Permian and Triassic Red Beds and the Penarth Group of Great Britain

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Chapter 4

British Penarth Group sites

INTRODUCTION

The Penarth Group, formerly the 'Rhaetic', represents a dramatic change in sedimentation style throughout the British Isles and much of western and central Europe at the end of the Triassic Period. The mainly continental, red and yellow mudstones and sandstones of the Germanic Keuper, and of the Mercia Mudstone Group, come to an abrupt halt, and are succeeded by grey, marine mudstones, limestones, and sporadic, thin, bone beds. This change has long been interpreted as reflecting a major marine transgression that apparently flooded much of north-west and central Europe a few million years before the end of the Triassic Period.

A number of GCR sites that show the highest part of the Mercia Mudstone Group, including red beds, also contain strata of the succeeding Penarth Group (see Figure 3.1). Their inclusion in the present volume is justified on the grounds that it provides an appropriate conclusion to the account of British Triassic continental sedimentation.

STRATIGRAPHY

The term 'Penarth Group' was introduced by Warrington *et al.* (1980) as a formal lithostratigraphical name for the rocks formerly called 'Rhaetic' in Britain, where it comprises the formations between the Mercia Mudstone Group and the base of the Lias Group. These formations are the Westbury Formation and the succeeding Lilstock Formation. The latter is formally subdivided into the Cotham and overlying Langport members. The relationships of these units to the older informal stratigraphy of the 'Rhaetic' is summarized in Figure 4.1, and two typical Penarth Group successions are shown in Figure 4.2, contrasting the styles of sedimentation in Somerset and Devon, and illustrating the current and former lithostratigraphical terminology.

The term 'Rhaetic' was based on the German 'Rhät' or 'Rhätkeuper', derived from the first identification of these rocks in the Rhaetic Alps in the 1820s and 1830s. The 'Rhaetic', as a localized rock unit in north-western Europe, was equated with the Rhaetian Stage, a chronostratigraphical unit that was defined biostratigraphically and identifiable worldwide. Like the other Triassic stages, the Rhaetian Stage was based on the marine Triassic sequence of the Alps, with its type section at Kendelbachgraben, St Wolfgang, Austria. Formerly, the Rhaetian stage was commonly included within the Jurassic System (e.g. Arkell, 1933), although it has been definitively and uniformly accepted as the last stage of the Triassic System since 1962.

Tozer (1967) presented detailed ammonite evidence for dating of the Triassic stages, and proposed a global stratotype section for the base of the Rhaetian Stage at Brown Hill, Peace River, north-east British Columbia, Canada.

The Westbury Formation overlies the Blue

Richardson (1911)		Warrington *et al.* (1980)			
Lower Lias	*planorbis* beds	Lias Group	Blue Lias Formation	*planorbis* zone	Hettangian
Lower Lias	Pre-*planorbis* beds	Lias Group	Blue Lias Formation	Pre-*planorbis* Beds	Rhaetian
Rhaetic – Upper	Watchet beds	Penarth Group	Lilstock Formation	Langport Member	Rhaetian
Rhaetic – Upper	Langport beds	Penarth Group	Lilstock Formation	Langport Member	Rhaetian
Rhaetic – Upper	Cotham beds	Penarth Group	Lilstock Formation	Cotham Member	Rhaetian
Rhaetic – Lower	Westbury beds	Penarth Group	Westbury Formation		Rhaetian
Rhaetic – Lower	Sully beds	Mercia Mudstone Group	Blue Anchor Formation		Rhaetian
Keuper	Tea green and grey marls	Mercia Mudstone Group	Blue Anchor Formation		Norian
Keuper	Red marl	Mercia Mudstone Group	Unnamed formation		Norian

Figure 4.1 The historical (Richardson, 1911) and current (Warrington *et al.*, 1980) lithostratigraphical terminology of the uppermost Triassic–lowest Jurassic strata of south-west Britain. Chronostratigraphical units are shown at the right.

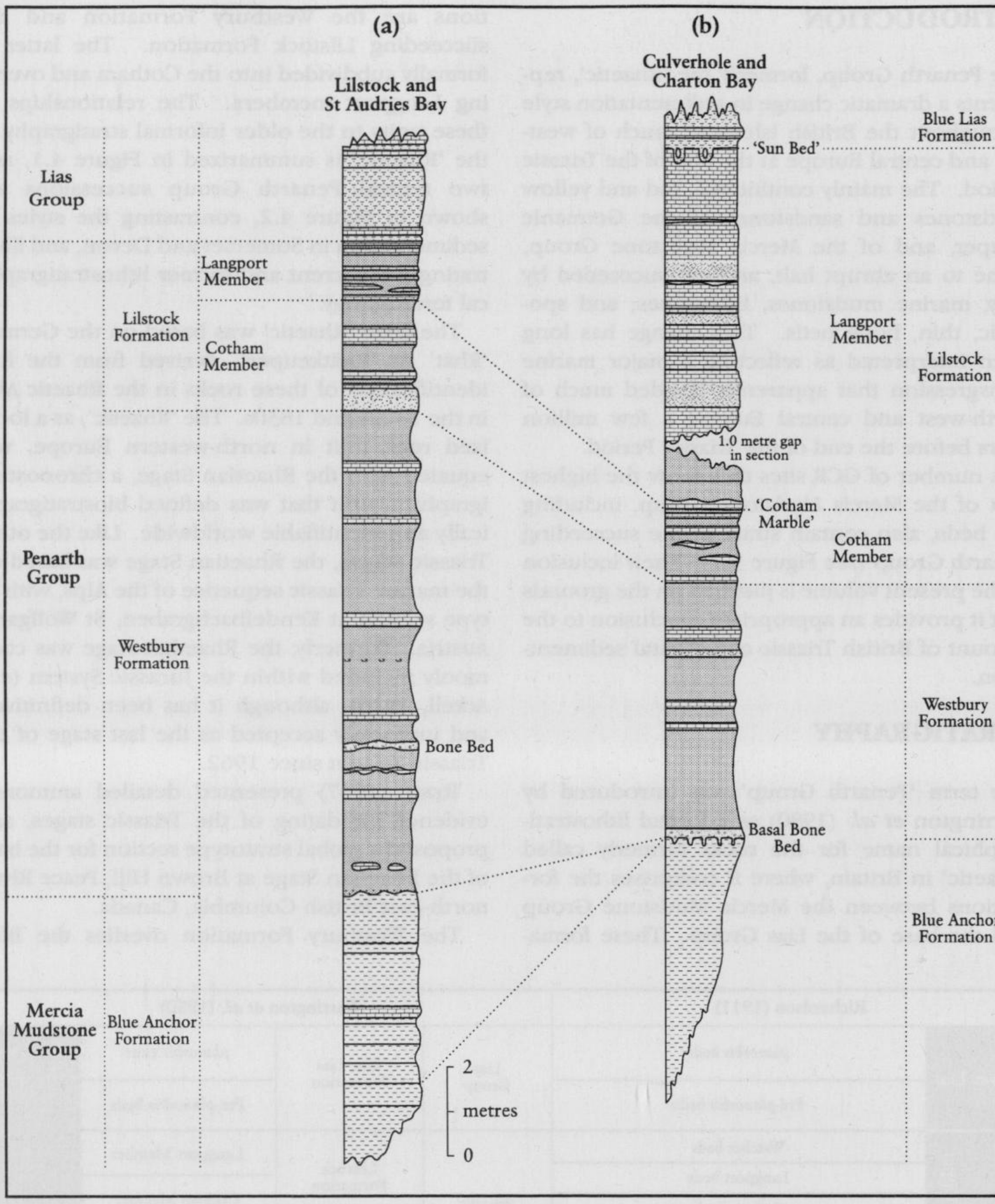

Figure 4.2 Two classic Penarth Group successions in southern England, on (a) the west Somerset coast, based on Lilstock and St Audries Bay, and (b) the south Devon coast, based on Culverhole and Charton Bay. (After Durrance and Laming, 1982.)

Anchor Formation, the uppermost unit of the Mercia Mudstone Group, usually unconformably. In many places, a thin, laterally impersistent bone bed, the famous 'Rhaetic bone bed', occurs at the base of the Westbury Formation. The remainder of the formation consists of dark grey mudstones or shales with subordinate thin limestones and sandstones. The formation was formerly termed the 'Westbury Beds' or 'Black Shales', and it corresponds approximately to the *contorta* Zone or Lower Rhaetic of various authors. The type area for the formation is the coastal section at Penarth and immediately north of Lavernock Point, South Glamorgan.

The overlying Lilstock Formation is bounded below by the Westbury Formation, and above by the base of the 'Paper Shale' of Richardson (1911). The lower part of this formation, the Cotham Member, is equivalent to the 'Cotham Beds', and the overlying Langport Member is equivalent to the remaining units below the 'Paper Shale'. The Langport Member shows considerable facies variation, with thick limestones ('White Lias') in South Devon and Mid-Somerset, passing laterally into a thin limestone representative in West Somerset and South Wales and parts of the Midlands (Swift, 1995).

*The Pre-*planorbis *beds and the Triassic–Jurassic boundary*

The position of the Triassic–Jurassic boundary has been a subject of debate for many years (see, for example, Pearson, 1970; Orbell, 1973; Morbey, 1975; Poole, 1979; Hallam, 1990, 1994; Hodges, 1994; Warrington *et al.*, 1994).

Up to 1980, the base of the Jurassic System in Britain was traditionally taken to be the base of the Lias Group, the succession of generally grey-coloured mudstones and limestones so characteristic of the Lower Jurassic Series throughout much of Europe. This interpretation placed the boundary at the base of the lithologically defined 'Blue Lias', in particular placing the Pre-*planorbis* Beds (see Figure 4.1) in the Jurassic System. However, this characterization of the base of the system in Britain was purely lithological, and a formal, biostratigraphical definition was required.

Since 1980, the base of the Jurassic System has been placed at the first appearance of the ammonite genus *Psiloceras*, and the species *P. planorbis* in particular, which thereby marks the base of the Hettangian Stage (Cope *et al.*, 1980; Warrington *et al.*, 1980). This view was not uniformly accepted (see, for example, Hallam, 1981), but international agreement now indicates that the Pre-*planorbis* beds of the Blue Lias are of Triassic, not Jurassic, age (Warrington *et al.*, 1994; Warrington and Ivimey-Cook, 1990).

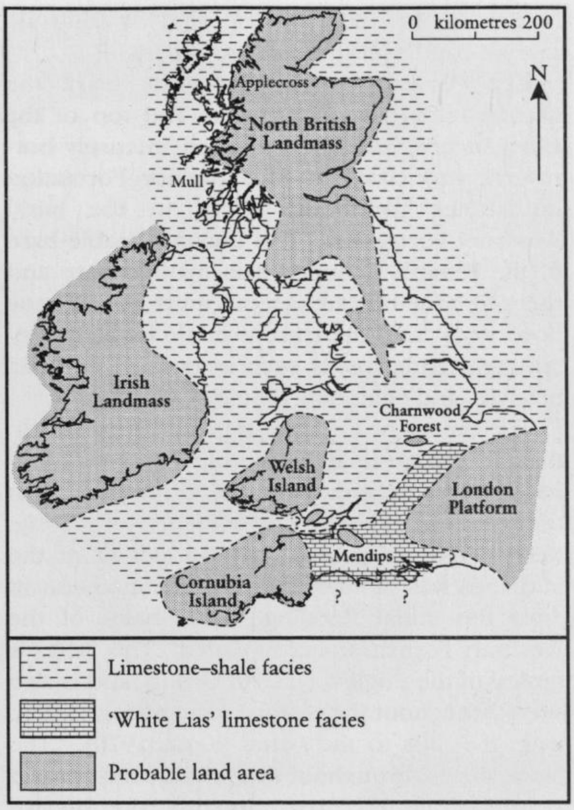

Figure 4.3 Palaeogeography of the British Isles during the Rhaetian Age. The classic sections in South Wales, Gloucestershire, Somerset, and Devon accumulated on marginal areas of the Welsh and Cornubian islands. The Langport Member is most fully developed in south. (After Poole, 1979.)

SEDIMENTOLOGY

The Rhaetian transgression

The Penarth Group reflects the widespread establishment of marine environments following a transgression that spread northwards through central and north-western Europe into Britain (Figure 4.3). At the same time, there was major rifting and volcanism in southern Europe, North Africa, and eastern North America, as proto-North Atlantic rifting opened up linear structures parallel to the current coastline of eastern North America, from North Carolina to Nova Scotia where thick lacustrine sediments of the Newark Supergroup accumulated.

The marine rocks of the Penarth Group succeed the greyish and greenish, dolomitic mudstones of the Blue Anchor Formation, formerly the 'Tea Green Marls' and 'Grey Marls', the highest formation in the Mercia Mudstone Group. Geochemical and palaeontological evidence of marine conditions are seen in the upper Mercia Mudstone Group (Warrington and Ivimey-Cook, 1995). These marine influences in the upper

Norian in the UK were followed by full-scale marine conditions in Rhaetian times.

The Penarth Group sediments mark the marine transgression proper. The top of the Blue Anchor Formation is often intensely burrowed, and clasts of Blue Anchor Formation mudstones commonly occur in the basal Westbury Formation. The unconformable base of the Penarth Group is also marked here and there by bone-rich arenaceous units, the 'Rhaetic bone beds', and these are overlain by beds containing marine fossils such as oysters, pectinid bivalves, and echinoids (Ivimey-Cook, 1974).

The timing of the transgression is unclear in Britain. It appears to have occurred rapidly, perhaps sweeping from the south to the north, but there is no independent evidence of dating. Kent (1970) suggested that the whole of the Midlands was inundated almost simultaneously. After the initial flooding, dark shales of the Westbury Formation accumulated. This facies is typical of the English Penarth Group, and is also seen throughout the region of the transgression, from the Alps to the Baltic (Kent, 1970). The black shales throughout this whole area contain a limited fauna, predominantly the bivalve *Rhaetavicula contorta,* hence the former name of the unit, the '*contorta* Zone'. *Rhaetavicula* is a specialized epifaunal bivalve that was presumably adapted to unfavourable conditions, particularly anoxic bottom waters, evidenced by the black colour of the shales and by associated pyrite.

The Westbury Formation bone beds

There are bone beds at several horizons in the Westbury Formation, not just at its base. In all cases the bones are heavily phosphatized and may be in superb and apparently unworn condition, or extensively rolled and abraded (MacQuaker, 1994, 1999; Storrs, 1994; Trueman and Benton, 1997; Martill, 1999). The contrast in styles of preservation is best brought out by a comparison of material from the bone beds at Westbury Garden Cliff, on the north bank of the River Severn, and Aust Cliff, on the south (Trueman and Benton, 1997; see Figure 4.4).

The horizon of the bone bed at Westbury Garden Cliff is hard to determine because of poor exposure. It occurs in a 20–30-mm-thick shelly sandstone, with mud laminations, and abundant pyrite crystals. Apatite fragments (heavily phosphatized bones, teeth, fish scales, phosphatic nodules, coprolites) occur uniformly throughout the bed, with no evidence of grading, and other clasts are quartz fragments, but there are no rip-up clasts of the underlying Blue Anchor Formation. The limited lateral extent of this bone bed suggests that it may represent a shallow channel in an estuarine environment. This is confirmed by the trace fossil assemblage (Wang, 1993) and the anoxic sediments with extensive pyritization and phosphate genesis. The bone bed may be a winnowed accumulation of bone debris in the channel base.

The Aust Cliff bone bed is a discontinuous deposit, varying in thickness from 0–300 mm. It rests on an uneven surface eroded on the Blue Anchor Formation, and has a fine grey carbonate matrix that comprises around 50% of the deposit. The matrix contains numerous clasts of four types: apatite clasts (bones, teeth, coprolites, phosphatic nodules), rip-up clasts of the underlying Blue Anchor Formation, and lithic clasts of both quartz and Carboniferous limestone. Of these, the first two are predominant. The apatite clasts grade normally, while the rip-up clasts are reverse-graded, presumably the result of the arrest of a turbulent sediment-rich flow. The dense apatite fragments sank through an unconsolidated matrix of carbonate mud, and the less dense mud fragments were suspended within this matrix after flow stopped. The final stages of deposition consisted of settling of fine clays from suspension, leaving a mud drape over the top surface of the bed. The Aust Cliff bone bed arose from a high-energy, storm-driven fluid flow, reworking an area rich in apatite debris, with occasional quartz and limestone lithic fragments.

The Westbury Garden Cliff and Aust Cliff bone beds show physical and chemical evidence of transport. Fossil material in the Westbury Garden Cliff bone bed comprises mainly small platy elements (*Gyrolepis* scales), distributed in thin layers on single laminae, and delicate unabraded remains of the small aquatic reptile *Pachystropheus*. The Aust Cliff bone bed, on the other hand, consists of a mixture of spherical, cylindrical, and platy elements, and most of these clasts are medium or large in size and well rounded. The physical evidence of apatite clasts shows that the Westbury Garden Cliff bone bed was deposited by low-energy currents that had picked up the bones and scales nearby, while the Aust Cliff bone bed consists of bony debris carried some distance by high-energy currents.

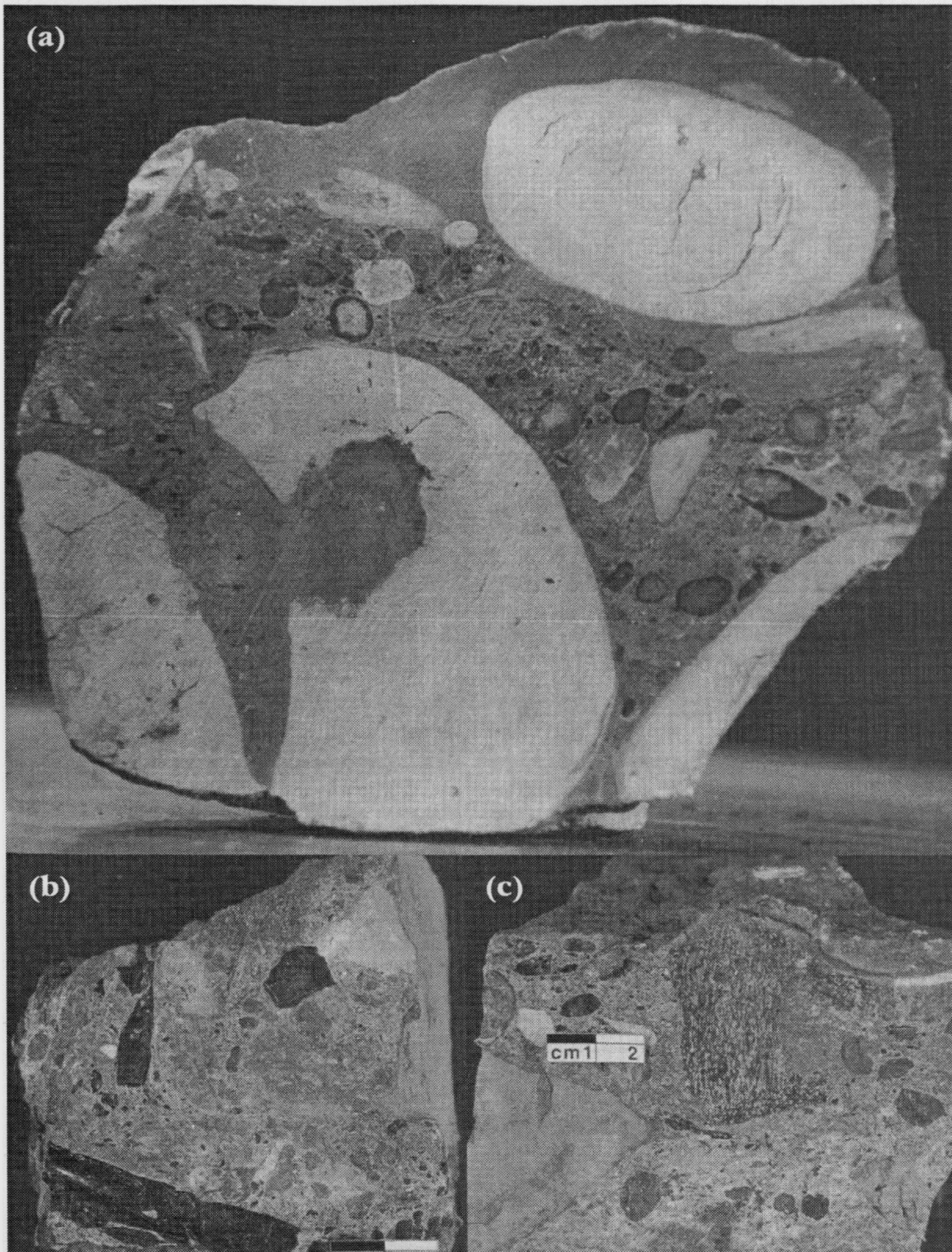

Figure 4.4 Cut sections through two basal 'Rhaetic bone beds', (a–c) from Aust Cliff. In cut section (a), about 15 cm wide, the large rounded objects are clasts of Blue Anchor Formation. The smaller, dark objects between are phosphatic nodules, coprolites and rolled bone fragments. In (b), a surface view, the elongated black objects are probably ribs of marine reptiles, and the squarish element could be part of a limb bone. Smaller black objects are fish scales and teeth, and other lighter pieces are nodules. In (c) there is a vertical cut section of a large bone (top, centre). (Photos courtesy C.N. Trueman.)

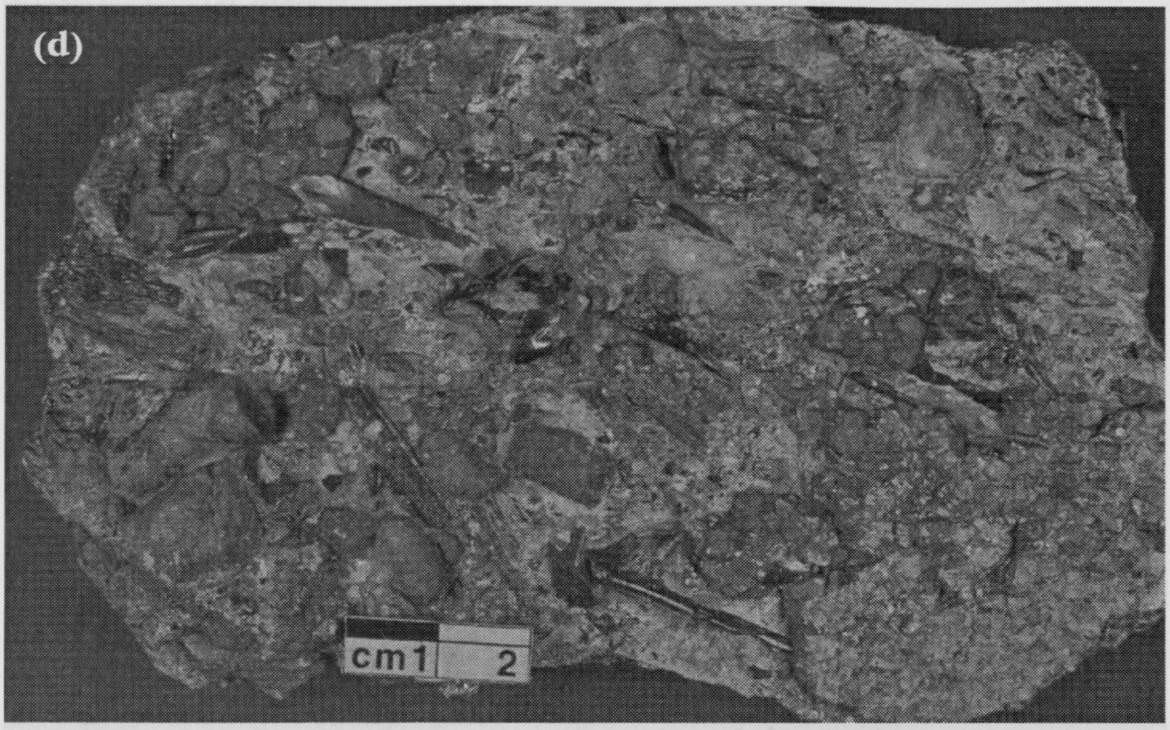

Figure 4.4 *–contd.* (d) Cut section through the basal 'Rhaetic bone beds' from Westbury Garden Cliff. The surface shows numerous well-preserved elongate bones of the small reptile ***Pachystropheus***, showing weak current alignment. Other clasts include coprolites (e.g. immediately above the scale bar), some larger, abraded, bone fragments (far left, middle) and inorganic phosphate nodules. White patches of crystalline pyrite occur in association with the bones; the matrix is 70% disseminated pyrite. (Photo courtesy C.N. Trueman)

Local mapping shows that the two bone beds are of nearly identical age, and the fossil taxa represented in both suggest that the source area for the bone material that was reworked into the Aust deposit was probably similar to that which produced the Westbury Garden Cliff deposit.

The bones and matrix at Aust Cliff contain disseminated euhedral pyrite crystals, and there is abundant phosphate, in the bones and teeth themselves and in numerous phosphatized coprolites and phosphatic nodules. The pyrite and phosphate indicate that the source of the Aust Cliff bone bed materials was a low-energy anoxic environment, since neither mineral could be produced in the high-energy storm beds that are seen at that locality. The physical indicators of transport are confirmed by the geochemistry of the two bone beds (Trueman and Benton, 1997): rare earth elements show that the bones and matrix in the Westbury Garden Cliff bone bed came from the same source, while the Aust Cliff bones came from a source different from their enclosing sediment.

In both cases, bones, spines, teeth, and scales have been swept in by storm activity of some kind. The remains represent aquatic, and presumably marine, vertebrates for the most part (fishes, ichthyosaurs, plesiosaurs, choristoderes), but there are some unequivocal dinosaur bones. Hence, the bone beds indicate a shallow marine setting, confirmed by the associated trace fossils and shelly fossils. Perhaps the transgressing sea swept over the playas and sabkha plains of the Mercia Mudstone Group, engulfing the remains of dinosaurs and other terrestrial fauna, and mixing them with those of fishes and marine reptiles living in the newly expanding sea.

The genesis of the classic bone beds is still debated. Martill (1999) reviewed the five main models for the generation of the basal bone bed:

1. *Mass mortality*: the idea, proposed first by Buckland (1829), that the accumulation of bones is simply the result of a dramatic mortality event, perhaps caused by anoxia or dramatic salinity changes associated with the transgression. There may be some truth in this idea, but physical processes (numbers 2–5, below) must have had a critical role.

2. *Winnowing*: the idea that the accumulation of bones was produced by repeated episodes of erosion of the sea floor, and removal of fine debris (Sykes, 1977). This is probably at least a contributory factor, but it does not explain the presence of terrestrial elements.
3. *Condensation model*: reduced rates of sedimentation would allow bones to make up a greater proportion of the deposit than usual, a model suggested by Richardson (1901) and Wickes (1904). There is no evidence, however, that the bone beds are anything other than short-term accumulations.
4. *Diagenetic concentration*: bones are concentrated by the selective dissolution of aragonitic and calcitic material. Some bone beds contain shells, so this model cannot apply in those cases, but others contain only lithic and phosphatic debris, and the carbonates may have been removed chemically.
5. *Transgressive lag model*: the transgressing Rhaetian sea eroded and picked up clasts from existing sediments, and deposited them later as a lag (MacQuaker, 1994). This model is certainly supported by the presence of lithic clasts from the Blue Anchor Formation in the basal Rhaetic bone beds. However, no likely source bed for the abundant vertebrate bones and coprolites has yet been identified (it may have been completely eroded away).

The Lilstock Formation

The black shales of the upper part of the Westbury Formation are overlain by grey-green and grey marls of the Cotham Member of the Lilstock Formation. At most localities, the Cotham Member marls contain small fossil crustaceans (*Euestheria*), which are comparable to modern forms from lakes in Africa. However, marine conditions evidently persisted, since dinoflagellate cysts occur abundantly in the member in Britain, and other marine biota, including bivalves, are also present (Mayall, 1983).

The environment in southern England was probably an extensive inhospitable hypersaline tidal flat. Such conditions are indicated by a range of sedimentary structures in the Cotham Member sediments. In places, domal stromatolites have been reported (Hamilton, 1961), formed by the growth of cyanobacteria and calcareous sediments, and indicating desiccating saline conditions. Locally, these form the famous landscape Cotham Marble in the Bristol district. Desiccation cracks cut these stromatolites in places. Deformed bedding in this member may reflect disturbance by earthquake activity locally, possibly associated with faulting.

The Langport Member consists mainly of limestones with dark shales, and indicates a renewal of fully marine conditions (Wignall, 2001). In Devon, the Langport Member, formerly known as the 'White Lias', is a clean, micritic limestone up to 8 m thick. The top bed was called the 'Sun Bed' because of supposed desiccation cracks on its upper surface (Hallam, 1960). On the south coast of Devon, the base of the overlying Blue Lias Formation (Lias Group) is marked by a sharp contact between the Sun Bed and an overlying laminated, organic-rich shale, traditionally called the 'Paper Shale'. In Somerset, an additional thin shale unit called the 'Watchet Member', occurs between the White Lias and the Paper Shale, and it may be contemporary with the thicker White Lias of Devon (Wignall, 2001).

Wignall (2001) offered a revised sedimentological account of the Langport Member of the south Devon coast in which he identifies five phases of facies history: the topmost White Lias (Sun Bed) represents a micritic hardground that was lithiifed and bored, and then eroded locally, probably in a shallow sea, to produce a spectacular intraformational conglomerate, which was in turn lithified. The surface was exposed subaerially and fissures and pits were formed. This short-term regression was then followed by a full-scale transgression marked by the base of the Blue Lias.

The Penarth Group sediments document an apparently rapid marine transgression at the base of the Westbury Formation, followed by shallowing and local exposure as hypersaline tidal flats during Cotham Member times, and a further inundation in the Langport Member times. The sea apparently deepened into Jurassic times.

PALAEONTOLOGY

Penarth Group fossils include a range of predominantly marine forms including foraminifera, corals, annelids, gastropods, bivalves, crustaceans, echinoderms, brachiopods, conodonts, and fishes (sharks, chimaeras, bony fishes, coelacanth) (Swift and Martill, 1999), and organic-walled microplankton (dinoflagellate cysts and acritarchs; Warrington, 1981), but also including continental organisms (plants, insects, lungfish and dinosaurs).

Fossil fish remains include abundant isolated teeth, dermal denticles, and fine spines ('ichthyodorulites') of sharks: *Polyacrodus*, *Lissodus*, '*Hybodus*', *Nemacanthus*, *Palaeospinax*, *Synechodus*, and *Vallisia* (Storrs, 1994; Cuny and Benton, 1999). Rare tooth plates of chimaeroids include the genera *Myriacanthus* and *Agkistracanthus* (Storrs, 1994). Bony fishes are represented by teeth, scales, and isolated bones of the actinopterygians *Gyrolepis*, *Birgeria*, *Severnichthys*, a coelacanth, and tooth plates of the lungfish *Ceratodus* (Storrs, 1994). Amphibians were reported, based on massive teeth with labyrinthine infoldings, and heavy jawbones, but these have been found to belong to the bony fish *Severnichthys* (Savage and Large, 1966; Storrs, 1994).

Penarth Group tetrapods (reviewed by Storrs, 1993, 1994, 1999) are represented mostly by isolated teeth, vertebral centra, limb bones, and occasional ribs. Such fossils may be referable to a broad group, or even to a genus, but it is hard to be more precise. Storrs (1999) noted the following fossil marine reptiles from the Penarth Group, primarily from the basal bone bed: ichthyosaurs (isolated teeth and vertebral centra; humerus of *Leptonectes*), plesiosaurs (isolated teeth and vertebrae, paddle elements), placodonts (armour plates of *Psephoderma*), and the choristodere *Pachystropheus rhaeticus* (limb bones and vertebrae), a small, superficially crocodile-like animal. Isolated remains of terrestrial reptiles reported from a number of bone-bed sites include the dinosaurs *Camelotia* (femur, claw, and vertebra) and (?) *Megalosaurus* (a lower jaw), and the phytosaur '*Paleosaurus*' (a tooth). In addition, isolated teeth of mammal-like reptiles and mammals have been noted (the cynodont *Tricuspes* and the haramiyids *Haramiya* and *Hypsiprymnopsis*). These scattered elements of terrestrial animals were presumably washed from landmasses some distance away, and incorporated into the essentially marine bone beds.

PENARTH GROUP SITES

Penarth Group sediments have been described from a large number of sites, especially in the south-west of England and South Wales, but also from occurrences in Gloucestershire, Hereford

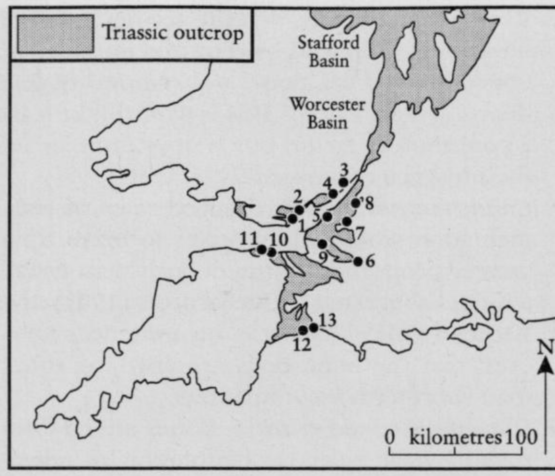

Figure 4.5 Map showing the locations of the 13 Penarth Group GCR sites: (1) Lavernock to Penarth*; (2) Stormy Down; (3) Wainlode Cliff*; (4) Westbury Garden Cliff*; (5) Aust Cliff*; (6) Hapsford Bridge; (7) Barnhill; (8) Wetmoor*; (9) Lulsgate; (10) St Audries Bay*; (11) Blue Anchor Point*; (12) Culverhole Point*; (13) Pinhay Bay. * Denotes that the site also exposes important Triassic red beds.

and Worcester, Warwickshire, Staffordshire, Cheshire, Leicestershire, Nottinghamshire, Lincolnshire, Yorkshire and Cumbria. The group was also identified in Scotland (Morayshire, Hebrides, Arran) and in Northern Ireland, as well as from boreholes in the North Sea, the Irish Sea, the Western Approaches, and in south-east England.

Thirteen GCR sites on the north and south shores of the River Severn and its Estuary, around the Mendips, and on the Dorset coast have been selected (Figure 4.5). More northerly localities do not show additional or better features. The sites include the type Penarth Group sections of Lavernock to Penarth, Stormy Down, and the famous bone-bed sites of Westbury Garden Cliff and Aust, on opposite sides of the Severn. Other sites in South Gloucestershire, north Somerset, and east Devon illustrate the range of sedimentary facies.

THE PENARTH GROUP OF SOUTH WALES

LAVERNOCK TO PENARTH, NEAR CARDIFF, SOUTH GLAMORGAN (ST 175 673–ST 190 702)

Introduction

The coastline between Lavernock Point and

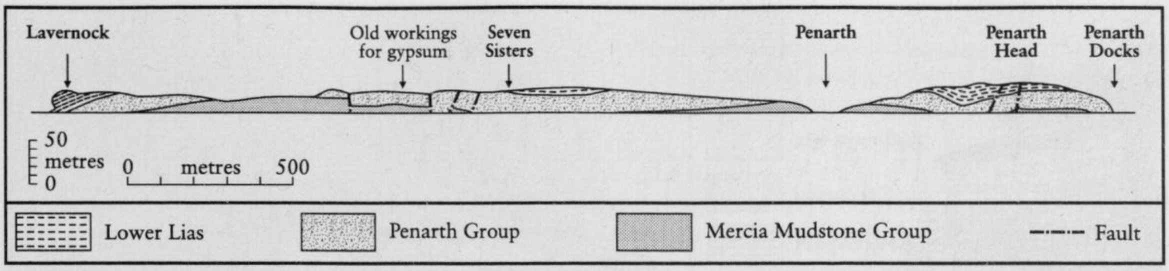

Figure 4.6 Section of the cliffs from Lavernock to Penarth, showing the occurrence of the Mercia Mudstone, Penarth, and Lias groups. (After Woodward, 1888.)

Penarth exposes one of the best sections of Rhaetian sediments in South Wales. The cliffs at Penarth, Lavernock Point and St Mary's Well Bay form the composite type section for the Penarth Group, and its constituents, the Westbury and the Lilstock formations, and hence this is one of the most stratigraphically important localities in the country. This area has also yielded many fossils from its famous bone bed.

The Upper Triassic sediments of South Wales have been studied for many years, the first brief description being by De La Beche (1846), and the first fuller account by Etheridge (1872). Since then, many accounts of the geology and palaeontology of this region of South Wales have been produced, for example Howard (1894), Strahan and Cantrill (1902), Richardson (1905), Ivimey-Cook (1974), Tucker (1977, 1978), Waters and Lawrence (1987), Hodges (1994), and Warrington and Ivimey-Cook (1995). Detailed studies of the isotopic composition of many of the lithologies have provided insights into the palaeoenvironments and geochemistry of the sediments (Leslie *et al.*, 1992). The fossils have been recorded by Etheridge (1872), Woodward (1888), Storrie (1883, 1895), Orbell (1973), Storrs (1993, 1994), and Dineley and Metcalf (1999), list fishes from this site.

Description

Sedimentology

The sea cliffs between Lavernock and Penarth expose some 16 m of sediments at the top of the Mercia Mudstone Group (Tucker, 1978; Warrington *et al.*, 1980; Waters and Lawrence, 1987), together with the Westbury and Lilstock formations of the Penarth Group and the Jurassic Lower Lias (Figure 4.6). The beds are folded in low amplitude folds with some faulting (Figures 4.6 and 4.7a). The lowest Mercia Mudstone Group beds seen consist largely of reddish or brownish, hard, silty mudstones with sporadic greenish patches and beds, some of which are laterally continuous, although it has not been possible to use them for local or regional correlation. The mudstones are often calcareous and dolomitic and there is little evidence of sedimentary structures. Units range in thickness from 0.5 to 3.0 m, with blocky mudstones at the base, becoming more fissile towards the top (Ivimey-Cook, 1974; Waters and Lawrence, 1987).

The Mercia Mudstone Group sediments in this area characteristically have more calcite and dolomite than comparable localities in south-western England. This has been attributed to the close proximity of an abundant source rock, the Carboniferous Limestone (Alkattan, 1976). Sulphate minerals are also common, for example gypsum and alabaster (Tucker, 1978). Several layers of gypsum nodules, each with an average thickness of 0.5 m, have been recorded within the red-brown Mercia Mudstone Group near Penarth (Tucker, 1978; Waters and Lawrence, 1987). Near Penarth, the gypsum nodules were once quarried for 'Penarth alabaster' (Ivimey-Cook, 1974).

The overlying Blue Anchor Formation follows the red mudstones above a disconformity that is characterized by a change in colour of the sediments from red to green and by the appearance of well-developed bedding. At Lavernock Point the junction is further highlighted by a green mudstone that contains abundant gypsum nodules (Waters and Lawrence, 1987).

The Blue Anchor Formation is best exposed to the north of Lavernock Point (ST 187 682; Figures 4.7a and 4.8), and this section is characteristic of localities in the area. The sediments

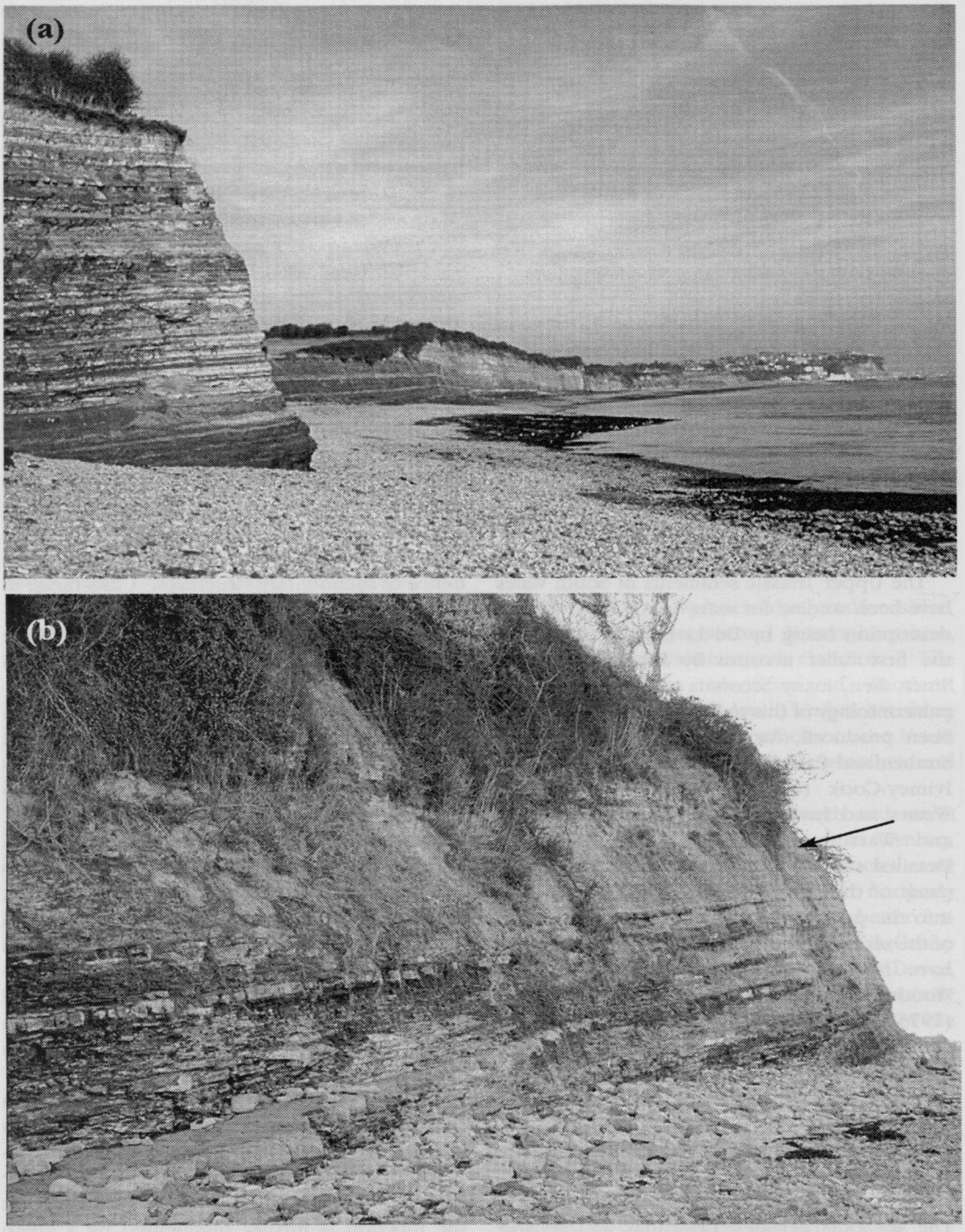

Figure 4.7 The Penarth Group, and underlying Mercia Mudstone Group, at Lavernock Point. (a) Overview of the cliffs and foreshore. The nearest face shows the Blue Anchor Formation of the Mercia Mudstone Group underlain by typical 'red beds' of the same group exposed in the core of a low anticline in the middle distance. To the north of this structure, the Penarth Group and lower beds of the overlying Lias Group occur in a shallow syncline. The town of Penarth is in the background to the right. (B) Cyclic units of sandstones, silty grey limestones and dark grey shales of the Westbury Formation, overlain by paler beds of the Lilstock Formation (arrowed). (Photos: Andrew Swift.)

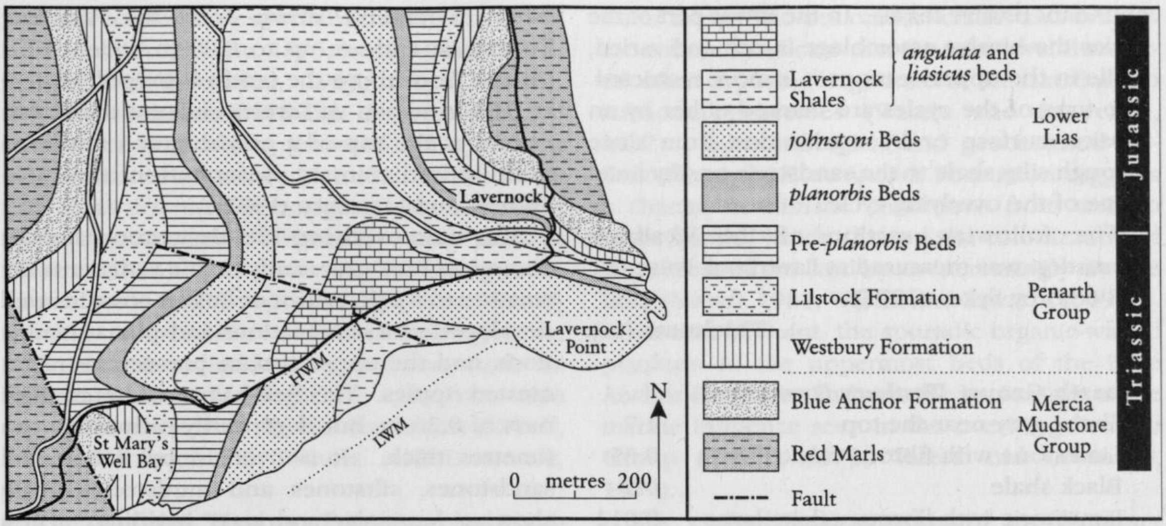

Figure 4.8 Geological map of the Lavernock–St Mary's Well Bay district, showing the Mercia Mudstone Group, Penarth Group, and Lower Lias sediments. (After Trueman, 1920.)

comprise fine-grained mudstones with some beds of limestone and dolomite, especially near the top of the formation, and thin beds of intraformational breccia (Waters and Lawrence, 1987). The mudstones are often bedded; some silt-laminated mudstones display well-developed desiccation cracks, and may be blocky, fissile or massive. The massive mudstones often have a conchoidal fracture caused by a high proportion of calcite and/or dolomite cement. The colour of the lithologies changes through the section, from dark green and greenish-yellow at the base, though a series of pinkish-red and green beds (the 'pink band' of Strahan and Cantrill, 1902), approximately 7 m from the base of the formation, to greyish-green and dark grey units at the top (Waters and Lawrence, 1987).

Gypsum is common in six units through the Mercia Mudstone Group, and takes the form of large nodules (0.2 m in diameter) and thin veins of satin spar. However, the nodules are rarely seen in outcrop: after dissolution, cavities remain that have occasionally been infilled with calcite.

The succeeding Penarth Group comprises the dark grey argillaceous facies of the Westbury Formation, followed by the dominantly argillaceous Cotham Member, which is overlain by porcellanous limestone and mudstones of the Langport Member (Waters and Lawrence, 1987). The junction between the Blue Anchor Formation and the Westbury Formation is an erosion surface. The top bed of the Blue Anchor Formation is seen on the foreshore slightly to the north of Lavernock Point (ST 188 681); here the eroded upper surface displays well-developed U-shaped burrows and cracks that are often infilled with mudstone, quartz grains and sporadic fish remains (Mayall, 1981; Waters and Lawrence, 1987).

At Lavernock Point the Westbury Formation (Figure 4.7b) has a thickness of *c.* 6.6 m (Warrington and Ivimey-Cook, 1995). A regionally important but laterally impersistent bone-bearing facies is seen within the basal metre of the formation. The basal beds at Lavernock consist of limestones and shales (Sykes, 1977) with abundant *Liostrea bristovi*, the presence of which has earned these beds the informal name, the '*bristovi* limestones' (Ivimey-Cook, 1974; Waters and Lawrence, 1987). These are overlain by a bone bed, the 'fish bed' of Storrie (1883), although Sykes (1977) also records the presence of vertebrate fossils in the sediments immediately overlying the Blue Anchor Formation contact (see below). The bone bed is composed of a coarse-grained, sandy conglomerate that often infills scours or channels in the top of the '*bristovi* limestone' (Storrie, 1883).

The Westbury Formation includes six sedimentary cycles (Ivimey-Cook, 1974; Waters and Lawrence, 1987). The cycles commence with fine-grained sandstone or silty limestone and fine upwards into shales with horizons with abundant bivalve fossils. In the lower part of the cycles the bivalve assemblage is rich and varied, while in the upper sections it is more restricted. The tops of the cycles are marked either by an erosion surface or by a transition from shale through silty shale to the sandstone or silty limestone of the overlying cycle.

The following section of the Westbury Formation was measured at Lavernock Point (ST 188 682) by Sykes (1977):

	Thickness (m)
Penarth Group: *Westbury Formation*:	
Shale, grey near the top	1.7
Limestone with fibrous calcite layers	0.05
Black shale	0.5
Limestone with fibrous calcite layer	0.012
Black shale	*c.* 1.2
Limestone	0.1
Black shale	1.3
Bone bed with shaly partings:	0.165
(e) black shale with impure limestone at the top	0.025
(d) black shale with light scattered bone bed and trace bone bed in patches	0.02
(c) sandy limestone, upper part contains coarse and fine quartz, vertebrate fossils and coprolites. Lower part is compact, with a shelly fauna and rare vertebrate fossils	0.065
(b) dark grey, impure limestone	0.015
(a) cemented and pyritic mudstone, with scattered coarse grains and vertebrate fossils	0.04
Black shale	0.075
Limestone, arenaceous, with isolated quartz grains, vertebrate fossils and bivalves	up to 0.025
Black shale, with scattered patches of trace bone bed	1.0

The Lilstock Formation (Penarth Group) is best seen in the cliffs at Lavernock Point and at nearby St. Mary's Well Bay; this formation is also exposed at Penarth, but is not easily accessible there. At Lavernock, the Cotham Member is dominated by pale grey, calcareous and silty mudstones; the lower beds of the member often contain well-developed wavy and lenticular beds, many of which exhibit ripples (Ivimey-Cook, 1974). The member is divided into two by a desiccation horizon. The cracks are often seen to extend down into the Westbury Formation and are up to 0.08 m wide. When viewed from above the cracks form polygons up to 0.90 m across. At Lavernock Point this feature occurs at the top of a greyish-green mudstone with synsedimentary deformation structures (Waters and Lawrence, 1987).

The unit overlying the desiccation horizon comprises blue-grey sandy oolitic sediments that weather to a pale brown or buff; it contains well-developed cross-laminations and planar laminations, and the upper surface preserves straight-crested ripples. This bed has a maximum thickness of 0.26 m, but is generally only a few centimetres thick. It is overlain by fine-grained sandstones, siltstones and mudstones, many showing lenticular and wavy bedding. These sediments grade upwards into micritic limestones (Waters and Lawrence, 1987).

The boundary with the overlying Langport Member is regionally variable, and includes examples of gradational and sharp contacts. The basal part of the Langport Member consists of thin, pale greenish-grey, porcellaneous limestones interbedded with shaly mudstones, and some coarser-grained, shell-rich limestones (Swift, 1995). This unit is no more than 0.35 m thick, and is best seen as a ridge on the foreshore. These beds were formerly called the 'Langport Beds' or the 'White Lias' by, for example, Richardson (1905, 1911).

The remainder of the Langport Member comprises about 2.2 m of calcareous mudstones with laterally impersistent developments of fine sandstone, siltstone and shelly limestone (Swift, 1995), which had been correlated with similar beds in the Watchet area that are now included in the Lias Group (Whittaker, 1978). These beds display a range of sedimentary structures and lithological textures, including planar bedding, cross-laminations, lenticular beds, massive blocky sediments, nodules, and *Chondrites* burrows (Waters and Lawrence, 1987).

Palaeontology

The Blue Anchor Formation has yielded several taxa, including trace fossils thought to represent the remains of burrows. Sporadic vertebrate fossils, including fishes (for example, *Acrodus*, *Birgeria*, *Ceratodus* (rare), *Dalatias*, *Hybodus*, *Lissodus*, *Saurichthys*, and *Nemacanthus monilifer*), reptiles and possibly amphibians have been recovered from some of the intraformational breccia units, especially towards the top of the formation (Storrie, 1895; Ivimey-Cook, 1974; Waters and Lawrence, 1987; Storrs, 1994). Plesiosaur remains were also discovered at the Penarth cement works (Howard, 1894), and a mammalian tooth crown identified by Etheridge (1872) as *Microlestes antiquus* was recovered from the Westbury Formation near Penarth (Storrs, 1993). Microfossils, including miospores such as *Gliscopollis meyeriana*, *Ricciisporites tuberculatus* and *Vesicaspora fuscus*, and organic-walled microplankton such as acritarchs and dinoflagellate cysts, are also known from the Blue Anchor Formation (Orbell, 1973; Warrington in Waters and Lawrence, 1987).

The overlying Westbury Formation has yielded many macrofossils characteristic of marine environments. Invertebrate taxa from the Westbury Formation include bivalves, foraminifera, ostracods, the inarticulate brachiopod *Orbiculoidea*, echinoid fragments, ophiuroids and cirripedes, all indicative of shallow marine conditions (Waters and Lawrence, 1987). At the base of the Westbury Formation, the presence of the marine bivalve *Liostrea bristovi* may indicate a correlation with the Williton Member of the Blue Anchor Formation in Somerset (Mayall, 1981; Waters and Lawrence, 1987). Palynomorphs are also present (Orbell, 1973; Warrington in Waters and Lawrence, 1987), and include terrestrial miospores and marine organic-walled plankton dominated by *Rhaetogonyaulax rhaetica*.

The Lilstock Formation contains several faunal assemblages, each associated with distinct palaeoenvironmental conditions. Bivalves, such as *Dimyopsis*, *Liostrea* and *Modiolus* and, rarely, *Plicatula* and *Tutcheria*, are known from these lithologies. The Langport Member has yielded a few miospores, as well as foraminifera and ostracods. Many of the taxa seen in the upper parts of this member are species more commonly associated with the Lias Group (Waters and Lawrence, 1987; Swift, 1995).

Interpretation

The red Mercia Mudstone Group sediments are characteristic of deposition in and around a large hypersaline water body in open connection with the sea (see Chapter 3). The overlying Blue Anchor Formation here indicates deposition in marginal environments close to a saline water body. The desiccation cracks and evaporitic minerals indicate that the lake level fluctuated, often exposing large areas of the lake floor to subaerial processes (Waters and Lawrence, 1987). Palaeontological and geochemical evidence from the Blue Anchor Formation suggests a change in climatic conditions from arid to more humid, which allowed the colonization of large areas of the land by an increasingly diverse flora (Mayall, 1981; Waters and Lawrence, 1987). At Lavernock Point, the sporadic organic-walled plankton in the uppermost beds of the Blue Anchor Formation indicate the beginnings of the marine influence seen in the overlying Penarth Group (Orbell, 1973; Waters and Lawrence, 1987).

The cyclical sedimentation of the Westbury Formation has been interpreted as an alternation of occasional periods of higher-energy conditions (for example turbulence in the water column) producing the coarser-grained beds, followed by a return to the low-energy regime typical of the Westbury Formation (Ivimey-Cook, 1974), characteristic of open water marine or marginal marine conditions (Hamilton and Whittaker, 1977; Whittaker and Green, 1983; MacQuaker *et al.*, 1985; MacQuaker, 1994). The '*bristovi* limestones' at the base of the Westbury Formation were deposited under relatively short-lived, but widespread semi-marine conditions (Waters and Lawrence, 1987). The bone bed was deposited as a transgressive lag, probably on a migrating shoreline (MacQuaker, 1994).

The Cotham Member includes restricted marine beds near the base, followed by sediments indicative of freshwater lagoonal conditions (Mayall, 1983). The lenticular beds, ripples, and desiccation cracks show that the lagoon waters were generally shallow, and that the lagoons periodically dried up.

The overlying porcellanous limestones, shelly limestones, thin sandstones and siltstones of the Langport Member were deposited under lagoonal and marine conditions. The sediments and fossils of the lower part of the Langport Member indicate marine flooding of the Cotham Member lagoons: the fauna is characteristic of shallow sub-tidal environments and the thin shelly limestones were deposited under storm conditions (Whittaker and Green, 1983; Waters and Lawrence, 1987; Swift, 1995). The overlying pale grey calcareous siltstones have been interpreted as offshore marine deposits, probably deposited in a shallow sea, with coarser sandstones and limestones representing episodic storm events.

The changing palynological diversity within the Penarth Group reflects changing palaeoenvironmental conditions. Generally, species diversity increases upwards through the Westbury Formation and the Cotham Member, but declines in the younger beds. This pattern reflects the colonization by plants of large areas of land during the deposition of the Westbury Formation beds, and the subsequent development of a more restricted, low-diversity assemblage associated with inundation of land during the Late Triassic marine transgression (Waters and Lawrence, 1987).

Conclusions

The sea cliffs between Lavernock Point and Penarth expose an excellent section of Upper Triassic rocks comprising the Mercia Mudstone Group (including the Blue Anchor Formation) and the Penarth Group (the Westbury Formation and the Cotham and Langport Members of the Lilstock Formation). This sequence reflects the transition from a terrestrial, arid, playa environment to fully marine conditions following the Late Triassic transgression. Along with St Mary's Well Bay, Penarth and Lavernock Point form the composite type locality for the Rhaetian Penarth Group (Warrington *et al.*, 1980), making this one of the most important stratigraphical sites in the country.

STORMY DOWN, NEAR BRIDGEND, MID GLAMORGAN (SS 844 809–SS 851 810)

Introduction

The Stormy Down road cutting and nearby quarries expose sandstones with subordinate marls belonging to the upper Mercia Mudstone and the Penarth groups. Sandstones in the Penarth Group represent, unusually, a beach deposit. Many fossil taxa have been recovered from this locality, for example invertebrates such as *Rhaetavicula contorta*, and vertebrates, including remains of a megalosaurid dinosaur and several fishes. Stormy Down is important for the interpretation of the Late Triassic palaeogeography of South Wales: it is thought that this locality lay between an island and the mainland.

Stormy Down has been studied for many years, and descriptions of the geology include Tawney (1866), Bristow (1867), H. B. Woodward (1893), Richardson (1905), Francis (1959), Ivimey-Cook (1974), and Wilson *et al.* (1990). Accounts of the invertebrate and vertebrate faunas have also been published by Newton (1899) and Francis (1959), and Dineley and Metcalfe (1999) list the fossil fishes from this site.

Description

The Stormy Down exposures occur in a cutting for the M4 motorway (SS 845 810), in nearby disused quarries, and in a quarry at the Stormy Down Cement Works (SS 852 816).

Sedimentology

The Stormy Down motorway cutting exposes an excellent section of Westbury Formation sediments that are unusual in being dominated by pale yellow, white, or brown, coarse-grained sandstones with thin lenses of conglomerate and dark shales (Wilson *et al.*, 1990). Broadly, the formation consists of lower and upper sandstone units and intervening black shales. The sedimentary log is adapted from Francis (1959), Sykes (1977), and Wilson *et al.* (1990):

	Thickness (m)
Penarth Group; *Lilstock Formation:*	
Langport Member:	
Mottled blue-green, purple-red and buff calcareous mud-stone	up to 6.0
Penarth Group; *Westbury Formation*:	
Upper Sandstone ('Quarella Stone'): sandstone, brown, fine-grained, flaggy, with clay partings and vertebrate fossils	2.4
Black Shales:	
Shales, dark green, rubbly, with dendritic markings and wood	0.90
Shales, brown, with nodular limestone	0.25
Shales, dark green, with thin nodular limestones	0.30
Conglomerate with abundant vertebrate material	0.1
'Lower Sandstone': sandstone, hard, massive, white and yellow, with vertebrate fossils	5.28
Mercia Mudstone Group	

The basal bed of the Penarth Group rests on a sharp and erosional contact with the upper Mercia Mudstone Group, marked in places by irregular hollows (Wilson *et al.*, 1990). The 'Lower Sandstone' is typically coarse-grained, white, yellowish or buff in colour, and contains thin lenses of quartz pebbles, pieces of wood, and vertebrate fossils. The lower beds are often quite friable, while those towards the top of the unit are harder and more compact (Francis, 1959). Sykes (1977) recorded galena in this sandstone. In places, the sandstones show well-developed sedimentary structures, including cross-bedding and rippled surfaces. At Stormy Down this unit is between 5 and 6 m thick, though it thins rapidly to the east (Francis, 1959; Wilson *et al.*, 1990).

Resting on an erosion surface at the top of the 'Lower Sandstone' is a thin conglomerate, which forms the basal bed of the 'Black Shales' (Francis, 1959). This conglomerate crops out over a wide area, and contains quartz clasts as well as pebbles of jasper and chert (Wilson *et al.*, 1990). Vertebrate fossils are especially common in this bed, although, generally, they are poorly preserved. The lithology resembles the typical Westbury Formation sediments, being fine-grained and generally having a dark grey or greenish colour. Fossil-bearing nodules associated with a pebbly limestone are common, especially towards the middle of the unit (Francis, 1959). Towards the top of this unit thin beds of sandstone and siltstone appear, forming a passage into the overlying 'Upper Sandstone' (Wilson *et al.*, 1990).

The 'Upper Sandstone', also known as the 'Quarella Stone', includes several distinctive lithologies. At the base, it consists of pale creamy-brown or brown, fine- to medium-grained sandstones, interbedded with thin, brown, blue, and green, mica-rich siltstones and shales (Francis, 1959). In places the sandstones contain flasers. This facies is overlain by medium-grained, light grey, yellow, and pale brown, planar and hummocky cross-laminated, calcareous sandstones. In places there is evidence of erosion (scours) and soft-sediment deformation (flame structures). Some of the more massive beds rest on erosion surfaces, and have thin, coarse-grained lag deposits that fine upwards into laminated sandstones and grey-green micaceous muds and silts. The top of the 'Upper Sandstone' consists of massive sandstones that may contain interbedded sandstones and shales and thin shell-rich limestones. These beds are generally greenish-yellow or pale brown in colour, commonly with a mottled appearance (Francis, 1959; Wilson *et al.*, 1990).

The overlying Cotham Member (Lilstock Formation) is dominated by mottled marls with thin lenses of fine sandstone and silt, nodular dolomite, and micritic and sandy limestones. The argillaceous sediments are mottled, mainly bluish-green, purple-red, and buff; the sandstones are green and red (Ivimey-Cook, 1974; Wilson *et al.*, 1990). The lower beds of the Cotham Member are pale cream in colour and cut by carbonate veins, some of which extend into the underlying sandstones. The upper beds are green, with minor patches of reddish sediment. At the top of the member is a thin limestone, which may be equivalent to the Cotham Marble (Strahan and Cantrill, 1904; Francis, 1959).

In the nearby Stormy Down Lime and Cement Works, a section of Upper Triassic sediments includes approximately 0.3 m of light-coloured limestones thought to belong to the Langport Member (formerly the 'White Lias') of the Lilstock Formation. Below these limestones are approximately 0.5 m of interbedded grey limestones and dark brownish-grey shales, resting on the '*Rhaetavicula contorta*' shales. These overlie approximately 2.7 m of greenish marls (Bristow, 1867; H. B. Woodward, 1893; Ivimey-Cook, 1974). Francis (1959, p. 164) recorded a fault in the quarry, responsible for the deformation of the 'Upper Sandstone'. The fault shows little vertical displacement, although some horizontal movement is suggested by the presence of folds. Small-scale thrusts were also recorded.

Palaeontology

Fossils are common throughout the Penarth Group beds. The 'Lower Sandstone' of the Westbury Formation contains abundant fragments of fossilized wood, as well as fish remains. Fish fossils are also found in the 'Black Shales' where they are preserved in limestone nodules (Wilson *et al.*, 1990). Poorly preserved bone has been recovered from the conglomeratic bed at the base of the 'Black Shales' (Ivimey-Cook, 1974). The fish teeth have been identified as ?*Saurichthys* sp., and the scale fragments as *Gyrolepis* sp. (Francis, 1959).

Invertebrates are common throughout the 'Lower' and 'Upper' sandstones, as well as in the intervening shales, especially in the flaggy sandstones at the base of the 'Upper Sandstone' (Francis, 1959). One of the most common fossils (Wilson *et al.*, 1990) is the bivalve *Rhaetavicula contorta*, and other taxa (Ivimey-Cook, 1974) include the gastropod *'Natica' oppelii*.

Rare dinosaurian remains have been described from Stormy Down, including a partial jaw attributed to the theropod *Megalosaurus*, although the assignment is uncertain (Benton and Spencer, 1995). This jaw was made the type specimen of *Zanclodon cambrensis* by Newton (1899).

Interpretation

The Upper Triassic sediments at Stormy Down record a range of palaeoenvironments, some of which differ from those represented at many other Penarth Group localities. The Mercia Mudstone Group offers evidence for dominantly terrestrial conditions, characterized by supra- and inter-tidal and playa lakes and sabkha flats (Wilson *et al.*, 1990).

The Westbury Formation arenaceous and argillaceous facies mark a change to littoral and marine conditions. The base of the 'Lower Sandstone' rests on an erosion surface produced during a period of regression; the overlying sediments were deposited under shallow marine conditions during a phase of transgression (Wilson *et al.*, 1990). Continued transgression is represented by the coarse-grained lag deposit that occurs immediately below the argillaceous lithologies. This conglomeratic deposit accumulated in a littoral environment, probably as a strandline beach deposit (Wilson *et al.*, 1990). The overlying 'Black Shales' are further evidence of continued transgression, and represent deeper-water conditions (Hamilton and Whittaker, 1977; Whittaker and Green, 1983), more typical of the Westbury Formation in Somerset and Gloucestershire.

The top of the Westbury Formation sees a change to sandstone deposition, interpreted as a progradational facies, and characterized by a coarsening-upwards sequence that consists of interbedded sandstones and shales; many of the massive sandstone beds contain coarse-grained lags produced during storms. The top of the progradational sequence comprises more massive sandstones with interbedded coquinas (Wilson *et al.*, 1990).

The overlying Lilstock Formation lithologies are indicative of a return to terrestrial conditions after a period of regression. Nodular dolomites in the 'Upper Sandstone' in the Bridgend area may represent pedogenic alteration (Wilson *et al.*, 1990).

Conclusions

The Upper Triassic strata in the quarries and road cuttings around Stormy Down near Bridgend, show unusual features for the Penarth Group. Unlike the marine black mudstone–limestone successions at the majority of Westbury Formation localities in south-west Britain, the Stormy Down sites show sandstones that indicate shallow marine and littoral deposition. The coastal nature of the site palaeogeographically (Figure 4.3), is indicated by the fossils, which include marine forms, as well as a megalosaurid dinosaur, rare in the Rhaetian anywhere in Europe.

THE PENARTH GROUP OF GLOUCESTERSHIRE, AVON AND NORTH SOMERSET

WAINLODE CLIFF, GLOUCESTERSHIRE (SO 845 257)

Introduction

Wainlode Cliff exposes a good section through uppermost Triassic rocks, and is an important fossil locality. The rocks exposed include the Mercia Mudstone Group and the overlying Penarth Group. Wainlode Cliff is the type locality for the crustacean *Euestheria minuta* var. *brodieana* (Jones, 1863), and is historically important for the evidence this fossil provides about the relative age of the Penarth Group.

The Wainlode Cliff section has been investigated by geologists since at least the early years of the 19th century. References include Strickland (1841), Brodie (1845, 1858), Wright (1860), Etheridge (1865), Richardson (1903a,b, 1947), Reynolds and Vaughan (1904), and Sykes (1977).

Description

The Wainlode Cliff section is on the east bank of the River Severn, near the village of Norton, between Tewkesbury and Gloucester. The section is good, although the beds towards the top of the cliff are virtually inaccessible (Swift, 1995).

Sedimentology

Wainlode Cliff exposes a sequence of Upper Triassic sediments, including the Twyning Mudstone and Blue Anchor formations of the Mercia Mudstone Group, the Westbury and Lilstock formations of the Penarth Group, and the Lower Lias at the top of the section (Figure 4.9). Several accounts have been published detailing the sedimentary sequence. The following is modified from Richardson (1903a, table 1) and Sykes (1977, pp. 205–6):

	Thickness (m)
Lias	
Hard blue limestone	0.10
Penarth Group	
Lilstock Formation ('Upper Rhaetic' of Richardson, 1903a):	
Shales, brown and grey, finely laminated, with a discontinuous limestone at the base	0.38
'Insect Limestone': hard, dark grey and blue	0.13
Shales, blue and brown, laminated, weathering to marly clay	1.57
'*Estheria* Bed': hard, yellow, nodular limestone, dendritic markings, irregular fracture	0.15
Shales, pale greenish-yellow, coarsely laminated, marly	1.83
Westbury Formation ('Lower Rhaetic' of Richardson, 1903a):	
Shales and limestone:	
(a) Shales, black, coarsely laminated, slightly calcareous	0.91
(b) Limestone, very hard, grey, slightly pyritic; an irregular but continuous band	0.03
Shales, black, imperfectly laminated	0.25
Pecten limestone, grey to black, with fibrous layers of limestone, shelly	0.025
Shale, black and fissile, with bivalves	1.5
Sandstone, discontinuous, pyritic	0.03

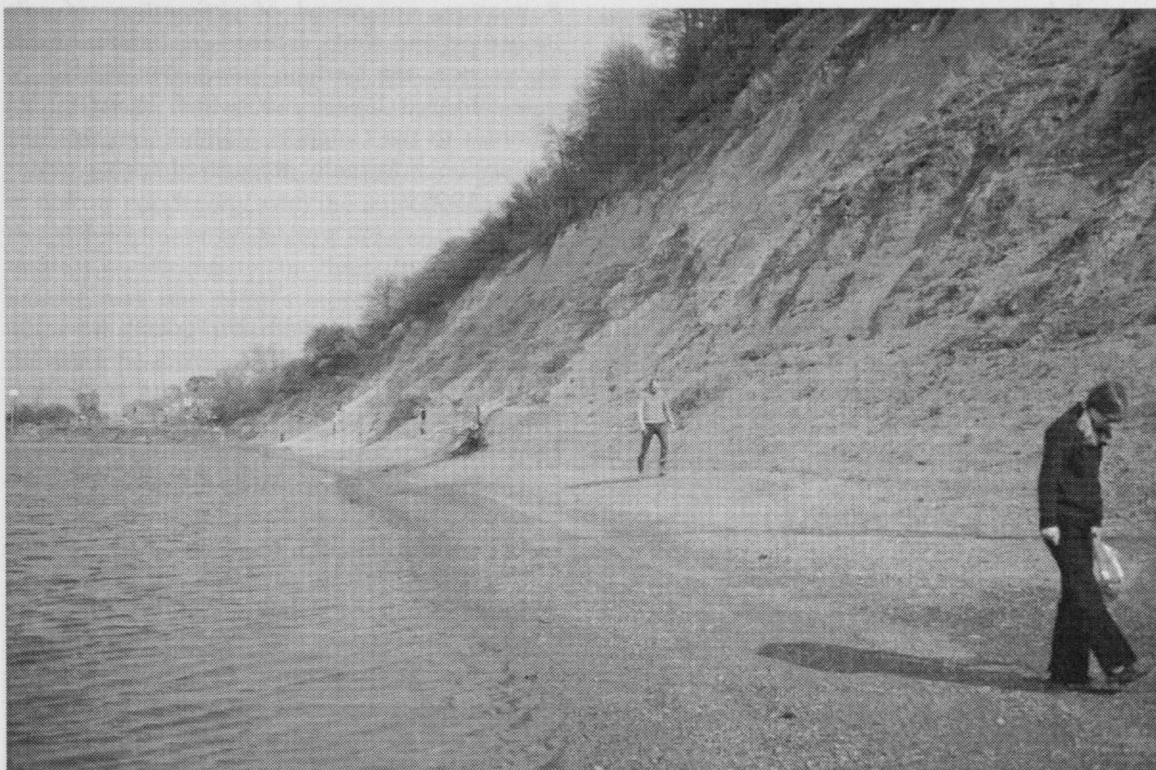

Figure 4.9 The Penarth Group in Wainlode Cliff, looking upstream (northwards). (Photo: K. A. Kermack.)

Shales, black, clayey, laminated	0.15
Sandstone, micaceous, pyritic, in one or two seams	0.03
Shales, black, firm, coarsely laminated	0.30
Interbedded sandstone and clay:	
(a) sandstone, hard, calcareous, micaceous, pyritic	0.03
(b) clayey parting, selenitic, variable	0.03
(c) sandstone, hard, calcareous, micaceous, pyritic	0.01
Shale, black and fissile, with some thin, calcareous siltstone lenses that have sporadic minute fossils	0.35
Sandstone and siltstone, calcareous, divided into six units:	0.17
(a) black shales with thin calcareous sandstone	
(b) fine, calcareous, pyritic sandstone with some medium sandstone concentrations associated with bony fossils	
(c) fine, calcareous, sandstone and siltstone with scattered fine bone remains	
(d) fine, calcareous, micaceous, light-grey sandstone, pyritic in part	
(e) fine, calcareous, light grey sandstone with much pyrite. Some small vertebrate fossils and occasional larger specimens and coprolites	
(f) light grey silt, calcareous, micaceous and unfossiliferous	
Shale, black and fissile, with occasional silts	0.5
Mudstone, black, poorly bedded, with some clay and some silt layers	0.1
Mercia Mudstone Group	
Blue Anchor Formation ('Upper Keuper' of Richardson, 1903a):	
Light greenish-grey marls, weathering bluish-grey. Conspicuous green layer at the top	7.00
Twyning Mudstone Formation (former 'undifferentiated red mudstone')	
Red mudstones; variegated red marls,with zones of grey and greenish-grey marl; angular and conchiodal fractures	22.86

The Twyning Mudstone Formation at the base of the cliff comprises mainly red clays and marls, with patches of grey, green, and blue sediment. Gypsum is occasionally present in these beds (Richardson, 1903a). Overlying these red beds are the paler greenish-grey, fine-grained sediments of the Blue Anchor Formation. Although poorly consolidated, argillaceous lithologies dominate, a band of hard, yellowish or white marl is seen in this formation close to the boundary with the Penarth Group (Richardson, 1903a).

Most of the Westbury Formation comprises dark shales with thin sandstones. Above the base of the formation is the 'bone bed'; an indurated calcareous and pyritic sandstone with abundant vertebrate remains, often occurring as three or four discrete beds separated by clay units. Although well developed, the bone-bearing facies frequently merges laterally with a thick (0.3 m) sandy, micaceous and non-calcareous sandstone that does not contain any fossils. The bone bed is best seen towards the north-east end of the exposure (Richardson, 1903a,b). One, and occasionally two, prominent grey sandstone beds occur some 0.2 to 0.3 m above the bone bed, and are associated with minerals such as barite and selenite (Richardson, 1903a).

Towards the top of the cliff, the Lilstock Formation, composed of alternations of pale limestone and shale, is exposed. At the top of the section, the Cotham Member is overlain by pale-coloured limestones, which show certain affinities to the Langport Member, but this unit has not been formally recognized at this locality (Swift, 1995).

Palaeontology

Many of the horizons in the Penarth Group at Wainlode Cliff have yielded remains of invertebrates and vertebrates, and the site is the type locality (Brodie, 1845, 1858; Jones, 1863) for the branchiopod crustacean *Euestheria minuta* var. *brodieana*. Vertebrate finds include fishes, for example *Gyrolepis*, *Hybodus*, and *Acrodus* (see Dineley and Metcalfe, 1999). Invertebrates are also present, often in large numbers, and include species of the bivalves *Protocardium*, *Ostrea*, and *Pecten*, all from the Westbury Formation. The fauna from the Cotham Member is significantly different, and includes insects, the crustacean *Euestheria minuta* var. *brodieana*, ostracods such as *Darwinula liassica*, bivalves, and plant remains (Richardson, 1903a). The Cotham Member at a neighbouring locality has yielded a marine microflora (Barclay *et al.*, 1997, p. 72).

The record of *Euestheria minuta* var. *brodieana* is historically important, since the taxon was named in the first report of this characteristic Rhaetian fossil from the Penarth Group (Jones, 1863), hence confirming for the first time direct equivalence with the Rhät of Germany, from which *Euestheria minuta* had already been described, in 1832. The variety *brodieana* was established to take account of the fact that the British form was smaller and had a finer network pattern on its outer surface, but is otherwise identical to the German form (Boomer *et al.*, 1999).

Interpretation

As with all late Triassic exposures in south-west Britain, the section at Wainlode Cliff shows the palaeoenvironmental change from terrestrial to marine conditions associated with the Late Triassic marine transgression. The oldest beds, the Twyning Mudstone Formation, record a dominantly terrestrial environment characterized by low-lying, supratidal plains with shallow hypersaline lakes. The overlying Blue Anchor Formation is marked by a change in colour, produced by a change in the geochemical environment. These sediments are also terrestrial in origin, although they show evidence of an increasing marine influence.

The Westbury Formation marks the beginning of marine conditions, with the transgression and the development of shallow seas and marginal marine conditions. The 'bone bed', as elsewhere, may represent a storm-driven process, with winnowing of sediment from among accumulated bones associated with the transgression. Succeeding beds in the Westbury Formation are characteristic of low-energy conditions, probably associated with shallow seas. The overlying Cotham Member of the Lilstock Formation includes sediments characteristic of marine and terrestrial environments with shallow, probably marine, lagoons.

Conclusions

Wainlode Cliff exposes a sequence of sedimentary rocks that range in age from Late Triassic to Early Jurassic. The sediments record a change in environmental conditions from terrestrial with hypersaline lakes (the Mercia Mudstone Group), through marine transgressive and shallow marine (Westbury Formation) and lagoonal–terrestrial (Cotham Member), to more fully marine conditions associated with the start of the Jurassic Period. It has historic importance, having been studied since at least 1841, and having provided the first evidence, from specimens of the crustacean *Euestheria minuta* var. *brodieana*, of direct correlation with the German Rhät.

WESTBURY GARDEN CLIFF, GLOUCESTERSHIRE (SO 719 129)

Introduction

Westbury Garden Cliff (simply 'Garden Cliff' in the GCR Unit records) exposes the Mercia Mudstone Group, Penarth, and Lias groups. This site is especially important for the Penarth Group bone bed that preserves fossils of exceptional quality, as well as for the associated trace fossils that are much richer than at other sites, and give detailed evidence on palaeoenvironment.

The first report on Westbury Garden Cliff was by Conybeare and Phillips (1822). Subsequent accounts include Brodie (1845, 1858), Wright (1860), Etheridge (1865, 1872), Lobley (1875), Richardson (1903a), Sykes (1977), and Green (1992). Descriptions of the palaeontology include Richardson (1903a), Benton and Spencer (1995), Storrs *et al.* (1996) and Dineley and Metcalfe (1999). Trueman and Benton (1997) presented an account of the geochemical taphonomy of the 'Rhaetic Bone Bed' from this section.

Description

Westbury Garden Cliff is on the north bank of the River Severn, some 9 km south-west of Gloucester. The cliff reaches a height of 21 m at the downstream (western) end, and exposes a 1-km-long section of Upper Triassic and Lower Jurassic sediments (Figure 4.10). The beds dip gently south-east and the Mercia Mudstone Group is exposed in the downstream part of the section; the Westbury Formation is seen at the upstream end of the section (Wang, 1993; Storrs *et al.*, 1996). Natural erosion keeps the site free of vegetation, although beds at the top of the cliff are generally inaccessible (Swift, 1995). The

Figure 4.10 Westbury Garden Cliff, looking downstream (westwards) showing loose blocks of phosphate-rich calcareous sandstone from the Westbury Formation Bone Bed on the shore, and Blue Anchor and Westbury formations in the cliff, the latter obscured by vegetation. (Photo: Andrew Swift.)

base of the cliff is covered by estuarine waters at high tide. Where the Mercia Mudstone Group forms the base of the cliff, tidal erosion is generally uniform, and produces a smooth base, which tends to undercut the overlying Westbury Formation, resulting in occasional rockfalls. Where the Penarth Group forms the base of the cliff, exposure is less uniform, as beds such as well-cemented sandstones are more resistant to erosion (Reynolds, 1906; Storrs *et al.*, 1996).

In the literature, the site is referred to as 'Westbury-on-Severn' (Sykes, 1977), 'Garden Cliff' (Etheridge, 1865; Swift, 1995; Storrs *et al.*, 1996), and 'Westbury Garden Cliff' (Trueman and Benton, 1997). The first mention of the 'Westbury Beds' was by Wright (1860) who used it to describe the dark-coloured shales and subordinate sandstones. The unit was formalized as the Westbury Formation by Warrington *et al.* (1980).

Sedimentology

The sedimentary log given here is modified from those of Richardson (1903a) and Sykes (1977, pp. 206–9):

	Thickness (m)
Lias Group	
Limestone, grey and blackish-blue, hard	0.05
Penarth Group	
Lilstock Formation ('Upper Rhaetic' of Richardson, 1903a):	
Brown and grey, calcareous, thinly laminated shales:	0.56
Ia: 'Insect Limestone', limestone, blue-grey to light brown, top 0.02 m fissile	0.06
Ib: limestone, blue-grey to light brown, conchoidal fracture	0.06
IIa: shales, grey, laminated, marly	1.82
IIb: sandstone, pyrite-rich, non-calcareous	0.01
IIc: shales, grey, laminated	0.28
IId: sandstone, calcareous, pyritic, ripples	0.01
IIe: shales, grey, marly, poorly laminated	0.18

Limestone, '*Euestheria*-bed' (Etheridge's bed 14, '*Estheria* Zone')	0.30
Shales, grey, marly, with conchoidal fracture	1.68
Westbury Formation ('Lower Rhaetic' of Richardson, 1903a):	
Shales and limestone (Etheridge's bed 12, with Lower and Upper *Pecten* Beds):	
(a) black shales, poorly laminated, selenitic; sandstone (calcareous and pyritic) 0.12m from top	0.86
(b) limestone, sandy in places	0.01
Interbedded calcareous and pyritic sandstone and black laminated shales	1.25
Limestone, hard, blackish-blue, slightly pyritic	0.02
Shales, black, laminated. Grey, micaceous, calcareous sandstone layers near the base and 0.30m below top	0.66
Shales, black, thinly laminated	0.55
Shales, black, imperfectly laminated	0.10
Sandstone, with black shale at middle of bed	0.05
Shale, black, fissile, with some layers of white silt	0.5
Bone bed, 1 to 4 layers, pyritic, bedded, crystalline on the upper surface, with layers of medium-grained sandstone with vertebrate fossils	0.025
Shale, black, fissile, and thin, grey, calcareous siltstones and thin Limestones	0.45
Sandstone ('Upper *Pullastra* Bed'). The upper (finer-grained) part contains minute phosphatic fragments. The lower medium-grained sandstone has more, and proportionally larger, fossils	0.30
Shale, black, fissile and calcareous, with bivalves and some layers of siltstone	0.61
Siltstone ('Lower *Pullastra* Sandstone'); calcareous, micaceous, slightly pyritic, light grey, weathers into two laminae, the lower is a bone bed	0.13
Shale, black and fissile, divided into:	
(a) shale with bivalves and sandy patches, with some bone bed constituents	0.1
(b) shale with some fine-grained sand patches	0.15
(c) shale without sand. Silt patches, flakes and pellets of Blue Anchor Formation mudstone in lowest 0.025 m	0.15
Bone bed: a coarse- and fine-grained sand with large and small fossils including bones and coprolites, and fragments of Blue Anchor Formation mudstones. Discontinuous over short distances	0.05
Mercia Mudstone Group	
Blue Anchor Formation:	
Greenish-grey marls, weathering bluish and yellowish-grey and white; conchoidal fracture	5.49
Twyning Mudstone Formation	
Red marls, with zones of grey and bluish-grey; angular fracture with rarer conchoidal and cuboidal fractures; very thin veins of gypsum	22.25

The Mercia Mudstone Group succession comprises red mudstones and marls of the Twyning Mudstone Formation. These argillaceous lithologies are commonly cut by vertical gypsum veins and in places are laminated or show rippled surfaces. The overlying Blue Anchor Formation is green or grey when freshly exposed but when weathered it acquires a yellowish or bluish tinge (Richardson, 1903a). These beds dip to the south-east at about 2°.

Fossils, especially the remains of fish and coprolites, appear in the Penarth Group. There are two bone-bearing levels, one at the base of the formation, the other some 2 m above the base and 0.4 m above the 'Upper *Pullastra* Bed' (Richardson, 1903a,b; Reynolds and Vaughan, 1904; Storrs *et al.*, 1996). This discontinuous bone-bearing unit varies in thickness and is approximately 0.03 m thick; it is composed of pyrite-rich, shelly silt or sandstone with mud laminations (Figure 4.4d). Euhedral unabraded pyrite crystals are commonly scattered across the basal surface of the layer, and the matrix consists of approximately 70% disseminated pyrite. Vertebrate remains, coprolites, and nodules occur throughout the bed and quartz grains occur sporadically (Storrs *et al.*, 1996; Trueman and Benton, 1997). The upper and lower surfaces of the bed often show ripples; on the

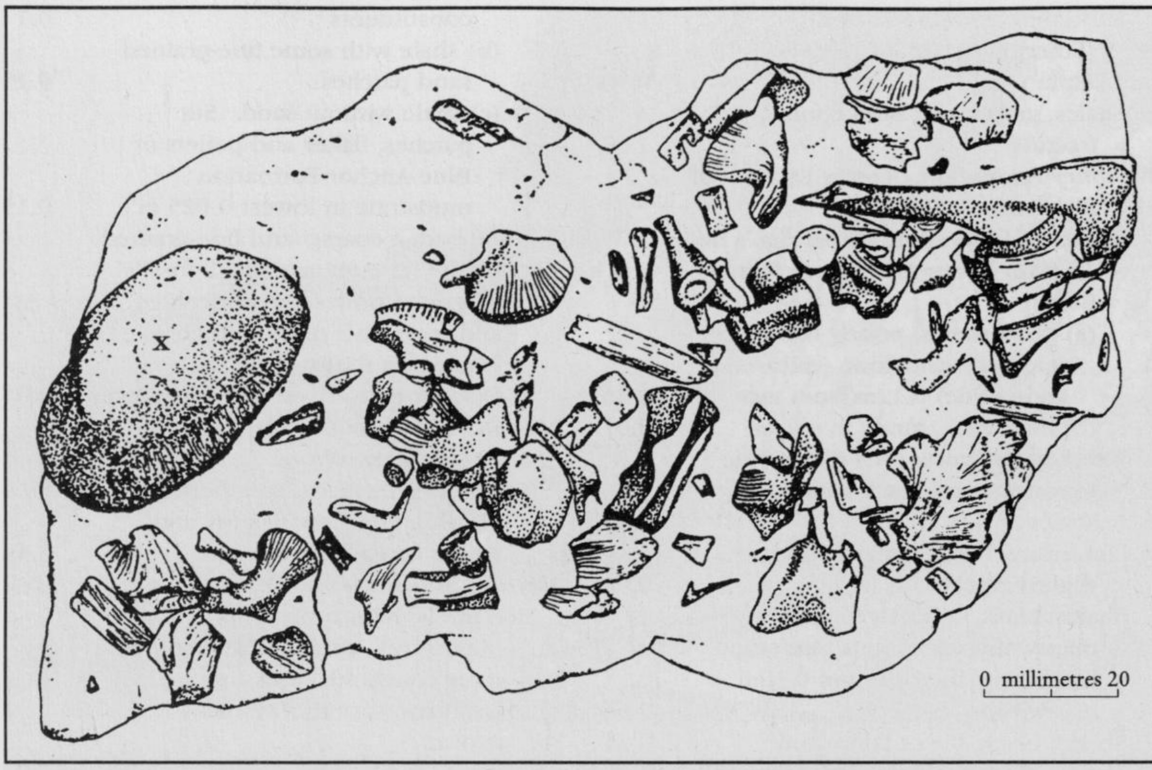

Figure 4.11 A slab of the basal bone bed from the Westbury Formation, Westbury Garden Cliff (Bristol City Museum, Geology Ce17770), containing a scatter of unabraded small bones from the aquatic reptile *Pachystropheus*, with some evidence of current alignment. A large, abraded plesiosaur epipodial (x) is at the left end. (After Storrs, 1994.)

upper surface, argillaceous sediments may infill small channels. Bones are exquisitely preserved on the lower surface of the bed and may show evidence of poorly developed current alignment (Figure 4.11). The bone beds all contain large quantities of vertebrate remains, as well as quartz pebbles, intraformational mud clasts, and pyrite (Richardson, 1903a; Wang, 1993).

Above the bone beds, the Westbury Formation comprises dark shales with sandstones and limestones, which are often especially fossiliferous. In places, the top surfaces of the sandier units are covered with shells and may also preserve trace fossils, seen for example on the upper surface of the 'Upper *Pullastra* Bed' (Wang, 1993).

At the top of the cliff section, the Lilstock Formation comprises alternations of pale shales, grey, brown, or blue-grey limestones and occasional sandstones. Many of the beds show primary sedimentary structures such as laminations and ripples. Of note are the 'Insect Limestone' and '*Euestheria* Bed', both remarkably rich in fossils (Richardson, 1903a).

Palaeontology

Many invertebrate trace and body fossils have been recorded from the Penarth Group in Westbury Garden Cliff. Invertebrate body fossils include rare and fragmentary remains of insects and gastropods from beds in the Cotham Member, and several species of bivalve genera such as *Ostrea*, *Protocardium*, and *Pecten*, many of which are preserved as isolated shells and are commonly pyritized (Wang, 1993), and the inarticulate brachiopod *Lingula* (Richardson, 1903a; Wang, 1993).

Many of the bed boundaries show evidence of bioturbation, and several ichnogenera have been identified. Beds in the lower part of the Westbury Formation show well-defined *Diplocraterion* burrows that have been infilled with the overlying black argillaceous sediment; also present are *Skolithos* traces (Wang, 1993).

The locality has received international attention for the large numbers of well-preserved *Pachystropheus* remains (Storrs and Gower, 1993; Storrs *et al.*, 1996), most of which are isolated bones and bone fragments that weathered out of the cliff (Wickes, 1904) or were found when sections of the cliff collapsed. The well-preserved material from Westbury Garden Cliff has enabled a thorough analysis of *Pachystropheus* to be completed, indicating that it may be the earliest known choristodere (Storrs *et al.*, 1996), a group of extinct, aquatic diapsid reptiles that were previously first known from Middle Jurassic strata.

Other vertebrate fossils include ichthyosaurs, plesiosaurs, and the fishes *Gyrolepis*, *Ceratodus*, and *Acrodus* (Etheridge, 1865; Richardson, 1903a; Wang, 1993; Benton and Spencer, 1995; Trueman and Benton, 1997; Dineley and Metcalfe, 1999).

Interpretation

The red mudstones of the Twyning Mudstone Formation were deposited under terrestrial conditions, in environments similar to modern sabkha flats. These conditions continued throughout the deposition of the Blue Anchor Formation, although the importance of influxes of water, probably marine, increased.

The Penarth Group marks the end of terrestrial conditions in the area, and the establishment of marginal or marine environments. The Westbury Formation bone beds have been interpreted as fillings of shallow channels within an estuarine environment, a view supported by the limited lateral development of the horizon and the trace fossil assemblage at Westbury Garden Cliff (Wang, 1993; Trueman and Benton, 1997). The presence of large quantities of pyrite and phosphate is consistent with this palaeoenvironmental interpretation. The bones probably accumulated as some form of winnowed channel lag deposit (Trueman and Benton, 1997), or possibly as a shoal or strandline deposit (Storrs *et al.*, 1996).

Analysis of the rare earth elements (REE) in the minerals preserving the bones at this site indicate that chemically there is little to separate them from the bones at Aust Cliff (see below), although the REE signatures of the associated sediments are distinct. This suggests that the two bone accumulations experienced similar early diagenetic processes, and that the Aust Cliff material probably originated in a bone bed similar to the one preserved at Westbury, but was then reworked (Trueman and Benton, 1997).

The remainder of the Westbury Formation is dominated by fine-grained sediments, indicative of shallow marine conditions. At the top of the section, the Cotham Member indicates marine conditions, but with evidence for fresh water and for subaerial exposure at some levels.

Conclusions

Westbury Garden Cliff provides an important sedimentological record of changing environments from terrestrial, hypersaline sabkha plains (Mercia Mudstone Group) to shallow marine (Penarth Group). Fossils, including invertebrate body and trace fossils, as well as vertebrates such as fishes, ichthyosaurs, and plesiosaurs are commonly preserved in the Penarth Group. Of great significance are the bone-bearing horizons, which have gained international fame as rich sources of vertebrate fossils, especially the choristodere *Pachystropheus*.

AUST CLIFF, AVON (ST 565 895–ST 572 901)

Introduction

Aust Cliff, on the southern side of the Severn Estuary, is one of the most famous exposures of Triassic rocks in the world. This is partly because it was one of the first to be studied and partly because of its striking location, now squarely beneath a major motorway bridge (see Figure 4.13), but mainly because of its record of Late Triassic and earliest Jurassic sedimentary environments and fossils. The vertebrate faunas from the basal Penarth Group bone bed are world famous.

The cliff exposes a section through the upper part of the Mercia Mudstone Group, comprising red marls overlain by the Blue Anchor Formation. The latter is overlain successively by Penarth Group and Lias Group deposits (Figure 4.12). The red marls show gypsum-bearing horizons and infilled desiccation cracks.

The Penarth Group bone bed at Aust is of international significance as a fossil-rich horizon that has been a valuable source of vertebrate materials since early in the 19th century. Fossils recovered from this site include marine reptiles such as ichthyosaurs and plesiosaurs, fishes, and sporadic dinosaur fossils (Wickes, 1904; Storrs, 1993, 1994; Benton and Spencer, 1995; Dineley

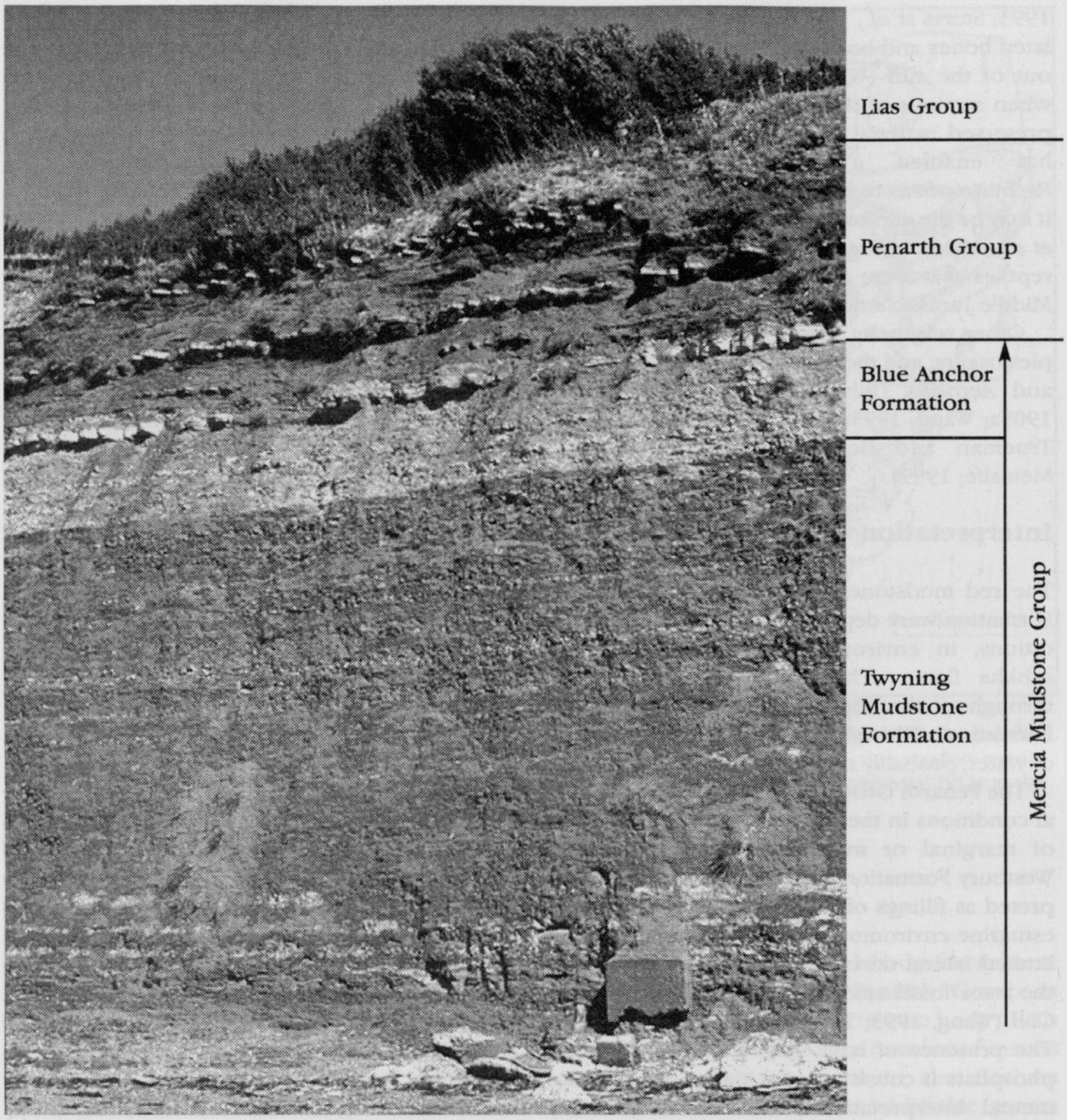

Figure 4.12 Aust Cliff: view on the north-eastern side of the Severn Bridge, looking south-east. Red mudstones of the Mercia Mudstone Group form the lower two-thirds of the cliff, below the light coloured Blue Anchor Formation, above which lies the Penarth Group. Basal Lias Group beds lie at the very top, in the vegetation line. (Photo: Andrew Swift.)

and Metcalfe, 1999).

The first description of the Aust Cliff exposure was made by Buckland and Conybeare (1824). Since then, the locality has commanded the attention of many geologists, for example Strickland (1841), Wright (1860), Etheridge (1867a,b), Short (1904), Reynolds (1929, 1946), Whittard (1949), Hamilton (1977), Sykes (1977), Curtis (1982), Kellaway and Welch (1993), Storrs (1993, 1994), Benton and Spencer (1995) and Swift (1995).

The site was selected independently for the GCR for five 'Blocks' – both the 'Permian and Triassic red bed' and the former 'Rhaetian' blocks, as well as for the Permian–Triassic Reptilia Block (Benton and Spencer, 1995), the

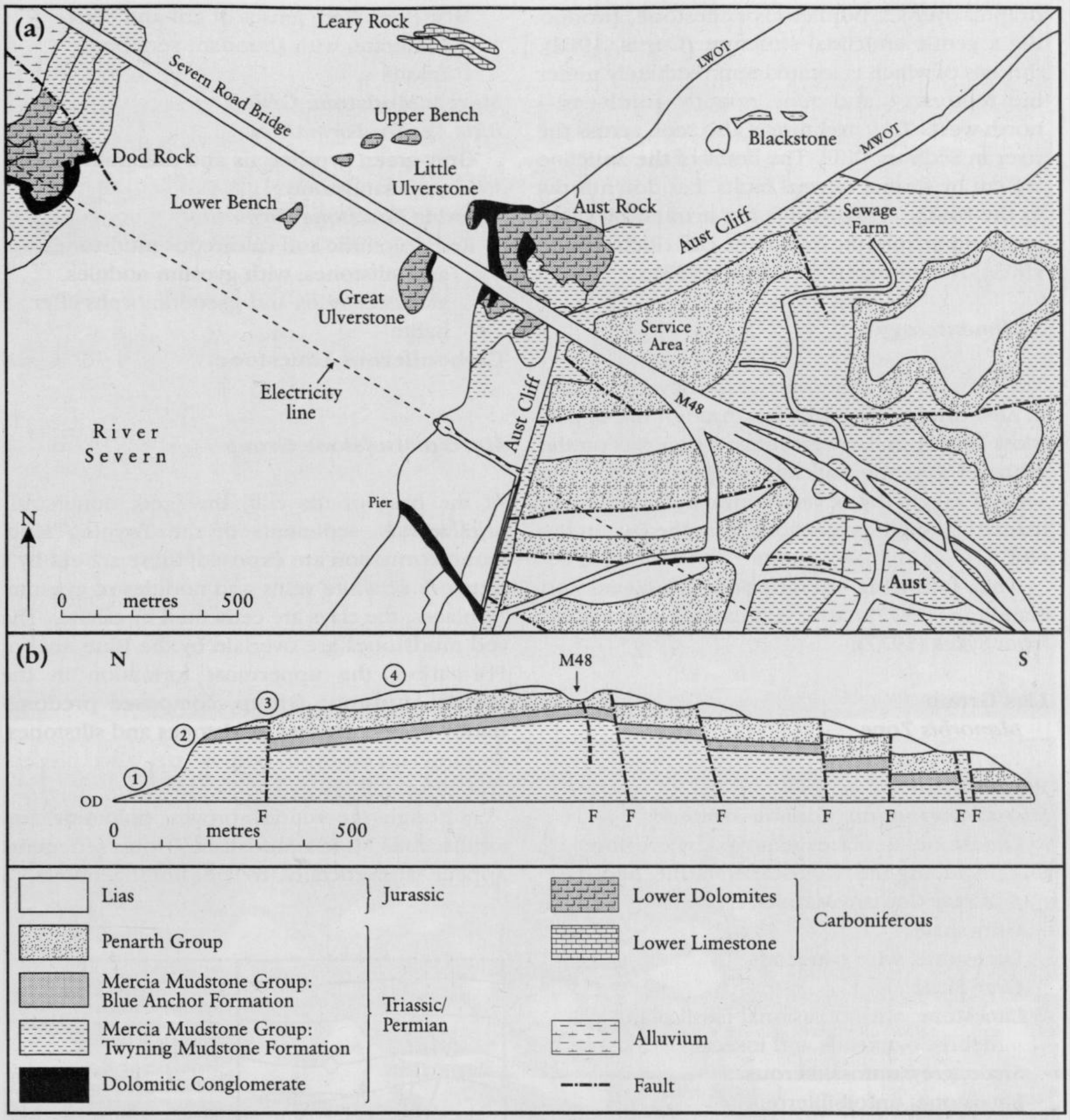

Figure 4.13 Aust Cliff. (a) Geological map; (b) the broad anticlinal structure, and the succession of (1) red mudstones of the Mercia Mudstone Group, (2) the Blue Anchor Formation, (3) the Penarth Group, and (4) the Lias Group. (After Hamilton, 1977.)

Mesozoic–Tertiary Fishes/Amphibia Block (Dineley and Metcalfe, 1999) and the Palaeoentomology Block.

Description

The Aust Cliff section has been subject to high rates of natural erosion, for example in fractures along joint planes, which has kept the section clear of vegetation (Reynolds, 1906), thus facilitating geological fieldwork. The construction of the first Severn Bridge, especially the stabilization of the cliff and increasing plant cover across the foreshore, have been blamed for decrease in the numbers of fossils reported from the site (Large, 1966; Storrs, 1994). However, this decline may reflect the great popularity of Aust Cliff with amateur and professional collectors.

The Aust Cliff section shows evidence of tectonic deformation. The Mesozoic deposits are draped over Carboniferous Limestone, producing a gentle anticlinal structure (Curtis, 1982), the axis of which is located approximately under the motorway, and runs roughly south-east–north-west. This structure is also seen across the river in Sedbury Cliff. The limbs of the anticline are cut by several normal faults that downthrow to the south. These faults are marked by slight projections from the line of the cliff (Richardson, 1903c; Hamilton, 1977; Curtis, 1982).

Sedimentology

The cliffs on the south side of the Severn Estuary at Aust display long sections through the uppermost Triassic and lowest Jurassic deposits on the limbs of a gentle anticline (Figure 4.13). The section is cut by several normal faults, often marked by slight projections from the face of the cliff.

The following description is based on Hamilton (1977), with additional information from Sykes (1977):

Lias Group
- *planorbis* Zone
- Pre-*planorbis* Beds

Penarth Group
Lilstock Formation: Cotham Member:
- Limestone, in places removed by erosion; including the 'Landscape Marble' and the 'Crazy Cotham Marble'.
- Grey shale
- Limestone, with ostracods
- Grey Shale
- Limestone, with occasional fossil plant debris, ostracods and insects
- Shale, grey, unfossiliferous
- Limestone, unfossiliferous

Westbury Formation:
- Dark greenish shale
- Upper *Pecten* Bed; dark grey, hard, shelly limestone
- Dark shale with sand lenticles in lower part
- Lower *Pecten* Bed; dark grey, shelly, sandy biosparite, with quartz pebbles at the base
- Black fissile shale with some pellets of Blue Anchor Formation marls, calcareous sandstone pellets and rare vertebrate fossils at the base. Selenite rosettes common.
- Shale with isolated sandstone ripples and trace fossils
- Basal sandstone
- Aust Bone Bed; lenses of grit and conglomerate, with abundant vertebrate fossils

Mercia Mudstone Group
Blue Anchor Formation
- Grey-green gypsiferous and dolomitic clays with sandstone

Twyning Mudstone Formation
- Red dolomitic and calcareous mudstones and siltstones, with gypsum nodules, alabaster veins and pseudomorphs after halite

Carboniferous Limestone

Mercia Mudstone Group

At the base of the cliff, the red, dominantly argillaceous, sediments of the Twyning Mudstone Formation are exposed; these are cut by a network of white veins and nodules of gypsum. In places, the clays are cemented by calcite. The red mudstones are overlain by the Blue Anchor Formation, the uppermost formation in the Mercia Mudstone Group, composed predominantly of fine-grained mudstones and siltstones, although sandstone bodies are also present (Hamilton, 1977).

Although the reddish-brown, dolomitic and argillaceous Mercia Mudstone Group sediments appear superficially to be homogeneous, a

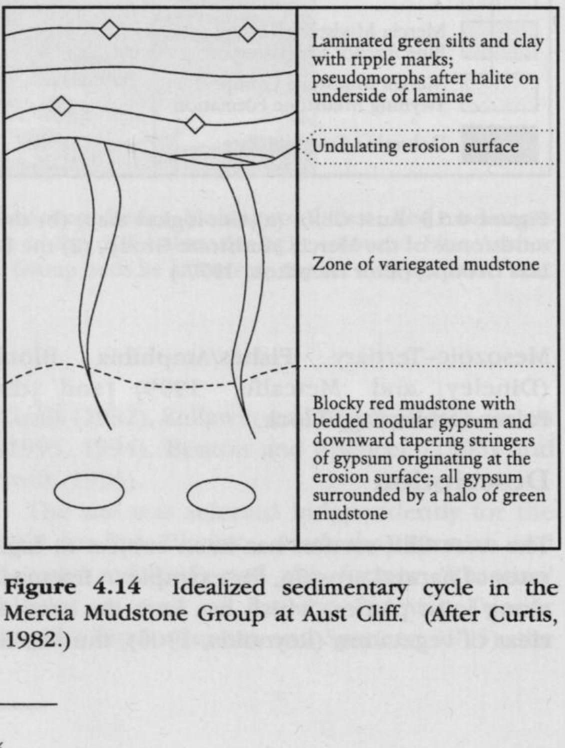

Figure 4.14 Idealized sedimentary cycle in the Mercia Mudstone Group at Aust Cliff. (After Curtis, 1982.)

Figure 4.15 Gypsum deposits in the red mudstones of the Mercia Mudstone Group in the lower portions of the Aust Cliff section. (a) Deep V-shaped fissures filled with gypsum, perhaps forming parts of large-scale polygons. (b) Nodules and veins of gypsum. (Photos: M. J. Benton.)

pattern of cyclicity has been described by Curtis (1982) and is best exposed to the north of the road bridge (ST 566 898; Figure 4.14). The base of the cycles is marked by a red mudstone that contains beds of gypsum nodules and vertically orientated gypsum stringers or veins. In places, long v-shaped fissures filled with gypsum extend downwards from horizontal gypsum beds (Figure 4.15a). The fissures are generally not perfectly vertical, having been distorted and curved by sediment compaction. Gypsum nodules may occur in isolation, or in concentrated patches within the red mudstones, and they are often linked by thin, wavy, sub-horizontal gypsum laminae (Figure 4.15b). The nodules are surrounded by halos of green sediment. This unit is overlain by further variegated mudstones that contain gypsum veins. The upper ends of the gypsum veins are truncated by an uneven erosion surface, which is succeeded by laminated greenish silts and mudstones. The lower surfaces of the laminations often contain pseudomorphs after halite, and are commonly rippled.

The Blue Anchor Formation consists of predominantly green and grey mudstones, siltstones, and sandstones. There is no lithological difference between the red and green sediments. This formation yields pale blue celestite, often to be found on joint planes. Marine fossils occur sporadically.

Penarth Group

The sequence through the upper part of the Twyning Mudstone Formation and the Blue Anchor Formation of the Mercia Mudstone Group, is overlain disconformably by the Westbury Formation of the Penarth Group. The famous 'Rhaetic' Bone Bed marks the base of the formation (Storrs *et al.*, 1996)

The Westbury Formation sediments are predominantly dark-coloured, carbonaceous, often fissile, shales with some sandstones and bioclastic limestones (Hamilton, 1977; Storrs, 1993, 1994), which form cycles bounded by erosion surfaces (MacQuaker, 1994). Two of the limestones, the Lower *Pecten* Bed and the Upper *Pecten* Bed, both comprise sandy sediment rich in shell debris; the Upper *Pecten* Bed is harder than the Lower (Hamilton, 1977).

Although much of the section at Aust is similar to that seen elsewhere, for example at Blue Anchor and St Audries Bay (see site reports below), the presence of the 'Rhaetic' Bone Bed sets this locality apart. Unlike other localities where there are several Penarth Group bone beds (Wickes, 1904; Storrs, 1994), at Aust there is only one. The Aust Bone Bed is composed of a breccio-conglomerate with clasts of quartz, potassium-feldspar, phosphate nodules, vertebrate material, a fine-grained shelly matrix and a calcitic and pyrite cement (MacQuaker, 1994; Trueman and Benton, 1997; Figure 4.4b). Many of the larger clasts are composed of sediment from the underlying Blue Anchor Formation that show evidence of soft-sediment deformation indicative of reworking before lithification (Hamilton, 1977; Storrs, 1993, 1994). Trueman and Benton (1997) described graded bedding of the apatite and lithic clasts in the bone bed. The apatite is coarser at the base of the bed, while the rip-up clasts of Blue Anchor Formation sediment are coarser at the top of the bed. Trueman and Benton (1997) explained this phenomenon by postulating deposition as an arrested turbulent sediment flow: the dense apatite sank to the bottom of the flow, leaving the larger, less dense lithic clasts to 'float' at the top.

The uppermost unit of the Penarth Group here is the Cotham Member, which is also composed of alternating limestones and shales, but is somewhat paler than the Westbury Formation. The Cotham Member comprises argillaceous limestones that pass upwards into clays (the Langport Member is missing). At the top of the limestone succession is the Cotham Marble, often used as an ornamental stone. The Cotham Marble has two forms: the 'Landscape Marble', with the appearance, in section, of a 'landscape' composed of a hedge, trees and sky, and the 'Crazy Marble' that contains angular flakes of limestone in a fine- to medium-grained matrix (Hamilton, 1961, 1977).

The upper surface of the Cotham Member is eroded and separated from the overlying brown, flaggy Pre-*planorbis* Beds by a disconformity. The base of the Lias Group is marked by a discontinuous conglomerate composed of clasts of limestone from the Langport Member in a dark matrix (Hamilton, 1977; Swift, 1995; Radley and Carpenter, 1999).

Palaeontology

The Penarth Group sediments at Aust have produced abundant and diverse fossil assemblages. The Aust Bone Bed has yielded remains of the sharks *Acrodus*, *Nemacanthus*, and *Hybodus*.

Bony fishes are represented by jaws of the actinopterygian *Birgeria acuminata* and tooth plates of the lungfish *Ceratodus latissimus*. Reptiles, such as *Plesiosaurus*, *Ichthyosaurus*, the choristodere *Pachyostropheus*, and a megalosaurid dinosaur have also been recorded here (Hamilton, 1977; Storrs and Gower, 1993; Storrs, 1994; Benton and Spencer, 1995; Storrs *et al.*, 1996).

The *Pecten* beds in the Westbury Formation have yielded a limited fauna of invertebrate body and trace fossils, including the bivalves *Pleurophorous elongatus*, *Rhaetavicula contorta* and *Chlamys valoniensis*, ophiuroids, and the inarticulate brachiopod *Orbicula townshendi*. Vertebrate fossils are often found in these limestones, but rarely occur in the intervening shales (Hamilton, 1977).

The Cotham Member preserves a distinct flora and fauna (Hamilton, 1977) consisting of the liverwort *Naiadita lanceolata*, ostracods, and the branchiopod crustacean *Euestheria minuta*.

Interpretation

Mercia Mudstone Group

Many lines of evidence have been put forward to explain the sequence of dolomitic red mudstones in the upper the Mercia Mudstone Group seen in Aust Cliff. The chemistry of the sediment (its dolomitic nature) and the presence of gypsum and pseudomorphs after halite indicate that deposition probably occurred in ephemeral, hypersaline water bodies (Hamilton, 1977) located within an extensive basin (Talbot *et al.*, 1994). Curtis (1982) described cyclical sedimentation, characteristic of deposition in sabkha environments subject to periods of heavy rainfall alternating with extremely arid conditions. The cycles have distinct phases that represent separate events during the deposition of the sediments as follows:

Phase 1: The blocky red mudstone and variegated mudstone at the base of the cycles (Figures 4.14 and 4.15a) contain bedded nodular gypsum and has an undulating upper surface. The red, fine-grained material accumulated when wind-blown material stuck to the damp sediment surface (produced by a high water table, surface run-off or dew). The growth of gypsum within the profile caused distortion of the surrounding sediments, thus causing the undulating surface.

Phase 2: A phase of erosion scouring the top of the variegated mudstones.

Phase 3: Laminated, rippled, greenish-coloured silts and clays were deposited during storm events as sheets of water washed across the land surface. The pseudomorphs after halite were formed as the storm waters evaporated. Halite crystals were dissolved by the subsequent floods, and the voids left in the sediment were infilled with coarser-grained material.

The gypsum in the Mercia Mudstone Group was formed by a variety of processes: the bedded nodular gypsum (Figure 4.15b) was precipitated from hypersaline groundwater, and the associated anhydrite may have been deposited as a primary mineral, or it may represent an early diagenetic replacement phase, or be a product of deep burial. Other minerals, for example celestite and calcite, may also be the result of primary sedimentological processes or secondary diagenesis (Curtis, 1982). Wright *et al.* (1988) and Talbot *et al.* (1994) consider the gypsum to be a result of pedogenic processes: the vertically orientated veins mark the position of roots within the soil profile. Alternatively, the vertical V-shaped structures could be gypsum infills of large-scale polygonal structures, a feature sometimes seen in the Triassic red mudstones associated with evaporites, and caused by thermal contraction (Tucker and Tucker, 1981).

The sandstone beds in the Blue Anc Formation are interpreted as the deposits of flood events that originated in the upland areas surrounding the basin. Generally, the sediments accumulated in the basin through a combination of aeolian and lacustrine processes (Talbot *et al.*, 1994). The colour change from the red mudstones to the blue-green-grey Blue Anchor Formation has a number of possible explanations (Hamilton, 1977). The red coloration is from ferric oxides (haematite and goethite), while the green colour is caused by ferrous oxides, and the red gave rise to the green during the reduction of the ferric oxides. However, it is not clear whether the colour difference is primary, perhaps caused by a switch from primarily continental to primarily marine conditions of deposition, or whether it is diagenetic and secondary.

The Aust Bone Bed

Many theories have been put forward to account for the formation of the Aust Bone Bed, ranging from mass mortality events to reworking of pre-existing fossil accumulations. For example, Jukes-Brown (1892) thought that the animals had died catastrophically when they swam into the hypersaline waters of the Mercia Mudstone lakes and lagoons. Wickes (1904), on the other hand, thought that the bone bed represented the location of a massive feeding frenzy of marine animals; the remains of their meals fell to the sea floor as pieces of carcass or as faecal pellets. Physical processes seem more likely. Storm activity was proposed by Short (1904) and MacQuaker (1994) and wave action by Donovan (1955). At Aust, the bone beds may have had tiers of oxygenated and oxygen-deficient sediment, as shown by the trace fossils. The large intraformational clasts are thought to have been produced by reworking during successive flooding events. MacQuaker (1994) concluded that the bone bed represents a transgressive lag deposit that forms a parasequence boundary. The bone bed lithofacies was formed in areas with little clastic input, but significant reworking of older materials; formation began and continued as the sea level rose, and ended with the deposition of argillaceous sediments.

The presence of marine and terrestrial vertebrate remains with a range of taphonomic characteristics (Storrs, 1994) suggests that the vertebrate material was sourced from a wide area and that reworking was a significant process in the formation of the bone bed. Trueman and Benton (1997) suggested that the Aust Bone Bed represents a 'frozen' flow of sediment and fluid. The dense apatite clasts, including the bone material, sank through the soupy mud matrix to the bottom of the flow, while the Blue Anchor Formation clasts remained at the top. Finally, fine-grained clays were deposited as a drape over the surface of the bone-bearing bed. Trueman and Benton (1997) suggested that a very high-energy fluid flow, probably generated by a storm event, was responsible for the reworking of the bone material and producing the rip-up clasts. The evidence provided by the analysis of the REE in the sediments and mineralizing crystals of the bones, and the absence of any other rip-up clasts, indicates that the bones were reworked from beds stratigraphically close to the Blue Anchor Formation (Trueman and Benton, 1997).

As a whole, the Westbury Formation was deposited in relatively shallow water environments (MacQuaker *et al.*, 1985; MacQuaker, 1994) subject to a series of transgressions and regressions. The overlying Westbury Formation was deposited under lagoonal conditions with periods of emergence.

The two varieties of the Cotham Marble formed under very different conditions: the 'Landscape Marble' represents the development of algal mats characteristic of an intertidal environment, while the 'Crazy Marble' was formed when channels or runnels were infilled with brecciated sediment (Hamilton, 1961; Wright and Mayall, 1981). The intertidal or lagoonal environment is supported by the remains of liverworts, which are terrestrial bryophytes (Hamilton, 1977).

At the top of the Aust Cliff section the Lias Group represents deposition in shallow marine waters (Hamilton, 1977).

Comparison with other localities

During the mid 1990s, excavation for construction materials for the Second Severn Crossing created a new section of the Mercia Mudstone and Penarth groups near Aust Cliff. At this new locality, Manor Farm (ST 574 896), sediments of Norian to Rhaetian age described by Radley and Carpenter (1999) were exposed in two large pits in fields behind the Aust Service Station. This locality was easy of access; the strata were exposed in small faces that could be readily climbed, in contrast with the high cliffs at Aust.

The temporary excavations at Manor Farm exposed the highest *c.* 1 m of the Twyning Mudstone Formation at the bottom of the pit, overlain by 3 m of grey-greenish silty mudstones of the Blue Anchor Formation. This is overlain by some 3.5 m of dark shale and limestone alternations of the Westbury Formation that are succeeded by the fine-grained, pale Cotham Member limestones, including the Cotham Marble. As at Aust Cliff, the Langport Member is not recognized; however the Pre-*planorbis* Beds are represented by flaggy brownish limestones (Radley and Carpenter, 1999). Part of this succession remained visible in October 2001 (G. Warrington, pers. comm.).

The Aust Bone Bed was well exposed at Manor Farm, and occupied scour hollows in the top of the Blue Anchor Formation.

Lithologically, it is very similar to that seen at Aust Cliff, and contains clasts of Blue Anchor Formation mudstone, quartz pebbles, and vertebrate remains, including ichthyosaur, plesiosaur, and possible theropod bones, as well as shark fin spines and coprolites. Invertebrate body and trace fossils (Radley and Carpenter, 1999) include the bivalves *Rhaetavicula contorta* and *Pleurophorous elongatus* and the trace fossils *Lockeia siliquaria* and *Arch-arenicola rhaetica*.

Conclusions

The internationally renowned cliffs at Aust provide one of the best exposures of Upper Triassic sediments in Britain. The lower part of the succession comprises red clays and mudstones of the Twyning Mudstone Formation of the Mercia Mudstone Group. The formation was deposited under dominantly terrestrial conditions in environments similar to modern-day sabkhas and playas.

The site is especially important for the fine exposures of the red marls of the Mercia Mudstone Group, with spectacular gypsum beds and enigmatic sub-vertical structures, overlain by the Blue Anchor Formation. Succeeding the Blue Anchor Formation is the Penarth Group, which comprises the marine Westbury and Lilstock formations. The succession is capped by the lowest beds of the Lias Group

Aust Cliff is world-famous for the Aust Bone Bed, a discontinuous, coarse-grained, transgressive lag deposit rich in vertebrate fossils that comprise one of the most diverse Late Triassic faunas in Europe.

HAPSFORD BRIDGE, VALLIS VALE, NEAR FROME, SOMERSET (ST 760 493)

Introduction

The Upper Triassic succession exposed at Hapsford Bridge, Vallis Vale, is one of the best seen in the east Mendip region. It is most famous as the site of De la Beche's (1846) unconformity between the Carboniferous and the Jurassic rocks, with evidence for the progressive overstep of the Carboniferous Limestone Mendip islands through Rhaetian and Jurassic time. The site shows a sequence of sediments developed against one of the limestone islands of the Mendip archipelago, and has yielded important fossil finds. Of particular importance are the occurrence of the Cotham and Langport members of the Lilstock Formation, which form the upper part of the Penarth Group of Rhaetian age.

Vallis Vale and Hapsford Bridge have been described by De la Beche (1846), Moore (1867), Richardson (1907, 1911), Duffin (1982), and Duff *et al.* (1985).

Description

Hapsford Bridge is situated approximately 1 km north-west of Frome, at the confluence of Egford Brook and Mells Stream. It was known in the older literature as 'Hapsford Mills' (Moore, 1867). Quarrying ceased some time ago. Together with other geologically significant sites, the various disused and overgrown quarries along the sides of the Egford Brook, it forms part of the Vallis Vale Site of Special Scientific Interest (SSSI).

Sedimentology

The Rhaetian sediments at Hapsford Bridge are best seen in the walls of a disused quarry in the south side of Vallis Vale (Figure 4.16). The Mesozoic strata in this area dip slightly to the north-east (Savage, 1977). The Upper Triassic formations are sandwiched between the Lower Carboniferous Limestones (Dinantian in age) and the Upper Inferior Oolite (Figure 4.17). The following section is taken from Duffin (1982, p. 157), with stratigraphical divisions taken from Richardson (1911, p. 65):

	Thickness (m)
Middle Jurassic, Upper Inferior Oolite	1.0
Penarth Group	
Lilstock Formation; Langport Member:	
Fine-grained micrites	0.60
Conglomeratic limestone	0.30–0.60
Lilstock Formation; Cotham Member:	
Interbedded clays, micrites and sparry limestones	0.15
Micrite	0.12
Pale clay	0.15
Micrite/calcisiltite	0.05
Pale clay	0.02
Micrite/calcisiltite	0.10

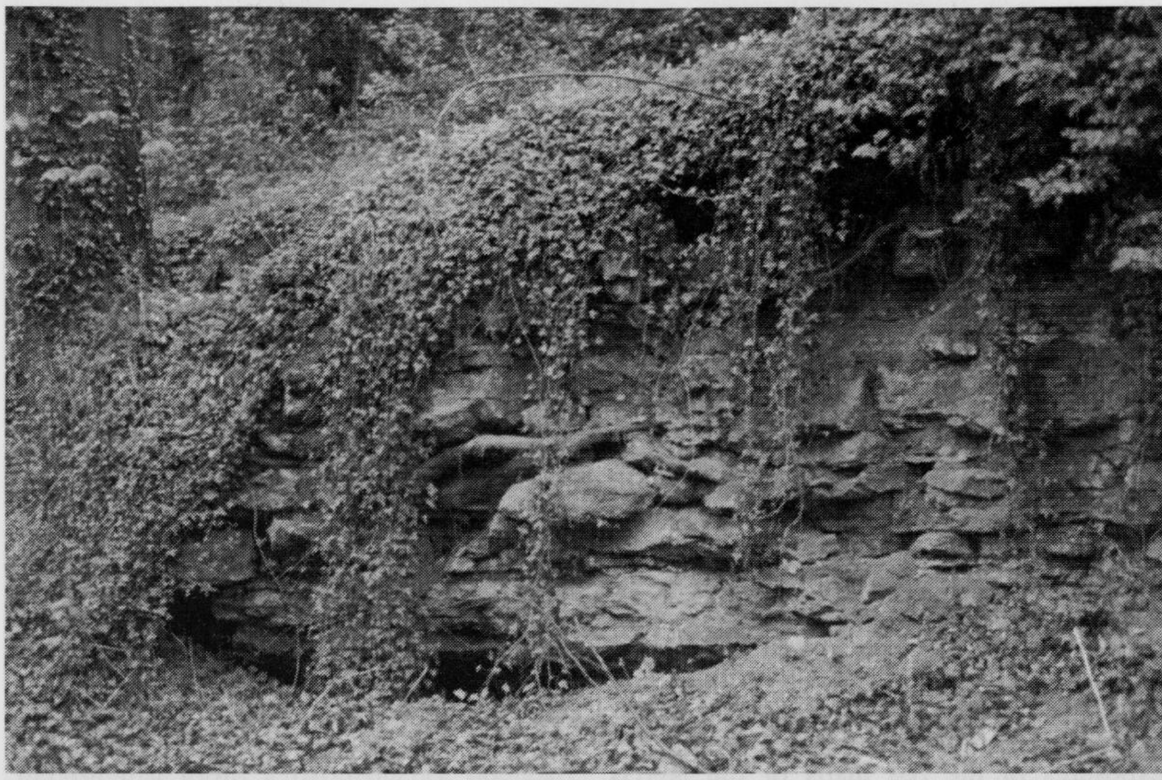

Figure 4.16 Hapsford Bridge, view of the Penarth Group sediments, which rest unconformably on Carboniferous Limestone. (Photo: R. Cottle.)

Westbury Formation:	
Finely laminated calcisiltites with pebbly base	0.40
Thin conglomerate	0.01
Micrite/calcisiltite with pebble lenses and ripple lamination	0.27
Ripple cross-laminated micrite with pebbly base	0.07
Organic clay, dark in colour	0.05
Conglomeratic limestone	0.12
Dark clay with lensoidal limestones	0.05
Conglomeratic limestone	0.30–0.45
Dark organic clay yielding *Vallisia*	0.05
Carboniferous Limestone	

Older sections, for example by Moore (1867) and Richardson (1911), record the presence of a basal Triassic conglomeratic bed lying on the Carboniferous Limestone, and other conglomerates throughout the sequence. The Rhaetian succession at Hapsford Bridge oversteps the Carboniferous Limestone, with the boundary marked by an unconformity.

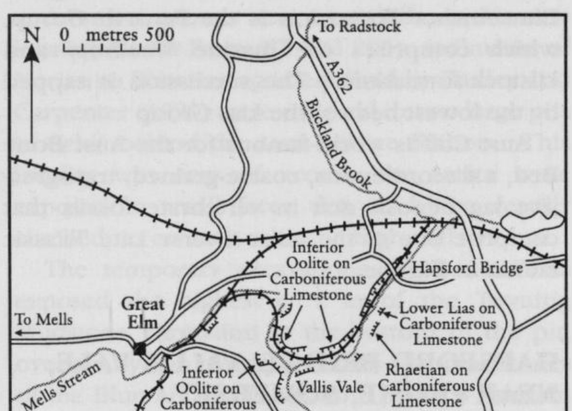

Figure 4.17 Map of the Vallis Vale and Hapsford Bridge localities. Various exposures along the stream sides show progressive onlap of first the Penarth Group, then the Lower Lias, and finally the Inferior Oolite (Middle Jurassic) onto the Carboniferous Limestone Mendip island. (After Savage, 1977).

Palaeontology

The Rhaetian sediments at Hapsford Bridge have yielded a wide variety of fossils, including palynomorphs (Orbell, 1973; Warrington, 1984), plants, invertebrates, and vertebrates (Savage, 1977, Dineley and Metcalfe, 1999). Invertebrates include typical Rhaetian forms, such as the bivalves *Rhaetavicula contorta*, *Ostrea*, and *Cardinia* (Moore, 1867; Savage, 1977) and the crustacean *Euestheria minuta*.

Vertebrate remains include the teeth of the shark *Vallisia coppi*, recovered from the dark clays that immediately overlie the Carboniferous Limestone. *Vallisia* was described by Duffin (1982) as a neoselachian, in other words, a modern shark, but the fine structure of its tooth enamel makes this assignment questionable (Cuny and Benton, 1999). Richardson (1911) noted remains of sharks and other fishes through much of the section. *Thecodontosaurus*, the prosauropod dinosaur described from here by Moore (1867), was initially thought to have come from Hapsford Bridge, but analysis of the material by Duffin (1978) suggests that this assumption may be incorrect. Benton and Spencer (1995, p. 72) mistakenly recorded prosauropod material from this site, based on this old record of *Thecodontosaurus*.

Plant fossils are found throughout the section, and are especially common within the dark clays of the Cotham Member. Noteworthy are well-preserved remains of the bryophyte *Naiadita lanceolata*, although other taxa such as *Lycopodites* are common (Harris, 1938; Savage, 1977).

Interpretation

The section at Hapsford Bridge records a range of marine environments. The Upper Triassic sediments were deposited directly upon the Carboniferous Limestone, which formed part of the Upper Triassic Mendip archipelago (Duffin, 1982).

The Westbury Formation is a marine facies dominated by dark clays (Hamilton and Whittaker, 1977). Interbedded with these lithologies are coarse-grained conglomeratic clastic rocks and limestones that may show evidence of ripple cross-laminations (Duffin, 1982). It is probable that the conglomeratic beds were deposited on the shoreline of the Carboniferous Limestone landmass.

The generally paler-coloured limestones and clays of the Cotham Member were probably deposited in shallow, probably freshwater pools (Mayall, 1983). The overlying Langport Member represents deposition in warm lagoons (Whittaker and Green, 1983).

Conclusions

Hapsford Bridge represents one of the most easterly exposures of the Penarth Group in the East Mendips, and therefore in southern England. These sediments were deposited against one of the islands in the Late Triassic Mendip archipelago, and seen now as the unconformity between the Carboniferous Limestone and the Upper Triassic strata. The site has produced many fossils, including the bryophyte *Naiadita lanceolata*, invertebrates, sharks, and possibly dinosaurs. This is an important site for studies of Rhaetian palaeogeography and palaeoenvironments.

BARNHILL QUARRY, CHIPPING SODBURY, AVON (ST 725 826)

Introduction

Barnhill Quarry exposes an excellent section of Carboniferous Limestone overlain unconformably by the Penarth Group. The site is especially important in showing the nature of this unconformity, and how the Late Triassic sediments filled fissures and faulted steps on the landscape formed on the Carboniferous Limestone. The Penarth Group includes the Westbury Formation with a basal bone bed and interbedded dark grey shales and muddy limestones, and pale limestones of the succeeding Cotham Member (Lilstock Formation).

Much of the geological and palaeontological research at Barnhill Quarry has concentrated on the Carboniferous strata (e.g. Coysh, 1927; Murray and Wright, 1971). The first description of the site was by Reynolds (1938), and Sykes (1977) included a brief analysis of the bone bed and a short description of the Rhaetian sediments.

Description

Barnhill Quarry provides a 2-km-long section of faulted and steeply dipping Carboniferous

Limestone with small sections of overlying Upper Triassic sediments. The south-east part of the quarry forms the GCR site, and is situated within the Severn Valley Natural Area (Reynolds, 1938). Most of the quarry is now disused, although the northern area remains in use. The site is also known as 'Chipping Sodbury Quarry' (Reynolds, 1938).

Sedimentology

The Upper Triassic deposits rest on eroded Carboniferous Limestone surfaces (Figure 4.18) that have been cut by three major thrust faults. The thrusts were propagated along bedding planes within the Carboniferous Limestones, and slickensides are common (Reynolds, 1938). In places, the Carboniferous strata are covered by Westbury Formation clays, and beneath these, the limestone is smooth. The exposed upper surface of the Carboniferous Limestone forms four platforms, two of which display well-developed clints and grykes, deep solution channels characteristic of karst landscapes produced by subaerial chemical weathering of limestone (Reynolds, 1938); the remaining limestone surfaces are generally smooth and planar, and are probably a result of intensive erosion.

The following section is adapted from Reynolds (1938, pp. 100–1) and Sykes (1977):

	Thickness (m)
Lias Group:	
seen as blocks of grey limestone in the soil	
Penarth Group	
Lilstock Formation, Cotham Member:	
Pale shale	0.61
Euestheria Bed: compact pale argillaceous limestone; variable thickness	up to 0.3
Grey shale	0.76
Westbury Formation:	
Irregular beds of greyish argillaceous limestone, sometimes sandy	0.15
Dark shale, sometimes very fissile. Selenite common, especially in the lower parts of the section. Towards the base of the bed is an impersistent ferruginous layer rich in vertebrate fossils	1.1
Pecten Bed: argillaceous limestone, sometimes very hard and crystalline; well-defined layers of 'beef' towards the base of the bed	up to 0.3
Dark grey shale:	
(a) dark grey shale with several fossil-rich bands	1.37
(b) compact black shale, common pyrite, very fossiliferous	0.91

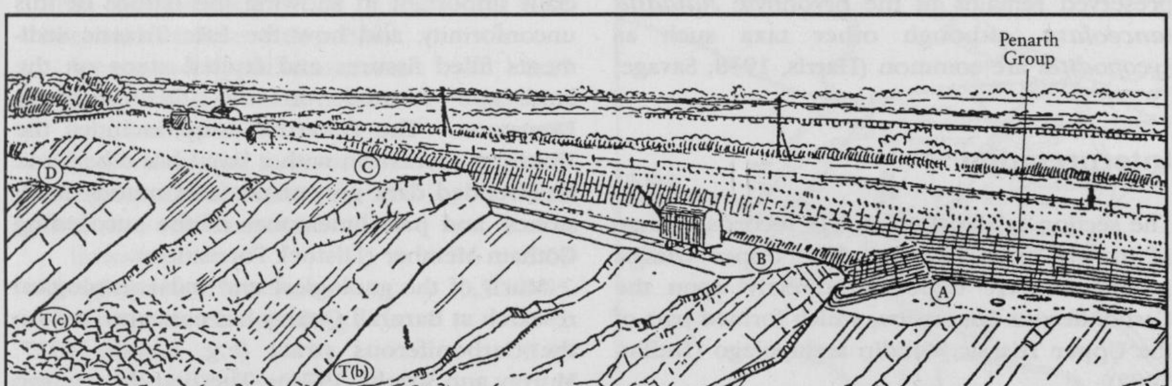

Figure 4.18 Perspective view of Barnhill Quarry, at the height of its operations in the 1930s, looking NNE. A, B, C, and D are Carboniferous Limestone platforms, and T(a), T(b), and T(c) are overthrusts. Penarth Group sediments rest unconformably on top of this stepped landscape. (After Reynolds, 1938.)

(c) black papery shale, no fossils 0.38
Bone bed: very irregular and patchy; variable thickness; containing bones of fishes and reptiles, and quartz pebbles 0.3 or less
Carboniferous Limestone

A bone bed occurs at the base of the Triassic succession, resting directly on the eroded Carboniferous Limestone. Two bone-bearing lithologies have been described (Reynolds, 1938), the first being a dark-coloured crystalline limestone containing phosphatic nodules, coprolites, and bone fragments, and the second characterized by large (up to 1.2 m long), rounded blocks, which may be partially coated with pyrite. In many cases these blocks are isolated, but when they occur in groups, bone-bearing and quartz pebble-rich sediment often infills the spaces, producing a very coarse-grained conglomerate. The distribution of this coarse conglomerate is somewhat patchy and corresponds to the occurrence of a grit bed within the Carboniferous Limestone (Reynolds, 1938).

The overlying sediments are typical Westbury Formation lithologies and comprise dark grey, often fissile shales with thin interbedded limestones and sandstones (Reynolds, 1938; Sykes, 1977).

The top of the section exposes the Cotham Member of the Lilstock Formation. This comprises pale buff-coloured shales and thinly bedded limestones (Reynolds, 1938). The Cotham Marble facies has not been recorded at this locality.

Palaeontology

Many fossils have been recorded from the Penarth Group sediments at Barnhill Quarry, principally from the Westbury Formation that contains abundant remains, including the bivalves *Eotrapezium*, *Protocardia*, and *Lyriomyophoria*. Vertebrates are especially common in the basal bone bed, but also occur scattered throughout the overlying Westbury Formation shales. Fish teeth, for example *Acrodus*, *Saurichthys*, *Sargodon*, and *Gyrolepis*, are abundant (Dineley and Metcalfe, 1999), while plesiosaur remains are rare (Reynolds, 1938). In contrast, the Cotham Member contains few, if any, fossils.

Interpretation

The Penarth Group sediments at Barnhill Quarry reflect the changing palaeoenvironmental conditions experienced by south-west England during the Late Triassic Epoch. The planar surface of the Carboniferous Limestone was produced, at least in part, during the Late Triassic transgression (Reynolds, 1938). The basal beds of the Westbury Formation are typical in that they contain a bone bed. Reworking of sediments and vertebrate material in the basal bone bed is important (Storrs, 1994): at Barnhill Quarry, coarse-grained grits have been reworked into the bone bed from the Carboniferous Limestone. The rest of the Westbury Formation shows typical marine sediments, as elsewhere.

The overlying pale-coloured limestones and shales of the Cotham Member were deposited in marine lagoons (Mayall, 1979).

Conclusions

Barnhill Quarry is one of the few inland sites where Penarth Group sediments are easily accessible. It is especially important for the extensive exposures of the irregular, eroded, karst-like surface of the Carboniferous Limestone and overlying Penarth Group sediments that rest on this Late Triassic land surface. This is a critically important site for the understanding of the Late Triassic transgression and palaeogeography of the region.

WETMOOR, NEAR WICKWAR, AVON (ST 741 877, ST 743 878, ST 746 877)

Introduction

Wetmoor is a particularly important site for the study of the Cotham Landscape Marble, which is developed at two levels at this locality. The exposures are particularly good, and include the Mercia Mudstone Group, and the Westbury Formation and the Cotham Member (Lilstock Formation) of the Penarth Group. Many fossils have been recovered, including vertebrates, for example remains of the fishes *Gyrolepis* and *Sargodon*. The site is historically important, having been noted by Roderick Murchison in 1839.

Although Wetmoor has been known to geologists since the early years of the 19th century, it has not been a major focus of scientific study. The first published documentation of the site was by Murchison (1839). Since then, the geology of the adjacent area has been briefly mentioned by Richardson (1904), Whittard and Smith (1944), and Cave (1977).

Description

Most of the exposures take the form of small stream sections at several locations within the Lower Woods, which form part of the Wickwar Site of Special Scientific Interest (SSSI) and the Wetmoor Wood Nature Reserve. There are three main areas of Upper Triassic exposure (Figure 4.19). To the west, a stream has cut a section into the Mercia Mudstone Group and the Westbury Formation. Streams in the central area of the nature reserve also expose the Westbury Formation. To the east, the Cotham and Langport members of the Lilstock Formation, and Lias Group strata are seen in stream banks.

Sedimentology

No complete Upper Triassic sections from Wetmoor have been published, although several descriptions of the geology of the surrounding area have been reported in the literature. Richardson (1904, p. 534) recorded the following Triassic and Jurassic succession nearby at Chase Hill, near Wickwar:

	Thickness (m)
Lias Group:	
Shales, pale-green, calcareous, with a few, thin, hard layers of limestone near the base	*c.* 0.20
Limestone, dark, earthy	0.02
Shale parting	
Limestone, hard, dark	0.09
Penarth Group:	
Cotham Landscape Marble	0.23

Richardson (1904) also recorded the 'Tea Green Marls', 'Red Marls' and 'Rhaetic Black Shales' (including the basal bone bed) from the nearby Chase Hill Lane.

Whittard and Smith (1944) produced a detailed account of the Palaeozoic and Mesozoic geology of the area around Wickwar. They described the valley of the Little Avon river as being cut into the horizontal Triassic strata; the Penarth Group stands out as a well-defined ledge. The following generalized stratigraphical summary for the area is modified from Whittard and Smith (1944, p. 66):

	Thickness (m)
Soil	
Penarth Group; *Westbury Formation*:	
Black shales with bone bed at the base	1.6
Mercia Mudstone Group:	
Blue Anchor Formation	3.96
Red Marls	11.58
Wenlock Limestone (Silurian)	1.68

In an unpublished report for English Nature, R. Cottle describes three locations within the boundaries of the nature reserve and SSSI. In the western end of the reserve a small stream has cut through the Upper Triassic sediments to expose a good section of the Mercia Mudstone Group and the overlying Westbury Formation. The sediments are exposed around a 'T'-shaped junction in the stream (Figure 4.19a). Here, the Mercia Mudstone Group comprises reddish-brown mudstones with small (0.01 m diameter) green spots and grey-green patches up to 0.10 m long, succeeded by grey and blue mudstones of the Blue Anchor Formation. The conglomeratic bone bed in the Westbury Formation is exposed here, along with the typical black or dark grey argillaceous layers and thin grey limestones of the formation. The bone bed contains the phosphatized remains of vertebrates (teeth, scales and bone fragments) and well-rounded quartz pebbles in a sandy matrix.

The Westbury Formation is also seen in the central area of the reserve. Here, the floodwaters that periodically flow along the course of a small ephemeral stream have eroded a channel in the shales and limestones. The eastern area of the reserve, in the vicinity of the footbridge, preserves the Lilstock Formation sediments, including the Cotham Landscape Marble (Figure 4.19b), and the Lower Jurassic facies. There are several small ephemeral and permanent streams here, exposing outcrops of varying quality.

Palaeontology

The Mercia Mudstone Group has not yielded any fossils. The basal Westbury Formation bone bed preserves many fossils, mostly phosphatized bones, teeth, and scales, although rare inverte-

Figure 4.19 Wetmoor stream sections showing small exposures of Triassic sediments. (a) Mercia Mudstone Group mudstones, seen in the northern end of the western GCR area; (b) Cotham Member limestones and clays, and the Cotham Marble, which are overlain by basal Lias units, in the eastern GCR area. (Photos: R. Cottle.)

brate remains, for example *Mytilus*, have been recorded. The vertebrates include the fishes *Gyrolepis* and *Sargodon*. Beds higher in the Westbury Formation have yielded the bivalves *Eotrapezium ewaldi*, *Protocardia*, and *Lyriomyophoria*, as well as ostracods. Small gastropods are often associated with the Landscape Marble of the Cotham Member.

Interpretation

The stream bank exposures at Wetmoor preserve sediments that record the changing environmental conditions affecting south-western England during the Late Triassic Epoch. The dominantly terrestrial hypersaline palaeoenvironments represented by the red beds of the Mercia Mudstone Group were replaced by marine conditions under which the Westbury Formation was deposited. A return to mixed marine and continental conditions took place during the deposition of the Lilstock Formation. The succeeding Lias Group strata mark the beginning of a prolonged period of marine sedimentation.

The Cotham Marble is especially significant at Wetmoor, often forming a double layer (Whittard and Smith, 1944). For many years the processes responsible for the formation of the 'Landscape Marble' variety were a matter of debate and controversy (Hamilton, 1961); now it is known that the strange tree-like patterns and laminations were caused by the interactions of algae and sediment as the stromatolites (algal mounds) were formed (Hamilton, 1961; Wright and Mayall, 1981).

Conclusions

The area of the Wetmoor stream sections is one of the few inland sites where the youngest Triassic formations are exposed in south-west England. Although the outcrops are small and discontinuous, they are of good quality. Units exposed here include the Mercia Mudstone Group, the Penarth Group, and the Pre-*planorbis* Beds of the Lias Group. The site is especially important for the Cotham Marble of the Cotham Member, an unusual algal limestone that has long been known from the Bristol area, but is now unavailable at most of the formerly rich locations.

LULSGATE QUARRY, AVON (ST 519 658)

Introduction

Lulsgate Quarry exposes a composite succession of Rhaetian sediments, banked against a steep and stepped surface of Carboniferous Limestone (Figure 4.20). Preserved here are Westbury Formation clays, as well as the Cotham Marble and Langport Member limestones. These Upper Triassic sediments lie unconformably on the Carboniferous Black Rock Limestone, one of the best examples of this unconformity. Of especial importance is a coral biostrome in the Lilstock Formation.

Although Lulsgate Quarry is an important locality, it has received little attention in the geological literature. Brief mention was made by Donovan and Kellaway (1984), Green (1992), and Kellaway and Welch (1993).

Description

Lulsgate Quarry is within the Avon Ridges and Valleys Natural Area. The following composite sedimentary section is taken from a report by K. N. Page to English Nature:

	Thickness (m)
Lias Group	
Blue Lias Formation ('Aldergrove Beds'):	
Coarse bioclastic limestone with some angular clasts and shell bands (containing *Modiolus hillanus*)	4+
Penarth Group	
Lilstock Formation:	
Massive limestone with corals	~ 1.2
Massive breccia with angular and subrounded clasts in yellow limestone matrix	~ 1.1
Massive breccia-conglomerate in yellow brown limestone matrix with encrusting *Areta intusstriata* near the base	~ 2.0
Rounded and angular limestone clasts in a creamy coloured matrix, some showing algal structures ('Cotham Marble')	~0.7
?*Westbury Formation*:	
Bored and encrusted cobbles in a clay matrix	~ 0.4
Carboniferous: Black Rock Limestone	

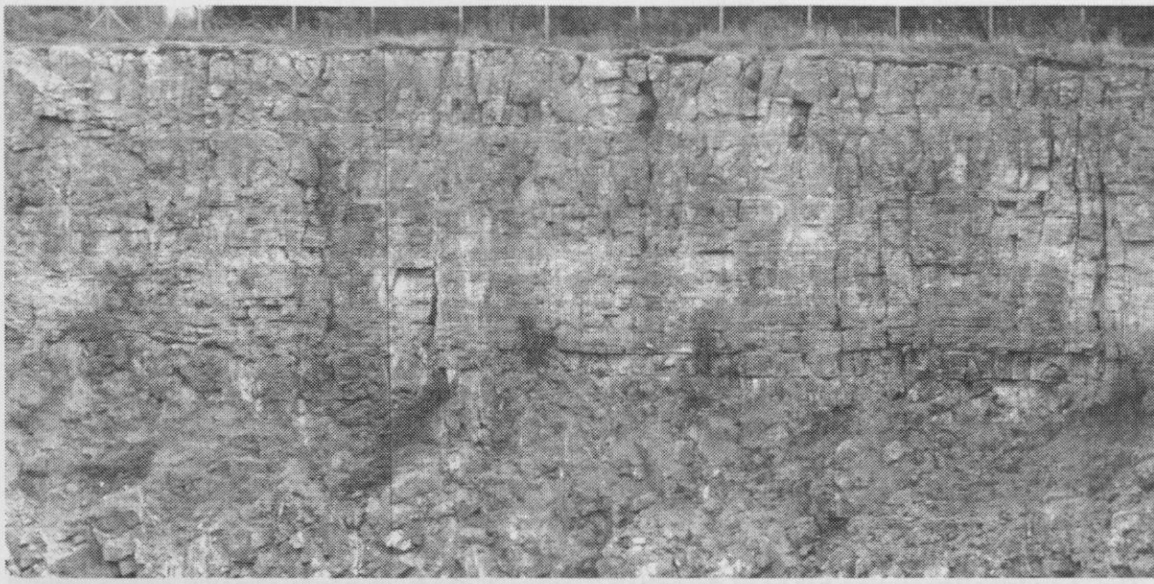

Figure 4.20 Lulsgate Quarry, view of the north face. This shows the steeply dipping Carboniferous Black Rock Limestone at the base, overlain unconformably by horizontal units of the Penarth Group. (Photo: D. Evans.)

The Upper Triassic sediments, including a coral biostrome, are banked up against the palaeo-landscape formed on Carboniferous Limestone. Fissures in the latter are common in Lulsgate Quarry, and infilling sediments include Lower Lias limestone and clay (Kellaway and Welch, 1993). The topmost unit represents the lower part of the 'Aldergrove Beds', an informal term proposed by Palmer (1972) for the basal Lias units in West Somerset, and now included in the Blue Lias Formation.

A range of fossil taxa has been described from Lulsgate Quarry, including the bivalve *Modiolus* from the upper unit, plus corals, crinoids, and bryozoans. The corals from the top of the Lilstock Formation include *Cyatharofenia dendroidia* and *Asteracoenia gibbosa*. Encrusting faunas, for example the bryozoan *Areta intusstriata*, are also known from a conglomeratic horizon in the Lilstock Formation.

Interpretation

The Upper Triassic sediments at Lulsgate Quarry preserve a record of changing environmental conditions superimposed on a Mesozoic landscape. The Carboniferous Limestone is cut into a series of steps and cliffs, and the Mesozoic sediments were deposited against this feature.

The clays immediately overlying the Carboniferous Limestone are thought to belong to the Westbury Formation. However, in certain parts of the quarry, the basal conglomerate, consisting of limestone blocks in a greenish-grey fine-grained limestone, is younger (Donovan and Kellaway, 1984). The Westbury Formation clays represent deposition in a shallow sea following a phase of marine transgression.

The overlying Lilstock Formation sediments are indicative of a lagoonal environment. The tree-like patterns in the Cotham Marble formed as algal growths (Hamilton, 1961). The algal mats probably grew in and around hypersaline lagoons. The remainder of the Lilstock Formation sediments have been interpreted as deposited in warm, shallow shelf lagoons; the presence of corals supports the interpretation of these beds as marine.

Conclusions

Lulsgate Quarry exposes Carboniferous, Triassic and Jurassic rocks. The section is important as it shows the relationships between the palaeoshoreline and the marine sediments of the Westbury Formation and the overlying lagoonal facies of the Lilstock Formation. The coral biostromes at the top of the Lilstock Formation are an unusual and notable feature of the site.

THE PENARTH GROUP OF WEST SOMERSET

ST AUDRIES BAY, NEAR WATCHET, SOMERSET (ST 907 433–ST 112 432)

Introduction

St Audries Bay includes a candidate Global Stratotype Section and Point (GSSP) for the base of the Jurassic System. This coast section also includes the type locality for the ammonite *Psiloceras planorbis*, the index fossil of the *planorbis* Zone, the basal unit of the Hettangian Stage, and hence of the Jurassic System (Warrington *et al.*, 1994; Warrington and Ivimey-Cook, 1995).

The St Audries Bay section has been described by many authors, including Richardson (1911), Warrington (1974b), Hamilton and Whittaker (1977), Sykes (1977), Mayall (1979, 1981, 1983), Whittaker and Green (1983), MacQuaker (1984, 1994), Warrington and Whittaker (1984), Leslie *et al.* (1993), Talbot *et al.* (1994), Warrington *et al.* (1994), and Swift (1995). The proposal that a site in this area should be the global standard for the base of the Jurassic System was discussed by George *et al.* (1969), Morton (1971), Warrington *et al.* (1994), and Warrington and Ivimey-Cook (1990, 1995). Briden and Daniels (1999) presented a magnetostratigraphical record of the Mercia Mudstone Group part of the section.

Description

The cliffs at St Audries Bay (Figure 4.21), 5 km east of Watchet, expose the upper Mercia Mudstone Group, the Penarth Group and Lower Lias deposits including the Pre-*planorbis* Beds, and overlying Lower Jurassic rocks of Hettangian and Sinemurian age. The beds dip to the south-west, so progressively younger units are exposed from east to west. The Penarth Group occurs in the cliffs in the western side of the bay and crops out on the foreshore. The unstable nature of the cliffs means that the 'fresh' exposures of the section are continually produced by natural erosive processes. St Audries Bay forms part of the extensive Blue Anchor to Lilstock Coast Site of Special Scientific Interest (SSSI).

Sedimentology

The Mercia Mudstone Group exposed here comprises red and green mudstones (*c.* 67 m seen) succeeded by the overlying Blue Anchor Formation (*c.* 37 m thick); the beds dip to the south-west and are affected by small faults (Leslie *et al.*, 1993).

The Blue Anchor Formation is divided into the Rydon and Williton members (Mayall, 1981). The 34 m-thick Rydon Member (approximately equivalent to the 'Tea Green Marls' and 'Grey Marls' of the former terminology) is characterized by grey, black, green and occasional red-brown, dolomitic mudstones and dolomites. The more resistant dolomites often form prominent bands, especially in the upper sections of the member. The beds also contain gypsum crystals; these comonly dissolve out, forming cavities or collapse breccias (Mayall, 1981). The thin Williton Member (formerly named the 'Sully Beds'), rests disconformably on the Rydon Member, above an erosion surface penetrated by *Diplocraterion* burrows. The Williton Member consists predominantly of grey shales with flaser and lenticular beds of fine sandstone and silt.

The Westbury Formation comprises alternations of thinly laminated black shales with occasional thin limestones. The Lilstock Formation is composed of mudstones, limestones and marls with rare sandstones that comprise the Cotham Member. Some Cotham Member sediments bear deep cracks on upper surfaces. The upper parts of the formation are the Langport Member.

The following detailed composite description is taken from Whittaker and Green (1983, pp. 47–58), measured west of St. Audries Slip (ST 1032 4327):

	Thickness (m)
Penarth Group	
Lilstock Formation: Langport Member:	
Mudstone, grey, with a green tint and with impersistent limestones	0.34
Limestones, brownish-grey, fine-grained, hard and splintery and divisible into four beds. The top is somewhat irregular. The lowest bed is composed of rubbly limestone and has an irregular base	0.3–0.33
Mudstone, greenish-grey, marly, silty and blocky. More fissile in	

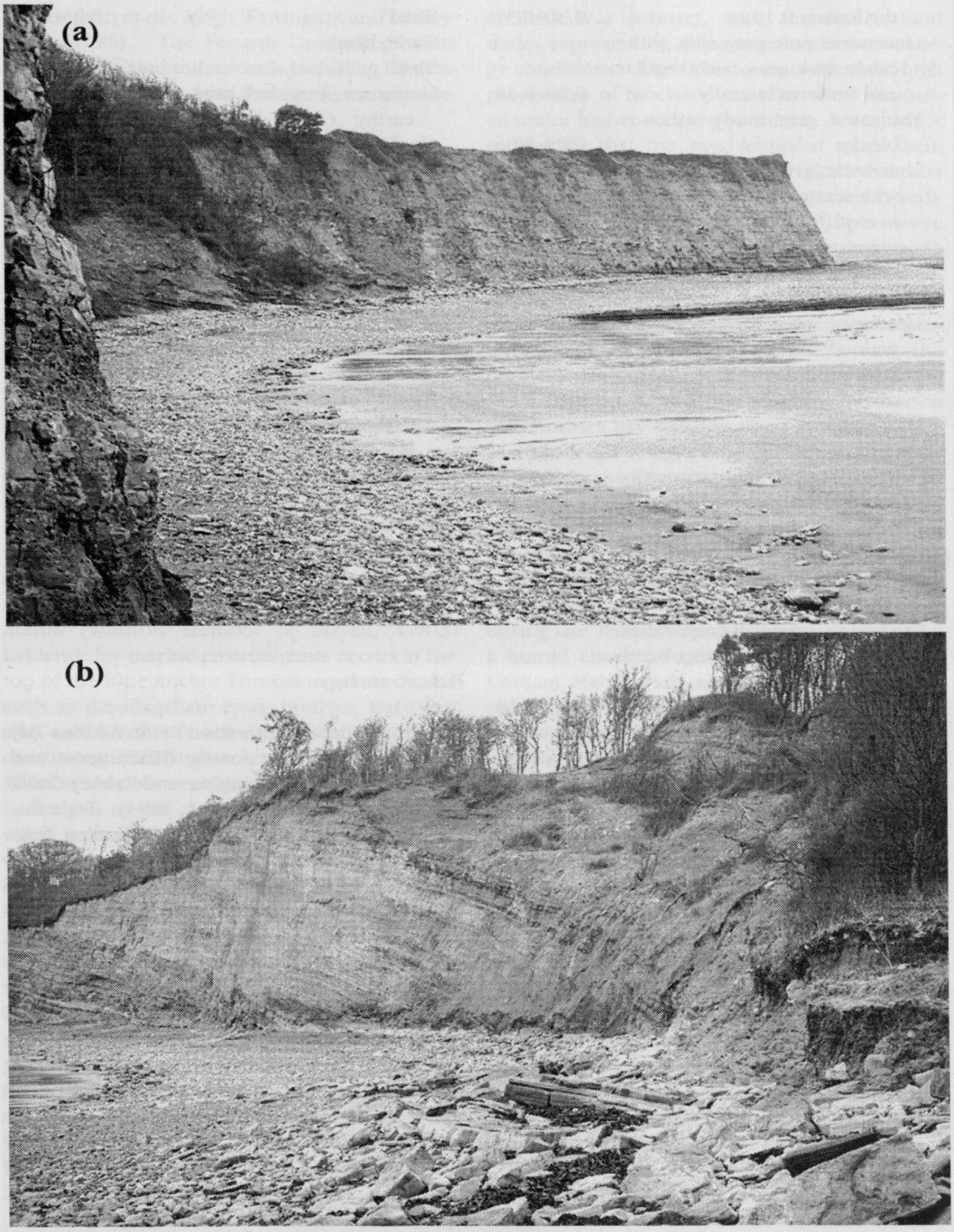

Figure 4.21 The Penarth Group at St Audries Bay. (a) The west side of the bay. The Blue Anchor Formation is in the left foreground. The Penarth Group is in the left middle distance and below the Lias Group in the cliff in the background. The base of the Jurassic succession is at the foot of the headland. (b) View looking east from the Penarth Group exposure at beach level. The cliff consists largely of the Rydon Member (Blue Anchor Formation) overlain by the Williton Member. The Westbury Formation dips towards the right from the highest point in the cliff. (Photos: Andrew Swift.)

the lowest 0.10 m	0.30–0.33
Limestone, pale grey, silty, with calcite stringers; fairly regular and uniform laterally	0.09–0.10
Mudstone, grey, marly, rather blocky	0.05–0.06
Limestone, grey, hard, splintery, with scattered pyrite. Locally in two (0.05 m thick) beds separated by a mudstone parting	0.10
Mudstone, dark grey, marly and rather shaly	0.06
Limestone, grey, hard, very fine-grained, almost porcellanous; laminated and with vertical calcite stringers	0.10–0.15
Marl, grey	0.03
Limestone, pale grey, fine-grained, porcellanous, splintery, with a conchoidal fracture. Not everywhere present	0–0.05
Lilstock Formation: Cotham Member:	
Shale, greenish-grey, laminated, fairly blocky in the top 0.08 m	0.38–0.46
Sandstone, greenish-grey. Small cavities are present in a band 0.05 m below the top; the bed is laminated in the lowest 0.06 m	0.15–0.18
Marl, greenish-grey or green, fairly fissile	0.03
Sandstone, dark greenish-grey	0.03–0.04
Siltstone, greenish-grey, hard, marly. Contortions and slump structures are present in the top half; the bed is laminated below	0.20–0.28
Mudstone, green or olive-green; marly but fairly fissile in the top 0.15 m and the bottom 0.10 m	0.43
Siltstone or silty marl, hard, calcareous; somewhat laminated, with a lensoid parting character	0.15–0.19
Marl, pale green, rather fissile, with contorted harder beds in places	0.63
Westbury Formation:	
Shale, black	0.05
Shale, black: a lensoid band of intercalated green marl	0.03–0.05
Shale, black, with green marl wisps and partings	0.05–0.08
Marl, dark grey, silty, hard, calcareous	0.05–0.08
'Beef'	0.03–0.05
Shale, black	0.53–0.61
'Beef'	0.03–0.05
Limestone, very dark grey, earthy	0.03–0.05
'Beef'	0.03–0.08
Shale, black	0.91–0.97
'Beef'	0.05–0.08
Limestone, dark grey, earthy	0.08–0.10
Shale, black	0.03
Limestone, dark grey, earthy	0.13–0.20
'Beef'	0.03
Shale, black	seen 0.15
Mercia Mudstone Group	
Blue Anchor Formation: Williton Member:	
Predominantly of greyish and dark marls with occasional shales. Hard siltstones at the top	3.0
Blue Anchor Formation: Rydon Member ('Tea Green Marl'):	
Green marls	34.0
Undifferentiated mudstones:	
Red and green mudstones, with a few green siltstone beds	seen 67.25

Palaeontology

The Blue Anchor Formation at St Audries Bay has yielded diverse fossils (Warrington and Whittaker, 1984; Warrington and Ivimey-Cook, 1992, 1995; Warrington *et al.*, 1994). Trace fossils, invertebrate body fossils, including fragmentary gastropods and remains of vertebrates such as the fishes *Gyrolepis*, *Hybodus* cf. *cloacinus*, '*Sphaerodus*', and '*Sargodon*' have been recorded from the upper beds in the formation (Warrington and Whittaker, 1984).

Dinoflagellate cysts occur sporadically in the uppermost metre of the Blue Anchor Formation (Warrington, 1974b). The palynomorph assemblage from the beds at the top of the Williton Member is one of the most diverse in the country from beds of this age, and includes miospores and organic-walled microplankton (Warrington, 1974b, 1981; Warrington and Whittaker, 1984; Warrington and Ivimey-Cook, 1995).

The Westbury Formation contains a diverse invertebrate and vertebrate faunal assemblage, including bivalves (*Chlamys*, *Protocardia*, *Rhaetavicula*), ophiuriods, scales and teeth of marine fishes (*Acrodus*, *Birgeria*, *Dalatias*, *Gyrolepis*, *Hybodus*) and marine reptiles

(Warrington *et al.*, 1994; Warrington and Ivimey-Cook, 1995). The Penarth Group sediments have also yielded microfossils including dinoflagellate cysts, miospores, foraminifera and scolecodonts (Warrington, 1974b, 1981).

Interpretation

The sediments at St Audries Bay document changing palaeoenvironments, from terrestrial hypersaline lakes to marine conditions. The oldest beds, the fine-grained, red, calcareous and dolomitic sediments of the Mercia Mudstone Group, are thought to have been deposited in water on a low-lying plain that was probably close to sea level (Hamilton and Whittaker, 1977; Talbot *et al.*, 1994). Palaeomagnetic measurements on the Mercia Mudstone Group red beds (Briden and Daniels, 1999) supported a general assumption that these units are Norian in age.

The Blue Anchor Formation sediments represent terrestrial evaporitic lakes (Rydon Member of Mayall, 1981) and shallow marine environments (Williton Member of Mayall, 1981). Evidence for marine environments occurs at the top of the Blue Anchor Formation, where fossils such as dinoflagellate cysts, bivalves, trace fossils, and foraminifera indicate shallow marine conditions (Warrington *et al.*, 1994) of the Williton Member sea (Mayall, 1981).

Analysis of the clays (Mayall, 1979) has provided a more complete understanding of the depositional environments of the Triassic sediments at several localities, including St Audries Bay. The presence of corrensite in the Williton Member suggests that North Somerset was located at the edge of an evaporitic drainage basin. Sedimentary structures such as ripples and mudcracks, as well as evaporite minerals, appear to support this view. Changes in the clay mineralogy (the appearance of vermiculite and an increase in the relative abundance of illite-smectite) across the boundary between the Williton Member and the overlying Westbury Formation suggest that the boundary represents a minor hiatus (Mayall, 1979).

The Westbury Formation is characterized by alternating beds of shales and limestones, which might indicate fluctuations in the energy regime associated with changing sea level and storm activity, or fluctuations in seawater chemistry. MacQuaker's (1984) petrographical analysis of the sediments led him to conclude that the cyclicity was primary, with the fine-grained shales representing deposition under low-energy conditions. The limestones, with their high proportion of bioclastic material, were deposited under higher-energy conditions. From this, it is thought that the two sediment types were deposited on a shallow marine shelf that was prone to storm activity. During storms, sediment and shells from the sea floor were reworked, producing the coarser-grained sediment fraction (MacQuaker, 1984). The sediments also display the results of early-stage diagenetic activity, for example micrite, the production of cone-in-cone structures and the decalcification of some of the shell material.

The basal 0.36 m of the Westbury Formation at St Audries Bay was described by Sykes (1977) as a black shale, with minor bone beds distributed through the sediment. It is thought that the bone beds represent a phase of reworking associated with storm events and transgression (MacQuaker, 1994).

The clay mineral kaolinite in the Lilstock Formation of Somerset and Devon suggests that during late Triassic times the region experienced a humid climatic regime (Mayall, 1979). The Cotham Member calcareous grey and greenish mudstones, siltstones and sandstones were deposited in a shallow lagoon, which may have experienced periods of emergence, as indicated by deep cracks in the surfaces of some beds (Mayall, 1981). A distinctive deformed bed in the lower part of the Cotham Member may have been deposited in an extensive shallow-water body, and deformed by dewatering or slumping of unconsolidated sediments (Whittaker and Green, 1983), possibly initiated by local vertical uplift or tectonic activity (Mayall, 1983). The Langport Member was deposited in warm, very shallow shelf lagoons. The porcellanous limestones are thought to have formed under emergent conditions where calcium carbonate crystallized very quickly. The greyish muds may have been deposited in slightly deeper waters (Whittaker and Green, 1983).

The ammonite *Psiloceras planorbis* has long been known from the Lias sediments of St. Audries Bay (Warrington *et al.*, 1994), and indeed, the Watchet area is the type area for this ammonite.

Conclusions

The Triassic and Jurassic sediments exposed in the sea cliffs and on the foreshore of St. Audries Bay form a classic example of the succession from the Mercia Mudstone Group, through the Penarth Group, into Lias Group, and span the Triassic–Jurassic boundary. These sediments record a transition from continental conditions, from supra- and inter-tidal sabkhas and lagoons in the Mercia Mudstone Group, to more established marine conditions in the Westbury Formation; a return to lagoonal environments characterized the Lilstock Formation. This excellent section is of international significance, as candidate GSSP for the base of the Jurassic System (Warrington *et al.*, 1994).

BLUE ANCHOR POINT, SOMERSET (ST 033 435–ST 056 434)

Introduction

This locality shows a section of Upper Triassic formations, from the Blue Anchor Formation at the top of the Mercia Mudstone Group, upwards through the Penarth Group into the basal Blue Lias. The Blue Anchor Formation and Penarth Group have yielded a large variety of fossils including fishes, reptiles, coprolites, and the remains of the possible early mammal *Hypsoprymnopsis*. Blue Anchor Point (ST 0385 4368) is the type locality of the Upper Triassic Blue Anchor Formation of the Mercia Mudstone Group (Warrington *et al.*, 1980; Warrington and Whittaker, 1984).

One of the first descriptions of the geology of the cliffs around Blue Anchor was by Boyd Dawkins (1864a), who also summarized the palaeontology. Since then, the sediments have been described by Richardson (1911) and the mineralogy by Bradshaw and Hamilton (1967). The most recent accounts are by Warrington and Whittaker (1984), Warrington and Ivimey-Cook (1995), and Edwards (1999).

Description

The coastal cliffs at Blue Anchor Point form part of the extensive Blue Anchor to Lilstock Coast Site of Special Scientific Interest (SSSI).

Sedimentology

The section at Blue Anchor is composed of deposits from the upper part of the Mercia Mudstone Group and the Penarth Group (Figure 4.22). The majority of the exposed Mercia Mudstone Group comprises red mudstones. The lower part of the overlying Blue Anchor Formation, the Rydon Member, comprises dark green and greenish-grey mudstones and siltstones. Its basal boundary is placed at the base of the lowest dark grey mudstone (Warrington and Whittaker, 1984), although the colour change from the underlying red mudstones is gradational over approximately 1 m.

The overlying Williton Member comprises siltstones and mudstones with gypsum present as nodules and veins that range in colour and form (Warrington and Whittaker, 1984). The gypsum occurs as nodules of pink or white, coarse-grained alabaster in the laminated mudstones, as thin veins of white, fibrous crystals parallel to the bedding, and as conjugate veins of pink satin spar (Bradshaw and Hamilton, 1967). In places, the gypsum has been partly replaced by silica (Mayall, 1981). The gypsum and alabaster veins show complex patterns of intersection that allow reconstruction of the fine-scale tectonic history of the rocks here (Figure 4.23).

The basal unit of the Penarth Group, the Westbury Formation, includes three main bone-bearing horizons, all containing large quantities of vertebrate fossils associated with sand-sized quartz grains and pebbles. Silica overgrowths have been recorded from many of the quartz grains (Antia and Sykes, 1979). The lowest of the bone-bed horizons, a 0.15 m thick sandstone, marks the base of the Westbury Formation; two bone beds occur approximately 1.5 and 6 m farther up the section. The remainder of the formation consists of black shales and dark shelly limestones, some of which contain concentrations of reworked shell debris and have channel fills on the lower surfaces of the bed and rippled upper surfaces. Fibrous calcite crystals are present within the limestone facies (Hamilton and Whittaker, 1977).

The overlying Cotham Member rests unconformably on the Westbury Formation. The Cotham Member comprises limestones with common ripples and desiccation cracks, and rarer septarian-type nodules (Hamilton and Whittaker, 1977). A deformed bed attributed to seismic activity is well exposed here (Mayall, 1983). At the top of the Blue Anchor section, the lowest beds of the Lias Group are seen (Hamilton and Whittaker, 1977; Edwards, 1999).

The following generalized section is taken

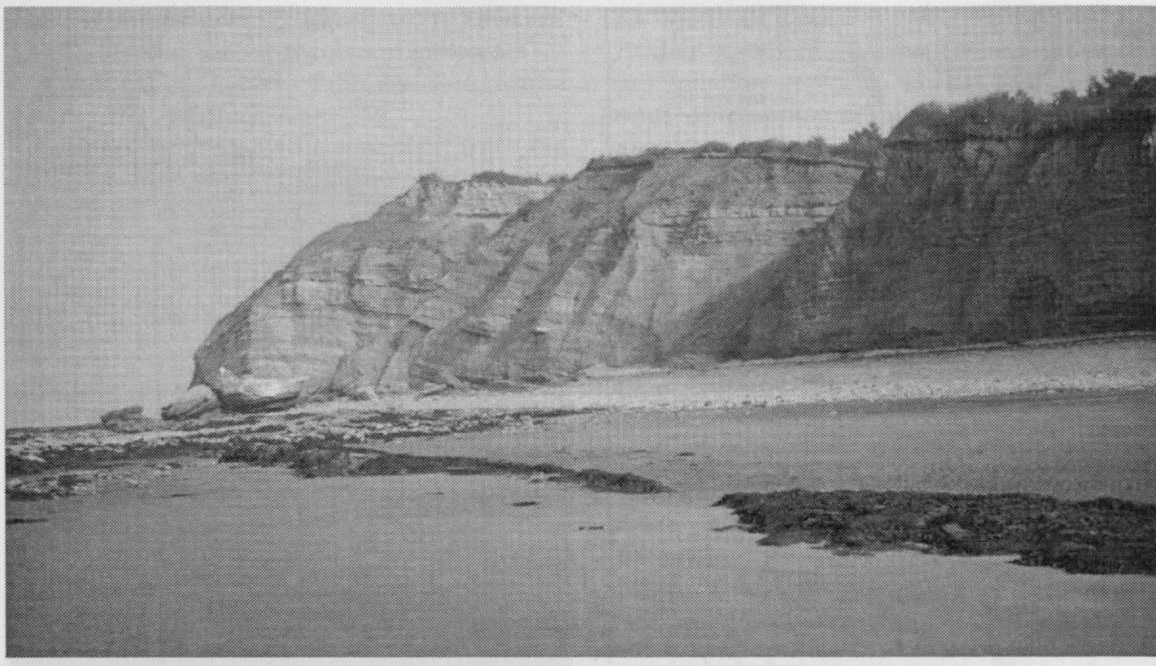

Figure 4.22 View of Blue Anchor Point, looking east, showing the anticlinal arrangement of the deposits at the far left, and multiple faults behind. (Photo: K. A. Kermack.)

from Sykes (1977, p. 231), for the Westbury Formation, and Warrington and Whittaker (1984, pp. 101–2) for the Blue Anchor Formation:

	Thickness (m)
Lias Group	
Penarth Group	
Lilstock Formation: Cotham Member:	
Shales, mudstones, and limestones	*c.* 4
Westbury Formation:	
Limestone (*Pleurophorus*), medium grey, with shells and fibrous calcite	0.23
Black fissile shale with bivalves	0.2
Bone bed: a composite bed:	0.28
(a) massive, calcareous gritstone with many vertebrate fossils, and rare coprolites. Thin, white veins pass through the bed and may cut across the fossils	up to 0.12
(b) transition to the bone bed below. Layers of calcareous bone bed sandstone, thin layers of black shale and some limestone; less quartz. Fines downwards	0.05
(c) alternations of non-calcareous, fissile, black shale and thin layers of calcareous bone bed sandstone. Ripples throughout. Shale contains bivalves, which may lie directly on the sandstone. Thin sandstone ranging in thickness from very thin to wedges 11 mm thick. Fine- to medium-grained sandstone, fossils scarce and scattered through the sandstone	0.07
(d) fibrous calcite with a variable thickness	up to 0.03
(e) calcareous sandy bone bed on black shale; shells in lower part; silty towards the top	0.018
Black, fissile shale, many bivalves	0.15
Massive, grey limestone with limestone and shales at the top	0.6
Shale and limestone, black shale and limestone with limestone at the base	not determined
Black shale	0.12
Limestone with fibrous calcite at the top and nodules at the base	0.15
Shales and limestone, poorly exposed	0.91
Limestone and shale. Limestone dark grey, unbedded. The first shales are bedded and unfossiliferous; others are unbedded in places. Silt occurs as a thin alternation with the black shale	0.9

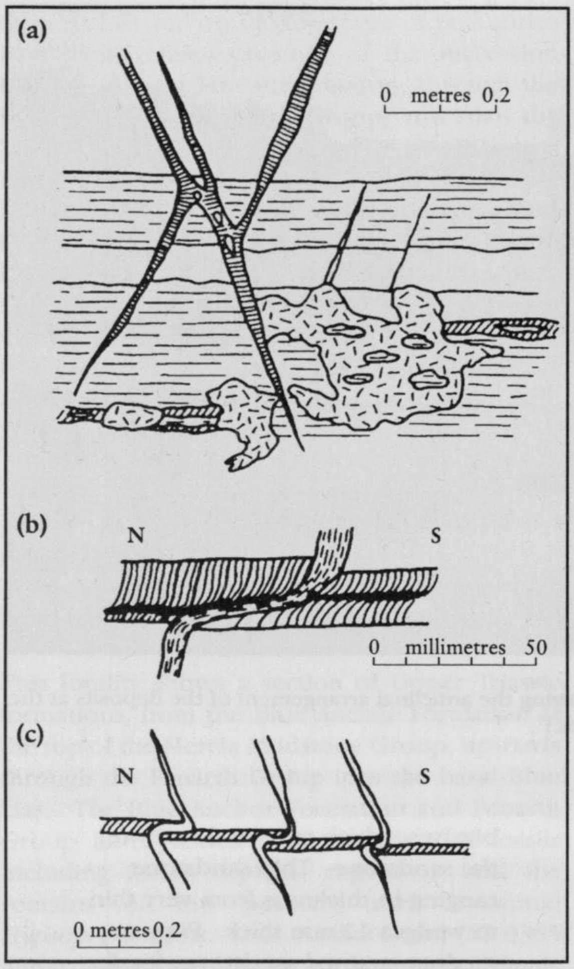

Figure 4.23 Relationships of the various forms of gypsum at Blue Anchor Point. (a) Nodular alabaster in the laminated beds, with white veins parallel and cross-cutting pink veins. (b, c) Horizontal white veins cut by thin, pink veins and both deformed by subsequent movements. (After Hamilton and Whittaker, 1977.)

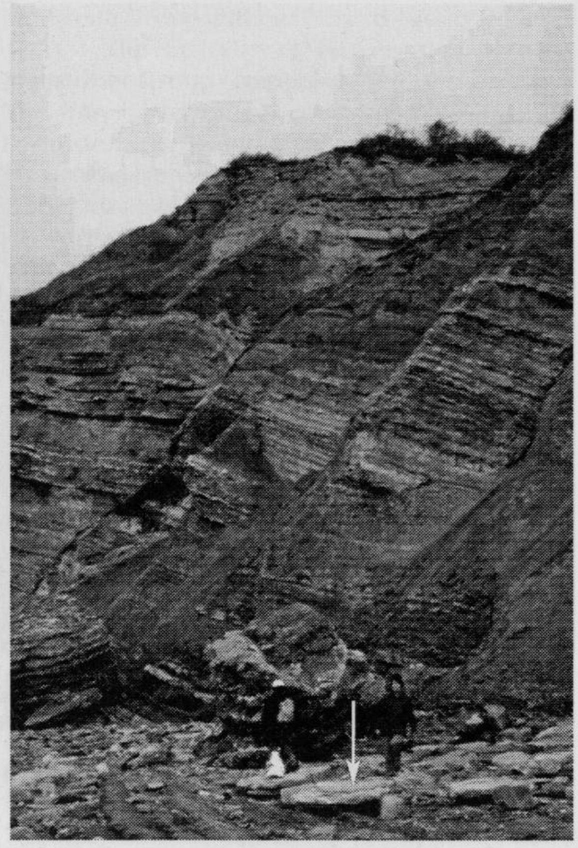

Figure 4.24 Detail of the multiple faults at Blue Anchor Point, disturbing the succession of Blue Anchor Formation (lower part of cliff) overlain by Westbury Formation at the top. A boulder of the latter, with the bone bed (arrowed), lies on the beach. (Photo: K. A. Kermack.)

Limestone, dark grey, with bivalves	not determined
Black fissile shale	0.9+
Thin sandy limestone with scattered, well-preserved vertebrates	0.025
Shelly mudstone, many shelly fragments in a mudstone matrix. Upper part is more shelly. Quartz and abraded bone fragments are scattered through the rock. Fragments of Blue Anchor Formation mudstone occur, especially near the base	0.12
Mercia Mudstone Group	
Blue Anchor Formation: Williton Member:	
Thin beds of greenish-grey or dark grey mudstone with paler shales and a few gypsum horizons	*c.* 4
Blue Anchor Formation: Rydon Member:	
Interbedded greenish or greyish siltstones, rarely pebbly, and greenish mudstones. One gypsum horizon	*c.* 30
Red-brown mudstones	

Structural Geology

The rocks around Blue Anchor Point have been faulted and folded. To the west of the Point, red-brown mudstones of the Mercia Mudstone Group have been faulted into contact with green and grey deposits in a downfaulted block that consists of the Blue Anchor Formation to Lias sequence (Figure 4.24). An asymmetrical anticlinal fold with an axis trending 100° is seen at Blue Anchor Point (Bradshaw and Hamilton, 1967; Hamilton and Whittaker, 1977; Edwards, 1999); the Blue Anchor Formation sediments are exposed within the core of this anticline (Figure 4.22).

On the foreshore at Blue Anchor Point the sediments that form the northern limb of the anticline dip seawards. These beds display more evidence of tectonic deformation as a few WNW-trending faults cut the exposure (Hamilton and Whittaker, 1977). Many of the gypsum veins seen in the sediments of the cliffs and foreshore owe their origin to the formation of the anticline (Bradshaw and Hamilton, 1967; Figure 4.22).

Small-scale synsedimentary microfaults have been described from the sediments of the Williton Member. These are thought to have been produced by the movement of sediment down small inclines (Mayall, 1981).

Palaeontology

A wide range of fossils including remains of plants, invertebrates, and vertebrates have been recorded from several horizons at Blue Anchor. Of particular note are the Westbury Formation bone bed (Boyd Dawkins, 1864a,b) and the sediments exposed some three metres below the bone bed (Hamilton and Whittaker, 1977; Warrington and Whittaker, 1984). Remains of fossil fishes from this area are listed by Dineley and Metcalfe (1999)

Invertebrate taxa are represented by trace fossils and body fossils. Boyd Dawkins (1864a) recorded holes, tracks, and trails from the top 1.83 to 4.17 m of the Blue Anchor Formation near its type locality (Warrington and Whittaker, 1984; Warrington and Ivimey-Cook, 1995). Other trace fossils include *Arenicolites*, *Diplocraterion*, *Muensteria*, *Planolites*, *Rhizocorallium*, and *Siphonites* from the vicinity of Blue Anchor (Mayall, 1981). Body fossils of several species of bivalve occur in the uppermost part of the Blue Anchor Formation (Warrington and Whittaker, 1984; Warrington and Ivimey-Cook, 1995). Palynomorphs, such as miospores and organic-walled microplankton, are also preserved within these sediments (Warrington and Whittaker, 1984).

Fish fossils include '*Sargodon tomicus*', *Saurichthys apicalis*, *Acrodus minimus*, *Gyrolepis alberti*, and *Gyrolepis tenuistriatus* from approximately 3 m below the top of the Blue Anchor Formation and from the top 1.83 m of this unit (Boyd Dawkins, 1864a,b; Warrington and Whittaker, 1984).

Other vertebrate remains include indeterminate (possibly reptilian) bones from the sediments outcropping between 2.44 and 4.27 m from the top of the Blue Anchor Formation near the type site (Boyd Dawkins, 1864a; Warrington and Whittaker, 1984). The Westbury Formation bone beds have produced possible crocodile remains and the bones of the semi-aquatic choristodere *Pachystropheus* (Richardson, 1911; Storrs and Gower, 1993; Storrs *et al.*, 1996; Storrs, 1999). From the bone beds, Boyd Dawkins (1864a, pp. 409–12) described a single tooth as belonging to a mammal, *Hypsiprymnopsis rhaeticus*. Owen (1871) thought that the specimen was possibly a broken haramiyid mammal tooth, while others (Clemens *et al.*, 1979; Storrs, 1994, 1999) have suggested it might be an indeterminate tritylodontid or other cynodont.

Interpretation

The sedimentary rocks exposed at Blue Anchor Point and Blue Anchor Bay represent a series of distinct palaeoenvironments, from the dominantly terrestrial conditions of the Mercia Mudstone through to the fully marine Lias.

The red, argillaceous sediments of the lower part of the Mercia Mudstone Group section were deposited in a supratidal sabkha or playa-lake environment (Warrington and Whittaker, 1984), with ephemeral lakes and occasional floods from the surrounding uplands.

The overlying grey and green mudstones and siltstones of the Blue Anchor Formation were deposited on a dominantly terrestrial supratidal and intertidal sabkha plain (Warrington and Whittaker, 1984). The Williton Member contains sulphate nodules and carbon-rich mudstones that may have been formed under the algal mats characteristic of a supratidal sabkha environment (Stevenson and Warrington, 1971; Warrington and Whittaker, 1984). Petrographical analysis of the gypsum nodules indicates that they formed penecontemporaneously with the sediment (Bradshaw and Hamilton, 1967). The algal mat lithologies alternate with various fine-grained sediments that represent low-energy conditions of deposition (Warrington and Whittaker, 1984). The very top of the Blue Anchor Formation represents a shallow-water environment, possibly with tidal influence (Hamilton and Whittaker, 1977).

The basal unit of the overlying Westbury Formation is thought to represent the development of marine or marginal marine conditions. The bone beds represent reworking caused by transgression (Whittaker and Green, 1983). The hard, shell-rich limestones contain sedimentary structures indicative of emergent tidal flat environments, for example oscillation truncated crested and terraced ripples. These pass vertically into laminated muds deposited in standing water (Hamilton and Whittaker, 1977). Sediments of the Cotham Member were deposited in shallow lagoons (Mayall, 1981).

Conclusions

The Upper Triassic sediments exposed in the cliffs and on the foreshore at Blue Anchor form part of one of the best exposures of Rhaetian age sediments in the country. Blue Anchor Point is the type locality for the Blue Anchor Formation, and the exposures here are additionally important as they show gypsum evaporites unusually well. The site has, over the years, produced a wide variety of fossils, including various invertebrates as well as rarer reptilian and mammalian remains, and is nationally important for stratigraphical and palaeoenvironmental reasons.

THE PENARTH GROUP OF DEVON

CULVERHOLE POINT, NEAR AXMOUTH, DEVON (SY 275 893)

Introduction

Upper Triassic strata including the Blue Anchor Formation, and the Westbury and Lilstock formations of the Penarth Group, are exposed in a 5-km-long coastal strip between Axmouth and Culverhole Point. The Penarth Group bone bed here is highly fossiliferous, and has yielded several archosaur fossils.

The area around Culverhole Point has been studied by geologists for many years. One of the first descriptions was published by Wright (1860) who studied the '*Avicula contorta* Zone' of the Westbury Formation. Subsequent studies include Woodward and Ussher (1899, 1906), Jukes-Brown (1902), Richardson (1906), Ager and Smith (1965), Stevenson and Warrington (1971), Warrington and Scrivener (1980), House (1989), and Warrington (1997a).

Description

The Triassic succession at Culverhole Point is overlain unconformably by Cretaceous sediments, including the Gault and Chalk (Sellwood *et al.*, 1970; House, 1989). Culverhole Point is a protected locality and forms a part of the Axmouth to Lyme Regis Undercliffs National Nature Reserve, and is also included in the Dorset–East Devon Coast World Heritage site, established December, 2001.

Sedimentology

The Penarth Group outcrops in several parts of the cliffs and foreshore at Culverhole Point. The western end of the section comprises the Westbury Formation and the underlying argillaceous sediments of the Blue Anchor Formation. The eastern part of the section includes the Blue Anchor Formation, Westbury Formation, Cotham Marble, and 'White Lias' (Richardson, 1906). The Penarth Group dips approximately 5° to the east. The following description is modified from Richardson (1906, table facing p. 406), Stevenson and Warrington (1971), and Sykes (1977):

	Thickness (m)
Penarth Group	
Lilstock Formation; Langport Member:	
Limestone, hard, grey, with an irregular upper surface	0.25
Shales, greenish-grey, thinly laminated, calcareous, darker at the base	0.13
Limestone	0.05
Rubbly, white limestone and greenish-grey, thinly laminated, calcareous shales	0.15
Limestone, hard, white, irregular top, pyritic, shelly and bored	0.28
Lilstock Formation; Cotham Member:	
Clay, dark brownish-black	0.09
'False Cotham Marble': pale greenish-grey, slightly pyritic	0.04–0.06
Shales, greenish-grey, thickly laminated, calcareous, with several hard, gritty layers	0.30
Limestone, cream coloured, earthy, shaly	0.25
Marls, pale greenish-yellow, indurated and laminated at the top; softer and	

darker in the middle; indurated and yellowish at the base; impersistent, pale grey, impure limestone and thin sandstone layers also occur	0.66
Dark, calcareous shales	0.13
Limestone, yellowish-grey, earthy, impersistent	0.11–0.20
Shales, indurated, dark, earthy	0.13
Westbury Formation:	
Shales, black, much selenite, upper portion dark green	0.61
Shales, brown, earthy; selenite present	0.10
Limestone, dark-grey, earthy, with a 0.01 m layer of 'beef' at the top	0.30
Shales, black, poorly laminated at the base, laminations well-defined towards the top; selenite-rich; thin sandstone layer 0.20 m from top	~1.14
'Beef'	0.03
Shales, black, laminated, earthy	0.05
Limestone, pale grey with a slight greenish tinge, nodular	0.10–0.25
Shales, black, earthy, selenite-rich	0.33
Limestone, very hard, dark grey; thin, shaly, pyritic layers near the top	0.20
Shales, black, laminated	seen 0.18
Culverhole Bone Bed: black shale, indurated and gritty, infills cracks in underlying marl	0.05
[non-sequence]	
Mercia Mudstone Group	
Blue Anchor Formation:	
Greenish-grey marls, harder at the top	~2.44
Greyish-green and blackish earthy marlstones, mixed with black shale	seen 1.52
Pale greyish-green marls, white in places	~2.44
Black marl, bounded top and bottom by whitish marlstones	0.61
Greyish-green marls and grey marlstones	4.11
Hard, greenish-grey marl, pink at the top and bottom	0.79
Marl, soft, greenish-grey	0.30
Grey, marlstone	0.30
Greenish marl, pinkish at bottom	0.30
Marlstone, in three beds	0.48
Series of greenish-grey, pinkish and black marls in regular units	~ 3.35
Marlstones, greyish-green, massive	0.61
Greyish-green, black and pink marls and marlstones	1.42
Marlstone, hard, greyish-white, with black shale on the underside	0.25
Greenish-grey marls and marlstones	0.62
Irregular zones of red, green, and dull-red marls	0.91
Red mudstones:	
Red marls, with several well-marked greenish units	

Low in the section, reddish-coloured mudstones are overlain by the greenish-grey muds and marls of the Blue Anchor Formation, both units of the Mercia Mudstone Group. Although there is little lithological difference between these two facies, they are mapped separately because of the clear colour difference. The Blue Anchor Formation is exposed at Culverhole on broad reefs on the foreshore and in Haven Cliff to the west. Many of these beds are finely laminated, in places contain nodules of gypsum, and may show evidence of desiccation cracking (Sellwood *et al.*, 1970). Small-scale structural features in the Blue Anchor Formation sediments include microfaults in finely laminated beds, suggesting movement after the rock was consolidated, and flame structures characteristic of soft-sediment deformation. Harder beds are occasionally folded into gentle folds with an amplitude of up to 0.30 m (Sellwood *et al.*, 1970).

The junction between the Mercia Mudstone Group and the overlying Penarth Group is marked by a clearly defined non-sequence (Richardson, 1906), probably associated with the Late Triassic transgression, and the change from dominantly terrestrial to marine conditions of deposition. The basal bed of the Westbury Formation is the bone bed, referred to by Woodward and Ussher (1911, p. 136) as the 'Axmouth Bone Bed', and termed here the 'Culverhole Bone Bed'. It is characterized by gritty sediment, including clasts of the Blue Anchor Formation, that may infill cracks and burrows in the surface of the underlying Blue Anchor Formation (Richardson, 1906; Sellwood *et al.*, 1970; Figure 4.25). At Culverhole Point the bone bed crops out at beach level, but is often obscured by modern beach sediments (House, 1989). The remainder of the Westbury Formation comprises laminated shales and thin limestones.

The Lilstock Formation is dominated by lime-

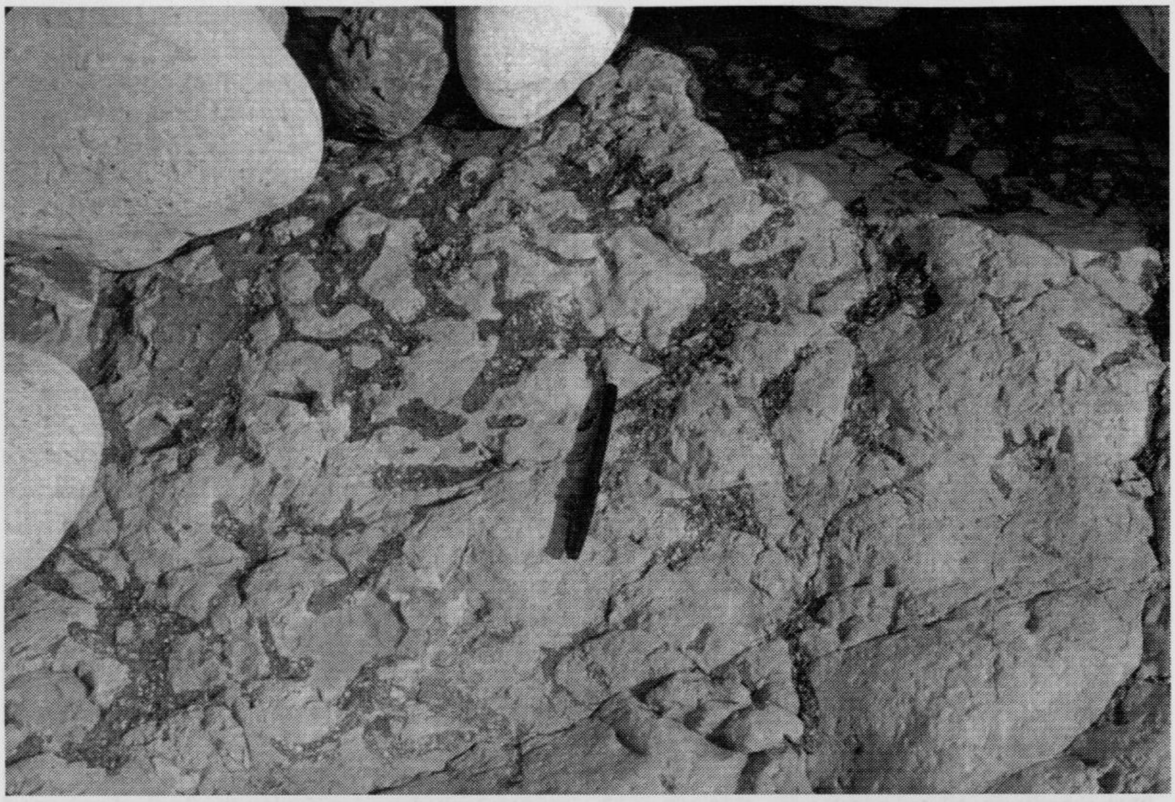

Figure 4.25 The basal Westbury Formation bone bed (the Culverhole Bone Bed) infilling cracks and burrows in the eroded surface of the Blue Anchor Formation at Culverhole Point. (Photo: R. J. G. Savage.)

stones, although the Cotham Member also includes a substantial quantity of dark and greenish shales (Richardson, 1906). Three of the Lilstock Formation beds are of special significance. The first is the Cotham Marble, represented here by the 'Crazy Cotham' variety, composed of a limestone breccia in a limestone matrix. This bed is seen at many localities over a wide area of south-western Britain, from Culverhole Point on the south coast northwards to Taunton and the Bristol district (Hamilton, 1961). The second unit, the '*Euestheria*-Bed', is also characterized by a wide geographical distribution. Richardson (1906) described several instances where these two beds have been confused, leading to the incorrect identification of the Cotham Marble. Finally, Mayall (1983) recorded the presence of the 'deformed bed', a part of the Cotham Member, which is also seen over much of south-west England, and is interpreted as possible evidence for contemporary seismic activity.

Only part of the Langport Member is seen at Culverhole Point; it is better exposed at nearby Pinhay Bay (see site report below). At Culverhole Point the Rhaetian is truncated below a major unconformity that separates the Triassic succession from the Cretaceous Chalk.

Palaeontology

Richardson (1906) described the Mercia Mudstone Group as being largely unfossiliferous, but the Blue Anchor Formation has yielded palynomorphs in this area (Stevenson and Warrington, 1971; Orbell, 1973; Warrington, 1997a).

The Culverhole Bone Bed has, since the last century, been a valuable source of vertebrate remains; a second bone-bearing bed is separated from the basal bone bed by a horizon of laminated black shales. Taxa recorded from this locality (p. 340 in Dineley and Metcalfe, 1999) include the fishes *Gyrolepis*, *Lepidotes*, and *Saurichthys*, as well as the sharks *Acrodus* and *Hybodus*. Most of these taxa are preserved as scales and teeth, although coprolites also occur. Rarer remains include those attributable to terrestrial vertebrates (Richardson, 1906), probably archosaurian reptiles (Benton and Spencer, 1995). Richardson (1906) recorded a reptilian coprolite from a layer of shale, and fish scales from a limestone bed some 5 m above this level, within the Cotham Member. Many of the vertebrate genera recorded at Culverhole Point are known from other Penarth Group localities.

Invertebrate body fossils are common throughout most of the Penarth Group sediments at Culverhole Point. These include bivalves such as *Pecten* and *Ostrea*, and the ostracod *Darwinula*. Trace fossils include burrows in the upper surface of the Blue Anchor Formation assigned to the ichnogenera *Diplocraterion* and *Thalassinoides* (Sellwood *et al.*, 1970), and others that have been tentatively identified as borings (Richardson, 1906).

Interpretation

The undifferentiated reddish-coloured argillaceous lithologies of the lower part of the exposed Mercia Mudstone Group have been interpreted as forming under the dominantly terrestrial conditions associated with supratidal sabkha flats or playa lakes, with localized developments of soils, infrequent floods and aeolian sedimentation. The colour change, from red to the greenish and grey sediments of the Blue Anchor Formation, indicates a change from oxidizing to reducing conditions. Cracks and burrows in the top of the Blue Anchor Formation indicate that the sediments were subaerially exposed. At Culverhole Point a well-defined non-sequence marks the boundary between the Mercia Mudstone Group and the overlying Penarth Group.

The Westbury Formation at Culverhole Point consists of alternating beds of shale and thin limestone deposited in shallow, possibly marginal marine, waters. The bone beds have been interpreted as transgressive lags of reworked older sediments and bones.

The Cotham Member was deposited in a lagoonal environment, as indicated by the sedimentary structures, and by dinoflagellate cysts from the Lyme Regis borehole (Warrington, 1997a). Of particular interest is the 'Crazy Cotham' Marble that was formed by the interaction of algae and sediment (Hamilton, 1961; Wright and Mayall, 1981) and is best described as a stromatolite horizon (Wright and Mayall, 1981). The various lamination patterns within the bed reflect the dynamic nature of the algal communities, brought about by environmental changes such as sediment input and salinity fluctuations (Wright and Mayall, 1981).

The Langport Member was deposited in warm shelf lagoons, which may have undergone phases of emergence (Hallam, 1960; Whittaker and Green, 1983).

Conclusions

The cliffs at and around Culverhole Point preserve a sequence through the uppermost beds of the red mudstones and the Blue Anchor Formation of the Mercia Mudstone Group, overlain by the Penarth Group, and capped unconformably by the Chalk. These lithologies reflect the change in palaeoenvironments that occurred over south-western Britain during the Late Triassic Epoch, from terrestrial playa-lake environments to marine conditions following the Late Triassic transgression. The famous Penarth Group bone beds at Culverhole Point have for many years been a valuable source of vertebrate remains. This is an important site for the study of Late Triassic palaeoenvironments and fossils.

PINHAY BAY, DEVON (SY 320 908)

Introduction

Pinhay Bay, near Lyme Regis, exposes a sequence of Triassic and Jurassic rocks including the Cotham and Langport members of the Lilstock Formation (Penarth Group) and the overlying Pre-*planorbis* and Hettangian beds of the Blue Lias. The site offers the best single exposure for the Langport Member in a thick development and shows diverse evidence of sedimentology and tectonic modification. The Langport Member is a regionally important unit, that is better-developed here than in sites farther north.

Pinhay Bay has not been extensively studied. Richardson (1906) includes a very brief mention of the site, as do Jukes-Brown (1902), Woodward and Young (1906), Woodward and Ussher (1906), Lang (1924), Sellwood *et al.* (1970), House (1989), Hesselbo and Jenkyns (1995) and Wignall (2001). Hallam (1960) wrote the classic account of the Pinhay Bay Langport Member.

Description

Pinhay Bay is also known as 'Pinney Bay' (Woodward and Ussher, 1906; Lang, 1924). The section is approximately 2.5 km west of Lyme Regis; it forms part of the Axmouth to Lyme Regis Undercliffs National Nature Reserve, and is included in the Dorset and East Devon Coast World Heritage Site, established December 2001. The cliffs and foreshore at Pinhay Bay are easily accessible, but are occasionally obscured by landslides and slumps.

Sedimentology

The cliffs and foreshore at Pinhay Bay expose beds of Late Triassic and Early Jurassic age. At the western end, the Blue Lias is brought into contact with the older Penarth Group by a fault (House, 1989). The following section is taken from Hallam (1960, pp. 48–9), with additional information from Richardson (1906, pp. 407–8), Hamilton (1961), Ager and Smith (1965, p.12), and House (1989):

	Thickness (m)
Lias Group: Blue Lias:	
Alternations of thin limestones and calcareous shales. Including the Pre-*planorbis* Beds (lowest 2.5 m)	
Penarth Group	
Lilstock Formation: Langport Member:	
'Sun Bed': limestone, locally a conglomerate with limestone pebbles in a marly matrix; thickens locally	0.05
Thin limestones with slightly irregular surfaces and partings of brown marl; some are rubbly or have perforated upper surfaces	0.41
Limestone, locally with an irregular upper surface: occurs only in east; replaced westwards by several thin limestones	0.25
Thin, rubbly limestones with irregular marl partings; shelly band near top	0.23
Shelly marl with lenses of limestone	0.02
Limestone, locally porcellanous, with eroded top	0.11
Main Slump Bed	1.37
Porcellanous limestone	0.05
Thin, rubbly limestones with irregular marl partings and pockets of small bivalves	0.86
Limestone with irregular base	0.20
Limestone, locally with a rubbly top, containing numerous subangular fragments of porcellanous limestone; minor slump structures	1.37
Thin limestones	0.51
Limestone with minor slump structures and locally a porcellanous top	0.58
Thin limestone locally becoming porcellanous and rubbly, with slightly irregular surfaces and partings of marl up to 0.01 m thick; rare pockets of small bivalves	1.83
Lilstock Formation: Cotham Member:	
Including the Cotham Marble, the '*Estheria* Bed', and black shales	1.5
Westbury Formation:	
'*Contorta*' Shales	5.0

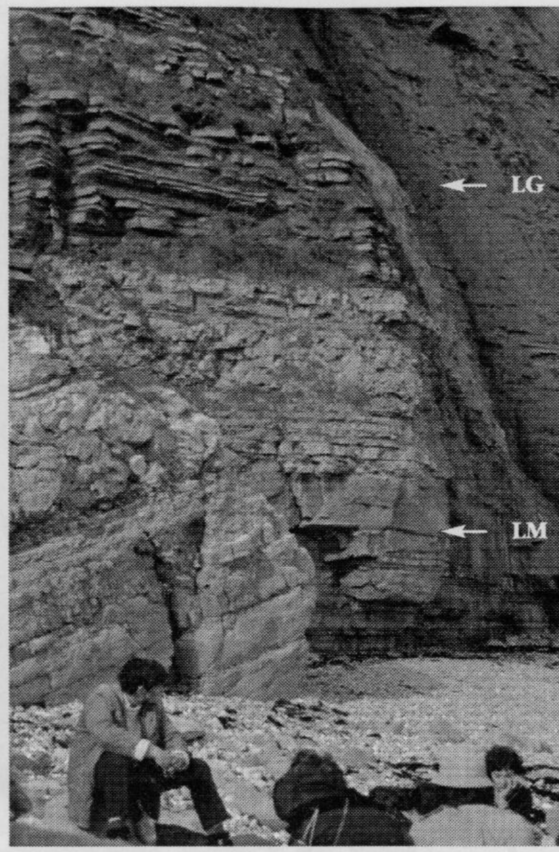

Figure 4.26 The Langport Member (LM) of the Penarth Group (paler beds) overlain by Lias Group (LG) at Pinhay Bay. (Photo: R. J. G. Savage.)

The Langport Member limestones seen at Pinhay Bay (Figures 4.26 and 4.27a) are chemically very pure and, when viewed in thin section, are seen to be composed almost entirely of interlocking calcite crystals. Rarer minerals and clasts include pyrite and detrital quartz. The limestones occur in two forms, the first pale yellowish-cream in colour, the second grey, porcellanous, and with a characteristic hard, smooth surface and porcellanous. The yellowish-cream limestone is commonly bounded on the upper and lower surfaces by the porcellanous type. Only the yellowish-cream facies shows any evidence of deformation (Hallam, 1960).

The rubbly limestone (Figures 4.27b and 4.28b), better described as an intraformational conglomerate, is characterized by angular and subangular pebbles that occur in layers, pockets, or lenses (Hallam, 1960). Primary sedimentary structures are common in many of the limestone beds and include evidence of subaerial exposure, such as polygonal cracks on the upper surface of the 'Sun Bed'; in places flakes of sediment created by the cracking have produced a conglomeratic horizon (Hallam, 1960).

Slump structures are especially well-developed in the 'Slump Bed' (Figures 4.27c–e, 4.28a) that is approximately 1.4 m thick and is characterized by large blocks of limestone and small pieces of the porcellanous limestone in a limestone matrix. The blocks include slump balls and detached and folded lumps of rock. The base of the bed is composed of fragments of the porcellanous limestone, probably reworked from the underlying bed. The top surface of the bed shows truncated sedimentary structures and organic borings. Similar features associated with penecontemporaneous deformation are seen at two lower beds in the Langport Member (Hallam, 1960). Ripples were noted by Richardson (1906), and wedge-shaped beds are also common (Richardson, 1906; Hallam, 1960).

At the base of the sequence, and exposed on the foreshore at low tides, is the Cotham Member. This was described very briefly by Richardson (1906), who recorded little more than the presence of the Cotham Marble, the '*Estheria* Bed' and the shales. The Cotham Marble recorded had the 'landscape' form; and the '*Estheria* Bed' was described as a pale limestone containing concretions and *Estheria minuta*. Mayall (1983) reported that a deformed bed from the middle of the Cotham Member is poorly exposed at Pinhay Bay, and that it can be correlated with the section at nearby Culverhole Point. This bed is approximately 0.4 m thick and consists of a calcitic mudstone with ripples, lenses of silty material, and evidence for sediment deformation, interpreted as possibly reflecting contemporary seismic activity.

Structural geology

The dominant structural feature at Pinhay Bay is the fault picked out by a small stream and with the Blue Lias downthrown to the west against the Langport Member (Woodward and Ussher, 1906; Lang, 1924; House, 1989). Hallam (1960) described small-scale faults that cut through the Langport Member and extend into the Blue Lias, where they plastically deform the Lower Jurassic beds.

Palaeontology

The Cotham Member has yielded a number of fossils. Of particular note are the well-developed algal mounds and mats that form the 'Landscape Marble' (Hamilton, 1961). Also present (Richardson, 1906) are remains of the crustacean *Estheria minuta*. Palynomorphs have been recovered from this unit in the nearby Lyme Regis borehole (Warrington, 1997a).

The Langport Member has yielded a diverse fossil assemblage, including many invertebrate taxa and ichnotaxa. A full listing the fauna was given by Hallam (1960, pp. 54–6). Many of the beds contain an assemblage composed of bivalves and gastropods with rarer solitary corals, which occur in dense concentrations approximately 1 m across and a few centimetres deep in the thinly bedded limestones. The shelly-marl horizon, seen towards the top of the exposure, contains abundant oysters and the bivalve *Modiolus* scattered throughout the sediment. Trace fossils include burrows and borings, for example the U-shaped tubes of *Rhizocorallium*, especially well exposed on the foreshore, where truncation has removed the top few centimetres of the burrows. Microfloras from a nearby section were documented by Orkell (1973) and Warrington (1997a)

Interpretation

The Cotham Member beds at Pinhay Bay represent a lagoonal environment. The sedimentary structures seen in this facies support this conclusion; for example the 'Landscape Marble' forms masses and mounds that were produced by algal mats growing in an intertidal environ-

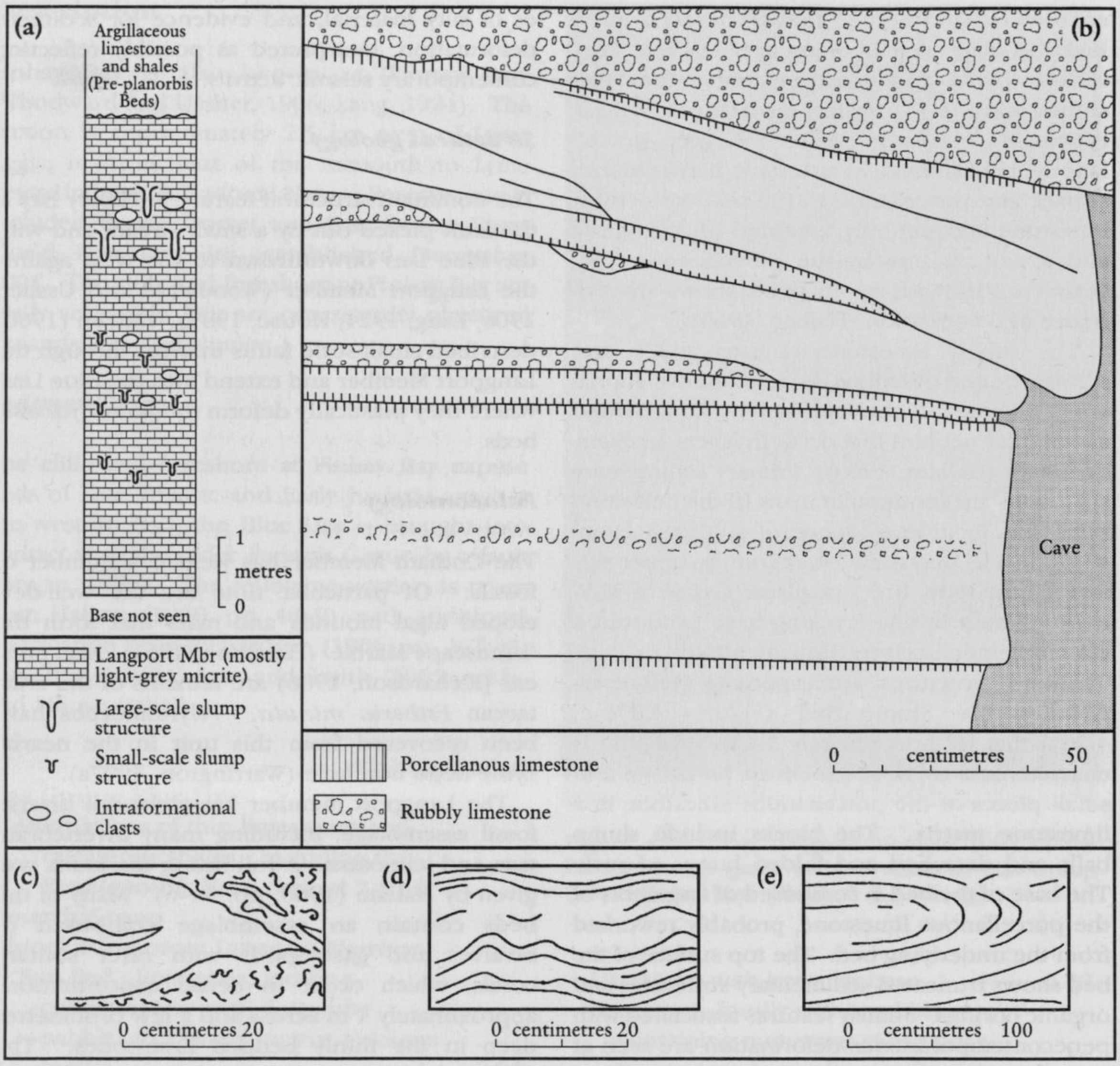

Figure 4.27 The Langport Member succession at Pinhay Bay. (a) Diagrammatic section. (b) Diagram of a section on the west side of Pinhay Bay, showing wedge bedding, rubbly limestones, and porcellanous selvages. (c–e) Synsedimentary deformation of the Langport Member; (c) part of a folded limestone bed in the Slump Bed, the core of which has been plastically squeezed and tapers to a point; (d) minor contortions, including pseudo-ripple marks, near the base of the section; (e) part of a limestone bed within the Slump Bed that has been folded on itself. (a, after Swift, (1995); b–e, after Hallam, 1960.)

ment (Hamilton, 1961).

The overlying Langport Member has been interpreted as representing an environment characterized by warm, shallow shelf lagoons, with periods of emergence (Hallam, 1960; Wignall, 2001). For example, the desiccation cracks and mud flake conglomerate of the 'Sun Bed', seen at the top of the section, are characteristic of temporary exposure and the associated drying out of the sediment surface. Hallam (1960) also presented evidence that these sediments were subjected to changes in relative sea level in the rapid lithification or consolidation of the limestones, for example intraformational conglomerates, burrows, and borings. The limestones were hardened during periods of exposure, and sedimentation resumed when the land was submerged again. Hallam (1960) estimated that there had been some 60 cycles of this nature at Pinhay Bay (see also Hesselbo and Jenkyns,

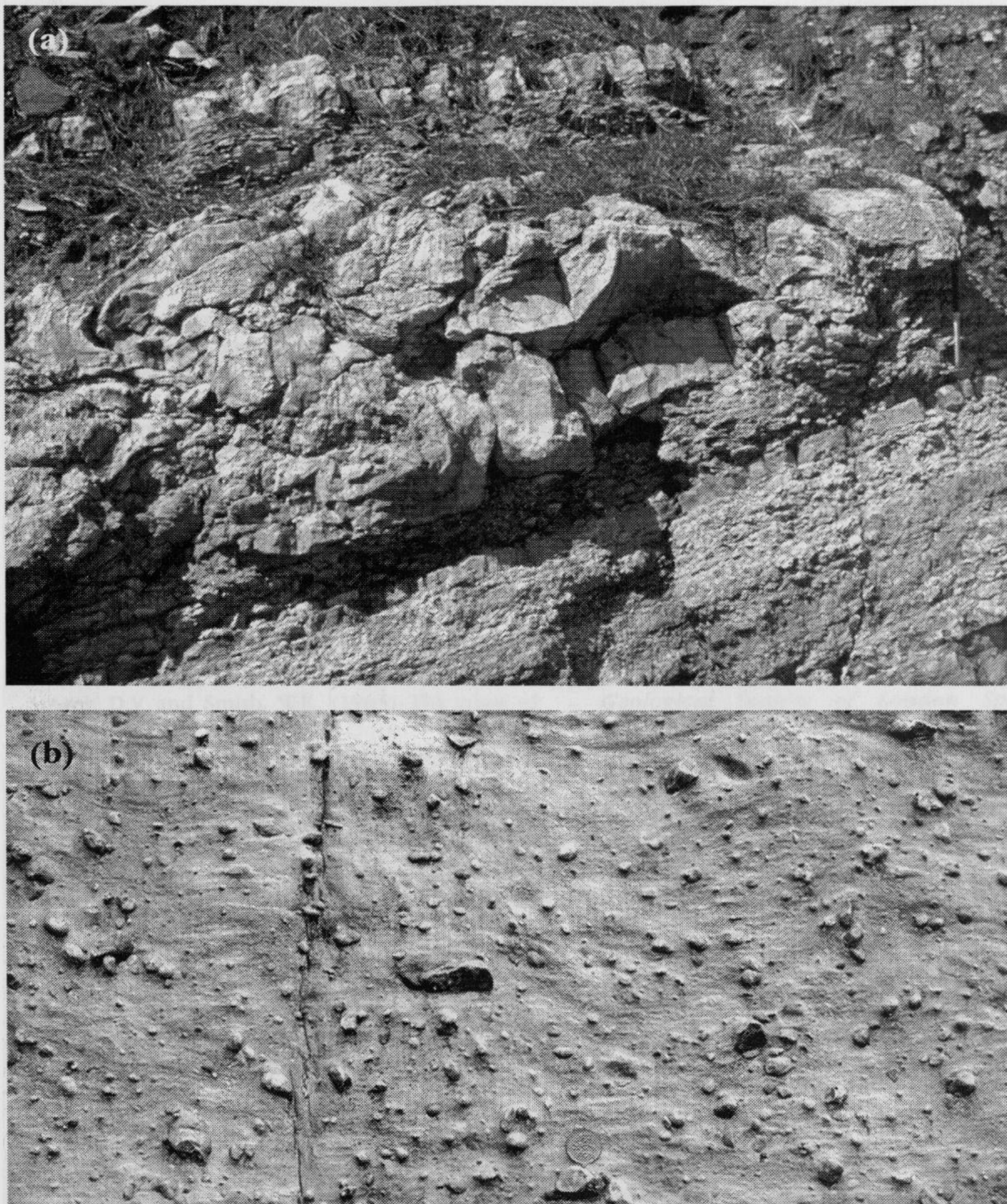

Figure 4.28 Sedimentary structures in the Langport Member at Pinhay Bay. (a) The 'main' slump bed, showing soft sediment deformation features caused by downslope movement of a semi-consolidated sediment (b) A thick resedimented limestone containing numerous pebbles derived from the break-up of earlier Langport Member beds. (Photos: Andrew Swift.)

1995).

The sedimentary structures seen in the main slump bed have been interpreted as indicating high levels of disturbance on the sea bed. Consolidated brittle limestones were broken into angular fragments, rather than plastically deformed. The mass flow incorporated parts of the underlying porcellanous limestone into the debris flow. The intraformational breccia may have formed in a three-phase process (Wignall, 2001): (1) formation of a hardground that was lithified and bored; (2) local erosion of the hardground under a shallow sea to produce the conglomerate which was itself lithified; and (3) subaerial emergence and production of a fissured and pitted top surface. At nearby Charton Bay the equivalent bed is dominated by fractured sediments, showing that the sea floor there was at least partially lithified (Hallam, 1960).

There are certain similarities between the main slump bed at Pinhay Bay and a deformed bed seen in the Cotham Member of the Lilstock Formation. The Cotham Member deformed bed is characterized by microfaults, water-escape structures, and folds. Mayall (1983) considered this bed to have been initially deposited under shallow water conditions. Tectonic activity caused the unconsolidated silty beds to liquefy and the more consolidated sediments to fracture.

Conclusions

Pinhay Bay shows an excellent exposure of Upper Triassic and Lower Jurassic sediments. The Penarth Group strata include the Cotham and Langport Members of the Lilstock Formation. Several of the limestone beds of the Langport Member display excellent examples of soft-sediment deformation associated with debris flows, probably initiated by earthquakes or other tectonic activity. The site is especially important for evidence for ancient palaeoenvironments and critical in reconstructing the palaeogeography of southern England, near the end of Triassic time.