudstone Group facies and Penarth Group lie beneath the Lias Group strata. Middle Lias strata are absent from the Radstock Shelf and only a small remnant of Upper Lias is present in the extreme north of the area. The Lower Lias succession across most of this area is overlain directly by bioclastic limestones of the (Upper Bajocian) Upper Inferior Oolite.

The Lower Lias succession developed on the Radstock Shelf is one of the most remarkable examples of a condensed sequence anywhere in the British Jurassic System. There are considerable local variations in thickness and completeness of the succession, but even at its maximum development the entire Hettangian and Sinemurian sequence attains a thickness of less than 10 m compared with over 200 m for equivalent strata in adjacent basinal settings. The succession is highly fossiliferous, with abundant ammonites that have enabled fine subdivision of the sequence. Among the published descriptions of the Lias of the area several have been distinguished by their great contributions to our understanding of these deposits. Moore (1867a) was the first to call attention to the greatly condensed succession in the area, and Tawney (1875) confirmed the presence of most of the Lower Lias ammonite zones. Their work was summarized by Woodward (1893). In a seminal work, Tutcher and Trueman (1925) described more than 30 exposures of the Lias Group in the Radstock area, including descriptions or lists of the contained fauna. Most of the exposures were small quarries, of which all but a handful are now infilled or obscured by vegetation. They recognized the significance of the facies changes and discussed in detail the conditions of deposition of the Radstock Lias and its relationship to underlying structural controls. Their account formed the basis of almost all subsequent descriptions, notable among which was that of Arkell (1933) who summarized this earlier work. Not until the publication, more than 50 years later, of a special memoir on the Lower Jurassic rocks of the Bristol district (Donovan and Kellaway, 1984) did any new information become available. Although still reliant in part on the descriptions of Tawney (1875) and Tutcher and Trueman (1925), Donovan and Kellaway took the opportunity to re-interpret much of the biostratigraphy and the controls on deposition in this area, as well as providing more detailed lithological descriptions of the main stratigraphical units.

GENERAL DESCRIPTION

Of the many sites described by Tutcher and Trueman (1925) most have long been infilled or overgrown. Three of the quarries in the Radstock area – **Bowldish Quarry**, **Kilmersdon Road Quarry** and **Huish Colliery Quarry** – have been selected as GCR sites. They represent the best sites that remain accessible and demonstrate some of the lateral changes that characterize the Radstock Lias. To understand the significance of the particular succession exposed at each site requires a knowledge of the overall Lower Lias sequence in the Radstock area together with the extent and nature of lateral and vertical variations in thickness and facies for which these three sites are considered representative. The succession can be broadly divided into three stratigraphical units displaying similar facies developments; the Hettangian succession, the Sinemurian to early Lower Pliensbachian succession, and the late Lower Pliensbachian succession.

Hettangian succession

The Hettangian succession of the Radstock district comprises mostly thin-bedded and commonly bioclastic impure limestones separated by thin shales or shaly partings. In early publications they were often termed the 'Corn Grits'. In most instances Tutcher and Trueman (1925) did not describe the Hettangian succession at each site in detail, instead citing only the total thickness of limestones and shales for each zone. However, the Hettangian part of several of these sections was described by Tawney (1875). Even at its maximum development, only the Planorbis and Liasicus zones are present, typically resting on the Pre-Planorbis Beds or 'Ostrea Beds' and, in turn, underlain by the distinctive Sun Bed at the top of the Langport Member (= White Lias) of the Penarth Group. The Angulata Zone is absent on the Radstock Shelf, the 'lower Angulata Zone' of Tutcher and Trueman's (1925) account being equivalent to the Liasicus Zone. On parts of the Radstock Shelf to the south of Radstock the Hettangian Stage is also absent (Figure 3.13), with Sinemurian deposits resting directly on the Sun Bed. Thicknesses of the Hettangian deposits increase northwards towards Bath and the Avon Valley (Figure 3.13), with the development of four distinct facies units within the Blue Lias Formation (Donovan and Kellaway, 1984).

Sinemurian succession

The Sinemurian succession on the Radstock Shelf is highly condensed with several substantial hiatuses and a number of ammonite subzones absent or known only from derived material in younger strata. Tutcher and Trueman (1925)

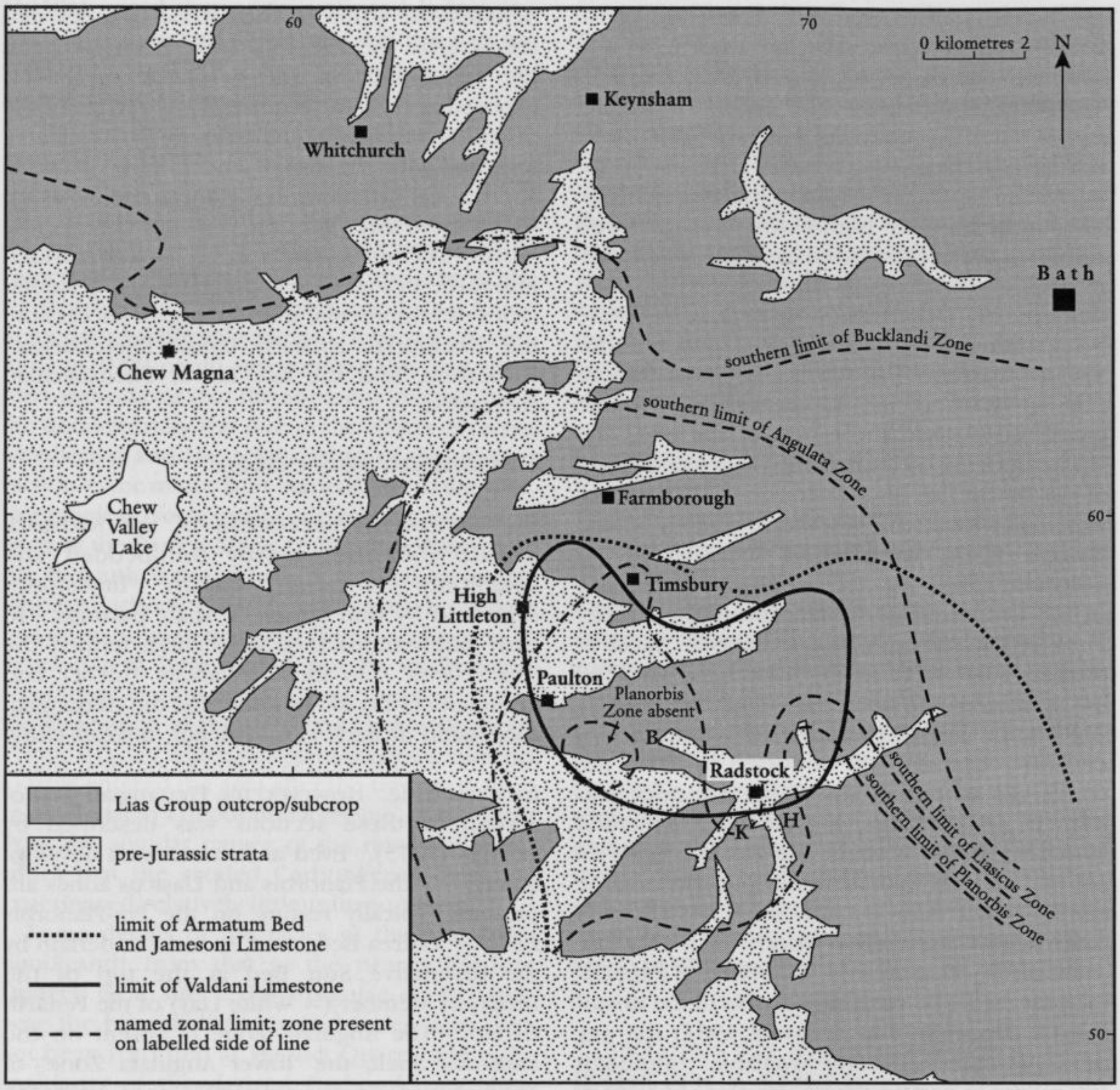


Figure 3.13 Sketch map showing the southern limits of the Planorbis to Bucklandi zones in the Radstock district and the distribution of the Armatum Bed, Jamesoni Limestone and Valdani Limestone. The letters B, K and H correspond to the approximate locations of the three GCR sites of Bowldish Quarry, Kilmersdon Road Quarry and Huish Colliery Quarry. After Donovan and Kellaway (1984).

and Donovan and Kellaway (1984) recognized five distinct units within the Sinemurian succession of the Radstock Shelf (Figure 3.14). The lowest of these, the 'Bucklandi Bed', is a 0.05–0.75 m-thick fossiliferous limestone, which at **Bowldish Quarry** and several other sites is continuous with the topmost preserved limestone of the underlying Hettangian succession. It has yielded a rich fauna of brachiopods, bivalves and other fossils. Geographically it is restricted to an area roughly bounded by Radstock, Timsbury and Paulton. Despite its name it is of Semicostatum Zone, Sauzeanum Subzone, age, for although Getty (in Cope *et al.*, 1980a) cited the occurrence of a fragmentary *Arietites* as evidence of the presence of the Bucklandi Zone, stout-ribbed coroniceratids similar to *Arietites bucklandi* also occur in the Scipionianum Subzone and are a more probable source for this specimen. It has also yielded derived and phosphatized *Arnioceras*, *Agassiceras*, *Euagassiceras* and *Coroniceras*.

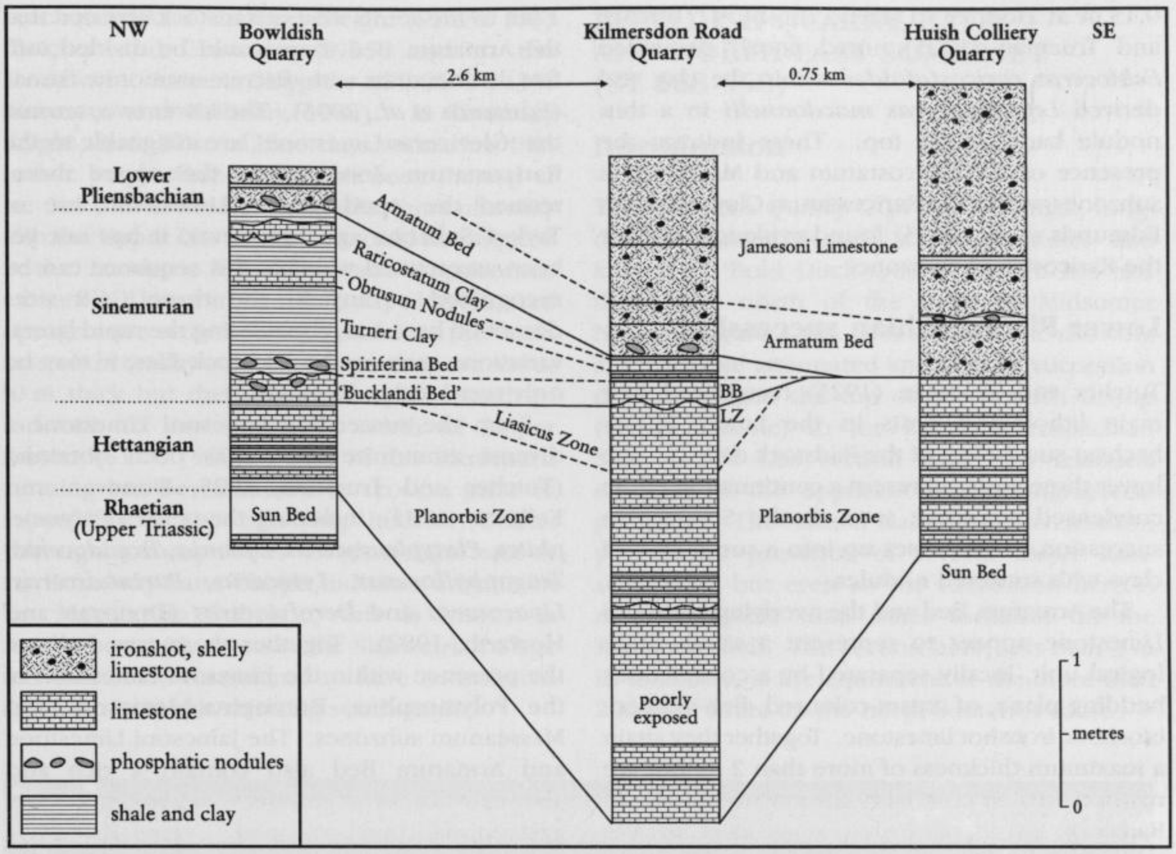


Figure 3.14 Lithostratigraphy and correlation of the Radstock GCR sites After Donovan and Kellaway (1984).

Donovan and Kellaway (1984) found no evidence for the presence of the Bucklandi Zone on the Radstock Shelf (Figure 3.13). The succeeding Spiriferina Bed comprises a few centimetres of grey sandy clay with abundant phosphatized nodules and fossils, notably the brachiopod *Spiriferina walcotti*. Derived ammonites of the genera *Arnioceras*, *Coroniceras* and *Euagassiceras* indicate a late Semicostatum Zone, Sauzeanum Subzone age. The Spiriferina Bed represents the lowest part of the Turneri Clay, which, around Radstock comprises a few centimetres to 1.2 m of blue, laminated clay. It thickens to the north. Moore (1867a) recorded 28 species of foraminifera from the Turneri Clay, which accordingly was termed by him and by Tate (1875) the Foraminifera-zone. The ammonites *Caenisites* and *Arnioceras* are present together with derived *Agassiceras* and *Euagassiceras*. The absence of *Microderoceras* and *Promicroceras* indicate that only the lower part of the Turneri Zone, the Brooki Subzone, is represented by the Turneri Clay (Donovan and Kellaway, 1984). The Turneri Clay is overlain by the Obtusum Nodules. At Timsbury 0.43 m of clay was present at this level and included two nodule bands. The upper of these was considered by Tutcher and Trueman (1925) to correspond with the single nodule layer or limestone band that is generally present elsewhere in this laterally persistent bed. The Obtusum Nodules have yielded *Asteroceras* and *Arnioceras*, together with rarer *Promicroceras*, *Xipheroceras* and *Cymbites*, which mostly indicate the Obtusum Subzone. Tutcher and Trueman (1925) also listed *Asteroceras stellare*, indicative of the succeeding Stellare Subzone, but without any stratigraphical or locality information for this species. The Denotatus Subzone of the Obtusum Zone, both subzones of the Oxynotum Zone and the Densinodulum Subzone at the base of the Raricostatum Zone have not been recorded in the Radstock succession. The limestone of the Obtusum Nodules is overlain by a thin greenish-brown clay, the Raricostatum Clay, which reaches a maximum recorded thickness of

0.45 m at Hodder's Quarry, Timsbury. Tutcher and Trueman (1925) noted poorly preserved *Echioceras raricostatoides* within the clay and derived *Leptechioceras macdonnelli* in a thin nodule band at the top. These indicate the presence of the Raricostatum and Macdonnelli subzones within the Raricostatum Clay, although Edmunds *et al.* (2003) found evidence only for the Raricostatum Subzone.

Lower Pliensbachian succession

Tutcher and Trueman (1925) recognized four main lithological units in the Lower Pliensbachian succession of the Radstock district. The lower three units represent a continuation of the condensed sequence seen in the Sinemurian succession. This passes up into a succession of clays with scattered nodules.

The Armatum Bed and the overlying Jamesoni Limestone appear to represent a single lithological unit, locally separated by a conspicuous bedding plane, of cream-coloured, fine-grained, bioclastic ironshot limestone. Together they attain a maximum thickness of more than 2 m, but are restricted to an area within a few kilometres of Radstock. Fossils, particularly ammonites, bivalves and brachiopods, are abundant. Echinoderm debris is abundant in thin-section although recognizable fragments are seldom evident in hand specimen. The basal part of the Armatum Bed contains abundant derived nodules and phosphatized ammonites, the latter often beautifully preserved. *Echioceras raricostatoides* is particularly common, along with various species of *Paltechioceras*, including *Paltechioceras tardecrescens* (= *P. aplanatum*). Species of *Paltechioceras* are preserved in light-grey limestone, in contrast to the dark-grey or black phosphatic limestone typical of specimens of *Echioceras*. These ammonites indicate the presence of the Raricostatum and Aplanatum subzones. Other ammonites in the lower part of the Armatum Bed include *Oxynoticeras*, *Gleviceras*, *Eoderoceras* and *Epideroceras* from the Raricostatum Zone. The higher part of the Armatum Bed contains taxa typical of the Taylori Subzone of the succeeding Jamesoni Zone, such as *Apoderoceras*, *Phricodoceras* and *Radstockiceras*. A single specimen of *Gagaticeras neglectum* from Rockhill Quarry (ST 6795 5540) may indicate the former presence of the Oxynotum Zone in this area (Donovan and Kellaway, 1984). Detailed investigation of a temporary section 1 km to the south-west of Radstock revealed that the Armatum Bed there could be divided into five distinct units with discrete ammonite faunas (Edmunds *et al.*, 2003). The lower two, termed the 'Gleviceras Limestone', are assignable to the Raricostatum Zone, while the upper three, termed the 'Apoderoceras Limestone', are of Taylori Subzone age. However, it has not yet been ascertained whether this sequence can be recognized at any of the three GCR sites described here and, considering the rapid lateral variations seen in the Radstock Lias, it may be only very local in its extent.

From the succeeding Jamesoni Limestone a diverse ammonite fauna has been obtained (Tutcher and Trueman, 1925; Donovan and Kellaway, 1984), including the genera *Polymorphites*, *Platypleuroceras*, *Uptonia*, *Tropidoceras*, *Tragophylloceras*, *Lytoceras*, *Parinodiceras*, *Liparoceras* and *Derolytoceras* (Donovan and Howarth, 1982). Together these taxa indicate the presence within the Jamesoni Limestone of the Polymorphus, Brevispina, Jamesoni and Masseanum subzones. The Jamesoni Limestone and Armatum Bed also contain a rich and abundant fauna of bivalves, brachiopods and gastropods, most of which were listed by Donovan and Kellaway (1984). Sellwood (1972) noted an abundance of infaunal and epifaunal suspension-feeding bivalves and trace fossils, indicating unconsolidated sediment beneath agitated, probably shallow, water. Most of the shells have been winnowed from life position but show little evidence for significant transportation. Corroded quartz grains within the Jamesoni Limestone indicate two phases of cementation.

The uppermost unit of the condensed Radstock Lias is the Valdani Limestone, which rests directly upon the Jamesoni Limestone across a restricted area between Radstock and Paulton (Figure 3.13). At its maximum development, in Old Pit Quarry (ST 6840 5563), it comprised 0.7 m of coarse-grained, hard crystalline limestone, becoming more ironshot towards the base. The ammonites present within it include *Acanthopleuroceras*, *Beaniceras*, *Liparoceras*, *Tragophylloceras* and *Lytoceras*, together indicating the Valdani Subzone. Bivalves and brachiopods also are abundant and diverse in this unit, though more difficult to extract than in the Jamesoni Limestone.

The succeeding clay units, the Striatum Clays and Capricornus Clays of Tutcher and Trueman (1925) are nowhere exposed today but sections were recorded at Timsbury Sleight (ST 656 593) (Tutcher and Trueman, 1925) and at the Broadway Lane Claypit (ST 6670 5635) (Donovan and Kellaway, 1984). At Timsbury Sleight about 37 m of blue clays with a few thin nodule bands were present between the top of the Valdani Limestone and the unconformity with the Upper Lias above and could be assigned to the Luridum, Maculatum and Capricornus subzones. Donovan and Kellaway (1984) noted a progressive reduction southwards in the thickness of these clays. At Clandown they are about 30 m thick but they diminish rapidly south of Radstock to less than 3 m north of Upper Vobster (ST 700 490). Much of this southward thinning can be attributed to erosion prior to deposition of the overlying Inferior Oolite. Although a conspicuous conglomeratic unit at the Broadway Lane Claypit indicates a hiatus in the Maculatum Subzone, this is minor in comparison with those in the Sinemurian Stage and cannot be considered to have contributed significantly to this thinning southwards.

BOWLDISH QUARRY, BATH AND NORTH-EAST SOMERSET (ST 668 558)

Introduction

The Bowldish Quarry GCR site is a small, long-disused quarry (Figure 3.15) sometimes also known as 'Bold Ditch Quarry', which lies less than 1 km north of the town of Midsomer Norton (Figure 3.13). It is a classic site showing a remarkable attenuated and broken succession extending from the top of the Penarth Group (Upper Triassic) to the lowest Pliensbachian Stage. The Lias section here is a textbook example of the application of stratigraphical principles. The refined Lias ammonite zonation proves the presence of several major non-sequences, but even so the succession here is more complete than other localities on the Radstock Shelf. The section here, less than 3 m in thickness, is the equivalent of the more than 200 m of strata on the north Somerset coast.

Figure 3.15 The section at Bowldish Quarry, Radstock. The thick limestone towards the top is the Bucklandi Bed, overlain by the Spiriferina Bed and Turneri Clay. The lower part of the face is of more thinly bedded limestones and mudstones of the Planorbis Zone. (Photo: M.J. Simms.)

The Bowldish Quarry succession was described by Tawney (1875), Woodward (1893) and, from the Spiriferina Bed upwards, by Tate (1875). It was 'site 6' of Tutcher and Trueman (1925) but they gave only a summary description of the succession. Discrepancies exist between some of the bed thicknesses cited by Tawney (1875), Woodward (1893), and Tutcher and Trueman (1925). Other brief accounts were given by Reynolds (1921), Tutcher (1929) and Macfadyen (1970), though these accounts were based largely on the earlier publications. It was mentioned only briefly by Donovan and Kellaway (1984), as their 'site R27', although they figured a summary log of the section. In addition to elements of the macrofauna mentioned in the various publications cited above, foraminifera were also recorded from various units by Moore (1867a) and Macfadyen (1941).

Description

Bowldish Quarry provides a more complete succession than any other now seen on the Radstock Shelf (Figure 3.14), preserving evidence of the Hettangian, Sinemurian and Pliensbachian stages. The section was overgrown at the time of writing (Figure 3.15) and the following description is based upon the full section as it was seen by Tawney (1875), Woodward (1893) and Tutcher and Trueman (1925).

The lowest part of the section exposed more than 1 m of creamy argillaceous limestones and thin shales assigned to the White Lias (Langport Member) at the top of the (Upper Triassic) Penarth Group. The highest of the limestones, 0.3 m thick, is the distinctive 'Sun Bed'. This is succeeded by a sequence of grey limestones and thin mudstones containing a typical basal Hettangian fauna and termed by Tawney (1875) the 'Ostrea and Planorbis Beds'. Tawney (1875) recorded less than 0.6 m of strata within this part of the succession but Tutcher and Trueman (1925) gave a figure close to 1 m (3 ft 2 in.). Tutcher and Trueman (1925) recorded *Psiloceras planorbis* from an unspecified horizon in this part of the sequence, although their statement that the uppermost Hettangian limestone is continuous with the Bucklandi Bed above would seem to imply that *Psiloceras* was found at this level. The Bucklandi Bed at the base of the Sinemurian succession is 0.20 m thick and yields a variety of ammonite taxa (*Agassiceras*, *Arnioceras*, *Euagassiceras* and *Paracoroniceras*) spanning the Semicostatum Zone. The Spiriferina Bed is well developed and distinctive, with abundant *Spiriferina walcotti* (Figure 3.16), and passes up into the Turneri Clay. These two units together were recorded as almost 0.8 m (2 ft 6 in.) thick by Tawney (1875) but less than 0.5 m (1 ft 6 in.) thick by Tutcher and Trueman (1925). Above the Turneri Clay the Obtusum Nodules form a fairly continuous, greenish-grey, laminated limestone about 0.1 m thick. This unit is succeeded abruptly by the Raricostatum Clay, with a tripartite division of two clay units separated by a 0.08 m-thick nodular grey limestone totalling some 0.45 m (1 ft 5 in.) in thickness. The limestone has yielded *Bifericeras subplanicosta* gr. and both the limestone and upper clay contain *Echioceras*, indicating the Raricostatum Subzone. Tutcher and Trueman (1925) recorded *Leptechioceras meigeni* from an unspecified horizon at Bowldish Quarry. The highest unit exposed at Bowldish Quarry is the Armatum Bed, of which 0.3 m is preserved. It is highly fossiliferous and has yielded a diverse assemblage of fossils, both primary and reworked, indicating a basal Jamesoni Zone age. The most conspicuous fossils are, however, the derived echioceratids and it is probably from the Armatum Bed that the record of *Leptechioceras* came.

Tutcher and Trueman (1925) published an extensive table listing non-ammonite macrofossil species and the horizons in which they occurred, though they made no reference to

Figure 3.16 The brachiopod *Spiriferina walcotti*, from the Spiriferina Bed at Bowldish Quarry, Radstock. The largest specimen is 43 mm across. Specimens from the T.R. Fry Collection, Bristol City Museum. (Photo: M.J. Simms.)

specific localities and the site descriptions cited only the most common or most distinctive taxa. Tawney (1875) also listed some of the more common taxa in his site descriptions. Moore (1867a) obtained a rich fauna of foraminifera from the Turneri Clay, while Macfadyen (1941) also recovered some from the lower unit of the Raricostatum Clay. The Spiriferina Bed here was the source of specimens used, and figured, by MacKinnon (1974) in an investigation of spiriferid shell structure.

KILMERSDON ROAD QUARRY, BATH AND NORTH-EAST SOMERSET (ST 689 542)

Introduction

Kilmersdon Road Quarry is a small quarry, sometimes referred to in the literature as 'Radstock Grove', which lies less than 1 km south of Radstock (Figure 3.13). It is a key Lias locality spanning much of the Hettangian, Sinemurian and Pliensbachian stages. However, this has developed in a greatly attenuated succession only 5 m in thickness. Evidence for six major non-sequences is found in this succession. The broken and condensed series of rocks is of outstanding importance in understanding the complete Lower Jurassic history of the north Mendip area.

The site has received less attention than some of the other Radstock sites although it is now the best exposed of those remaining and is visited by many collectors in search of the derived echioceratid ammonites in the Armatum Bed. Tutcher and Trueman (1925) were the first to describe the site, as their 'site 10', but stated only which beds were present in the quarry and their thickness. Nonetheless, they provided a more detailed log of the succession as part of their figure 3. Getty (in Hemingway *et al.*, 1969) and Macfadyen (1970) provided a little more detail and the site was also mentioned briefly by Sellwood (1972). A graphic log of the section (Figure 3.14) was published by Donovan and Kellaway (1984), who summarized the current state of knowledge for this site. The site has recently undergone major re-excavation (Figure 3.17).

Figure 3.17 The recently cleared face of Kilmersdon Road Quarry. The main face is in thinly bedded limestones and mudstone of the Planorbis and Liasicus zones, capped by the planed-off surface of the Bucklandi Bed. The thin Sinemurian succession and the thicker bioclastic limestones of the Armatum Bed and Jamesoni Limestone are exposed in the low face above the conspicuous ledge. (Photo: M.J. Simms.)

Description

The lowest strata seen by Tutcher and Trueman (1925) at Kilmersdon Road Quarry were of late Triassic age, comprising the upper beds of the Langport Member (= White Lias) capped by the distinctive Sun Bed. Above lies just over 3 m (10 ft) of Hettangian limestones with thin shales (Figure 3.14). Tutcher and Trueman recognized two main units within the Hettangian succession. The lower 2.6 m (8 ft 6 in.) comprised alternating limestones and thin shales containing *Franziceras ruidum*, and can be assigned to the Planorbis Zone. The uppermost 0.45 m (1 ft 6 in.) is limestone-dominated with only minor shale partings and is assigned to the Liasicus Zone.

Getty (in Hemingway *et al.*, 1969) considered that, as at **Bowldish Quarry**, the upper limestone of the Hettangian succession was continuous with the Bucklandi Bed at the base of the succeeding Sinemurian Stage, a view maintained by Donovan and Kellaway (1984). The Bucklandi Bed is a massive, pale, coarse shelly limestone with an irregular lower surface, and varies from 0.05 m to 0.30 m in thickness. The upper surface is commonly ferruginous, traversed by cracks and pierced by small borings. In places it is capped by a phosphatic horizon, the Spiriferina Bed, while locally the phosphatic crust is overlain by a 0.1 m-thick limestone riddled with bivalve borings. In some instances these bivalve crypts are present both on the upper surface and on the sides of these blocks. The remainder of the Sinemurian succession is extremely attenuated, comprising from 0.15 m to 0.30 m of clay with lumps and nodules of limestone at two levels. The lower nodule band lies within the Turneri Clay, and has yielded *Arnioceras semicostatum*, while above lie the Obtusum Nodules, which contain both *Arnioceras semicostatum* and *Asteroceras confusum*. The succeeding Raricostatum Clay is never more than a few centimetres thick.

The massive Lower Pliensbachian limestones above are well developed and clearly exposed around the quarry (Figure 3.17). The Armatum Bed at the base is 0.6 m (2 ft) thick and clearly divisible into two distinct units, the lower of which contains abundant phosphate nodules and derived fossils. Echioceratid ammonites are a conspicuous element of the fauna of this lower unit, while large specimens of *Apoderoceras* are also common in the Armatum Bed. A specimen of the rare late Sinemurian liparoceratid *Vicininodiceras simplicicosta* has also been recovered from the lower unit (Donovan, 1990). Donovan and Kellaway (1984) noted preservational differences between specimens of *Echioceras*, *Paltechioceras* and *Gleviceras* in this bed (Figure 3.18), suggesting distinct origins for each, though they also inferred that specimens of *Gleviceras* and of *Phricodoceras lamellosum* probably were contemporary with deposition of the bed. Nominal ammonite taxa described from the Armatum Bed of this site include *Tutchericeras*, now considered a synonym of *Gleviceras*, and the genotype of *Paltechioceras*.

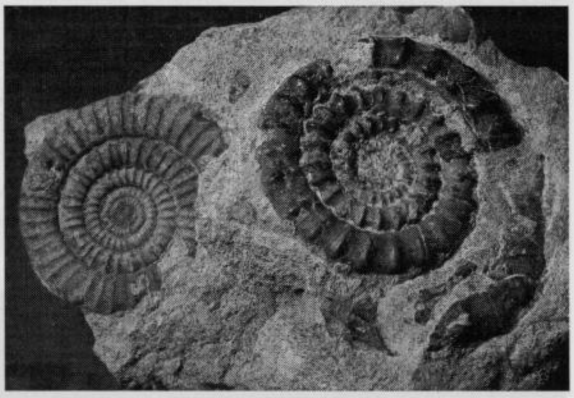


Figure 3.18 Phosphatized specimens of *Paltechioceras aureolum* (left) and *Echioceras raricostatum* (right) from the Armatum Bed of Kilmersdon Road Quarry. *Paltechioceras* is 65 mm across. From the T.R. Fry Collection in Bristol City Museum. (Photo: M.J. Simms.)

The Armatum Bed is overlain directly by the Jamesoni Limestone, comprising 1.55 m (5 ft) of ironshot, bioclastic, fossiliferous limestone, which at this site was the source of the holotypes of *Platypleuroceras bituberculatum* and of *Aegolytoceras rotunidicosta* (Donovan and Howarth, 1982). A magnified thin-section through a sample of Jamesoni Limestone from this site was figured by Tutcher and Trueman (1925, fig. 4), revealing an abundance of echinoderm and shell debris. The basal part of the Striatum Clays was indicated on Tutcher and Trueman's section (1925, fig. 3) as resting directly on the Jamesoni Limestone, but they cannot be seen at present.

HUISH COLLIERY QUARRY, BATH AND NORTH-EAST SOMERSET (ST 695 542)

Introduction

Huish Colliery Quarry sometimes also known as 'Branch Huish Quarry', 'Foxhole Quarry' or 'Writhlington Quarry', lies little more than 500 m south-east of Radstock and only 600 m due east of **Kilmersdon Road Quarry** (Figure 3.13). It is a key site in the stratigraphically complex Lias of the Radstock area. Most of the Hettangian and virtually all of the Sinemurian lithostratigraphical units typical of the local Lower Lias successions are absent here due to erosion prior to Lower Pliensbachian deposition. Instead Jamesoni Zone limestones rest directly on lowest Hettangian units of the Planorbis Zone.

This site is an essential part of the classic story of erosion and attenuation on the Lower Lias of the Radstock area, showing as it does the most extreme local example of a non-sequence involving the loss of almost two entire stages. A remarkable counterpart of this is the fact that the Lower Pliensbachian lithostratigraphical units just above the non-sequence are much better developed here than at other key sites, such as **Bowldish Quarry** and **Kilmersdon Road Quarry**. It was described for the first time, and in some detail, by Tawney (1875, 1878). Richardson (1910a) mentioned the site briefly and figured a photograph of the section under the name of 'Writhlington Quarry'. It was described briefly by Tutcher and Trueman (1925) as their 'site 13', by Savage (1977) and by Donovan and Kellaway (1984) as their 'site R55'.

Description

The lowest part of the section seen by Tawney (1875) comprised some 1.5 m (5 ft) of 'ordinary White Lias', cream-coloured limestone in many thin beds now assigned to the Langport Member of the Penarth Group. This is capped by the 0.6 m (2 ft)-thick Sun Bed, a cream-coloured limestone that splits into several beds; in more recent times this has formed the lowest part of the section visible (Figure 3.14). Above this Tawney (1875) recorded some 1.3 m (4 ft 3 in.) of 'Corn Grits' (Hettangian) comprising ten pale limestones separated by thin clay partings. Donovan and Kellaway (1984) noted a similar thickness. From the presence of *Psiloceras planorbis* in the top few centimetres of the uppermost limestone it is evident that of the Hettangian Stage only the Planorbis Zone is represented at this site. This limestone is succeeded directly by the Armatum Bed and Jamesoni Limestone (Figure 3.19), and no intervening strata of Sinemurian age are preserved. Woodward (1876) ascribed these Lower Pliensbachian limestones exposed in a quarry behind Branch Huish Farm to the Inferior Oolite Group, but Tawney (1878) recovered fossils that confirmed that it was the Jamesoni Limestone. The Armatum Bed is about 0.45 m thick and contains abundant phosphatic nodules and derived fossils, including *Echioceras* (Tawney, 1875), in its lower part; the upper 0.10 m is a clay with scattered lumps of limestone. Above this Donovan and Kellaway (1984) recorded 1.5 m of limestone, with a 0.1 m-thick clay band about 0.3 m from the base. Tutcher and

Figure 3.19 The limestone-dominated succession at Huish Colliery Quarry. The lower part of the face exposes limestones and thin mudstones of the Planorbis Zone, overlain by more massive bioclastic limestones of the Armatum Bed and Jamesoni Limestone in the upper part of the picture. (Photo: M.J. Simms.)

Trueman (1925) assigned the top 0.3 m (1 ft) to the Valdani Limestone and the remainder to the Jamesoni Limestone. Davidson (1876–1878) described the brachiopod *Lobothyris radstockiensis* from the Armatum Bed of this site, which he referred to as 'Huish Quarry'. The brachiopod was re-figured and described by Ager (1990). Up to 2.5 m (8 ft) of the overlying Striatum Clays was recorded in earlier accounts, though mistaken by Tawney (1875) for the Upper Lias clays. The Striatum Clays yielded *Androgynoceras sparsicosta* from the lowest 0.15 m, indicating the Maculatum Subzone. Tutcher and Trueman (1925) observed that rubbly (Bajocian) Inferior Oolite limestones appeared to overlie this modest thickness of Striatum Clays, but recognized that these limestones might have slipped and concealed the true thickness of the clays.

GENERAL INTERPRETATION

The observations made by Tutcher and Trueman (1925) in the Radstock district enabled them to undertake a detailed bed-by-bed interpretation of the sequence of events during deposition of this condensed Lower Lias succession. Many of their conclusions remain valid today although they need to be placed in a broader regional context, as was done to some extent by Donovan and Kellaway (1984). Although each of the three GCR sites provides a unique record of the local Lower Jurassic succession in that part of the Radstock Shelf, their greatest value is the way in which together they demonstrate the rapid lateral thickness variations, which are such a characteristic feature of the Lias succession in this area.

Hettangian succession

The Hettangian succession on the Radstock Shelf is the least distinctive of the three Lower Jurassic stages represented in the area. It lacks the distinctive facies of the Sinemurian or early Pliensbachian units, instead comprising limestones and thin shales not dissimilar to those seen elsewhere in the Blue Lias Formation. Nonetheless, the Hettangian sequence is highly attenuated, reaching no more than a few metres in thickness, and only the Planorbis and Liasicus zones are present (Figure 3.14). This reflects slow rates of subsidence and deposition across the Radstock Shelf during this period.

The Hettangian strata here are locally underlain by an exceptionally thick (about 5–6 m) development of the Langport Member (= White Lias) of the Penarth Group, which occupies a narrow east–west belt in this area. Comprising pale mudstones and calcilutitic limestones with desiccation cracks and a restricted fauna of bivalves, gastropods and ostracods, it was deposited in a shallow, occasionally emergent, marginal-marine environment. The Hettangian strata show an increasing marine influence as the early Jurassic transgression flooded across the area allowing more diverse faunas, including ammonites, to become established. Structurally, the Hettangian strata show a similar disposition to that of the White Lias (Langport Member), again thickening into an E–W-trending belt passing roughly through Radstock. This is the same general trend as many of the faults that have been mapped out in this area, and for the Mendip region as a whole (see Figure 2.1, Chapter 2), suggesting that, in late Triassic and Hettangian times at least, minor fault-bounded basins developed within the confines of the Radstock Shelf, as has been demonstrated to the south of the Mendip Hills (Jenkyns and Senior, 1991). Although Tutcher and Trueman (1925) identified two distinct east–west troughs, Donovan and Kellaway (1984) suggested that, on the limited data available, this was not the only interpretation possible to account for the Hettangian subcrop pattern. Thickness variations in the Planorbis and Liasicus zones, and the configuration of the Hettangian subcrop pattern beneath the Sinemurian strata (Figure 3.13), indicate an interplay between primary controls on Hettangian deposition and subsequent erosion in late or post-Hettangian times (Green, 1992). The Hettangian strata appear to have been gently folded prior to early Sinemurian planation and deposition of the Bucklandi Bed. The most severe of these minor flexures is located about Radstock itself, where a more than 7 m-thick Hettangian succession, extending up into the Liasicus Zone, thins northwards to 1 m or less in under 2 km (Donovan and Kellaway, 1984). This roughly coincides with similar thickness changes already noted in the Langport Member below and indicates a common underlying control on sedimentation and/or erosion. The relatively thin successions on basement highs, notably an extensive area to the south of Radstock, were removed by erosion whereas the thicker successions in the minor basins survived.

Hence, although **Bowldish Quarry** is the most northerly of the three GCR sites (Figure 3.13), its position on this flexure led to pre-Sinemurian removal of all but a thin remnant of Hettangian sediments (Figure 3.14). Even at **Huish Colliery Quarry**, more than 3 km to the south-east, a greater thickness of Hettangian strata has survived than at Bowldish Quarry, while at **Kilmersdon Road Quarry**, located between the two other sites, the Hettangian succession extends up through the entire Planorbis Zone and part of the Liasicus Zone.

Throughout the area the Angulata and Bucklandi zones are absent (Figure 3.13). Tutcher and Trueman (1925) did record *Epammonites isis* from the Spiriferina Bed of Bowldish Quarry, a species known to be diagnostic of the Bucklandi Subzone (Page, 1992), but no other evidence of either the Bucklandi or Angulata zones has been found among the diversity of derived ammonites in the Bucklandi Bed, suggesting absence is due to non-deposition rather than to pre-Semicostatum Zone erosion. In support of this, Hallam (1981) noted a late Hettangian regression following on from a minor deepening phase in the Liasicus Zone. Basinward from the Radstock Shelf, towards Keynsham and Bristol (Figure 3.13), this can be recognized in the transition from the Saltford Shales of the Liasicus Zone (Division B of Donovan and Kellaway, 1984) to the more limestone-dominated successions of the Angulata Zone (Division C), and Bucklandi to early Semicostatum zones (Division D). Early Bucklandi Zone shallowing is particularly clearly indicated by the condensed Calcaria Bed (Donovan and Kellaway, 1984). This late Hettangian to early Sinemurian period of regional shallowing evident in basinal successions appears to correlate closely with the stratigraphical gap between the Hettangian and Sinemurian stages on the Radstock Shelf.

Sinemurian succession

The Sinemurian succession is the most striking part of the Lower Lias succession on the Radstock Shelf. Its south-eastward pattern of thinning is thought largely to reflect original depositional controls (Green, 1992), a view supported by the remarkable persistence across much of the Radstock Shelf of all of the characteristic Sinemurian lithostratigraphical units despite their local extreme attenuation. All are well represented at **Bowldish Quarry**, where they total more than 1.5 m. At **Kilmersdon Road Quarry** (Figures 3.13 and 3.14), 3 km to the south-east, this part of the succession is less than 0.5 m thick, yet still retains all of the characteristic lithostratigraphical units of the Sinemurian Stage in this area. At **Huish Colliery Quarry**, 1 km farther east, the Sinemurian succession has been removed by early Pliensbachian erosion and its former presence is represented only by derived Raricostatum Zone fossils in the base of the (Lower Pliensbachian) Armatum Bed, which here rests directly on the Planorbis Zone.

Sinemurian deposition in the Radstock district commenced in the Scipionianum Subzone, as indicated by derived *Agassiceras* in the Bucklandi Bed, and correlates closely with a widespread transgression (Hallam, 1981) marked by mudstone-dominated successions in the Wessex and Severn basins and by the early Sinemurian transgression across the London Platform (Donovan *et al.*, 1979). By latest Semicostatum Zone times this transgression had advanced to affect deposition across the entire Radstock Shelf. Hence the Bucklandi Bed is found in nearly all exposures except where it has been removed by post-Sinemurian erosion. Continued deepening of the sea led to deposition of the Turneri Clay, almost all of which was removed by erosion from the southern part of the shelf around Radstock, prior to renewed deposition in the Obtusum Zone. There is no evidence of a hiatus between the Turneri and Obtusum zones in the adjacent Severn Basin to the north and Wessex Basin to the south and hence it can be attributed at Radstock to localized tectonic movement. The Obtusum Nodules are remarkably constant in character over almost the entire area: the associated mudstones were winnowed away at most localities to leave what is essentially a remanié nodule bed. The lithology of the Obtusum Nodules – dark laminated limestone containing ammonites and fish scales – is reminiscent of similar nodules encountered in the Obtusum Zone elsewhere, notably in the Black Ven Marl Member of the Dorset coast (Lang and Spath, 1926). The latter were deposited in an anoxic benthic environment and indicate that such conditions were widespread during Obtusum Zone times and hence must reflect an underlying eustatic control.

The absence of the Denotatus Subzone, the Oxynotum Zone and the Densinodulum

Subzone on the Radstock Shelf is evident also in the Dorset coast succession. The Oxynotum Zone in particular appears largely confined to the thicker basinal successions of the Severn and Wessex basins (Hollingworth *et al.*, 1990), and suggests a eustatic control since it correlates with a Europe-wide shallowing event (Hallam, 1981). The succeeding Raricostatum Clay appears to represent a late Sinemurian transgression well documented on the Dorset coast, the London Platform (Donovan *et al.*, 1979), Europe and South America (Hallam, 1981). Hence it is probably also eustatic in origin. The Sinemurian–Pliensbachian boundary in the Radstock district, with its conspicuous reworking of fossils from the Raricostatum Clay, bears some similarities to the successions in Dorset and Yorkshire, which also show evidence of shallowing and reworking. In Dorset both the Macdonnelli and Aplanatum subzones are absent, removed by erosion prior to deposition of Hummocky (Bed 103 of Lang and Spath, 1926). Hummocky contains reworked and encrusted nodule fragments and echioceratid ammonites, though none from the missing two subzones. It is clearly condensed and shows many similarities with the Armatum Bed of the Radstock succession, although the latter includes evidence for the Macdonnelli and Aplanatum subzones. It suggests that the event which caused erosion of the Raricostatum Clay, whether due to uplift or regression, was not confined to the Radstock Shelf, though Hallam (1981) notes the lack of evidence for a large-scale eustatic fall at this time.

The remarkable lateral persistence of each of the distinctive lithostratigraphical units of the Sinemurian succession indicates that subsidence rates on the Radstock Shelf throughout the Sinemurian Stage were minimal but increased slowly northwards. The sometimes striking correlation of some of the lithostratigraphical units, such as the Turneri Clay or Obtusum Nodules, with periods of transgression or eustatic highstand, suggests that eustasy was a major factor influencing the nature of the Sinemurian succession on the Radstock Shelf. The effects of erosion, rather than original depositional controls, increase southwards but appear largely confined to winnowing of the clay units, leaving a still more highly condensed sequence of reworked nodules and remanié fossil horizons. There seems to be no progressive loss southwards of individual lithostratigraphical units from the Sinemurian succession, analogous to that seen in the Hettangian Stage. Instead the loss of the Sinemurian strata passing southwards appears to be sudden and complete, as exemplified in passing from **Kilmersdon Road Quarry** to **Huish Colliery Quarry** (Figure 3.14). The widespread occurrence of abundant reworked late Sinemurian fossils in the Armatum Bed testifies to a significant episode of erosion at about the Sinemurian–Pliensbachian boundary. It suggests that on the southern part of the Radstock Shelf, where the Sinemurian sequence was already highly attenuated, this erosion event was sufficient to remove the Sinemurian succession in its entirety, as apparently occurred at Huish Colliery Quarry. Although the derived fauna of the Armatum Bed is largely of Raricostatum Zone age, Donovan (1958a) recorded the occurrence of derived *Promicroceras* in this unit at Upper Vobster (ST 707 497), where the Jamesoni Limestone and Armatum Bed rest directly on a planed surface of Carboniferous Limestone, indicating that erosion extended down at least to the Obtusum Zone. It may have removed the last remnants of the Hettangian succession here. Still farther south, on the Carboniferous Limestone periclines of the Mendip Hills, the Lias is absent as a discrete stratigraphical unit although the former presence of early Jurassic sediments is indicated by fissure fills of Sinemurian age (Jenkyns and Senior, 1991; Simms, 1997), as at the **Cloford Quarry** GCR site.

Pliensbachian succession

The massive bioclastic limestones of the Jamesoni and Valdani limestones show a strikingly different pattern to that of the underlying Sinemurian succession. Both are restricted to the Radstock Shelf, passing northwards into more typical open-water clay facies (Donovan and Kellaway, 1984), but the Valdani Limestone occupies a considerably more restricted area than the underlying Jamesoni Limestone (Figure 3.13). Unlike the Sinemurian strata, the Jamesoni Limestone continues southwards, finally disappearing only where overstepped by the (Bajocian) Inferior Oolite Group. At Upper Vobster, the Jamesoni Limestone is the sole representative of the entire Lias succession. The striking contrast between the distribution of the

Sinemurian deposits and that of the basal Pliensbachian limestones indicates a significant change in depositional regime around the Sinemurian–Pliensbachian boundary. Both indicate deposition on a shallow shelf dipping gently to the north or north-west. In Sinemurian times subsidence rates across this shelf were negligible and periods of deposition, represented by the main lithostratigraphical units, correlate fairly closely with transgressions or eustatic high-stands. The southward spread of the Jamesoni Limestone, onto areas where earlier Liassic sediments were absent, suggests that subsidence of the shelf was the dominant control on deposition in early Pliensbachian times. The shallower southern parts of the shelf extending towards the Mendip periclines favoured the accumulation of clean-washed bioclastic limestones analogous to the Southerndown Member of the Hettangian Stage at the **Pant y Slade to Witches Point** GCR site. The region of maximum development of the basal Pliensbachian limestones roughly coincides with that where the White Lias (Langport Member) reaches its maximum thickness and Hettangian thicknesses are reduced. This suggests that a local basement high, probably associated with one of the re-activated Mendip thrusts, persisted in this region throughout late Triassic and early Jurassic times and exerted a major control on deposition. Passing northwards into deeper water these limestones gave way to mudstone facies more typical of the basal Pliensbachian succession elsewhere. The Valdani Limestone appears to represent the final episode of this shallow-shelf deposition, confined to the local basement high. Later subsidence rates were sufficient over the whole shelf for deposition of normal open-water mudstone facies, the Striatum Clays and Capricornus Clays, to occur. Nonetheless, even this part of the succession shows significant attenuation compared with correlative strata farther north (Donovan and Kellaway, 1984).

The persistence of condensed deposits through the Jamesoni Zone contrasts with the 20 m-thick mudstone succession which comprises much of the Belemnite Marl Member on the Dorset coast. Similar thick mudstone-dominated successions occur in the Severn Basin (Cope *et al.*, 1980a) and on the Yorkshire coast (Hesselbo and Jenkyns, 1995) suggesting that the highly condensed nature of the Radstock Shelf succession is due to local tectonic controls. The succeeding Valdani Limestone encompasses the Masseanum and Valdani subzones, and may also be attributed largely to local tectonic control. On both the Yorkshire and Dorset coasts, the Ibex Zone successions are greatly reduced in comparison with those of the Jamesoni Zone, suggesting that there might also be some eustatic influence.

Above the Valdani Limestone there is an abrupt change to a much thicker, mudstone-dominated succession on the Radstock Shelf, not dissimilar to that encountered in more basinal settings. The Davoei Zone and upper-most Ibex Zone, represented by the 'Striatus and Capricornus Clays', together exceed the entire thickness of the condensed Lower Lias sequence suggesting that the local tectonic controls on sedimentation were greatly reduced during the later interval. This appears to have been a temporary feature: at most localities the remainder of the Lower Jurassic succession was removed by erosion prior to deposition of Upper Inferior Oolite (Upper Bajocian) limestones.

GENERAL CONCLUSIONS

The three GCR sites at **Bowldish Quarry**, **Kilmersdon Road Quarry** and **Huish Colliery Quarry** exemplify the various factors, including subsidence rates, eustasy and erosion, which together determined the nature of the preserved succession on the Radstock Shelf in Hettangian to Lower Pliensbachian times. Although there was a southward depositional attenuation of the Hettangian succession, pre-Sinemurian tectonic flexuring and subsequent erosion exerted a greater influence on the distribution of individual Hettangian strata across the Radstock Shelf. Bowldish Quarry, located on the largest of these flexures, experienced greater pre-Sinemurian erosion than the successions at Kilmersdon Road Quarry or Huish Colliery Quarry farther south. The main lithostratigraphical units of the succeeding Sinemurian sequence show a remarkable continuity between Bowldish Quarry and Kilmersdon Road Quarry despite a more than three-fold attenuation, suggesting considerable stability of the Radstock Shelf during this interval, with depositional and erosional episodes largely under eustatic control. The Jamesoni and Valdani limestones of the basal Pliensbachian succession mark a striking contrast to patterns of sedimentation during the Sinemurian Stage. They reach their maximum development on local highs, extending south onto progressively older rocks ultimately to rest directly on the Palaeozoic basement, and pass northwards into thicker basinal clay facies. They appear to represent a high-energy, shallow-water marginal facies that developed during the initial stage of a general subsidence of the Radstock Shelf and which culminated in the resumption of normal open-water mudstone deposition across the entire shelf.

FISSURE DEPOSITS OR 'NEPTUNIAN DYKES'

Some of the most interesting Lower Jurassic sediments in Britain occur within 'fissures' in older rocks. These fissure deposits are almost all confined to areas where the Carboniferous Limestone was exposed during early Jurassic times. Examples have been reported from south Wales (Robinson, 1957; Simms, 1990b; Benton and Spencer, 1995) and the Mendip Hills (Moore, 1867a; Savage, 1977, 1993; Benton and Spencer, 1995), and they are of exceptional importance for the terrestrial vertebrate faunas, including early mammals, that they have yielded (Moore, 1867a; Kermack *et al.*, 1968; Savage, 1993). Their faunas show that some fissure fills were terrestrial in origin while others were marine. The south Wales fissures, and some of those in the Mendips, contain terrestrial fills that have proved difficult to date precisely. In others, the associated flora indicates an early Jurassic age (Harris, 1957; Lewarne and Pallot, 1957). A significant proportion of the fossiliferous Mendip fissures have yielded both vertebrate and invertebrate marine fossils that indicate a late Triassic to at least mid-Jurassic age range (Copp in Duff *et al.*, 1985).

A diverse range of lithologies in the Mendip fissure-fills, includes breccias, red pebbly mudstones and grey mudstones similar to typical bedded Liassic sequences, and limestones. The limestones are the most characteristic facies and comprise a very fine-grained micritic limestone, often yellowish or pinkish in colour. Bedding within these sediments may be sub-horizontal, and may exhibit post-depositional sagging, but most commonly appear to have been deposited sub-parallel to the fissure walls. A minority of examples appear to represent karstic conduits or caves, and appear to be mostly of Triassic age (Simms, 1990b). The dominant fissure-type in the Mendip Hills is elongate, sometimes extending for hundreds of metres, straight and parallel-sided, with most orientated WSW–ENE. Commonly they are associated with lead and zinc mineralization (Stanton, 1991; Simms, 1997). Most of these fissures extend below the quarry floors and hence their depth is unknown. Moore (1862, 1867a) recorded a rich Lias fauna from sediments intercepted at a depth of 270 ft (83 m) in a lead mine at Charterhouse, as did Stanton (1991) more recently.

The origin of the fissures has been controversial. Simms (1990b) suggested that they represent solutional 'giant grikes' but it is now clear that they are 'pull-apart' structures developed on major joint sets during brief periods of extension during late Triassic to mid-Jurassic times. This basic mechanism was suggested by Moore (1867a) and expanded upon by Copp (in Duff *et al.*, 1985) and Smart *et al.* (1988). Jenkyns and Senior (1991) attributed the presence of Hettangian to Bajocian sediments in these fissures to a period of extensional faulting in this region, correlating with the early rifting phase of the Central Atlantic area. The frequency and widths of these fissures should provide an indication of the scale of this extension across the Mendip Hills, on the northern margin of the Wessex Basin. Moore (1867a) estimated that as much as a quarter of the face of the **Holwell Quarries** GCR site comprised Lower Jurassic sediments, indicating a crustal extension of up to 25%. This is probably an over-estimate (Jenkyns and Senior, 1991) but it broadly corresponds to the figure of 13–17% cited by Chadwick (1986) for basinwide crustal extension in the Wessex Basin.

Three GCR sites exemplify the fissures and their unusual associated facies in the Mendip Hills. The **Cloford Quarry** GCR site exposes numerous fissures, which have yielded a significant marine invertebrate fauna, and shows more clearly than elsewhere the relationship of the fissures to the surrounding country rock. The **Holwell Quarries** GCR site is of considerable historical importance as well as yielding a diverse fauna with both marine and terrestrial elements. Finally, the **Leighton Road Cutting** GCR site exposes the interface between the fissures and normal-bedded marine sediments.

CLOFORD QUARRY, SOMERSET (ST 718 444)

Introduction

Cloford Quarry, a large disused aggregate quarry, is a nationally important site exposing the finest assemblage of Mesozoic fissure-fills seen anywhere in Britain, ranging from Triassic to early Jurassic in age. These are overlain by Middle Jurassic limestones that cap the unconformity on the Carboniferous Limestone. Some of the fissures here have been crucial to understanding the mechanism of fissure development and in reconstructing the history of this area in early Jurassic times. The fissure fills have been the subject of several research projects notably by Charles Copp and subsequently by Gavin Wall, but little has been published. Copp (in Duff *et al.*, 1985) tabulated the main facies and ammonite zones present at Cloford Quarry and other Mendip fissure sites, but otherwise the only publications that specifically referred to this site were by Copestake (1982) who described the significance of foraminifera and ostracods from one of the fissures, by Fraser (1994) who noted some of the vertebrate material, and by Simms (1997, fig. 7) who figured the clearest example of a pull-apart fissure from here.

Description

Cloford Quarry is excavated into Lower Carboniferous limestones of the Vallis Limestone Formation, part of the Clifton Down Group, on the south-east flank of Beacon Hill, about 1 km west of the village of Holwell (Figure 3.20). Bedding is on a metre-scale and dips at about 18° to the south-west, broken only by slight flexuring in the north-west corner. The Carboniferous limestones are truncated by a planar unconformity, above which lies a thin, near-horizontal, development of bioclastic limestones of the (Upper Bajocian) Upper Inferior Oolite Group (Copestake, 1982). The Carboniferous Limestone is cut by numerous sub-vertical, sediment-filled fissures (Figure 3.21), which are truncated at the unconformity surface. Copp (unpublished) identified 21 fissures at Cloford Quarry, numbered CI to CXXI, but recognized that some probably linked up across the quarry. On a visit to the site in May 2000 at least 26 'fissures' of various types were

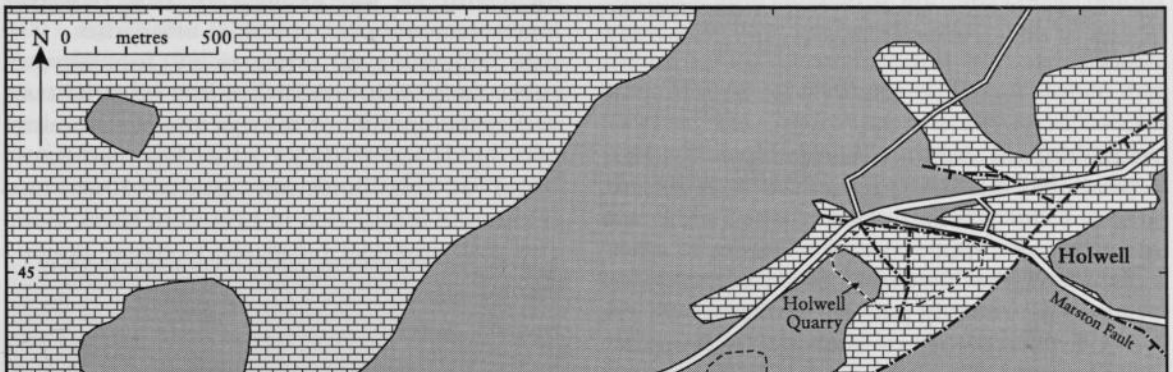


Figure 3.20 Sketch map of the geology in the Cloford and Holwell area of the eastern Mendip Hills.

Figure 3.21 Pull-apart, sediment-filled fissure (Fissure 24 of Figure 3.22) at Cloford Quarry. At least three distinct events are discernable in this example; (1) extension to form a 0.5 m-wide joint-guided pull-apart fissure subsequently filled with pale fine-grained sediment; (2) lateral offset of parts of this fissure by movement on a bedding plane (on which the hammer rests); (3) further extension to form a 0.1 m-wide fissure whose sediment fill (slightly darker and coarser than the earlier fill) is continuous across the bedding plane on which the earlier offset occurred. The bedding plane offset and opening of the second fissure probably represent different phases of the same extensional event. (Photo: M.J. Simms.)

noted (Figure 3.22), although several clearly represented different parts of the same fissure. At least some of these can be matched with those identified by Copp.

Most of the fissures have an ENE–WSW orientation, roughly parallel to the axis of the Beacon Hill pericline, although a few have discordant trends. By far the largest is Fissure 1, and its continuation farther west as Fissure 25 (= CI and CXXI of Copp, unpublished), which has been left as an unquarried ridge of Carboniferous Limestone and fissure-fill sediments extending across the quarry floor. This fissure is up to 6 m wide and 15 m high, though extending to an unknown depth below the quarry floor, and can be traced along-strike for several hundred metres. Copp (unpublished) recorded a complex assemblage of distinctive facies occurring in a definite sequence, from the margins towards the centre, within this fissure and also within Fissure 5 (= CIV of Copp, unpublished). Against the walls of the fissure is commonly found a red, haematite-stained limestone and limestone breccia. Observations of Fissure 5, made in May 2000, revealed that here at least this marginal layer is a thin flowstone, analogous to re-deposited calcite flowstones found in many limestone caves and fissures. This is succeeded by three distinct units; a 'Complex Breccia', a clastic limestone, and a pink crinoidal limestone. The fissure fill is commonly divided medially by a vuggy calcite vein, with this same facies sequence mirrored on the opposite side. The 'Complex Breccia' comprises an assemblage of intermixed breccias, conglomerates and marine limestones. The marine limestones include pale-yellow calcilutite, pale-grey calcarenite and pink biosparite, while the breccias and conglomerates contain clasts of Carboniferous Limestone, chert and weathered andesites and tuffs. One conglomerate type has rounded clasts of calcilutite in a clastic limestone matrix and this, and the other rudaceous facies, are sometimes rich in late Triassic (Rhaetian or Penarth Group) fish teeth. Laminations are predominantly sub-parallel to the fissure walls but some blocks are horizontally bedded and may show soft-sediment deformation.

Succeeding the 'Complex Breccia', towards the centre of the fissure, are pale bioclastic limestones and pink crinoidal biosparites. The pale limestone is often richly fossiliferous, particularly with bivalves, mostly infaunal taxa, and brachiopods but also yielding belemnites, gastropods and solitary corals. The base (outer edge) of this limestone grades down into calcarenite locally rich in hybodont shark teeth. The pink crinoidal biosparite is coarse grained

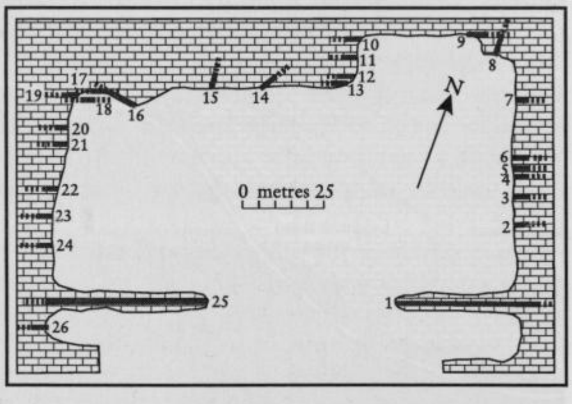


Figure 3.22 Sketch map of the distribution of Mesozoic fissures identified in Cloford Quarry in May 2000 (widths of fissures not to scale).

and contains occasional angular clasts of Carboniferous Limestone and chert. It contains a fossil fauna similar to, though better-preserved than, that of the pale limestone beneath including the brachiopods *Cirpa fronto*, *Zeilleria subdigona*, *Z. sarthacensis* and *Tetrarhynchia subconcinna*, the bivalves *Chlamys*, *Oxytoma*, *Placunopsis* and *Gryphaea*, and rare ?echioceratid ammonite fragments.

Although these two limestone types occur towards the centre of the largest fissures, they may also comprise the main infill of some of the smaller fissures. Additional facies associated with these two limestone facies are a blue-grey argillaceous limestone, with belemnites and brachiopods, and a brown siltstone in the centre of Copp's Fissure CXIV (Fissure ?22). The latter facies yielded a rich microfauna dominated by the foraminifera *Planularia protracta* and representatives of the *Lingulina tenera* group, along with several other species and some indeterminate cytheacean ostracods (Copestake, 1982). Pale cream-coloured, ironshot limestone in Copp's Fissure CXX yielded well-preserved Toarcian ammonites, including *Hildoceras*, *Hildaites*, *Nodicoeloceras* and *Lytoceras* (Figure 3.23).

Of the remaining fissures it is Fissure 24 (figured by Copestake, 1982, fig. 3; Simms, 1997, fig. 7) that is perhaps of greatest interest. Copestake (1982) noted that this had sub-parallel sides and a flat base coincident with a bedding plane in the Carboniferous Limestone, but observations in 1991 showed that this apparent base represented a plane of offset, of

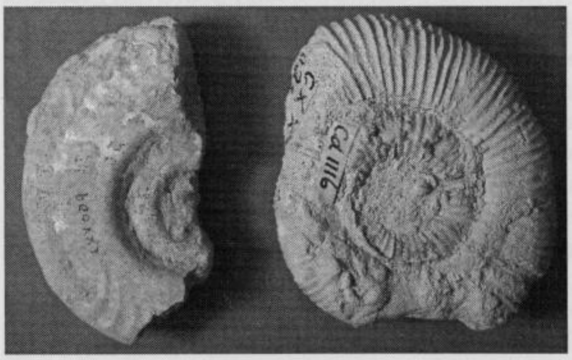


Figure 3.23 *Hildoceras* (left) and *Nodicoeloceras* (right) from Fissure CXX at Cloford Quarry, indicating a Lower Toarcian Bifrons Zone age for the infill. Specimens from the Charles Copp Collection at Bristol City Museum. *Nodicoeloceras* is 50 mm across. (Photo: M.J. Simms.)

about 0.5 m to the south, with the fissure continuing down below the quarry floor. Furthermore, the main fissure-fill is cut by a second parallel fissure, filled with slightly darker and coarser sediment, which passes across the bedding plane without any offset (Figure 3.21).

In general the narrower fissures have fissure-parallel sediments, such as in fissures 6, 12 and 13 but the larger ones often have slumped, sub-horizontal sediments, such as in fissures 5 and 23. Although the fissure walls tend to be sub-parallel, they often converge upwards or downwards; for instance Fissure 11 narrows upwards, the adjacent Fissure 12 narrows downwards, while Fissure 4 pinches out altogether about halfway up the quarry face and Fissure 19 bifurcates and then rejoins in the upper part of the quarry face.

Copp (unpublished) recorded the presence of at least one fissure (his Fissure CIX), since destroyed, that appeared to have uneven, 'water eroded' walls but no similar examples were visible in May 2000 or on an earlier visit in 1991.

Interpretation

The history of the fissures at Cloford Quarry is complex and enigmatic, although observations made here have proven crucial to understanding their origin. The straight and often sub-parallel sides of many of the fissures has established that most of the fissures at this site, and indeed throughout the Mendip region, are 'pull-apart' structures resulting from extensional tectonic activity. Their orientation sub-parallel to the major Leighton Fault suggests that their development was associated with intra-Jurassic movement on this structure, as was proposed for similar fault-parallel fissures at the **Leighton Road Cutting** GCR site (Jenkyns and Senior, 1991). Fissure 24 is particularly illuminating in this respect since the offset of the earlier fissure-fill but not the later one (Figure 3.21) indicates at least two extensional events, with the later one initially being accommodated by bedding-plane sliding prior to further widening of the original fissure.

The presence of red flowstone against the walls of Fissure 4 demonstrates that its initial phase of development must have occurred in a subaerial environment, probably in late Triassic times (Simms, 1990b), but the major early Jurassic transgression clearly led to the relatively rapid submergence of the area, with the result that all subsequent sediments are demonstrably marine in origin. Copp (in Duff *et al.*, 1985) proposed a model whereby much of the Jurassic sediment was sucked into the fissures as they opened abruptly beneath a cover of sediment on the sea floor. He termed these 'injection fissures' and cited various lines of evidence to support this interpretation, among them the lack of solutional modification of the fissure walls, the common occurrence of fissure-parallel laminations, and the frequent reworking of older sediments. However, all can be accounted for by more conventional processes. The lack of solutional modification may reflect limited hydrological input during the subaerial phase and exclusion of light, upon which marine bio-erosion is dependent, following submergence (direct dissolution of limestone by seawater does not occur; see Simms, 1990c). The accretion of sediment parallel to the walls is a well-documented phenomenon in caves and fissures (Bull, 1981), while collapse and reworking of earlier sediments might be expected if the fissure experiences more than one episode of extension. It is clear that the largest fissures experienced several successive episodes of widening, now represented by the distinct 'zones' of fissure-parallel sediments and an often central calcite vein. It is unlikely that many of these fissures were open on the sea floor during the early Jurassic Period for more than very short periods of time. Certainly, upward-narrowing fissures, such as Fissure 4, cannot have done so while even those that extended to the sea floor may well have had the actual opening blocked by collapse debris and accumulated sediment, such that sediments and fossils worked their way only slowly down into the lower parts of the fissures (Simms, 1997). The presence of angular blocks of Carboniferous Limestone within the finer Jurassic sediments is clear evidence of instability and collapse of the fissure walls, while the presence of large rounded clasts and larger fossils, indistinguishable from those in normal bedded sequences such as those of the Radstock Shelf, indicates periods when the fissures were more open to the sea floor. It is unlikely that most of the fossils were actually living in the fissures, while the rounded calcilutite clasts, of presumed reworked Jurassic sediment, cannot have reached this state within the confines of the fissure and indicate erosion on the sea floor before being incorporated into the fissure. The presence of 'fissure facies' limestones in a 'normal' bedded sequence at the **Leighton Road Cutting** GCR site is particularly significant in this respect, but the lithology of other clasts in the conglomerates indicate that the Mendip Massif was already deeply eroded, with the presence of andesitic clasts indicating that even the Silurian volcanic rocks were unroofed by earliest Jurassic times.

The inferred age range of the various facies represented in the Cloford Quarry fissures is considerable and their relationship to each other apparently complex. The results were summarized in a table by Copp (in Duff *et al.*, 1985). Conventionally the reddened sediments close to the fissure walls have been interpreted as Triassic in age although there is no conclusive proof of this. Copp (in Duff *et al.*, 1985) considered much of the 'Complex Breccia' to be latest Triassic (Penarth Group) or earliest Hettangian in age. The pale bioclastic limestones and calcilutitic conglomerates were assigned a Raricostatum Zone age and the succeeding pink crinoidal limestones were considered to be of Jamesoni Zone age, although at least one of the brachiopods, *Tetrarhynchia subconcinna*, is known only from the Spinatum Zone (Ager, 1956–1967). Copp (in Duff *et al.*, 1985) also noted the presence at Cloford Quarry of sediments of the (Upper Pliensbachian) ?Margaritatus Zone, the (Toarcian) Serpentinum and Bifrons zones and the (Upper Bajocian) Garantiana Zone.

Only the microfossil work by Copestake (1982) has been published in any detail. He noted that most of the foraminifera recovered from the brown siltstone in Fissure CXIV were of long-ranging taxa known to extend from at least the Rhaetian or Hettangian strata to high in the Lower Jurassic succession. However, most of these taxa are characteristic of the Lower Sinemurian Substage and, by comparison with other well-documented sites such as **Hock Cliff**, he suggested that the fauna indicated a Bucklandi Zone or Semicostatum Zone age.

Conclusions

The Carboniferous Limestone at Cloford Quarry is cut by an unusually clear and diverse assemblage of the sediment-filled, tectonic pull-apart fissures which are such a long-noted feature of the Mesozoic succession in the Mendip Hills. Certain of the fissures here provide important evidence for the mechanism by which these fissures form, whereas others record a clear sequence of distinctive facies demonstrating a long and complex history of extension in this region. The earliest phase of fissure opening appears to have been in a subaerial (?Triassic) environment although subsequently this was inundated by the early Jurassic transgression and all subsequent sediments are exclusively marine. The presence in the fissure fills of locally derived Silurian, Devonian and Carboniferous clasts testifies to the extent of erosion of the Mendip Massif already by Early Jurassic times.

HOLWELL QUARRIES, SOMERSET (ST 726 450)

Introduction

The Holwell Quarries GCR site is a site of international importance both geologically and historically, from which Charles Moore obtained some of the earliest known mammals. Fissure fills here range from late Triassic to mid-Jurassic in age and include a diverse fauna of both terrestrial and marine vertebrates and invertebrates. The site provides important evidence for the relationship between faulting and the pull-apart fissures, and the relationship of the fissures to late Triassic and mid-Jurassic palaeosurfaces also exposed in the quarry complex.

Limestone was being quarried at this site in the first half of the 19th century and this quarrying continued for the next 150 years, leading to a complex of abandoned quarries that straddle the A361, the main Frome–Shepton Mallet road (Figure 3.20). Charles Moore was the first to recognize that the Carboniferous Limestone here was cut by numerous fissures filled with substantially younger material. His investigations, described in a major paper (Moore, 1867a) revealed that these fissure fills were Mesozoic, principally late Triassic and early Jurassic, in age. The discovery of teeth of what, at that time, were the earliest known mammals provoked most interest in the fissures at Holwell Quarries. Further work on the vertebrates was undertaken by Kühne (1947), Robinson (1957), Benton and Spencer (1995) and Dineley and Metcalf (1999). Savage and Waldman (1966) included a description of the site and a sketch map of the main geological features visible in the quarry complex at Holwell, and Savage (1971) described a tritylodontid maxilla from here. Savage (1977) published an updated description of the quarry and (Savage, 1993) described the history of investigation of the site and included a photograph, taken in 1864, of the main face described by Charles Moore. There have been many other brief references or descriptions, such as those of Richardson (1909), Reynolds (1921) and Macfadyen (1970), particularly in relation to the taxonomy of the mammals and other vertebrates. However, since the vertebrates are considered to be largely Triassic in age (Evans and Kermack, 1994) they are not considered in any detail here.

Although much discussed by Moore (1867a), the Lower Jurassic marine invertebrate fauna from the fissure fills has been largely neglected. Some elements were mentioned by Copp (in Duff *et al.*, 1985), who described the disused quarry at Holwell Brook (ST 729 450), and Copestake (1982) discussed the microfauna obtained from one fissure fill here.

Description

Carboniferous Limestone of the Vallis Limestone Formation crops out in an elongate window, extending north-east towards Frome, but otherwise is concealed beneath a cover of Middle Jurassic (Upper Bajocian–Bathonian) limestones and clays. In the vicinity of the quarry complex the Carboniferous Limestone dips almost due south at about 20° and is traversed by several major faults with east–west or north-east–south-west trends. Savage and Waldman (1966) provide the only sketch map of the distribution of fissures and other geological features within the quarry complex covered by the GCR site. A third quarry is currently operating to the north of those figured by Savage and Waldman (1966), but lies beyond the GCR site boundary. In the original description by Moore (1867a) it was observed that several of the fissures narrowed upwards, from 8 m or 9 m near the quarry floor to almost nothing at the top. Moore (1867a) noted a range of lithologies within these fissures, including clays, laminated limestone and conglomeratic units, and listed (Moore, 1867b) 32 Lower Jurassic species from them. In particular he recorded the brachiopods *Spiriferina walcotti*, *S. munsteri*, '*Rhynchonella*' *variabilis* (possibly *Cirpa* sp.; see Ager, 1956–1967, pp. 55–56) and *Lobothyris punctata* from two of the wider fissures. Moore (1867a) commented on the diversity of small gastropods obtained from one fissure, citing the presence of ten genera; Hudelston and Wilson (1892) subsequently produced a revised list of 11 gastropod species. Copestake (1982) recorded four species of foraminifera and three species of ostracod from a grey siltstone in one fissure on the southern wall of the southern quarry. The vertebrate fauna has always formed the main focus of palaeontological interest at this site. It was recognized by Moore and by others subsequently as being largely Triassic in age.

Although some of the fissure fills are at least partly Triassic in age, the site is important for demonstrating the relationship of the fissures to the geology. Most of the fissures cut the Carboniferous Limestone. Savage (1977) noted that they were truncated by horizontally bedded Middle Jurassic limestones which overlie the planed-off Carboniferous Limestone just to the north of the GCR site. In the southern part of the site several almost vertical fissures penetrate an extensive boulder conglomerate, of presumed Triassic age, described and mapped out by Savage and Waldman (1966). Another fissure cutting through Carboniferous Limestone on the west face is developed on a minor dip-slip fault.

Interpretation

Most of the fissures in the Holwell Quarries GCR site do not differ significantly in their configuration and in the nature of their sediment infills from examples seen at the **Cloford Quarry** GCR site. However, at least one shows a clear relationship between faulting and fissure development. Other fissures within this site cut through boulder conglomerates that were interpreted by Savage and Waldman (1966) as Triassic wadi deposits. The relationship of the fissure boundaries, which cut some of the larger clasts, demonstrates that these wadi-fill conglomerates were well cemented by the onset of fissuring.

The age range of the fissures cannot be constrained precisely although at least some post-date emplacement of the boulder conglomerates and many, if not all, pre-date deposition of the Inferior Oolite Group limestones above the unconformity surface. Much of the vertebrate material appears to be latest Triassic in age. Kühne (1947) noted considerable similarities between the Holwell Quarries fauna and that isolated from the basal Penarth Group bone bed at Aust Cliff. Although *Oligokyphus* is considered an early Jurassic taxon on the basis of evidence from Windsor Hill Quarry (ST 614 452) (Kühne, 1956), Savage and Waldman (1966) did not make any assumptions concerning the age of the specimen found at Holwell Quarries. This was subsequently shown to be referable to an indeterminate tritylodontid, a group known to span the Triassic–Jurassic boundary (Savage, 1971). The invertebrate fauna also does not enable fissure fills to be precisely dated, particularly since no ammonites have been found. Moore (1867b) claimed a Pliensbachian age for at least one fissure, on the basis of gastropods, but accepted a late Triassic, Rhaetian, age for another fissure on the basis of its vertebrate fauna. The brachiopods suggest an age range spanning much of the Sinemurian and Pliensbachian stages. Copestake (1982) deduced that the microfauna indicated a Lower Sinemurian, Bucklandi Zone, age for the sample he analysed. Most of the remaining fauna is of little biostratigraphical value, although *Isocrinus tuberculatus* also suggests a Lower Sinemurian age.

Conclusions

The importance of the fissure fills at the Holwell Quarries GCR site concerns the early mammalian fauna that they have yielded. Although traditionally this fauna has been considered late Triassic in age, other elements of the invertebrate fauna from this site indicate a substantial early Jurassic component to the fissure fills. The site is also important for demonstrating the relationship of the fissures to minor faults and to earlier Mesozoic terrestrial deposits.

LEIGHTON ROAD CUTTING, SOMERSET (ST 702 437)

Introduction

The Leighton Road Cutting GCR site is a small road cutting on the north side of the A361, about 8 km south-west of Frome (Figure 3.20), which was excavated during road improvements in the 1970s. It exposes the only section through a normally bedded Lower Jurassic sequence in facies analogous to those encountered more widely in fissure fills across the Mendip Hills. As such it is fundamental to understanding the nature of these fissure fills and their relationship to the early Jurassic palaeosurface in this area. The section was investigated by Charles Copp and was also visited by Hugh Jenkyns, some of whose notes and sketches were published subsequently (Jenkyns and Senior, 1991). These remain the only published account of this crucial site.

Description

In 1999 the section at Leighton Road Cutting was largely obscured by soil and vegetation, but in 1977 Jenkyns made a sketch of the exposure (Jenkyns and Senior, 1991, fig. 12). This showed a knoll-like outcrop of moderately dipping Carboniferous Limestone overlain unconformably by Jurassic sediments (Figure 3.24). The unconformity surface was penetrated by '*Lithophaga* and other borings' and, on its lower flanks, by small cavities filled with laminated sediment. The main body of the limestone was cut by several small clastic dykes orientated roughly north-east–south-west and filled with red crinoidal limestone. These yielded a brachiopod fauna including *Quadratirhynchia*, *Prionorhynchia* and juvenile *Cirpa*. Above the unconformity surface, and onlapping onto the lower part of the 'knoll', was up to 0.75 m of red crinoidal limestones capped by an oyster-encrusted planar unconformity surface and overlain by Upper Bajocian (Parkinsoni Zone) limestones. The latter onlapped directly onto the upper part of the 'knoll'. Copp (unpublished) reported a more complex sequence below the Upper Bajocian limestone, passing from pale limestone, through pink crinoidal limestone with *Cirpa*, to a yellowish crinoidal limestone some distance above. Jenkyns and Senior (1991) reported that these normally bedded sediments were themselves cut by clastic dykes and bed-parallel fissures filled with fine-grained laminated carbonates.

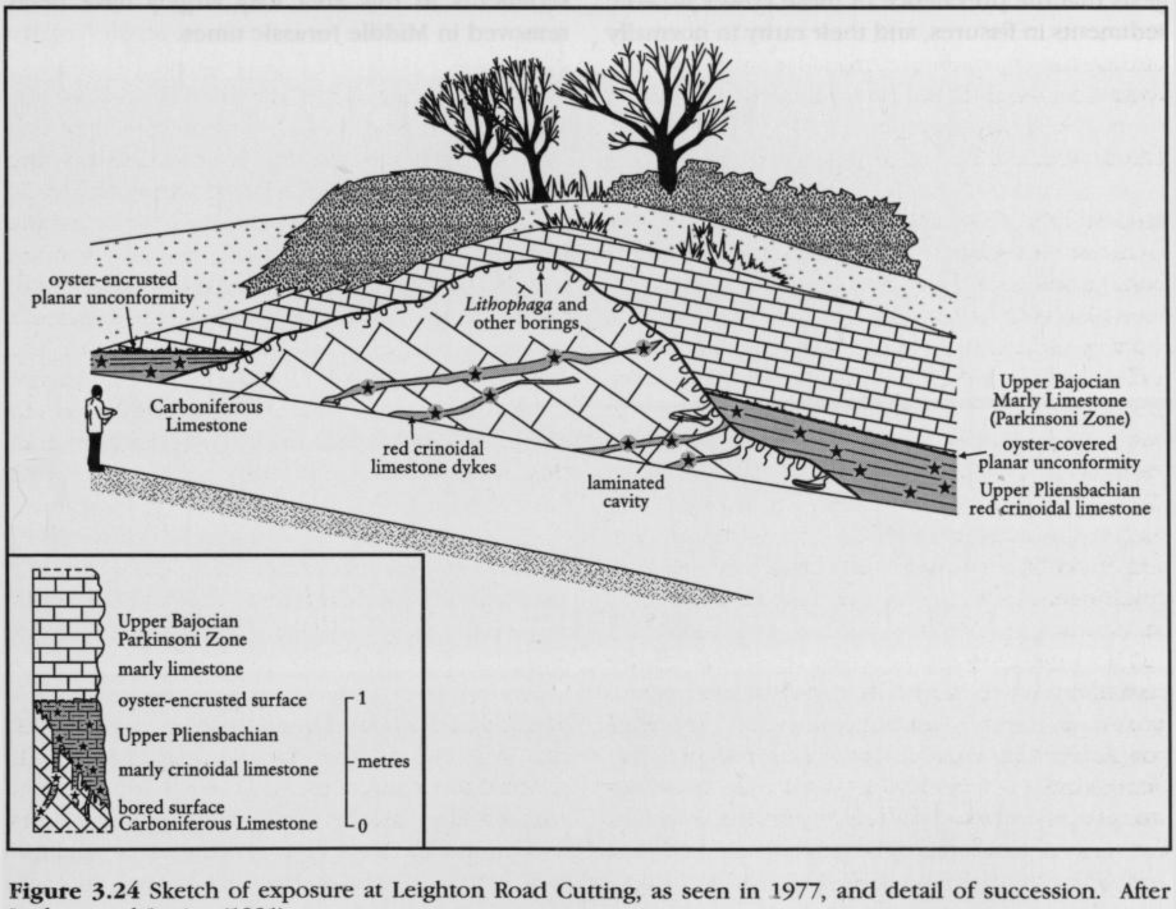


Figure 3.24 Sketch of exposure at Leighton Road Cutting, as seen in 1977, and detail of succession. After Jenkyns and Senior (1991).

Interpretation

The various facies, and the sequence in which they occur here, show similarities to the successions which have been observed in some of the fissures at sites such as **Cloford Quarry** and **Holwell Quarries**. The ages of these facies, as deduced from the biota, are broadly comparable between the two settings, being of Upper Sinemurian to Upper Pliensbachian age. Of significance is the fact that these normally bedded sediments are indistinguishable from their correlatives in the fissure fills, indicating that they were deposited in similar environments. The presence of an intensely bored surface on the Carboniferous Limestone beneath the Lower Jurassic sediments indicates that there was a period of marine erosion and non-deposition before the earliest Jurassic sediments represented here. Similarly, the oyster-encrusted surface immediately below the Upper Bajocian limestone indicates that higher parts of the Lower Jurassic succession may have been removed by erosion in Middle Jurassic times. Indeed it suggests that the prevalence of these Lower Jurassic sediments in fissures, and their rarity in normally bedded sequences on the southern flanks of the Mendip Massif, may be attributable largely to Middle Jurassic erosion. Jenkyns and Senior (1991) noted the parallel orientation of most of the clastic dykes here with the trend of the Leighton Fault just to the south (Figure 3.20), and suggested that they may have developed in association with movement on this fault.

Conclusions

The facies and ages of the Lower Jurassic normally bedded succession at the Leighton Road Cutting GCR site are similar to those recorded from fissure fills at other sites in the area, such as at **Cloford Quarry** and **Holwell Quarries**. The presence of these sediments here demonstrates that those contained within the fissures do not represent a distinct and unique 'fissure facies' but are marine shelf sediments that have collapsed into the fissures. Their relationship to the Carboniferous Limestone below and the Upper Bajocian limestones above suggest that outcrops of these sediments in this area may largely have been removed in Middle Jurassic times.