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

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Chapter 3

British Triassic red beds

BRITISH TRIASSIC RED-BED GCR SITES

It is impossible to document a typical succession of the British Triassic red beds in any single part of the country since each sedimentary basin shows its own unique developments (Warrington *et al*., 1980). Therefore, in this chapter, the GCR localities are assigned to regional site networks, broadly representing the major basins of sedimentation.

- Moray Firth Basin, north-east Scotland (2 sites),
- the Western Highlands and Islands and Arran (4 sites),
- West Cumbria and East Irish Sea Basin (5 sites),
- the Cheshire Basin (5 sites),
- the western North Sea Basin (4 sites),
- the Central Midlands (6 sites),
- South Wales (4 sites), and
- Devon (2 sites).

The broad stratigraphy and sedimentary features of each basin are outlined section by section; a total of 32 GCR sites have been selected to illustrate the key features (Figure 3.1). However, some sites described in Chapter 4 of the present volume – primarily selected for the GCR for the Penarth Group successions – also contain important Triassic red beds. In fact, in the 1980s, Aust Cliff (described in Chapter 4) was selected for both the Permian–Triassic Red Beds and the former 'Rhaetian' GCR Blocks independently.

THE TRIASSIC RED BEDS OF THE MORAY FIRTH BASIN, NORTH-EAST SCOTLAND

INTRODUCTION

The relative ages of the stratigraphical units of the Permo–Triassic of Morayshire (Figure 2.2) have long been debated. Initially, all the buff-coloured sandstones were regarded as part of the Old Red Sandstone, and probably Late Devonian in age. Finds of reptile bones and footprints raised some doubts, and the issue was hotly debated in the mid-19th century. By the 1890s, most workers accepted a Permo–Triassic age (see also Chapter 2).

A rich reptile fauna was found in quarries around Elgin and Lossiemouth, in what is now known as the 'Lossiemouth Sandstone Formation'. These have long been regarded as Late Triassic in age, but there has been some debate about their exact age. They were first compared with faunas from the Keuper of Germany, especially those of the Stubensandstein, and that suggested an early to mid Norian age (Walker, 1961; Warrington *et al*., 1980; Benton and Walker, 1985). However, wider comparisons suggest that they are more clearly equivalent to faunas from the upper part of the Maleri Formation in India, the upper part of the Santa Maria Formation of Brazil, and from the Ischigualasto Formation of Argentina, with which they share the rhynchosaur genus *Hyperodapedon*. The Ischigualasto Formation is dated radiometrically as younger than 228 Ma, from an ash band at its base, and hence is mid to late Carnian in age. The aetosaur *Stagonolepis* may be shared with the Lower Petrified Forest Member of Arizona, which is dated biostratigraphically as late Carnian (Tuvalian Substage). This is equivalent to the Adamanian land vertebrate faunachron (Lucas and Hunt, 1993) and the *Rutiodon* Assemblage Zone (Lucas, 1998).

The geology of the Triassic successsion of the Moray Firth Basin has been described by many authors, for example Duff (1842), Mackie (1897, 1902a,b), Watson and Hickling (1914), Westoll (1948), Peacock *et al*. (1968), Williams (1973), Peacock (1977), Benton and Walker (1985), and Gillen (1987). The Permo–Triassic of Morayshire is, in addition, merely a small onshore expression of a major basin beneath the Moray Firth (Frostick *et al*., 1988; Andrews *et al*., 1990).

Two GCR sites have been selected to illustrate the Triassic rocks of the Moray Firth Basin – Burghead and Lossiemouth, type locations for the Burghead Sandstone Formation and for the Lossiemouth Sandstone Formation respectively.

BURGHEAD, MORAYSHIRE (NJ 107 691–NJ 122 691)

Introduction

The coastal cliffs and foreshore exposures in the vicinity of Burghead, especially close to the harbour wall, and along the coast to Cummingstown, are the type locality for the Burghead Sandstone Formation. This is a set of predominantly fluvial deposits, with coarse sediments indicating high-energy deposition. The unit occurs between the Late Permian Hopeman

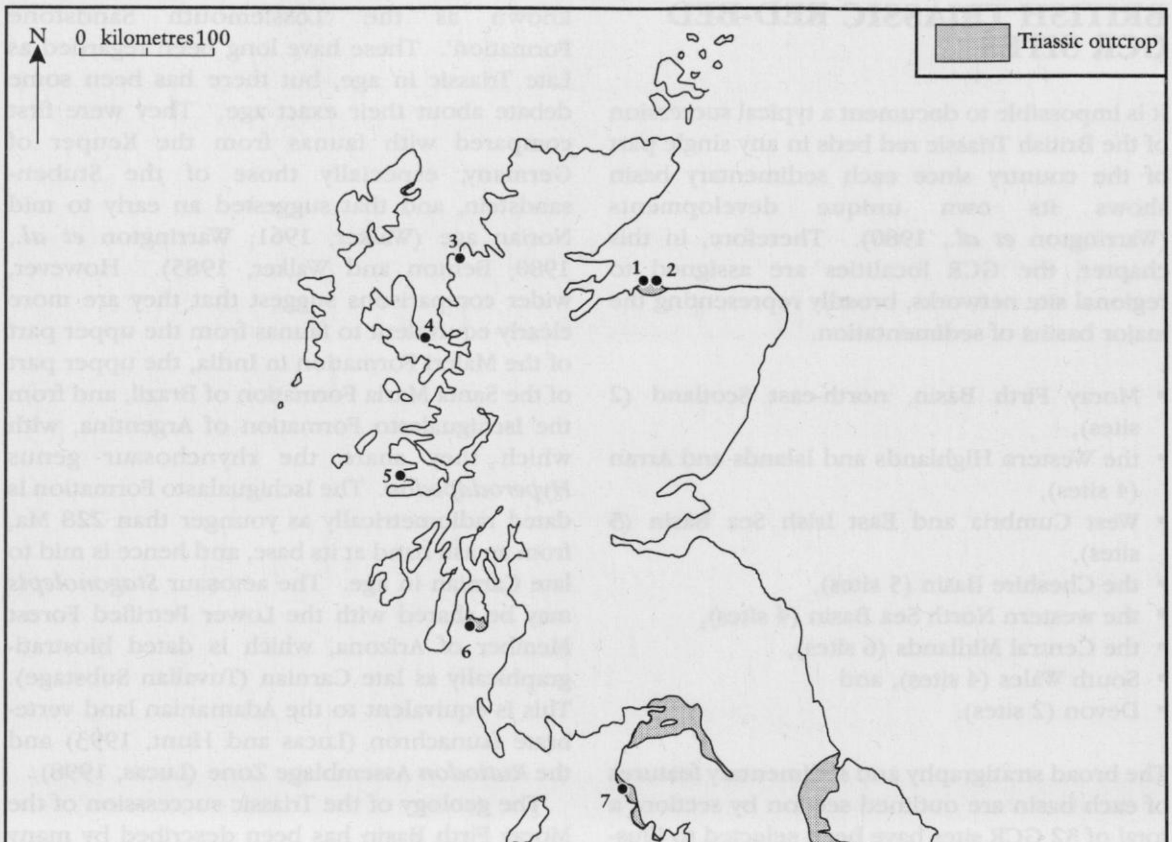


Figure 3.1 Map showing the distribution of Triassic rocks in Great Britain. GCR Triassic red-bed sites are indicated: (1) Burghead; (2) Lossiemouth; (3) Gruinard Bay; (4) Eyre Burn; (5) Gribun; (6) King's Cave to Drumadoon; (7) Fleswick to St Bees; (8) Burton Point; (9) Hilbre Island; (10) Thurstaston; (11) The Dungeon; (12) Dee Cliffs; (13) Bickerton Hill; (14) Frodsham; (15) Red Brow; (16) Grinshill; (17) Nottingham Castle; (18) Styrrup Quarry; (19) Scrooby Top Quarry; (20) Colwick; (21) Hulme Quarry; (22) Brocton; (23) Wollaston Ridge; (24) Claverley Road Cutting; (25) Burcot; (26) Shrewley; (27) Sutton Flats; (28) Barry Island; (29) Hayes Point to Bendrick Rock; (30) Sully Island; (31) Aust Cliff (see Chapter 4); (32) Budleigh Salterton; (33) Ladram Bay to Sidmouth. The Triassic red-bed/Penarth Group sites described in Chapter 4 are shown on Figure 4.5.

Sandstone Formation (see Chapter 2) and the Late Triassic Lossiemouth Sandstone Formation, but its age cannot be more precisely constrained.

Details of the Burghead Sandstone Formation have been documented by Westoll (1951), Peacock *et al.* (1968), and Frostick *et al.* (1988). The formation was initially termed the 'Burghead Sandstones' (Westoll, 1951), and subsequently the 'Burghead Beds' (Peacock *et al.*, 1968), and then formalized as the 'Burghead Sandstone Formation' (Warrington *et al.*, 1980). This formation may be partially coeval with the Lossiemouth Sandstone Formation (Peacock *et al.*, 1968).

Description

The Burghead area is encompassed within the GCR site known as 'Masonhaugh', selected not only for its Triassic stratigraphy, but also for coverage of the Late Permian Hopeman Sandstone Formation (see Chapter 2, GCR site report for Clashach to Covesea). It is protected within the Masonshaugh Site of Special Scientific Interest (SSSI), and was independently selected for the GCR for its fossil reptiles (see site report in Benton and Spencer, 1995).

The Burghead Sandstone Formation overlies the Hopeman Sandstone Formation and in places unconformably overlies Old Red Sandstone sediments; it is in turn overlain by the Lossiemouth Sandstone Formation (Warrington *et al.*, 1980). The contact between the Burghead Sandstone Formation and the Hopeman Sandstone Formation is not exposed at Burghead (Andrews *et al.*, 1990), although it can be seen farther east along the coast at Masonshaugh (Gillen, 1987), and is known from data collected from a borehole at Clarkly Hill (Figure 3.2). The Burghead Sandstone Formation is also exposed at Masonshaugh Quarry, Clarkly Hill and Inverugie, and Raddoch Wells.

The Burghead Sandstone Formation (Figure 3.2) comprises a thick sequence (up to 73 m) of cross-bedded and parallel-laminated, yellowish-brown and greyish-orange, medium- to coarse-grained sandstones, with some discontinuous pebbly and greenish-yellow silty beds that dip gently towards the north. Clay is rarely seen in the coastal sections around Burghead. The sediments are cemented to various degrees by silica and calcite. Some of the bed boundaries and joint surfaces are marked by a thin layer of dark reddish-brown, haematite iron pan; these are most commonly associated with the finer-grained, silty sediments (Peacock *et al.*, 1968; Peacock, 1977; Gillen, 1987; Andrews *et al.*, 1990).

At the western end of Burghead Harbour wall (Figure 3.2, columns 2 and 3), the cliffs expose a 3 m section of cross-bedded fine- to coarse-grained sandstone with thin beds of silt and strings of reworked siltstone pebbles (Figure 3.3). Pebbles are common and some are concentrated in conglomeratic beds; they consist largely of reddish quartzite, but include rarer clasts of vein quartz, gritty sandstone, and granulite. A small washout channel is exposed in the cliff section. The infilling sediments are cross-bedded, and the foresets dip towards the north-east (Peacock *et al.*, 1968).

North of the harbour wall, in Burghead Cliffs (Figure 3.2, column 1), the sections are approximately 8 m high, and are dominated by thick, cross-bedded sandstone units. Pebble-rich beds and conglomeratic horizons may reach a maximum thickness of 1.3 m. Desiccation cracks have been recorded at this locality. The sediments here show varying degrees of induration, and may be cemented by either silica, or occasionally calcite (Peacock *et al.*, 1968).

North of Burghead, the Burghead Sandstone Formation is exposed on the wave-cut platform of the foreshore, where sandstones very similar to those exposed in the cliff sections (above) are overlain by approximately 1.5 m of calcareous sandstone with scattered quartz pebbles. The latter facies is also seen at Roman Well, in Burghead village, in an old railway cutting close to Masonshaugh, and on the foreshore close to the faulted contact with the stratigraphically older Hopeman Sandstone Formation (see Chapter 2, Figures 2.5 and 2.6.

Thin-section analyses of the Burghead Sandstone Formation show that the sandstones are composed primarily of quartz, with approximately 5% feldspar (microcline and untwinned alkali feldspars), and rare metamorphic quartz, granular quartz, strained vein quartz, chert, muscovite, and leucoxene. The heavy mineral suite includes zircon, tourmaline, and apatite. The cement may be either silica or calcite, as secondary quartz or chalcedony or plates of calcite that partially encase the clasts (Peacock *et al.*, 1968).

The calcareous sandstone, exposed in the intertidal zone to the north of Burghead village, is characterized by a bi-modal distribution of

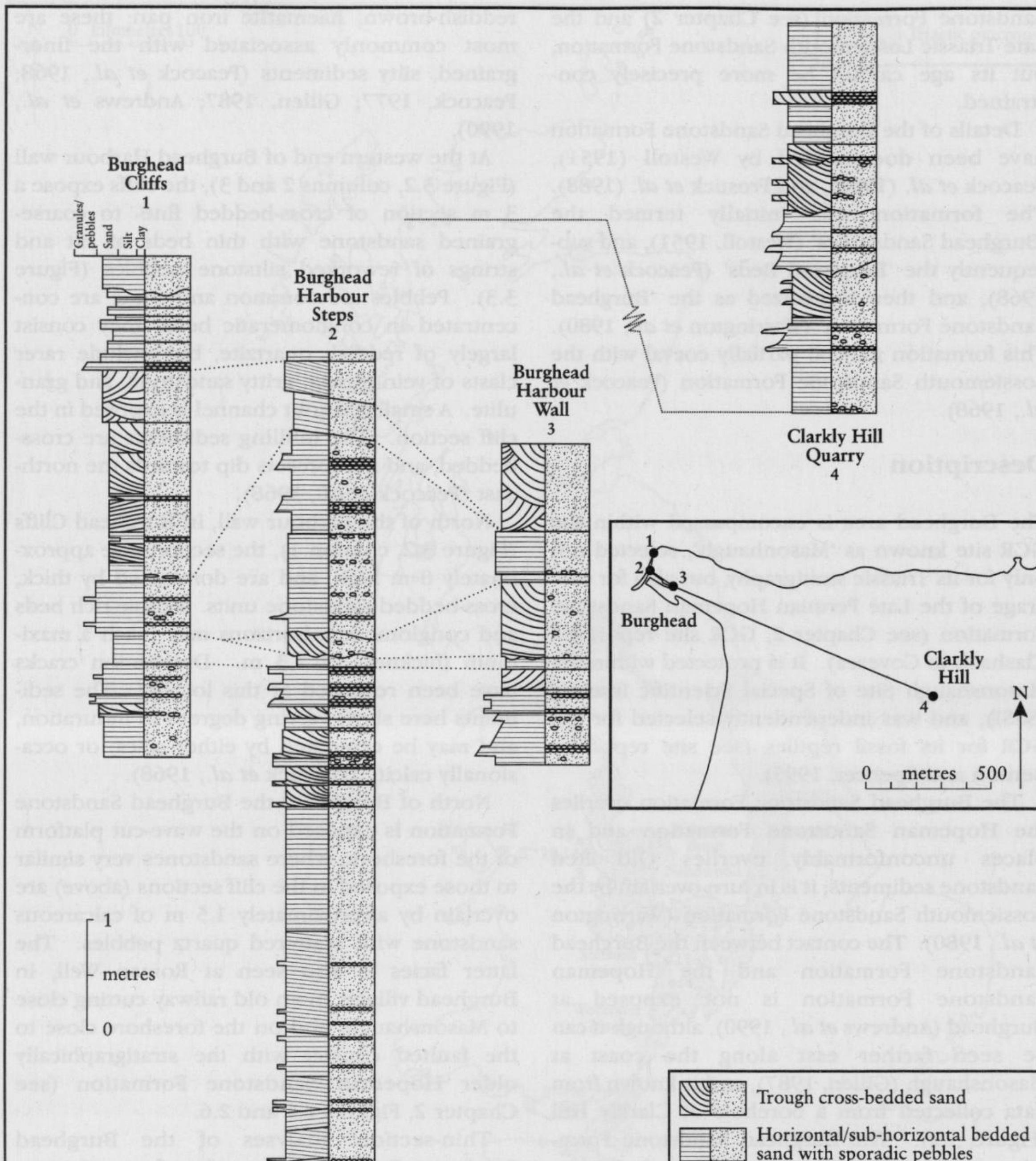


Figure 3.2 Measured sections at four sites in the Burghead GCR site, showing characteristic sequences and lateral relationships. (After Frostick *et al.*, 1988.)

clasts. The coarser fraction typically comprises well-rounded grains and small pebbles of quartz, quartzite, strained vein quartz, calcareous sandstone, and chert. The finer-grained matrix comprises well-sorted material, with an average grain size of 0.2 mm. The clasts are composed of subrounded to angular quartz, with chert, calcite and untwined feldspars. Accessory minerals include haematite, leucoxene, zircon, tourmaline, and possibly rutile and epidote. The

Figure 3.3 The Burghead Sandstone Formation in Burghead Cliffs, Masonshaugh site. The cross-bedding in the sand dune deposits of the Hopeman Sandstone Formation is of a much larger scale than the cross-bedding in these water-lain deposits. (Photo: C. MacFadyen.)

cement is granular and platy calcite, which preserves structures that may be organic in origin (Peacock *et al.*, 1968).

In the cliffs below the Coastguards' Station the Burghead Sandstone Formation has been disrupted by a substantial fault, and large blocks of sandstone are scattered across the foreshore. The Burghead Sandstone Formation sediments are unfossiliferous.

Interpretation

The Triassic sediments in the Burghead area were deposited in a subsiding half-graben, associated with movements along the Great Glen Fault (Frostick *et al.*, 1988).

The environment of deposition of the Burghead Sandstone Formation has been debated. Peacock *et al.* (1968) thought that the 'Burghead Beds' were deposited in a floodplain environment, while Williams (1973) found evidence for both point-bar sequences and floodplain environments. Frostick *et al.* (1988) ascribed the whole sequence to ephemeral streams. The dominance of plane bedding, the abundance of clay intraclasts (mud curls ripped from pools where suspended sediment had settled out), imbricated pebbles, large channel width/depth ratios, and high sediment loads are all characteristic of ephemeral streams. The lower plane-bed facies gives way to trough cross-bedded sand facies at intervals in the succession (Figure 3.2), which suggests a change to more incised channels and deeper flood flows with better-developed secondary currents.

The sediments suggest that the rivers experienced abrupt changes in gradient, associated with fault movement, followed by periods of tectonic stability (Frostick *et al.*, 1988). The orientation of the infilled river channel and the associated cross-bedding foresets indicate that sediment transport was mainly from the south-west, in rivers and streams flowing towards the north-east (Gillen, 1987).

The iron pan layers, associated with joint and bedding plane surfaces, have a diagenetic origin and were formed by the precipitation of iron minerals (for example haematite) from circulating groundwaters (Gillen, 1987).

The Burghead Sandstone Formation appears to grade into the Lossiemouth Sandstone Formation, and hence it may be Carnian (?and pre-Carnian) in age. How far down it goes in the Triassic System is unclear. Peacock *et al.* (1968) and Warrington *et al.* (1980) hint, in a diagram, that it might fill the whole time between the Hopeman and Lossiemouth Sandstone formations, hence some 20–25 million years, and including the Induan, Olenekian, Anisian, Ladinian, and early Carnian stages. For such a coarse clastic unit, such an age span is unlikely and there is probably a major hiatus in deposition between the Hopeman Sandstone and Burghead Sandstone formations.

Conclusions

The cliffs and foreshore exposures around Burghead are the type locality for the Burghead Sandstone Formation, and an important site for the interpretation of Triassic stratigraphy and palaeoenvironments in the Moray Firth region. The sediments comprise thick sequences of cross-bedded sandstones, with pebble beds and occasional siltstone horizons, deposited on point bars and floodplains by a system of rivers and streams.

LOSSIEMOUTH SHORE AND QUARRIES, MORAYSHIRE (NJ 226 710–NJ 231 713; NJ 234 706–NJ 238 708)

Introduction

The foreshore, raised cliffs, and sandstone quarries in the vicinity of Lossiemouth are the type locality for the Lossiemouth Sandstone Formation. The sediments are dominated by white, fine-grained sandstones, although siltstones and calcrete horizons have been reported. They were deposited by a combination of aeolian and fluvial processes, and have yielded a rich fauna of fossil reptiles that suggest a late Carnian age. The aeolian sandstones are overlain by the Cherty Rock, a highly cemented calcite and silica-rich sediment that has many similarities to present-day siliceous soils of arid and semi-arid areas.

Numerous papers, books and field guides describing the geology of the Lossiemouth area have been published, for example Mackie (1897, 1902a,b), Wallace (1902), Watson and Hickling (1914), Peacock *et al.* (1968), Gillen (1987), Frostick *et al.* (1988), and Naylor *et al.* (1989a). Boreholes have been drilled in the Lossiemouth area (for example Berridge and Ivimey-Cook, 1967). The vertebrate fossils from Lossiemouth have been the subject of many studies, for example, Huxley (1859a,b, 1869), Burkhardt (1900), Walker (1961, 1964), Benton (1983, 1999), Benton and Walker (1985), and Fraser and Benton (1989).

Description

Sedimentology

The best localities in the Lossiemouth area (Figure 3.4) are the quarry west of the School Brae (NJ 231 704), east of the School Brae (NJ 236 707), and the post-glacial raised beaches and associated cliffs to the north (Peacock *et al.*, 1968). These sediments were termed the 'sandstones of Spynie, Lossiemouth and Findrassie' by Peacock *et al.* (1968, pp. 67–70). The dominantly arenaceous sediments at all of these localities are lithologically very similar; the site was independently selected for the GCR for its fossil reptiles, which came mainly from Lossiemouth East Quarry (Figure 3.5; Benton and Spencer, 1995).

The lowest unit in the sequence exposed at Lossiemouth is approximately 2 m of calcareous siltstones and pebbly sandstones that are yellow, grey or reddish-brown in colour, and are probably attributable to the Burghead Sandstone Formation (Peacock *et al.*, 1968, p. 66). The clasts consist mostly of quartz, with rarer microcline and potassium feldspar, chert, muscovite, and biotite. Small grains of magnetite are scattered across some bedding plane surfaces. Most of the rock is cemented by calcite, although there are patches of siliceous cement. This facies is overlain conformably by the Lossiemouth Sandstone Formation; the contact is exposed in the eastern part of the area (Peacock *et al.*, 1968).

In Lossiemouth East Quarry approximately 9 m of hard, white, well-sorted, commonly well-laminated, fine-grained sandstone has two well-defined sub-vertical joint sets (Figure 3.6); the dominant joint orientation is WNW, the subordinate one NNE. Locally the joints are infilled with minerals such as barite and fluorite (Peacock *et al.*, 1968). Farther east, approximately 7.6 m of the Lossiemouth Sandstone Formation is seen 360 m WSW of the old railway station, and is a

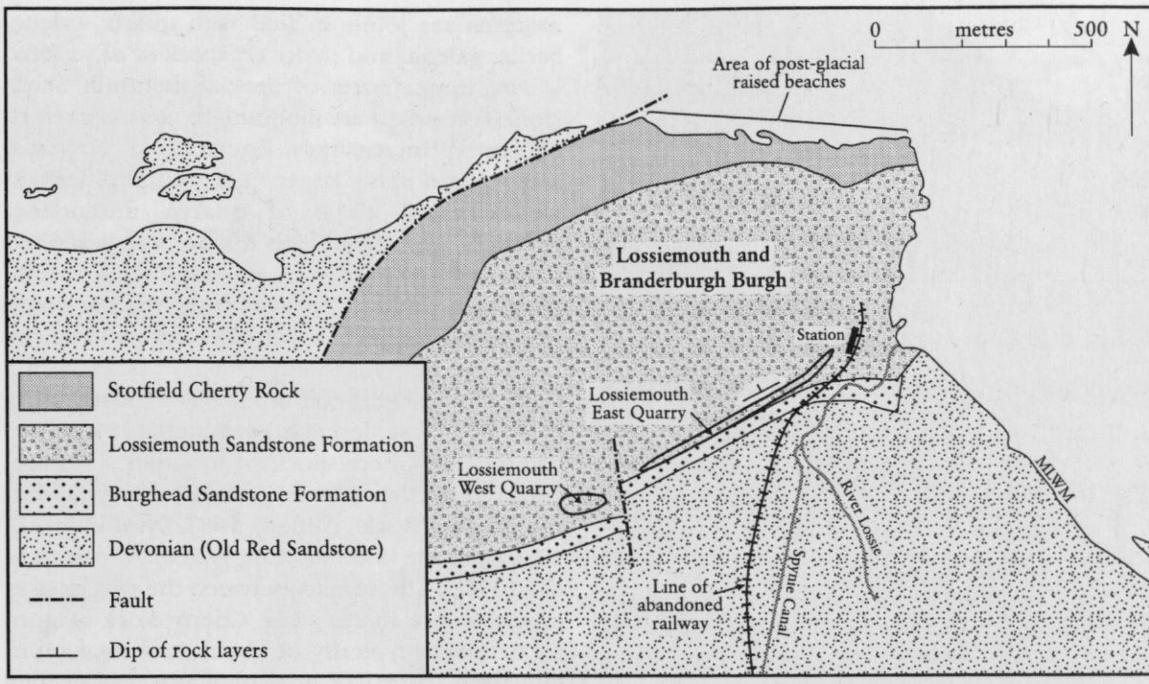


Figure 3.4 Occurrence of the Lossiemouth Sandstone Formation in its type location, in Lossiemouth, and on the foreshore north of the town.

Figure 3.5 Lossiemouth East Quarry, showing water-laid Burghead Sandstone Formation at the base, and large aeolian cross-bedded sandstone sets in the Lossiemouth Sandstone Formation above. The face is about 9 m high. (Photo: C. MacFadyen.)

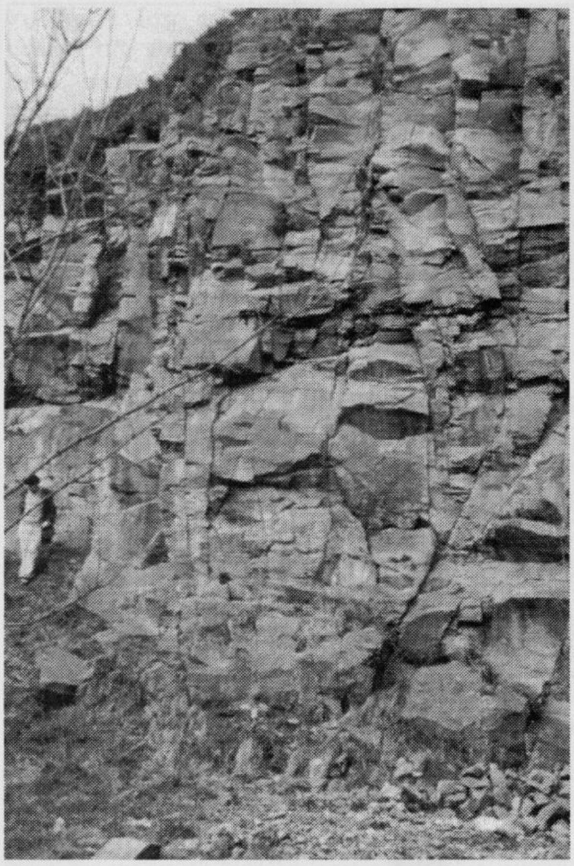


Figure 3.6 Lossiemouth East Quarry: view of heavily jointed, dune cross-bedded sandstones at the eastern end of the site. (Photo: M. J. Benton.)

fine-grained, pinkish-white, massive, and siliceous sandstone. In the middle of the nearby quarry, the sandstone is hard or friable, yellow and grey, and displays excellent examples of large-scale cross-bedding, with individual units 4 to 6 m thick and traceable laterally for over 30 m (Peacock *et al.*, 1968).

The Triassic sediments are also exposed in the post-glacial beaches and cliffs. Here, to the east, the lower part of the section exposes approximately 4.5 m of interbedded yellow and pink sandstones with micaceous siltstones and lenses of quartz pebbles. These are overlain by a pinkish-grey sandstone unit, which is in turn overlain by a hard, grey, 'millet seed' sandstone with well-defined cross-bedding. In the coastal exposures to the west and north of the town, the Lossiemouth Sandstone Formation typically consists of hard, light grey to pinkish-grey, siliceous arenaceous sediments. Cross-bedding is common, as are joints infilled with quartz, calcite, barite, galena, and pyrite (Peacock *et al.*, 1968).

The upper parts of the Lossiemouth Sandstone Formation are medium- to coarse-grained, becoming increasingly fine-grained upwards, and contain many larger (1–2 mm in diameter) well-rounded clasts of quartz, microcline, quartzite, and chert. This texture was described by Peacock *et al.* (1968, pp. 67, 71) as 'resembling sago pudding'. Close to the top the dominant cement type changes from calcite to silica.

The Lossiemouth Sandstone Formation is succeeded by a chert-rich unit (well-exposed at NJ 226 707), first described by Judd (1873), and named the 'Cherty Rock of Stotfield' (Wallace, 1902), the 'Cherty Beds' (Peacock *et al.*, 1968), the 'Cherty Rock' (Gillen, 1987; Naylor *et al.*, 1989a), or the 'Stotfield Cherty Rock' (Frostick *et al.*, 1988). The contact between the two units is irregular but sharp. The Cherty Rock (Figure 3.7) consists typically of about 3 m (maximum thickness, 10 m) of grey or white, arenaceous limestone containing chert clasts, banded chert, and a honeycomb-textured mixture of chert and limestone (Wallace, 1902; Peacock *et al.*, 1968; Naylor *et al.*, 1989a). Thin-section analysis shows that the grains are small pellets (90 to 100 μm diameter) composed of concentric micrite layers, arranged in sub-parallel laminae and matrix-supported. The rock is strongly cemented by low-magnesium calcite that occurs as micrite, microspar, and sparry crystals. Ferroan calcite occurs as a later cement, generally infilling tension gashes. Silica cements are also prevalent in the Cherty Rock, and consist of chalcedony, microquartz, semi-opaque crystalline silica, and coarsely crystalline quartz (Naylor *et al.*, 1989a).

Veins and cavities are common throughout this facies, and are infilled by quartz, calcite, pyrite, and galena intergrown with sphalerite. The rare mineral phosgenite has been recorded from the Cherty Rock in the vicinity of Lossiemouth, and is thought to have formed from the interaction of sea water with galena (Starkey, 1988).

Palaeontology

Most of the vertebrate remains recovered from the Lossiemouth area come from the East Quarry, and probably from sediments exposed towards the base of the Lossiemouth Sandstone Formation (Benton and Walker, 1985). The

Figure 3.7 The Cherty Rock on the foreshore north of Lossiemouth, a close-up showing its fractured nature. (Photo: C. MacFadyen.)

bones may be well-preserved and articulated, although they are normally preserved as soft and friable bone (Walker, 1961), natural moulds (Fraser and Benton, 1989), or are replaced by minerals such as goethite and fluorite (Benton and Spencer, 1995). The assemblage (Benton and Spencer, 1995, Benton, 1999) consists of the procolophonid *Leptopleuron lacertinum*, the sphenodontian *Brachyrhinodon taylori*, the rhynchosaur *Hyperodapedon gordoni*, and the archosaurs *Stagonolepis robertsoni*, *Ornithosuchus longidens*, *Erpetosuchus granti*, *Scleromochlus taylori*, and *Saltopus elginensis*. The site was also selected for the GCR for its fossil reptile fauna (Benton and Spencer, 1995)

Interpretation

The sediments at Lossiemouth were deposited in terrestrial environments under both fluvial and aeolian conditions, in a half-graben associated with the Great Glen Fault (Frostick *et al.*, 1988).

The poorly sorted, yellowish, grey, and reddish-brown sandstones and siltstones, with scattered, angular quartz clasts, of the Burghead Sandstone Formation are indicative of deposition by rivers. In some localities in the Elgin district, ventifacts are present (Peacock *et al.*, 1968), suggesting that aeolian processes were important. The small-scale cross-bedding and associated silty laminae, desiccation cracks and rare mud-pellet conglomerates imply that the rivers were located on floodplains that experienced semi-arid to arid climatic conditions (Peacock *et al.*, 1968; Williams, 1973).

The overlying Lossiemouth Sandstone Formation is characteristically well-sorted, well-cemented and preserves large-scale cross-bedding, features that are typical of aeolian sedimentation (Shotton, 1956; Peacock *et al.*, 1968). The formation consists of sand reworked from the Burghead Sandstone Formation and deposited from large dunes as they migrated across floodplains. The directions of dip of the dune cross-bedding indicate that the dominant palaeowind direction was from the south (Williams, 1973; Benton, 1983). The reptile fossils are known only from the aeolian sandstones. The animals lived in and around the dunefields, and probably moved to vegetated floodplain and interdune areas for food (Benton, 1983). The 'sago pudding' sandstone has features, such as large, angular clasts and many heavy minerals that are consistent with transport by water (Peacock *et al.*, 1968).

The overlying Cherty Rock shows textures similar to those of modern and ancient calcrete and silcrete soils, such as the concentrically laminated pellets that resemble glaebules seen in silcretes (Naylor *et al.*, 1989a). The presence of silica in calcrete profiles is common (see, for example, Goudie, 1973). It is thought that the silica in the Cherty Rock is a replacement of calcite precipitated as soil carbonate or calcrete, followed by repeated cycles of solution and reprecipitation (Naylor *et al.*, 1989a). The calcrete and silcrete palaeosol horizons support the hypothesis that the region experienced a semi-arid or arid climatic regime during the Triassic Period. The Cherty Rock has been recorded in numerous boreholes in the Moray Firth, and is a useful marker horizon for correlation (Frostick *et al.*, 1988); it can be correlated with a cherty limestone that outcrops in the vicinity of Dunrobin (Phemister, 1960; Gillen, 1987; Andrews *et al.*, 1990; Cameron, 1993) on the northern side of the Moray Firth.

Dating the Lossiemouth Sandstone Formation is difficult. The vertebrate assemblage suggests a late Carnian (Tuvalian Substage) age, by comparison with faunas from North and South America (Benton, 1994). This is equivalent to the Adamanian land vertebrate faunachron (Lucas and Hunt, 1993) and the *Rutiodon* Assemblage Zone (Lucas, 1998). The Cherty Rock is assigned a Rhaetian age, based on its occurrence above the Carnian Lossiemouth Sandstone Formation, and below Lower Jurassic shales, which contain Sinemurian ammonites (Peacock *et al.*, 1968).

Conclusions

Lossiemouth is the type locality of the Lossiemouth Sandstone Formation. The dominantly arenaceous rocks were deposited under terrestrial conditions, and include sediments of aeolian and fluvial origin. The Lossiemouth Sandstone Formation is internationally famous as a source of Triassic reptiles. The overlying Cherty Rock has been interpreted as a fossil soil horizon with a complex geological history.

THE TRIASSIC RED BEDS OF THE WESTERN HIGHLANDS AND ISLANDS, AND ARRAN

INTRODUCTION

There are several Triassic successions on the Western Isles of Scotland that differ from both the Morayshire succession and those of England. Triassic deposits have been identified in small patches along the west coast of the mainland, on the Ardnamurchan and Morvern peninsulas, and at Applecross, Gairloch, Gruinard Bay and Aultbea, and on the islands of Skye, Raasay, Rum, Mull, and Arran (Figure 3.8). Most of these occurrences have been dated as Triassic in age, even if circumstantially, but others (e.g. on Lewis, Islay, and the Kintyre peninsula) are of disputed age, and there are red and buff sandstone formations in the north of Scotland (e.g. at Tongue) that might be Devonian or Permo–Triassic in age.

In the West Highlands and the Hebrides, up to 300 m of mudstones, sandstones, conglomerates, and breccias are termed informally the 'Stornoway Formation' (Figure 3.9), but their age range is almost impossible to determine. Warrington *et al.* (1980) simply assigned a time range through the whole Triassic Period. The succession on Mull is capped by Rhaetian rocks – 10 m or more of Westbury Formation, and about 1.5 m of Lilstock Formation (Lee and Bailey, 1925) representing of the Penarth Group. Elsewhere, the Triassic strata are capped by the Jurassic Blue Lias or Broadford Beds on Skye. The *planorbis* Zone was thought to be absent in the Hebrides, but it has been reported from Mull (Oates, 1978) and probably from Skye (Morton, 1999), where the Triassic–Jurassic boundary may occur in unfossiliferous red-bed sediments – the red-bed succession seems to extend to higher stratigraphical levels in the Skye area. Extensive searches have been made for fossils in all the western Scottish successions, but with minimal success, and those shelly fossils and palynomorphs that have been found have not offered much biostratigraphical information (Warrington *et al.*, 1980, pp. 23–4).

The nomenclature and dating of these red-

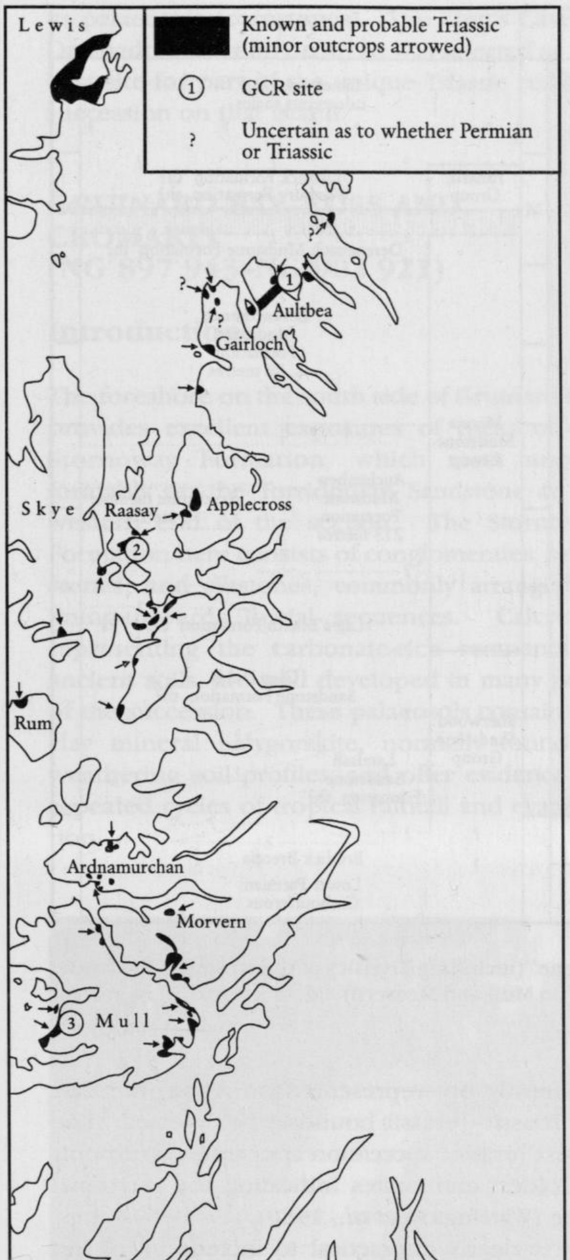


Figure 3.8 'New Red Sandstone' (including Triassic) outcrops on the west coast of Scotland, the Hebridean islands and Arran. GCR sites are numbered: (1) Gruinard Bay; (2) Eyre Burn; (3) Gribun.; (4) Kings Cave to Drumadoon. There are possible occurrences on Islay and the Kintyre Peninsula. (After Warrington *et al*., 1980.)

bed deposits have long been disputed, but more recent studies (e.g. Bruck *et al*., 1967; Steel, 1971, 1974a,b; Steel and Wilson, 1975; Steel *et al*., 1975; Nicholson, 1978) have elucidated the sedimentology of the Raasay, Scalpay, Skye, Rum, and Lewis successions in some detail. In all cases, the facies appear similar and indicate deposition in continental alluvial fans and floodplains. This suggests possible contemporaneity of such sequences, and their link to contemporaneous movement of the Minch Fault (Steel, 1971). The succession on Lewis was termed the Stornoway Formation by Steel (1971) and the Camas Malag Formation was established for the unit on Skye by Nicholson (1978), but the latter has since been shown to be Jurassic in age (Farris *et al*., 1999). Warrington *et al*. (1980, pp. 24–5) rightly urged caution in establishing a formal stratigraphical nomenclature for the area until the relationships of the rocks have been worked out in more detail and evidence of age obtained.

On Arran, a more complex stratigraphy has been erected for the Triassic succession (Figure 3.9). 'New Red Sandstone' was first identified here by Sedgwick and Murchison (1829b). Numerous studies have been published since; the more recent ones include Lovell (1971, 1981), Warrington (1973), Pollard and Lovell (1976), Pollard and Steel (1978), and Astin and MacDonald (1983). Stratigraphical terms derive from the detailed work of Tyrrell (1928), were revised by later workers, and formalized by Warrington *et al*. (1980, pp. 25–6).

The Brodick Breccia, probably late Permian, is overlain by the Lamlash Sandstone Formation and the Glen Dubh Sandstone Formation, which may interdigitate. Both are dated tentatively as Early Triassic since the overlying Lag a'Bheith Formation has yielded miospores (Warrington, 1973) that indicate a Mid Triassic age. This unit, and the succeeding Auchenhew Mudstone, Levencorroch Mudstone, and Derenenach Mudstone formations, are assigned to the Mercia Mudstone Group.

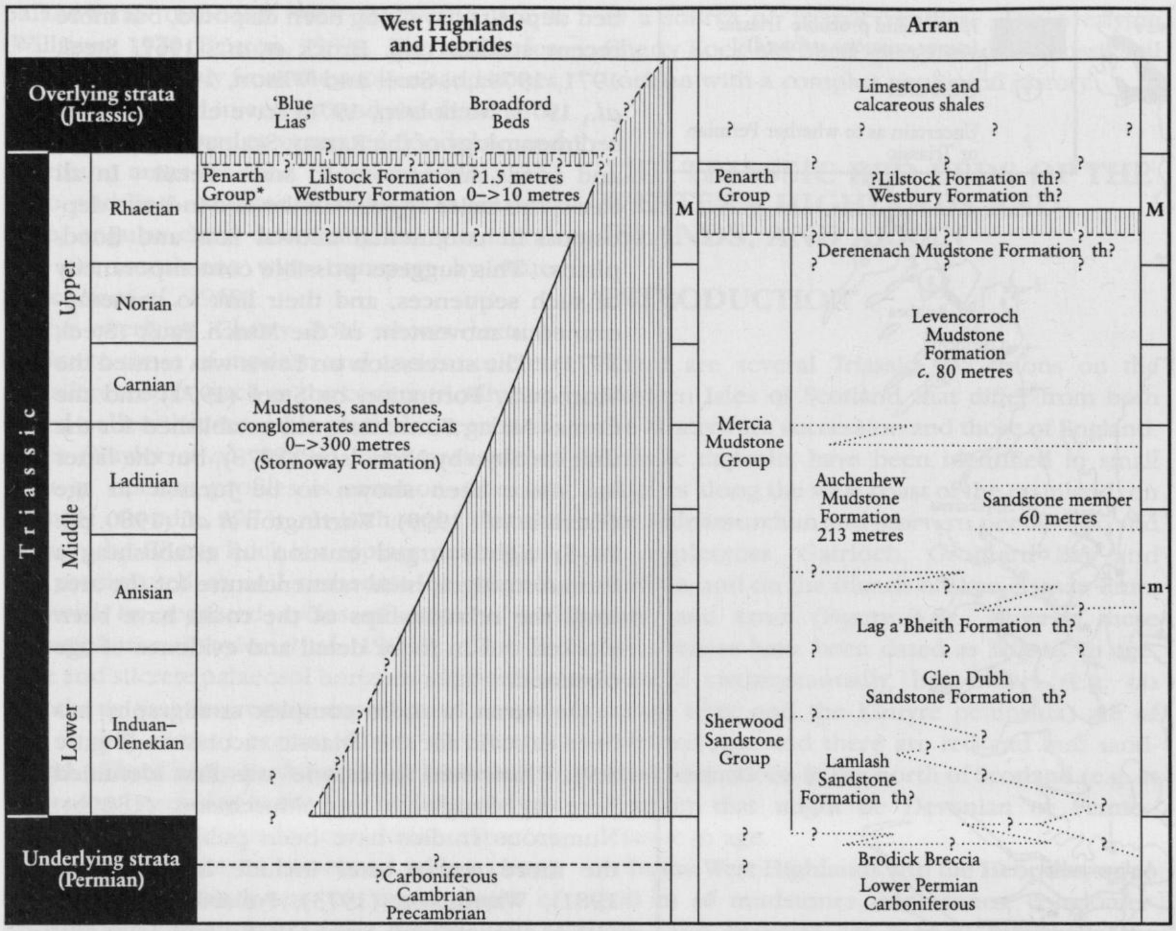


Figure 3.9 Stratigraphical columns for the 'New Red Sandstone' (including Triassic) of the western Highlands, the Hebrides, and Arran. (*The Penarth Group is known only on Mull and Morvern). M, macrofossils; m, microfossils. (After Warrington *et al.*, 1980.)

Datable fossils have not been obtained from the group above the Lag a'Bheith Formation, although plant remains and trace fossils have been recorded (Gregory, 1915; Tyrrell, 1928). The trace fossils indicate lacustrine-fluvial conditions (Pollard and Lovell, 1976). In places, indicators of marine influence, such as acritarchs (Warrington, 1973) and pseudomorphs after halite and have also been found in the Mercia Mudstone Group, indicating some similarity with the lower parts of that group in England. Otherwise, the Arran succession is comparable with that of Northern Ireland.

The Derenenach Mudstone Formation is presumably equivalent to the old 'Tea Green Marls', now part of the Blue Anchor Formation in England. Overlying this unit on Arran are black shales and thin limestones with *Rhaetavicula contorta* and other Westbury Formation fossils (i.e. Rhaetian age). The Lilstock Formation is apparently not represented on Arran, nor can the Triassic–Jurassic boundary be detected. The lowest Jurassic succession appears to be absent, the oldest ammonites indicating the *angulata* Zone (Warrington *et al.*, 1980).

It is clearly impractical to include all of the twenty or so isolated patches of Triassic, or possible Triassic, rocks in western Scotland and the Heridean region within the GCR sites. In fact, many of these small outcrops are poorly exposed and were excluded from consideration. However, four with good exposure, and each documenting key aspects of the geology of the British Triassic red beds on the western side of Scotland were selected: Gruinard Bay, Ross and Cromarty; Eyre Burn, Raasay; and Gribun, Mull all illustrate key aspects of the rather extensive, and ill-defined, Stornoway Formation, including its unconformable contact on Torridonian and Moine rocks, its alluvial fan sedimentation, and its palaeosols (cornstones). The King's Cave to Drumadoon section on Arran was selected as the best site for part of the unique Triassic red-bed succession on that island.

GRUINARD BAY, ROSS AND CROMARTY (NG 897 943–NG 902 921)

Introduction

The foreshore on the south side of Gruinard Bay provides excellent exposures of rocks of the Stornoway Formation, which rests unconformably on the Torridonian Sandstone at the western end of the section. The Stornoway Formation here consists of conglomerates, sandstones, and siltstones, commonly arranged in fining-upwards fluvial sequences. Calcretes, representing the carbonate-rich remnants of ancient soils, are well developed in many parts of the succession. These palaeosols contain the clay mineral palygorskite, normally found in weathering soil profiles, and offer evidence for repeated cycles of tropical rainfall and evaporation.

The succession at Gruinard Bay has been described in detail by Steel (1974b) and *en passant* by Craig (1965), Steel *et al.* (1975), Storetvedt and Steel (1977), Stewart (1978), and Hudson (1983).

Description

The sea cliffs and rocky foreshore on the south side of Gruinard Bay expose approximately 300 m of sediments (Steel *et al.*, 1975) assigned to the Stornoway Formation, which have been downfaulted against older strata (Craig, 1965). The sedimentary sequence at Gruinard Bay consists of the Torridonian Sandstone Formation (late Precambrian), overlain unconformably by a thick, almost continuous succession of Stornoway Formation conglomerates, sandstones and siltstones (Figure 3.10), with localized developments of calcrete throughout the sequence. The contact between the Triassic sediments and Jurassic rocks to the east is obscured by a break in exposure (Steel, 1974b). The mineral palygorskite is commonly found on the Torridonian Sandstone–Stornoway Formation unconformity surface.

The rudaceous and arenaceous sediments at

Figure 3.10 Stornoway Formation sediments at Gruinard Bay, with geological hammer for scale (arrowed). (Photo: C. MacFadyen.)

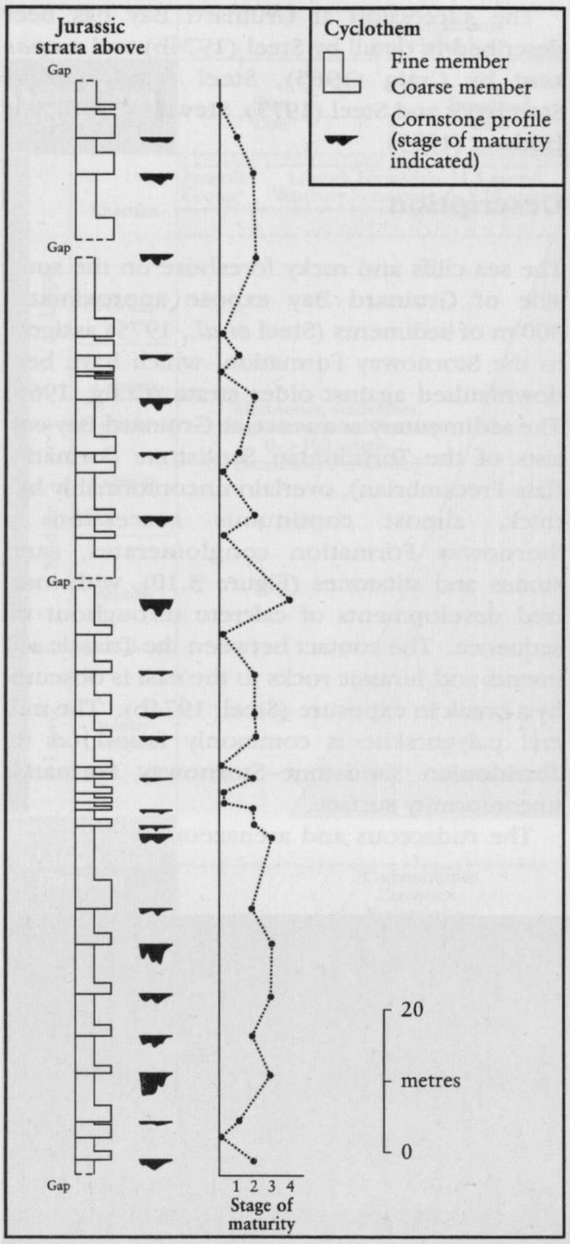


Figure 3.11 The calcrete ('cornstone') facies at Gruinard Bay. Stages 1 to 4 represent informal measures of palaeosol maturity based on depth of palaeosol and intensity of palaeosol formation. (After Steel, 1974b.)

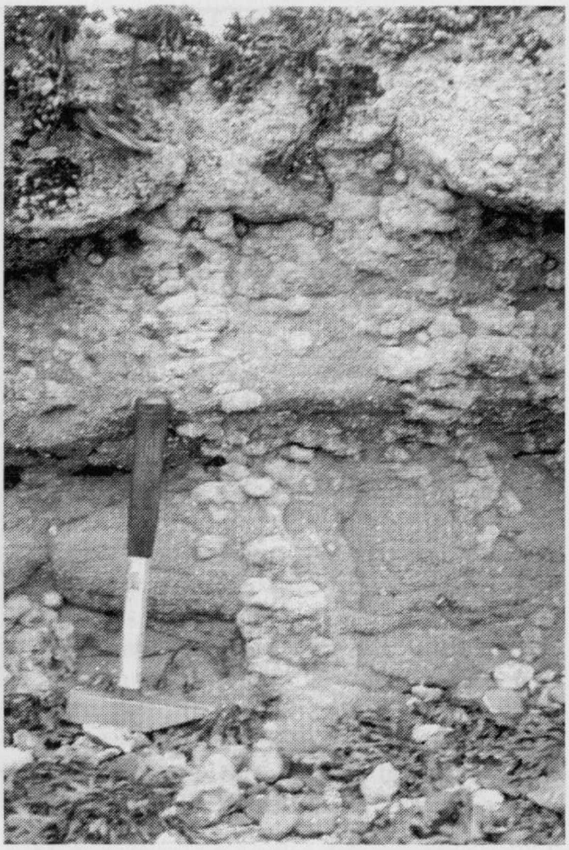


Figure 3.12 Close-up of a vertical nodular structure interpreted as a large rhizocretion, within a palaeosol at Gruinard Bay. (Photo: P. Turner.)

Gruinard Bay are arranged in a series of approximately 30 fining-upwards sequences (Figure 3.11) in a succession some 155 m thick. The boundaries between the cycles are generally erosion surfaces. The calcretes are more common in the fine-grained sections of the sequences (Steel, 1974b).

The calcretes at Gruinard Bay take many forms that reflect the maturity of the palaeosol profiles. They often reach a maximum thickness of 1 m, and are dominated by irregular nodules, sometimes elongate, vertically orientated, and of rhizocretion form, which range from 10 to 150 mm in diameter (Figure 3.12). In many cases there is a gradual increase in nodule size upwards through the calcrete units. Of lesser importance are vertical pipes and sheets, which form up to 50% of the sediment. The final calcrete form is characterized by a predominance of calcium carbonate, with only small, localized patches of host sediment. Generally, any sedimentary structures within the host sediment, such as mudstone laminae interbedded with micro-breccias, are preserved in the calcrete. Clasts within the breccia are locally derived carbonate material, although chert is also present. The pore spaces may be infilled with quartz, spherulitic chalcedony, sandy sediment or pisolites (Steel, 1974b).

No fossils have been reported from the Stornoway Formation at Gruinard Bay. Age evidence has been obtained from palaeomagnetic studies, which confirm an assignment to the Permo–Triassic (Storetvedt and Steel, 1977), but nothing more precise.

Interpretation

The Stornoway Formation at Gruinard Bay was deposited under predominantly terrestrial conditions. The fining-upwards sequences are interpreted as fluvial deposits that record repeated changes in the environment of deposition, from high-energy processes characteristic of alluvial fans, responsible for the coarse-grained conglomeratic facies, through a gradual decline in energy and sediment grain size, indicating river sand and floodplain facies.

The well-developed calcrete horizons indicate a semi-arid climate (Hudson, 1983). The mineral palygorskite at the boundary between the Torridonian Sandstone Formation and the Stornoway Formation suggests that pedogenic processes were a common phenomenon. The physical and textural characteristics of the calcrete horizons, for example the presence of laminae, micro-breccias, pisolitic clasts, and the association of calcite with silica, indicate pedogenic and diagenetic processes that operate above the water table. The unusually thick calcrete horizons at Gruinard Bay are probably the result of many phases of palaeosol development in a subsiding basin, as it is unlikely that one calcrete horizon would result from a single rainfall, percolation and desiccation cycle alone (Steel, 1974b). The relative thickness of the Gruinard sequence of cornstone (calcrete) cycles in comparison with similar successions indicate that the Gruinard area was subsiding more frequently and more rapidly than that, for example, on the Isle of Rum.

Conclusions

The coastal sequence at Gruinard Bay exposes an excellent accessible section through the Stornoway Formation. The sediments unconformably overlie the Precambrian Torridonian Sandstone Formation. The Stornoway Formation consists of fining-upwards sequences of conglomerates, sandstones, and siltstones. Calcretes are common in parts of the sequence, and indicate tropical climatic conditions. These sediments were deposited under predominantly terrestrial conditions by rivers, with soils forming on the river floodplain.

EYRE BURN, ISLAND OF RAASAY, SKYE AND LOCHALSH (NG 577 342)

Introduction

The raised beach at the mouth of Eyre Burn shows an excellent succession within the Stornoway Formation. The sequence rests unconformably on the Torridonian Sandstone Formation and comprises a sequence of alluvial fanglomerates sandwiched between red sandstones with calcrete. The conglomerates are very poorly sorted; sedimentary structures such as imbrication and cross-bedding are poorly developed. Maximum particle size shows a significant correlation with bed thickness and this, along with the lack of basal erosion surfaces, suggests these sediments were the product of debris flows. This is an important site for the elucidation of sedimentary processes in the alluvial fan environment.

The Triassic sediments of Raasay and other nearby locations have been described by Judd (1878), Peach *et al.* (1910), Lee (1920), Lee and Pringle (1932), Bruck *et al.* (1967), and Bell and Harris (1986).

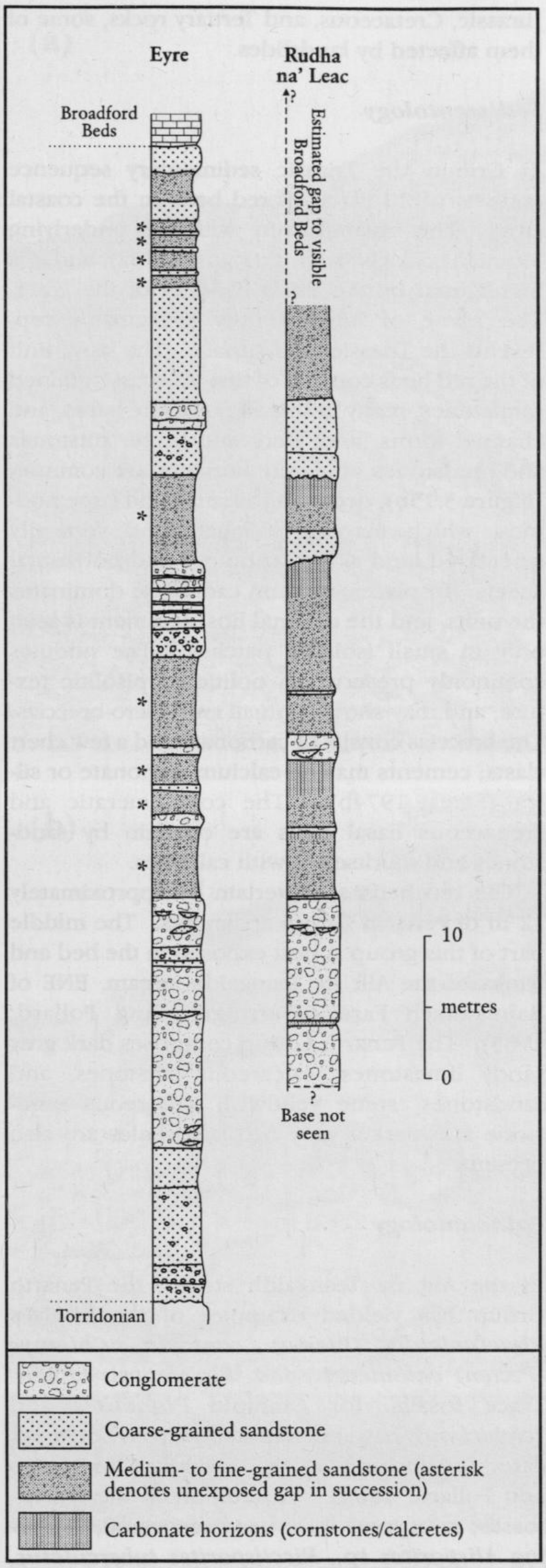
Description

In Eyre Burn, and along the cliffs of the raised beach to the east, seen behind the track that runs parallel to the sea, about 76 m of sediments of the Stornoway Formation are exposed (Figure 3.13). These dip towards the north-west, and are commonly cut by small, vertical, inclined, or curving dykes (Peach *et al.*, 1910).

The lowest unit exposed in the vicinity of Eyre Burn comprises arenaceous sediments of the Torridonian Sandstone Formation (Precambrian). The boundary between this unit and the overlying sediments is slightly irregular. The Stornoway Formation (Figure 3.14) falls naturally into three units, a basal, mainly sandstone, unit, overlain by a thick succession of conglomerates and sandstones, which are succeeded by more sandstones.

The basal sandstones, some 9 m thick, are generally coarse-grained, have a calcareous

Figure 3.13 Triassic sediments at the Eyre Burn GCR site; (a) a conglomerate deposited as a sheet flood on an alluvial fan; and (b) a palaeosol, comprising a siltstone with calcretes. (Photos: C. MacFadyen.)



matrix, and include a 0.07 m thick pebble band that contains clasts of quartzite, and Torridonian Sandstone and Durness Limestone Formation sediments (Figure 3.13a). The upper 3 m of this basal unit contains calcretes and extensive developments of a fine-grained carbonate (Figure 3.13b).

This unit is overlain conformably by conglomerates seen below and above a break in exposure, which may correspond, by comparison with the surrounding area, with a medium-grained sandstone unit. Below this break, 16m of conglomerates are seen; above it *c.* 21m are seen, but only in the Eyre Burn (Bruck *et al.*, 1967). The top of the Eyre sequence consists of sandstones, many of which are white or very pale in colour. The sandstones are overlain by reddish sandstones and clays, followed by the Jurassic Broadford Beds (Bruck *et al.*, 1967).

The Stornoway Formation on Raasay has been sampled in an attempt to recover palynomorphs, but without success (Warrington and Pollard, 1985); it is assumed here to be Triassic in age (see above).

Interpretation

The sediments at Eyre resemble the sequences of Rudha na' Leac (Figure 3.14) and Suisnish Hill on Raasay and Eilean Leac na Gainimh on Scalpay. The Stornoway Formation was deposited on the eastern margins of the Inner Hebrides Trough (as defined by McQuillin and Binns, 1973; Hudson, 1983; Morton, 1992). The basin was infilled by braided channels down the south-west palaeoslope, and by alluvial fans towards the north-east and north-west. The Raasay sediments were deposited in a small extension of the Inner Hebrides Trough. The source for these sediments was the higher relief areas of central Skye. The Eyre sediments are thought to be younger than comparable facies on Skye (Steel *et al.*, 1975).

Figure 3.14 The Triassic section in the GCR site at Eyre Burn (left), and through the neighbouring site at Rudha na' Leac (right), showing the transition upwards from conglomerates deposited by braided rivers in alluvial fans at the base, through fine sandstones and palaeosols. (After Bruck *et al.*, 1967.)

Conclusions

The Stornoway Formation around Eyre Point and Eyre Burn is dominated by conglomerates, red siltstones and calcretes, and was deposited on large alluvial fans. The conglomerates at Eyre Point are spectacular, being thick and displaying varied textures; they are critical for establishing the nature of Triassic deposition in western Scotland, and in demonstrating the relationships of sedimentation to relief and tectonic activity.

GRIBUN SHORE AND CRAGS, MULL, STRATHCLYDE (NM 444 334–NM 480 362)

Introduction

The sea cliffs and foreshore at Gribun expose an excellent section through the conglomerates and sandstones of the Stornoway Formation. The basal contact with ancient Moinian rocks is magnificently exposed, and the red beds are overlain by fossiliferous Rhaetian deposits. The Stornoway Formation includes a range of conglomerates formed in alluvial fan and braided stream situations and associated with siltstones. Many of the siltstones have well-developed columnar and nodular calcrete profiles, often with oolitic or pisolitic texture. The site is important for its demonstration of alluvial fan deposits and calcrete horizons in the red beds, and for their unusual exposure in continuity with the overlying Penarth Group.

Brief accounts of the Gribun site have been given by Bailey and Anderson (1925), Lee and Bailey (1925), Craig (1965), Steel (1974b), Hudson (1983), Walker *et al.* (1985), and Warrington and Pollard (1985).

Description

The Gribun Shore and Crags Site of Special Scientific Interest (SSSI), on the west coast of the Isle of Mull, contains three areas of geological interest: the shoreline, the crags, and a small area close to Balmeanach Farm. The Stornoway Formation is seen in a narrow strip along the shore, overlying the Moinian rocks, and overlying red beds and marine sediments of the Penarth Group are seen in the banks of the Allt na Teangaidh upsteam from Balmeanach Farm. Above it is a representative of the Penarth Group, which is overlain successively by Jurassic, Cretaceous, and Tertiary rocks, some of them affected by landslides.

Sedimentology

At Gribun the Triassic sedimentary sequence consists of 20–30 m of red beds in the coastal strip. The unconformity with the underlying Moinian rocks is striking (Figure 3.15a), and it is highlighted by the tilted banding of the latter. The plane of unconformity presumably represents the Triassic land surface. The basal unit of the red beds consists of fine- to coarse-grained sandstones, many with conglomeratc bases, and channel forms, and, here and there, siltstones and mudstones. Calcrete horizons are common (Figure 3.15b), occurring as small and large nodules, which may be elongate and vertically orientated, and as vertical pipes and horizontal sheets. In places, calcium carbonate dominates the units, and the original host sediment is seen only in small isolated patches. The nodules commonly preserve an oolitic or pisolitic texture, and may show laminae and micro-breccias. The breccias consist of carbonate and a few chert clasts; cements may be calcium carbonate or silica (Steel, 1974b). The conglomeratic and arenaceous basal beds are overlain by sandstones and mudtsones with calcretes.

The red beds are overlain by approximately 12 m of Penarth Group sediments. The middle part of this group is best exposed in the bed and banks of the Allt na Teangaidh stream, ENE of Balmeanach Farm (Warrington and Pollard, 1985). The Penarth Group comprises dark grey sandy limestones, calcareous siltstones, and sandstones; some yellowish calcareous sandstone and darker grey or black shales are also present.

Palaeontology

In the Allt na Teangaidh stream the Penarth Group has yielded examples of the bivalves *Rhaetavicula (Pteria) contorta*, *Chlamys (Pecten) valoniensis*, and ?*Placunopsis alpina*. Trace fossils, for example *Planolites* and *Teichichnus*, have been recorded from sandy calcareous siltstones in this section (Warrington and Pollard, 1985). In addition to the macrofossils, miospores have been recovered, including *Alisporites* sp., *Ricciisporites tuberculatus*, and ?*Ovalipollis pseudoalatus*, all from the dark silty mudstones and shales exposed in the

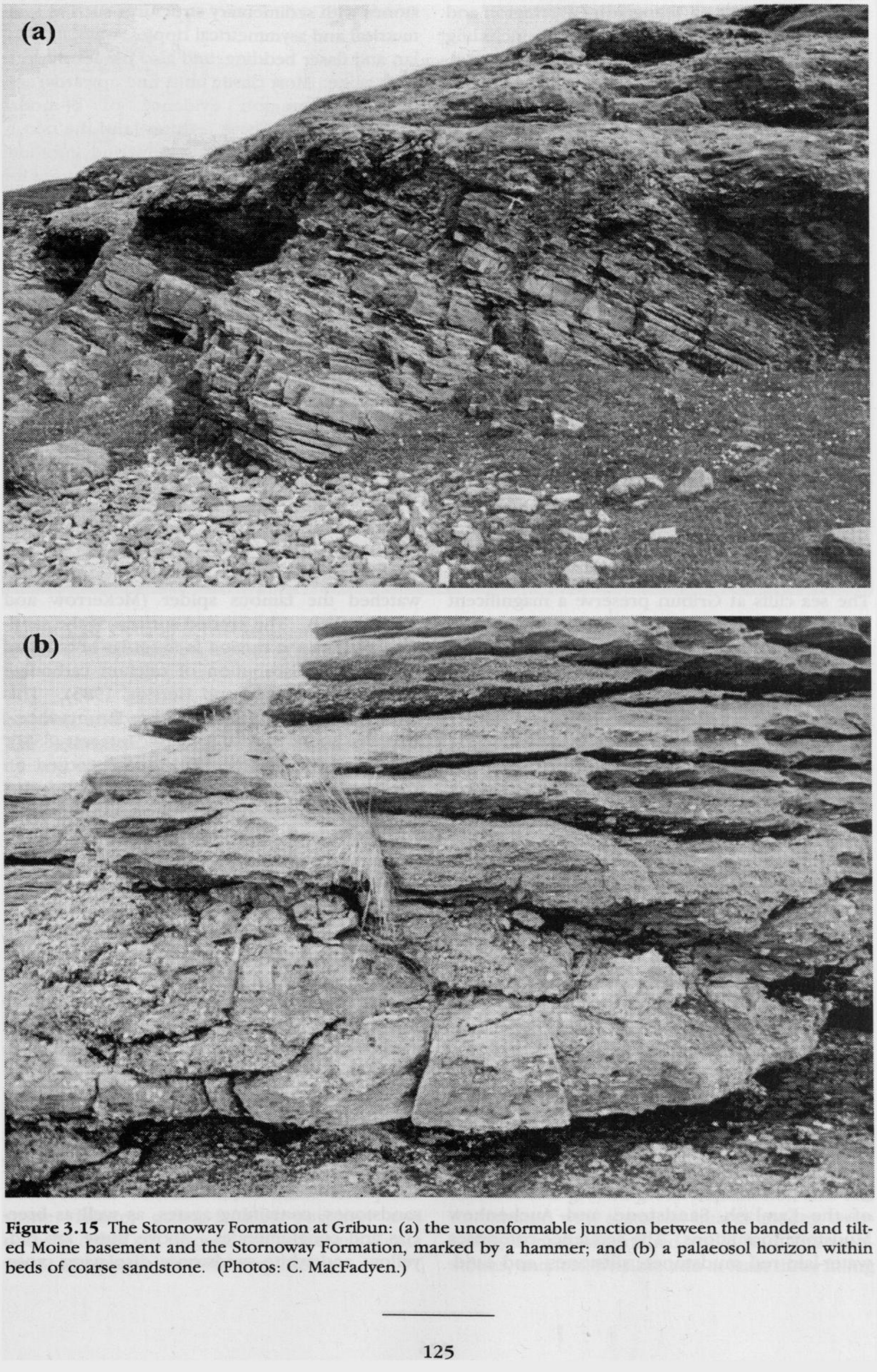


Figure 3.15 The Stornoway Formation at Gribun: (a) the unconformable junction between the banded and tilted Moine basement and the Stornoway Formation, marked by a hammer; and (b) a palaeosol horizon within beds of coarse sandstone. (Photos: C. MacFadyen.)

course of the Allt na Teangaidh (Warrington and Pollard, 1985). Plant macrofossils, including small pieces of woody and vascular material, have also been recovered from dark grey siltstones and mudstones and black shales.

Interpretation

The Triassic rocks of Gribun, Mull, were deposited on the margins of an asymmetrical sedimentary basin. The conglomeratic sediments accumulated as fans against the active margins of the basin. The finer-grained siltstones, with their associated calcretes, represent a fluvial environment with soils developing on the interfluves and banks. The presence of calcareous nodules is evidence for periodic flooding and a semi-arid climate (Hudson, 1983). The plant remains suggest a continental humid environment.

The miospores indicate a correlation of the upper mudstone units with the Penarth Group of England (Warrington and Pollard, 1985).

Conclusions

The sea cliffs at Gribun preserve a magnificent section through conglomerates, sandstones, siltstones, mudstones, and calcretes of the Stornoway Formation, with, inland, a succession that extends up to the Penarth Group. The Stornoway Formation was deposited under dominantly terrestrial conditions, in part of a large-scale river system characterized by braided channels and alluvial fans. The presence of calcrete nodules indicates that soil profiles formed on the sediments. The succession here is important in documenting the basal unconformity spectacularly, and in showing, in close association, the Penarth Group sediments that are usually absent in the western Scottish region.

KING'S CAVE TO DRUMADOON, ARRAN, STRATHCLYDE (NR 884 309–NR 884 291)

Introduction

The coastal exposures between King's Cave and Drumadoon on the west coast of Arran present a good sequence of Triassic continental sediments of the Lamlash Sandstone and Auchenhew Mudstone formations. The sequence comprises water-lain red mudstones, siltstones, and sandstones with sedimentary structures such as symmetrical and asymmetrical ripples, wavy, lenticular, and flaser bedding, and also pseudomorphs after halite. Most clastic units fine upwards, and there is common evidence of bi-modal palaeocurrents. These features, and the occurrence of burrows, indicate a marine intertidal environment and make this an important site for understanding the Triassic palaeogeography of south-western Scotland.

Publications that relate specifically to the area of King's Cave and Drumadoon include Lovell (1971), Pollard and Lovell (1976), and Pollard and Steel (1978), and general accounts have been given by MacDonald and Herriot (1983) and McKerrow and Atkins (1989).

Description

The coastline between King's Cave and Drumadoon Point is characterized by high cliffs and a series of well-developed wave-cut platforms (Figure 3.16); several natural caves have been cut into the cliffs. The largest of these is King's Cave, where Robert the Bruce may have watched the famous spider (McKerrow and Atkins, 1989). The eroded surface of the sandstones along the section is irregular because of the uneven distribution of calcium carbonate cement (MacDonald and Herriot, 1983). This GCR site is included in the Drumadoon–Tormore Site of Special Scientific Interest (SSSI).

In many places, the sandstones exposed on the foreshore and in the cliffs are cut by faults. The faults do not appear to have a large throw, and igneous dykes commonly follow the fault planes (Pollard and Lovell, 1976).

Sedimentology

The cliffs expose a thick sequence of grey and reddish sandstones, many of which are cross-laminated. The lower portions are assigned to the Brodick Breccia, or Brodick Beds, probably Permian in age (Warrington , 1973). Above these are about 400 m of the Lamlash Sandstone Formation (Warrington *et al.*, 1980), formerly 'the Lamlash Beds' (Tyrrell, 1928; Piper, 1970; Lovell, 1971; Warrington, 1973), consisting of a lower and an upper portion. The lower half of the formation is composed of cross-bedded red sandstones, containing agates, as well as breccias and conglomerates. Above these are red, yellow, and white sandstones displaying cross-

Figure 3.16 Outcrop of red sandstones of the Lamlash Sandstone Formation on the wave-cut platform on the foreshore at Drumadoon, looking south. (Photo: C. MacFadyen.)

bedding, and with sporadic conglomerate units. The sediments become finer-grained towards the top of the unit. The Glen Dubh Sandstone Formation appears to be of similar age (Warrington *et al.*, 1980) and interdigitates with the Lamlash Sandstone Formation and perhaps also with the Brodick Breccia.

These sandstone units are overlain by a largely argillaceous unit, formerly termed simply 'the Auchenhew Beds' (Tyrrell, 1928; Piper, 1970; Lovell, 1971; Warrington, 1973), but since divided into the Lag a'Bheith Formation and the overlying Auchenhew Mudstone Formation. The former is dominated by mudstones, but contains some sandstone units, and the latter is almost entirely argillaceous.

The Auchenhew Mudstone Formation (Warrington *et al.*, 1980, p. 26) comprises red and greenish marls with thin sandstone units (Figure 3.17a). The sediments are generally parallel-bedded. Several small faults and pitchstone, felsite, quartz-feldspar-porphyry and dolerite dykes cut through the sediments (Judd, 1893; MacDonald and Herriot, 1983).

A composite section through the Auchenhew Mudstone Formation (Figure 3.18) has been compiled by Pollard and Steel (1978). The lower parts of the succession are best seen in the central part of the bay to the south of King's Cave. The sediments here consist of a repetition of coarsening-upwards cycles. At the base are red, blocky, muddy siltstones, which may include laminae with scattered pseudomorphs after halite, that are overlain by red and red-green mottled silty mudstones, which may preserve ripple laminations. At the top are greyish-green or white sandstones with ripple laminations, sporadic low-angle cross-bedding and occasional interbedded mudstones with mudcracks.

The middle part of the sequence was measured north of the waterfall gully at the top of the cliff, on the upthrown side of a fault (Figure 3.18). It comprises approximately 16 m of interbedded greyish-green sandstones and red mudstones, with scattered quartz geodes, overlain by 2 m of fine-grained, reddish, quartz sandstones, and it is divisible into at least three fining

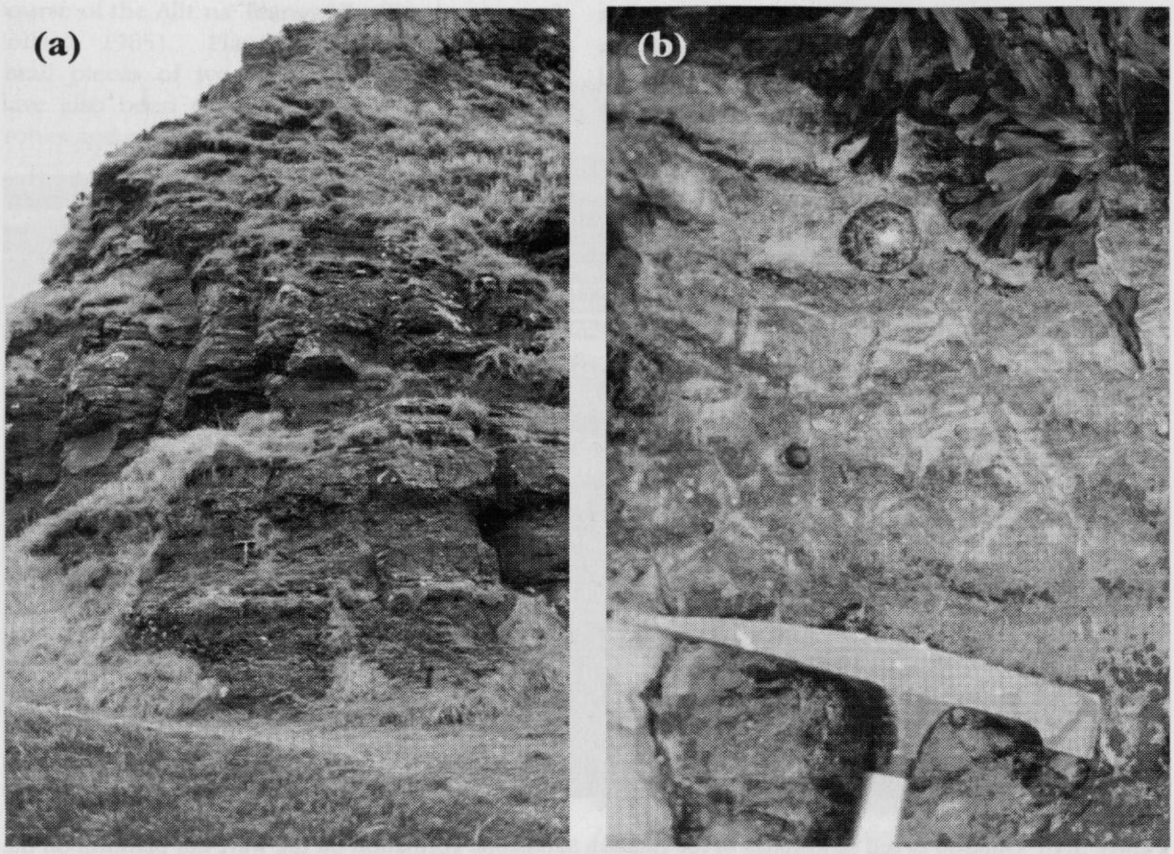


Figure 3.17 The Triassic sediments between King's Cave and Drumadoon: (a) succession of siltstones and mudstones of the Auchenhew Mudstone Formation; and (b) burrows, cf. *Cylindricum*, on the surface of a ripple-marked, fine-grained sandstone. (Photos: C. MacFadyen.)

upwards cycles. The lowest part of the basal cycle is characterized by megaripple bedding. The basal section of the top cycle typically preserves fine examples of climbing-ripple laminations. Sedimentary structures, such as flaser and lenticular bedding, are common throughout, and trace fossils (*Siphonites*, *Cylindricum*; Figure 3.17b), bioturbation and pseudomorphs after halite, which often take the form of partial hopper crystals and are associated with rippled sandstone, are also present (Pollard and Steel, 1978).

The upper part of the Auchenhew Mudstone Formation is best exposed in the cliffs of a hanging gully and waterfall near Cleiteadh nan Sgarbh (NR 886 302; Pollard and Lovell, 1976). The sequence exposed here is approximately 25 m thick (Figure 3.18). At the base are massive micaceous sandstones with ripple cross-laminations and some mudcracked surfaces. These are overlain by thinly bedded micaceous mudstones, siltstones, and quartz sandstones, which grade up into a thin unit of nodular and lenticular sandstones that contain fragments of rock and feldspar and have been cemented with calcite. The upper part of the cliff section has been divided into four units. Unit I consists of red-green, calcareous, silty mudstones that contain irregular and laterally discontinuous beds of well-cemented sandstone. Unit II is dominated by red-green calcareous silty mudstones, and has a thin (approximately 0.2 m thick) sandstone bed just over half-way up the unit. The overlying Unit III is more complex, and contains red-green siltstone, cross-laminated sandstone, three well-cemented sandstone beds, which preserve ripple cross-laminations, climbing ripple laminations and wavy bedding, and silty mudstones. The top of the gully cliff consists of a thin basal sandstone and red-green silty mudstone (Unit IV). In all four units the silty sediments contain carbonate nodules, the 'potato stones' reported by Gregory (1915), (Pollard and Lovell, 1976; Pollard and Steel, 1978).

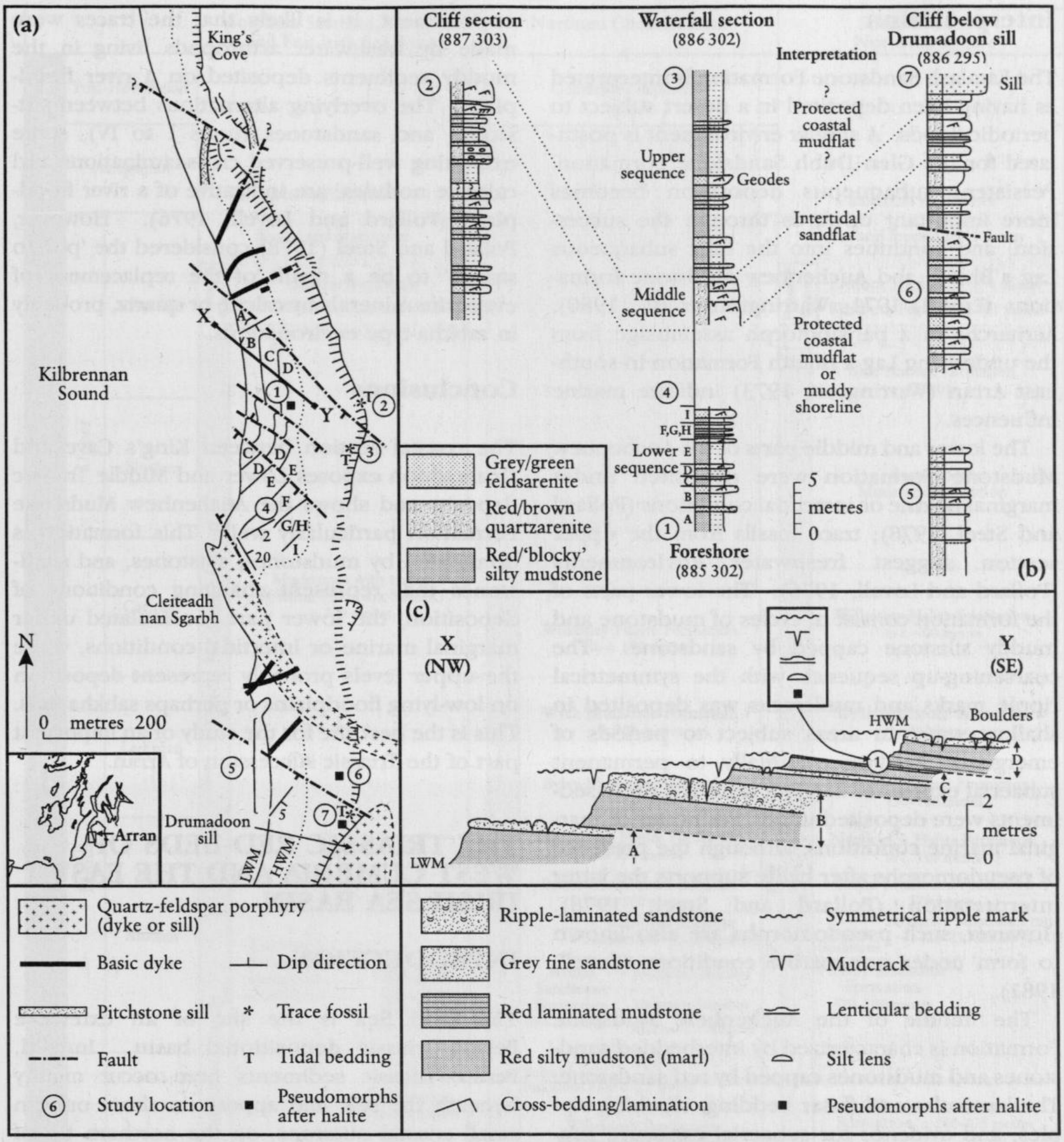


Figure 3.18 (a) Map of the west coast of Arran; (b) sedimentary logs through the King's Cave to Drumadoon Triassic succession, and (c) diagrammatic NW–SE cross-section of the foreshore and cliffs (see map (a) for location). The logs are composed from measurements made in seven locations shown on the map. (After Pollard and Steel, 1978.)

Palaeontology

Pollard and Lovell (1976) discovered a trace fossil assemblage in fallen blocks of Auchenhew Mudstone Formation below the cliffs near Cleiteadh nan Sgarbh (NR 886 302). Three trace fossil morphologies have been recorded: '*Siphonites*', *Cylindricum*, and epichnial ridges. The age of the Auchenhew Mudstone Formation is constrained by an Anisian miospore assemblage recovered by Warrington (1973) from the underlying Lag a'Bheith Formation in south-eastern part of the Isle of Arran.

Interpretation

The Lamlash Sandstone Formation is interpreted as having been deposited in a desert subject to periodic floods. A similar environment is postulated for the Glen Dubh Sandstone Formation. Persistent subaqueous deposition becomes more important upwards through the succession, and continues into the fully subaqueous Lag a'Bheith and Auchenhew Mudstone formations (Lovell, 1971; Warrington *et al.*, 1980). Acritarchs in a palynomorph assemblage from the underlying Lag a'Bheith Formation in south-east Arran (Warrington, 1973) indicate marine influences.

The lower and middle parts of the Auchenhew Mudstone Formation were deposited under marginal marine or intertidal conditions (Pollard and Steel, 1978); trace fossils from the upper section suggest freshwater environments (Pollard and Lovell, 1976). The lower parts of the formation consist of cycles of mudstone and muddy siltstone capped by sandstone. The coarsening-up sequence with the symmetrical ripple marks and mudcracks was deposited in shallow water in areas subject to periods of emergence, leading eventually to permanent subaerial exposure. It is not known if these sediments were deposited under freshwater or marginal marine conditions, although the presence of pseudomorphs after halite supports the latter interpretation (Pollard and Steel, 1978). However, such pseudomorphs are also known to form under non-marine conditions (Lovell, 1981).

The middle of the Auchenhew Mudstone Formation is characterized by interbedded sandstones and mudstones capped by red sandstone. The lenticular and flaser bedding, climbing ripples, and evidence for subaerial exposure suggest deposition on prograding low-energy tidal flats. The isolated sandstone wedges, with their well-developed cross-bedding, are thought to have been deposited in small channels or creeks incised in a low-lying landscape. Palaeocurrents indicate that the dominant direction of flow was towards the south-west, and may indicate ebb currents in the channels and across the intertidal flats (Pollard and Steel, 1978).

The sediments and trace fossils of the lower parts of the waterfall section are characteristic of deposits that accumulated under dominantly terrestrial conditions. Although the trace fossil assemblage is not diagnostic of any palaeoenvironment, it is likely that the traces were made by freshwater arthropods living in the muddy sediments deposited on a river floodplain. The overlying alternations between siltstones and sandstones (units I to IV), some exhibiting well-preserved cross-laminations and calcrete nodules, are indicative of a river floodplain (Pollard and Lovell, 1976). However, Pollard and Steel (1978) considered the 'potato stones' to be a result of the replacement of evaporite minerals by calcite or quartz, probably in sabkha-type environments.

Conclusions

The coastal section between King's Cave and Drumadoon exposes Lower and Middle Triassic deposits and shows the Auchenhew Mudstone Formation particularly well. This formation is dominated by mudstones, siltstones, and sandstones that represent changing conditions of deposition; the lower part accumulated under marginal marine or intertidal conditions, while the upper levels probably represent deposition on low-lying floodplains or perhaps sabkha flats. This is the best site for the study of an important part of the Triassic succession of Arran.

THE TRIASSIC RED BEDS OF WEST CUMBRIA AND THE EAST IRISH SEA BASIN

INTRODUCTION

The Irish Sea is the site of an extensive Permo–Triassic depositional basin. Indeed, Permo–Triassic sediments here occur mainly beneath the sea, and appear on shore only in small coastal outcrops, on the northern tip of the Isle of Man, along the Solway Firth, the coastal margin of Cumbria, and west Lancashire and on the Wirral Peninsula (Figure 3.1). Many of these outcrops are masked by glacial and other superficial deposits, and good exposures are rare. The onshore representatives were summarized by Warrington *et al.*, (1980), and the offshore geology described by Colter and Ebbern (1978), Jackson *et al.* (1987), Warrington and Ivimey-Cook (1992), Cowan (1993), Jackson and Mulholland (1993), Meadows and Beach (1993), Jackson *et al.* (1995), Jackson and Johnson (1996), and Meadows *et al.* (1997).

The East Irish Sea Basin consists of eight or

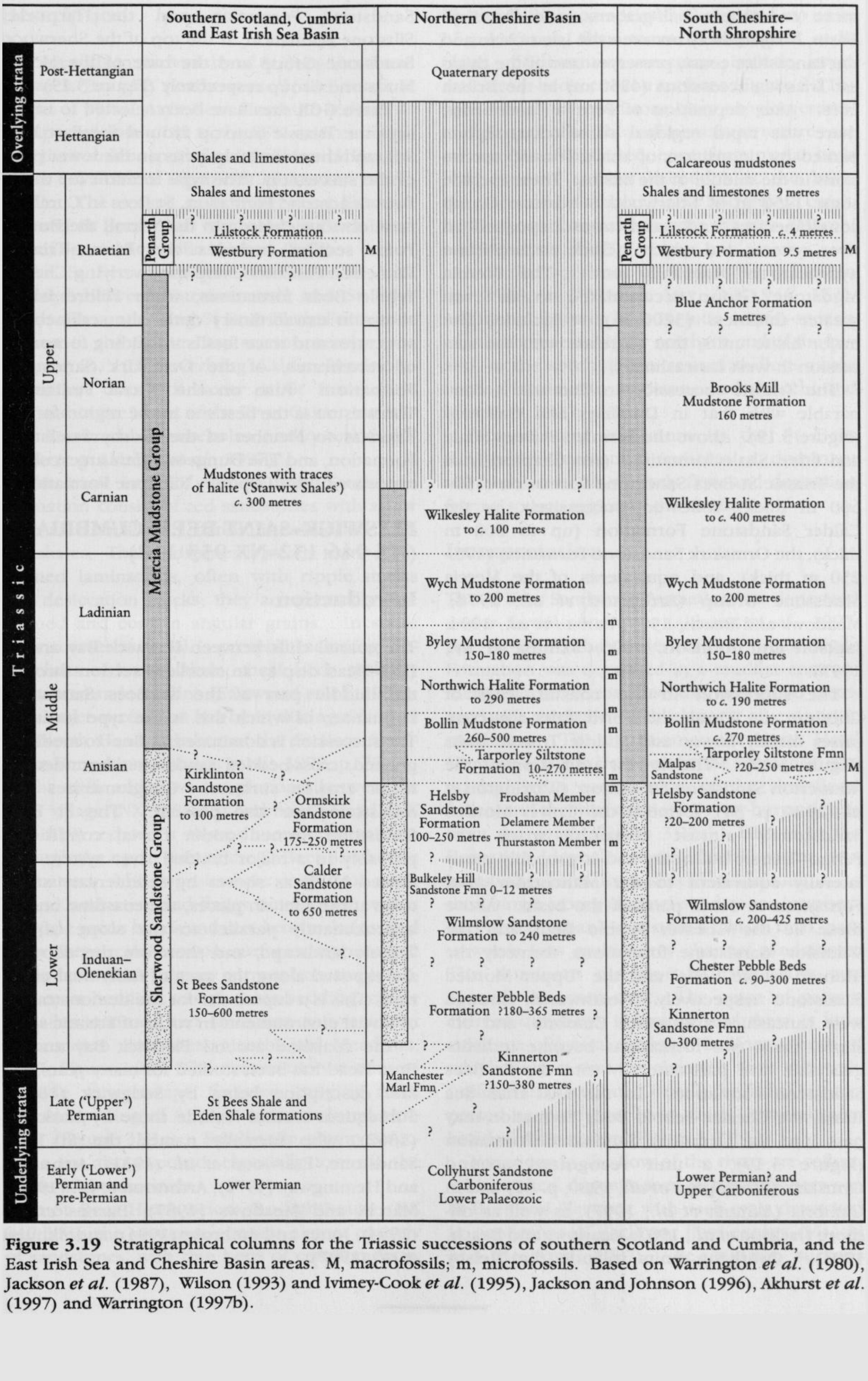


Figure 3.19 Stratigraphical columns for the Triassic successions of southern Scotland and Cumbria, and the East Irish Sea and Cheshire Basin areas. M, macrofossils; m, microfossils. Based on Warrington *et al.* (1980), Jackson *et al.* (1987), Wilson (1993) and Ivimey-Cook *et al.* (1995), Jackson and Johnson (1996), Akhurst *et al.* (1997) and Warrington (1997b).

more constituent half-grabens, and the Keys Basin, lying midway between the Isle of Man and the Lancashire coast, preserves one of the thickest Triassic successions (4250 m) in the British Isles. After deposition of Permian sediments, there was rapid regional subsidence, accompanied by deposition of thick Triassic successions in the middle of the basins. These include some 1450 m of Sherwood Sandstone Group conglomerates and sandstones deposited in river systems and which include an important hydrocarbon reservoir unit. The Mercia Mudstone Group accumulated to an even greater thickness (3200 m); it includes five major halite units, that correlate with the succession in west Lancashire.

The Triassic succession in Cumbria is comparable with that in Dumfries and Galloway (Figure 3.19). Above the Permian St Bees Shale and Eden Shale formations (see Chapter 3), is the Triassic St Bees Sandstone Formation (150–600 m thick), followed, successively, by the Calder Sandstone Formation (up to 600 m thick), the Ormskirk Sandstone Formation (175–250 m thick), and equivalents of the Mercia Mudstone Group (Arthurton *et al.*, 1978; Meadows and Beach, 1993; Barnes *et al.*, 1994; Jackson and Johnson, 1996; Akhurst *et al.*, 1997).

The succession in the coastal areas of Cheshire, the Wirral, and North Wales also comprises mainly Lower and Middle Triassic units (Figure 3.19). The lowest unit, termed the 'Kinnerton Sandstone Formation' (Warrington *et al.*, 1980, p. 31), formerly the 'Lower Mottled Sandstone', almost certainly spans the Permo–Triassic boundary and is probably partly laterally equivalent to the Manchester Marl Formation in other parts of the basin. Above these lie the Chester Pebble Beds and the Wilmslow Sandstone formations, formerly the 'Bunter Pebble Beds' and the 'Upper Mottled Sandstone' respectively. Northwards, through west Lancashire and south Cumbria, and offshore, these two formations become indistinguishable and pass laterally into the St Bees Sandstone Formation. In the East Irish Sea Basin, the Chester Pebble Beds Formation may pass into the Ormskirk Sandstone Formation (Figure 3.19), a unit recognized around Ormskirk (Warrington *et al.*, 1980, p. 32) and in Cumbria (Akhurst *et al.*, 1997), as well as offshore (Jackson *et al.*, 1987; Meadows and Beach, 1993). Overlying units include the Helsby Sandstone Formation and the Tarporley Siltstone Formation, at the top of the Sherwood Sandstone Group and the base of the Mercia Mudstone Group respectively (Figure 3.19).

Three GCR sites have been selected to represent the Triassic outcrop around the East Irish Sea, and they inevitably focus on the lower parts of the succession. The type location for the St Bees Sandstone Formation, St Bees in Cumbria, is an obvious choice. In the Wirral, the Burton Point section includes the Permo–Triassic Kinnerton Sandstone and the overlying Chester Pebble Beds formations, while Hilbre Island shows in extraordinary detail the sedimentary structures and trace fossils, including footprints of vertebrates, of the Ormskirk Sandstone Formation. Also on the Wirral Peninsula, Thurstaston is the best site in the region for the Thurstaston Member of the Helsby Sandstone Formation, and The Dungeon offers an excellent exposure of the Tarporley Siltstone Formation.

FLESWICK–SAINT BEES, CUMBRIA (NX 946 132–NX 953 118)

Introduction

The coastal cliffs between Fleswick Bay and St Bees Head display an excellent section through the middle part of the St Bees Sandstone Formation, of which this is the type location. The succession is dominated by fine- to medium-grained, cross-bedded sandstones bounded by major erosion surfaces. Conglomerates and mudstones are also present. The St Bees Sandstone formed under fluvial conditions, probably in a major braided river system that flowed NNW, as shown by sedimentary structures at the site. In places, the coastline here is approximately parallel to the slope of the Triassic landscape, and therefore the deposits are exposed along the axes of individual channels. This is a superb site for the demonstration of fluvial environments in rocks of Triassic age.

The coastline around Fleswick Bay and St Bees Head has been studied for many years, the first description being by Sedgwick (1832). Subsequent studies include those by Harkness (1862), who formally named the St Bees Sandstone, Eastwood *et al.* (1931), Arthurton and Hemingway (1972), Arthurton *et al.* (1978), Macchi and Meadows (1987), Barnes *et al.* (1994), Jones and Ambrose (1994), and Akhurst *et al.* (1997).

Description

The sea cliffs in the vicinity of St Bees Head and Fleswick Bay are nearly vertical and reach a height of 90 m. At St Bees Head the sediments dip approximately 12° to the SSW or occasionally to the south or south-east. At Fleswick Bay the dip is towards the south-east (Eastwood *et al.*, 1931). The coastal section between Fleswick Bay and St Bees Head forms the St Bees Head Site of Special Scientific Interest (SSSI).

The St Bees Sandstone Formation is well exposed between Barrowmouth and St Bees Head. The underlying St Bees Shale Formation is seen in the Saltom Bay section nearby (see Chapter 2). The overlying Calder Sandstone Formation does not occur at St Bees; it is exposed in the banks of the River Calder but it is best known from boreholes onshore and offshore (e.g. Akhurst *et al.*, 1997).

The basal beds of the St Bees Sandstone Formation consist of red sandstones with a few blue and bluish-grey bands, interbedded with red shales. The sandstones typically show well-defined laminations, often with ripple marks and desiccation cracks; they are generally fine grained and contain angular grains. In some beds coarser material is present, including rip-up clasts of brown shale; these beds typically contain rounded grains (Eastwood *et al.*, 1931). This lower succession has been distinguished as the North Head Member of the St Bees Sandstone Formation (Akhurst *et al.*, 1997, p. 79).

The cliffs and wave-cut platform between St Bees village (NX 958 118) and South Head (NX 952 119) expose a three-dimensional section through the upper part of the St Bees Sandstone Formation. The deposits here consist of micaceous, laminated, and flaggy sandstones, with a few pale green bands and rare brown shales, and show large-scale erosion surfaces, upper-stage plane beds (with primary current lineation), tabular cross-bedding, trough cross-bedding, ripple cross-laminations, and abundant soft-sediment deformation structures (Macchi and Meadows, 1987; Figure 3.20). The deformation structures include water-escape features, ranging from over-steepening of foresets to convoluted bedding (Figure 3.21a). Small-scale slump structures are also exposed, especially towards the edges of the channels.

At St Bees Head, below the lighthouse (NX 940 143), the sequence consists almost entirely of sandstones, with thin beds of conglomerate. The sandstones comprise thick (up to 4 m) units of micaceous, fine- to medium-grained sediment. Sedimentary structures include large-scale cross-beds, erosion surfaces (Figure 3.21b) with associated mudstone-clast conglomerates, and planar beds. The sedimentary structures are arranged in a vague sequence, from planar beds with primary current lineations at the base, through units of tabular planar and trough cross-bedding, to laminations with ripples (Macchi and Meadows, 1987).

A similar sequence of sandstones is seen in the cliffs at Fleswick Bay (NX 946 133). Additional features here include a cross-section of a small channel at the northern end of the bay and, to the south, gutter casts with flute marks cutting into a thin mudstone bed (Macchi and Meadows, 1987, p. 121).

Palaeocurrent indicators in the St Bees Sandstone Formation indicate a dominant northerly to north-westerly flow and derivation from a source region to the south.

Interpretation

The St Bees Sandstone Formation was deposited under fluvial conditions (Akhurst *et al.*, 1997, pp. 81–3). The underlying St Bees Shale Formation was deposited in a mudflat environment as wind-borne dust and sheetflood detritus, with periodic establishment of evaporitic conditions. The transition to the North Head Member of the St Bees Sandstone Formation was marked by a continuation of the sheetflood facies, and the introduction of river-borne debris from the south (Figure 3.22a). Higher in the formation, deposits of this fluvial system progressively evolve from sheetflood sediments to thin, single-storey channel sandstones interbedded with overbank mudstones that, in turn, pass upwards into multi-storey channel sandstones. The dominant direction of river flow was towards the north-west. The range of palaeocurrent directions is limited, and there is little evidence of lateral accretion bedforms, both of which suggest that the channels were relatively uniform in direction. Overall, the facies is interpreted as produced by a sandy, low-sinuosity, braided river system (Figure 3.22b).

Variations in the flow of the rivers are reflected in cyclical deposits seen in the cliffs between St Bees and Fleswick, with each cycle deposited in conditions of declining flow energy (Macchi and Meadows, 1987). Re-activation surfaces

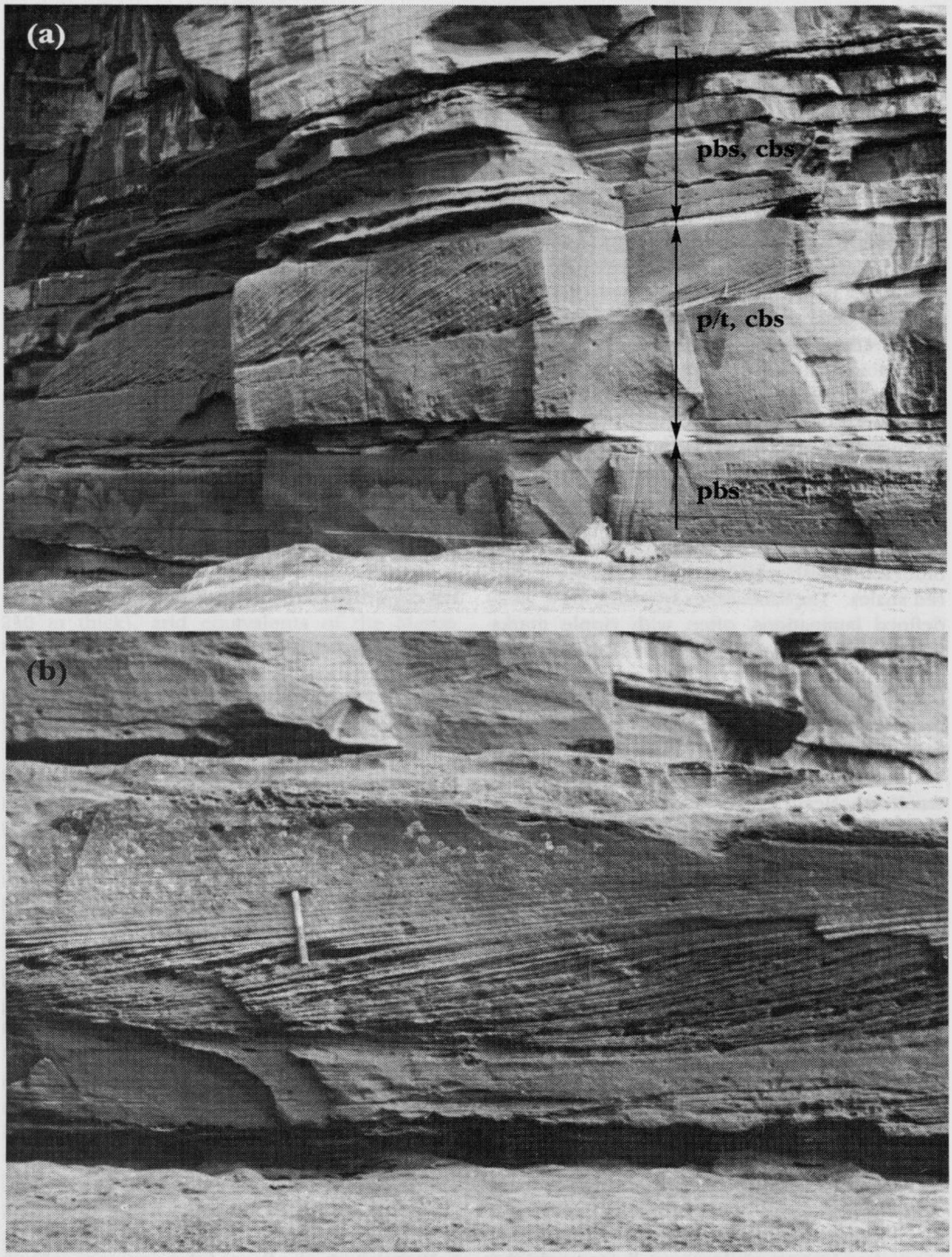


Figure 3.20 The Lower Triassic St Bees Sandstone Formation at St Bees Head on the Cumbrian coast showing vertical profiles through transverse bars. (a) Plane-bedded sandstones (pbs) overlain by planar/tabular cross-bedded sandstones (p/t, cbs), and then more plane-bedded and cross-bedded sandstones (pbs, cbs) with multiple erosion surfaces; rucksack for scale. (b) Multiple cross-bedded units and a large sinusoidal bedform with re-activation surfaces. (Photos: P. Turner.)

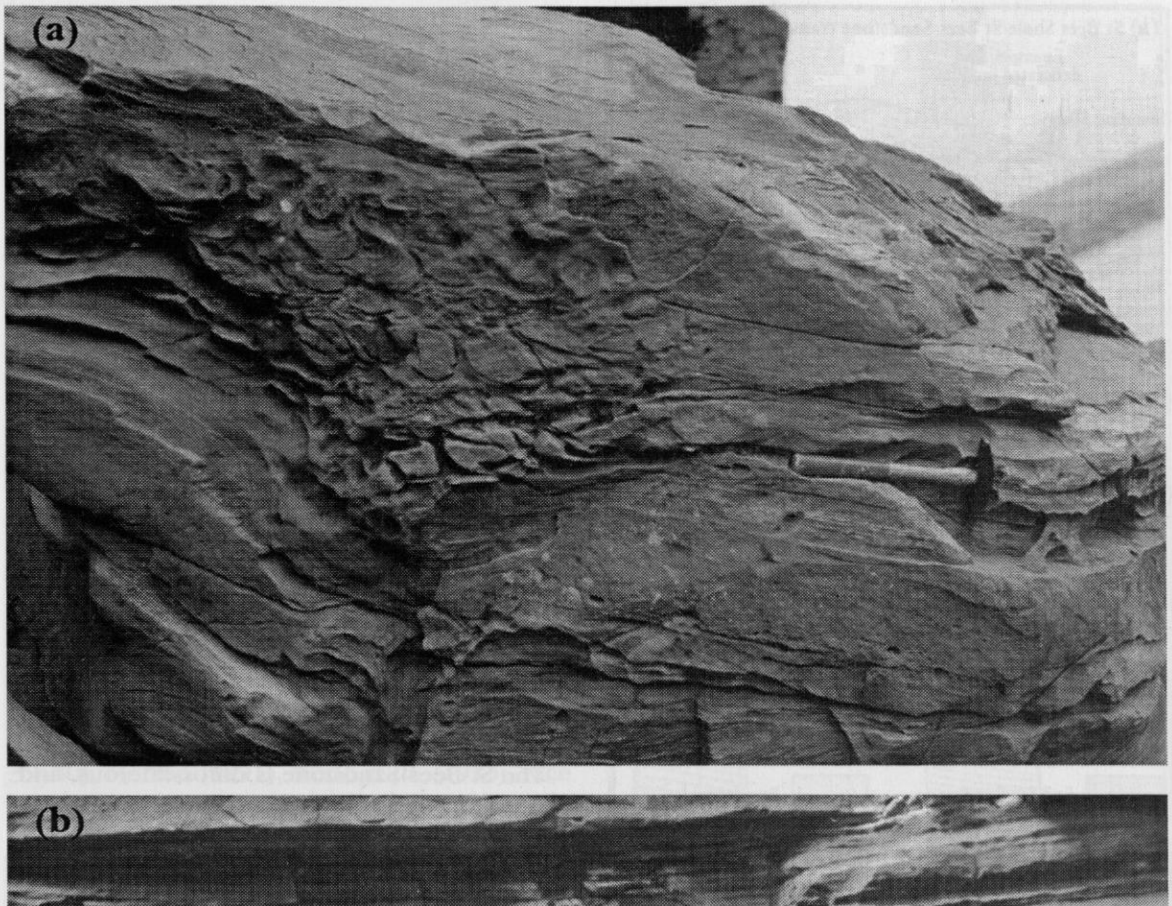


Figure 3.21 The Lower Triassic St Bees Sandstone Formation at St Bees Head on the Cumbrian coast. (a) Cross-bedded sandstones that have been distorted shortly after deposition. (b) A scour-and-fill structure, in which cross-bedded sandstones occupy a hollow eroded into the underlying sandstones. (Photos: P. Turner.)

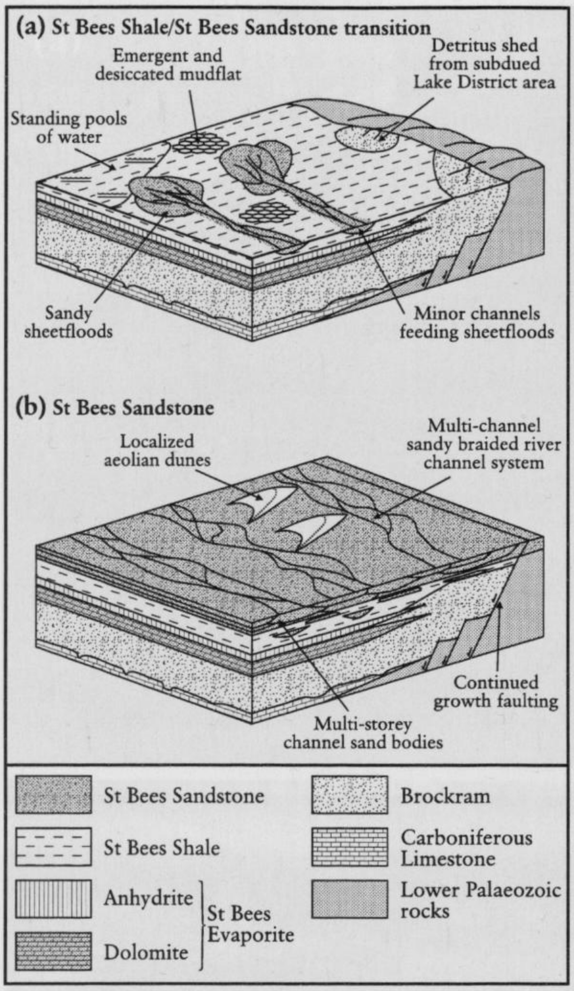


Figure 3.22 Depositional models for the St Bees Shale and the St Bees Sandstone formations, showing major sediment types, and proposed sedimentary environments. (After Akhurst *et al.*, 1997.)

within the sandstone units indicate that the river was subject to frequent periods of flooding. An idealized sequence begins with a conglomeratic lag deposit overlying an erosion surface. The lag deposit is overlain by a plane-bedded sandstone with primary current lineation, a bed-form feature characteristic of high-flow regimes that probably occurred during flooding events. Above the plane bedded units are planar-tabular and trough cross-bedding, structures formed during moderately high-flow rates, and representing the migration of transverse linguoid channel bars. The tabular planar cross-beds were deposited in large transverse bars on the river bed. As the floodwaters declined these bars caused the river to split into many smaller channels, producing a braided profile. The trough cross-bedding was produced in the braided channels, and represents small dunes with curved crests that migrated around the larger transverse bars. At the top of these sequences are laminated beds that commonly show ripples, indicative of lower energy-flow conditions.

This idealized sequence is not always encountered. For example, some of the thicker sandstone units reflect several floods within the same channel, in the form of planar beds of the upper flow regime, with primary current lineations, alternating with planar cross-bedding (Macchi and Meadows, 1987, p. 117).

The section between St Bees and South Head shows evidence for small pools or areas of low flow velocity between the major transverse bars. Within the pools, fine-grained micaceous sandstones were deposited in rippled beds. Mudstone drapes are often preserved overlying the ripples (Macchi and Meadows, 1987). The fine-grained units sometimes show evidence of emergence and desiccation and possible local development of aeolian dunes (Figure 3.22b).

The St Bees Sandstone is unfossiliferous, and cannot be dated directly or precisely. It is assumed to be of Early Triassic age. It conformably overlies the St Bees Shale, a lateral equivalent of the Eden Shale and Manchester Marl formations (Figure 3.19) that contain a late Permian microflora and fauna. It passes laterally southwards into the Chester Pebble Beds Formation, which is overlain by the Wilmslow Sandstone Formation, and that by the Helsby Sandstone Formation, which has yielded miospores indicative of a Mid Triassic, Anisian, age (Warrington *et al.*, 1999).

Conclusions

The cliffs, wave-cut platform and foreshore around St Bees and Fleswick Bay provide excellent three-dimensional exposures of the St Bees Sandstone Formation, of which this is the type location. This outcrop allows detailed study of the bedforms of a braided river system that was prone to periods of violent flooding. The extensive exposure enables single channels to be traced downstream for many hundreds of metres. The site is critically important in showing the nature of beds of the presumed Permian–Triassic transition, and the character of the Sherwood Sandstone Group on the northern flank of the East Irish Sea Basin.

BURTON POINT, THE WIRRAL, CHESHIRE (SJ 303 735)

Potential GCR site

Introduction

The cliffs at Burton Point provide a section through the contact between the Kinnerton Sandstone Formation and the overlying Chester Pebble Beds Formation. The former comprises cross-bedded, medium- to coarse-grained sandstone and thinly bedded siltstones, interpreted as deposited both in ephemeral channels and by aeolian processes. The overlying Chester Pebble Beds Formation comprises pebbly sandstones, arranged in fining-upwards sequences, deposited in a series of sandy, braided, river channels. The site provides the best exposure of the Permo–Triassic Kinnerton Sandstone Formation, and its contact with the Chester Pebble Beds Formation.

The geology of the Triassic rocks of the Wirral area has been documented by Hull (1869, pp. 39–40), Morton (1891), Wedd *et al.* (1923), Rice (1939a,b), Thompson (1970b, 1985), Somerville *et al.* (1986), Macchi and Meadows (1987), and Jackson and Mulholland (1993).

Description

Burton Point is located on the western side of the Wirral Peninsula, close to the town of Neston, near the head of the Dee Estuary. The sediments are exposed in a series of low cliffs that border salt marshes.

The Kinnerton Sandstone Formation, formerly the 'Lower Mottled Sandstone', is a thick sequence (150–300 m) of sandstones that has not been subdivided (Warrington *et al.*, 1980). On the Wirral Peninsula, this formation comprises slightly gritty and arenaceous sandstones. Pebbles are uncommon in the formation, although there are intraformational mudstone rip-up clast layers, for example near the top (Thompson, 1986; Macchi and Meadows, 1987).

The sandstones are arranged in a series of cross-bedded and planar-bedded units (Figure 3.23). Although the cross-bedding is generally small-scale, there is evidence for bar-scale bedforms. One cross-bedded sandstone unit has been distorted by a slumping event, producing an excellent example of contorted bedding (Figure 3.24a). The planar-bedded units are

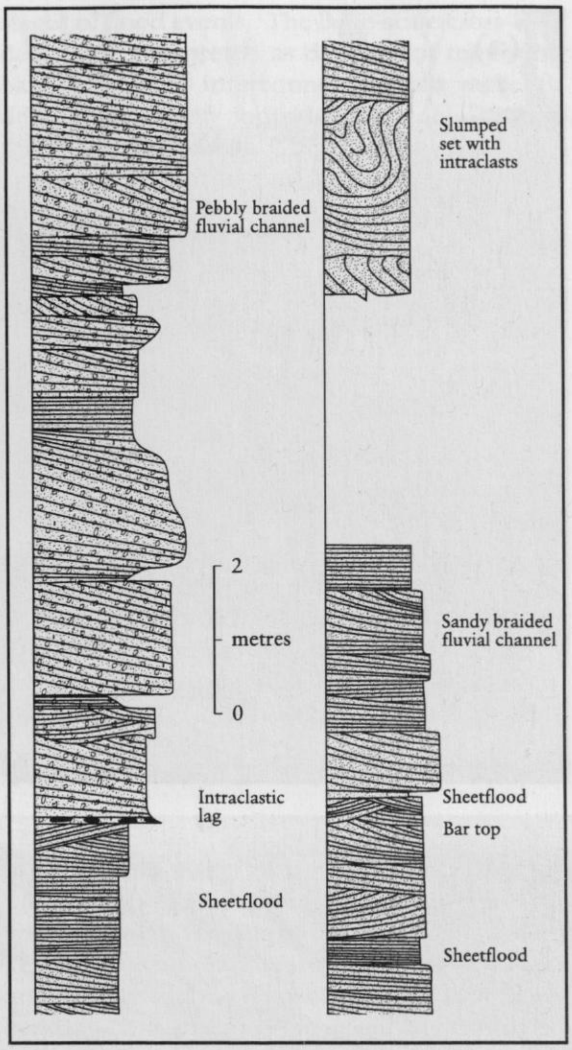


Figure 3.23 Two sedimentary logs through the Kinnerton Sandstone Formation, recorded at two localities at Burton Point, showing a mix of fluvial styles. (After Macchi and Meadows, 1987.)

characterized by irregular surfaces, and grain size varies between laminae on a scale of millimetres or centimetres. Rarely, the sandstones occur as thin sheets that have a bi-modal grain-size distribution. Small-scale bedforms are associated with this facies, including fining-upwards sequences and rippled surfaces (Macchi and Meadows, 1987).

The boundary between the Kinnerton Sandstone Formation and the overlying Chester Pebble Beds Formation is clearly marked by the appearance of pebbles in the sequence (Figure 3.24b). Hull (1869, p. 39) described the contact,

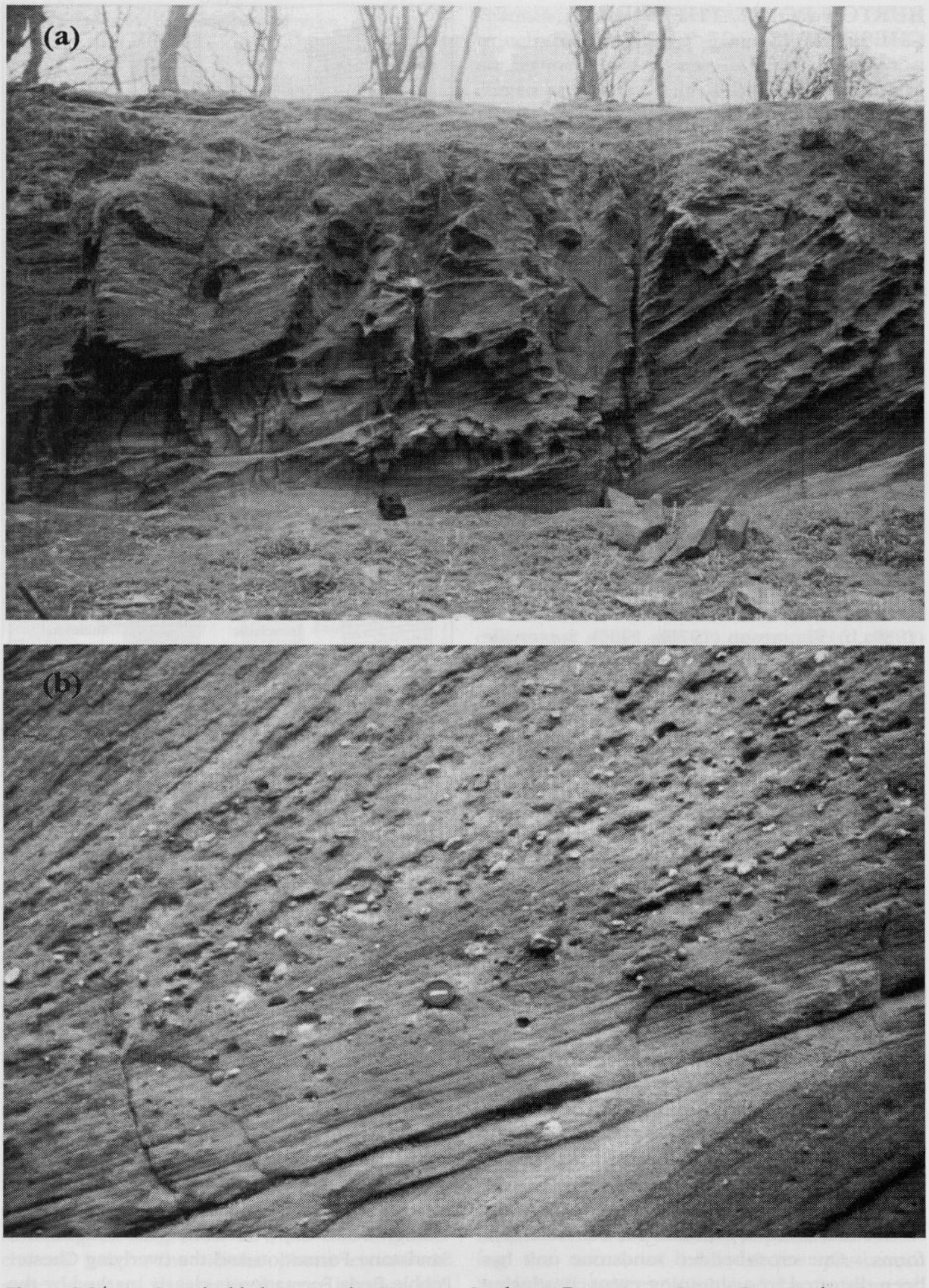


Figure 3.24 (a) Cross-bedded units in the Kinnerton Sandstone Formation at Burton Point, with major synsedimentary slumping. (b) Pebbly sandstones with large-scale planar-tabular cross-bedding in the lower part of the Chester Pebble Beds Formation. (Photos: P. Turner.)

and how he measured some 130 m of pebble beds above the contact. The Chester Pebble Beds Formation is characterized by coarse-grained sediments in cross-bedded sets up to 2.5 m thick. Fining-upwards sequences are common, and many have coarse-grained pebble lags at the base, often resting on an erosion surface. The sandstones are generally coarse- and medium-grained, although there are some finer-grained beds. The finer-grained units are generally associated with small-scale cross-bedding. Coarse units contain abundant intraformational and extraformational pebbles, often arranged in large lenses. Most of the pebbles are vein quartz or fragments of volcanic rock; reworked intraformational mudstones are present, but uncommon (Wedd *et al.*, 1923; Macchi and Meadows, 1987).

Interpretation

The sedimentary succession at Burton Point documents a change in terrestrial depositional conditions in an overall arid or semi-arid climatic regime. The Kinnerton Sandstone Formation shows several depositional styles. Planar cross-stratified sediments, representing fluvial conditions, are frequently overlain by trough cross-bedding, features interpreted as produced by the falling stage of a flood. The planar-bedded sandstones and rare ripple clasts are not associated with channel structures, suggesting that these sediments were deposited by sheet floods (Figure 3.23). Together, the sheetflood sediments and cross-bedded channel sediments suggest that the Kinnerton Sandstone Formation was deposited in a series of ephemeral braided channels. The contorted bedding and slump structures indicate that the sediments accumulated close to the water table (Macchi and Meadows, 1987). It has been suggested that the cross-bedding might have an aeolian origin: the grains often have the well-rounded outline and frosted surfaces characteristic of aeolian deposition. There are also a number of thin bi-modally laminated sheet sandstones that have wavy lamination and adhesion structures charactersitic of damp aeolian interdune deposits However, it is possible that many of the aeolian sediments were reworked by fluvial processes (Macchi and Meadows, 1987).

The Chester Pebble Beds Formation was deposited in higher-energy conditions. The fining-upwards sequences represent the falling stages of flood events. The large-scale cross-bedded units, interpreted as deposits of transverse bars, frequently interconnect, which makes it difficult to identify individual channels. Small-scale cross-bedding represents bedforms emplaced on the top of bars and in interbar areas. Together, these features indicate a complex pattern of braided channels (Macchi and Meadows, 1987).

The age of the Kinnerton Sandstone Formation is not clearly defined (Thompson, 1986), having been placed in the Permian by Smith *et al.* (1974) and spanning the Permian–Triassic boundary by Warrington *et al.* (1980). It probably interfingers laterally with the Manchester Marl Formation, which has yielded late Permian fossils. The overlying Chester Pebble Beds Formation lacks fossils, but is overlain successively, in the Cheshire Basin, by the Wilmslow Sandstone Formation, and the Helsby Sandstone Formation; the latter contains miospores indicative of a Mid Triassic, Anisian, age (Warrington *et al.*, 1999).

Conclusions

The succession exposed at Burton Point includes the Kinnerton Sandstone and the Chester Pebble Beds formations, and is considered to span the Permian–Triassic boundary. The Kinnerton Sandstone Formation is fine grained and shows cross-bedding and planar bedding; it is interpreted as the deposit of an ephemeral braided river system that transported largely reworked aeolian sand. The Chester Pebble Bed Formation sediments are coarse-grained, cross-bedded and arranged in fining-upwards sequences. These sediments were deposited in braided river channels. This is the best site for the study of the presumed Permian–Triassic transition and the Chester Pebble Beds Formation on the margins of the East Irish Sea Basin.

HILBRE ISLAND AND HILBRE POINT, THE WIRRAL, CHESHIRE (SJ 186 876; SJ 203 885)

Potential GCR site

Introduction

At Hilbre Island and Hilbre Point, the reddish sandstones with minor, laterally impersistent, beds of silty mudstone, are assigned to the Ormskirk Sandstone Formation. Sedimentary structures, such as trough cross-bedding, rippled bedding surfaces, and desiccation surfaces indicate deposition in river channels and emergence. Trace fossils are common at this locality, and include invertebrate burrows and many fine examples of vertebrate footprints. The site is important for documenting the palaeoenvironment of the Ormskirk Sandstone Formation in detail, and for its spectacular trace fossil assemblages.

The Triassic geology of the Wirral area has been documented by several authors (see above, Burton Point), and the Hilbre site was described briefly by Hull (1869, p. 57) and Macchi and Meadows (1987), and more fully by Thompson (1998) and King and Thompson (2000a,b).

Description

Hilbre Island is a small island situated in the Dee Estuary, approximately 1.5 km west of West Kirby. Hilbre Point is on the mainland, approximately 1 km north of West Kirby, and is bordered by the Dee Estuary and Liverpool Bay. The Triassic sediments are exposed in a series of low cliffs and foreshore reefs. Hilbre Island, together with the smaller islands of Little Eye and Middle Eye, forms a local Nature Reserve, and the sites fall within the boundaries of the Dee Estuary Site of Special Scientific Interest (SSSI). Joints and fractures cutting the Triassic sediments are generally aligned parallel or subparallel to a large-scale fault located within the Dee Estuary (Macchi and Meadows, 1987).

Sedimentology

The Ormskirk Sandstone Formation reaches a maximum thickness of more than 250 m in the Liverpool area (Jackson *et al.*, 1987). The unit typically consists of predominantly red, well-cemented, even-grained, unfossiliferous sandstones. Scattered pebbles occur in the lower parts of the formation, but pebbles are generally more common in the upper parts. The pebbles have an average diameter of 60 mm and are mainly well-rounded and composed of reddish or purplish quartzite. Less common clasts

Figure 3.25 The Ormskirk Sandstone Formation on the southern point of Hilbre Island, showing planar-bedded and cross-bedded sandstone units. (Photo: M. J. King.)

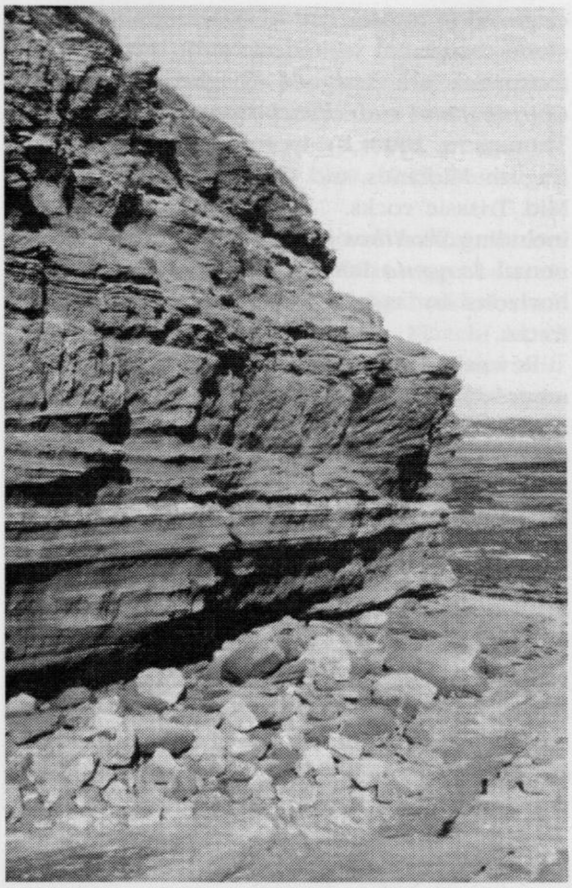


Figure 3.26 The Ormskirk Sandstone Formation on the southern point of Hilbre Island, close to the site that yielded trace fossils, including vertebrate footprints. (Photo: M. J. King.)

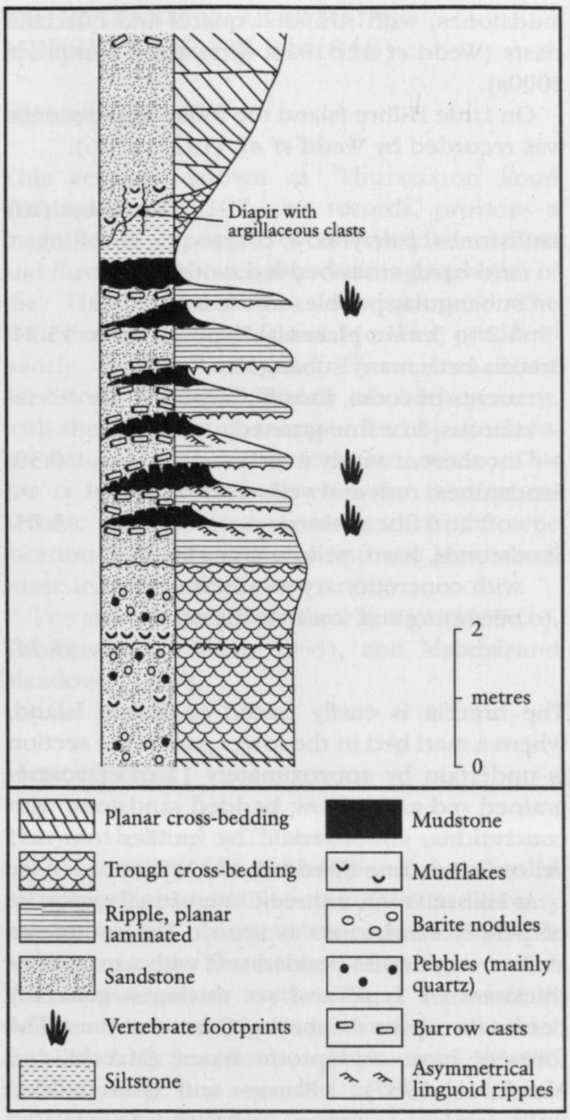


Figure 3.27 Simplified graphic sedimentary log through the Ormskirk Sandstone Formation at the southern tip of Hilbre Island. (After King and Thompson, 2000a.)

include grits, siliceous breccia, sandstone, granite, mica-schist, and tourmaline-schist (Wedd *et al.*, 1923; Jackson *et al.*, 1987; Macchi and Meadows, 1987).

The section exposed on the south-west coast of Hilbre Island (Figure 3.25) is dominated by red and yellowish, medium-grained sandstones, with occasional bands of breccia. Some of the beds are micaceous, and nodules of barite are scattered throughout the section. The pebbles are typically composed of vein quartz, reworked sandstone and intraformational mudstone clasts. Occasional beds of argillaceous material are present, and are characterized by grey and red, silty mudstones. Sedimentary structures are well preserved in the sediments on the south-west coast of Hilbre Island. At the base of the cliffs (Figures 3.26 and 3.27), the sandstones display well-developed trough cross-bedding, and they are overlain by a sequence of interbedded sandstones and mudstones, which may be laterally impersistent. Desiccation cracks are frequently associated with the mudstone beds. The interbedded sandstones are overlain by a substantial unit of flat-bedded sandstones, which is in turn overlain by trough cross-bedded sandstones. Within the trough cross-bedded sandstones is a conspicuous layer of rudaceous sediments, the Hilbre Island Breccia, which is matrix-supported, and contains angular and subangular clasts of sandstones, gritstones and mudstones, with rounded quartz and quartzite clasts (Wedd *et al.*, 1923; King and Thompson, 2000a).

On Little Hilbre Island the following sequence was recorded by Wedd *et al.* (1923, p. 76):

	Thickness (m)
Sandstones, pale-yellow, coarse and hard, cross-bedded, with subangular pebbles in the lower 1.2 to 3 m in places.	Exposed up to 15.24
Breccia-bed; many subangular fragments of rocks, mostly Carboniferous, in a fine-grained, incoherent sandy matrix	0.30
Sandstones, red- and yellow-streaked, soft and fine-grained	3.05
Sandstones, hard, yellow, cross-bedded, with concretionary weathering; becoming red towards the main island	15.24

The breccia is easily traced to Hilbre Island, where a marl bed in the lower part of the section is underlain by approximately 15 m of coarse-grained red and yellow, bedded sandstone with concretions, and overlain by mottled red and yellow sandstone (Wedd *et al.*, 1923).

At Hilbre Point, a three-dimensional exposure of pebbly sandstones is seen. The sediments show trough cross-bedded sets with a maximum thickness of 1 m, and set thickness generally decreases upwards through the section. The foresets have asymptotic bases (Macchi and Meadows, 1987). Planar- and cross-bedded units are less common, and may be associated with deformed cross-bedding, several scales of rippled surfaces (bar- and dune-scale) and re-activation surfaces. Intraformational clasts are common in many of the beds (Thompson, 1986). Although the sandstones are frequently pebbly there are no breccia beds at Hilbre Point (Wedd *et al.*, 1923).

Palaeontology

The reddish sandstones exposed in the south-west area of Hilbre Island (Figure 3.27) have yielded abundant vertebrate footprints and trackways (King and Thompson, 2000a). The footprints are preserved at several horizons (Figure 3.27), for example in poorly cemented friable sandstones associated with thin beds of clay, and in a thick bed of coarse-grained sand-stone associated with desiccation cracks. The footprints are assigned to the ichnogenera *Chirotherium* and *Rhynchosauroides* (King and Thompson, 2000a,b), typical trace fossils of the English Midlands and Cheshire Basin Early to Mid Triassic rocks. Invertebrate trace fossils, including *Skolithos* and *Planolites* of the continental *Scoyenia* Ichnofacies, occur at some 15 horizons in association with the vertebrate tracks.

Reworked invertebrate fossils have been recorded from the sediments at Hilbre Island, including an orthid brachiopod and a silicified Carboniferous coral (Davies, 1961).

Interpretation

Hilbre Island and Hilbre Point are situated on the south-eastern margin of the East Irish Sea Basin (Jackson *et al.*, 1987; Cowan, 1993; Jackson and Mulholland, 1993; Meadows and Beach, 1993), and comparison with offshore borehole records has helped to elucidate the stratigraphy to some extent. The stratigraphical position of the 'Bunter Pebble Beds' and the 'Bunter Upper Mottled Sandstone' around Liverpool has been debated. For example, Greenwood (1916) used evidence from the mineralogical composition of the sandstones to suggest that they are more similar to the Helsby Sandstone Formation than the Chester Pebble Beds Formation of the central Cheshire Basin. The whole pebbly and coarse sandstone unit of the area was more generally equated simply with the Chester Pebble Beds Formation, but the definition of the Ormskirk Sandstone Formation for a unit previously recognized around Formby, Ormskirk, and Preston in west Lancashire (Warrington *et al.*, 1980), and its recognition offshore (Jackson *et al.*, 1987; Meadows and Beach, 1993) indicates that the sandstone units on the Wirral might in fact represent this formation (Figure 3.19). This view is followed by King and Thompson (2000a) who noted that the pebbles in the Hilbre conglomerates are compositionally similar to those of the Chester Pebble Beds Formation, having presumably been reworked from that unit into the Ormskirk Sandstone Formation essentially unchanged in relative proportions and general appearance.

The Ormskirk Sandstone Formation marks the top of the Sherwood Sandstone Group, and correlates with the Helsby Sandstone Formation of the central Cheshire Basin. Miospores indicate an Anisian age for the latter formation and the overlying Tarporley Siltstone Formation, a date corroborated by comparison of macrofossils (Warrington *et al.*, 1980, 1999; Benton *et al.*, 1994).

The dominantly arenaceous sediments on Hilbre Island and at Hilbre Point suggest a continental setting, characterized by braided river channels (Thompson, 1986; Macchi and Meadows, 1987). The three-dimensional cliff exposures at Hilbre Point, with their elongate sand bodies with trough cross-bedding, have been interpreted as tongues of sediment deposited parallel to the direction of water movement. The decrease in cross-bedding set thickness upwards through the sequence, and the associated bar-scale and megaripple-scale bedforms, indicate a steady decrease in current velocity (Macchi and Meadows, 1987). The high degree of lateral and vertical variation characterisitic of the Ormskirk Sandstone Formation is consistent with a braided channel system interpretation (Thompson, 1986).

In detailed palaeogeographical reconstructions of the East Irish Sea Basin during deposition of the Ormskirk Sandstone Formation, Meadows and Beach (1993, pp. 261, 262), show a major braided river system running northwestwards over Hilbre Island, and feeding clastic sediments into the centre of the offshore basin. The region was the site of a complex of braided channels separated by sand flats, with aeolian dunes and playa lakes in some of the major interchannel areas.

Conclusions

The sediments in the cliffs and foreshore reefs at Hilbre Island and Hilbre Point provide an excellent onshore record of the Ormskirk Sandstone Formation, which continues offshore where it provides a major hydrocarbon reservoir unit. The sediments, comprising reddish, pebbly sandstones, with occasional mudstone beds, are continental, and were deposited by a complex system of braided rivers and streams. The vertebrate tracks, associated with argillaceous sediments and mud cracks, indicate periods of emergence. This is a key site for stratigraphical and palaeoenvironmental studies on the margin of the East Irish Sea Basin.

THURSTASTON COMMON, MERSEYSIDE (SJ 244 848)

Introduction

This section, known as 'Thurstaston Road Cutting' in the GCR unit records, provides a magnificent exposure of interbedded aeolian and fluvial sandstones, representing a portion of the Helsby Sandstone Formation. The Thurstaston Soft Sandstone Member, predominantly aeolian, and the Thurstaston Hard Sandstone Member (fluvial) are both present, with the former unit characterized by spectacular soft-sediment deformation structures. This site is important for the evidence it offers on Triassic palaeoenvironments, and as the type location of the Thurstaston Soft and Hard sandstone members.

The site has been described by Rice (1939a,b), Thompson (1970a,b, 1985), and Macchi and Meadows (1987).

Description

The road cutting at Thurstaston is said to have been excavated for the owner of the Cunard Shipping Line so that his view of the Dee estuary would not be obstructed by common people walking across Thurstaston Common. The Triassic succession in the Wirral Peninsula is thinner than in adjacent parts of the Cheshire and East Irish Sea basins, and overlies a NE–SW-trending ridge that separates these major basins.

The section offers a continuous exposure of the upper part of the Wilmslow Sandstone Formation and the lower part of the Helsby Sandstone Formation. At the north-western end of the road cutting the lowest beds, belonging to the Wilmslow Sandstone Formation, are exposed. These comprise red, fine-grained sandstones with flat bedding and high-angle cross-stratification. The sands are well sorted and grains have a 'millet-seed' texture. One of the cross-bedded dune sets in this part of the section is 2 m thick, and it is overlain by a thinly bedded sequence of predominantly flat- to low-angle cross-bedded sandstones, some exhibiting adhesion structures.

Within these cross-bedded sequences is a wavy-bedded sandstone unit, some 0.5 m thick, which exhibits considerable variation in grain

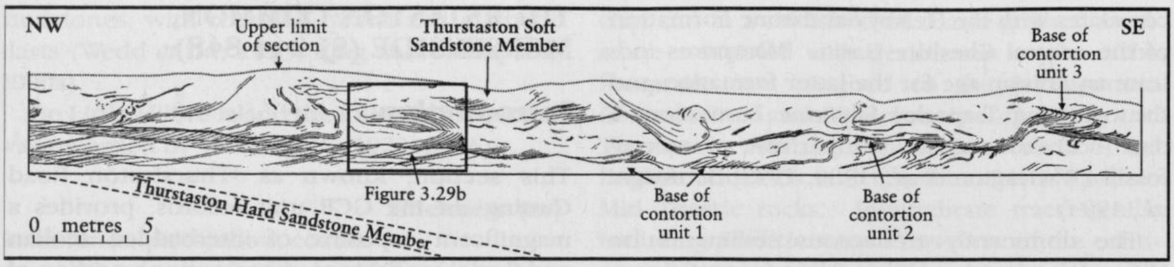


Figure 3.28 Contorted bedding in the Thurstaston Soft Sandstone Member. The area of Figure 3.29a is at the far north-western end of the section shown here. (After Rice, 1939b.)

size. Small-scale fining-upwards units and ripple cross-lamination are common. This sequence passes up into very finely flat-laminated sandstones with evidence for variably wetter and drier interdune surfaces.

This succession is truncated by an erosion surface exhibiting considerable relief (Figure 3.29a). In one place the surface appears to be undercut, a feature that was interpreted to indicate that the underlying sandstones has been cemented prior to the erosion. Macchi and Meadows (1987), however, suggest that the erosion surface is the result of downcutting by a fluvial channel into wet, but not cemented, sediment. The channel-fill unit overlying the erosion surface comprises medium- to coarse-grained sandstones exhibiting planar and trough cross-bedding with evidence of the former presence of intraformational clasts. This unit is noticeably more thoroughly cemented by silica than the units above or below. It comprises the 'Thurstaston Hard Sandstone Member' (Thompson, 1985), and is the basal unit of the Helsby Sandstone Formation of this locality.

The overlying Thurstaston Soft Sandstone Member at the south-east end of the section is notable for large-scale cross-stratification in which some of the beds show spectacular soft-sediment deformation structures (Figures 3.28, and 3.29b). Three sets of contorted bedding are distinguishable, the middle one showing the most spectacular distortion, with foresets in the large-scale cross-stratification swept up and overturned into extraordinary shapes. Deformation structures include water/air escape structures, oversteepened cross-bedding, slumped and inverted beds, brecciation (probably of a moistened surface or evaporitic crust), and complete liquefaction resulting in structureless zones.

Interpretation

The depositional environment of the Wilmslow Sandstone Formation has been debated. Thompson (1970a) suggested that the sediments were deposited by braided rivers, while Macchi and Meadows (1987) preferred an aeolian origin. The textural maturity, the absence of both pebbles and mudstone horizons, and the rounded 'millet-seed' character of the sand grains suggest an aeolian depositional environment with dry sand flats and individual migrating dunes. Variations in the style of cross-stratification, from high-angle, sharply based to asymptotically based, and the numerous re-activation surfaces represent changes in bed-form consequent on variations in wind velocity and direction. The overlying thinly bedded upper portion of the formation was probably deposited in an interdune environment. The adhesion structures indicate variations in the aridity of the climate, and exposure of the water table at times. Flat-bedded sands may indicate aeolian reworking of fluvially deposited sands.

The Thurstaston Hard Sandstone Member is clearly fluvial in origin, as shown by the presence of small-scale cross-stratification and mudstone intraclasts. The succeeding Thurstaston Soft Sandstone Member was, in contrast, deposited in aeolian dunes, as indicated by the sandstone texture and the large-scale cross-stratification.

The contorted bedding in the Thurstaston Soft Sandstone Member (Figure 3.29b) has long been a classic attraction of the site (Rice, 1939b; Thompson, 1970a,b). Smaller-scale deformed bedding is often explained as a result of a sudden increase of bed traction forces, which effectively pull the foresets over. Larger-scale deformation, as at Thurstaston, might result from changes of pore-water pressure and thixotropic

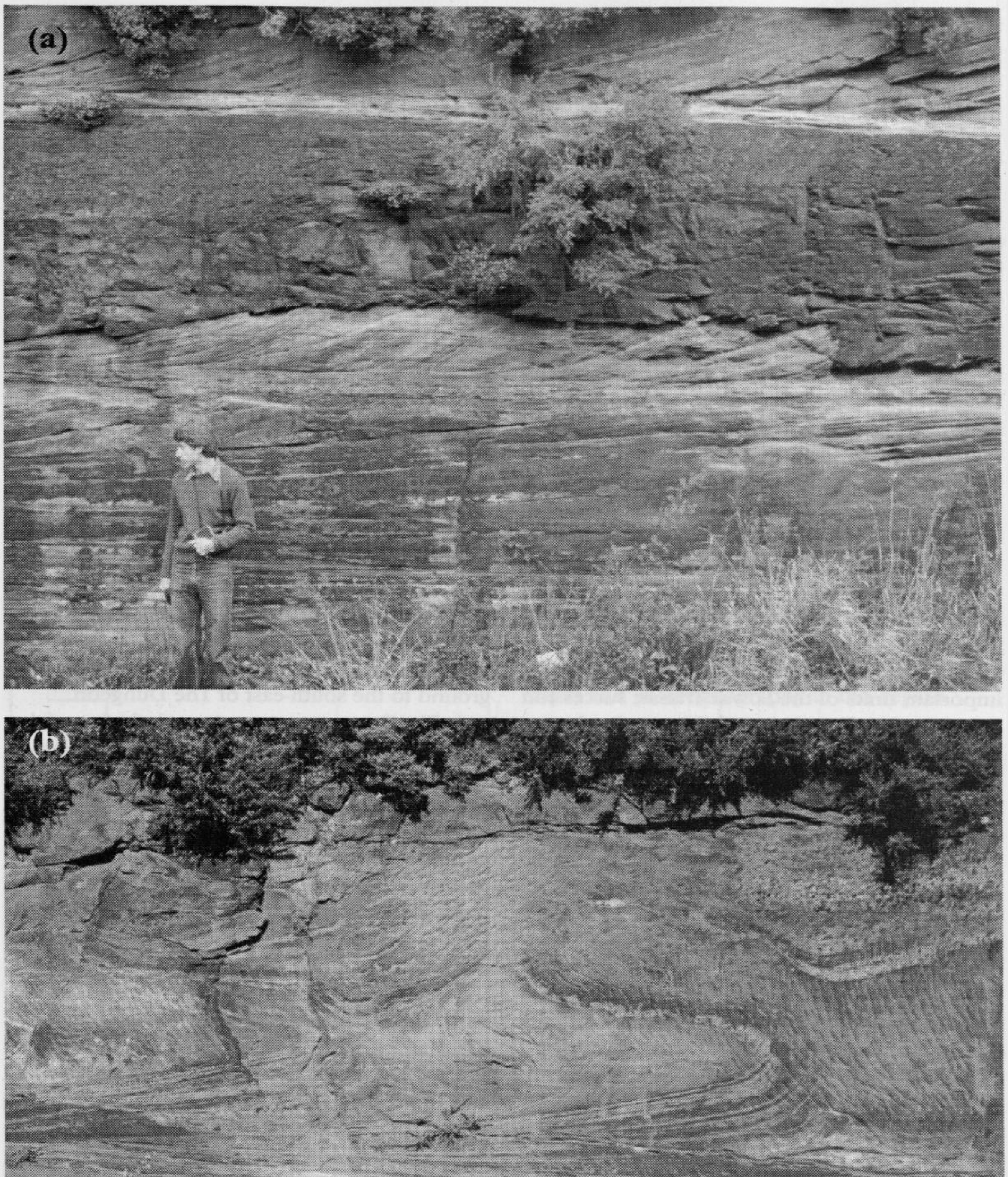


Figure 3.29 Thurstaston Common road cut. (a) The lower bounding erosion surface of the Thurstaston Hard Sandstone Member, overlying the Wilmslow Sandstone Formation. (b) Deformed cross-bedding in contortion unit 1 in the Thurstaston Soft Sandstone Member. Field of view of (b) is about 5 m. (Photos: (a) M. J. Benton, (b) P. Turner.)

action at, for example, points of spring emergence in a fluvial regime (Thompson, 1970a). It is not clear, however, whether the deformation happened during deposition, or after. The scale of the deformation, and the fact that the deformed foresets do not lose their cohesiveness, despite some extraordinary contortions, may suggest that the porous, well-sorted sandstone was swamped with water some time after deposition and partial, but not complete, consolidation. Deposition of further sediment might have put pressure on this saturated sediment below, and forced the water to rise, pulling the foreset laminations upwards and creating the spectacular distortions. Macchi and Meadows (1987), on the other hand, suggest that it is equally likely that the large-scale recumbent slump folds in the Thurstaston Soft Sandstone Member could have arisen from slope instability of wet sediment, or disturbance by local tectonic activity.

Conclusions

The Thurstaston road cutting shows three important units of the Lower Triassic succession in the Wirral, the Wilmslow Sandstone Formation, and the Thurstaston Hard and Soft sandstone members of the Helsby Sandstone Formation. These represent major changes in depositional regime, from aeolian to fluvial, and then aeolian again. The soft-sediment deformation structures are classic examples, well known to generations of students. This is a critically important site for the study of Triassic sedimentology.

THE DUNGEON, MERSEYSIDE (SJ 252 832)

Introduction

This site shows a section through the Tarporley Siltstone Formation, at the base of the Mercia Mudstone Group, in faulted contact with the older Wilmslow Sandstone Formation. The Tarporley Siltstone Formation comprises red, fine-grained sandstones and siltstones, with parallel and rippled bedding, and pseudomorphs after halite, indicating deposition in a marine intertidal environment, an unusual sedimentary setting for the British Mid Triassic red beds, but providing evidence of a marine incursion contemporary with the marine Muschelkalk in Germany. This site has been described by Thompson (1970a, 1986).

Description

The Dungeon is a natural stream section that exposes the Tarporley Siltstone Formation on the eastern side of the Dee Estuary near Thurstaston. The Mercia Mudstone Group crops out here within a N–S-oriented graben bounded to the west by the Thurstaston fault. The underlying Helsby Sandstone Formation is seen on the western (footwall) side of the fault in the Thurstaston roadcutting GCR site (see site report, above).

At the south-western end of The Dungeon section, the Tarporley Siltstone Formation is seen faulted against the Wilmslow Sandstone Formation. The contact between the Tarporley Siltstone Formation and the underlying Frodsham Soft Sandstone Member of the Helsby Sandstone Formation is not exposed here, but can be inferred to run east–west across the low ground to the south-east of The Dungeon.

In The Dungeon, approximately 24.5 m of the Tarporley Siltstone Formation strata (Figure 3.30) are exposed between the Thurstaston Fault and the bridge at the north-east end of the section. The formation comprises sandstones, mudstones, and heterolithic facies, with an increase in units of very fine-grained sandstones towards the top. Many of the features described by Ireland *et al.* (1978) at the Red Brow GCR site (see below) can be seen at The Dungeon, but the dominant facies at the latter site is red shales with thinly interbedded fine and very fine rippled sandstones. The ripple marks are predominantly asymmetrical current ripples, and indicate flow directions to the north-west. The upper part of the section includes thicker, fine-grained, micaceous, red sandstones with abundant mudstone rip-up clasts. Sedimentary structures and features include desiccation cracks, injection structures, intraformational mud clasts, armoured mud balls, mud drapes on foreset surfaces, trace fossils, pseudomorphs after halite, and calcite-filled geodes.

At the top of the section is another fault, above which lie poorly exposed interbedded siltstones and mudstones with pseudomorphs after halite and symmetrical ripples, presumably also part of the Tarporley Siltstone Formation.

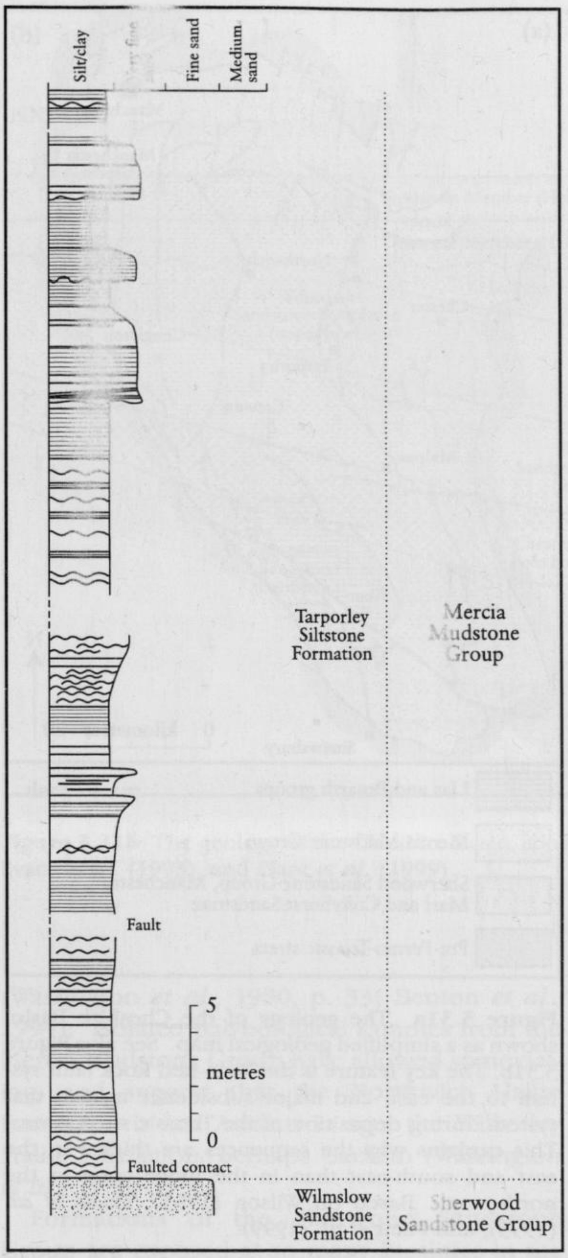


Figure 3.30 Sedimentary log of the Wilmslow Sandstone and Tarporley Siltstone formations in the stream section at The Dungeon. (P. Turner, unpublished information.)

Interpretation

The Tarporley Siltstone Formation at The Dungeon was deposited in a lake-marginal or intertidal environment (Thompson, 1986). Subaerial emergence is indicated by the desiccation cracks and pseudomorphs after halite, while the ripple marks and trace fossils indicate subaqueous deposition. The continuous sequence of 4 m of red mudstones at the base of the succession indicates deposition on a high to low transitional mud flat. The succeeding 4 m of red mudstones with rare siltstones were presumably deposited on a low-energy intertidal flat or estuary area. The intercalation of fine-grained sandstones in the top 3 m of the section suggests continuing deposition in an intertidal flat, but with occasional channels or sand bars.

Conclusions

The Tarporley Siltstone Formation is well exposed in The Dungeon section. The mudstones, siltstones, and sandstones of this unit record evidence for deposition on the margins of a shallow sea, contemporary with the major Muschelkalk transgression that flooded Germany and the North Sea region. This site provides a useful onshore representation of a formation that extends offshore into the East Irish Sea Basin, and hence is important for the interpretation of Mid Triassic palaeoenvironments and palaeogeography in this region.

THE TRIASSIC RED BEDS OF THE CHESHIRE BASIN

INTRODUCTION

The Cheshire Basin is represented by a large area of outcrop (Figure 3.31a) of continental deposits, where up to 3000 m of sediment accumulated during the Triassic Period (Evans *et al.*, 1993; Plant *et al.*, 1999). In the northern part of the basin, the sequences terminate with Mercia Mudstone Group units of Mid Triassic age, whereas, farther south, higher beds are preserved and the successions continue through the Late Triassic Epoch, and include red mudstones of the classic 'Keuper Marl', overlain by the Blue Anchor Formation, which is succeeded by the Penarth Group. The Cheshire Basin was fault-controlled, subsiding against the Wem-Red Rock fault system (Figure 3.31b) to the SSE. Individual units are thicker in the north, but the succession there has been truncated by erosion of the higher beds.

The stratigraphical succession in most of the Cheshire Basin has already been encountered in the Cumbria–East Irish Sea Basin area (see above; Figure 3.19). The transitional Permo–Triassic Kinnerton Sandstone Member of the Wirral and the Manchester Marl Formation of the north-east Cheshire Basin are absent farther south. The Chester Pebble Beds Formation is, however, widespread, as is the overlying Wilmslow Sandstone Formation. In the west of the Cheshire Basin, there is a passage from the Wilmslow Sandstone Formation into the locally developed Bulkeley Hill Sandstone Formation. The highest unit in the Sherwood Sandstone Group in the Cheshire Basin is the Helsby Sandstone Formation, which has been divided into members (Thompson, 1970b; Warrington and Thompson, 1971; Warrington *et al.*, 1980).

Borehole data and seismic surveys have indicated that a major unconformity, probably equivalent to the Europe-wide Hardegsen Unconformity, occurs within the Helsby Sandstone Formation (Evans *et al.*, 1993). This unconformity lies above the Bulkeley Hill Sandstone Formation, which has only local distribution (Figure 3.31b), and below the Helsby Sandstone Formation. Tectonic activity on the major fault system may have declined at this time, and the overall rate of accumulation of sediment diminished, with sedimentation styles switching from dominantly arenaceous to a mix of argillaceous and evaporitic units.

The lowest unit of the Mercia Mudstone Group is the Tarporley Siltstone Formation, formerly called the 'Waterstones', which overlies the Helsby Sandstone Formation. Then follows a succession of mudstones, with major halite units interbedded, the Northwich Halite Formation, up to 290 m thick, and the Wilkesley Halite Formation, up to 405 m thick (Wilson, 1990, 1993). Warrington *et al.* (1980) did not name the Mercia Mudstone Group mudstones in the Cheshire Basin, but Wilson (1993) has since termed the mudstone between the Tarporley Siltstone and Northwich Halite formations, the 'Bollin Mudstone Formation', and that between the two named halite formations the 'Byley' and the 'Wych' mudstone formations. The Wilkesley Halite Formation is succeeded by the Brooks Mill Mudstone Formation (see Figure 3.19).

Biostratigraphical control of the Triassic succession in the Cheshire Basin is patchy. The position of the Permian–Triassic boundary is poorly constrained; it lies above the Manchester Marl Formation that has yielded Permian fossils (Pattison *et al.*, 1973; Warrington *et al.*, 1980, p. 31), and below the Helsby Sandstone

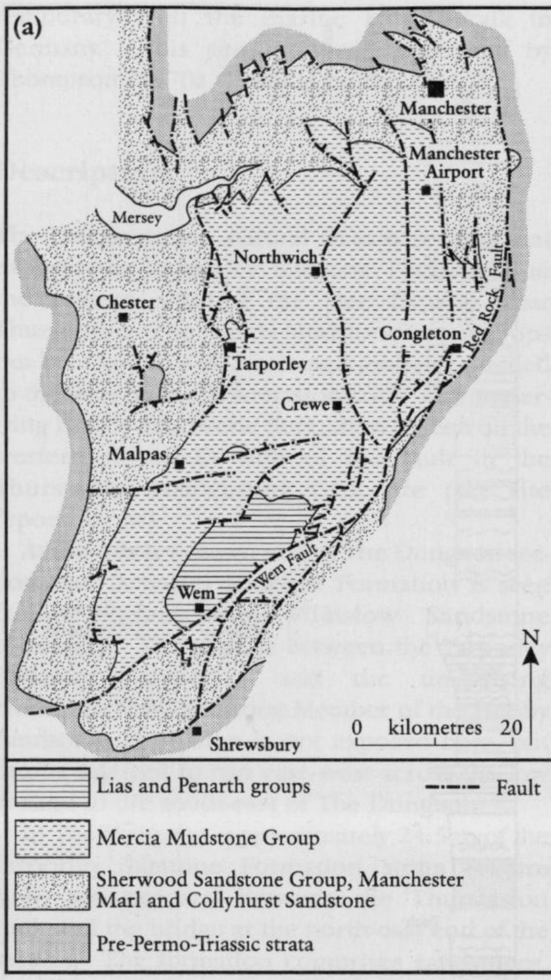


Figure 3.31a The geology of the Cheshire Basin, shown as a simplified geological map. See also Figure 3.31b. The key feature is the Wem-Red Rock fault system to the east, and major subsidence against that system during deposition of the Triassic successions. This explains why the sequences are thicker in the east and south-east than in the hinge zone to the north-west. Based on Wilson (1993), Evans *et al.* (1993), and Plant *et al.* (1999).

Formation, which has yielded Anisian (Mid Triassic) miospores (Warrington, 1967, 1970a,b; Warrington *et al.*, 1999). The intervening Chester Pebble Beds, Wilmslow Sandstone, and Bulkeley Hill Sandstone formations do not contain fossils, but the Chester Pebble Beds are conventionally regarded as Triassic in age. The reptile ***Rhynchosaurus*** from the Helsby Sandstone and Tarporley Siltstone formations of Grinshill, north Shropshire, is also Mid Triassic, probably Anisian, in age, by comparison with independently dated reptile faunas from the Midlands

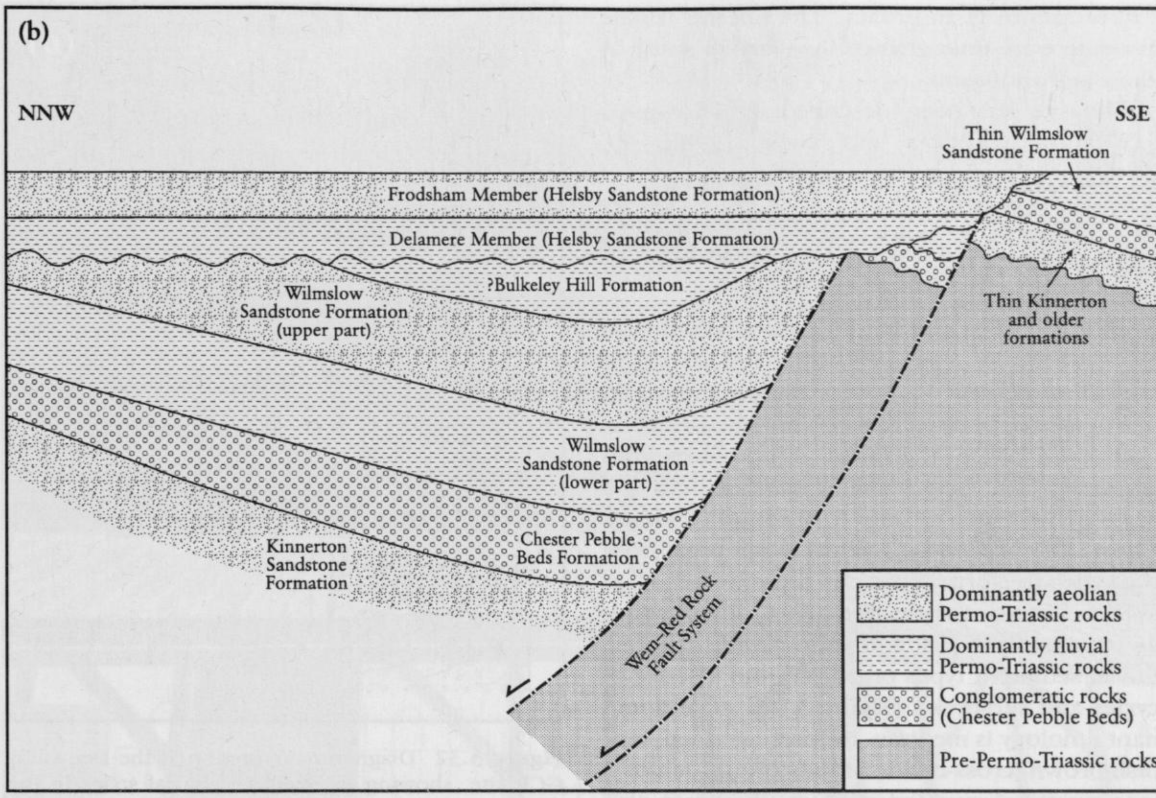


Figure 3.31b The geology of the Cheshire Basin, shown as a schematic cross-section. Based on Wilson (1993), Evans *et al.* (1993), and Plant *et al.* (1999).

(Warrington *et al.*, 1980, p. 33; Benton *et al.*, 1994). Isolated palynological samples from the Mercia Mudstone Group have allowed some dating, and suggest that the Northwich Halite Formation is late Anisian in age, the Wilkesley Halite Formation, perhaps Carnian (Warrington *et al.*, 1980, p. 34).

Formations of the Sherwood Sandstone Group are exposed at so many localities in the Cheshire Basin that it was hard to make a selection for the GCR. The Mercia Mudstone Group is much less well exposed. Five proposed GCR sites were chosen with the intention of documenting the lower parts of the Triassic succession, and of showing the key sedimentological and palaeontological evidence for palaeoenvironments. The five sites are, in approximate stratigraphical order, in the northern and central Cheshire Basin: Dee Cliffs (Chester Pebble Beds Formation); Bickerton Hill (Wilmslow, Bulkeley Hill, and Helsby sandstone formations); Frodsham (Frodsham Member of the Helsby Sandstone Formation); Red Brow Cutting (Tarporley Siltstone Formation); and in the southern Cheshire Basin: Grinshill (Helsby Sandstone and Tarporley Siltstone formations).

DEE CLIFFS SECTION, CHESHIRE (SJ 409 546–SJ 415 541)

Introduction

The Dee Cliffs section exposes the Chester Pebble Beds Formation, a sequence of sandstones and pebbly sandstones with large-scale tabular cross-stratification, smaller scale trough cross-stratification, and planar bedding. Sand body units are separated by prominent erosion surfaces. The depositional environment can be interpreted as that of a low-sinuosity sandy braided river that drained west and north-west towards the East Irish Sea Basin. The site provides a good opportunity to study the characteristic features and sedimentary structures of sandy braided river deposits typical of the Lower

Triassic deposits in Britain. The Chester Pebble Beds here are finer-grained than farther south in the Cheshire Basin.

The site has been described by Thompson (1970a,b) and Earp and Taylor (1986, pp. 16–19).

Description

Cliffs on the eastern bank of the River Dee at Farndon expose a superb continuous section in the Chester Pebble Beds Formation in the north-west part of the Cheshire Basin. The bridge at Farndon is one of the few crossing places from Cheshire into North Wales; it was first built 650 years ago by monks from St Werburgh's Abbey, Chester, and carried the valuable salt trade from Nantwich to North Wales.

The Chester Pebble Beds here dip at about 16° to the south-east and show a wide range of fluvial sediment types organized into a series of cycles and sub-cycles (Figure 3.32). The dominant lithology is medium- to coarse-grained, reddish-brown, cross-bedded sandstone, much of it incorporating rounded pebbles; there are also beds of sandstone with few or no pebbles, thin bands of biscuit-coloured, argillaceous sandstone, and a few thin layers of chocolate-coloured mudstone. The pebbles are mostly smooth and well rounded, and rarely exceed 150 mm in length, the majority being 50 to 80 mm across. Most pebbles are brown, reddish, or grey quartzites; a few vein quartzites, as well as rarer sandstones, cherts, and igneous and metamorphic rocks, are also present.

West of the bridge, the lower part of the sequence shows pebbly sandstones arranged in large-scale (2 m) planar-tabular cross-bed sets that indicate palaeoflow to the NNW. The pebbly sandstones are interbedded with fine- to medium-grained sandstones showing smaller-scale cross-beds, plane beds, and soft-sediment deformation structures.

Immediately east of the bridge, at the picnic site, the lowest unit seen comprises rather friable, red, fine-grained sandstones with thin white bleached zones (Figure 3.33a). Sedimentary structures include small-scale (0.1–0.2 m thick) cross-bedding with planar horizontal and low-angle planar bedded units. This unit is overlain, above an erosion surface (Figure 3.32), by greyish-red, slightly coarser-grained sandstones, which are better cemented and

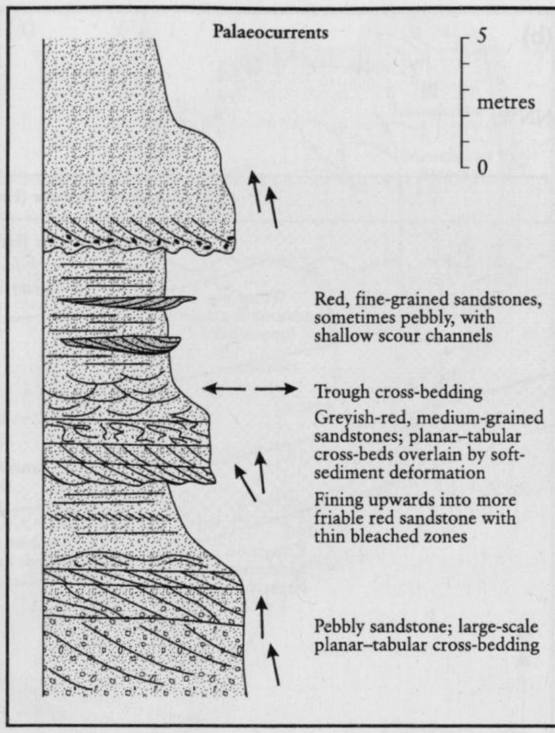


Figure 3.32 Diagrammatic section at the Dee Cliffs GCR site, showing the range of fluvial styles in the Chester Pebble Beds Formation. Logged by P. Turner.

show a wide range of sedimentary structures. The lower beds have planar-tabular cross-bedding (Figure 3.33b) that records consistent flow to the north and north-west. These are overlain by sandstones with prominent water-escape and other soft-sediment deformation features, which are overlain in turn by trough cross-bedded sandstones. Palaeoflow indicators in these beds are oriented towards the east and west, in contrast to those in the planar-tabular units.

South-east of the picnic site, these beds are overlain by thinly bedded, fine-grained, red sandstones and pebbly sandstones cut by shallow scour channels (Figure 3.32).

Interpretation

The Chester Pebble Beds Formation was deposited in a fluvial environment. Pebbles in the lower unit were deposited from high-energy streams as lags; strong currents winnowed the pebble lags, resulting in concentrations of the coarse debris. In places, the pebble beds fill erosive scours. The quartzite pebbles appear to have been

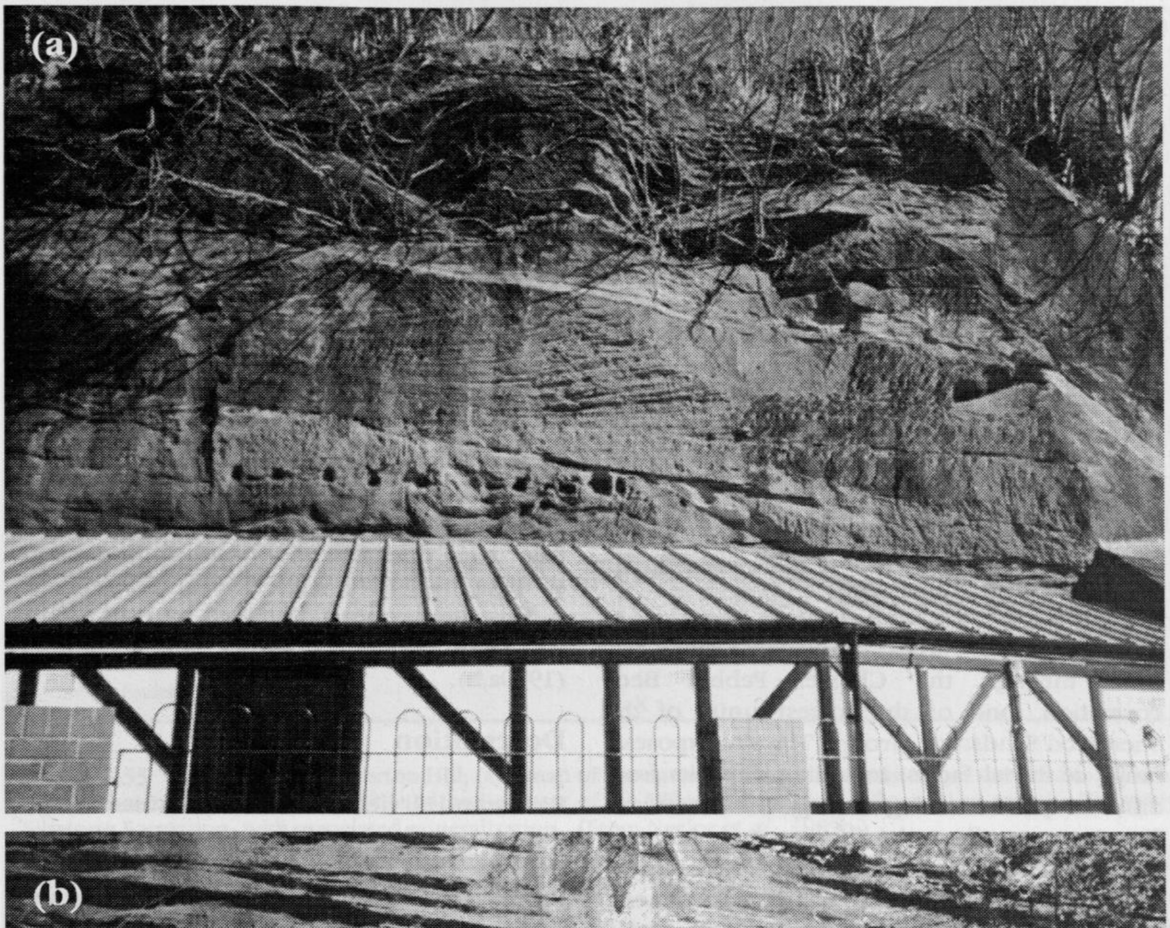


Figure 3.33 The Chester Pebble Beds Formation at Dee Cliff, (a) the lower planar-tabular cross-bedded sets at the picnic site; (b) stratigraphically higher plane-bedded sandstones with thin (upper left) scour fills. The height of the section in (b) is about 10 m. (Photos: P. Turner.)

transported a long distance, probably from a source of early Palaeozoic rocks far to the east and south. This is the case also for the metamorphic and igneous clasts. Thin sandstone pebbles appear to be intraformational. Palaeocurrent directions vary from north-west to west, and indicate varying flow directions, typical of complex braided streams.

The middle unit of planar-tabular cross-bedded sandstones (Figure 3.32) can be interpreted as the deposits of dunes that migrated around larger bar forms during low flood stages of the river. The upper unit of thinly bedded, intercalated sandstones and pebbly sandstones may represent ephemeral flood deposits that cut the floodplain of the perennial fluvial system.

Conclusions

The Dee Cliffs at Farndon provide excellent sections through the Chester Pebble Beds Formation, one of the lowest units of the Sherwood Sandstone Group. The site exposes a range of fluvial facies, including deposits from different phases of high-energy flood streams. This is an excellent site for the study of high-energy fluvial sedimentology, and for the understanding of the early phases of Triassic sedimentation in the Cheshire Basin.

BICKERTON HILL, CHESHIRE (SJ 508 547)

Introduction

The escarpment between Tower Wood and Droppingstone Well reveals natural exposures in the Wilmslow, Bulkeley Hill, and Helsby sandstone formations of the Sherwood Sandstone Group. The sediments are mainly fine-grained, red sandstones, interpreted as sandy braided river deposits, but conglomerate beds of the Delamere Pebbly Sandstone Member (Helsby Sandstone Formation) are prominent in the upper parts of the section and record the transition to more proximal, braided river deposition. This is an important site for the study of Triassic palaeoenvironments, and for illustrating several stratigraphical units in the Cheshire Basin.

This site has been described by Hull (1869), Poole and Whiteman (1966), and Thompson (1970a,b).

Description

Bickerton Hill lies towards the southern end of the central Cheshire Ridge that stretches from Beeston Castle in the north, through the Peckforton Hills, to Larkton Hill in the south. The area is an old copper mining district, and it has long been a classic spot for geologists (Figure 3.34).

Figure 3.34 West side of the Peckforton Hills, looking north, as shown in a classic view by Hull (1869).

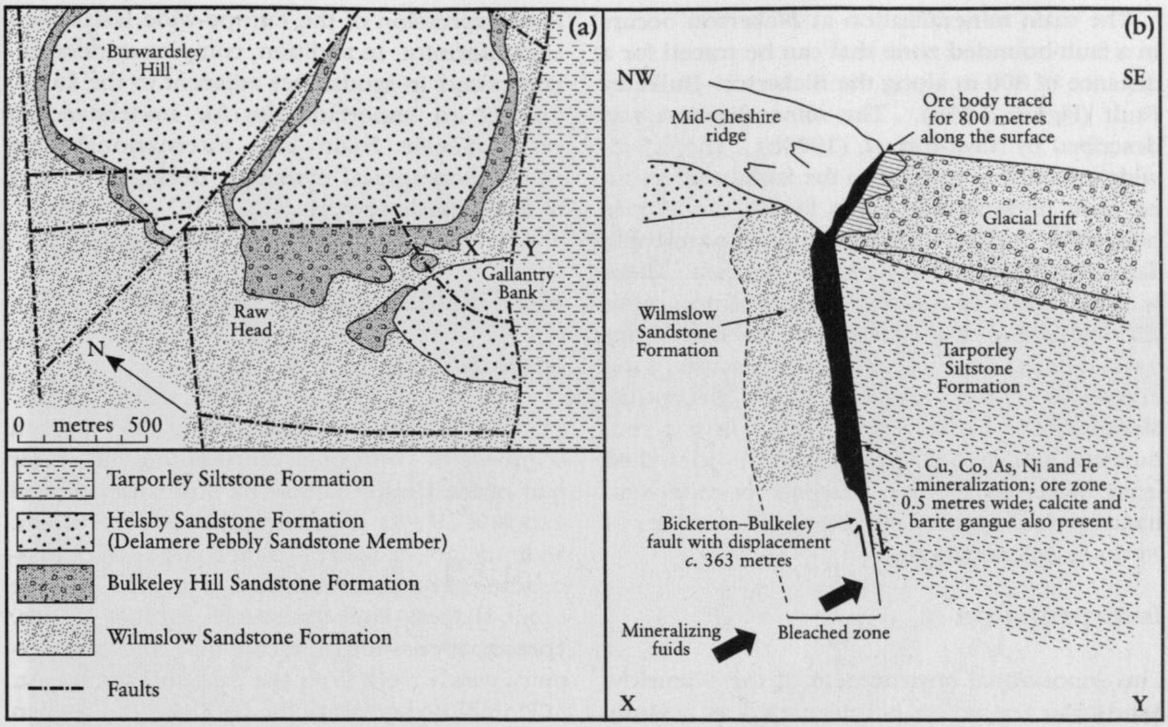


Figure 3.35 The geology of Bickerton Hill; (a) a map of the outcrop of the main divisions of the Triassic System; (b) cross-section (X–Y), showing the faulted contact of the Wilmslow Sandstone Formation and the Tarporley Siltstone Formation, with associated mineralization. (From Naylor *et al.*, 1989b.)

The Triassic stratigraphy of this area shows some variation from that of the Wirral and other parts of the Cheshire Basin (Figure 3.19). The tripartite division of the Helsby Sandstone Formation is not recognized in this area, with only the Delamere Pebbly Sandstone Member being present. A distinctive unit, the Bulkeley Hill Sandstone Formation, is present between the Wilmslow Sandstone and the Helsby Sandstone formations. The area is bounded to the east by a major NE–SW fault, the Bickerton–Bulkeley Fault, with a downthrow of at least 360 m to the east (Figure 3.35). This fault explains the major change in topography from the high Cheshire Ridge in the west to the low-lying Cheshire plain. Throughout the sandstones are granulation seams and fracture systems with orientations (strike 360°, dip 66° west; strike 300°, dip 70° east), which are conjugate with the main fault system.

The outcrop of the Wilmslow, Bulkeley Hill, and Helsby sandstone formations around Bickerton (Figure 3.35a) relates in part to topography and to additional faults. The area between Droppingstone Farm and Raw Head has magnificent exposures of the Wilmslow Sandstone Formation, which comprises a thick sequence of red and variegated, very fine-, fine-, and medium-grained sandstones. The main sedimentary structures are small-scale (0.1 to 0.3 m) cross-bedding and sets of horizontal or low-angle planar stratification. Many of these units demonstrate a pseudo-pin-striped appearance. Measurements of cross-bedding azimuths indicate sediment transport consistently towards the north-west and NNW.

The overlying Bulkeley Hill Sandstone Formation comprises fluvial and aeolian sandstones, and is capped by the conglomerates and sandstones of the Delamere Pebbly Sandstone Member of the Helsby Sandstone Formation. Southwards and westwards, the Bulkeley Hill Sandstone Formation is progressively cut out below the Helsby Sandstone Formation, which comes to rest directly upon the Wilmslow Sandstone Formation. The Delamere Pebbly Sandstone Member consists of red, secondarily buff or white, lenticular planar- or trough-cross-bedded, mostly coarse, ill-sorted, pebbly sandstone, rich in mud clasts.

The main mineralization at Bickerton occurs in a fault-bounded zone that can be traced for a distance of 800 m along the Bickerton–Bulkeley Fault (Figure 3.35b). The mineralization was described by Naylor *et al.* (1989b). The 0.5-m-wide ore zone is parallel to the fault, and resulted from mineralizing fluids in the sandstones becoming trapped against the impermeable Tarporley Siltstone Formation to the east. There is little evidence of the mineralization now, although some of the more porous sandstones have abundant barite cements and some of the exposures of the Delamere Pebbly Sandstone Member have barite rosettes up to a few centimetres in diameter. Ore minerals identified from Bickerton include bravoite, bornite, tennantite, chalcopyrite, covellite, and a range of Ni-Co-Fe sulpharsenides.

Interpretation

The depositional environment of the Wilmslow Sandstone Formation is interpreted as a sandy braided fluvial system. The plane and pseudo-pin-striped sandstones may represent low-amplitude sand waves or macroforms reflecting the relatively low-energy (aggradational) nature of the depositional system.

The Bulkeley Hill Sandstone Formation contains evidence for a mixed fluvial and aeolian regime.

The Delamere Pebbly Sandstone Member is the product of high-energy fluvial deposition. The change from the Bulkeley Hill Sandstone Formation to the Helsby Sandstone Formation is the manifestation of a regional angular unconformity (Evans *et al.*, 1993), which may reflect rejuvenation and uplift of source areas to the south and west, and may be equivalent to the Hardegsen unconformity seen in the North Sea basins and in continental Europe.

Conclusions

The Wilmslow, Bulkeley Hill, and Helsby sandstone formations at Bickerton Hill show an excellent succession through fluvial, mixed aeolian and fluvial, and high-energy fluvial depositional systems respectively. The change from relatively slow, low-energy deposition systems to the high-energy one of the Helsby Sandstone Formation occurs at a boundary that is interrupted as an unconformity that reflects a phase of uplift and enhanced erosion and may be the local expression of the Europe-wide Hardegsen Unconformity. In addition, complex mineralization occurs in sandstones adjacent to the faults. This is an important site for understanding regional-scale basin and international-scale palaeogeographical evolution during the Early to Mid Triassic epochs.

FRODSHAM, CHESHIRE (SJ 519 781)

Introduction

The Frodsham Soft Sandstone Member, a sequence of sandstones representing the upper part of the Helsby Sandstone Formation, is well exposed at its type locality at Frodsham. Sedimentary structures include large-scale cross-bedding, interpreted as having formed in large dome-shaped and transverse aeolian dunes. Foreset orientations indicate that the contemporary winds blew from the east and south-east. At Pinmill Brow, part of the GCR site, the aeolian dunes are overlain by the Tarporley Siltstone Formation (basal Mercia Mudstone Group), which had a strikingly different, marine intertidal and fluvial origin.

The site has been described by Hull (1860), Thompson (1969, 1970a,b, 1985, 1991), Mader and Yardley (1985), and Macchi and Meadows (1987).

Description

Frodsham lies in the north-west margin of the Cheshire Basin in a series of NNW fault-bounded structures termed the 'Wigan–Warrington half-graben system' by Macchi and Meadows (1987). This system is continuous with the large East Irish Sea Basin to the north-west that contains the hydrocarbon fields of Morecambe Bay and the Liverpool Bay Complex.

The best exposures are in the railway cutting at Frodsham, the type locality of the Frodsham Soft Sandstone Member, the uppermost division of the Helsby Sandstone Formation, and locally representing the top of the Sherwood Sandstone Group (Figure 3.19). Access to the railway is restricted, but good views of the spectacular cross-stratified sandstones (Figure 3.36a) are available from the footbridge (SJ 519 779) and part of the section can be examined in the car park adjacent to Frodsham railway station.

The sandstones at Frodsham are some 55 m

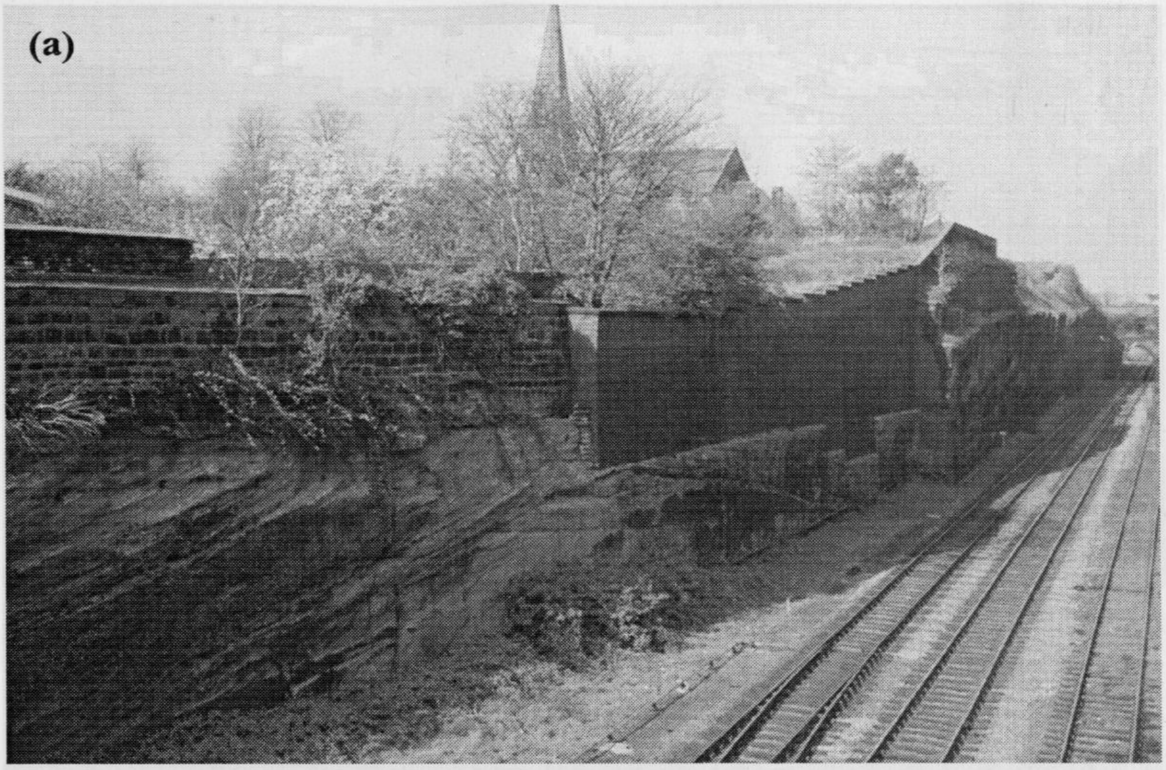


Figure 3.36 The Frodsham site displays (a) aeolian dune cross-bedding in the railway cutting and (b) a spectacular dome-shaped structure in an adjacent quarry. (Photos: D.B. Thompson.)

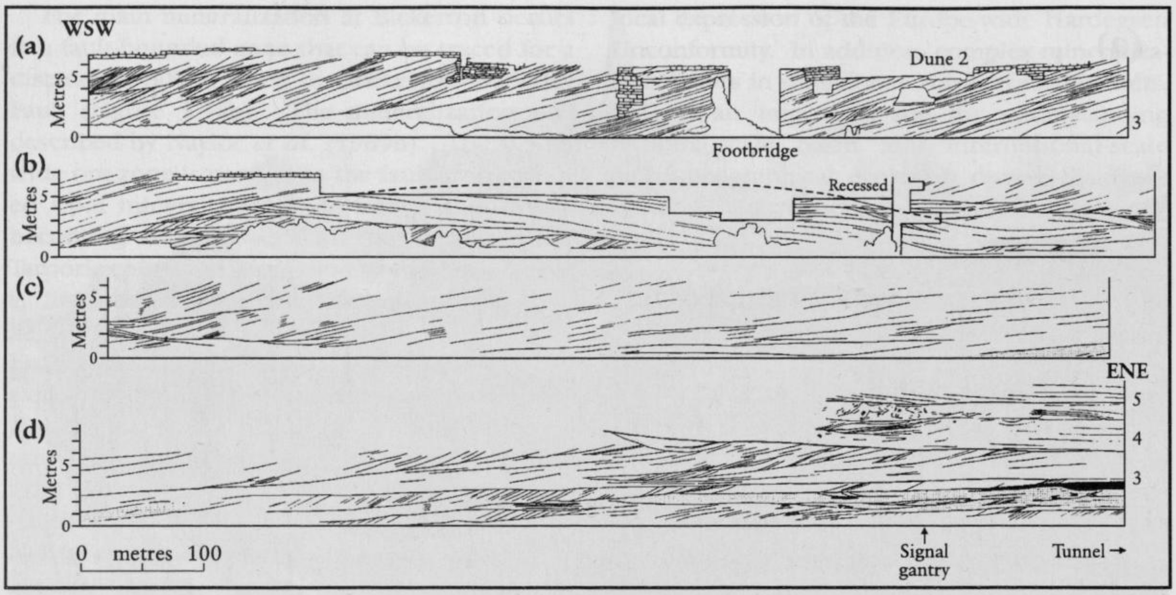


Figure 3.37 Sections through the aeolian Frodsham Soft Sandstone Member on the north side of the railway cutting at Frodsham. Sections (a) to (d) fit together as a continuous strip running from WSW (a) to ENE (d). These diagrams show the main dune (No. 3) throughout, while dunes No. 4 and No. 5 appear at the right-hand end of strip (d). Joints are omitted. (After Thompson, 1969.)

thick. Thompson (1969) noted four lithofacies: interbedded red mudstone and chocolate-red, laminated shale, mudstone and siltstone; interbedded chocolate shale and fine-grained, argillaceous, flat-bedded, ripple-bedded, and cross-bedded sandstone; foxy-red, cross-bedded, fine-grained sandstone in sets commonly less than 1.5 m thick; and a similar sandstone, but cross-bedded in very large sets with very long laminated foresets. Sedimentary structures include cross-stratification, contorted beds, intraset cross ripples, and straight and concave-upwards foresets.

Thompson (1969) identified eight separate cross-stratified dune sets at Frodsham, of which three (Numbers 2–4) occur in the railway cutting (Figure 3.37). These show large- to very large-scale planar-tabular foresets (height up to 10 m or more), with mainly straight, but sometimes slightly curved (both convex-up and convex-down), laminae. Occasionally, asymmetrically infilled trough sets, and rarely wedge-shaped sets, also occur. The foresets are mainly composed of grainfall laminae with minor amounts of grainflow strata and contain internal erosion surfaces of relaxation type. Low-angle to horizontal sheet sands, mainly comprising climbing ripple cross-laminae, are rarely intercalated between the foresets. The erosional boundaries between cosets are horizontal, or slightly scoop- or trough-shaped, or occasionally wavy and irregular.

The main dune at Frodsham (No. 3) can be traced laterally for almost 500 m (Figure 3.37). A key feature of this dune is the upper bounding surface, which is convex-upwards (Figure 3.37b). In addition, many of the smaller-scale bedforms show convex-upwards stratification surfaces and there is a general absence of discrete grainflow laminations.

The Frodsham dune deposits can be seen elsewhere in and around Frodsham, most notably on Main Street (SJ 518 780, SJ 519 781; Figure 3.38), and around St Luke's Rectory (SJ 519 781). At Pinmill Brow (SJ 518 774), there is a small exposure that shows the overlying Tarporley Siltstone Formation (Thompson, 1991).

Interpretation

The Frodsham Soft Sandstone Member is almost entirely aeolian in origin, and the cross-stratification indicates that the unit is built up from sands deposited by straight-crested transverse dunes in a fluctuating wind system. The trans-

Figure 3.38 Aeolian dune cross-bedding in a section of the Frodsham Soft Sandstone Member on the High Street of Frodsham village. (Photo: D. B. Thompson.)

verse dunes in places evolved into dome-shaped dunes during degradation by strong winds. Thompson (1969) suggested that the main cross-stratified set (No. 3) represents a dome-shaped dune (Figure 3.37b) because of the convex-upwards upper bounding surface, the convex-upwards stratification surfaces in many of the smaller-scale bedforms, and the general absence of discrete grainflow laminations, a feature that suggests that avalanche slip faces were rare.

There is some evidence for simple migration of large dunes or draas, but in most cases such migration was interrupted. The isolated to abundant intrasets of relaxation type reflect repeated to persistent interruption of migration by modification events that created minor erosional boundaries, and subsequent migration of superimposed smaller bedforms along or around the draa. Palaeowind directions measured from the dip directions of cross-stratal surfaces are consistently from the east, although minor variations between north-east and south-east occur between the different dune units. Counterdipping intrasets record some cross-winds blowing along or across the foreset slope.

The dunes were also modified by blowout and erosional processes. In the upper parts of the exposed sequence, large troughs, frequently infilled by migrating sinuous-crested transverse bedforms, attest to dune-top blowout (the loss of sand from the top of a dune structure by a sudden burst of wind). Elsewhere, lower bounding surfaces of dune sets show that subsequent dunes cut down into pre-existing bedforms, destroying the upper parts of the cross-stratification, and reworking the sand.

Occasional intercalations of thin sand sheets show that there were narrow, dry interdune corridors. Occasional small-scale slump structures on foreset laminae, which occur between undisturbed foresets, might indicate movement of animals 'along or across the damp surface of a lee-side slope of the dune' (Mader and Yardley, 1985, p. 173). The generally dry conditions were interrupted by rare, heavy rainfall events, which caused ephemeral floods. Water rushed through the interdune corridors, creating gullies. However, water clearly drained away rapidly into the porous sand, and arid conditions prevailed for most of the time.

Thompson (1969) related the history of dune development at Frodsham to changes in wind speed. During periods of moderate breezes, sand from dried-out river courses was built into embryonic transverse dunes, which reached considerable heights. The onset of periods of strong breeze and moderate gales degraded the transverse dunes into dome-shaped mounds by stripping off the upper portions. When average winds abated to moderate and fresh breezes, steep foresets built up and transverse dunes developed again.

The Frodsham Soft Sandstone Member documents the end of aeolian deposition in the Cheshire Basin. During the Early Triassic Epoch, dunes formed between river channels over much of the Cheshire Basin, and the Frodsham aeolian unit is one of the last expressions of this desert in Mid Triassic (Anisian) times. Following this, a marine transgression ushered in dominantly intertidal and lacustrine deposition of the Mercia Mudstone Group.

Conclusions

The Frodsham railway cutting displays an excellent section through the Frodsham Soft Sandstone Member, for which this is the type location. The exposures show the internal structure of a huge dune, some 500 m long, as well as associated, smaller, dunes. This is a classic site for the study of aeolian sedimentology, and for understanding British Mid Triassic palaeoenvironments and palaeogeography, especially the major transition from arid inland sand sea deposition, shown here, to marine intertidal and lacustrine conditions in the succeeding Mercia Mudstone Group.

RED BROW CUTTING, CHESHIRE (SJ 568 817)

Introduction

This widened lane cutting shows a section of about 25 m of the Tarporley Siltstone Formation, the basal unit of the Mercia Mudstone Group. The formation consists largely of red, fine-

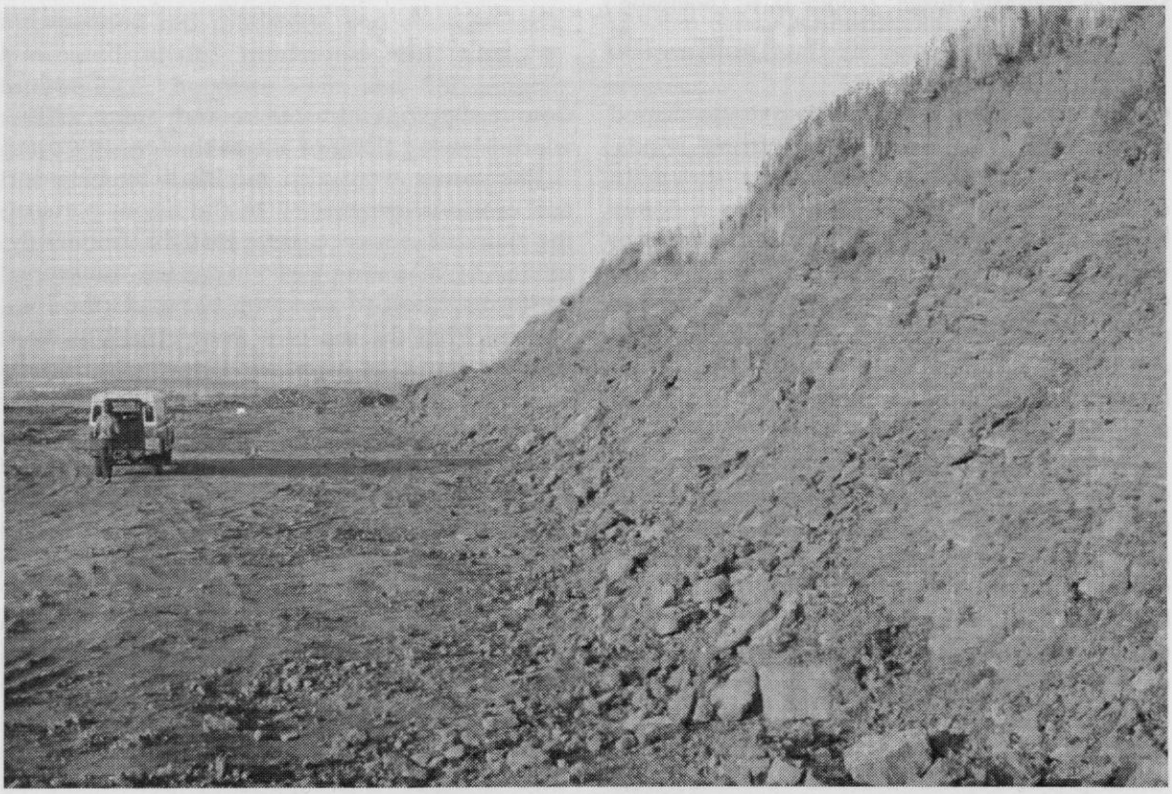


Figure 3.39 The section at Red Brow, showing the succession of red sandstones and mudstones. (Photo: M. J. Benton.)

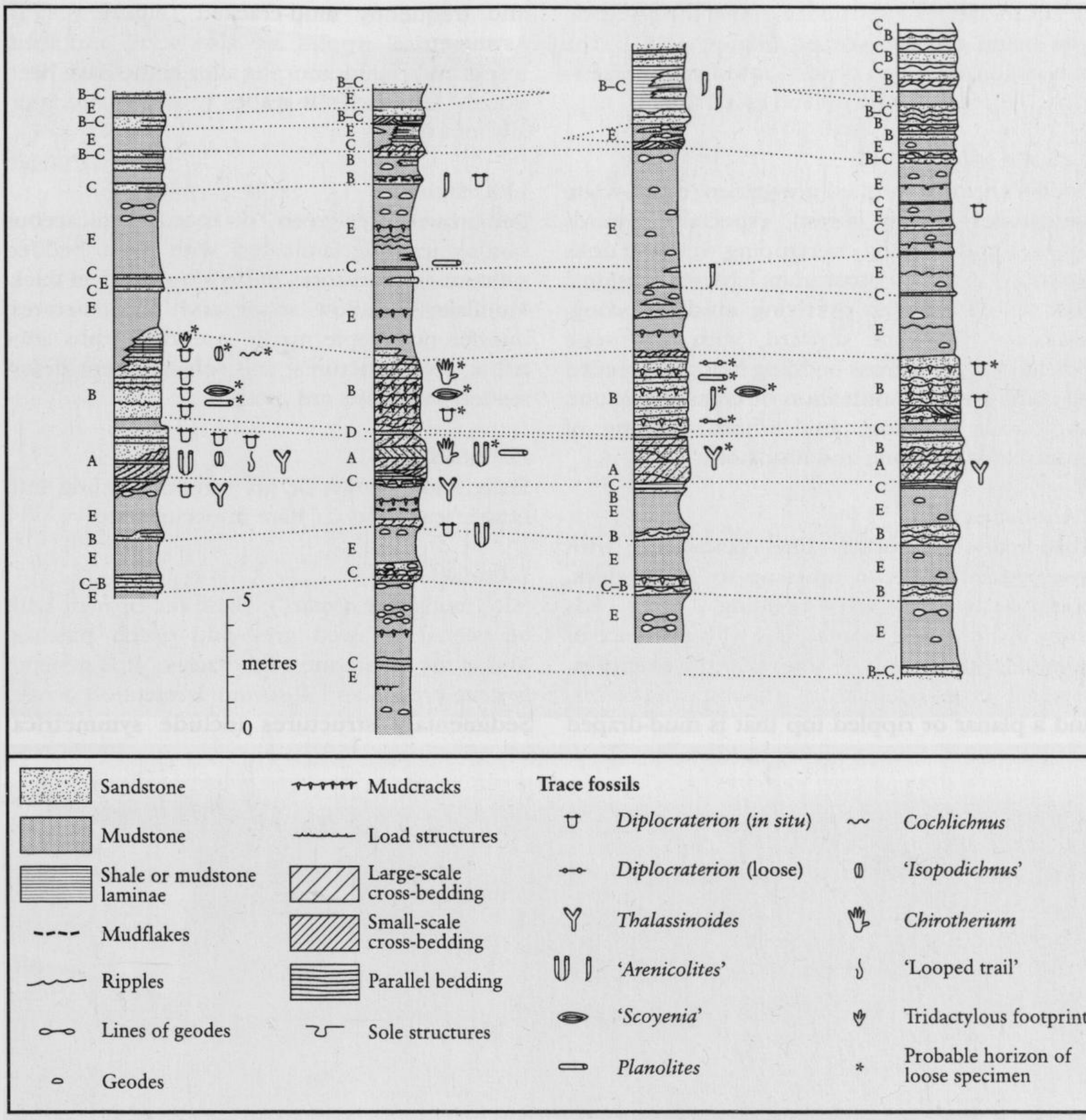


Figure 3.40 Sedimentary logs measured through the Red Brow section, showing the interplay of facies A–E. (From Ireland *et al.*, 1978.)

grained sandstones and siltstones, with parallel rippled bedding, including flaser and wavy bedding in some of the thicker sandstone units. Trace fossils, including *Planolites* and *Isopodichnus*, occur in abundance. In some of the sandstone units there are parallel rows of calcite-infilled geodes that represent replaced nodular gypsiferous evaporites. The section is sedimentologically and environmentally important. It shows sediments deposited under marine intertidal conditions that developed over a wide tract of central England during the Anisian.

The site has been described by Thompson (1970a,b), and in detail by Ireland *et al.* (1978).

Description

Sedimentology

The Red Brow section is dominated by red sandstones and mudstones that were studied in detail in the 1970s when a 500-m-long section was being actively worked (Figure 3.39). The succession has been divided into five lithofacies (A–E, Figure 3.40) by Ireland *et al.* (1978):

Lithofacies A

Reddish-brown, mottled grey-green, or off-white sandstones, poorly sorted, especially towards the top, and forming overlapping wedging units up to 2.5 m thick. Most units have an erosional base, often with an overlying mudflake conglomerate; they fine upward, with large-scale planar or trough cross-bedding being succeeded by plane parallel lamination or cross-lamination and flaser bedding, and a thin capping of bioturbated siltstone and mudstone.

Lithofacies B

Thin-bedded, muddy, fine sandstone with interbedded shale, in units up to 3.5 m thick. Some units show wavy bedding. Most beds show a sharp base, sometimes with evidence of erosion (tool marks) and slump structures, internal cross-lamination, flasers, mudflakes, and a planar or rippled top that is mud-draped and frequently mud-cracked (Figure 3.41a). Asymmetrical ripples are also seen, and foam marks and pseudomorphs after halite have been noted. Lithofacies B grades vertically and laterally into C.

Lithofacies C

Red-brown, grey-green, or mottled micaceous sandstones interlaminated with flaser-bedded siltstone or mudstone, in beds up to 0.5 m thick. Mudflakes, shallow scour and fill structures, interference ripple marks, pseudomorphs after halite, sole structures, and soft-sediment deformation structures are present.

Lithofacies D

Shale, dark brown or grey-green, grading into lithofacies B and C. Rare in occurrence.

Lithofacies E

Silty mudstone ('marl'), dark red-brown, with occasional reduced grey and green patches. This is the commonest lithofacies. It is generally structureless and ill-sorted; lamination is rare. Sedimentary structures include symmetrical

Figure 3.41 Sedimentary structures and trace fossils from the Red Brow section, indicative of an intertidal depositional regime. (a) Mud cracks viewed from above, with the cracks filled with overlying sandstone. (Photo: M. J. Benton.)

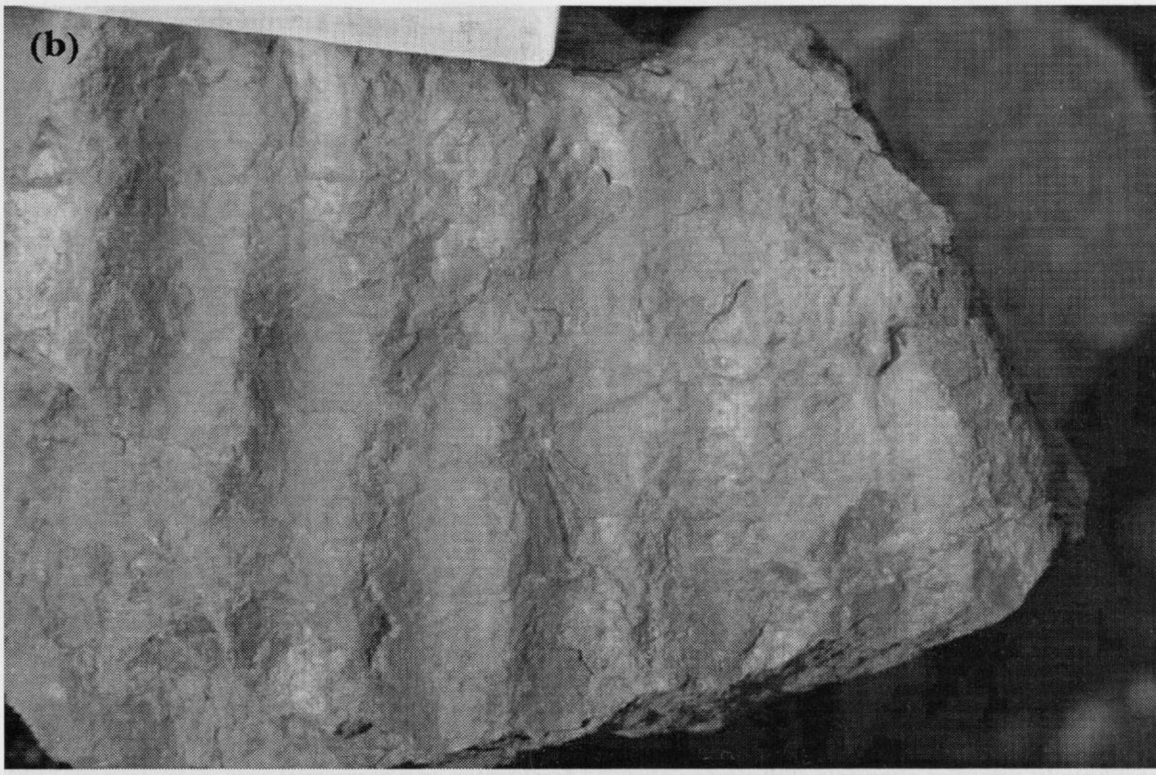


Figure 3.41 – *contd.* Sedimentary structures and trace fossils from the Red Brow section, indicative of an intertidal depositional regime. (b) Symmetrical ripple marks. (c) Numerous scattered burrows (*Planolites*), on the lower surface of a mudstone bed. (Photos: M. J. Benton.)

ripples (Figure 3.41b), mudcracks, lenticular beds of cross-laminated silt, and sporadic pseudomorphs after halite. The mudstone contains dolomite and scarce gypsum. It is interlaminated with lithofacies B and C.

Palaeontology

The Red Brow site is well known for its rich trace fossil fauna (Figure 3.41c). Ichnotaxa recorded (Ireland *et al.*, 1978) include *Thalassinoides* cf. *suevicus*, *Diplocraterion luniforme*, *Arenicolites* sp., cf. *'Scoyenia?' triadica*, *Planolites*, *Isopodichnus*, looped trails, and the vertebrate footprint *Chirotherium*.

Interpretation

The suite of sediments at Red Brow is interpreted (Ireland *et al.*, 1978) as the deposits of an intertidal flat. Various sub-environments are recognized: lower and middle intertidal sandflat (lithofacies B and C), high intertidal mudflat to possibly impersistent sabkha (lithofacies E), and sand bars in tidal flat channels (lithofacies A).

Lithofacies A was deposited by waning currents, as indicated by its fining-up nature, probably in a bar or complex dune, and there is evidence for lateral migration, as bars grew over each other, eroding earlier-formed bars, or grew marginally on mud or silt surfaces.

Lithofacies B shows evidence of frequent alternations of subaqueous and subaerial conditions. The small fining-upwards units were deposited under water by traction currents, with settling out of mud from suspension to form top drapes. Rippled top surfaces were frequently modifed by wave action to form nearly symmetrical ripples. The foam marks indicate exposure and wind action, and the pseudomorphs after halite and mudcracks show evidence of emergence and desiccation. Lithofacies C is interpreted as having formed under similar conditions, but at lower energy.

Lithofacies D resulted from pulses of suspended matter. Lithofacies E displays alternations between subaqueous and subaerial conditions. The structureless mudstone may have been deposited irregularly from suspension of wind-borne dust, or internal structures may have been destroyed by thorough bioturbation. The symmetrical ripples indicate wave activity. Exposure is indicated by the mudcracks and evaporites.

Overall, the site is interpreted as offering clear evidence for marine marginal conditions (Ireland *et al.*, 1978). Where formerly the 'Waterstones' had been interpreted as probably lacustrine in origin, the combination of detailed, modern, sedimentological study, with evidence from the trace fossil associations, indicates that the finer-grained units at Red Brow represent marine environments.

The trace fossils include a range of associations, indicating environments from fully marine, through intertidal, to continental. The branching burrow system *Thalassinoides* is typical of deeper seawater, normally below wave base, and is at least from a low intertidal or subtidal position. Several other invertebrate traces indicate the *Skolithos* ichnofacies. In particular, *Diplocraterion* and *Arenicolites*, classic U-shaped burrows, are indicators of intertidal conditions. *Scoyenia* and *Isopodichnus*, in association with mudcracks and vertebrate tracks are continental indicators, belonging to the *Scoyenia* Ichnofacies. Hence, the trace fossils indicate a range of conditions from sub-tidal to freshwater and terrestrial.

Conclusions

Red Brow provides an excellent exposure of Mid Triassic sediments of sub-tidal to continental origin and was the site of a classic study using sedimentary structures and trace fossils for palaeoenvironmental interpretation. The site comprises deposits from a range of environments, from sub-tidal to continental. Studies here contributed to the resolution of the origin of the Tarporley Mudstone Formation, formerly the 'Waterstones', and had wider implications for understanding British Triassic successions, by providing corroborative evidence of shallow marine incursions into the Cheshire Basin and Midlands during the Anisian Age. This is an important site for the study of palaeoenvironmental indicators.

GRINSHILL QUARRIES, SHROPSHIRE (SJ 520 237)

Potential GCR site

Introduction

The quarries in the vicinity of Grinshill and Clive are historically important as a source of verte-

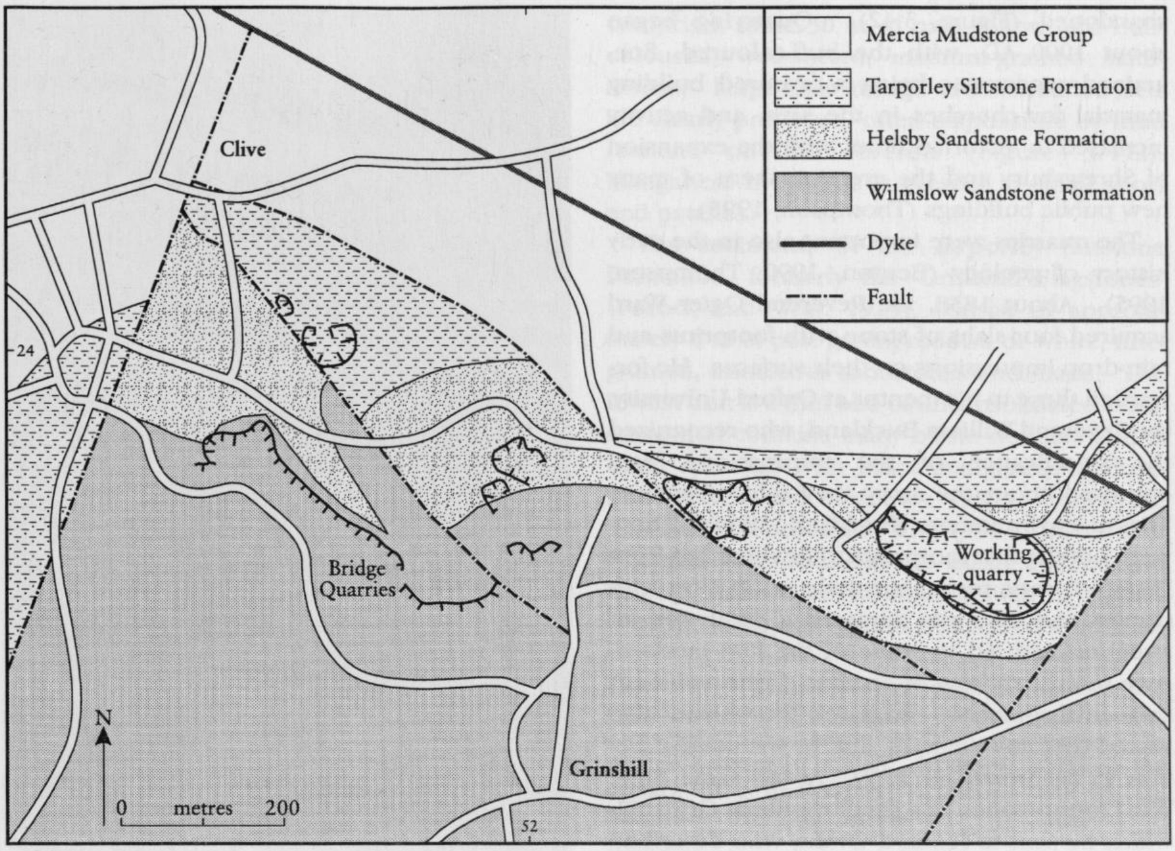


Figure 3.42 The Grinshill localities. The map is based on published maps of the British Geological Survey (BGS 1:63 3000 scale Geological Sheet 138, Wem), and on field observations by M.J.B.

brate fossils, footprints, and for exposures of the Helsby Sandstone Formation and the Tarporley Siltstone Formation.

At the time of writing, the site was being considered for addition to the GCR on account of the contribution that it makes in helping to understand Mid Triassic palaeoenvironments in central England. However, it is already a confirmed GCR palaeontological locality for its fossil reptiles (Benton and Spencer, 1995).

The old quarries show spectacular large-scale cross-bedding in the Helsby Sandstone Formation, and ripples, rain-pits, mud-cracks, and footprints in the Tarporley Siltstone Formation. Skeletal fossils of *Rhynchosaurus* have been found in the upper parts of the succession, and specimens still come to light. This site offers evidence of the environmental changes that occurred through the transition from the Sherwood Sandstone Group to the Mercia Mudstone Group. It is important as one of the best Triassic sites in the south of the Cheshire Basin, and is historically important for work there in the 1830s on sedimentology and palaeontology.

Many descriptions of these quarries have been published. Murchison (1839) provided one of the first records of the succession at Grinshill. Later accounts of the geology include Hull (1869, pp. 64, 73), Pocock and Wray (1925), Thompson (1970a,b, 1985, 1995), and Macchi and Meadows (1987). The footprints were described by Ward (1840) and Beasley (1902), and the reptile remains by Owen (1842), Walker (1969), Benton (1990), and Benton and Spencer (1995), among others.

Description

There are many quarries in the area (SJ 520 239, SJ 523 238, SJ 524 238, and SJ 526 238), however, all but one (at SJ 526 238) have been abandoned (Figure 3.42). Quarrying began about 1000 AD, with the buff-coloured, fine-grained sandstones being a favoured building material for churches in the area, and activity increased in Victorian times with the expansion of Shrewsbury and the erection there of many new public buildings (Thompson, 1995).

The quarries were important also in the early history of geology (Benton, 1990; Thompson, 1995). About 1838, the Reverend Ogier Ward acquired four slabs of stone with footprints and rain-drop impressions on their surfaces. He forwarded these to his mentor at Oxford University, the Reverend William Buckland, who recognized the significance of the impressions, and enthused about the story they told of ancient Triassic environments (Buckland, 1844). These were not the first footprints to be recorded from Permo–Triassic rocks, but their association with ripples and rain pits attracted a great deal of attention and led to some of the first modern-style interpretations of ancient clastic sedimentary environments. Roderick Murchison also visited Grinshill quarries, and he included a section in his *Siluria* in 1839. At the same time, Ward found bones of a small reptile at Grinshill, which he sent to Richard Owen, who described them (Owen, 1842) as remains of an ancient lizard. So, around 1840, Grinshill had attracted the attention of three of the leading geologists of the day – Buckland, Murchison, and Owen – and the finds of sedimentary structures, footprints, and bones caused a sensation.

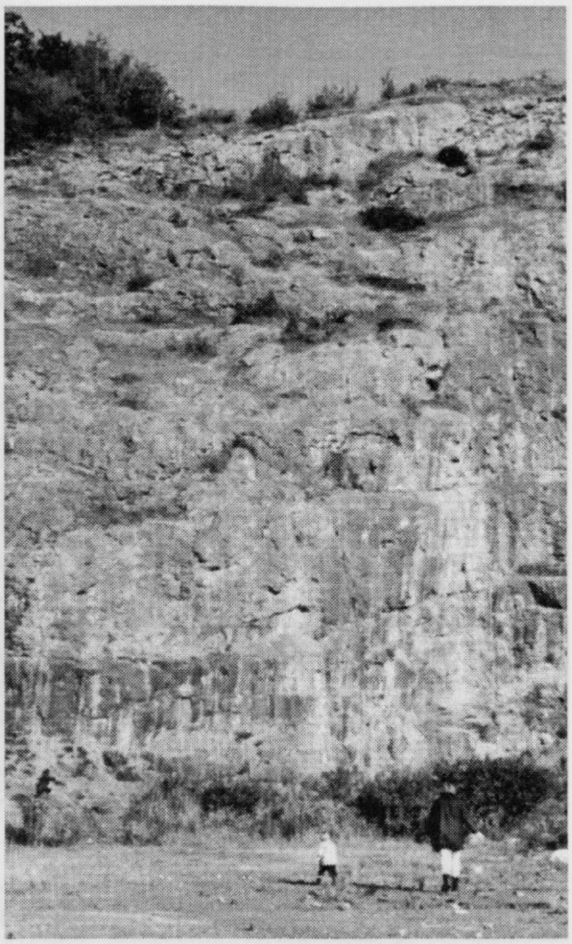


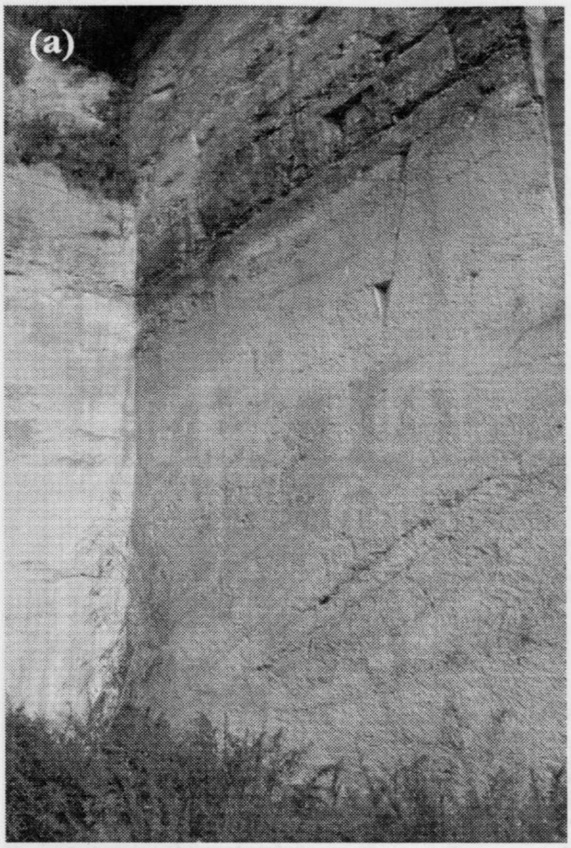
Figure 3.43 The operational quarry at Grinshill: view of the north face, showing the massive cross-bedded Helsby Sandstone Formation at the base, and the softer, more thinly bedded Tarporley Siltstone Formation above. (Photo: M. J. Benton.)

Sedimentology

The sedimentary sequences in the quarries at Grinshill (Figure 3.43) are dominated by sandstones of the Helsby Sandstone Formation, which are overlain by red marls of the Mercia Mudstone Group. The following sedimentary log is taken from Pocock and Wray (1925, pp. 39–40), with updated stratigraphical terminology:

	Thickness (m)
Mercia Mudstone Group; *Bollin Mudstone Formation*:	
Fee (quarrymen's term): red marl	0.6
Mercia Mudstone Group; *Tarporley Siltstone Formation*:	
Flag rock: grey and light yellow sandstone, evenly bedded, with thin, reddish seams; ripple marks	6.1
Esk bed: unconsolidated grey sandstone and sand, with harder patches; full of specks of manganese dioxide	0.22
Sherwood Sandstone Group; *Helsby Sandstone Formation*:	
Hard burr: hard, coarse-grained, yellowish-white sandstone	0.76
Hard, yellowish freestone	0.76
White and pale yellow freestone, with iron-stained patches towards the base	10.06
White freestone with iron-stained and speckled patches	1.68

The Helsby Sandstone Formation at Grinshill was formerly termed the 'Grinshill White Sandstones' (Pocock and Wray, 1925); it



comprises some 30 m of pale yellow and buff-coloured, well-sorted, medium-grained sandstones. Large-scale trough cross-stratified sets are clearly preserved, often emphasised by mud laminae on the foresets (Figure 3.44a). Manganese hydroxide is present in small spots and patches.

The sediments of the Tarporley Siltstone Formation, formerly the 'Grinshill Flagstones' (Pocock and Wray, 1925), consist of approximately 6 m of pale green, reddish or white, fine-grained, micaceous sandstones and marls. The lowest unit is a thin bed of unconsolidated sandstone that contains many barite nodules and is often speckled with black manganese hydroxides (Macchi and Meadows, 1987), termed the 'Esk Bed' by Pocock and Wray (1925, pp. 39–40). The overlying sediments are thinly bedded and display well-defined structures such as ripples (Figure 3.44b), rain prints, desiccated mudstone

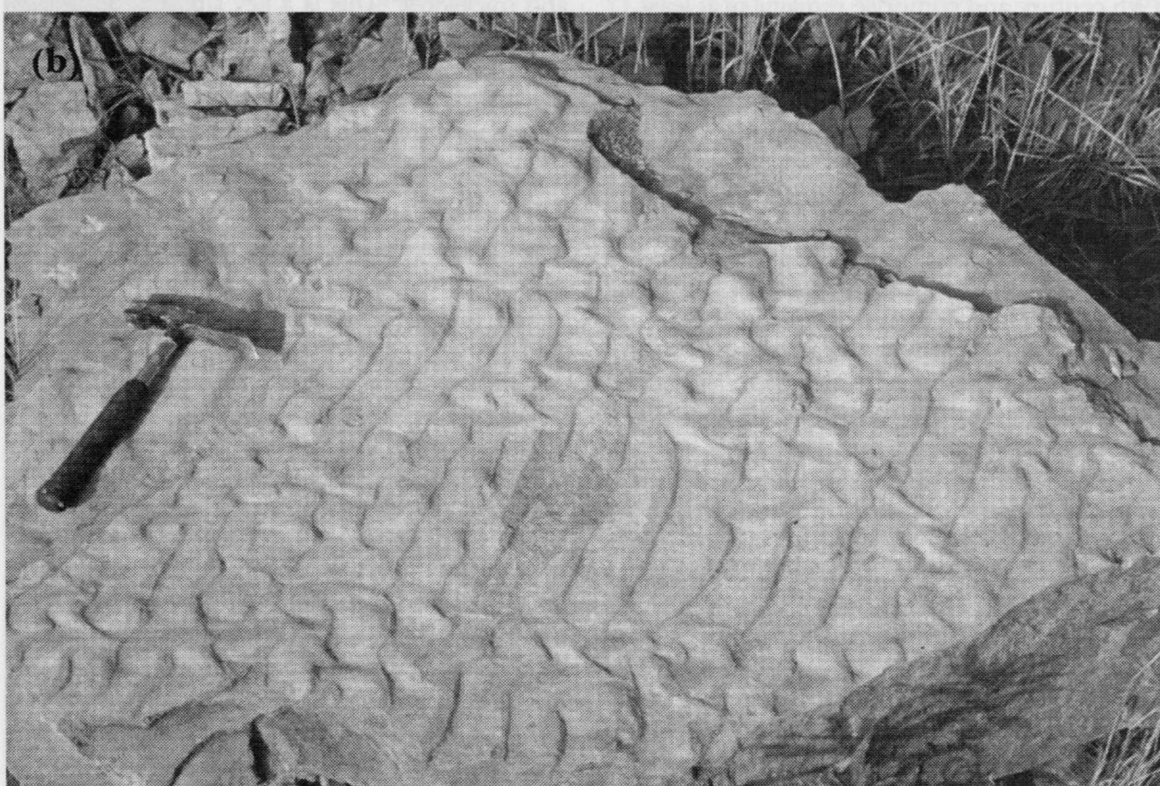


Figure 3.44 Sedimentary structures in the Grinshill quarries. (a) Lower portions of large-scale aeolian cross-beds in the Helsby Sandstone Formation. The section is about 10 m high. (b) Ripple marks on the surface of a fine-grained sandstone unit in the Tarporley Siltstone Formation. (Photos: M. J. Benton.)

drapes, and reptile footprints. The great abundance of ripples, best seen in the southwestern side of the Grinshill Stone Quarry (SJ 526 238), gives the sandstones a wavy appearance. The ripples take many forms, including isolate and transverse types, and are occasionally seen superimposed on larger-scale ripples (Macchi and Meadows, 1987).

At the top of the quarry sections at Grinshill about 1 m of the reddish siltstones and mudstones of the Mercia Mudstone Group is recorded (Macchi and Meadows, 1987). This unit is the basal part of the Bollin Mudstone Formation of Wilson (1993; see also Thompson, 1995). It was formerly termed the 'Fee' (pronounced 'fay').

In the north-western part of the Grinshill Stone Quarry (SJ 526 238) a few porphyritic dolerite dykes are exposed (Macchi and Meadows, 1987), which are thought to form a part of a larger, regionally important Tertiary dyke swarm (Thompson, 1985, 1995).

Palaeontology

The Grinshill Quarries are famous for the well-preserved remains of reptiles, although no other body fossils have been discovered here (Walker, 1969). Specimens have been collected since the 19th century and comprise remains of at least 17 individuals of *Rhynchosaurus articeps*, a rhynchosaur (Benton, 1990). These remains are thought to have been recovered from both the fine-grained sediments of the Tarporley Siltstone Formation, and possibly the top of the coarser-grained Grinshill Sandstone (Walker, 1969; Benton and Spencer, 1995).

Trace fossils are also present in the Tarporley Siltstone Formation – small reptilian footprints with clearly defined claw marks. These have been assigned to *Rhynchosauroides* and *Chirotherium* and are commonly associated with current and wave ripples (Benton and Spencer, 1995).

Interpretation

The sediments at Grinshill reflect a marked change in palaeoenvironment between the deposition of the Helsby Sandstone Formation and of the Tarporley Siltstone Formation. The large-scale cross-beds of the Helsby Sandstone Formation have been interpreted as evidence for aeolian deposition, possibly by large, transverse barchan dunes (Thompson, 1985; Macchi and Meadows, 1987), with the prevailing wind blowing from the east.

The Tarporley Siltstone Formation, characterized by fine-grained wavy-bedded sandstones, represents intertidal conditions associated with a marine transgression at the onset of Mercia Mudstone Group deposition (Macchi and Meadows, 1987). The basal 'Esk Bed' represents a phase of environmental transition (Benton and Spencer, 1995). The ripples in overlying units display characteristic features of intertidal and estuarine environments. Large-scale linguoid ripples formed during the ebb flow of the tide, and smaller ripples formed on the large-scale features as the sand flats were exposed (Macchi and Meadows, 1987).

Conclusions

The sedimentary sequence in the quarries at Grinshill provides an excellent illustration of the change from the Sherwood Sandstone Group to the overlying Mercia Mudstone Group, and from aeolian to intertidal or estuarine environments. The Grinshill quarries have been an important source of Mid Triassic reptile remains, and have provided some well-preserved partial skeletons and trackways. This is a key site for the understanding of Mid Triassic palaeoenvironments in central England, and is especially significant for the sedimentary structures, the fossil tracks, and the skeletal remains of reptiles.

THE TRIASSIC RED BEDS OF THE WESTERN MARGIN OF THE NORTH SEA BASIN

INTRODUCTION

The Triassic succession in the Southern North Sea Basin (SNSB), revealed by hydrocarbon exploration, has aided correlation between the British Triassic succession and the classic German Triassic sequence. The stratigraphy of the offshore sections, taken from many boreholes and from seismic sections, has been summarized by many authors, including Kent (1967, 1975), Geiger and Hopping (1968), Balchin and Ridd (1970), Rhys (1974), Warrington (1974c), Warrington *et al.* (1980), Lott and Warrington (1988), Cameron *et al.* (1992), and Johnson *et al.* (1994). There is a close lithostratigraphical

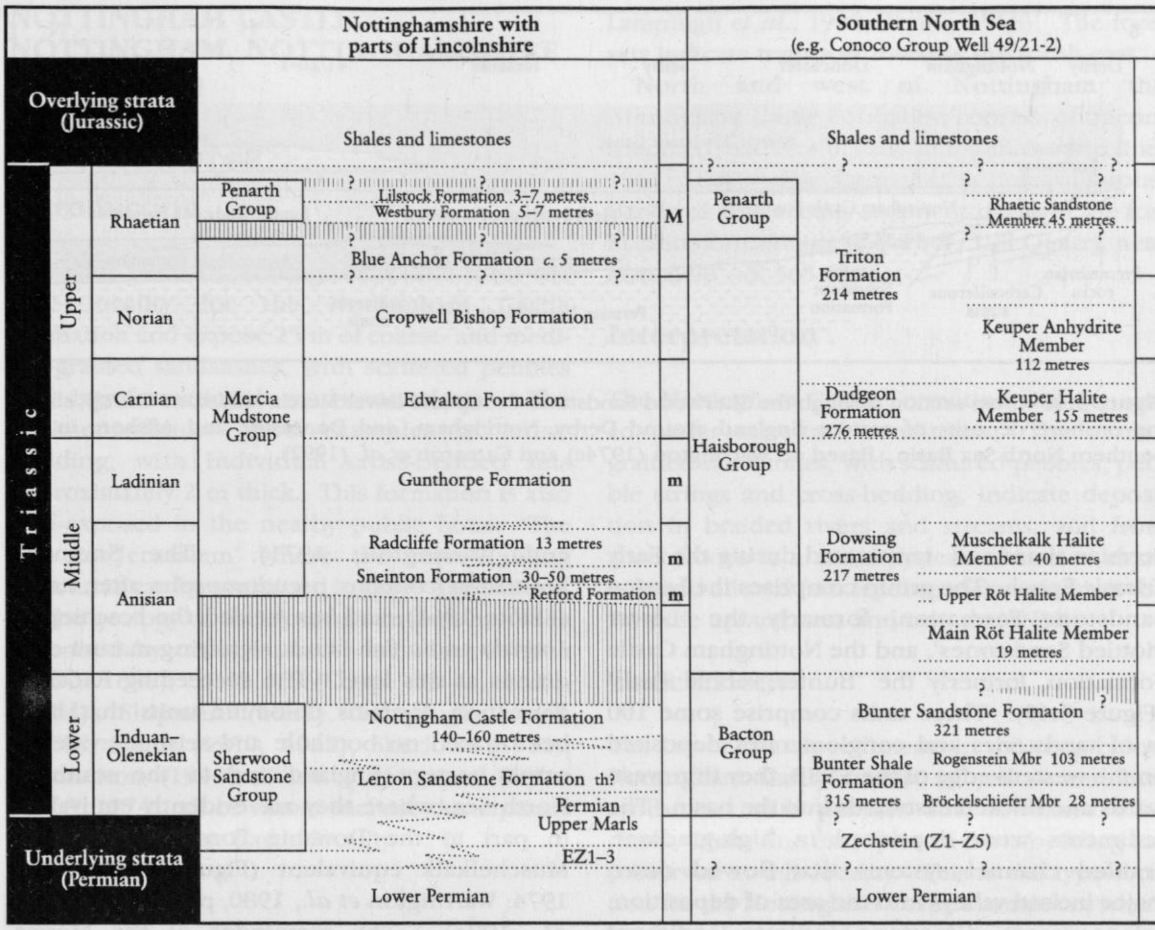


Figure 3.45 Stratigraphical columns for the Triassic of central Nottinghamshire and for the southern North Sea. Based on Warrington *et al.* (1980), Cameron *et al.* (1992), and Johnson *et al.* (1994).

link between the offshore North Sea sections and parts of that seen onshore in eastern England. The Triassic succession in eastern England differs from that seen in the Cheshire Basin not least because the two areas were separated by the Pennine Chain.

Sequences are thicker in the north and east of the region, in Yorkshire and Lincolnshire, and thinner in Nottinghamshire, which was closer to the basin margin and to the upland sources of sediment. Some of the best exposures are in Nottinghamshire.

In central Nottinghamshire, and in parts of Leicestershire, there is a relatively complete Triassic sequence; an unconformity occurs between the Sherwood Sandstone and Mercia Mudstone groups, and a minor break in sedimentation may have occurred between the deposition of the Mercia Mudstone and Penarth groups (Figure 3.45). There is no objective palaeontological evidence for the location of the Permo–Triassic boundary, either in eastern England or in the SNSB (Warrington *et al.*, 1980, p. 50). In the SNSB, the base of the Triassic System is arbitrarily located at the base of the Bröckelschiefer, which overlies Permian deposits of the Zechstein succession (Rhys, 1974; Johnson *et al.*, 1994). To the west, the Bröckelschiefer passes laterally into the Bunter Shale Formation (Figure 3.45) through the Saliferous Marls and the Permian Upper Marls, which are partly Permian and partly Triassic in age (Figure 3.46). The Sherwood Sandstone and Mercia Mudstone groups are broadly equivalent to the Bacton and Haisborough groups respectively of the offshore succession (Rhys, 1974).

In Nottinghamshire, Sherwood Sandstone Group deposition probably began in Late

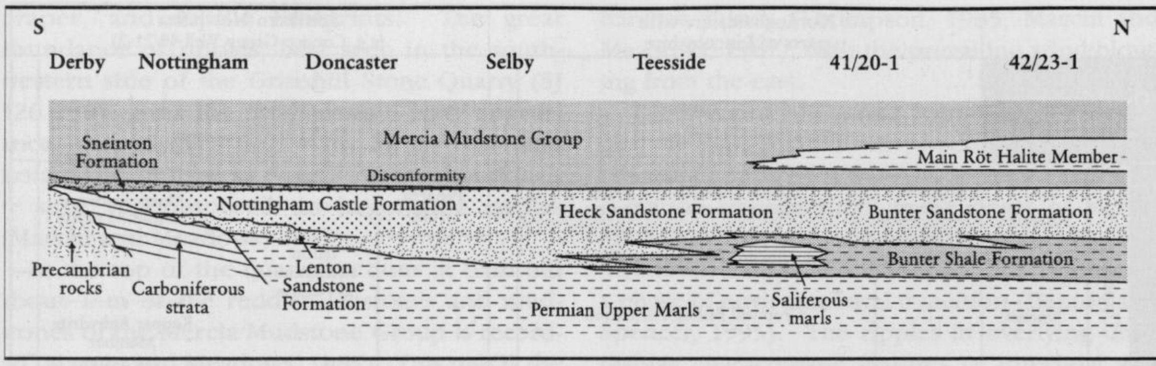


Figure 3.46 Cross-section through the Sherwood Sandstone Group and lower Mercia Mudstone Group, showing onshore deposits of eastern England around Derby, Nottingham, and Doncaster, and offshore in the Southern North Sea Basin. Based on Warrington (1974c) and Cameron *et al*. (1992).

Permian times and terminated during the Early Triassic Epoch. The group comprises the Lenton Sandstone Formation, formerly the 'Lower Mottled Sandstones', and the Nottingham Castle Formation, formerly the 'Bunter Pebble Beds' (Figure 3.45). These units comprise some 100 m of sandstones and conglomerates deposited on the western edge of the SNSB; they thin westwards and thicken eastwards into the basin. The sediments were deposited in high-gradient, braided channel systems that flowed down major incised valleys into the area of deposition. Palaeocurrent directions indicate sediment transport from the Pennine upland to the south-west and west. The predominant depositional environment represented by the Sherwood Sandstone Group around Nottingham is alluvial fans. The sandstones show evidence of cyclicity, with cycles terminated by channel migration. Rarely, palaeosols, ventifact horizons, mudstones, and mud intraclasts are seen at the tops of cycles (Swinnerton, 1914; Taylor, 1968); these reflect low-energy overbank deposition and aeolian processes, but have been mostly removed by subsequent channel migration.

The Mercia Mudstone Group rests unconformably on the Sherwood Sandstone Group (Figure 3.45). The succession was divided by Elliott (1961) into nine formations, which were formalized by Warrington *et al*. (1980, pp. 51–2), and further modified by Charsley *et al*. (1990). The thin Retford Formation, formerly the 'Green Beds', passes southwards into the Sneinton Formation, formerly the 'Waterstones', both of them dominated by mudstones, and north and eastwards into largely undifferentiated Mercia Mudstone Group sediments (Smith and Warrington, 1971). The Sneinton Formation contains pseudomorphs after halite (Elliott, 1961), and has yielded the brachiopod *Lingula* and a fish fauna, signifying marine conditions at this level. The succeeding Radcliffe Formation contains dolomitic units that have been traced on borehole and seismic evidence across eastern England and to the southern North Sea, where they are evidently equivalent in part to the Dowsing Formation and the Muschelkalk equivalent (Figure 3.45; Rhys, 1974; Warrington *et al*., 1980, p. 52; Johnson *et al*., 1994). The remainder of the Mercia Mudstone Group succession comprises the Gunthorpe, Edwalton, Cropwell Bishop, and Blue Anchor formations, and is succeeded by the Penarth Group (Charsley *et al*, 1990).

Dating of the Nottingham sequence has been attempted using macrofossils, such as the fish fauna from the Sneinton Formation, as well as trace fossils, and sporadic arthropods, but these offer only general information on age (Warrington *et al*., 1980, pp. 52–3). More useful are palynomorphs (Smith and Warrington, 1971) recovered from several levels, and borehole geophysical logs and seismic surveys (Balchin and Ridd, 1970) in which regional markers have been identified.

Among the exposures of the SNSB Triassic succession in eastern England considered for selection for the GCR, four locations near Nottingham were chosen, Nottingham Castle, Styrrup Quarry, and Scrooby Top Quarry for their superb exposures of the Nottingham Castle Formation, and Colwick railway section for the Sneinton Formation at the base of the Mercia Mudstone Group.

NOTTINGHAM CASTLE, NOTTINGHAM, NOTTINGHAMSHIRE (SK 569 394)

Potential GCR site

Introduction

The cliffs beneath Nottingham Castle form the type locality for the Nottingham Castle Formation and expose 25 m of coarse- and medium-grained sandstones, with scattered pebbles and intraformational mudstone clasts. The sediments show good examples of cross-bedding, with individual cross-bedded sets approximately 2 m thick. This formation is also well-exposed in the nearby public house 'The Trip to Jerusalem' where the cross-bedding structures can be examined in three dimensions.

The geology of the Nottingham area has been described by many authors, including Aveline (1861, 1880), Hull (1869, pp. 53–4), Irving (1874), Shipman (1881), Lamplugh *et al.* (1908), Smith (1910, 1912), Sherlock (1911), Swinnerton (1918), Elliott (1961), and Taylor (1968, 1974), all of whom include descriptions of the Nottingham Castle locality.

Description

The Nottingham Castle Formation, formerly the 'Bunter Pebble Beds', outcrops in Nottingham and the surrounding area. Exposures are generally man-made, and include road and railway cuttings, as well as storage rooms, cellars and dwellings carved into the rock (Aveline, 1861, 1880). At Nottingham Castle, the type locality for the formation, approximately 25 m of sediments are best exposed on the eastern and southern sides of the Castle Rock and are traceable along Castle Boulevard (Taylor, 1968).

The sediments range from unconsolidated mixtures of sand and pebbles, to hard conglomerate, and are buff, yellow, brown or reddish in colour; the sandstone is medium to coarse, with angular grains. The small, well-rounded pebbles are composed of reworked Devonian and Cambrian quartzites, with some Carboniferous Limestone and Permian dolomite and large intraformational mudstone clasts (Taylor, 1968). The sandstones are arranged in thick units of cross-bedded sets, each approximately 2 m thick, separated by hierarchical bounding surfaces, with few joints (Aveline, 1861, 1880; Lamplugh *et al.*, 1908; Taylor, 1968). The foresets indicate transport towards the south-east.

North and west of Nottingham the Nottingham Castle Formation consists of unconsolidated mixtures of sand and pebbles (Aveline, 1861, 1880). The formation is unfossiliferous. Bands of argillaceous sediment occur in the formation, for example at Barbers Hill Quarry, near Mansfield (SK 565 538).

Interpretation

The Nottingham Castle Formation was deposited under terrestrial conditions. The coarse-grained sandstones, with scattered pebbles, pebble strings and cross-bedding, indicate deposition in braided rivers and streams, and from sheet floods in a major system of incised channels and alluvial fans feeding eastwards from the Pennine upland area and into the SNSB.

Conclusions

The Lower Triassic sediments in the crags below Nottingham Castle consist of yellow and buff sandstones with pebbles and reworked mud clasts. Many fine examples of cross-bedding are preserved at this locality. This is the type location for the Nottingham Castle Formation, which has been interpreted as the deposits of a major system of alluvial fans. This is a key stratigraphical and sedimentological site near the western margin of the Southern North Sea Basin.

STYRRUP QUARRY, NOTTINGHAMSHIRE (SK 605 902)

Introduction

The quarry exposes a good section of the Nottingham Castle Formation, showing accreted sand bodies transverse to the palaeocurrent direction; both major and minor channel forms are distinguishable. Together with the nearby Scrooby Top Quarry, where exposure is parallel to the channel forms, this site provides an excellent opportunity to study the geometry of the deposits of large-scale rivers flowing off the Pennine Chain to the west, and the characters of the Nottingham Castle Formation.

Accounts of the Nottingham Castle Formation at Styrrup Quarry have been give by Lamplugh *et al.* (1908), Swinnerton (1910, 1914, 1918),

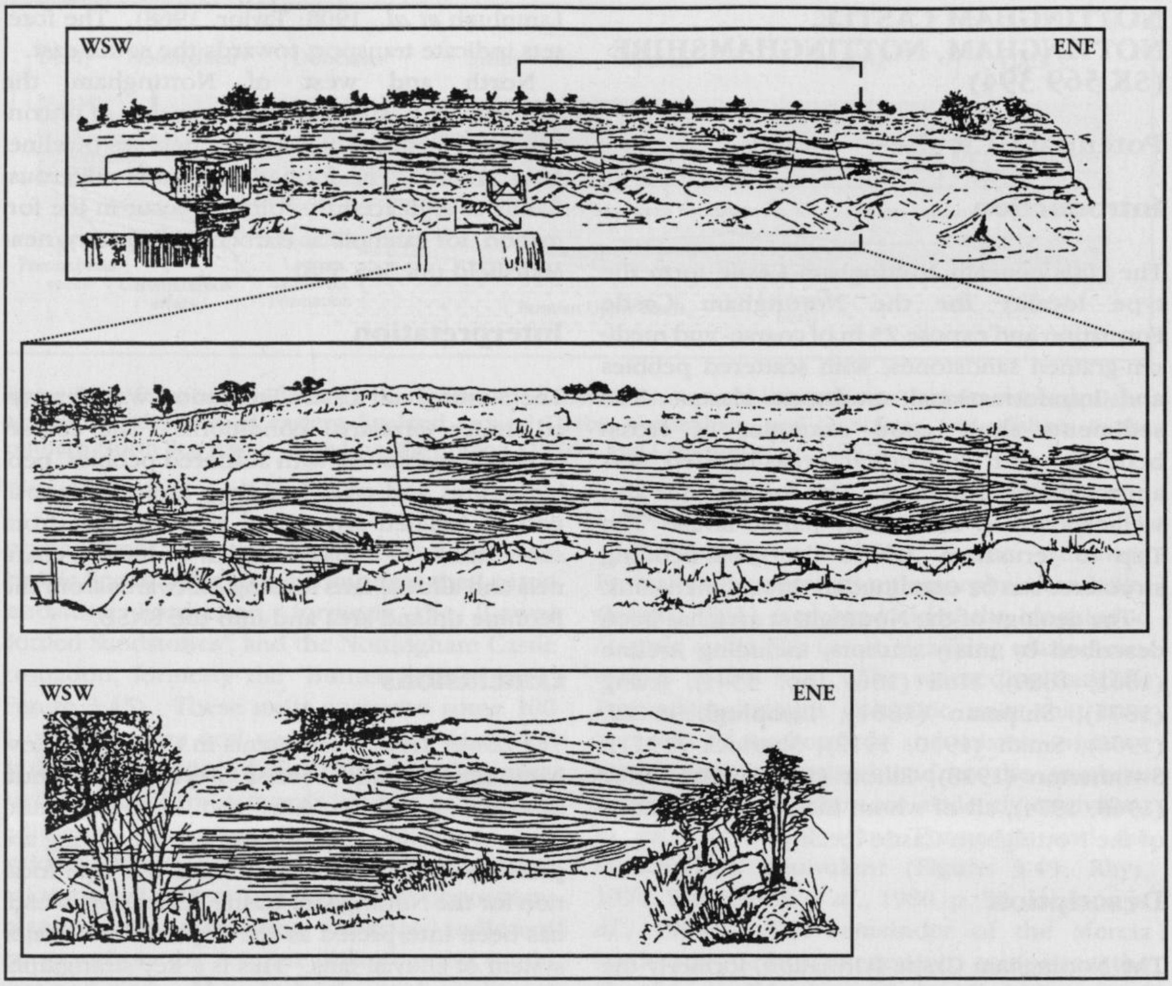


Figure 3.47 Field sketches of the Triassic channel systems in the Nottingham Castle Formation at Styrrup Quarry, viewed roughly transverse to flow. Based on unpublished work by S. D. Burley.

Elliott (1961), Taylor (1968, 1974), and Burley (1984).

Description

Styrrup Quarry displays excellent sections in the Nottingham Castle Formation, showing both large and small channels (Figure 3.47). The commonest sedimentary structure is large-scale planar cross-bedding. The sets have asymptotic bases and a gently curving form over horizontal distances of tens of metres. The sets are usually less than 2 m, but occasionally up to 4 m, in thickness. The sandstones contain horizons of pebbles and mudstone intraclasts aligned along foresets and concentrated on scour surfaces at the base of sets. Palaeocurrent indicators from cross-bed foresets are mainly to the east and north-east. The bounding surfaces between the larger cross-bedded sets have a lenticular form and a hierarchy of such surfaces is recognized.

Trough cross-bedding is rarer, on a smaller scale, and shows a greater spread of palaeocurrent orientations than the planar cross-bed sets. Horizontally laminated sediments, often showing parting lineation, form a minor part of the succession. The larger-scale cross-bed sets and associated smaller-scale structures are separated by sub-horizontal erosion surfaces of greater lateral extent than the foreset packages.

Palaeosols and ventifact horizons are reported from the top of the sequence at Styrrup Quarry (Swinnerton, 1914; Taylor, 1968), but are almost entirely absent lower in the sequence. Well-rounded 'frosted' grains are also present in the sandstones.

Interpretation

The most prominent and laterally persistent bounding surfaces are interpreted as the result of migration of channels. Lower-order surfaces are interpreted as defining laterally and vertically accreted packages of sediment and the form of the second-order channel fills. Palaeocurrent indicators suggest derivation of the sediment from the west and south-west, presumably ultimately from the Pennine upland area to the west, or the London Platform to the south.

Re-activation surfaces and falling-stage modifications of some foresets, together with the lateral extent of foreset packages, indicate an origin by intermittent migration of gently sinuous-crested transverse bars. The relationship between the trough- and planar-cross-bed sets suggests that the former were deposited by the migration of sinuous-crested megaripples in flows deflected by larger transverse bars.

The sandstones of the Nottingham Castle Formation may be interpreted by comparison with modern river systems, such as the Platte River in Nebraska (Blodgett and Stanley, 1980). The large-scale foresets are considered to indicate the presence of large bars (tens of metres wide, tens to hundreds of metres long, and over 2 m in height), which were overtopped and migrated downstream by slip-face progradation at high discharges. At lower discharges, these bars were modified by deposition of horizontal-laminated sands on their top surfaces and by megaripple migration on their margins and in shallow second-order channels.

The well-rounded 'frosted' sand grains found at certain horizons suggest that aeolian deposits were present in the area. Similarly, the widespread occurrence of mudstone intraclasts suggests deposition of muds in overbank, bar top, or high-level channels as depositional energy fell. Together with the widespread occurrence of sub-horizontal erosion surfaces, this evidence suggests that only the lowest part of each depositional cycle has been preserved and may, in turn, help to explain the absence of aeolian deposits from the sequence, since these would have been reworked by each successive phase of channel reoccupation. Thus, the truncated nature of the sequences is probably a reflection of low rates of subsidence relative to the frequency of channel migration.

Conclusions

Styrrup Quarry offers good sections through the river-deposited sandstones of the Nottingham Castle Formation. Major and minor channel bedforms are seen, most of them cut transverse to the dominant north-easterly flow direction. These illustrate classic coarse-grained fluviatile sedimentary features of a major channel system running out into alluvial fans off the eastern margin of the Pennine Upland. This is a key sedimentological and stratigraphical site near the western margin of the Southern North Sea Basin.

SCROOBY TOP QUARRY, NOTTINGHAMSHIRE (SK 652 890)

Introduction

Scrooby Top Quarry is a working quarry with exposures of the Nottingham Castle Formation parallel to river channel direction. Medium to coarse pebbly sandstones show cross-bedding characteristic of transverse burial bars. Large-scale foresets show very low inclinations, and these represent complex accretionary bar forms. Sediment transport was to the north. Together with the exposures at the nearby Styrrup Quarry (see above), it affords a three-dimensional insight into the deposits of large rivers of Early Triassic age.

Scrooby Top Quarry has not been described in detail in the literature, but much of the geology and features of the Nottingham Castle Formation are comparable with those seen in Styrrup Quarry (see site report, above).

Description

Sections in this working quarry are some 20 m high, and over 100 m in lateral extent (Figure 3.48). Cross-stratified sets are typically 1–2 m thick, indicate transport towards the north-east and are separated by sub-horizontal erosion surfaces. In places, as the faces are worked, excellent sections showing the lateral transition from foreset bedding to horizontal bedding are revealed (Figure 3.48). Six cross-bedded sets have been identified (Figure 3.48), each representing a bar that migrated parallel to the

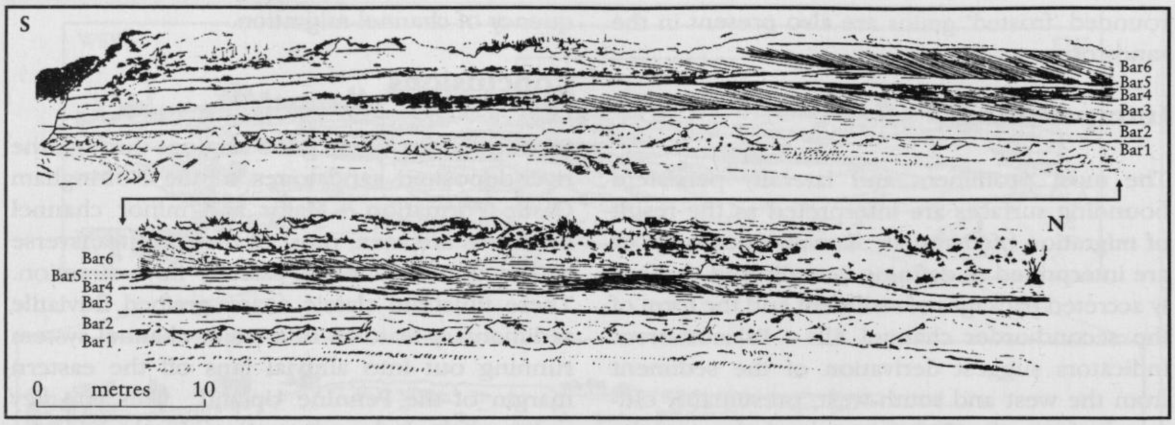


Figure 3.48 Field sketches of the Triassic channel systems in the Nottingham Castle Formation at Scrooby Top Quarry. Major erosional bounding surfaces are shown in bold, and six successive bar systems are distinguished. Based on unpublished work by S. D. Burley.

section face. Successive bar deposits are separated by sub-horizontal erosional bounding surfaces. Deposits of bars 1 and 2, at the base of the succession, are characterized by low-angle cross-bedding; those of bars 3, 4, and 6 are dominated by tabular cross-bedding. The bar 5 deposits are thinner than the others and were substantially cut out by erosion prior to deposition of bar 6; they are exposed more obliquely to the palaeoflow direction and exhibit flat bedding and low-angle cross-bedding.

The medium- to coarse-grained sandstones contain abundant extra-formational pebbles up to 20 mm in diameter, and larger intra-formational mudstone clasts. The pebbles occur as basal lags, but are aligned parallel to the cross-bedding foresets and concentrated in small scour pockets.

Interpretation

The Scrooby Top Quarry sections expose deposits of up to six successive major transverse bars that migrated north-eastwards. Each bar unit overlies a sub-horizontal erosional surface, and its top is truncated by that below the subsequent bar. Extraformational pebbles suggest derivation from the uplifted Palaeozoic uplands of the Pennine region, and intra-formational clasts (mudstone flakes) hint at the tops of bars or at overbank (vertical accretion) deposits that have been eroded away. The nature of the rivers, the depositional cycles, and the missing low-energy portions of those cycles, are discussed in the Styrrup Quarry GCR account (see above).

Conclusions

Scrooby Top Quarry offers good sections in the Nottingham Castle Formation, showing all the features seen at its type locality at Nottingham Castle (SK 569 394), but in fresher and more accessible exposure. The principal distinction is that the sections are parallel to the direction of flow compared to those at Styrrup Quarry, which are transverse to the flow direction. As a working quarry, Scrooby Top Quarry offers the best opportunity to see fresh sections through the Nottingham Castle Formation and is a key site for understanding Triassic river system dynamics and the palaeogeography of eastern England and the margin of the Southern North Sea Basin.

COLWICK RAILWAY SECTION, NOTTINGHAMSHIRE (SK 603 398)

Introduction

This site shows the Sherwood Sandstone–Mercia Mudstone group boundary with the Sneinton Formation, a unit of mudstones, siltstones, and thin sandstones arranged in fining-upwards units, resting unconformably on the Nottingham Castle Formation. Sedimentary structures present include ripple marks, wavy bedding, pseudomorphs after halite, and abundant desiccation cracks and suggest a marine intertidal depositional environment. The age of the formation is probably Anisian, and it correlates with other former 'Waterstones' units across Central

England. The locality illustrates aspects of the initial Mercia Mudstone Group sedimentation in eastern England.

Key references on the Sneinton Formation include Irving (1874), Lamplugh *et al.* (1908), Smith (1910, 1912), Swinnerton (1918), Elliott (1961), Smith and Warrington (1971), Charsley (1989), and Lowe *et al.* (1990).

Description

This site is a cliff alongside a working railway, and access is restricted. The western end of the cliff lies a few metres from the tracks, but the central section is close to the tracks; the eastern end of the section is lower than the rest.

The Colwick railway section is close to the type locality for the 'Colwick Formation' (a quarry at SK 601 397; Warrington *et al.*, 1980), formerly termed the 'Waterstones' (Elliott, 1961). The 'Colwick Formation' overlies the former 'Woodthorpe Formation' in much of Nottinghamshire. As a result of the British Geological Survey Nottingham project, these former formations have been combined as the 'Sneinton Formation', of which Colwick is the type location (Charsley *et al.*, 1990).

In the railway section some 23 m of the Sneinton Formation are exposed, overlying the Nottingham Castle Formation. The beds generally dip 30° to the ESE. Charsley (1989) gives a detailed section, reproduced in Lowe *et al.* (1990), which is summarized here:

	Thickness (m)
Sneinton Formation	
Sandstone units, yellow-brown and yellow, very fine-grained, with subordinate, red-brown, silty mudstones	2.76
Succession of yellow, fine-grained sandstone units, each 0.2–1.1 m thick, ripple marks in the lowest sandstone unit	*c.* 6.70
Gap	*c.* 2.45
Sandstone– mudstone couplet, resting on an erosion surface and grading up from a pale orange, fine- to medium-grained sandstone, with dominantly rounded grains, red-brown mud flakes, through a very fine-grained, pale yellow to red-brown sandstone interbedded with red-brown mudstone, and terminating in a dark red-brown silty mudstone	*c.* 3.00
Mudstone, red-brown and grey-green, silty, with subordinate green-yellow sandstone and siltstone laminae	4.10
Sandstone, yellow, very fine-grained, with red-brown mudstone partings, and, at the base, subangular to sub-rounded pebbles and overlying an erosion surface in places	1.24
Nottingham Castle Formation	
Sandstone, pale yellow and pale red-brown, fine- to medium-grained, with rare pebbles	2.45

Elliott (1961) reported a range of sedimentary structures in the Sneinton Formation in the Colwick railway section and neighbouring locations; these include parallel bedding planes, ripple-marks in micaceous fine-grained sandstones and siltstones, mudcracks, and pseudomorphs after halite. Fossils from the Colwick area include remains of fishes, vertebrate tracks, and a cast of a possible *Equisetites* (horsetail) stem from Colwick Wood (although the latter may be an artefact, Elliott, 1961, p. 216). In some locations, the Sneinton Formation sediments are dolomitized and contain gypsum.

Interpretation

The Sneinton Formation sediments indicate intertidal conditions, with terrestrial input, but with strong indications of marine influence (pseudomorphs after halite and, farther north, (Rose and Kent, 1955) the brachiopod *Lingula*). The dolomitization and the occurrence of gypsum confirm marine influence, and provide important links eastwards to the Dowsing Formation, a lateral equivalent of the German Muschelkalk in the SNSB (Rhys, 1974; Figure 3.45).

The Sneinton Formation is dated as Anisian on the basis of palynological evidence from surrounding areas, and from cross-country correlations using geophysical marker horizons (Warrington *et al.*, 1980). The unit had long been treated as part of the 'Lower Keuper Sandstones', and was formerly equated with the German Upper Triassic succession, although

Irving (1874, p. 317) was remarkably prescient when he noted, with respect to the 'Waterstones' at Colwick and around Nottingham: 'May not these be homotaxial with part of the Muschelkalk?'.

Conclusions

The Colwick railway section provides a good exposure in the lowest formation of the Mercia Mudstone Group in the Nottingham area and shows its contact with the Sherwood Sandstone Group. Colwick is the type location for the Sneinton Formation, a unit of fine-grained sandstones and mudstones, that was deposited in intertidal, marginal marine environments. The site is important for an understanding of part of the stratigraphy of the western part of the Southern North Sea Basin, and the palaeogeography of the region.

THE TRIASSIC RED BEDS OF THE CENTRAL MIDLANDS

INTRODUCTION

Triassic rocks crop out extensively in the central English Midlands and thick successions accumulated in a number of deep basins. The Triassic strata generally rest unconformably on Carboniferous or Permian sediments. Rapid subsidence in fault-bounded basins in the north and north-west of the region led to the accumulation of thick sequences, while the southern and south-eastern areas, close to the London Platform, were more stable, and successions are thinner (Warrington *et al.*, 1980, pp. 35–7). The sequence of formations comprising the Sherwood Sandstone and the Mercia Mudstone groups represents the upward transition from continental fluvial to deltaic and littoral marine

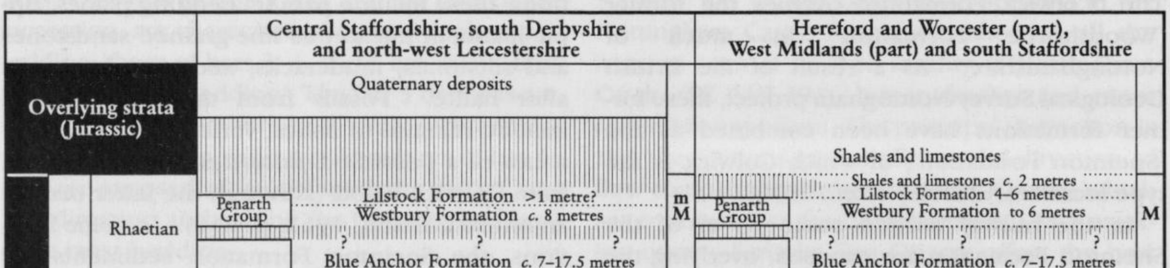


Figure 3.49 Stratigraphical columns for the Triassic successions of the northern and southern Central Midlands regions of England. M, macrofossils; m, microfossils. (After Warrington *et al.*, 1980, Charsley *et al.*, 1990 and Barclay *et al.*, 1997.)

deposits in the former, and to playa and hypersaline epeiric sea environments in the latter (Wills, 1910, 1935, 1970a; Warrington, 1970a; Warrington and Ivimey-Cook, 1992).

As elsewhere, the Permo–Triassic boundary cannot be located objectively in the Central Midlands area. The lowest presumed Triassic units (Figure 3.49), resting unconformably on presumed Permian clastic sediments, are the conglomeratic lower member of the Cannock Chase Formation in Staffordshire and the Kidderminster Formation in the West Midlands and in Hereford and Worcester. These units, both formerly called the 'Bunter Pebble Beds', are present only in the western and northern parts of the district. They contain two types of rudaceous sediment, either separately or intermixed:

1. Breccias with clasts of fairly local origin, found in the western parts of the outcrop area, and interpreted as gravel fans at the mouths of wadis that discharged from mountainous areas bordering the basins;
2. Conglomerates with large, well-rounded pebbles transported a long distance (perhaps from southern England or the Armorican Massif of northern France) by powerful river systems (Wills, 1935, 1948; Campbell Smith, 1963).

The latter facies shares characters with the Budleigh Salterton Pebble Beds of Devon, with which the Midlands units may correlate. The pebbly conglomeratic facies occurs mainly in the lower parts of these units, and diminishes upwards. Study of palaeocurrents in the pebbly facies throughout the Central Midlands region and the Cheshire Basin allowed Wills (1948) to reconstruct the patterns of a number of major river systems in the Lower Triassic Series (Figure 3.50). The link to Devon and northern France is confirmed by detailed study of the provenance of the included clasts (Campbell Smith, 1963).

The disappearance of rounded extraclasts marks the poorly defined, and probably diachronous, base of the Wildmoor Sandstone Formation (Figure 3.49), formerly the 'Bunter Upper Mottled Sandstone', and equivalent perhaps to the upper member of the Cannock Chase Formation. Fossils occur sporadically in the Kidderminster and Wildmoor Sandstone formations: invertebrate trace fossils (Wills, 1970b), a perleidid fish (White, 1950), and the crustacean *Euestheria*, none of which provides evidence for age, although these fossils do not contradict the assumed Early Triassic age assigned to these units (Warrington *et al.*, 1980, p. 38).

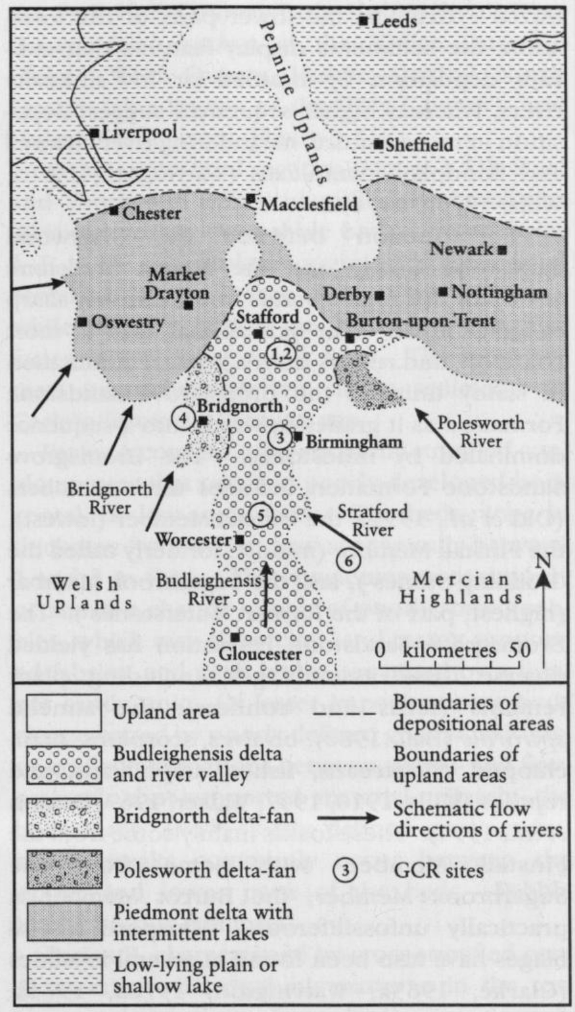


Figure 3.50 Early Triassic palaeogeography of Central England, showing postulated major river systems, based on palaeocurrent measurements and studies of clast provenance. 1, Hulme Quarry; 2. Brockton Quarry; 3, Wollaston Ridge; 4, Claverley Road Cutting; 5, Burcot; 6, Shrewley. (After Wills, 1948.)

A further sandstone unit, termed the 'Bromsgrove Sandstone Formation', formerly the 'Keuper Sandstone', rests unconformably on these formations south of Birmingham (Figure 3.49). This unit is marked by the reappearance of breccias and conglomerates in its lower half, and the incoming of fresh perthite feldspar suggests a renewal of tectonic activity and a rejuvenation of river systems. The Bromsgrove Sandstone Formation displays fining-upwards fluvial cycles. In the lower parts of the formation, the sediments display features that indicate deposition by braided or low-sinuosity rivers, whereas higher sequences suggest deposition in more mature, meandering river channel and floodplain complexes (Warrington, 1970a; Wills, 1970a, 1976).

The junction between the Sherwood Sandstone Group and the Mercia Mudstone Group in this region varies from relatively sharp to gradational. The gradational case is most common, and results from a gradual elimination of sandy units in the Bromsgrove Sandstone Formation as it grades upwards into a sequence dominated by mudstones. The Bromsgrove Sandstone Formation includes three members (Old *et al.*, 1991): the Burcot Member (lowest), the Finstall Member (middle: formerly called the 'Building Stones'), and the Sugarbrook Member (highest; part of the former 'Waterstones'). The Bromsgrove Sandstone Formation has yielded diverse fossil assemblages, including plant remains (ferns and conifers), the annelid *Spirorbis* (Ball, 1980), bivalves, scorpions, branchiopod crustaceans, fishes, amphibians, and reptiles (Wills, 1910, 1947; Walker, 1969; Benton *et al.*, 1994). These fossils mainly come from the Finstall Member, with some from the Sugarbrook Member; the Burcot Member is practically unfossiliferous. Miospore assemblages have also been found at several localities (Clarke, 1965a; Warrington, 1970a, 1974a; Warrington *et al.*, 1980), and these indicate an Anisian age for the Bromsgrove Sandstone Formation. Earlier studies of the tetrapods led to suggestions of a Ladinian age, but an Anisian age is now preferred (Benton *et al.*, 1994).

The Mercia Mudstone Group in the northern and eastern parts of this region has been revised stratigraphically by correlation with Elliott's (1961) divisions of the Nottinghamshire region, as revised by Charsley *et al.* (1990). In western and southern parts of the region, an alternative stratigraphy has been established (Figure 3.49; Old *et al.*, 1987; Worssam and Old, 1988; Barclay *et al.*, 1997; Powell *et al.*, 2000). Lower parts of the mudstone succession include some sulphates and, locally, halite, while the upper parts lack halite, but include locally important sulphate deposits. These two sequences are separated by a distinctive and widespread unit, the Arden Sandstone Formation, of Carnian age, present in Worcestershire, Warwickshire, and Gloucestershire, and which correlates with comparable lithostratigraphical units of that age in Leicestershire, the Bristol region, Somerset, and Devon (Warrington *et al.*, 1980). The Blue Anchor Formation, at the top of the Mercia Mudstone Group, is recognizable throughout the region, lying below the Penarth Group, which is succeeded by the Lias.

Six GCR sites have been selected to represent the Triassic rocks of the Central Midlands area: Hulme Quarry and Brocton Quarry in the Stafford Basin to illustrate different sedimentological aspects of the Cannock Chase Formation; Wollaston Ridge to show the Kidderminster Formation; Claverley Road Cutting to show the Wildmoor Sandstone Formation; Burcot to show the Wildmoor Sandstone and the Bromsgrove Sandstone formations; and Shrewley to show the Mercia Mudstone Group mudstones and the Arden Sandstone Formation.

HULME QUARRY, CANNOCK CHASE, STAFFORDSHIRE (SJ 928 445)

Introduction

The 'Hulme Quarry' GCR site exposes the Cannock Chase Formation of the Sherwood Sandstone Group resting unconformably upon Carboniferous or Permian rocks. The formation comprises texturally mature pebble/cobble conglomerates, arranged in poorly sorted horizontal sheets or better-sorted cross-bedded sets. Thick sheets of conglomerate are associated with interbedded sandstones, in coarsening-upwards units. Rapid lateral facies changes from conglomerate to sandstone are also seen. Comparison with recent fluvial sediments indicates that the Cannock Chase Formation was deposited in a substantial braided stream system carrying coarse-grained material from uplands to the south and south-west. This is, therefore, an important site for the study of Early Triassic palaeoenvironments and palaeogeography.

The unconformity underlying the Cannock Chase Formation in the quarries near Hulme was briefly described by Gibson (1905). The sedimentology of the formation was described by Hull (1869, pp. 50–1), Stevenson and Mitchell (1955), Steel and Thompson (1983), and Rees and Wilson (1998, pp. 77–9, 82).

Description

Four substantial exposures are located within

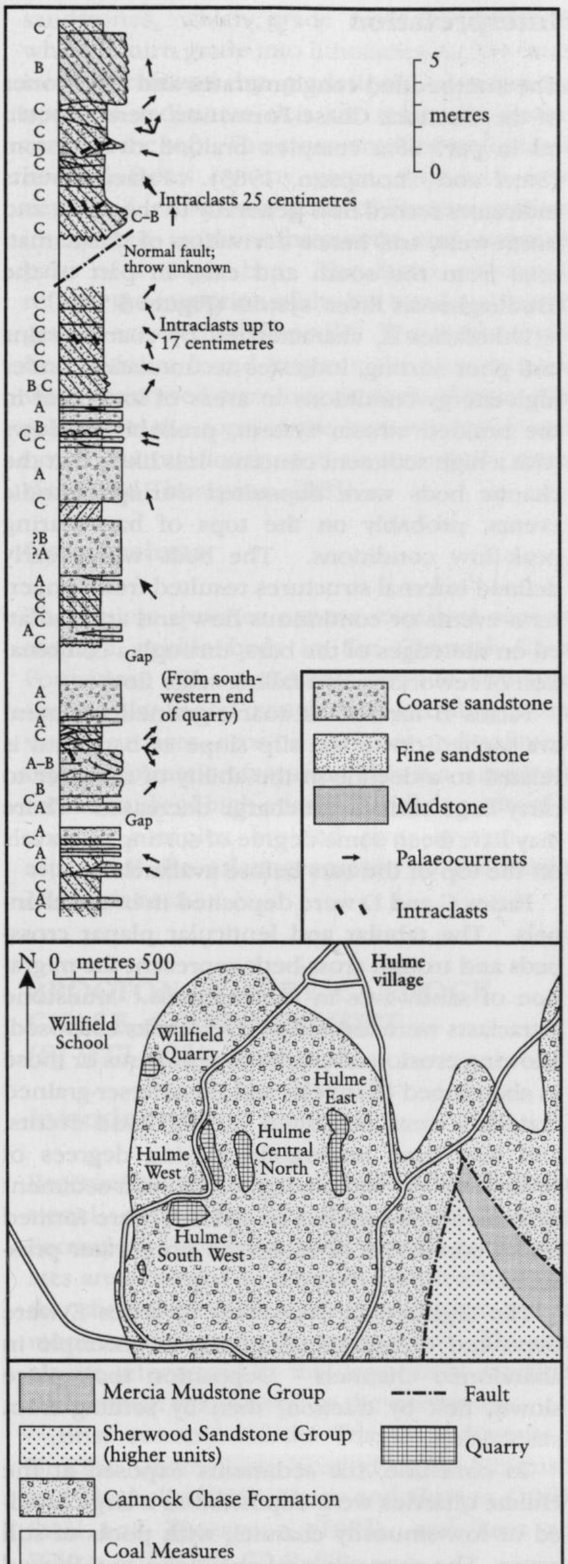


Figure 3.51 Sedimentary log recorded in the Hulme quarries, showing the five lithofacies in the succession of the Cannock Chase Formation. (After Steel and Thompson, 1983.)

the Park Hall Country Park: Hulme South West Quarry (also known as the 'Gulch Quarry'), Hulme West Quarry, Hulme Central North Quarry (also known as the 'Play Canyon'), and Hulme East Quarry (Figure 3.51).

In their measured sections (Figure 3.51), Steel and Thompson (1983) identified five lithofacies divisions within the pebble beds, termed facies A–E. In the Hulme quarries lithofacies C accounts for more than 50% of the exposure, while facies A and B are less important, and facies D and E are rarely seen. The sequence rests unconformably on clastic sediments of Carboniferous to Permian age.

Facies A consists of horizontally stratified conglomerates that occur in poorly developed horizontal, or low-angle, beds. The beds range in thickness from 1–5 m, and are typically between 1 and 3 m thick. The conglomerate commonly occurs as a chaotic jumble of poorly sorted pebbles, which may show clast- and matrix-supported fabrics, and each bed is separated by a thinner sandy unit. Of lesser importance are beds characterized by poorly defined graded bedding, or graded alternations between coarse- and fine-grained, clast-supported material. Rarely, the beds rarely show clearly defined grading, but sharp breaks commonly occur between the upper and lower parts of the beds. Pebble imbrication is common.

Facies B, characterized by cross-stratified conglomerates with rhythmic patterns in the textures and structures, forms beds approximately 2 to 5 m thick. These units generally occur as composite sequences that may be interbedded with sandstones. The facies B conglomerates display well-developed planar cross-bedded and trough cross-bedded units. The planar cross-beds range from less than 1 m to more than 4 m thick. The thicker units may extend laterally for more than 100 m. The trough cross-bedded sediments are not as common as the planar cross-beds, and are associated with scour structures. The foresets of facies B consist of a conglomerate of small pebbles, which is clast supported, and grades up from the coarser-grained material or infills erosional scours, generally in the upper parts of the foresets. In places, the conglomerate is coarser grained and matrix-supported, and in this situation, the lower boundaries are generally sharp and clearly defined, but may be gradational. Some of these conglomerates pass laterally into siltstones and silty sandstones.

Facies C is typified by cross-bedded, medium-grained sandstones, with varying amounts of pebbles. The sheet-like sand bodies are well exposed in the middle of the eastern wall in Hulme Central North Quarry. The cosets are between 2 and 5 m thick; some represent broad channel fillings and overlie erosion surfaces. Sedimentary structures include tabular and lenticular planar cross-beds, up to 1.5 m thick. Some of the trough cross-beds may be interbedded with pebble lag deposits and troughs infilled with gravel. Re-activation and erosion surfaces are common, and are often associated with coarse-grained lags. Large angular fragments of argillaceous sediment (facies E) are present in the bases of some of the sets. These clasts may show imbrication or penetrate into the underlying beds. Single sheets (2 to 5 m thick) of trough cross-bedded argillaceous sediment, thin lenses of pebbly sandstone with sharp bases and erosional upper surfaces, and thick wedges of cross-bedded pebbly sandstone are common throughout this facies.

Facies D consists of argillaceous and fine-grained, cross-bedded sandstones, some with slump structures. These sediments occur as thick and thin sandstone sheets, and laterally wedging units often associated with conglomerates. The thick sheet sandstones are characterized by trough and planar cross-bedding, and the foresets are often marked by yellow and green streaks. Soft-sediment deformation structures are common. The thin sheet sandstones consist of lenticular planar sets up to 0.75 m thick, and contain gravel lenses and stringers. The thick wedges are best seen at the base of large cross-bedded sets in Central North Hulme Quarry.

Facies E is dominated by fine-grained, parallel-bedded sandstones, with interbedded red micaceous shales and argillaceous silty-sandstones. The beds of this facies are typically laterally impersistent, reach a maximum thickness of 1 m, and are interbedded with facies C and D, or occur as drapes in the gravel troughs and bottom sets of facies B.

The pebble types do not vary between lithofacies; they consist of quartzite, with smaller proportions of vein quartz, and minor amounts of sandstone, chert, rhyolite, agate, and rhyolitic tuff. Occasional reworked ventifacts have been identified (Thompson, 1970a; Steel and Thompson, 1983).

Interpretation

The interbedded conglomerates and sandstones of the Cannock Chase Formation were deposited in part of a complex braided river system (Steel and Thompson, 1983). Palaeocurrents indicators record flow generally to the north and north-west, and hence derivation of clastic material from the south and east, in part of the 'Budleighensis River' system (Figure 3.50).

Lithofacies A, characterized by coarse grains and poor sorting, indicates accumulation under high-energy conditions in areas of low relief in the braided stream system, probably in flows with a high sediment content. It is likely that the chaotic beds were deposited during episodic events, probably on the tops of bars during peak-flow conditions. The beds with clearly defined internal structures resulted from longer-term events or continuous flow and accumulated on the edges of the bars, through a combination of reworking and falling-stage flow.

Facies B formed as coarse-grained sediment avalanched down the slip slope of bars, and is related to a decline in the ability of the river to carry large clasts as discharge decreased. There may have been some degree of sorting of gravels on the top of the bars before avalanching.

Facies C and D were deposited in broad channels. The tabular and lenticular planar cross-beds and trough cross-beds represent the migration of sandwaves in the channels. Mudstone intraclasts were formed as river banks collapsed, allowing erosion of overbank sediments or those in abandoned channels, and the coarser-grained materials were deposited during flood events, and may have undergone varying degrees of reworking or winnowing. The soft-sediment deformation structures of facies D were formed under conditions of increased pore-water pressures.

The argillaceous sediments of facies E were deposited in ephemeral pools, for example in abandoned channels. Deposition took place slowly, first by traction, then by settling from suspension.

To conclude, the sediments exposed at the Hulme quarries were deposited in a large braided or low-sinuosity channel, with pools of still water. The river was probably deep, and flowed continuously, but with varying discharge rates. Two common sequences have been identified; the first is the multi-storey, generally coarsening-up, lithofacies A; the second consists of thin sandstones, which grade into lithofacies B, which in turn grade into lithofacies A. The latter is characterized by gradational, coarsening-upwards sediments that are texturally mature towards the top. The cross-stratified and planar-bedded facies in any given sequence were deposited in the same reach of the river, and are interpreted as the subaqueous and emergent parts of a single bar. The facies association reflects the migration of the bar head and bar tail gravels across the bar pools. The better-organized beds are found lower in the sequence and were winnowed over long periods of time. The gravels on the tops of the bars were only winnowed during floods, and so are poorly sorted (Steel and Thompson, 1983).

Conclusions

The Hulme quarries expose excellent sections through pebble beds in the Cannock Chase Formation. The sediments include structures such as planar and trough cross-bedding, re-activation surfaces, erosion surfaces and soft sediment deformation features. This is a superb site for the study of high-energy fluvial deposits of an ancient complex braided river system, and aspects of the palaeogeography of the Central Midlands area.

BROCTON QUARRY, CANNOCK CHASE, STAFFORDSHIRE (SJ 977 191)

Introduction

Brocton Quarry provides excellent three-dimensional exposures of the Cannock Chase Formation. These texturally mature conglomerates are arranged in laterally continuous sheets that show large-scale cross-stratification, but are more usually internally structureless. The gravels are interpreted as the deposits of a braided river system that flowed to the north-east.

Brief accounts of the Triassic sediments in Brocton Quarry have been given by Stevenson and Mitchell (1955), Hains and Horton (1969), Steel and Thompson (1983), and Rees and Wilson (1998, pp. 77–9, 82).

Description

Brocton Quarry, a disused gravel and sand pit, is located in the north-western corner of Cannock Chase. The quarry has two main faces, which are at right angles to each other, and provide a three-dimensional exposure of the sediments and sedimentary structures. The face trending north-west to south-east is approximately 250 m long and reaches a maximum height of 30 m. The other face is some 100 m long and 10 m high. The faces are vertical towards the top and have talus slopes, planted with trees, at the base.

The sediments at Brocton Quarry are dominated by conglomerates, with subordinate sandstones and mudstones (Figure 3.52), and are similar to those in the Hulme quarries (see GCR site report, above). The lithologies seen at Brocton have been classified into lithofacies by

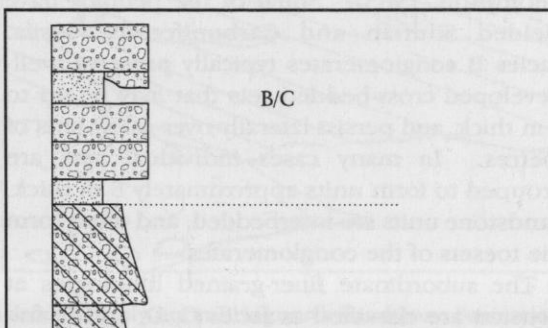


Figure 3.52 Sedimentary log recorded at Brocton Quarry, showing the lithofacies A, B, C and E in the Cannock Chase Formation, as defined by Steel and Thompson (1983).

Steel and Thompson (1983).

The conglomerates at Brocton Quarry are texturally mature. They form large, laterally continuous sheets, which at the base of the section have little internal structure. However, farther up the succession, well-developed cross-stratification is visible. Two lithofacies are recognized. Facies A is a clast- or matrix-supported conglomerate characterized by horizontal stratification. Clasts generally range in size from 50 to 100 mm, although larger cobbles with a diameter of around 200 mm are present. The surfaces of the clasts are often pitted, and have siliceous rims at contact points. Imbrication of the elongate clasts is common. Clasts in lithofacies A consist of quartzites, vein quartz, sandstones, cherts, rhyolites, agates, and rhyolitic tuffs (Steel and Thompson, 1983). Some of the pebbles have yielded Silurian and Carboniferous fossils. Facies B conglomerates typically preserve well-developed cross-bedded sets that may be up to 2 m thick, and persist laterally over many tens of metres. In many cases individual sets are grouped to form units approximately 8 m thick. Sandstone units are interbedded, and often form the toesets of the conglomerates.

The subordinate finer-grained lithologies at Brocton are classified as facies C, D, and E, following the scheme of Steel and Thompson (1983). These include thin sheet sandstones (Facies C) that are often associated with the rudaceous units. The lower surfaces of these sandstones are sharp and the upper surfaces commonly show evidence of erosion; internal structures include tabular cross-bedding. Fine-grained silty or clayey sandstones (Facies D) occur as thin sheets associated with the conglomerates. Facies E consists of 1-m-thick units of interbedded red micaceous shale, clayey siltstone, and very fine-grained sandstone. Pebble-filled gutter casts are known from this lithofacies, and the crustacean *Euestheria* cf. *minuta* has been noted in the mudstones.

Palaeocurrent measurements from the small tabular cross-beds of Facies C indicate flow directions predominantly towards the north, as in the Hulme quarries (see GCR site report for 'Hulme Quarry', this volume).

Interpretation

The sediments of the Cannock Chase Formation in Brocton Quarry represent deposition under predominantly fluvial conditions in the major northwards-flowing 'Budleighensis River' system (Figure 3.50).

Lithofacies A reflects deposition in a high-energy regime, with high levels of sediment input, probably in a braided river system. The cross-bedded units of facies B are characteristic of the accumulation of sediments on river bars.

The finer-grained components of the sedimentary sequence reflect lower-energy conditions. The sandstones of lithofacies C and D were deposited during low flow conditions, or perhaps in the sheltered lee of large bedforms. The finest sediments (facies E) were deposited from suspension in quiet pools and abandoned channels.

Conclusions

The faces in Brocton Quarry display the Cannock Chase Formation sediments in three dimensions. The sediments, including conglomerates, sandstones, and silty-mudstones, represent deposition in a complex braided river system that brought sediment from upland areas farther south. Brocton Quarry is complementary to the Hulme quarries in that it provides excellent three-dimensional exposures of the sandy and conglomeratic bedforms, essential for adequate sedimentological study and the interpretation of palaeoenvironments and aspects of Early Triassic palaeogeography.

WOLLASTON RIDGE QUARRY, STAFFORDSHIRE (SO 883 848)

Introduction

Wollaston Ridge is a topographical feature that reflects the presence of the Kidderminster Formation, the local representative of the former 'Bunter Pebble Beds', resting unconformably on the Permian Bridgnorth Sandstone. The locality (known as 'Wollaston Quarry' in the GCR unit records) shows the unconformity and also the contrasting aeolian and fluvial sedimentary characteristics of the Bridgnorth Sandstone and Kidderminster formations respectively. An important feature is the occurrence of eroded, cemented clasts of Bridgnorth Sandstone within the Kidderminster Formation. This site gives important evidence on the Early Triassic landscape and sedimentation.

Although exposure at Wollaston Ridge Quarry was excellent, the site has rarely been

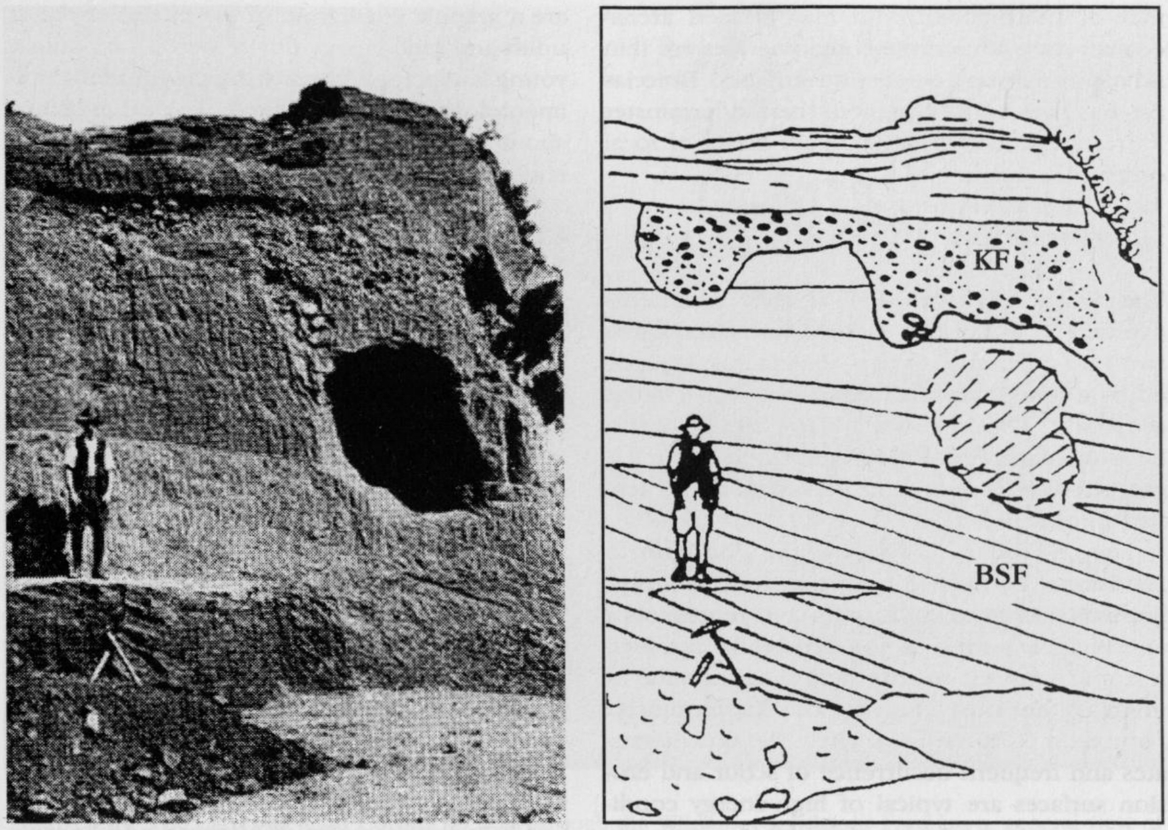


Figure 3.53 The Kidderminster Formation (KF) resting unconformably upon Bridgnorth Sandstone Formation (BSF) in Wollaston Ridge Quarry; (a) as seen in the 1930s, (b) an interpretive sketch. (After Whitehead and Pocock, 1947.)

mentioned in the literature. Brief descriptions were given by Whitehead and Pocock (1947, p. 111), Wills (1948) and Shotton (1956).

Description

Wollaston Ridge Quarry is situated in the garden of a private residence, 'Sand Ridge'. Although formerly well exposed, at the time of writing much of the quarry face was covered by ivy that obscured the unconformity between the Bridgnorth Sandstone and the Kidderminster Formation. The faces of the quarry are vertical and reach a height of approximately 8 m. In earlier times, without the obscuring vegetation, the unconformity was clearly seen (Figure 3.53).

The lower part of the sequence exposed in Wollaston Ridge Quarry comprises some 8 m of the Bridgnorth Sandstone (Permian). These sediments consist predominantly of reddish, fine- to medium-grained sandstones. Excellent examples of large-scale dune trough cross-bedding, and dunes climbing the backs of other dunes are to be seen.

The boundary between the Bridgnorth Sandstone and the overlying Kidderminster Formation is marked by an irregular, well-defined unconformity, best seen at the southern end of the exposure. The surface of the unconformity is an erosion surface with steep-sided gullies, indicating that the Bridgnorth Sandstone had been lithified prior to erosion and the deposition of the Kidderminster Formation.

The Kidderminster Formation is a conglomerate facies that contains clasts of the Bridgnorth Sandstone, as well as quartz, quartzite, haematite-rich mudstones, Silurian limestones (Wills, 1948), and calcareous sandstones. Clasts range up to cobble size, some 200 mm across. A calcareous sandstone pebble, presumably derived with minimal abrasion directly from the Bridgnorth Sandstone, was found (Shotton, 1956) to consist of quartz and feldspar, with the high degree of rounding and sorting, and red coloration typical of desert sediments. The conglomerates are stratified horizontally, and may be interbedded with finer-grained arenaceous rocks. Within the conglomerates are thin sandstones resting on erosion surfaces. Breccias are also common throughout the Kidderminster Formation and typically contain clasts of local origin.

Interpretation

The Lower Permian and Triassic sediments exposed in Wollaston Ridge Quarry represent two very different palaeoenvironments, separated by a time interval of unknown, but lengthy, duration. The large-scale dune trough cross-bedding of the Permian Bridgnorth Sandstone is characteristic of sediments deposited under aeolian conditions.

The boundary between the Bridgnorth Sandstone Formation and the Kidderminster Formation is an unconformity, and represents a considerable period of non-deposition and high levels of erosion, corresponding to the time of uplift of the Welsh massif. The Kidderminster Formation is fluvial in origin. The conglomerates and frequent occurrence of scour and erosion surfaces are typical of high-energy conditions. Detailed analysis of lithofacies indicates that these sediments are characteristic of two palaeoenvironments. The breccias were sourced from the local area and have been interpreted as fan gravels deposited at the mouths of wadis. The associated conglomerates are composed of material with a southerly provenance, in the Armorican Massif (northern France) or southern England. These sediments were transported northwards in a large braided river system (see Figure 3.50).

The age of the Kidderminster Formation cannot be established directly, but, like the corresponding Cannock Chase Formation, and equivalent pebble-rich units elsewhere in the Midlands, it is generally considered to be earliest Triassic (Warrington *et al.*, 1980, p. 38).

Conclusions

Wollaston Ridge Quarry exposes an important suite of sedimentary rocks. The Permian Bridgnorth Sandstone and the overlying Triassic Kidderminster Formation represent a change in palaeoenvironments from continental aeolian to fluvial. The unconformable contact, and the reworking of Bridgnorth Sandstone into the conglomerates of the Kidderminster Formation, are a graphic illustration of the effects of major uplift and high-energy fluvial systems eroding a young landscape. The site offers important sedimentological and palaeogeographical evidence about the Early Triassic Epoch in the English Midlands.

CLAVERLEY ROAD CUTTING, SHROPSHIRE (SO 794 940)

Introduction

Claverley Road Cutting exposes an excellent section through the Lower Triassic Wildmoor Sandstone Formation. The formation consists predominantly of sandstones, which preserve a wide range of sedimentary structures, such as flat bedding, and planar-tabular and trough cross-bedding. It is thought that this sequence was deposited in rivers, although there is some evidence for aeolian processes. The site is important for the study of Lower Triassic stratigraphy and for the analysis of palaeoenvironments.

Although this site is of great regional and national importance, it is only mentioned very briefly in the literature (Whitehead and Pocock, 1947). The sedimentary characteristics of the Wildmoor Sandstone Formation have been documented in detail by Wills (1970a,b, 1976).

Description

The site consists of a steep-sided road cutting, up to 3 m high and about 150 m in length, located south-west of Woodfield House, north of the village of Claverley.

The section shows a thick sequence of bright red, fine-grained sandstones of the Wildmoor Sandstone Formation, formerly termed the 'Upper Mottled Sandstone'. Towards the base of this unit the sediment contains many spots and streaks of green sandstone (Whitehead and Pocock, 1947). Sedimentary structures are well preserved, particularly towards the top of the section, and include planar bedding and trough cross-bedding (Figure 3.54). Palaeocurrent indicators, including the cross-beds, indicate flow to the north-west.

A borehole sunk near Claverley has sampled rocks with a range of ages, including the Permian Clent Breccia (Whitehead and Pocock, 1947). The Permo–Triassic sediments in the borehole section consisted of red marls and

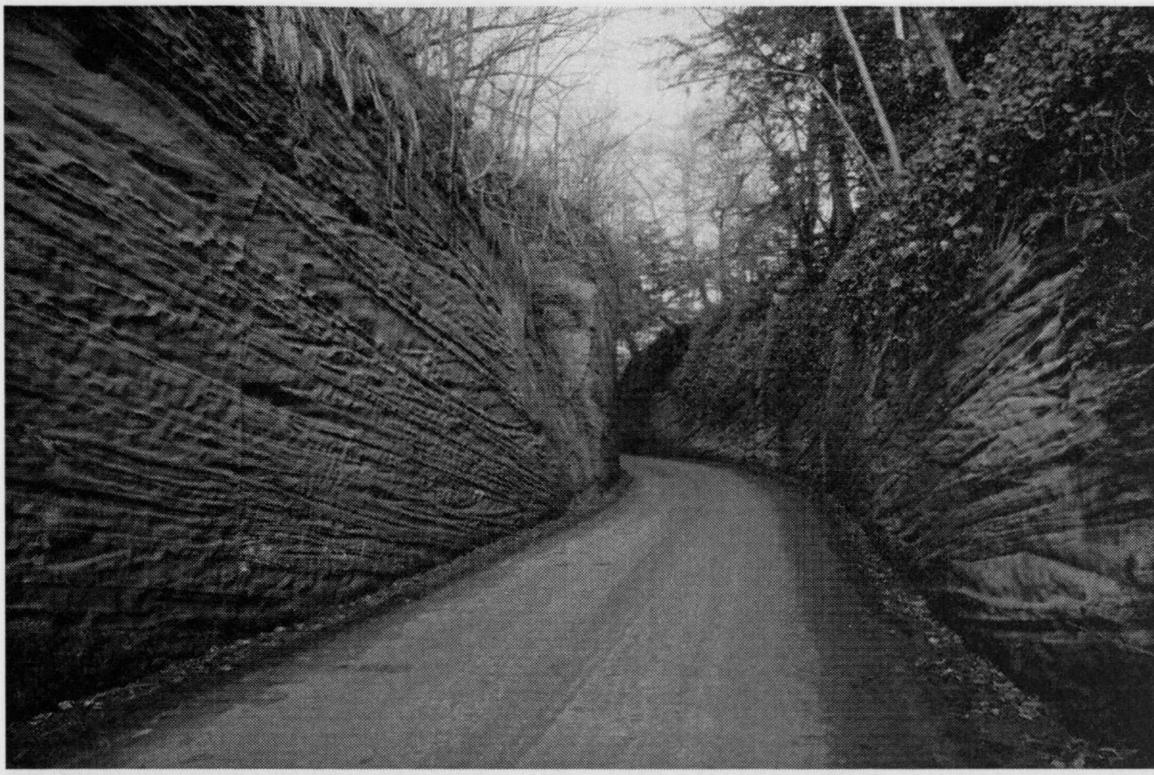


Figure 3.54 The Claverley Road Cutting section through the Wildmoor Sandstone Formation, general view of the steep-sided cutting. (Photo: English Nature/Peter Wakely.)

sandstones, with occasional beds of breccia.

Interpretation

The Triassic sediments in the road cutting at Claverley were deposited under predominantly terrestrial conditions. Their sedimentological characteristics, for example the trough cross-bedding, reflect deposition under fluvial conditions. Some of the sediments exposed here show features that suggest that the dominant fluvial deposition may have been interrupted periodically by aeolian processes. The north-westerly palaeocurrent indicators in the fluvial deposits suggest that the rivers here formed part of the generally NW-flowing Bridgnorth river system identified by Wills (1948; Figure 3.50).

There is no direct evidence of the age of the Wildmoor Sandstone, either at Claverley or elsewhere. The unit overlies the Kidderminster Formation, which is usually placed in the lowest part of the Triassic System. The Wildmoor Sandstone has yielded some fossils elsewhere (see above), but these do not offer objective evidence of age, so the unit is simply dated conventionally as Early Triassic (Warrington *et al.*, 1980, p. 38).

Conclusions

The section exposed at Claverley is a key locality for the interpretation and study of Lower Triassic palaeoenvironments in the Midlands. The sandstones were deposited by a large river system, with occasional phases of aeolian deposition.

BURCOT, HEREFORD AND WORCESTER (SO 972 716)

Introduction

This small road cutting exposes an excellent section of the Bromsgrove Sandstone Formation resting unconformably upon the Wildmoor Sandstone Formation. The Bromsgrove

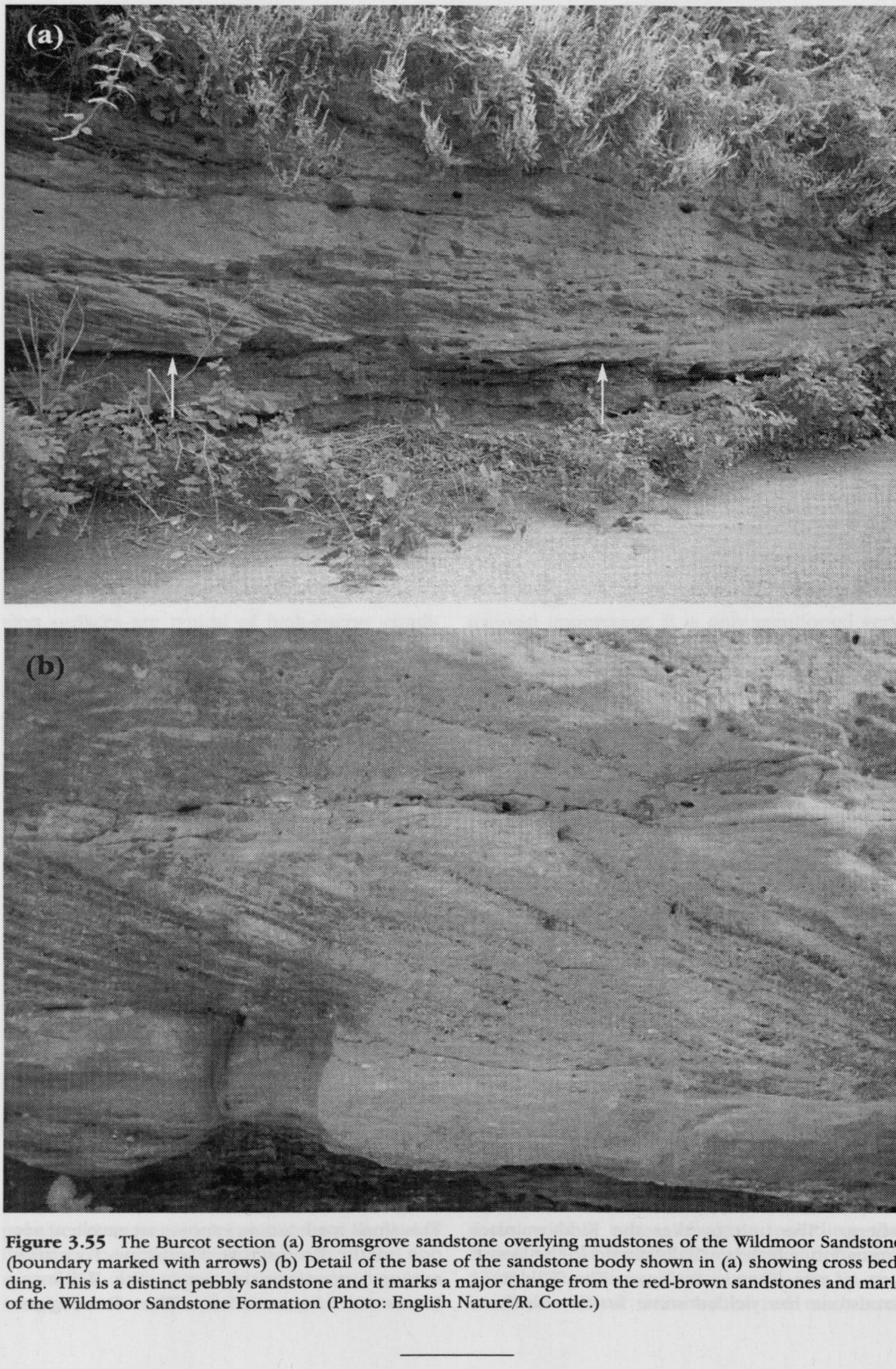


Figure 3.55 The Burcot section (a) Bromsgrove sandstone overlying mudstones of the Wildmoor Sandstone (boundary marked with arrows) (b) Detail of the base of the sandstone body shown in (a) showing cross bedding. This is a distinct pebbly sandstone and it marks a major change from the red-brown sandstones and marls of the Wildmoor Sandstone Formation (Photo: English Nature/R. Cottle.)

Sandstone Formation is of fluvial origin and consists of planar-tabular- and trough-cross-bedded, pebbly sandstones with a broad spread of palaeocurrent directions, features consistent with deposition in a meandering river. Two discrete sand bodies are exposed, separated by a red siltstone with a development of oolitic and pisolitic calcrete near the top. The site shows a regionally significant unconformity and has features reflecting deposition in a variety of Triassic palaeoenvironments.

The Burcot section has been described by Wills (1948, 1976), Mitchell *et al.* (1961), and Old *et al.* (1991).

Description

The road cutting at Burcot exposes a 350-m-long section through the Wildmoor Sandstone Formation and the Burcot Member of the succeeding Bromsgrove Sandstone Formation (Figure 3.55). The lower part of the succession consists of the reddish sandstones and siltstones of the Wildmoor Sandstone Formation, formerly known as the 'Upper Mottled Sandstone'. The sandstones are characteristically dark red, fine-grained, and soft, and contain a scattering of small pebbles; they show large-scale sedimentary structures, for example trough cross-bedding. Palaeocurrent directions, measured from cross-beds, indicate a uni-modal direction of transport of sediment from the south-east.

The boundary between the Wildmoor Sandstone and the overlying Bromsgrove Sandstone Formation is marked by a clearly defined unconformity. The Bromsgrove Sandstone Formation comprises numerous upward-fining sedimentary cycles, of which several are exposed in the Burcot section. This lower unit of the Bromsgrove Sandstone Formation has been named the 'Burcot Member' (Old *et al.*, 1991). The sediments are reddish- or yellowish-brown clastic deposits and range from conglomerates to fine-grained sandstones and thin mudstones. The basal unit rests on a deeply eroded surface, and two channels are cut into the Wildmoor Sandstone and filled with Bromsgrove Sandstone conglomerates. The Bromsgrove Sandstone Formation conglomerates are structureless and polymict, occur in beds no more than about 1 m thick, and contain pebbles of quartz, quartzite, chert, quartz-tourmaline rock, tuff, sandstone, siltstone, and feldspar, as well as intraformational sandstone, siltstone, and mudstone clasts, with a diameter of approximately 0.05 m. The conglomerates are overlain by thick units of fine- to medium-grained sandstone that display planar, lenticular, and trough cross-bedding and pass up into finer-grained sandstones with small-scale cross-bedding and occasional ripple marks. The sandstones, especially those towards the top of the section, contain abundant carbonate nodules and a bed of pisolitic and oolitic calcrete. Palaeocurrent directions measured on cross-beds indicate a north-easterly current flow.

The base of the Burcot Member of the Bromsgrove Sandstone Formation is also visible at other localities nearby, for example where the railway crosses the road between Tutnall and Burcot (SO 986 713). Near to this (SO 9835 7137), the Burcot Member sandstone contains fresh feldspar clasts, quartz pebbles up to 70 mm in diameter, and rounded mudstone clasts up to 100 mm across (Old *et al.*, 1991, p. 29).

Fossils have not been recorded from Burcot itself, but the Bromsgrove Sandstone Formation has yielded an extensive flora and fauna (Wills, 1910, 1947; Warrington, 1970a; Old *et al.*, 1991, pp. 26–9; Benton *et al.*, 1994; Benton and Spencer, 1995). Most of the fossils, however, come from the higher Finstall and Sugarbrook members of the formation. The Burcot Member has yielded sparser remains, including teeth of the shark *Acrodus* from near Tutnall (Wills, 1910); burrows and bioturbation occur in the upper parts of the member in the Sugarbrook No. 3 Borehole (Old *et al.*, 1991, pp. 20, 27).

Interpretation

The Triassic sediments at Burcot are indicative of a range of palaeoenvironments. The trough cross-bedding in the Wildmoor Sandstone Formation has been interpreted as evidence for a fluvial mode of deposition. However, the sand grains are well sorted and rounded, which might indicate an origin as an aeolian deposit. Overall, the evidence suggests that this formation was deposited in seasonally active braided streams that reworked and transported sediment from areas of sand dunes a relatively short distance away to the south-east (Old *et al.*, 1991, pp. 17–18). The unconformity with the overlying Bromsgrove Sandstone Formation, and the pebble bed lying at its base, represent a phase of intense erosion.

The Bromsgrove Sandstone Formation, characterized by cross-bedded, often coarse-grained sandstones, was deposited under fluvial conditions. The basal, coarse-grained conglomeratic beds were rapidly deposited as channel lags, and are associated with the period of erosion responsible for the unconformity. The overlying cross-bedded sandstones are indicative of fluvial conditions and were deposited in braided, low-sinuosity channels (Old *et al.*, 1991, p. 25). The fine-grained sandstones and rare mudstones represent overbank deposits. The calcretes at the top of the section are typical of pedogenic processes and represent soils.

The shark *Acrodus*, and the bioturbation, in the Burcot Member confirm the presence of habitable rivers, ponds, and other shallow bodies of water, mainly at the tops of depositional cycles. Other fossils, including miospores, from higher in the Bromsgrove Sandstone Formation, confirm an Anisian age.

Conclusions

The Burcot road cutting exposes an excellent section through the Wildmoor Sandstone and Bromsgrove Sandstone formations of the Sherwood Sandstone Group. These sediments include sandstones, siltstones and conglomerates, deposited under fluvial conditions. The site exposes the locally important unconformity between these clastic units and sedimentary structures indicative of the fluvial palaeoenvironments within the Bromsgrove Sandstone Formation.

SHREWLEY, WARWICKSHIRE (SP 212 674)

Introduction

The canal cutting at Shrewley exposes a section of the Arden Sandstone Formation, a distinctive and widespread unit in the Mercia Mudstone Group of central England. The sequence comprises an overall coarsening-upwards succession in which grey-green shales and siltstones with wavy and lenticular bedding pass into white, fine-grained, well-sorted, dolomitic sandstones; the facies indicates intertidal marine deposition conditions. The formation has yielded plant remains and a diverse fauna. Palynological evidence indicates a Carnian age. This is a superb site for palaeoenvironmental and regional geological studies. It is also historically important, especially for its fossil faunas.

The Arden Sandstone Formation was first described by Murchison and Strickland (1840) who referred to it as the 'Keuper Sandstone'. Subsequent names include the 'Upper Keuper Sandstone' (Phillips, 1848; Symonds, 1855; Wills and Campbell Smith, 1913; Wills, 1948), the 'Shrewley Sandstone' (Lapworth, 1898), and the 'Arden Sandstone Member' (Warrington *et al.*, 1980). The sediments of the Shrewley Canal Cutting have been described by these authors, as well as by Brodie (1856, 1886, 1887, 1893, 1894), Howell (1859), Hull (1869, pp. 89–90), Matley (1912), Hains and Horton (1969), Hardie *et al.* (1971), and Old *et al.* (1991, pp. 32–5).

Description

Sedimentology

The Shrewley Cutting exposes up to 8 m of flat-lying interbedded sandstones and green marls of the Arden Sandstone Formation (Figure 3.56) with red mudstones of the underlying and overlying formations of the Mercia Mudstone Group (Matley, 1912; Old *et al.*, 1991, p. 32). The Arden Sandstone Formation consists of grey and green sandstones, siltstones, and mudstones, commonly finely interbedded and laminated, and with a great deal of bioturbation, and minor soft-sediment deformation features. The sandstones and siltstones exhibit trough, planar, and small-scale ripple-drift cross-bedding. Approximately 0.3 m above the base of the formation is a thin band of small pebbles, associated with many fish bones, scales, and teeth.

The following section, adapted from Brodie (1856, pp. 374–5) and Howell (1859, p. 42), may be compared with a modern log (Figure 3.57):

	Thickness (m)
Mercia Mudstone Group	
Red marl	seen 3.0
Arden Sandstone Formation	
Thin beds of sandstone, divided by green marls; with the remains of plants	3.04
Hard sandstone, with poorly preserved casts of *Euestheria*	1.06
Green marl	0.05
Fine-grained sandstone, with ripple marks and footprints	0.68
Green marl	0.06
Beds of grey and light-coloured fine-	

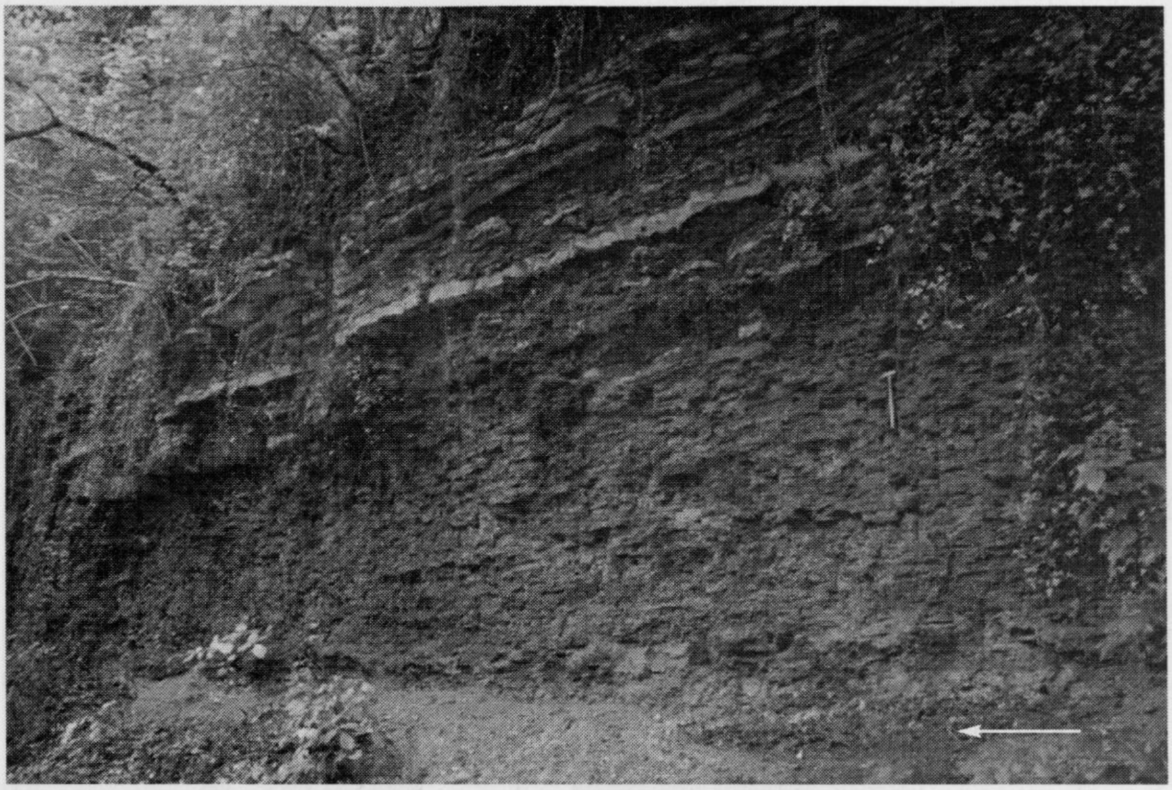


Figure 3.56 The Shrewley canal cutting, showing the Arden Sandstone Formation of the Mercia Mudstone Group; red mudstones underlie the formation at the bottom right (arrowed). (Photo A13530 reproduced with permission, IPR/22–26C, British Geological Survey, © NERC. All rights reserved.)

grained sandstone, divided by marl, with *Euestheria minuta*, and ripple marks. In the middle occurs a coarse, gritty sandstone with white specks, which contains bones, teeth, and spines of *Acrodus*	0.53
Green marl (*base of the Arden Sandstone Formation*)	~ 0.10
Red marl	9.1 seen

The Shrewley canal cutting exposes a thicker succession than in many neigbouring sections (Figure 3.57). At other locations, such as Rowington (SP 202 691), thick sandstone units occur in the Arden Sandstone Formation. Measurements made on cross-beds and ripple marks indicate a generally easterly current flow, although palaeocurrent directions are highly variable within the formation.

Palaeontology

A range of plant and animal fossils has been recorded from the Arden Sandstone Formation, including plants (horsetails, conifers), bivalves, the crustacean *Euestheria minuta*, fishes (sharks, bony fishes, lungfishes), amphibian remains, and invertebrate and vertebrate trace fossils (Brodie, 1856, 1886, 1887, 1893, 1894; Howell, 1859; Newton, 1887; A.S. Woodward, 1893; Matley, 1912; Old *et al.*, 1991, pp. 32–4; Warrington and Ivimey-Cook, 1992). Miospores from the formation, and from mudstones immediately below, indicate a probable late Carnian age (Warrington *et al.*, 1980, pp. 40–1; Warrington and Ivimey-Cook, 1992). The fossil assemblage from the Arden Sandstone Formation is very similar to those of the North Curry Sandstone Member in Somerset (Warrington and Williams, 1984).

Interpretation

The red marls and mudstones in the lower parts of the section at Shrewley were deposited on a broad, low-lying plain that supported a series of large ephemeral playa lakes (Warrington *et al.*, 1980; Old *et al.*, 1991; Warrington and Ivimey-

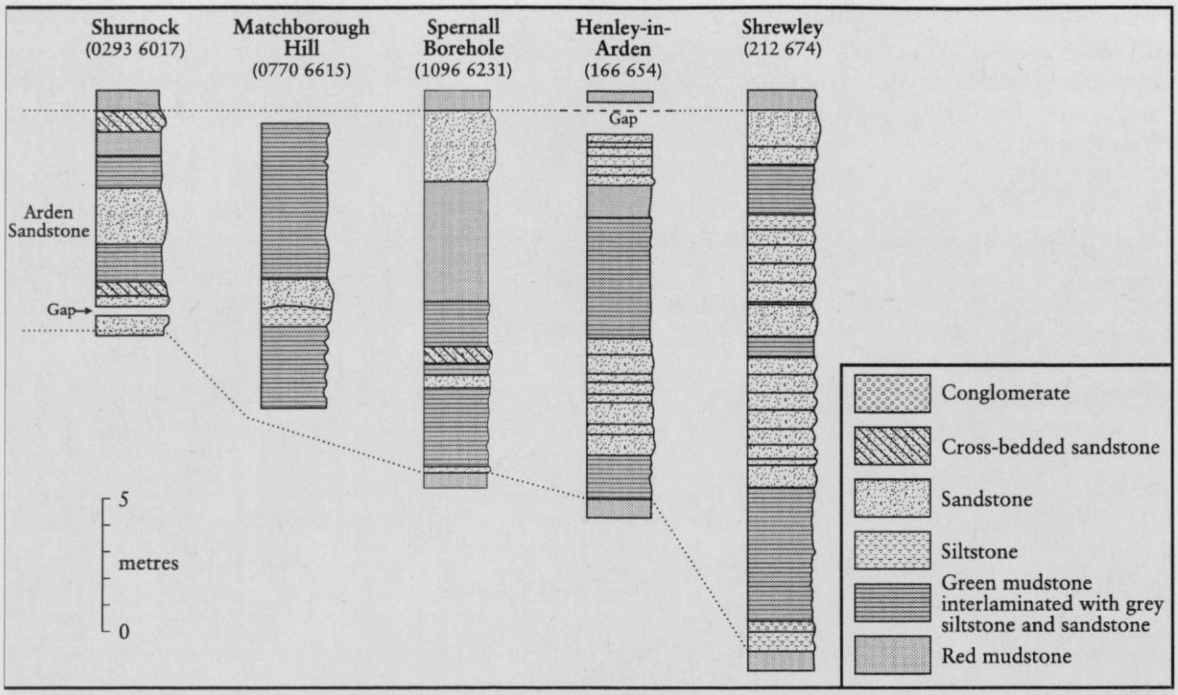


Figure 3.57 Comparative sections through the Arden Sandstone Formation at Shrewley, and at neighbouring sites. (After Old *et al.*, 1991.)

Cook, 1992). Evidence for this comes from the presence of thin gypsum veins and gypsum or anhydrite nodules and occasional pseudomorphs after halite in the mudstones.

The Arden Sandstone Formation, and its equivalents farther south in England, were probably deposited in distributary channels and interdistributary areas separated by broad intertidal mudflat areas in a deltaic to estuarine environment (Warrington and Williams, 1984; Old *et al.*, 1991; Warrington and Ivimey-Cook, 1992;). Subaerial conditions are indicated in some areas by vertebrate tracks and possible insect burrows. Most of the sediment accumulated in water that ranged from fresh to brackish in character, as indicated by the presence of the crustacean *Euestheria*, but was subject to periodic drying out, as suggested by the lungfish remains. A connection to a marine source is implied by the occurrence of the teeth of hybodont and xenacanth sharks, and by sporadic bivalves of marine character.

The succession reverts to mudstones more typical of the Mercia Mudstone Group, above.

The Arden Sandstone Formation crops out over a wide geographical area, which includes much of Warwickshire (Matley, 1912) and Worcestershire, and is thought to correlate with the Dane Hill Sandstone Member of the Leicester region (Warrington *et al.*, 1980), the Butcombe and North Curry Sandstone members of Avon and Somerset, and the Weston Mouth Sandstone Member of the Wessex Basin, all of which are of Carnian age (Lott *et al.*, 1982; Warrington and Williams, 1984; Holloway, 1985c). This horizon has also been correlated with similar units of Carnian age in France and Germany, notably the Schilfsandstein (Warrington, 1970a; Warrington and Ivimey-Cook, 1992).

Conclusions

Shrewley Canal Cutting exposes an excellent section of the Arden Sandstone Formation and the under- and overlying red mudstones in the Mercia Mudstone Group. The Arden Sandstone Formation is an important, widespread stratigraphical marker, and represents a temporary, but major, change in the environments of deposition within the Mercia Mudstone Group. Most of the Mercia Mudstone Group comprises red-brown and some green clays, marls, and mudstones deposited in terrestrial-lacustrine or playa lake environments. The Arden Sandstone Formation was probably deposited under deltaic or estuarine conditions. This is an important site for British Triassic stratigraphy and palaeoenvironmental interpretation, and is historically significant for the fossils, recovered from the formation.

THE TRIASSIC RED BEDS OF SOUTH WALES

INTRODUCTION

The Sherwood Sandstone Group is poorly represented at outcrop in this area. The main representatives are the Budleigh Salterton Pebble Beds and succeeding Otter Sandstone formations seen in west Somerset (Edmonds and Williams, 1985; Edwards, 1999). The Mercia Mudstone Group succession in South Wales and around Bristol consists mainly of undifferentiated red mudstones, the old 'Keuper marls', and no attempt has been made to erect a formal stratigraphical scheme (Warrington *et al.*, 1980, pp. 47–8). In the Bristol area, the lower part of this succession appears to pass laterally into the Redcliffe Sandstone Formation (Kellaway and Welch, 1993).

The Mercia Mudstone Group consists mainly

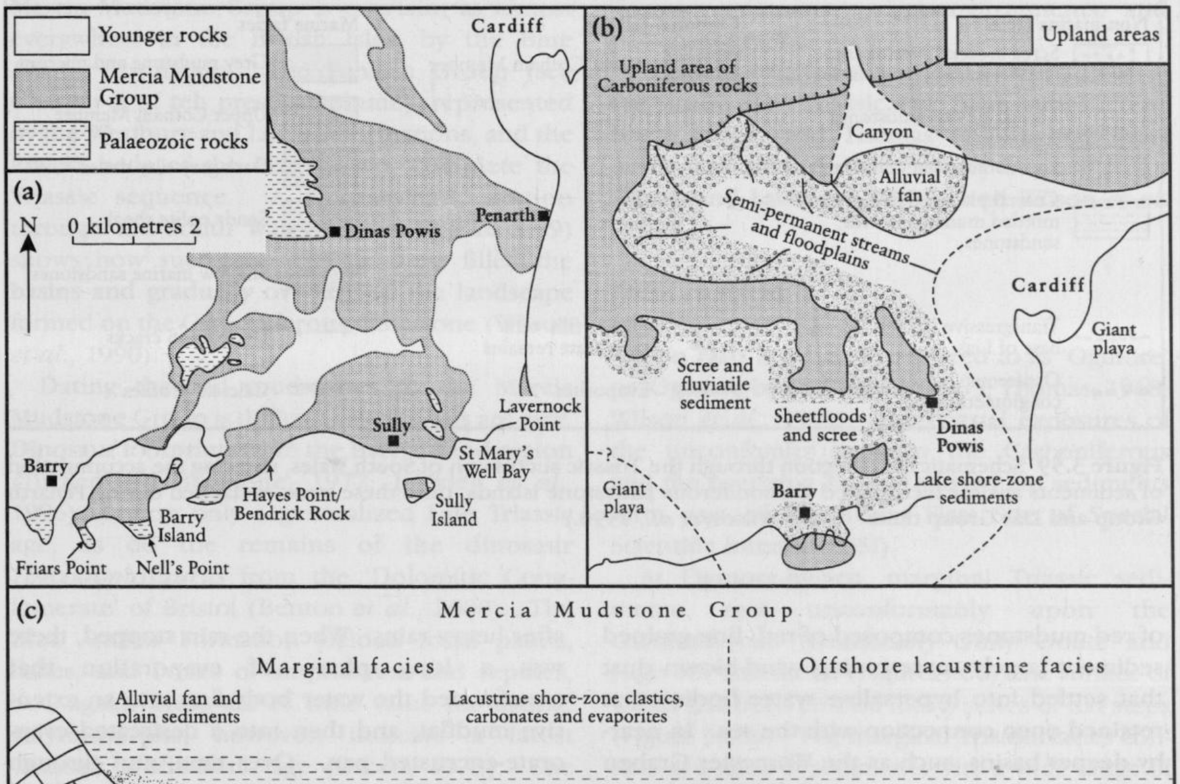


Figure 3.58 The palaeogeography and sedimentary environments of South Wales in the Late Triassic Epoch: (a) sketch map showing the key localities, and the outcrop of major rock groups; (b) reconstructed palaeogeography of the area, showing uplands, a canyon and alluvial fan, major stream systems, shore-face platforms and screes, and the offshore giant playa; (c) cross-section, showing the shoreline features. All based on Tucker (1977, 1978).

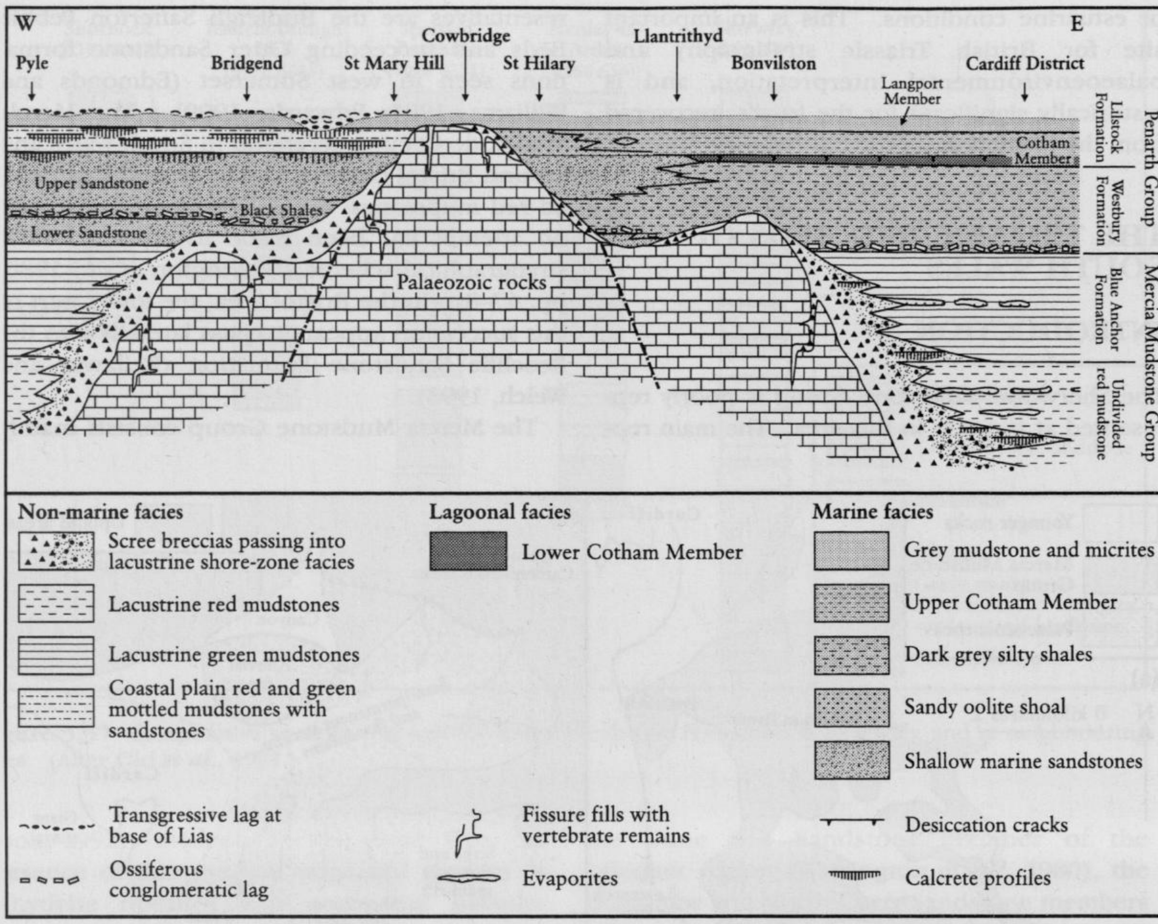


Figure 3.59 Schematic cross-section through the Triassic succession of South Wales, showing the accumulation of sediments against the uplifted Carboniferous Limestone islands, until these were ovelapped during Penarth Group and Lias Group times. (After Wilson *et al.*, 1990.)

of red mudstones composed of red, fine-grained sediment largely representing wind-blown dust that settled into hypersaline water bodies that retained open connection with the sea. In nearby deeper basins, such as the Worcester Graben and the Somerset Basin, considerable thicknesses of halite also accumulated.

The upper part of the Mercia Mudstone Group succession, probably all that above the level of the Arden Sandstone Formation, is best known in South Wales, especially in Glamorgan and Gwent (Ivimey-Cook, 1974), where the sediments rest unconformably on Palaeozoic rocks, mainly the Carboniferous Limestone, which formed a series of islands in the South Wales area (Figure 3.58). The low-lying regions between the limestone islands were occupied by broad, hypersaline, water bodies that were probably seasonal (Tucker, 1977, 1978), and filled after heavy rains. When the rain stopped, there was a long phase of evaporation that transformed the water body first into an extensive mudflat, and then into a desiccated evaporate-encrusted pan. Over time, and through many such filling-evaporation cycles, vast thicknesses of undifferentiated red mudstones accumulated, with numerous sedimentary indicators of evaporation and desiccation, such as pseudomorphs after halite, algal laminae, mudcracks, syneresis cracks, and tepee structures (Tucker, 1978).

The palaeogeography of South Wales at the time has been reconstructed in detail (Tucker, 1977). It has been possible to map the major river systems, palaeochannels, and alluvial fans that brought coarse sediment down from the Welsh uplands into the northern margin of the water body (Figure 3.58b). Sheet floods and screes accumulated around the margins of the uplands. In places, the pattern of erosion of the Carboniferous Limestone rocks at the margin of the water body shows stepping and other evidence that this was precisely the coastline, where water lapped on the low cliffs, creating shore platforms (Figure 3.58c). In these marginal shore regions, stromatolites developed, an indication of brackish-water conditions (Tucker, 1977, 1978).

The coarse basal and marginal facies within the Mercia Mudstone Group in South Wales has long been called the 'Dolomitic Conglomerate', which, of course, is likely to be a diachronous unit. The red mudstone succession in the Mercia Mudstone Group is overlain, as almost everywhere in the British Isles, by the Blue Anchor Formation. The Penarth Group (see Chapter 4 of teh present volume), represented by the Westbury and Lilstock formations, and the lowest beds of the Lias Group, complete the Triassic sequence. A diagrammatic section through the South Wales region (Figure 3.59) shows how successive Triassic units filled the basins and gradually overlapped the landscape formed on the Carboniferous Limestone (Wilson *et al.*, 1990).

Dating the red mudstones in the Mercia Mudstone Group is difficult since fossils are rare. Dinosaur footprints from the Barry Island region (Tucker and Burchette, 1977; Lockley *et al.*, 1996) confirm only a generalized Late Triassic age, as do the remains of the dinosaur *Thecodontosaurus* from the 'Dolomitic Conglomerate' of Bristol (Benton *et al.*, 2000). The Blue Anchor Formation yielded fossil plants, fishes, and bones of amphibians and reptiles, but, again, these are of little value for dating. Palynomorphs, however, indicate a latest Triassic, or Rhaetian, age (Orbell, 1973). The Penarth Group has produced rich microfloras and faunas of Rhaetian age (Orbell, 1973; Waters and Lawrence, 1987; Swift and Martill, 1999).

Four GCR sites have been selected to represent the palaeogeographical and palaeoenvironmental aspects of the South Wales area of the Severn Basin Late Triassic stratigraphy: Sutton Flats for the alluvial fans; Barry Island for the stepped shoreface features; Hayes Point to Bendrick Rock for the sedimentary evidence of the playa and the dinosaur footprints, and Sully Island for evidence of evaporitic conditions in the playas.

SUTTON FLATS, MID GLAMORGAN (SS 861 757–SS 864 745)

Introduction

This locality provides excellent three-dimensional sections through Triassic alluvial fan deposits, that formed by both stream and mudflow processes on the palaeoslope of a Carboniferous Limestone landmass. Particle size in the deposits varies markedly between clay grade and boulders approaching three metres in diameter. The fan deposits occupy channels in the surface of the underlying Carboniferous Limestone. This is an important locality for the study of Triassic sediments, palaeoenvironments, and palaeogeography.

Detailed descriptions of the sedimentology of the Sutton Flats Triassic have been published by Bluck (1965) and Thomas (1968), and short notes are included in Ivimey-Cook (1974), Waters and Lawrence (1987), and Wilson *et al.* (1990).

Description

Sutton Flats is generally referred to as 'Ogmore' or 'Ogmore-by-Sea' (Bluck, 1965; Thomas, 1968; Wilson *et al.*, 1990). The coastal exposures of the unconfomity between the Carboniferous and the overlying Triassic alluvial fan sediments form part of the Sutton Flats Site of Special Scientific Interest (SSSI).

At Ogmore-by-Sea, marginal Triassic sediments rest unconformably upon the Carboniferous (Dinantian) Gully Oolite and High Tor Limestone (Figure 3.60), the surface of which has been eroded into a series of flat steps (Figure 3.61a). The marginal Triassic facies consists of a mass of sediments with a wide range of grain sizes. The dominant lithology is a breccio-conglomerate, which is interbedded with red arenaceous and argillaceous sediments (Bluck, 1965). The basal bed is a poorly sorted conglomerate, overlain by a series of well-sorted conglomerates (Figure 3.61b). The conglomeratic facies contains clasts of Carboniferous Limestone up to 3 m in diameter, although most have a diameter of only a few centimetres, in a reddish-brown sandy matrix with local patches of pale buff marl. The fabric of the conglomerate varies from poorly sorted to well-sorted, and in places contains irregular, often erosional, bedding planes. Trough cross-bedding and imbrica-

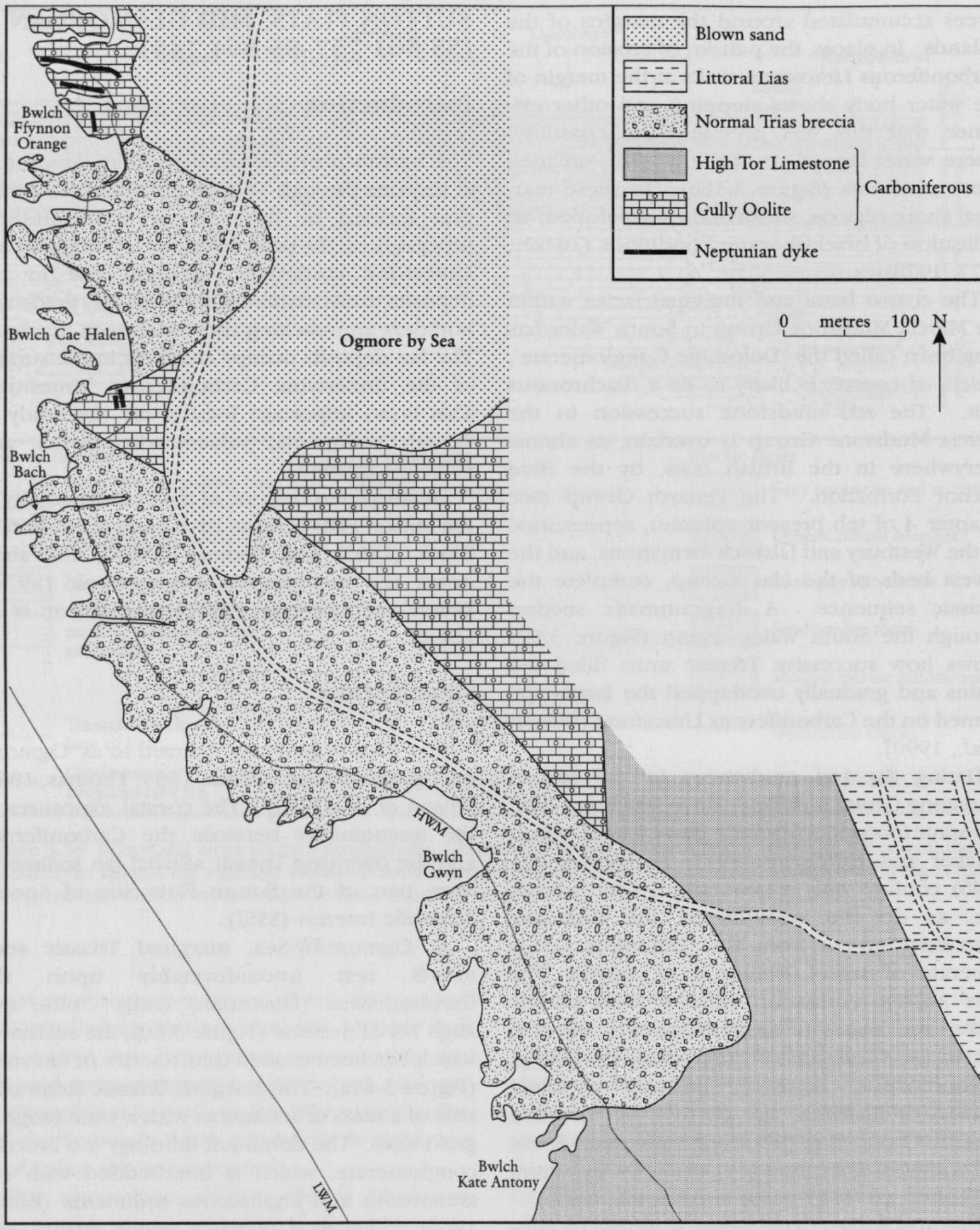


Figure 3.60 Map of the coastal exposure of the Carboniferous and Triassic deposits at Sutton Flats, Ogmore-by-Sea. (After Thomas, 1968.)

tion of some of the smaller, flatter pebbles have been recorded. The sediments are cemented by calcium carbonate (Bluck, 1965). Within the breccio-conglomerates, thin beds of reddish calcarenite, sandstone, siltstone, and reddish mudstone occur, often containing angular pieces of limestone and chert (Ivimey-Cook, 1974).

There is some lateral variation in the sediments. Towards the northern end of the low-lying sea cliffs, in the vicinity of Bwlch Cae Halen

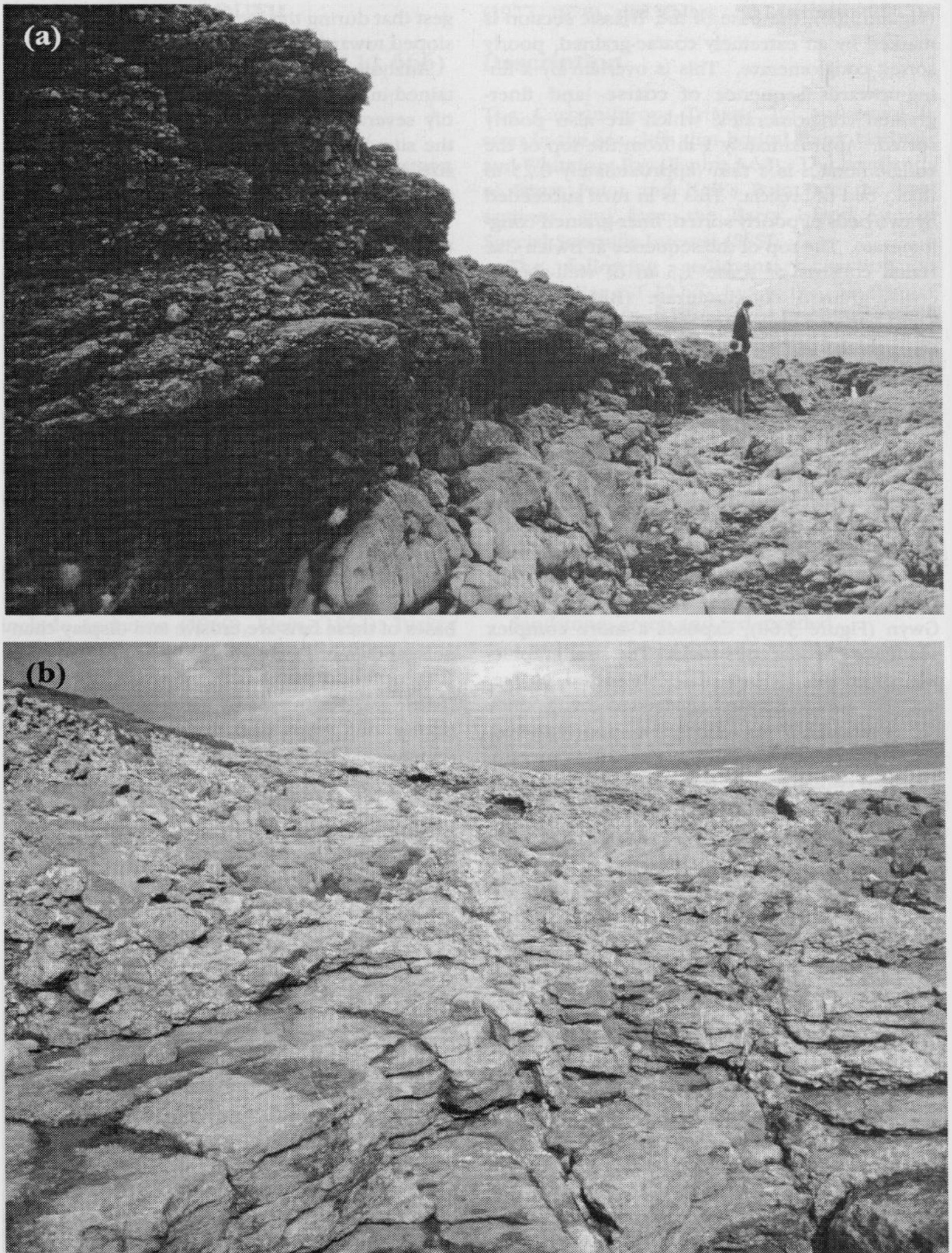


Figure 3.61 Triassic clastic sediments overlying Carboniferous Limestone at Sutton Flats, Ogmore-by-Sea. (a) Irregular beds of Triassic conglomerate resting unconformably on steeply dipping Carboniferous Limestone. (b) Close-up of the lower portion of a poorly sorted Triassic conglomerate, showing incorporation of boulders of Carboniferous Limestone; field of view in (b) is about 5 m. (Photos: K. A. Kermack.)

(Figure 3.60), the base of the Triassic section is marked by an extremely coarse-grained, poorly sorted conglomerate. This is overlain by a fining-upwards sequence of coarse- and finer-grained conglomerates, which are also poorly sorted. Approximately 1 m from the top of the conglomerates is a thin (approximately 0.25 m thick) bed of breccia. This is in turn succeeded by two beds of poorly sorted, finer-grained conglomerate. The top of the sequence at Bwlch Cae Halen consists of some 1.5 m of well-sorted, coarse-grained conglomerate (Bluck, 1965). Thin sedimentary dykes and calcite veins cut through the sediments in this area. The dykes consist of red calcarenite and reddish breccia composed of very angular fragments of limestone (Thomas, 1968).

Approximately 50 m farther south, the relative proportions of the rudaceous lithologies change. Here, the poorly sorted coarse conglomerates comprise less than half of the sedimentary section. As at Bwlch Cae Halen, they are overlain by well-sorted conglomerates. The southernmost part of the sea cliffs, near Bwlch Gwyn (Figure 3.60), exposes a more complex sequence of rudaceous rocks. The stratigraphically lower unit consists of poorly sorted, coarse-grained conglomerate, succeeded by a thick (approximately 7 m) sequence of poorly sorted, often extremely coarse-grained conglomerate. This bed contains large fragments (rip-up clasts) of the well-sorted conglomeratic sediment (Bluck, 1965).

Interpretation

The poorly sorted breccio-conglomeratic sediments have been interpreted as a chaotic mudflow (Ivimey-Cook, 1974) or a preserved scree deposit (Wilson *et al.*, 1990). These are overlain by conglomerates characterized by a high degree of sorting and cross-bedding, thought to have been deposited by ephemeral rivers on an alluvial fan, probably during flash floods caused by heavy storms in an otherwise arid climatic regime. The well-sorted conglomerates generally overlie erosion surfaces and occupy channels, often directly on the Carboniferous Limestones. The fan sediments were deposited initially as screes in the steep-sided canyons cut into the Carboniferous Limestone. Reworking of the screes during torrential rainstorms produced the alluvial fan sediments (Ivimey-Cook, 1974). The positioning and orientation of the fans suggest that during the Late Triassic the land surface sloped towards the south-east (Bluck, 1965).

Analysis of the grain sizes of the clasts contained in the conglomerates has helped to identify several generations of sedimentary fans at the site (Bluck, 1965), based on the maximum size of the clasts. The fans range in size from 150 to 300 m long, and have a maximum thickness of 12 m, although they tend to thin distally. Bluck (1965) defined two categories of fan based on the data collected from Ogmore and other nearby localities, for example Sker Point and Newton. Type-A fans are characterized by a triangular plan, poor sorting of the sediments, channelled bases, cross-bedding (trough and planar), imbricated pebbles, and a low proportion of argillaceous and arenaceous grains. An example is seen in the northern part of the Ogmore coastal section. It is thought that type-A fans were deposited by streams occupying an alluvial fan.

Type-B fans have a lobate outline, are poorly sorted, and generally contain a higher proportion of argillaceous sediments than type A. The bases of these fans are erosive and display channels; at Ogmore a channel in excess of 9 m deep is recorded in the cliffs to the south of Bwlch y Ballring. Sedimentary bedding is generally poorly defined. Soft-sediment deformation structures that incorporate fragments of pre-existing sediment are common towards the bases of the beds. These characteristics are in keeping with deposition by mudflows or stream floods (Bluck, 1965).

The associated finer-grained sandstones and calcarenites are typical of sediments deposited by sheet floods and probably accumulated on the more distal parts of the alluvial fans. These sediments often separate phases of conglomerate deposition (Bluck, 1965).

Conclusions

The Upper Triassic sediments at Ogmore-by-Sea preserve an excellent example of the facies changes within an alluvial fan complex. The lithologies and sedimentary structures have been interpreted as a complex of stream sediments, probably reworked screes, which overlie mudflow or river flood deposits. The site is critical for the understanding of the marginal palaeoenvironments of the upper Mercia Mudstone Group and for the Late Triassic palaeogeography of this area.

BARRY ISLAND, SOUTH GLAMORGAN (ST 107 664–ST 112 664, ST 107 664–ST 111 666)

Introduction

The marginal facies of the Mercia Mudstone Group is seen in unconformable relationship with the Carboniferous Limestone at Barry Island. Several horizontal to sub-horizontal terraces up to 15 m wide are cut into the Carboniferous Limestone. These terraces are joined by vertical cliffs up to 5 m high and covered by marginal facies of the upper Mercia Mudstone Group. The marginal facies includes by poorly sorted angular breccias, interpreted as fossil screes, and better-sorted gravels associated with wave-rippled and finer-grained, desiccated sediments that are interpreted as shore-zone (beach) sediments. The locality is famous for these marginal facies.

The Triassic deposits at Barry Island have been studied for many years (Strahan and Cantrill, 1902, 1904). More recent reports include Anderson (1960), Klein (1962), Tucker (1977, 1978), and Waters and Lawrence (1987).

Description

The Carboniferous–Triassic unconformity is seen in the sea cliffs that bound Barry Harbour and Whitmore Bay (Figure 3.62). The headlands of Friars Point and Nell's Point are the best sections, and form the Barry Island Site of Special Scientific Interest (SSSI).

The following sedimentary section at Jackson's Bay (ST 12 66), just to the east (Figure 3.62), is taken from Waters and Lawrence (1987, p. 58)

	Thickness (m)
Mercia Mudstone Group; *Blue Anchor Formation*	~ 8.7
Mercia Mudstone Group; 'red mudstones':	
Siltstone: green and red mottled, dolomitic	0.20
Mudstone: red-brown, silty, with three thin, green calcareous siltstones	0.95
Sandstone: green and red mottled,	

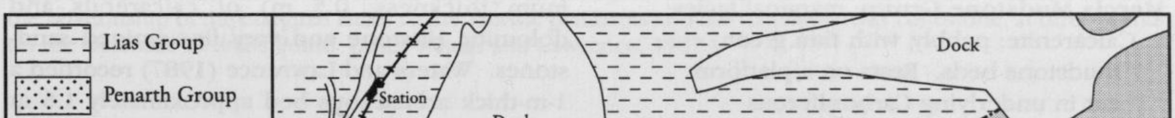


Figure 3.62 Sketch map of the Barry Island outcrops of Triassic sediments overlying Carboniferous Limestone. (After Anderson, 1960.)

calcareous, very fine-grained; scattered granules and rare pebbles of Carboniferous Limestone; tabular bedded, laminated and cross-laminated in top 0.03 m	0.80
Mudstone: red-brown, local green streaks; bed of gypsum nodules, partly dissolved and replaced by calcite, to 0.6 m in middle	2.16
Sandstone: green and red mottled, calcareous, very fine-grained, in part laminated; mudstone parting in middle; scattered gypsum nodules, partly dissolved and replaced by calcite	0.55
Mudstone: red-brown, silty to sandy; scattered gypsum nodules, partly dissolved and replaced by calcite, up to 0.45 m; rare, thin, very fine sandstones and siltstone beds	8.40
Sandstone: green, very fine-grained, calcareous; mudstone parting in the middle; local voids after gypsum; laminated in part	0.40
Mudstone: red-brown, silty; abundant gypsum nodules, partly dissolved and replaced by calcite	0.70
Mercia Mudstone Group; marginal facies:	
Calcarenite: pebbly, with thin green mudstone beds. Rests on a platform cut in underlying Carboniferous Limestone	0.15

The contact between the Carboniferous Limestones and the Upper Triassic sediments is best seen on the eastern and western flanks of Friars Point. Here, the Carboniferous Limestone was eroded during the Triassic, producing a step-like pattern of wave-cut platforms and cliffs (Figure 3.63). The steps (up to five) are up to 15 m wide and have a height of between 0.5 and 5 m. Each step is eroded into the underlying Carboniferous rocks, as well as into Triassic beach sediments of the previous cycle. The cliff faces are generally vertical, although they may overhang slightly. Sheeting of the surface layers of the terraces, produced by weathering in arid conditions, is common (Tucker, 1978). This palaeotopographical feature is unconformably overlain by Upper Triassic breccias.

The basal Upper Triassic beds comprise an exceptionally coarse-grained, massive breccio-conglomerate wedge that is backed up against the cliffs (Anderson, 1960; Tucker, 1977; Figure 3.63). The clasts consist largely of reworked Carboniferous Limestone, and occur as blocks, some more than 1 m in length, set in a grey marly sediment; clast size generally decreases away from the cliffs. A short distance away from the cliffs the breccia wedges occasionally display asymptotic cross-stratification, with a maximum angle of 20°. The breccias may be cut by channels and frequently preserve calcite nodules (Tucker, 1977, 1978; Waters and Lawrence, 1987).

The poorly sorted rudaceous sediments pass laterally and vertically into planar-bedded breccio-conglomerates, through calcarenites, into reddish-brown marls (Anderson, 1960; Tucker, 1977, 1978; Waters and Lawrence, 1987), which are often streaked with green and lie on the eroded terrace surfaces. The well-sorted breccio-conglomerates and associated sandstones contain channel structures up to 2 m wide and 0.5 m deep; the arenaceous lithologies (calclithites) preserve wave ripples.

The finer-grained lithologies are characteristic of the 'transition zone' of Waters and Lawrence (1987, p. 55), and consist of mudstones, which may contain clasts of quartz and Carboniferous Limestone, and thin parallel-sided beds (maximum thickness, 0.5 m) of calcareous and dolomitic siltstone and very fine-grained sandstones. Waters and Lawrence (1987) recorded a 1-m-thick arenaceous bed approximately 1.6 m below the base of the Blue Anchor Formation. The thinner arenaceous beds rarely contain sedimentary structures, although the thicker units display laminations and cross-laminations, or even cross-bedding. These units may infill small channels cut into the underlying sediments.

The lateral variability of the sediments is clearly demonstrated on the western flank of Friars Point (ST 101 663). The poorly sorted, massive breccias blend into tabular breccias and associated calcareous, symmetrically rippled sandstones. To the north, the calcarenites contain fewer pebbles and dewatering structures are common. Thin units of dolomitic mudstone are present. This sequence is comparable with the reddish-brown mudstones seen underlying the Blue Anchor Formation sediments in Whitmore Bay (Waters and Lawrence, 1987, p. 68).

At Nell's Point there is a similar sequence of eroded platforms and wave-notched cliffs overlain by Triassic breccias and silty-marls (Tucker, 1977, 1978). On the western side of the headland, the rocks exposed below the footpath provide an excellent example of the transition

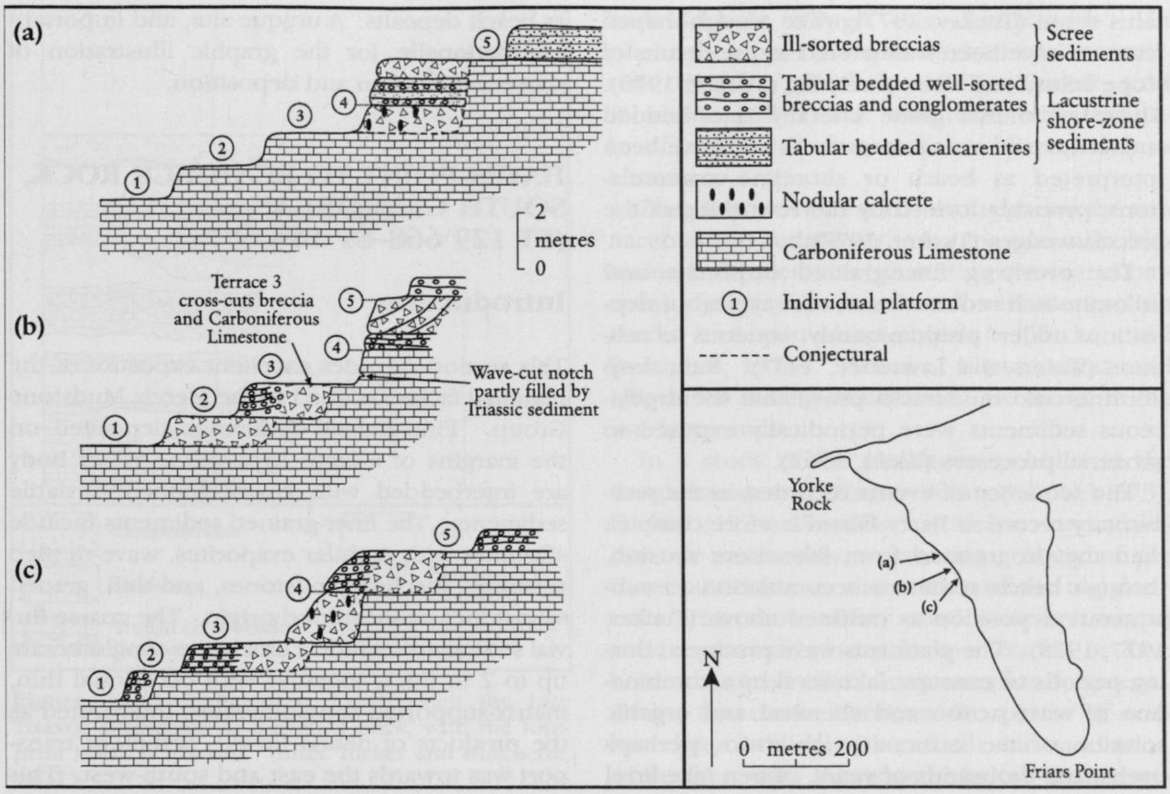


Figure 3.63 Horizontal sketch sections through the marginal facies on the west side of Barry Island, to show the relationship of the marginal facies to the Triassic platforms and the Carboniferous Limestone, at three points on the west side of Friars Point. (After Waters and Lawrence, 1987.)

between the well-sorted breccias, the calcareous sandstones and siltstones, with pebbles and nodules throughout, and the red argillaceous and dolomitic sediments.

At Jackson's Bay (ST 12 66), the surfaces of reddish-brown mudstones and marls are spotted with small holes produced by the dissolution of gypsum nodules, some of which are lined with calcite crystals (Waters and Lawrence, 1987).

In the eastern parts of the locality, at Nell's Point, the red marls of the lower part of the Mercia Mudstone Group sequence are overlain by greenish marls characteristic of the Blue Anchor Formation (formerly the 'Tea Green Marls') succeeded by the Westbury Formation (part of the former 'Rhaetic') of the Penarth Group (Anderson, 1960).

Interpretation

The sequence at Barry Island records a history of changing palaeoenvironmental conditions associated with the fluctuating water levels of a large hypersaline water body (Waters and Lawrence, 1987). The five stepped platforms and cliffs (Figure 3.63) mark the limit of deposition here late in Triassic times and were formed by major erosive events associated with fluctuations in the level of the water body; they formed a surface for deposition of marginal sediments, some of which were partially eroded during the creation of the next higher terrace.

In some places, the eroded surface of the Carboniferous Limestone shows evidence of sheeting, preserved as thin layers of the parent rock aligned parallel to the ancient land surface (Tucker, 1977). This is the result of weathering under arid conditions, and is seen commonly in modern deserts, but is rarely preserved. Similar features were described from Bendrick Rock (ST 131 668) by Tucker (1974).

The poorly sorted breccias found backed up against the vertical cliff faces have been interpreted as scree deposits. The poorly defined cross-bedding associated with some of these deposits reflects the critical angle of rest of the talus slope (Tucker, 1977). The trough-shaped features have been interpreted as the results of slope failure and scree slumping (Tucker, 1978). These sediments grade laterally into bedded rudaceous and arenaceous rocks and have been interpreted as beach or shoreline accumulations, probably formed by the reworking of the breccia wedges (Tucker, 1977).

The overlying finer-grained carbonate and dolomite-rich red mudstones are typical of deposition under predominantly aqueous conditions (Waters and Lawrence, 1987). Rain drop imprints and mudcracks prove that the argillaceous sediments were periodically exposed to subaerial processes (Klein, 1962).

The sequence of events recorded in the sedimentary record at Barry Island is more complex than the progression from lake-shore erosion, through beach sediment accumulation to subaqueous deposition as outlined above (Tucker, 1977, 1978). The platforms were produced during periods of constant lake level by a combination of wave action and chemical and organic solution of the carbonate-rich rocks, perhaps over many thousands of years. When lake level fell, the scree formed against the cliffs, and the beach sediments accumulated between the cliffs and the open water, often through reworking of the scree slopes. Continued falling water level enabled evaporite minerals, possibly of pedogenic origin, to precipitate within the scree and beach sediments, and they probably took several thousands of years to form. Subsequent rises in lake level resulted in further erosion of the Carboniferous Limestone.

Conclusions

The exposures in the vicinity of Barry Island, and especially those at Friars Point and Nell's Point, provide an excellent example of the marginal rocks of the Upper Triassic of South Wales. The sediments include coarse-grained breccias and conglomerates, as well as sandstones and carbonate- and dolomite-rich mudstones. These rocks were deposited on a series of wave-cut platforms incised into the Carboniferous Limestone around the shoreline of a large hypersaline water body. At times of high water level the lake cut the platforms and cliffs, and marginal deposits on earlier terraces were partially eroded during the creation of the next higher terrace. During periods of low water level the screes associated with the cliffs were reworked as beach deposits. A unique site, and important internationally, for the graphic illustration of shore-face erosion and deposition.

HAYES POINT TO BENDRICK ROCK, SOUTH GLAMORGAN (ST 129 668–ST 144 677)

Introduction

This section provides excellent exposure of the marginal facies assigned to the Mercia Mudstone Group. Fine-grained sediments deposited on the margins of a large hypersaline water body are interbedded with coarse-grained fluviatile sediments. The finer-grained sediments include siltstones with nodular evaporites, wave-rippled siltstones and fine sandstones, and thin, graded sandstones of sheetflood origin. The coarse fluvial sediments include a limestone conglomerate up to 2 m thick, together with occasional thin, matrix-supported conglomerates, interpreted as the products of debris flows. Sediment transport was towards the east and south-west. This is a key locality for the interpretation of the environments of Triassic marginal depositional areas.

The Triassic succession between Bendrick Rock and Hayes Point has been described in detail by Tucker (1974, 1977), Tucker and Burchette (1977), and Lockley *et al.* (1996), and reviewed by Ivimey-Cook (1974) and Waters and Lawrence (1987).

Description

Sedimentology

The coastal section between Bendrick Rock and Hayes Point preserves sediments of the marginal facies, or 'Dolomitic Conglomerate', of the Upper Triassic Series. The sequence is dominated by arenaceous sediments, with some argillaceous lithologies. Of these it is the thin graded sandstones and silty mudstones that are especially well exposed at this locality.

The lower part of the section (Figure 3.64) consists of a sequence of dolomite beds, the nodular limestones described by Tucker and Burchette (1977). These comprise nodules of calcite and dolomite with a vertical fabric or polygonal ribs enclosed in fine-grained marl and rest unconformably on the Carboniferous

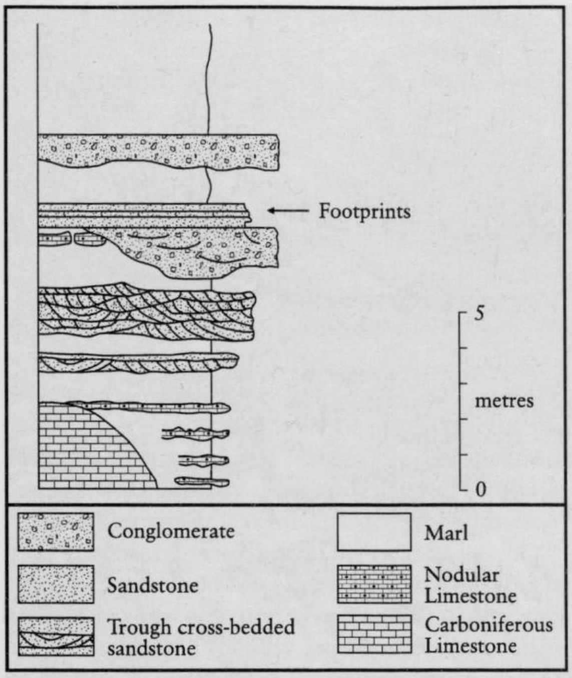


Figure 3.64 Sedimentary log through the Late Triassic succession at Bendrick Rock, with the footprint horizon marked. (After Tucker and Burchette, 1977.)

Limestone, which is seen especially well at Hayes Point.

The overlying sediments (Figure 3.64) consist of a series of sandstones and conglomerates, separated by marls (Tucker, 1977). The bases of the sandstones and conglomerates generally rest on erosion surfaces that show evidence of scouring. The conglomerates occur as discrete beds that show well-developed cross-bedding, and bedding planes may preserve lunate megaripples or dunes. The conglomerates are composed of well-rounded and well-sorted pebbles in a sandy matrix (locally the matrix may be absent), and bed thickness varies, with a maximum of 2 m. The lowest sandstone is approximately 0.5 m thick, with evidence of trough cross-bedding in the lower parts of the bed. A thicker unit of cross-bedded sandstone follows, above an argillaceous bed, and is succeeded by more marl, then a substantial conglomeratic horizon.

Immediately overlying this conglomerate is a series of thin sandstones (Figure 3.64), which often show evidence of graded bedding; at the bases of the individual beds are scour surfaces overlain by gravel lags, which fine upwards through coarse- to fine-grained sandstone. The beds include trough cross-laminations. In places the upper surfaces of the beds bear current ripples (Tucker, 1977; Tucker and Burchette, 1977). The sandstones consist mainly of sand-sized fragments of Carboniferous Limestone.

The siltstones and marls that separate the arenaceous and rudaceous units are generally thin-bedded. Ripples with bifurcating crests are common, and may be associated with desiccation cracks and rain drop imprints (Tucker and Burchette, 1977). Flakes of siltstone and marl (produced during desiccation) are found in the overlying units.

In a study of the limestone pebbles in the conglomerates at Hayes Point (ST 143 673), Tucker (1974) described evidence for exfoliation, or onion-skin weathering. Many of the limestone clasts on the surface of the conglomerate unit show either concentric spheres of rock separated by very narrow cracks, or have been shattered into sharp angular fragments. Often, the cracks between the pieces of rock have been infilled with red silt and sandstone, while the cracks that extend below the palaeoland surface are generally infilled with calcite. Similar features have been recorded at Bendrick Rock (ST 131 668). Here, the upper 0.3 m of the Carboniferous Limestone has been split into thin sheets of rock that run parallel to the former land surface.

Palaeontology

The Hayes Rock to Bendrick Point succession is especially famous for its dinosaur footprints (Tucker and Burchette, 1977; Lockley *et al.*, 1996), and it is has been selected for the GCR, independently of its stratigraphy, for its fossil reptiles, for its tracks (Benton and Spencer, 1995). The footprints occur over wide areas in the finer-grained sandstones, and many individual trackways may be identified on single bedding planes (Figures 3.65 and 3.66). The footprints have two morphologies, one tridactyl and rather slender, and the second larger, tridactyl and with heavier digits. Both forms were initially assigned to the ichnotaxon *Anchisauripus* (Tucker and Burchette, 1977; Benton and Spencer, 1995), but, in a more detailed study, Lockley *et al.* (1996) concluded that the tracks should be assigned to five ichnogenera: *Grallator*, *Anchisauripus*, *Chirotherium* or *Tetrasauropus*, *Pseudotetrasauropus*, and

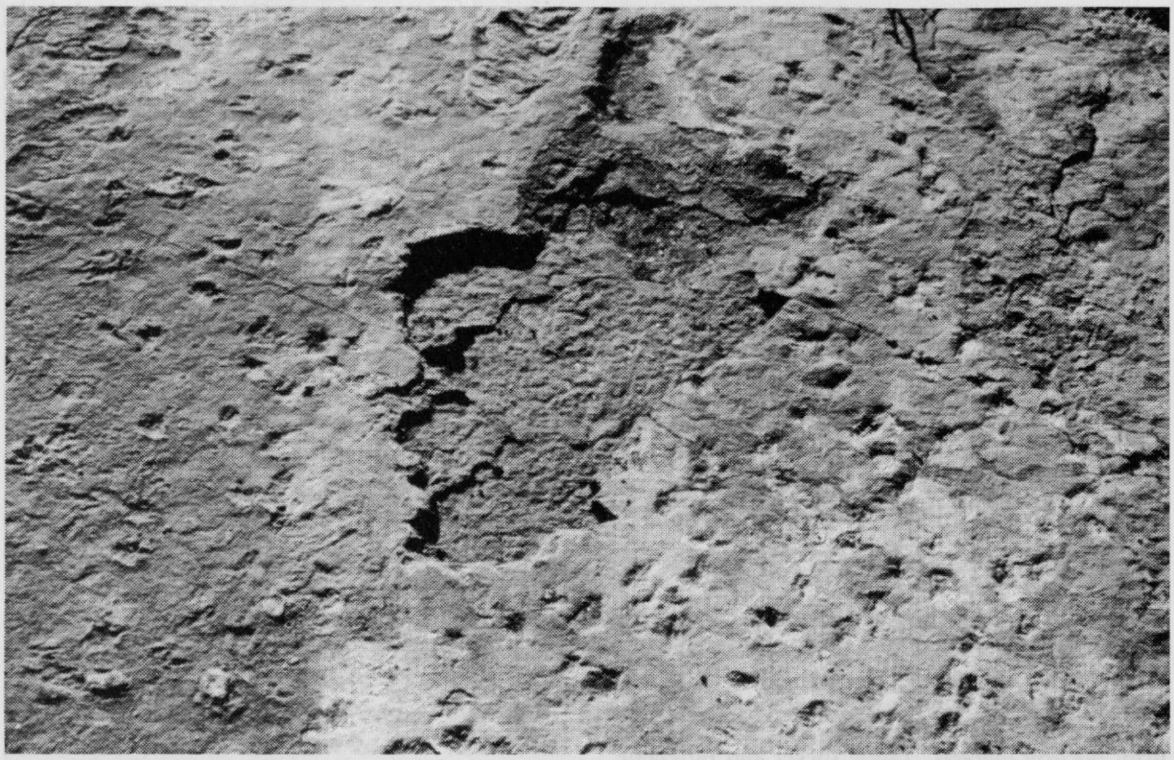


Figure 3.65 A bedding plane on the foreshore at Bendrick, covered with three-toed dinosaur footprints, probably *Anchisauripus* and *Grallator*. Each small depression is a footprint. Width of the field of view is about 5 m. (Photo: M. J. Benton.)

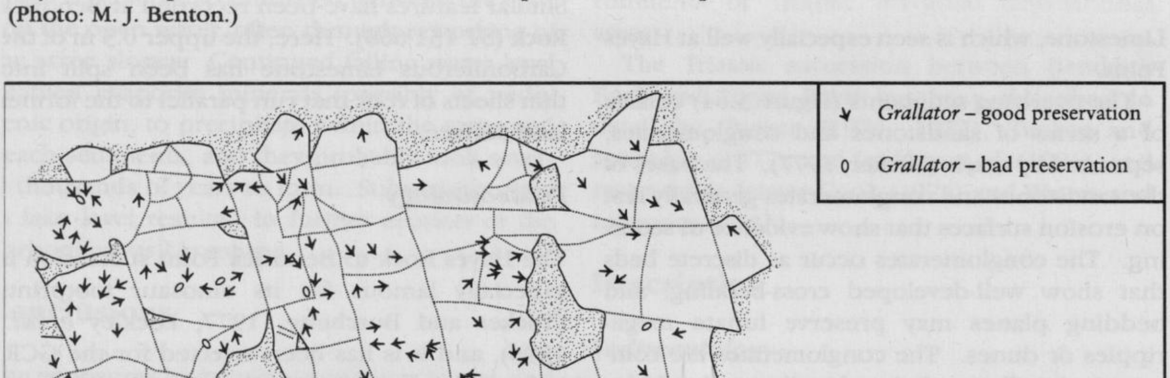


Figure 3.66 Map of the track-bearing surface collected near Bendrick Rock, and currently on display in the National Museum of Wales. The rose diagram (inset) shows the predominant orientation of *Grallator* tracks. (After Lockley *et al.*, 1996.)

Otozoum. The first two were made by theropod dinosaurs, small and large respectively. The last three might have been made by prosauropod dinosaurs of differing sizes, or they may be attributable to a variety of unknown basal archosaurs.

Interpretation

The sedimentary rocks between Bendrick Rock and Hayes Point have been interpreted as deposits of a marginal environment (Tucker, 1977). The region was low-lying and was dominated by a hypersaline water body fed by many ephemeral streams and rivers. The Triassic sediments were initially deposited against knolls of Carboniferous Limestone, which, as sedimentation continued, were gradually buried.

The basal dolomites in red marls and siltstones have been interpreted as replaced evaporite minerals, probably gypsum and/or calcite (Tucker, 1974; Tucker and Burchette, 1977). The dolomitization is probably a post-Triassic diagenetic feature. Such lithologies represent a period of emergence, when the water levels were relatively low, and must have required high levels of evaporation, little precipitation, and low rates of sedimentation. The associated marls and silts indicate deposition on a floodplain or in a playa basin (Waters and Lawrence, 1987; Talbot *et al*., 1994), and may have been deposited either in shallow muddy ponds formed after floods, or on the floodplains bordering the ephemeral rivers, or they may have an aeolian origin.

Despite this picture of an arid climate, there is evidence for periodic, probably heavy, rainfall. The thin, laterally extensive graded sandstones are typical of sediments deposited during flash floods or sheet flows (Tucker and Burchette, 1977). The presence of symmetrical ripples in some of the sandstones suggests that the water formed pools, because the ripples reflect small waves.

The coarse conglomeratic units have been interpreted as stream-flood deposits (Tucker, 1977; Tucker and Burchette, 1977). A number of river forms may have been present: lenticular pebble beds are characteristic of braided channels subject to downstream migration of bars (as indicated by the cross-bedding), while other sedimentary structures suggest ephemeral streams and stream-flood events.

Combining the sedimentary information and the above interpretation, it is possible to produce a picture of the changing environmental conditions that affected South Wales during the Late Triassic Epoch. The fine-grained lithologies were deposited in a large hypersaline water body in open connection with the sea, similar to a modern sabkha or playa basin. These are interbedded with coarser-grained facies deposited during periodic flooding events that occurred when the water level was low. During periods of low water level, stream floods cut channels into the playa plain, and deposited the conglomeratic units. During times of low rainfall, and therefore low water level and reduced sheet and stream flooding, soils could form on the playa sediments (Tucker, 1977). Palaeocurrent directions measured from sedimentary structures indicate that material was transported to the area from the west and north-west.

The sheeting of the Carboniferous Limestones at Bendrick Rock is typical of surface weathering (insolation) of exposed rocks in arid and semi-arid environments (Tucker, 1974). Thin layers of rock peel away from the outcrop surface as a result of processes such as diurnal temperature changes, the growth of salt crystals, and chemical weathering. The low latitude of this region during the Triassic Period probably discounts freeze-thaw activity, but the close proximity to the Triassic hypersaline lakes makes the growth of salt crystals a viable alternative. The onion-skin weathering and shattered pebbles at Hayes Point are also thought to have formed under arid conditions; these features are commonly observed in modern deserts. The conglomerate was deposited rapidly during a flood. There then followed a prolonged period of weathering that produced the exfoliated and shattered pebbles.

The dinosaur and other archosaur footprints indicate that appropriate habitats existed in the vicinity, although these are not preserved. The footprints indicate a range of dinosaurs, including herbivores and carnivores. The assemblage compares with ichnofaunas from Colorado and Utah, and a late Norian to Rhaetian age is inferred (Lockley *et al*., 1996).

Conclusions

The coastal section between Bendrick Rock and Hayes Point preserves one of the best examples of the finer-grained lithologies of the marginal Triassic strata in Britain. These late Triassic sediments record a fluvial-marginal environment that was inhabited by dinosaurs and other reptiles. Weathering products, such as exfoliated pebbles and sheeting, are rarely seen in the geological record, although they are commonly recorded in modern deserts. They confirm that the climate of South Wales during the Late Triassic Epoch was arid. This is an internationally important site for the evidence it provides on Late Triassic palaeoclimates, depositional palaeoenvironments, palaeogeography, and faunal associations.

SULLY ISLAND, SOUTH GLAMORGAN (ST 167 670)

Introduction

The sea-cliff exposures of Sully Island provide excellent sections in the marginal facies of the Triassic Mercia Mudstone Group. These rocks include a series of breccias and sands, interpreted as deposited at the margin of a large hypersaline water body, overlain by nodular evaporites and carbonates. They rest unconformably upon a terraced surface of Carboniferous Limestone. This site, therefore, demonstrates the regionally significant unconformity between Carboniferous and Triassic rocks, as well as a range of sediments that illustrate graphically the brackish-water and evaporitic conditions of the Late Triassic playas of the South Wales region.

Many accounts of the geology of Sully Island have been published, including Strahan and Cantrill (1904), Anderson (1960), Cope (1971), Ivimey-Cook (1974), Tucker (1977, 1978), Waters and Lawrence (1987), and Leslie *et al.* (1992, 1993).

Description

Sully Island is located to the south of the village of Swanbridge. At high tide the island is cut off from the mainland, although at low tide it is possible to walk across the rocks exposed in Sully Sound. The island is roughly oval in outline, and measures about 0.5 km from west to east, and 0.2 km from north to south. The north shore of the island faces the mainland and for the most part has low relief, especially where it faces Swanbridge Bay. The rest of the island is bounded by substantial cliffs, and at low tide a rocky foreshore is exposed. The Triassic sections are best seen at the south-east corner of the island (Figure 3.67).

Figure 3.67 The marginal Triassic sediments at Sully Island, showing the Carboniferous Limestone overlain unconformably by shore-zone clastic deposits, then replaced evaporites, and finally carbonates (see Figure 3.68). (Photo: M. J. Benton.)

The Upper Triassic sediments at Sully Island consist of a wedge of breccias that pass upwards into sandstones and siltstones, which are in turn overlain by dolomites and limestones (Figure 3.68). Sedimentary structures including ripples are preserved within the clastic sediments, which show graded bedding. As is often the case with sediments deposited under terrestrial conditions, there is a high degree of lateral variation. These sediments have been grouped together as the 'Marginal Triassic', also known as the 'Littoral Triassic' or 'Dolomitic Conglomerate' (Strahan and Cantrill, 1904; Ivimey-Cook, 1974), and are laterally equivalent

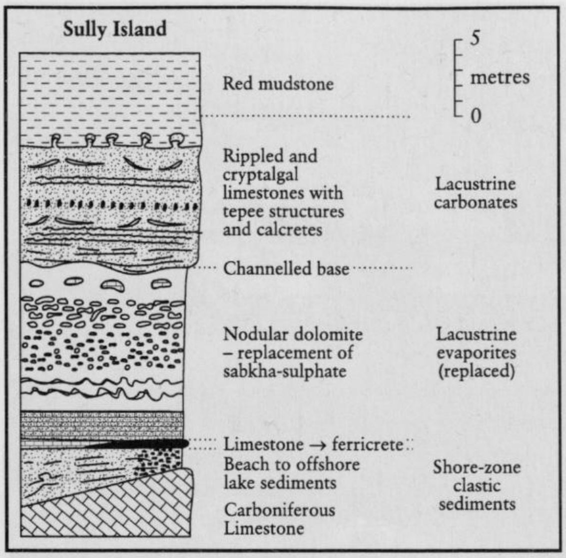


Figure 3.68 Section at Sully Island, showing the main marginal playa facies (see Figure 3.67). (After Tucker, 1978.)

to the red mudstones that are more characteristic of the Mercia Mudstone Group.

Tucker (1978, p. 207) identified three lithofacies at Sully Island: (1) lacustrine shore-zone clastics, (2) lacustrine evaporites, and (3) lacustrine carbonates, all showing rapid lateral variation and overlain by red mudstone. The following simplified sedimentary section is adapted from information in Tucker (1977, 1978) and Leslie *et al.* (1992, 1993):

	Thickness (m)
Mercia Mudstone Group; Marginal Triassic	
Limestones and dolomites	6–9
Nodular dolomite	0.3
Sandstones and siltstones	max. 5
Breccia and coarse sandstone	3–5
Carboniferous Limestone	

The Carboniferous Limestone dips about 50° to the east. The contact with the overlying Upper Triassic lithologies is a sharp, clearly defined, angular unconformity at an angle of between 5° and 10° to the bedding in the Triassic sediments that dip gently to the north. Many of the Triassic arenaceous beds show clear evidence of later deformation including contorted bedding, recumbent folds, and symmetrical anticlinal folds (Tucker, 1978, p. 210).

The basal Upper Triassic beds consist of a wedge of well-sorted breccias that grade into a thick sequence of sandstones and siltstones (Figure 3.68; Tucker, 1977, 1978). Grain size varies across the wedge; the thickest section contains fine-grained arenaceous sediments and these pass eastwards into coarse-grained well-sorted conglomerates and breccias that are interbedded with pebbly sandstones. In places, the coarse-grained lithologies have been dolomitized, and may include low breccia ridges. The breccia beds are characterized by grain-supported fabrics, and may occur as lenses with low-angle planar cross-stratification and imbricated pebbles, the bed boundaries are at least locally gradational.

The finer-grained parts of the sedimentary wedge comprise red pebbly sandstones, sandstones and siltstones, and are classified as calcilithites (Tucker, 1977, 1978). These sediments display wave ripples (straight-crested with rounded and sharp profiles), lenses with cross-laminations, continuous beds with well-developed cross-laminations, impersistent graded bedding, and dewatering structures such as folds and disturbed bedding. In places, for example by the side of the natural causeway to the mainland, spectacular tepee structures are seen.

The thickest part of the clastic wedge is overlain by a series of nodular dolomites that contain scattered quartz nodules (Tucker, 1977, 1978; Leslie *et al.*, 1992, 1993). Dolomite also occurs associated with limestones, and consists of calcarenites and cryptalgal limestones with interbedded calcretes. The calcarenites typically comprise laminated and rippled fenestral intrapelsparites, which may show evidence for desiccation. The cryptalgal limestones consist of stromatolite mounds and algal mats (Figure 3.69). The main limestone unit contains many cavities, which may be aligned parallel to bedding. Laterally the dolomitized limestones are replaced by a haematite-rich dolomite that rests directly on the Carboniferous Limestone.

Large (5–6 m diameter and up to 1 m thick) patches and mounds of travertine occur interbedded with the laminated and stromatolitic limestones. The travertine takes many forms, including sheets of flowstone that preserve the shape of the underlying topography, small columnar structures composed of fibrous calcite, pisoids, and floë calcite (aragonite; Leslie *et al.*, 1992, 1993).

The red mudstones and siltstones of the

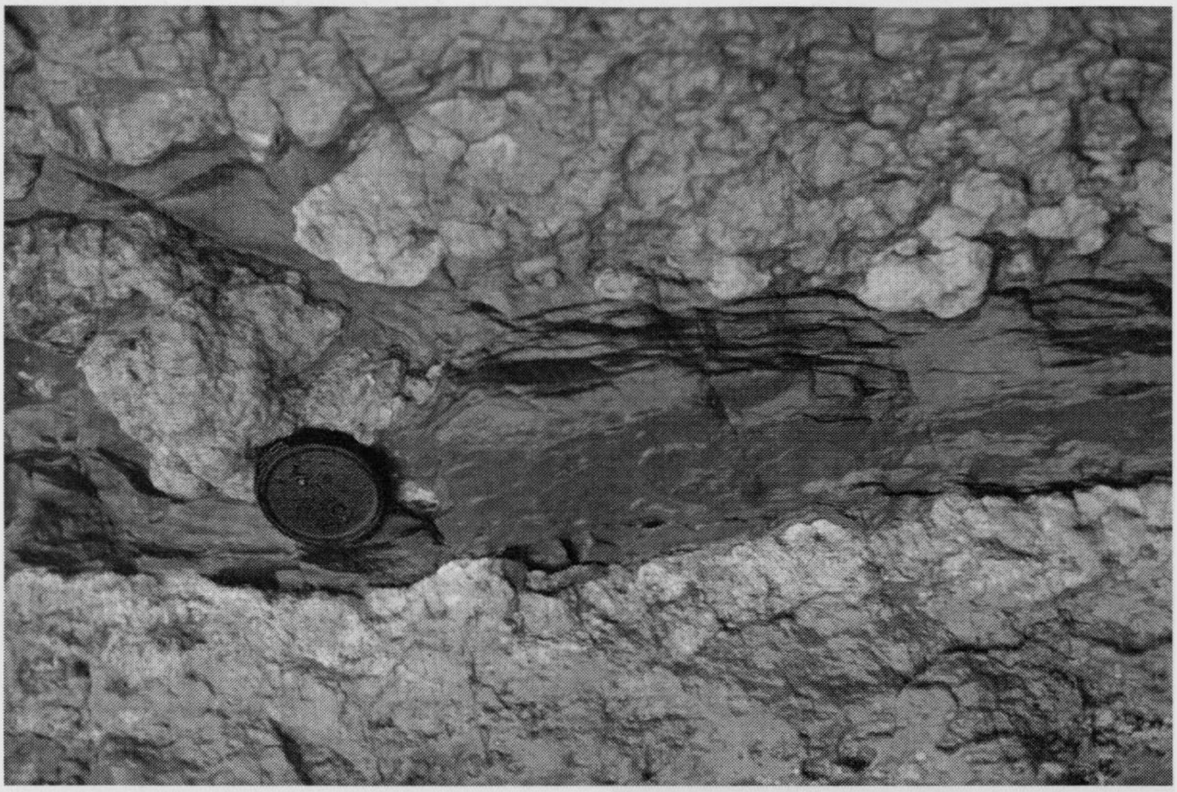


Figure 3.69 Thinly laminated cryptalgal limestones with nodular dolomites in the Sully Island succession. (Photo: M. J. Benton.)

Mercia Mudstone Group are seen on the causeway between Sully Island and the mainland and in the cliffs towards the western edge of the island (Anderson, 1960). Recently, a series of vertebrate tracks from the foreshore of the mainland close to Sully Island have been assigned to the ichnotaxa *Grallator*, *Tetrasauropus*, and *Pseudotetrasauropus* (Lockley *et al.*, 1996).

Interpretation

The thick sequences of clastic sediments at Sully Island have been interpreted as forming on the shore of a hypersaline water body that was probably a permanent feature in the Late Triassic landscape. Rapid lateral changes in lithology, reflect deposition on a narrow beach in an environment with some wave action (Tucker 1977, 1978).

The coarse-grained breccias, seen at the thin end of the clastic wedge, are typical of lacustrine beach gravels: the clasts are generally angular, reflecting the limited amount of wave-induced abrasion. The breccia ridges and associated cross-bedding are thought to have developed on the planar erosion surface as berms on the shores during periods of intense wave activity (Tucker, 1978).

The sandstones and silts, lateral equivalents to the breccias, were formed in the shallow waters at the edge of the water body. Water depth probably never exceeded more than a few metres, but was probably subject to marked fluctuations. During periods of low water level, the sediments were affected by wave activity in the form of breakers and swash and backwash action, as shown by wave-current ripples, cross-laminations, and wave-formed oscillation ripples (Tucker, 1978).

The fine-grained sandstones and siltstones were probably deposited in deeper water, well below average wave-base (Tucker, 1977, 1978). This sediment would have been carried into the water body by rivers, with the fines slowly falling out of suspension. Coarser sediments originated in the areas of shallower water, and were transported into the deeper water by storms. The soft-sediment deformation and dewatering structures were caused by mass movement of the unconsolidated sediments, probably triggered by local tectonic activity. Tepee structures in this unit are rare, but graphic, indicators of dewatering and intense evaporation.

The thin limestones are interpreted as deposits of a shore-zone mud flat. The haematite-rich replacement of the limestone is characteristic of a palaeosol, possibly a ferricrete. The nodular dolomites are typical of evaporitic environments such as sabkha plains, where concentrations of evaporitic minerals often accumulate. The nodules were formed as replacements after anhydrite (Tucker, 1977, 1978), and represent several phases of precipitation of sulphate evaporites associated with regression–transgression cycles. The overlying thin limestones and dolomites contain a variety of sedimentary features characteristic of deposition in shallow lakes and mudflats, for example fenestral intrapelsparites, stromatolites, ripples, and laminated sediments. Cavities in the limestones were created by solution by meteoric (vadose) waters; the resultant cavities were later infilled with calcite and sediment (Leslie *et al.*, 1992, 1993). From this evidence, the local environment of deposition has been interpreted as a series of low-lying mud-flats that were periodically flooded.

The travertines associated with these sediments indicate ephemeral (interbedded sheets) and semi-permanent springs (mounds), although their formation is not thought to have been linked with the deposition of the limestones. The springs were formed by groundwaters upwelling from the Carboniferous Limestone basement (Leslie *et al.*, 1992, 1993).

The red dolomitic mudstones and siltstones were deposited under arid and hypersaline conditions in areas around the margins of the water body (Leslie *et al.*, 1992, 1993), that were subject to periodic flooding.

Conclusions

Sully Island preserves an excellent section of Upper Triassic marginal and intertidal rocks. It is especially important for the evidence of hypersaline conditions (algal beds, evaporites) and desiccation (mud cracks, tepee structures). These facies are unusual in the sedimentary rock record, and are shown exceptionally well here. The site is critically important for understanding the nature of the arid playa margins in Late Triassic South Wales, a setting unique in the British Triassic succession.

THE TRIASSIC RED BEDS OF DEVON

INTRODUCTION

The Triassic strata of Devon are seen in continuity with the Permian succession in the coastal exposures that extend, almost unbroken, from Tor Bay in the west to Pinhay Bay in the east. Some of the units that crop out in the west have been dated tentatively as Permian in age, by lithostratigraphical correlation with more securely dated units in the Crediton–Exeter area (see Chapter 2). The sequence and dating of the Devon Triassic succession, and correlation with units in the English Midlands, is relatively more straightforward above the Budleigh Salterton Pebble Beds, and Mid and Late Triassic ages have been assigned to units above that level.

The first stratigraphical attempts were by Ussher (1875, 1876), who divided the Devon coast red-bed succession into five lithostratigraphical units (Figure 3.70), a scheme that continued in use until the 1970s. Laming (1966, 1968) and Henson (1970, 1972, 1973) introduced major revisions to this scheme, and formalized the terminology, providing the basis for the names adopted by Warrington *et al.* (1980, pp. 42–5; Figure 3.70).

The Budleigh Salterton Pebble Beds and Otter Sandstone Formation of Henson (1970) comprise the Sherwood Sandstone Group, and the overlying 'Upper Marls' are assigned to the Mercia Mudstone Group that presently comprises largely unnamed units, except for a thin sandstone unit, the Weston Mouth Sandstone Member, and, at the top, the Blue Anchor Formation. The Weston Mouth Sandstone Member is regarded as a correlative of the North Curry and Butcombe sandstone members of Somerset, and the Arden Sandstone Formation of the Midlands (see above).

The Permo–Triassic boundary cannot be recognized in Devon, but the problem of the boundary seems to have attracted more attention here than elsewhere. The Aylesbeare Mudstone Group (Smith *et al.*, 1974), comprising the Exmouth Mudstone and Sandstone and the Littleham Mudstone formations, is placed in the basal Triassic (Edwards and Scrivener, 1999); it is devoid of stratigraphically useful fossils.

The overlying Budleigh Salterton Pebble Beds contain fossiliferous clasts reworked from Ordovician and Devonian sources (Cocks, 1989,

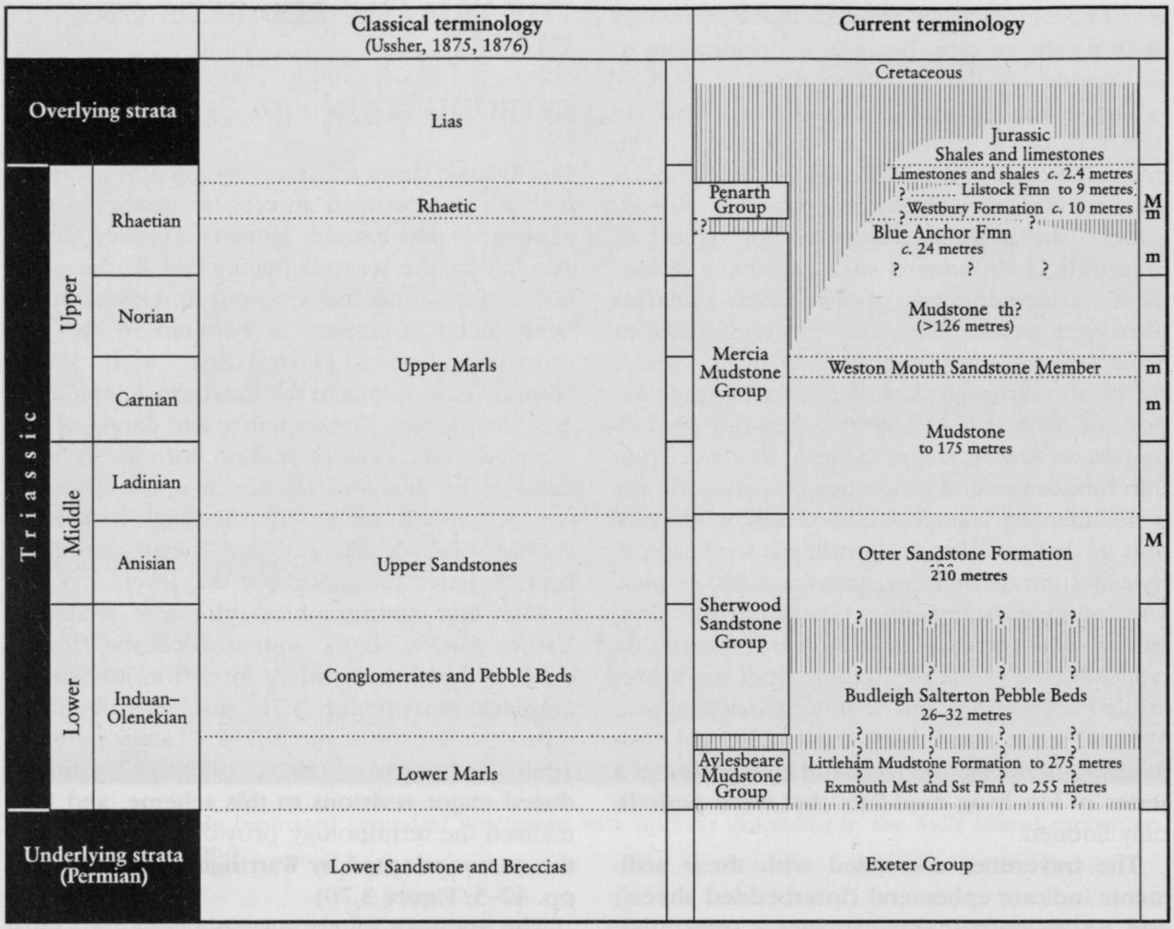


Figure 3.70 Stratigraphical columns for the Triassic succession of Devon, showing the current, and the older nomenclature. M = macrofossils; m = microfossils. Based on Ussher (1875, 1876), Warrington *et al.* (1980), and Edwards and Scrivener (1999).

1993). No contemporary fossils have been found, and this unit has been regarded as Triassic in age on the basis of lithological similarities to the 'Bunter Pebble Beds' of the Midlands. The similarities are indeed close, and a strong case has been made, by close comparison of clast types, that the Sherwood Sandstone Group pebble beds in Worcestershire, the West Midlands, and south Shropshire were all deposited in a major river system that flowed northwards from France and through southern England (Figure 3.50; see also Figure 3.74). An Early Triassic age for the Budleigh Salterton Pebble Beds has been widely accepted, although without definitive evidence.

The overlying Otter Sandstone Formation has produced a diverse assemblage of fossils, including remains of plants, insects, molluscs, fishes, amphibians, and reptiles (Walker, 1969; Milner *et al.*, 1990; Benton *et al.*, 1994), which indicate an Anisian age. Beds in the middle of the Mercia Mudstone Group of the Devon coast have yielded Carnian palynomorph assemblages (Warrington, 1971), and the Blue Anchor Formation, at the top of that group, has yielded Rhaetian palynomorphs (Warrington, 1971; Stevenson and Warrington, 1971; Orbell, 1973). Similar Carnian and Rhaetian palynomorphs have also been recorded from the nearby Lyme Regis borehole (Warrington, 1997a).

Despite the problems in dating the succession, the Triassic rocks of the south Devon coast appear in spectacular exposures that are of considerable palaeogeographical and sedimentological importance, and two have been selected as GCR sites: Budleigh Salterton for the spectacular pebble beds, and Ladram Bay to Sidmouth for the Otter Sandstone Formation, both now part of the Dorset and East Devon Coast World Heritage site, declared in 2001.

BUDLEIGH SALTERTON, DEVON (SY 055 815–SY 073 820)

Introduction

The site comprises a magnificent coastal section that exposes the full thickness of the Lower Triassic Budleigh Salterton Pebble Beds, a sequence of texturally mature conglomerates deposited by braided rivers. These include pebbles of Ordovician and Devonian rocks with indigenous faunas derived from erosion of a ridge of Palaeozoic rocks to the south or southwest. The conglomerates are overlain unconformably by aeolian and fluvial sandstones of the Otter Sandstone Formation that rest on a layer of wind-facetted pebbles (dreikanter).

Early accounts of the Budleigh Salterton Pebble Beds include Vicary (1864), Whitaker (1869), Ussher (1876), Irving (1888), and Woodward and Ussher (1911). More recent descriptions include Laming (1966, 1968), Henson (1970), Selwood *et al.* (1984), Cocks (1989, 1993), Holloway *et al.* (1989), Smith (1990), Smith and Edwards (1991), and Wright *et al.* (1991).

The site is part of the Dorset and East Devon Coast World Heritage site.

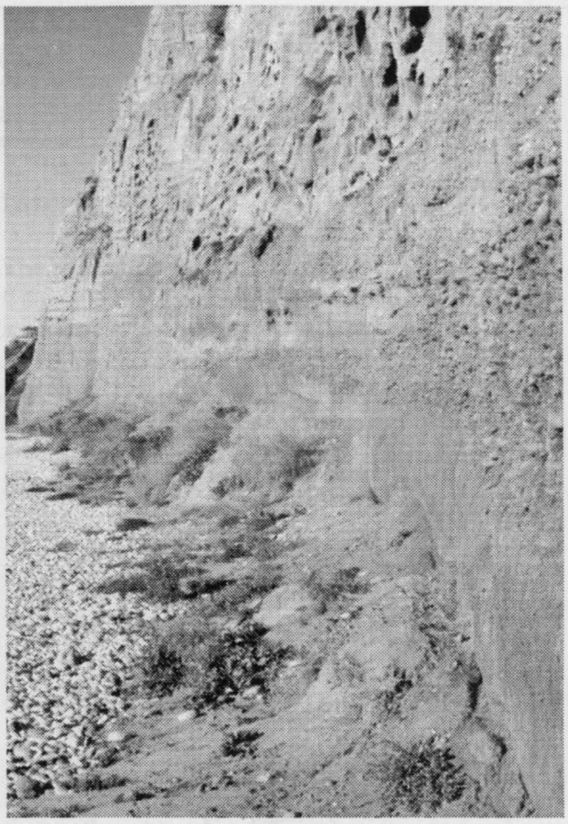


Figure 3.71 The lower part of the cliff at Budleigh Salterton, showing pebble beds and coarse sandstones in the lower part of the cliff, overlain by cavernous weathering Otter Sandstone Formation. The cliff is15–20 m high. (Photo: M. J. Benton.)

Description

The Triassic sequence is best seen in the cliffs west of the town of Budleigh Salterton (Figure 3.71), where the Budleigh Salterton Pebble Beds (BSPB) are seen resting on the Littleham Mudstone Formation of the Aylesbeare Mudstone Group, and underlying the Otter Sandstone Formation. The sequence dips to the ESE at 3° to 8°.

The conglomeratic BSPB is the lower formation of the Sherwood Sandstone Group at Budleigh Salterton, and is well exposed west of the sea front (SY 062 816). The unit is some 30 m thick and generally fines upwards (Figure 3.72a). It is composed of well-rounded pebbles, cobbles, and boulders in a sandy matrix that contains sporadic sandstone and mudstone lenses (Selwood *et al.*, 1984; Holloway *et al.*, 1989; Smith and Edwards, 1991). The clasts are predominantly of quartzite; minor amounts of vein quartz, schorl, sandstone, and porphyry also occur (Henson, 1970). Some of the quartzite pebbles contain Ordovician and Devonian fossils (Vicary, 1864; Cocks, 1989, 1993; Holloway *et al.*, 1989). Towards the base of the formation, the sediments largely comprise thick sheets of horizontally bedded conglomerates with sand lenses and patches of cross-bedding. These are overlain by thin beds of sandy conglomerate interbedded with sandstone lenses and sheets (Smith, 1990).

The lower part of the BSPB, approximately 14 to 18 m thick, contains planar-bedded and cross-bedded conglomerates that grade laterally into sandstone lenses and then back into conglomerates (Figure 3.72a). The cross-bedded conglomerates typically show high-angle foresets with rhythmically bedded pebbly sandstone and gritty layers (Figure 3.73a), and have layers of pebbles overlying scoured surfaces (Smith and Edwards, 1991).

The upper section of the BSPB, some 12 to 14 m thick, is characterized by thinner beds of conglomerate with a higher sand content and the presence of large gravelly foresets, all of which display a very crude fining-upwards

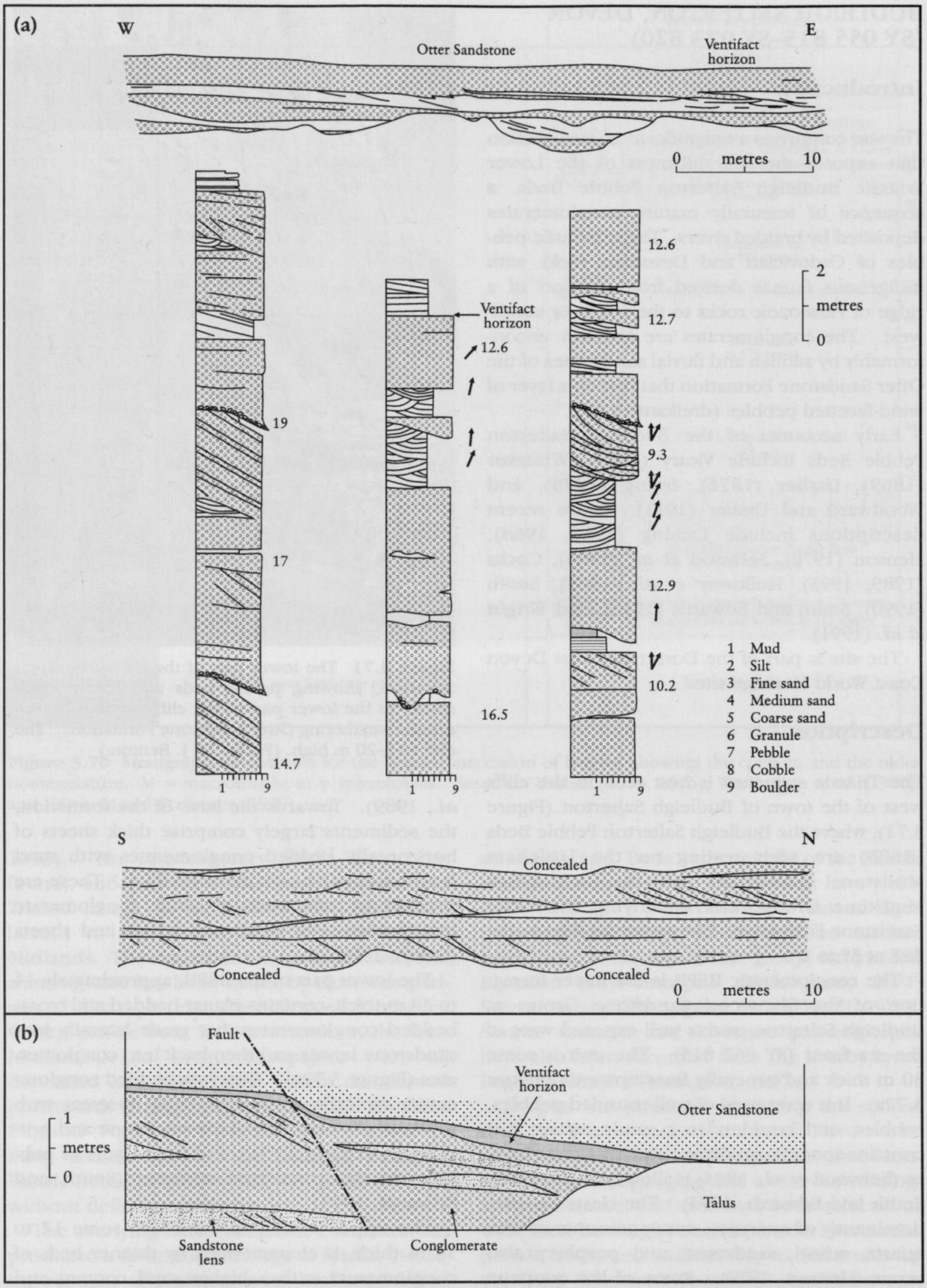


Figure 3.72 Sedimentary features in the Budleigh Salterton coast section: (a) graphic sedimentary logs measured at three points through the Budleigh Salterton Pebble Beds (BSPB), and sketches of the upper and lower parts of the cliff section; (b) field relationships of the top of the BSPB, at the eastern end of the GCR section (SY 062 816). Based on Smith and Edwards (1991) and Wright *et al.* (1991) respectively.

sequence (Figure 3.72a; Smith, 1990; Smith and Edwards, 1991). The conglomerates form sheets with lenses and partings of sandstone. The highest beds show well-developed multi-storey and multi-lateral channels infilled with trough cross-bedded pebble-rich sandstones and conglomerates, which merge laterally with cross-bedded conglomerates.

The BSPB is succeeded by a 0.3 m thick deposit of red mudstone that is, in turn, overlain by a layer of facetted pebbles (Figures 3.72b, 3.73b) that marks the boundary with the Otter Sandstone Formation. Wright *et al.* (1991, p. 517) described the red sediment, a palaeosol, as a 'clay- and silt-rich sand' that rests on a thin conglomerate below the slope of a bar, and on the cross-bedded rudaceous sediments of the bar top. The red clay has a blocky, angular texture and the blocks may have striated skins; it is composed of illite and semi-ordered illite-smectite. The silt and sand-grade component consists of quartz and feldspar. This layer also contains scattered clasts, many of which (especially towards the top of the horizon) have haematite or clay coatings.

The pebbles overlying this layer have facetted upper surfaces and flattened or rounded lower surfaces. The upper surfaces are polished and show flutes and pits, producing zweikanter, dreikanter, and multi-facetted forms (Leonard *et al.*, 1982). The upper surfaces display pockmarks and microscopic striations, and are coated with haematite. The lower surfaces are smoothed and irregular.

The overlying thick sequence of medium- to fine-grained, reddish-brown, cross-bedded sandstones belong to the Otter Sandstone Formation (Holloway *et al.*, 1989), which is described in more detail in the Ladram Bay to Sidmouth site description (below). At Budleigh Salterton, this formation is exposed in the cliffs near to the town (SY 071 819) and to the east of the Otter River (SY 080 821). The lower beds of the Otter Sandstone Formation, immediately above the BSPB (Figure 3.73b), consist of cavernous weathering, cross-bedded aeolian sandstones that pass upwards into horizontally and cross-bedded fluvial sandstones that contain abundant concretions and sheets of calcite (Purvis and Wright, 1991). The concretions are typically elongate (up to 1 m long) and cylindrical, with a diameter between 0.1 and 0.15 m. They generally cut the bedding planes at right angles and are limited to laterally continuous sandstone horizons, which are often capped by channel lag deposits (Purvis and Wright, 1991). The sheets of calcite, each up to 0.1 m thick, are laterally continuous for up to 10.0 m and are preserved parallel to the bedding planes.

Interpretation

The sediments cropping out along the coastline west of Budleigh Salterton preserve evidence for a complex palaeoenvironmental regime, dominated by fluvial and aeolian activity. Of particular significance are the ventifacts and deflation layer, and the palaeosol, at the top of the BSPB. During the deposition of the Sherwood Sandstone Group the climate of this part of Britain was hot and dry, as suggested by the presence of anhydrite, calcretes, and deflation surfaces with ventifacts (Henson, 1970; Leonard *et al.*, 1982; Holloway *et al.*, 1989).

The conglomerates and sandstones of the BSPB were deposited in substantial, low-sinuosity, gravel-bedded rivers on an alluvial fan or fluvial braidplain (Laming, 1966; Leonard *et al.*, 1982; Smith, 1990). The lower part of the formation, consisting of thick units of planar cross-bedded sandstone, has been interpreted as large channel-fills with distinct phases of conglomerate and sandstone deposition, the sediments having been deposited on the edges of large linguoid bars, probably in a gravel-bed stream. The upper part, typified by thinner beds and more sandstone, was deposited as sheets in shallow, poorly-channelized streams. Here, the coarser-grained material was deposited in the deeper parts of the channel, and the sandstone in the shallower areas. The contact between these two distinct facies is erosional, and was produced during the lateral migration of the river channels (Smith, 1990; Smith and Edwards, 1991).

The rivers that deposited the BSPB drained an area of high ground that was situated to the south of the Wessex Basin (Figure 3.74). This is confirmed by palaeocurrent measurements on the BSPB at outcrop, which indicate transport to the north and NNE. The fossil-bearing clasts indicate a source from the Armorican Massif (Cocks, 1989, 1993), which lay to the south-west, in the present area of Brittany and Normandy.

The fine-grained horizon with angular pebbles at the top of the BSPB has been interpreted as a 'reg' palaeosol (Wright *et al.*, 1991). Reg soil profiles typically consist of a ventifact

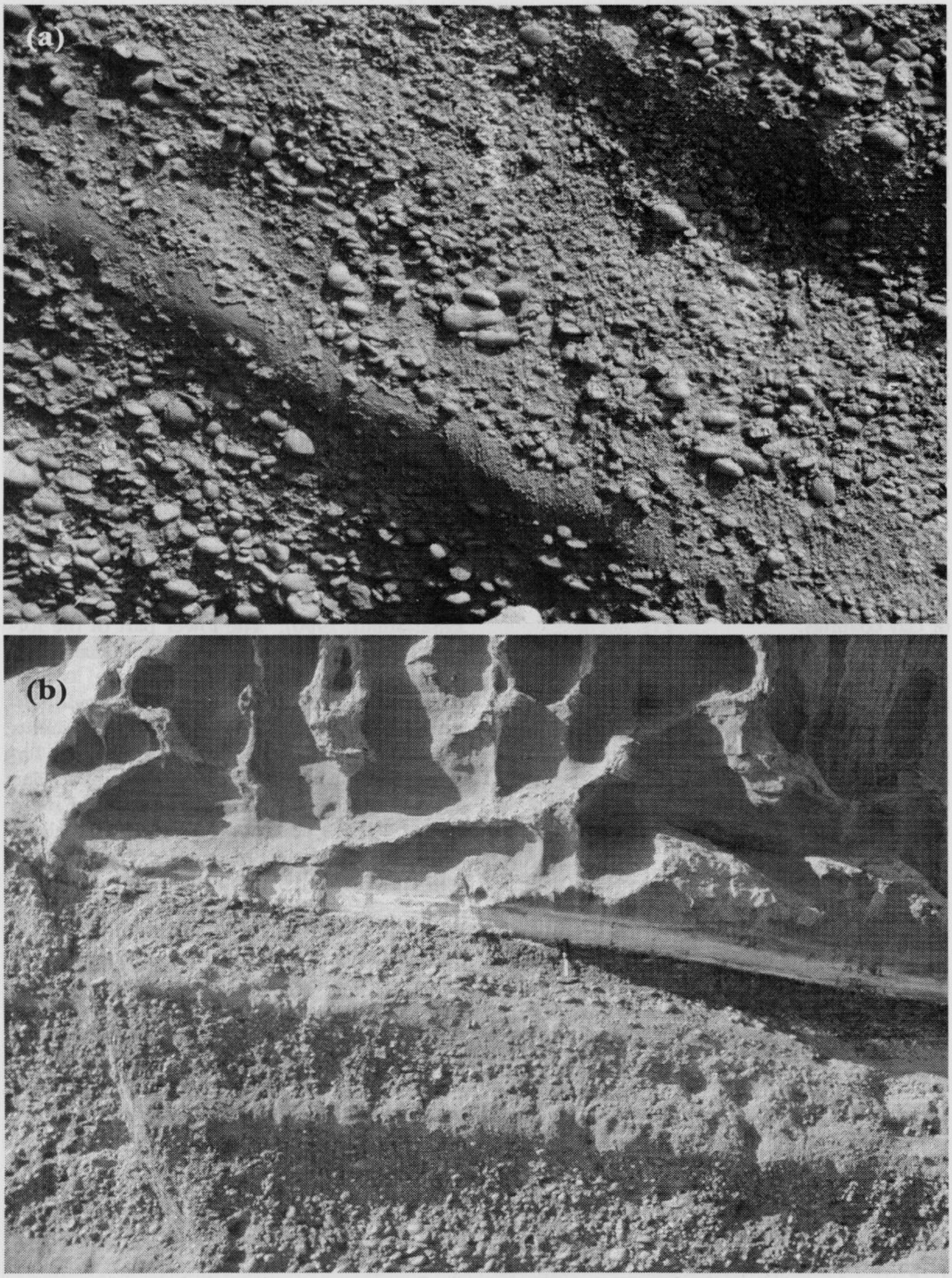


Figure 3.73 Sedimentology of the Budleigh Salterton Pebble Beds. (a) Close-up view of rounded pebbles, partly imbricated, in large foresets; field of view about 1 m. (b) The top of the Budleigh Salterton Pebble Bed overlain by cavernous weathering sandstones of the Otter Sandstone Formation. The ventifact horizon underlies the light-coloured band at the base of the Otter Sandstone Formation, and is marked by the top of the hammer shaft. (Photos: P. Turner.)

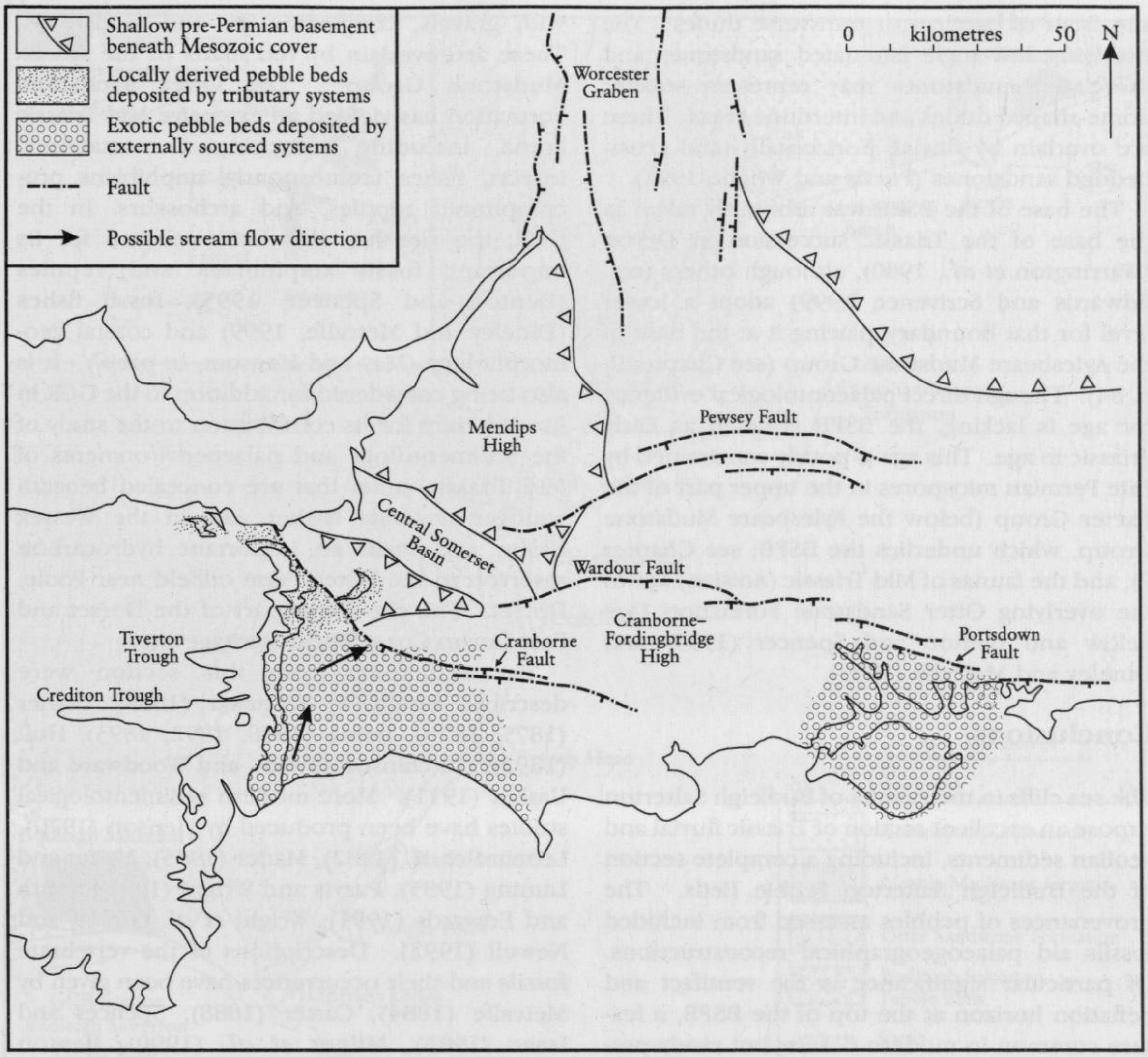


Figure 3.74 Palaeogeography of the south of England during the deposition of the Budleigh Salterton Pebble Beds, showing the location of outcrops, and concealed occurrences detected by boreholes in Dorset and in the Hampshire Basin. Major palaeocurrent flow directions are indicated. Abbreviations: CF, Cranborne Fault; CFH, Cranborne–Fordingbridge High; CSB, Central Somerset Basin; MH, Mendips High; PF, Pewsey Fault; PDF, Portadown Fault; WF, Wardour Fault; WG, Worcester Graben. (After Smith and Edwards, 1991.)

horizon overlying a fine-grained layer that shows evidence of clay enrichment and coated grains, and are characteristic of desert environments. It is thought that this palaeosol bed represents an extended period of land surface stability, probably of many thousands of years in duration (Holloway *et al.*, 1989). The ventifact layer represents a deflation surface characterized by little or no net sediment deposition, and probably formed over an extended period of time.

The ventifact layer is overlain by the Otter Sandstone Formation, the lowest 14 m of which has been interpreted as deposited by aeolian processes, which resulted in erosion of pebbles to form ventifacts, followed by the formation of large dunes (Henson, 1970). This interpretation is supported by the presence of large-scale cross-bedding, an absence of mica and coarse-grained clasts in the sandstone, and the high degree of rounding of the clasts (Newell, 1992). The sedimentary sequence preserves enough detail for tentative identifications of the dune types to be made. The lower sequence of trough cross-bedded sandstones was probably deposited on the slip faces of barchan or transverse dunes. The overlying low-angle laminated sandstones and associated mudstones may represent smaller dome-shaped dunes and interdune areas. These are overlain by fluvial, horizontally- and cross-bedded sandstones (Purvis and Wright, 1991).

The base of the BSPB was arbitrarily taken as the base of the Triassic succession in Devon (Warrington *et al.*, 1980), although others (e.g. Edwards and Scrivener, 1999) adopt a lower level for that boundary, placing it at the base of the Aylesbeare Mudstone Group (see Chapter 2, p. 84). Though direct palaeontological evidence for age is lacking, the BSPB is dated as Early Triassic in age. This age is poorly constrained by Late Permian miospores in the upper part of the Exeter Group (below the Aylesbeare Mudstone Group, which underlies the BSPB; see Chapter 2), and the faunas of Mid Triassic (Anisian) age in the overlying Otter Sandstone Formation (see below and Benton and Spencer (1995) and Dineley and Metcalfe (1999).

Conclusions

The sea cliffs in the vicinity of Budleigh Salterton expose an excellent section of Triassic fluvial and aeolian sediments, including a complete section of the Budleigh Salterton Pebble Beds. The provenances of pebbles assessed from included fossils aid palaeogeographical reconstructions. Of particular significance is the ventifact and deflation horizon at the top of the BSPB, a feature common in modern deserts but rarely preserved in the geological record. This is a world-famous site, with a classic section through fluvial conglomerates, and critical for the understanding of British Early Triassic palaeoenvironments and palaeogeography.

LADRAM BAY TO SIDMOUTH, DEVON (SY 097 848–SY 131 873)

Potential GCR site

Introduction

The coastal cliffs around Ladram Bay and towards Sidmouth preserve an excellent section through the upper part of the Mid Triassic (Anisian) Otter Sandstone Formation.

The formation comprises approximately 210 m of cross-bedded sandstones associated with gravels, conglomerates, and mudstones. These are overlain by red marls of the Mercia Mudstone Group. The Otter Sandstone Formation has yielded an extensive Mid Triassic fauna, including branchiopod crustaceans, insects, fishes, temnospondyl amphibians, procolophonid reptiles, and archosaurs. In the GCR, the site has also been selected for its important fossil amphibians and reptiles (Benton and Spencer, 1995), fossil fishes (Dineley and Metcalfe, 1999) and coastal geomorphology (May and Hansom, in prep.). It is also being considered for addition to the GCR in its own right for its contribution to the study of the sedimentology and palaeoenvironments of Mid Triassic strata that are concealed beneath younger deposits farther east in the Wessex Basin, and form an important hydrocarbon reservoir in the Wytch Farm oilfield near Poole, Dorset. The site forms part of the Dorset and East Devon Coast World Heritage site.

The sediments from this section were described briefly by Whitaker (1869), Ussher (1875, 1876), Irving (1888, 1892, 1893), Hull (1892), Hutchinson (1906), and Woodward and Ussher (1911). More modern sedimentological studies have been produced by Henson (1970), Leonard *et al.* (1982), Mader (1985), Mader and Laming (1985), Purvis and Wright (1991), Smith and Edwards (1991), Wright *et al.* (1991), and Newell (1992). Descriptions of the vertebrate fossils and their occurrences have been given by Metcalfe (1884), Carter (1888), Spencer and Isaac (1983), Milner *et al.* (1990), Benton (1990), Benton and Gower (1997) and Benton *et al.* (1994).

Description

Triassic sediments are exposed in cliffs of varying height, and on the foreshore, between Ladram Bay and Sidmouth (Figure 3.75). The succession is almost continuously exposed through the greater part of its thickness in the coast from Otterton Point northwards, past Ladram Bay, to High Peak. The thickest succession ia seen in High Peak, the 150-m-high cliff immediately to the west of Sidmouth, where Triassic rocks are capped by Cretaceous strata.

Sedimentology

The sandstones of the Otter Sandstone Formation are typically red and were deposited

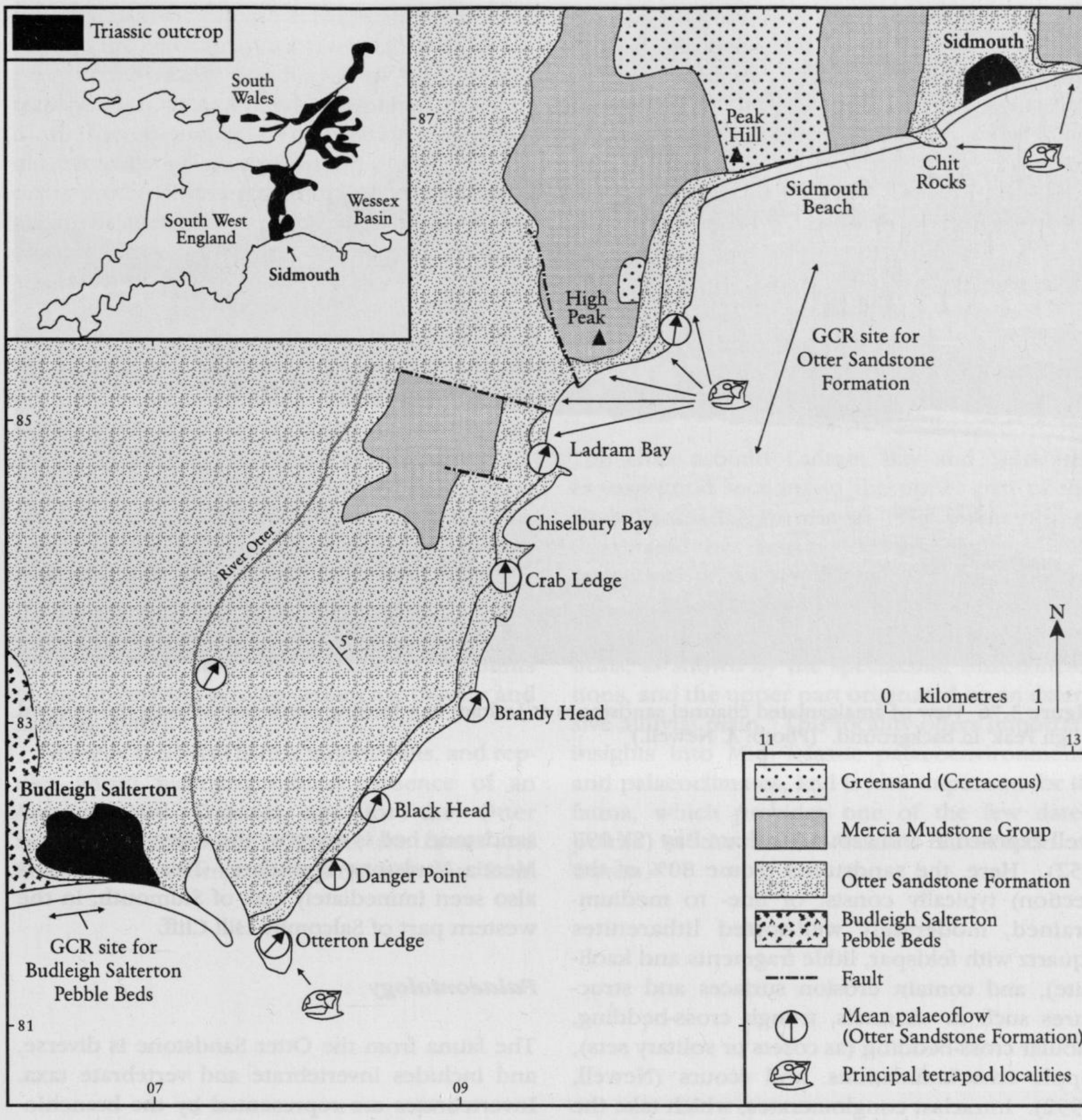


Figure 3.75 Map of the coastal outcrop of the Otter Sandstone Formation between Sidmouth and Budleigh Salterton, together with mean fluvial palaeoflow directions, and showing principal localities for fossil tetrapods. (From Benton *et al.*, 1994.)

in a series of fining-upwards cycles up to 2 m thick. These cycles rest on erosion surfaces that are commonly overlain by thin beds of conglomerate; finer-grained siltstone or mudstone units occur at the tops of some cycles. Cross-bedding and calcrete horizons are common, and mud cracks are occasionally preserved in the finer-grained sediments.

The lowest, aeolian, part of the Otter Sandstone Formation is best seen at Budleigh Salterton (see above). The boundary between these and the overlying fluvial sandstones is not seen in the coastal outcrops around Budleigh Salterton. South of Ladram Bay and between Ladram Bay and Sidmouth, the formation contains calcite in the form of vertically orientated, elongate cylindrical concretions (rhizocretions) or as laterally extensive sheets.

Fluvial sandstones of the upper part of the Otter Sandstone Formation (Figure 3.76) are

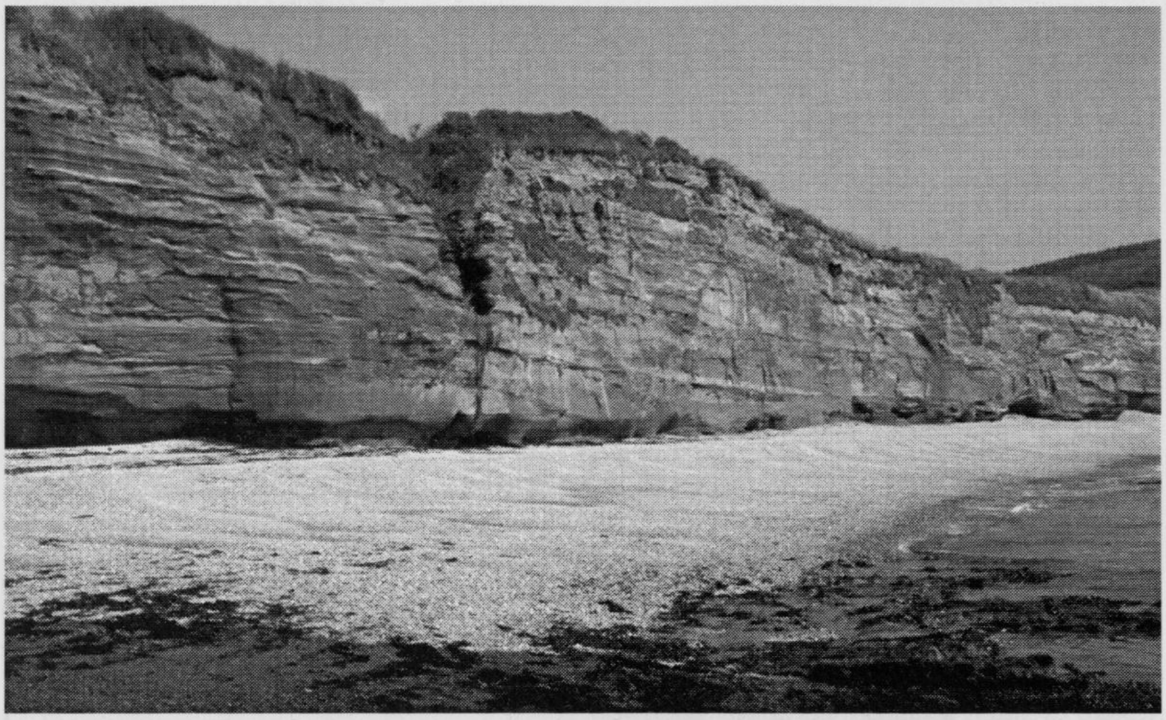


Figure 3.76 View of amalgamated channel sandstones at Ladram Bay, looking north-east towards the wooded 'High Peak' in background. (Photo: A. Newell.)

well exposed in and around Ladram Bay (SY 097 852). Here, the sandstones (some 80% of the section) typically consist of fine- to medium-grained, moderately well-sorted litharenites (quartz with feldspar, lithic fragments and kaolinite), and contain erosion surfaces and structures such as channels, trough cross-bedding, tabular cross-bedding (as cosets or solitary sets), ripple cross-laminations, and scours (Newell, 1992). Intraclast conglomerates, which take the form of horizontally bedded to massive conglomerates and associated tabular cross-bedded conglomerates, as well as mudclast-lined erosion surfaces, mudrocks, and carbonate concretions are also present (Mader, 1985; Newell, 1992).

The top of the Otter Sandstone Formation marks the boundary of the Sherwood Sandsone Group with the overlying Mercia Mudstone Group. The contact is seen in the vicinity of High Peak Hill (SY 104 858) and is traceable down-dip eastwards to the western end of Sidmouth Beach (SY 110 866), where it reaches beach level. Mudstone becomes more abundant towards the top of the Otter Sandstone Formation, and the top of the highest prominent sandstone bed is taken as the Otter Sandstone–Mercia Mudstone boundary. This boundary is also seen immediately east of Sidmouth, in the western part of Salcombe Hill Cliff.

Palaeontology

The fauna from the Otter Sandstone is diverse, and includes invertebrate and vertebrate taxa. Invertebrates are represented by the branchiopod crustaceans *Lioestheria* and *Euestheria*, and insects. Vertebrates include the fishes *Dipteronotus cyphus*, *Gyrolepis*, and *Lepidosteus* (Dineley and Metcalfe, 1999). The tetrapods are especially important and include the temnospondyl amphibians *Mastodonsaurus lavisi*, *Eocyclotosaurus*, and an indeterminate capitosaurid, reptiles such as the procolophonid *Kapes*, the rhynchosaur *Rhynchosaurus spenceri*, and rauisuchian archosaurs (Benton and Spencer, 1995; Benton and Gower, 1997).

Interpretation

The Otter Sandstone Formation is interpreted as a sequence of continental sediments. The vertical cylindrical calcitic concretions formed around the vertical tap roots of plants and were precipitated under conditions of high evapotranspiration, in an arid environments subject to a monsoonal climate. The calcrete sheets are characteristic of precipitation within the sediment profile from groundwaters, at or slightly above the ancient water table, and formed under arid climatic conditions (Purvis and Wright, 1991).

The Otter Sandstone Formation, above the basal aeolian beds seen at Budleigh Salterton (see GCR site report, this volume) was deposited under predominantly fluvial conditions. These sediments are typically coarse-grained towards the base, and consist of intraformational conglomerates with cross-bedded sandstones. Many of the conglomerates rest on erosion surfaces that may have well-developed scour structures (Newell, 1992). It is thought that the fluvial sandstones were deposited on a broad plain that supported many braided rivers that were responsible for reworking substantial amounts of the underlying aeolian sediments (Mader and Laming, 1985).

Some of the fossil fishes, amphibians, and reptiles afford biostratigraphical evidence of an Anisian (Mid Triassic) age for the Otter Sandstone Formation. Overall, the fauna and flora from this formation is similar to that from the Bromsgrove Sandstone Formation in the English Midlands, the Upper Bundsandstein of Germany and the *Voltzia* Sandstone of France (Milner *et al.*, 1990; Benton *et al.*, 1994). The procolophonid *Kapes* provides a correlation with the Russian Triassic succession; this genus is known from the Gam Svita of the Yarenskian Gorizont, and from the Donguz Gorizont, which are dated, respectively, as upper Olenekian and upper Anisian to lower Ladinian respectively (Spencer and Benton, 2000).

Conclusions

The cliffs around Ladram Bay and Sidmouth expose good sections in the upper part of the Otter Sandstone Formation. The sediments are dominated by cross-bedded sandstones, with occasional gravel and pebble beds, mudstones, and calcretes. The lower part of the formation here was deposited under monsoonal conditions, as shown by the spectacular rhizoconcretions, and the upper part originated on an extensive alluvial plain. This locality offers important insights into Mid Triassic palaeoenvironments and palaeoclimates, and is also important for its fauna, which provides one of the few dated points in the Permo–Triassic succession of Devon.