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

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GCR Editor: **G. Warrington**

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Chapter 2

British Permian red beds

PERMIAN RED-BED GCR SITES

It is impossible to document a typical succession of the British Permian red beds in any single part of the country since each sedimentary basin has unique features (Smith *et al.*, 1974). Therefore, in this chapter, the GCR localities are assigned to regional site networks, broadly representing the major basins of sedimentation during the Permian Period:

- Moray Firth Basin, north-east Scotland (2 sites),
- south-west Scotland (3 sites),
- north-east England (1 site),
- west Cumbria (1 site),
- the Vale of Eden (6 sites),
- the English Midlands (3 sites), and
- Devon (7 sites).

The broad stratigraphical and sedimentary conditions of each basin are outlined section-by-section; a total of 23 GCR sites have been selected to illustrate the key features of the British Permian red beds (Figure 2.1).

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

INTRODUCTION

The age of red beds now assigned to the Permian and Triassic systems of the area around Elgin (Figure 2.2) in the Moray Firth Basin has been debated extensively since the 1830s. At first, these sandstone units were mapped as part of the Devonian Old Red Sandstone. Discovery of the first fossil at Lossiemouth, a cuirass of armour plates, named *Stagonolepis* by Louis Agassiz in 1844, did nothing to change this view: *Stagonolepis* was interpreted as a large, excessively well-armoured ganoid fish. Doubts arose in 1850, with the discovery of footprints at Cummingstone (Clashach–Covesea GCR site) and the skeleton of *Leptopleuron* at Spynie. Charles Lyell was keen to argue that these were clearly advanced reptiles from definitively Devonian rocks. Others, however, had doubts; to Richard Owen such seemingly advanced fossils appeared incompatible with rocks of that age, and Thomas Henry Huxley concurred. With finds of further bones of larger reptiles in the late 1850s, it generally became recognized that both Devonian and Permo–Triassic ('New Red Sandstone') rocks occurred around Elgin.

With further work, it became clear that there were three main formations within the Morayshire Permo–Triassic succession (Peacock *et al.*, 1968), formalized as the 'Hopeman Sandstone Formation', the 'Burghead Sandstone Formation', and the 'Lossiemouth Sandstone Formation' by Warrington *et al.* (1980). The first and last of these formations contained relatively abundant reptilian fossils, and hence could be dated in a general way. The intervening Burghead Sandstone Formation lacks fossils, and cannot be dated directly. The Hopeman Sandstone Formation has long been equated with Late Permian or Early Triassic reptile-bearing units in the Karroo of South Africa and the South Urals in Russia. Most authors have preferred a Late Permian age, although Walker (1973) opted for an Early Triassic one, a view followed by Smith *et al.* (1974) and Warrington *et al.* (1980). Re-consideration of the reptiles and footprints (Benton and Walker, 1985) now points firmly to a latest Permian age, and hence the representative GCR sites are described in the present chapter.

The geology of the Permian strata 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 (1966, 1977), Peacock *et al.* (1968), Williams (1973), Benton and Walker (1985), Gillen (1987), and Edwards *et al.* (1993). The Permo–Triassic rocks of Morayshire are, in addition, merely a small onshore expression of an extensive development of those deposits offshore in a major basin beneath the Moray Firth (Frostick *et al.*, 1988; Andrews *et al.*, 1990; Edwards *et al.*, 1993).

Two GCR sites have been selected to illustrate the Permian strata of the Moray Firth Basin, the Clashach–Covesea coastal section and Masonshaugh (Figure 2.2) in the type area of the Hopeman Sandstone Formation.

CLASHACH TO COVESEA, MORAYSHIRE (NJ 162 703–NJ 173 706)

Introduction

The coastal exposures between the quarries of Clashach and Covesea provide an excellent section in the Hopeman Sandstone Formation. This formation is dated as latest Permian in age

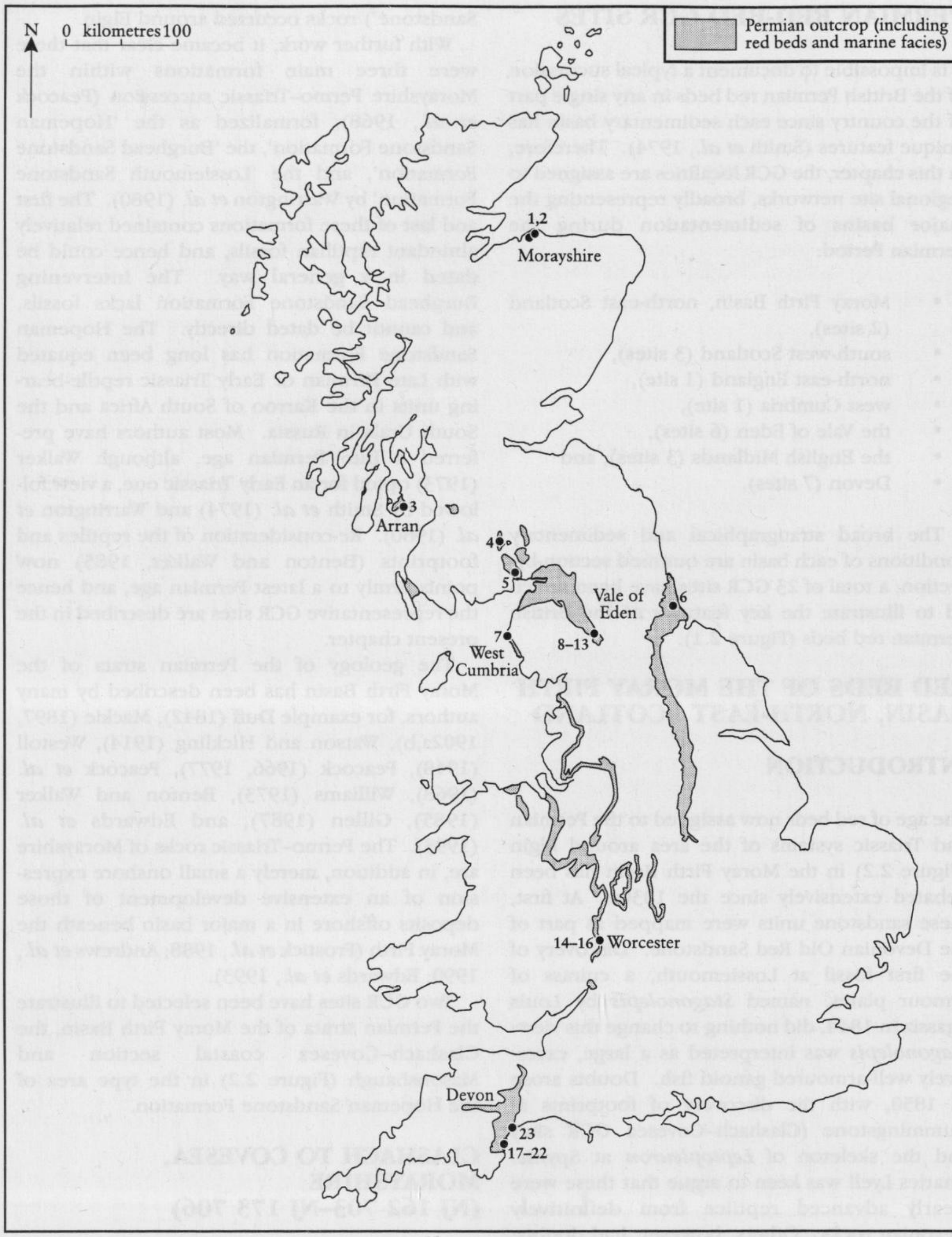


Figure 2.1 Map showing the outcrop of Permian rocks in Great Britain. Some major basinal areas are indicated. GCR Permian red-bed sites are numbered as follows: (1) Clashach–Covesea; (2) Masonshaugh Quarries; (3) Corrie Shore; (4) Hapland Burn; (5) Locharbriggs North Quarry; (6) Crime Rigg Quarry; (7) Saltom Bay; (8) Burrells Quarry; (9) Cowraik Quarry; (10) George Gill; (11) Hilton Beck; (12) Stenkrith Beck; (13) River Belah; (14) Sling Common; (15) Osebury Rock; (16) Kinver Edge; (17) Shoalstone; (18) Saltern Cove; (19) Roundham Head; (20) Oddicombe Beach; (21) Coryton's Cove; (22) Dawlish; (23) Orcombe Rocks.

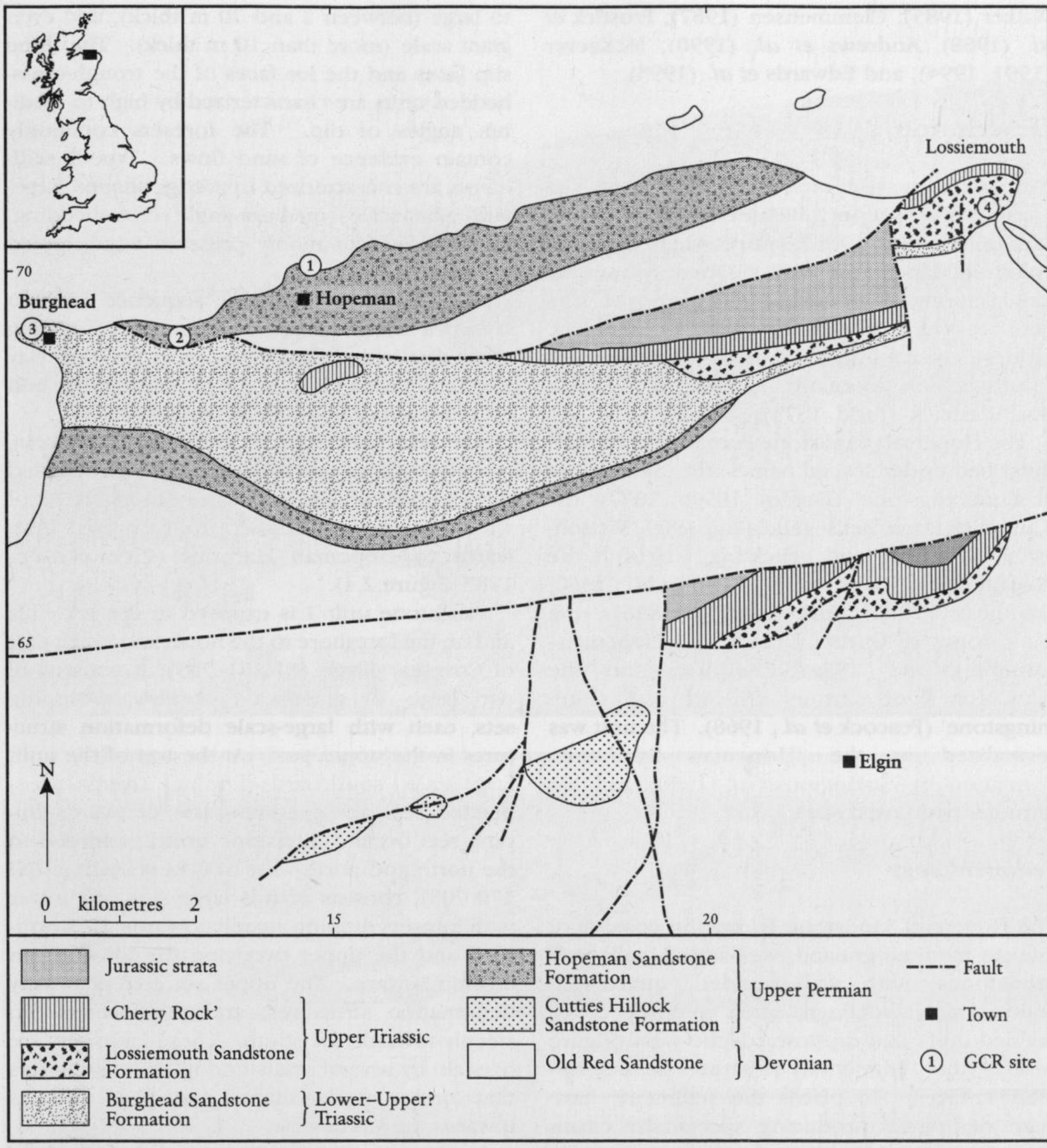


Figure 2.2 The distribution of Permo–Triassic sediments around Elgin, Morayshire. GCR sites are: (1) Clashach–Covesea (Permian); (2) Masonshaugh Quarries (Permian); (3) Burghead (Triassic); (4) Lossiemouth (Triassic). Based on Peacock *et al.* (1968) and Benton and Walker (1985).

on the basis of its contained fossil reptile remains and footprints. The sandstones show a variety of sedimentary lamination types within large-scale dune bedding. The site is significant for the detailed evidence it affords for a variety of desert dune types, including the unusual large-scale star dune form. Cross-strata, often affected by spectacular post-depositional deformation structures, dip generally to the west, indicating that contemporary winds blew from the east.

The sediments and palaeoenvironmental reconstruction of the Hopeman Sandstone Formation have received much attention, with descriptions by Peacock *et al.* (1968), Williams (1973), Glennie and Buller (1983), Benton and

Walker (1985), Clemmensen (1987), Frostick *et al.* (1988), Andrews *et al.* (1990), McKeever (1991, 1994), and Edwards *et al.* (1993).

Description

Numerous quarries were opened along the coastal cliff section between Covesea and Clashach in the 19th century, when the buff-coloured sandstone was shipped by sea to neighbouring towns for building purposes. The quarries were all abandoned until recently; modest quarrying has been resumed at Clashach. An alternative spelling of Clashach was 'Clashack' (Judd, 1873).

The Hopeman Sandstone Formation has been described under several names: the 'Sandstones of Cummingstone' (Huxley, 1859b, 1877), the 'Cummingstone Beds' (Hickling, 1909; Watson, 1909; Watson and Hickling, 1914), the 'Reptiliferous Sandstone' (Symonds, 1860; Harkness, 1864; Judd, 1873, 1886), the 'Sandstones of Cutties Hillock and Hopeman–Cummingstone' (Westoll, 1951), and the 'Sandstones of Cutties Hillock and Cummingstone' (Peacock *et al.*, 1968). The unit was formalized as the 'Hopeman Sandstone Formation' by Warrington *et al.* (1980), and that term has been used since.

Sedimentology

The Hopeman Sandstone Formation consists of fine- to medium-grained, well-sorted, yellowish sandstones, with well-rounded, quartz-rich grains and well-defined, often complex, cross-bedded units that dip towards the west (Figure 2.3a). Other sedimentary structures include rippled surfaces. In places the sediments have been deformed, producing spectacular examples of contorted bedding (Peacock *et al.*, 1968; Glennie and Buller, 1983; Clemmensen, 1987; Figure 2.3b). The formation has been divided into two informal units by Glennie and Buller (1983): the lower unit, exposed on the foreshore, consists of large-scale cross-bedded sandstones that pass laterally into substantial areas of deformed sediments; the upper unit has large-scale cross-bedding, but lacks soft-sediment deformation.

Two main sediment types have been distinguished (Clemmensen, 1987). Type-I sediments are typically arranged in trough-cross-bedded units that range from small (less than 1 m thick) to large (between 1 and 10 m thick), and even giant scale (more than 10 m thick). The dune slip faces and the lee faces of the trough-cross-bedded units are characterized by high to medium angles of dip. The foresets commonly contain evidence of sand flows. Type-II sediments are characterized by wedge-shaped large- and giant-scale, medium-angle cross-bedding. The foresets commonly preserve wind-rippled surfaces.

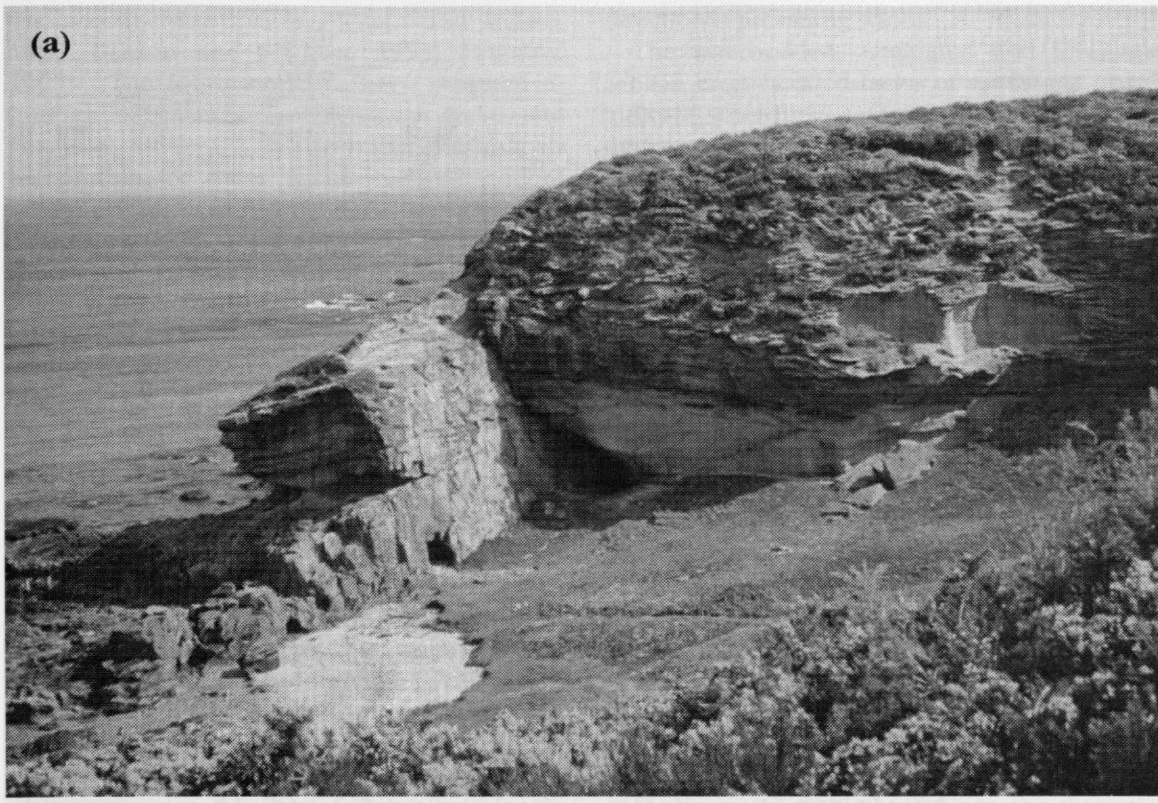
Scattered throughout the sequence are thin layers of coarser-grained sediments containing clasts that include granules, small pebbles, clay curls and flakes encrusted with sand grains, and intraformational clay rip-up clasts.

The excellent exposure of the sediments, especially along the coast, has enabled detailed descriptions of the sandstone units, nine of which have been identified from Covesea westwards to Hopeman Harbour (Clemmensen, 1987; Figure 2.4).

Sandstone unit 1 is exposed in the sea cliffs and on the foreshore to the north and north-east of Covesea village (NJ 171 705); it consists of two large- or giant-scale, southward-dipping sets, each with large-scale deformation structures in the upper part. At the top of the unit, large-scale, southwards-dipping, trough-cross-bedded sets and medium-scale eastwards-dipping sets occur. Sandstone unit 2, exposed to the north and north-west of Covesea village (NJ 170 705), consists of two large sets, the lower with foresets dipping steeply towards the north-east, and the upper overlying the lower at an erosion surface. The upper set contains many deformation structures, and the foresets dip steeply towards the south. These large sets are overlain by several small- and medium-scale sets that form a wedge-shaped unit that thickens towards the south-west.

Sandstone unit 3 is exposed in the cliffs to the south-west of sandstone unit 2 (Figure 2.3a). It comprises approximately 10 m of interbedded horizontally bedded and low-angle cross-stratified sandstone with multiple angles of dip, which infills the low-lying areas between sandstone units 2 and 4.

Sandstone unit 4 consists of two giant-scale sets, with maximum thicknesses of 15 m (set 4) and 30 m (set 5). Set 4 foresets dip towards the north and north-east and the angle of dip decreases towards the north, set 5 foresets dip towards the west, and there are well-developed tangential foresets. This set is subdivided into a



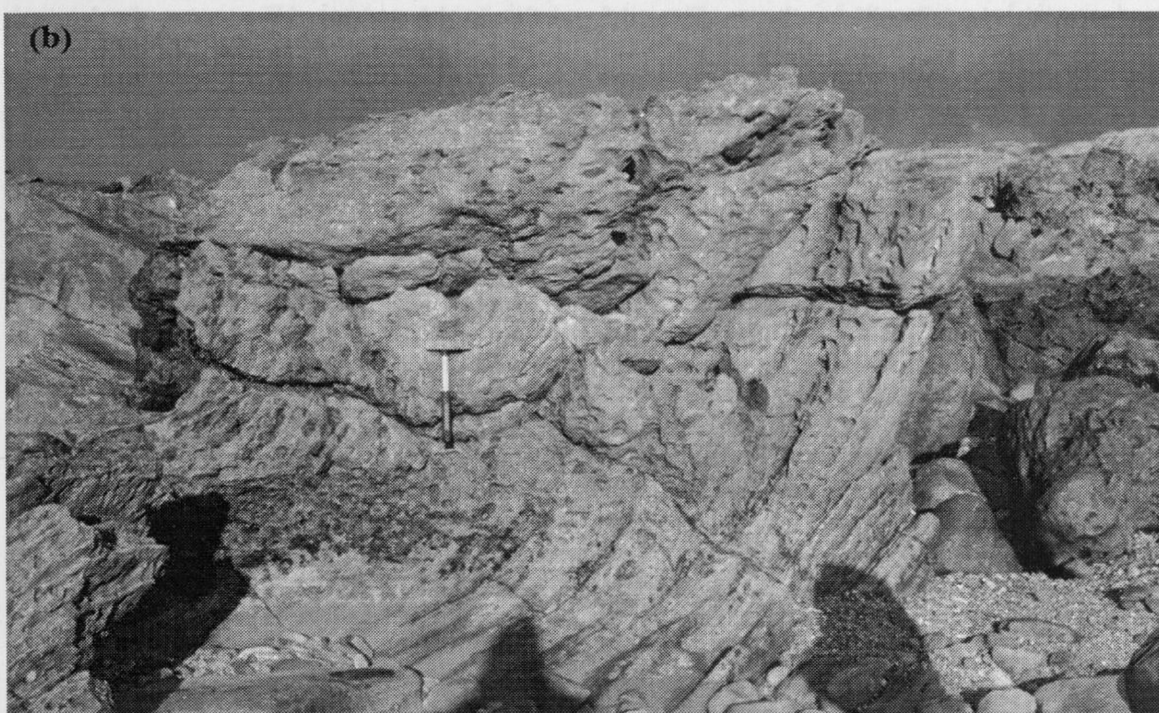


Figure 2.3 The Permian Hopeman Sandstone Formation in the cliffs between Clashach and Covesea. (a) Cliff section (looking east) showing cross-bed dune sets representing a complex star dune. (b) Sand dune deposits north of Covesea Quarry, showing localized synsedimentary deformation; part of dune No. 5 on Figure 2.4 (Photos: (a) C. J. MacFadyen, (b) P. Turner.)

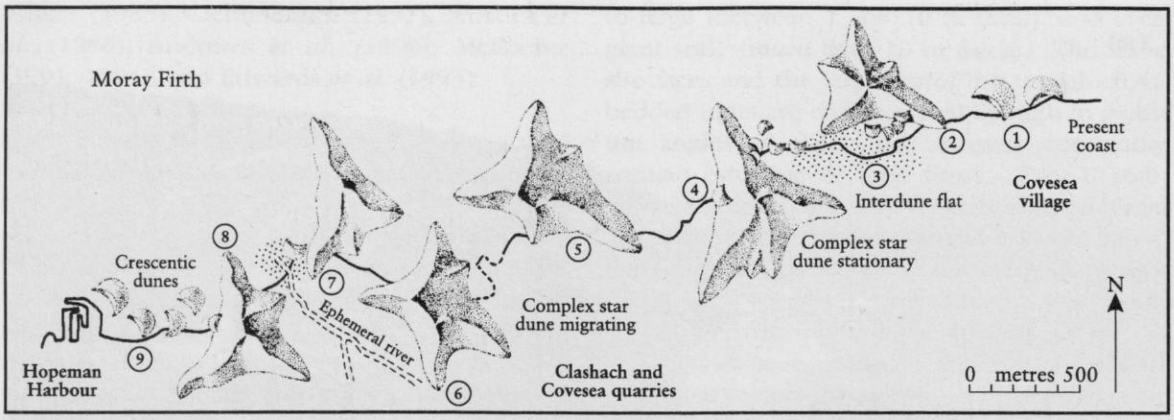


Figure 2.4 Reconstruction of the large-scale star dunes shown by outcrops in the Clashach–Covesea section. Numbers (1) to (9) are the individual dunes, as referred to in the text. (After Clemmensen, 1987.)

series of small subsets that generally dip towards the north-east, and often wedge out in either the up-dip or down-dip directions. The giant-scale sets are associated with numerous intrasets, which are typically trough-formed and wedge-shaped.

On the foreshore between the Clashach and Covesea quarries (NJ 167 705) the two giant sets, with clearly defined bounding surfaces, of sandstone unit 5 are exposed. Set 6 is characterized by foresets that dip towards the south-west and south-east, and is trough-formed. Set 7 shows a range from trough to planar bedding and foresets dip towards the SSE.

Beds of sandstone in unit 6 are best seen in Clashach Quarry (NJ 162 702) and in the nearby coastal exposures. These sediments have a complex geometry and consist of several overlapping units; they display sand-flow layers, trough cross-bedding, and low-angle stratified sand sheets with a wide range of angles and directions of dip.

Sandstone unit 7 is composed of bi-modally-dipping large- and giant-scale sets, and is associated with low-angle beds with channels, scatters of granules, and small current ripples.

Near Hopeman Harbour (NJ 145 700), sandstone unit 8 is characterized by two bi-modally-dipping, large- and giant-scale sets. Towards the east, a sequence of low-angle interdune and channel sediments occurs. To the west, the large-scale trough-cross-bedded sets of sandstone unit 9 occur; these generally have a high angle of dip towards the south-west.

Deformation structures are common throughout the Hopeman Sandstone Formation, and frequently occur in the lower unit of Glennie and Buller (1983); they are complex and take several forms (Figure 2.3b). In the cliffs close to the coastguard's station (NJ 176 708), the cross-bedded sandstones preserve a 10-m-high, triangular-shaped, fluid escape structure (Glennie and Buller, 1983, p. 58). Within the core of this structure, the deformed bedding is very poorly defined, although at the margins the laminae and beds are better preserved; crumpling of the beds suggests that vertical compaction of the sediments also took place. Close to Hopeman, the sandstone has been deformed into a shallow saucer shape, composed of laminated sediments cut by narrow vertical bands of structureless sediment. The laminated sediments were deposited on the upper windward face of the dunes, and appear to have collapsed into an underlying patch of quicksand. Also close to Hopeman, 3 m of deformed sandstones have been inverted over a low-angle fold plane that dips towards the north-west.

The sediments are unevenly cemented by silica and iron oxides, with smaller patches of barite and carbonates. Where carbonate cements predominate, the softer, less resistant sediment has been removed by erosion, producing hollows and cavities (Mackie, 1902a; Peacock *et al.*, 1968; Clemmensen, 1987).

Palaeontology

The Hopeman Sandstone Formation has yielded many vertebrate footprints. At Clashach Quarry a substantial slab of sandstone displays a series of large footprints arranged in a short length of trackway (Sarjeant, 1974; Benton and Walker, 1985; Benton and Spencer, 1995; Hopkins, 1999). The footprints have been assigned to four ichnospecies of *Chelichnus* (McKeever and Haubold, 1996). It is likely that the animals responsible for these tracks were dicynodont mammal-like reptiles and pareiasaurs (McKeever, 1991, 1994). A skull of *Dicynodon* (*Gordonia*) has also been reported from the working Clashach Quarry (Clark, 1999).

Interpretation

The Hopeman Sandstone Formation sediments were deposited on the southern edge of the largely offshore Moray Firth Basin (Clemmensen, 1987; Frostick *et al.*, 1988; Andrews *et al.*, 1990; Edwards *et al.*, 1993). The sandstone units exposed along the coastline between Covesea, Clashach, and Hopeman Harbour have been collectively interpreted as part of a substantial dune field. The dominant processes of sediment accumulation and deposition were aeolian, although there is evidence for periodic, minor, fluvial activity. The individual sandstone units represent localized features within the desert environment. The dominant wind direction during deposition was from the NNE, with secondary winds from the SSE, and subordinate winds from the north-west (Clemmensen, 1987). Glennie and Buller (1983) interpreted the main dune type as transverse dunes, while Clemmensen (1987) regarded them as mainly crescentic and star dunes (Figure 2.4); the latter interpretation is followed below.

Sandstone unit 1, characterized by large-scale southward dipping foresets capped with smaller-scale east and southwards dipping troughs and sets, has been interpreted as the slip-face deposits of a southwards-migrating crescentic dune, or possibly as an incipient star dune, that were eroded and overlain by sandsheet deposits. The dominant wind direction was from the north, although the dips of the foresets in the upper beds suggest alternation between southerly and north-easterly winds (Clemmensen, 1987).

Sandstone unit 2, with two sets with foresets that dip at high angles to the north-east and south, and are overlain by smaller-scale sets arranged in a wedge, is interpreted as the two faces of a NW–SE-trending arm of a star dune. This feature was eroded and replaced by sand sheets deposited under the influence of bi-directional prevailing winds.

The interbedded, laminated and low-angle aeolian cross-bedded facies of sandstone unit 3 indicate interdune sedimentation. The great thickness of this unit suggests that contemporary star dunes were relatively static features of the landscape.

Sandstone unit 4, characterized by two giant-scale sets, with widely differing angles of foreset dip, formed part of a NNW–SSE-trending arm of a star dune. The intrasets formed during periods when the wind direction fluctuated between the north-east and south. This resulted in the faces of the star dune arm alternating between the lee- and stoss-side. Set 5 is interpreted as the west-facing side of the dune arm, and also preserves features consistent with deposition under fluctuating wind directions. The north-east face of the dune merges into an area dominated by relatively small barchans (Clemmensen, 1987).

The trough and planar cross-bedded sediments of sandstone unit 5 were deposited by crescent-shaped dunes, probably as part of a complex star dune migrating to the south-west. A similar mode of deposition is considered likely for the unit 6 sandstone. Here, the characteristic wide range of directions of dip is best explained in terms of a complex star dune with many crescent-shaped segments. The unit 6 star dune is a development of the feature recorded by sandstone unit 5, and it continued to migrate towards the south-west.

The bi-modally dipping large-scale sets with the associated coarse-grained material and channels of sandstone unit 7 record both aeolian and fluvial environments. The aeolian sediments were deposited on a large arm of a star dune. Nearby, interdune areas contained small channels, and the presence of small current ripples indicate that the interdune regions were periodically flooded (Clemmensen, 1987). Sandstone unit 8 represents deposition on and around the arm of a sinuous-crested star dune arm.

The overlapping large-scale trough-cross-bedded sets of unit 9 were deposited by barchan dunes that were migrating mainly towards the south-west (Clemmensen, 1987).

The soft-sediment deformation structures have been interpreted as either the result of a major phase of air escape following a dramatic transgression event (Glennie and Buller, 1983), or as liquefaction induced by heavy rainfall (Peacock, 1966; Clemmensen, 1987). The latter interpretation seems more likely, by comparison with soft-sediment deformation structures seen elsewhere in aeolian sequences. Frostick *et al.* (1988) suggested that the deformation happened by slumping of the sands down the flanks of large dunes following heavy rainfall. The air-escape and marine inundation idea is weakened by the fact that there is no evidence of erosion anywhere, nor are there any superincumbent marine beds.

The age of the Hopeman Sandstone Formation has been the subject of much discussion (see above). The footprints, and the recent find of *Gordonia* (*Dicynodon*), from Clashach and Masonshaugh, and the reptile skeletons from probably coeval sandstones inland at Cutties Hillock, have been used to posit either a Late Permian or an Early Triassic age. The dicynodonts *Gordonia* and *Geikia* from Cutties Hillock, and the interpretation of most of the footprints as having been made by dicynodonts, is not immediately helpful since dicynodonts range from Late Permian to Late Triassic in age. However, *Gordonia* is virtually identical with *Dicynodon* from the Late Permian rocks of South Africa, and this indication of a latest Permian age is confirmed by the pareiasaur *Elginia* from Cutties Hillock; pareiasaurs are known only from latest Permian deposits.

The deformation structures might also offer evidence of age. Glennie and Buller (1983) argued that they matched those in the Weissliegend of Germany (see Figure 1.3) and the southern North Sea, and hence indicated a Mid Permian age. The deformation structures in both units were linked to the Zechstein transgression. However, analysis by Clemmensen (1987) indicates that there is no stratigraphical relationship between the various examples of deformation structures, and the palaeontological evidence for age takes precedence.

Conclusions

The Permian sediments of the Hopeman Sandstone Formation preserve rare examples of star dunes. The dominantly arenaceous sediments were deposited in a substantial dune field characterized by crescentic barchan dunes, mobile and stationary star dunes, and interdune accumulations and coarse-grained fluvial deposits. Fossil footprints, and the skull of a dicynodont, indicate that the dune field was inhabited by a fauna of reptiles.

MASONSHAUGH QUARRIES, MORAYSHIRE (NJ 122 691–NJ 133 692)

Introduction

The disused quarries at Masonshaugh and coastal sections to the east and west provide excellent exposures of the Hopeman Sandstone Formation. The sandstones show large-scale cross-bedding and other features that indicate sediment transport by wind in a desert. Abundant footprints found in the quarry in the 19th century provide age and environmental evidence. The faulted contact with the younger Burghead Sandstone Formation, at the western end of this part of the site, is associated with barite, fluorspar, and silica mineralization, and these minerals locally act as a cement. This is an important site for the interpretation of Late Permian palaeoenvironments and sedimentology, and the effects of faulting.

The sediments and trace fossils of the Hopeman Sandstone Formation were first described by Huxley (1859b, 1877). Recent descriptions of the locality and surrounding area are included in Clemmensen (1987), Gillen (1987), and Edwards *et al.* (1993). The vertebrate tracks and body fossils preserved in the Hopeman Sandstone Formation have been described more recently by Benton and Walker (1985), McKeever (1991, 1994), and McKeever and Haubold (1996). See also Clark (1999) and Hopkins (1999).

Description

The Masonshaugh GCR site is part of the Burghead–Masonshaugh coastal Site of Special Scientific Interest (SSSI), and is in continuity with another GCR site selected for coverage of the Triassic Burghead Sandstone Formation (see Chapter 3). The Masonshaugh section has also been selected for the GCR independently for its fossil reptiles (Benton and Spencer, 1995).

Sedimentology

The Hopeman Sandstone Formation, which crops out along the southern margin of the Moray Firth, is well exposed at Masonshaugh Quarry. The sediments consist predominantly of yellow and white, strongly cemented sandstones with well-rounded, often spherical quartz grains and with some feldspar and scarce mica (Watson and Hickling, 1914; Gillen, 1987). On the coast, the formation is typically less well-cemented, and is brownish-yellow in colour.

The sandstones preserve excellent examples of cross-bedded units, whose foresets dip south-west, and in places contain lenses of coarser-grained sandstones and pebbles. Watson (1909) recorded cross-bedding foresets with an apparent dip of 40° to the south-west, but the true angle of dip is probably only a few degrees, and is highly variable. The cross-bedding takes two forms; trough cross-bedding in large-scale sets, 1 to 10 m thick, and giant sets more than 10 m thick; and large- and giant-scale bi-modally dipping overlapping sets (Clemmensen, 1987).

In places the sediments are flaggy, and contain a relatively high proportion of clay minerals in lenses that contain some crude small-scale cross-bedding and slump structures (Peacock *et al.*, 1968), sometimes associated with ripple marks and mud cracks (Judd, 1873). Vertebrate tracks are preserved on the bedding planes of these flaggy beds (Watson, 1909).

A substantial E–W-trending fault, the Splay Fault (Figure 2.5), part of the major Lossiemouth Fault Zone (see Figure 1.8), brings the Hopeman Sandstone Formation into contact with the stratigraphically younger Burghead Sandstone Formation (Peacock *et al.*, 1968). Minerals such as galena and fluorite, both occurring as cubic crystals, are found close to the fault planes (Watson, 1909; Watson and Hickling, 1914). Edwards *et al.* (1993) mapped zones of mineralized cements in the Hopeman Sandstone Formation beside the Lossiemouth Fault (Figure 2.5). Barite is the dominant cement for 1 km to the east of the fault, then fluorspar for the next 1 km, and silica east of that, around Covesea. Close to the major fault, and around all minor faults, there is a zone of hard, splintery, strongly cemented sandstone, which weathers more slowly than the remaining sandstone (Figure 2.6). The main fault is associated with numerous, complex deformation zones through the Hopeman Sandstone Formation, and these affected the nature of mineralization. Deformation zones decrease in frequency away from the major faults.

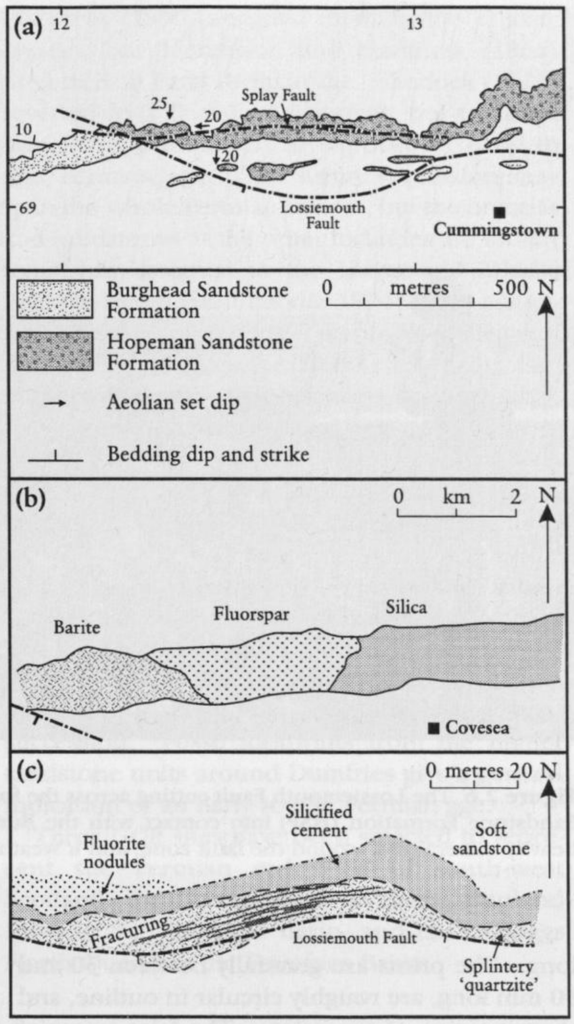


Figure 2.5 The Hopeman Sandstone Formation at Masonshaugh. (a) Detail of the faulted contact between the Burghead Sandstone Formation (Triassic in age) and the Hopeman Sandstone Formation (Permian), showing the major fault zone, western termination of the Lossiemouth Fault. (b) The regional zonation of barite, fluorspar, and silica cements in the Hopeman Sandstone Formation along the north coast of Morayshire. (c) Details of the cement zone around the Lossiemouth Fault as it cuts across the beach at Masonshaugh at NJ 131 693, showing zones of fluorite and silicified cements in the sandstone. (After Edwards *et al.*, 1993.)

Palaeontology

Four distinct forms of footprints have been described from the Hopeman Sandstone Formation at Masonshaugh Quarries (McKeever, 1994; McKeever and Haubold, 1996; Hopkins, 1999), although only a small and a large form had been distinguished previously (Brickenden, 1852; Huxley, 1859b, 1877; Benton and Walker, 1985). The smaller form, *Chelichnus bucklandi*, is seen in a trackway approximately 145 mm

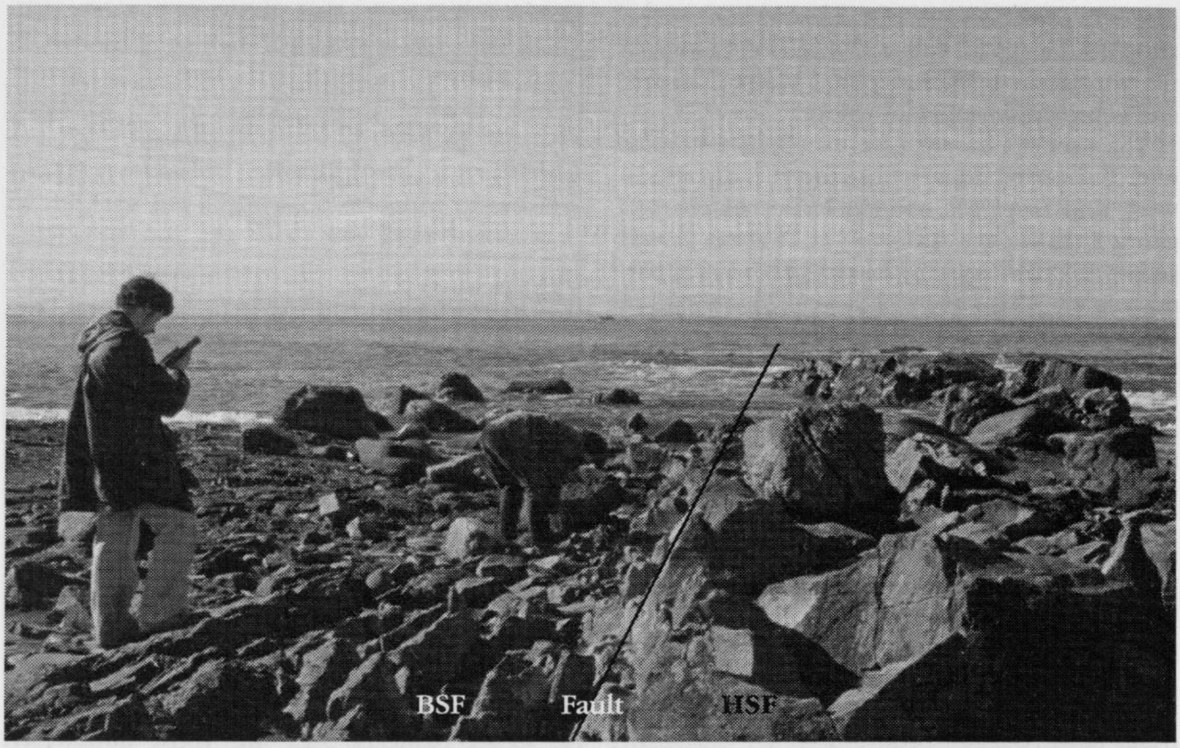


Figure 2.6 The Lossiemouth Fault cutting across the foreshore at Masonshaugh Quarry, bringing the Hopeman Sandstone Formation (HSF) into contact with the Burghead Sandstone Formation (BSF). The sandstone is heavily mineralized around the fault zone, and it weathers slowly. (Photo: M. J. Benton.)

long. The prints are generally between 30 and 40 mm long, are roughly circular in outline, and show no sign of toe prints. The faint traces of tail drag marks are seen between some of the prints.

The larger prints show clearly defined impressions of toes. The fore prints are semicircular in outline, 40 mm long and 60 mm wide, with four or five claw marks at the front. The hind prints are 90 mm long and 80 mm wide, with five claws. A mound of sediment is preserved behind each print, suggesting that the animals were walking up a slope (Benton and Walker, 1985). McKeever and Haubold (1996) assigned these larger prints to the ichnotaxa *Chelichnus duncani*, *C. gigas*, and *C. titan*.

Interpretation

The sandstones and pebbly sandstones at Masonshaugh Quarry have been interpreted as deposits of a complex environment dominated by aeolian deposition, but which also experienced periods of heavy rainfall and localized flooding. The sediments accumulated in a half-graben, associated with tectonic activity along the Great Glen Fault (Frostick *et al.*, 1988).

The well-sorted, cross-bedded sandstones of the Hopeman Sandstone Formation are indicative of aeolian deposition. The sedimentary geometry of this stratigraphical unit has been extensively studied by Clemmensen (1987), who interpreted the structures as complex star dunes and crescentic barchans. An analysis of the foreset orientations of these dunes indicates that the dominant wind directions were from the NNE, although there were subordinate, but significant, winds blowing from the SSE and northwest. The second type of aeolian deposits, characterized by large- and giant-scale, bi-modally dipping, overlapping sets, are interpreted as the arms of large star dunes that were orientated parallel to the dominant wind directions. The coarser-grained, pebbly sandstones were deposited during flash flood events (Williams, 1973).

The deformation zones at Masonshaugh indicate major tectonic activity, dominated by extension (Edwards *et al.*, 1993). The Burghead Sandstone Formation, on the west side of the fault was less affected since it has a less even grain-size distribution than the Hopeman Sandstone Formation. The faults initially acted as conduits to mineral-bearing fluids that penetrated the porous sandstones and precipitated cements in the deformation zones. Sandstones outside the deformation zones are less heavily cemented.

Conclusions

The sandstones of the Hopeman Sandstone Formation were deposited in a large desert, dominantly in large star- and crescent-shaped aeolian sand dunes. Interbedded with these deposits are thin beds of pebbles, deposited during flash floods. The sandstones exposed at Masonshaugh Quarry preserve many fine examples of vertebrate tracks. The Masonshaugh site is complementary to the Covesea–Clashach GCR site because it shows the rare fluviatile and flash-flood deposits better, and displays the unusual mineralization associated with the faulted western contact with the Burghead Sandstone Formation.

THE PERMIAN RED BEDS OF SOUTH-WEST SCOTLAND

INTRODUCTION

In south-west Scotland, the Permian red beds are preserved on the island of Arran and in the Mauchline Basin, just south of Glasgow, and the Thornhill, Moffat, Lochmaben, Dumfries, and Stranraer basins in Dumfries and Galloway (Figures 1.7 and 2.1). The succession in each occurrence begins with a breccia unit, above which are red- and yellow-coloured sandstones overlain, in some cases, by further breccias and water-laid sandstones (Smith *et al.*, 1974). On Arran, the succession is overlain, without a clear break, by Triassic strata (see Chapter 3), while, in the other basins, the Permian red beds are capped by Quaternary sediments. In the Mauchline Basin the basal breccia is associated with volcanic tuffs and rare basaltic lavas; similarly the basal part of the Permian succession in the Thornhill Basin is associated with basalt flows.

The age of the south-west Scottish 'New Red Sandstone' deposits has long been debated. Harkness (1850) assigned them to the Triassic System, but Murchison and Harkness (1864) preferred an Early Permian age. Sherlock (1926) reverted to a Triassic assignment, but evidence has since accumulated to support an Early to Mid Permian age. The Arran succession may span the whole Permian System, but the breccias and sandstones at the other localities are mostly tentatively assigned to the Lower and Middle Permian series (Smith *et al.*, 1974). This assignment is based on the fossil plants from the basal units of the Mauchline Basin succession that indicate a latest Carboniferous to, probable, Early Permian age (Wagner, 1983). Radiometric dates of 286 ± 7 Ma from the Mauchline Basin tuffs are not satisfactory because of the condition of the sampled rock, the analytical technique, and the poor biostratigraphy (De Souza, 1982, cited in Forster and Warrington, 1985). The breccias and conglomerates at the base of the Permian successions elsewhere in south-west Scotland are then correlated, on broad lithological comparisons, with the Mauchline succession. Fossil footprints from the higher sandstone units around Dumfries give a general indication of an Early to Mid Permian age.

Three GCR sites have been selected to represent the Permian red beds of south-west Scotland: the Corrie Shore on Arran, Hapland Burn in the Thornhill Basin, and Locharbriggs North Quarry in the Dumfries Basin.

CORRIE SHORE TO BRODICK, ISLE OF ARRAN (NS 026 422–NS 026 432)

Introduction

The coastline around the harbour at Corrie, on the east coast of Arran, exposes an excellent section through the Corrie Sandstone and the Brodick Breccia. The sandstones show fine examples of large-scale cross-bedding, often in three dimensions. Associated with the dunes are laminated interdune deposits and features, such as deflation lags, that are indicative of a desert environment. Fluvial sandstones, characterized by small-scale cross-bedding and desiccation cracks, are interbedded with the aeolian sediments. Also present at this locality are fulgurites, created by lightning strikes that entered the sand and fused the grains. This is a key locality for the study of the Permian palaeoenvironments of Scotland.

The sediments exposed at Corrie Shore have been described by Gregory (1915), Piper (1970), Lovell (1971), Steel (1974b), Astin and MacDonald (1983), Clemmensen and Abrahamsen (1983), Clemmensen and Hegner (1991), Clemmensen *et al.* (1994), and Frederiksen *et al.* (1998). Field guide accounts include MacDonald and Herriot (1983) and McKerrow and Atkins (1989).

Description

The sequence at Corrie Shore includes Carboniferous rocks, as well as the Corrie Sandstone (Figure 2.7a) and the overlying Brodick Breccia (Figure 2.7c). The Carboniferous succession is unconformably overlain by the coarse-grained basal sandstones and breccias which are in the basal Corrie Sandstone, which is about 740 m thick, and comprises well-sorted, reddish-orange, flat- and cross-bedded sub-greywacke sandstones containing major bounding surfaces (Piper, 1970).

The major bounding surfaces are erosive surfaces that overlie cross-bedded draa or dune deposits (Clemmensen and Hegner, 1991). They are marked by a concentration of coarse sand grains, and are overlain by flat-bedded aeolian deposits. There are 33 such major bounding surfaces in the 740 m of the Corrie Sandstone, thus defining 34 phases of aeolian sand accumulation (Figure 2.8a).

The flat-bedded aeolian sandstones comprise horizontal to low-angle sets bounded below by a major surface (Figure 2.7a). Thicknesses vary from 0.5 to 7.0 m, with a mean of 2.9 m. Flat-bedded sets are generally tabular, but some taper out in the downwind direction. Sedimentary structures include wind ripples, lag layers, and straight or gently curved erosion surfaces. These units grade up into the cross-bedded aeolian sandstones that show a wide range of grain sizes. Cross-bedded sets are bounded above and below by sub-horizontal erosion surfaces, and range from 3 to 70 m in thickness, with a mean of 18 m. These sets are commonly composed of subsets, some 5 to 10 m thick, separated by erosion surfaces. Small-scale sedimentary structures include sandflow (especially common in the large dune deposits), inverse graded

Figure 2.7 Aeolian deposits at Corrie Shore, Arran. (a) Coastal exposure showing cross-bedding indicative of aeolian dunes. (Photo: C. MacFadyen.)

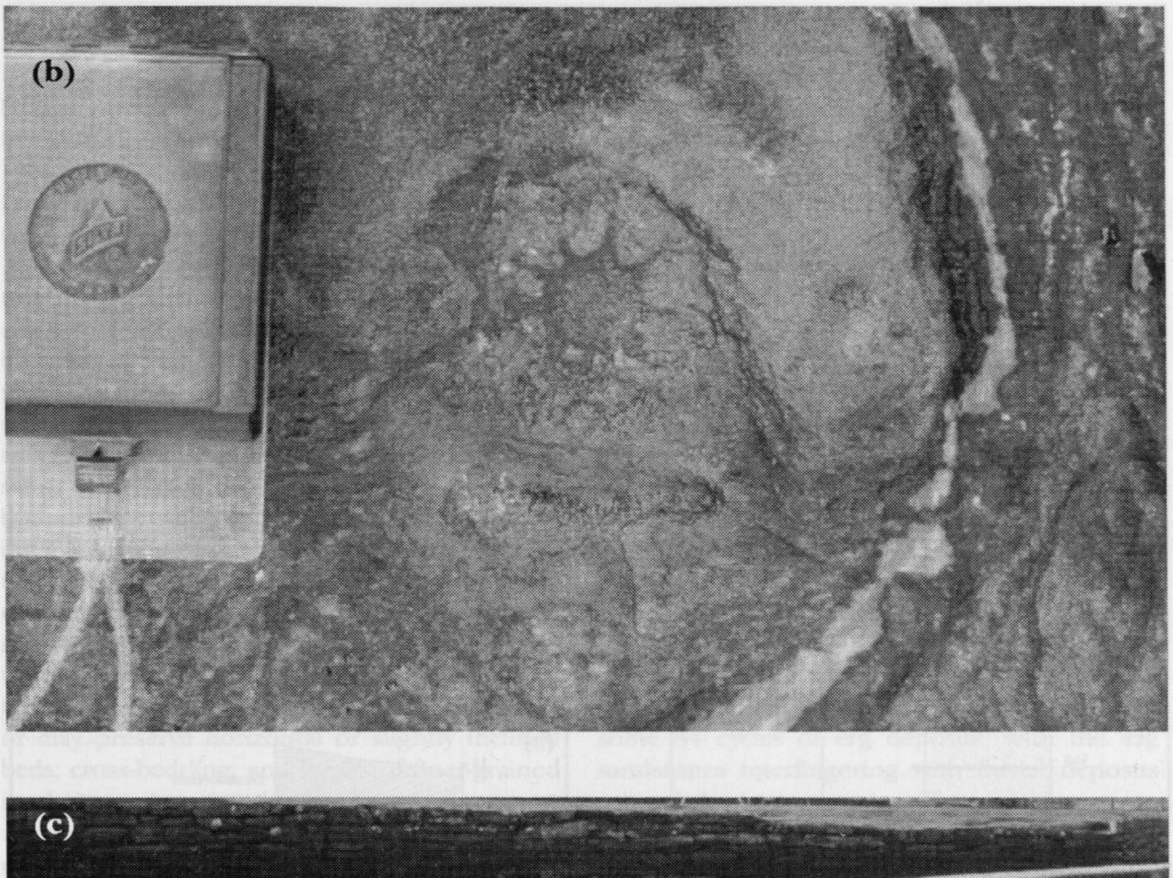


Figure 2.7 – *contd*. Aeolian deposits at Corrie Shore, Arran. (b) A fulgurite, top view of the site of a lightning strike. (c) Dune cross-bedded Corrie Sandstone overlain unconformably by the Brodick Breccia. The compass is 100 mm long. (Photos b,c: D.E.G. Briggs.)

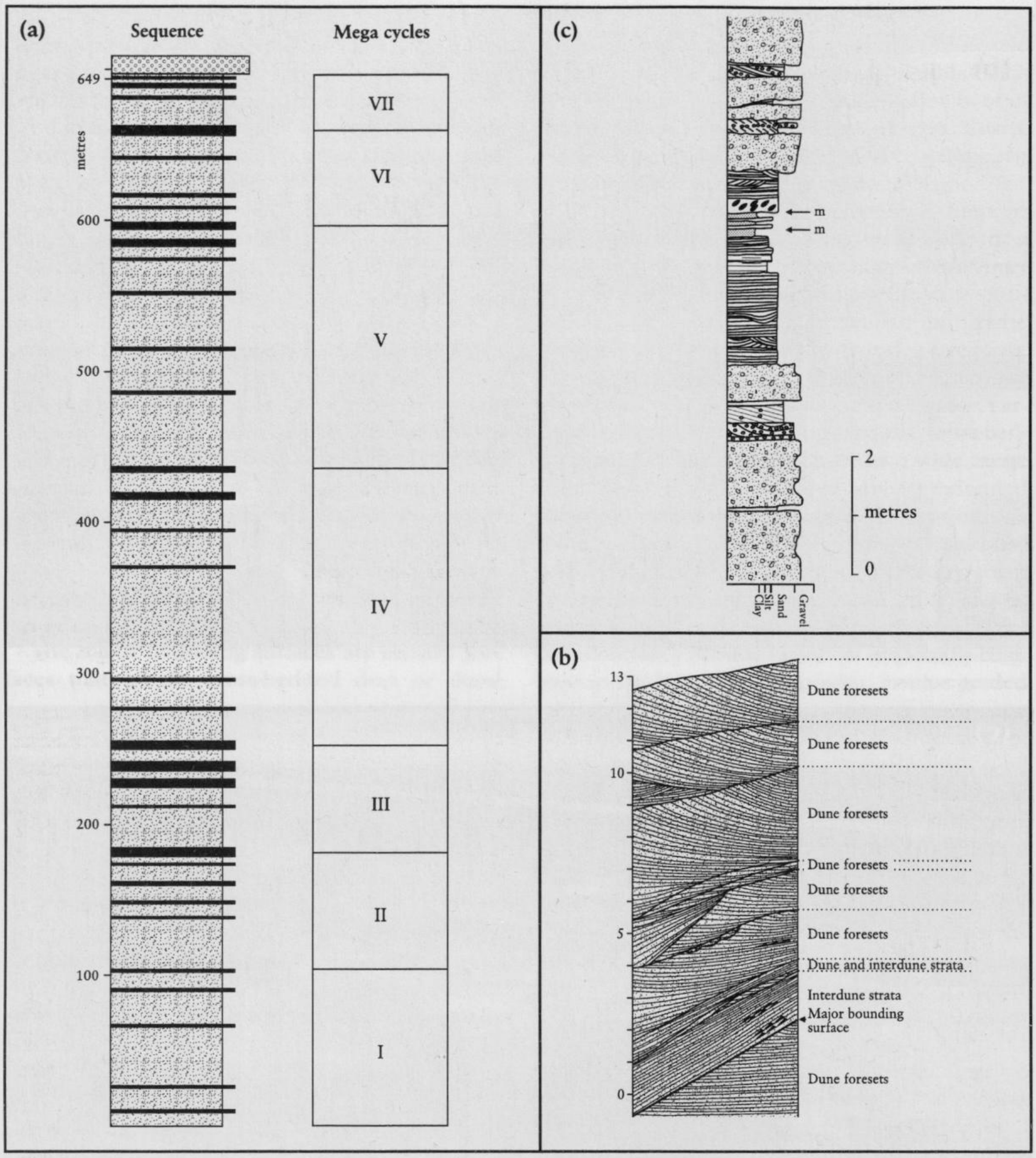


Figure 2.8 The aeolian and fluvial successions at Corrie Shore, Arran. (a) Generalized succession through the aeolian Corrie Sandstone, showing proposed division into seven erg megacycles (I–VII), and 34 superimposed units. (b) Detail of part of a dune sequence from low in the succession, showing dune foresets and interdune strata. (c) Succession of breccia units in the Brodick Beds at Corrie Shore; m, mudcracks. Based on Astin and MacDonald (1983), Clemmensen and Abrahamsen (1983), and Clemmensen and Hegner (1991).

bedding, and ripple laminations (Clemmensen and Abrahamsen, 1983).

In places lamination is present, and occurs either as groups of very thin laminae with thin layers of silty sediment preserved at the bases of the sets, or as single thicker laminae with no internal structures (Piper, 1970). At higher levels, the sediments are generally finer-grained, commonly parallel-bedded, and red, yellow, or green in colour. In places nodular limestones have been reported (Lovell, 1971; Steel, 1974b).

The Corrie Sandstone at Corrie Shore, and farther north along the eastern coast of the island, contains fulgurites (Harland and Hacker, 1966; Piper, 1970; Turner, 1980), produced by lightning strikes fusing dry, subaerially exposed sediment (Figure 2.7b).

The overlying Brodick Breccia is best seen near the bus shelter in Brodick (NS 020 360) and *c.* 100 m farther east (NS 021 359). It comprises breccias and conglomerates interbedded with sandstones (Figure 2.7c). The breccias contain clasts ranging in diameter from several millimetres to over 3 m in size and are clast-supported; sand is present interstitially. At Corrie, the boundary between the breccia and the underlying Carboniferous strata is highly variable, and may be vertical, inclined, or horizontal. The conglomerates incorporate clasts of vein quartz, schist, and quartzite, all originating locally from the Old Red Sandstone. The conglomerates form beds 1 to 2 m thick, which may be massive or may preserve horizontal or slightly inclined beds, cross-bedding, and lenses of finer-grained sandstone. Associated with the conglomerates are sandstones with trough cross-bedding or laterally extensive tabular cross-bedding. The sandstones are occasionally draped by mudstones that display mud cracks, and contain mudflake conglomerates (Astin and MacDonald, 1983).

Syndepositional faults are common along the Corrie Shore and Brodick Bay exposures. Those cutting through the Brodick Breccia formed small scarp faces and produced gaps between the blocks of sediment. In most cases the cracks were then infilled with sand, cobbles, and boulders that detached from the fault walls during tectonic activity. There is evidence that the breccia accumulated against the fault scarps during deposition (Astin and MacDonald, 1983).

Interpretation

The large-scale cross-bedding of the Corrie Sandstone is interpreted as having formed in dunes deposited in deserts, by a combination of aeolian (Gregory, 1915) and fluvial processes (Piper, 1970; Lovell, 1971). The presence of fulgurites indicates that the sands were dry, as opposed to the waterlogged sediments of river beds.

Much of the Corrie Sandstone succession is dominated by large-scale cross-bedding, consistent with an aeolian origin. Under the microscope, the sand grains have frosted surfaces, a feature indicative of aeolian transport. The nature of the dunes has been debated. Clemmensen and Abrahamsen (1983) suggested that the aeolian sediments accumulated as a series of large, compound crescentic dunes, with substantial interdune deposits (Figure 2.9), and with the prevailing wind coming from the north-east, as noted also by Piper (1970). Sneh (1988), however, argued that the sedimentary evidence from Corrie indicates a series of simple and complex oblique dunes, with a crest orientation and elongation from NNW to SSE; lateral migration was interpreted as towards the west, suggesting that the dominant wind direction was from the north. Clemmensen and Hegner (1991) disputed Sneh's (1988) re-interpretation and confirmed that the main direction of sediment transport was from the ENE.

Clemmensen and Hegner (1991) interpreted the Corrie Sandstone as a thick accumulation of some 34 cycles of erg deposits, with the erg sandstones interfingering with fluvial deposits around the basin margin. The cycles are separated by major bounding surfaces interpreted as erg-order deflation surfaces, where fine sand was blown off and the coarser material left behind as an armoured deflation lag. The flat-bedded sandstones are interpreted as amalgamated interdraa or interdune deposits. Each fining-upward bed is probably the result of a downwind migrating draa-interdraa or dune-interdune couplet at very low angles of climb. Only the lower parts of these structures are preserved, since the next migrating dune removed the upper parts. The cross-bedded sandstones are interpreted (Clemmensen and Hegner, 1991) as compound deposits formed by the downwind migration of several aeolian bedforms. Some elements represent mainly draa deposits, while others are almost entirely composed of dune or draa slipface deposits. The amalgamated nature of these units, and their great thickness, implies that they represent erg deposits, not simple draa deposits. Clemmensen and Hegner (1991) used their measurements to define seven erg megacycles (Figure 2.8a), representing seven phases of sand accumulation in a major sand sea.

Field measurements, combined with mathematical analyses, have identified a range of scales of cyclicity in the Corrie Shore sequence that

Frederiksen *et al.* (1998) interpreted as Milankovitch cycles. These authors suggested that the long aeolian succession at Corrie shows evidence for short-term and long-term cyclicity of climate and of depositional patterns that reflect control by the orbital fluctuations of the Earth. Spectral analysis of the sedimentary logs and of geochemical measurements has yielded repeated patterns on the order of 25.7–29.3 m, 34.5 m, and 64.5m, and fieldwork has demonstrated cycles of 155 m and 675 m. These cycles were presumably produced by orbital climatic forcing, related to axial precession, orbital eccentricity, and obliquity, but Frederiksen *et al.* (1998) were not able to determine the precise causal relationship.

The poorly sorted laminated sediments, with pebbles, cross-bedding, and desiccation cracks, which are interbedded with the aeolian sediments, are interpreted as fluvial in origin (Piper, 1970), and possibly accumulated in interdune areas (Figure 2.9).

In places the Corrie Sandstone is interbedded with the overlying Brodrick Breccia, reflecting an interplay of aeolian and fluvial deposition (Turner, 1980; Astin and MacDonald, 1983). Tyrrell (1928) considered the Brodrick Breccia to be the result of volcanic activity. However, more recent studies cited above indicate that it formed under a range of depositional conditions, and accumulated in steep-sided valleys with stepped walls, incised into the slightly older underlying sediments. The valleys were formed when local tectonic uplift caused the rejuvenation of the rivers, resulting in down-cutting rather than fluvial deposition. The conglomerates were probably deposited by a braided river with a gravel bedload. The poorly defined stratification is characteristic of the internal structure of bars. The associated trough-cross-bedded sandstones accumulated in inter-bar channels or possibly on the downstream margins of bar complexes. The laterally continuous tabular or low-angle sheet sandstones were formed during single sheetflood events, probably during the transitional or upper flow regime. Trough cross-bedding associated with these sheet sandstones was formed in deeper water with lower-velocity currents. Smaller-scale ripples are indicative of declining current activity. These may have thin mudstone drapes characteristic of low-energy conditions. Palaeocurrent analysis of the trough

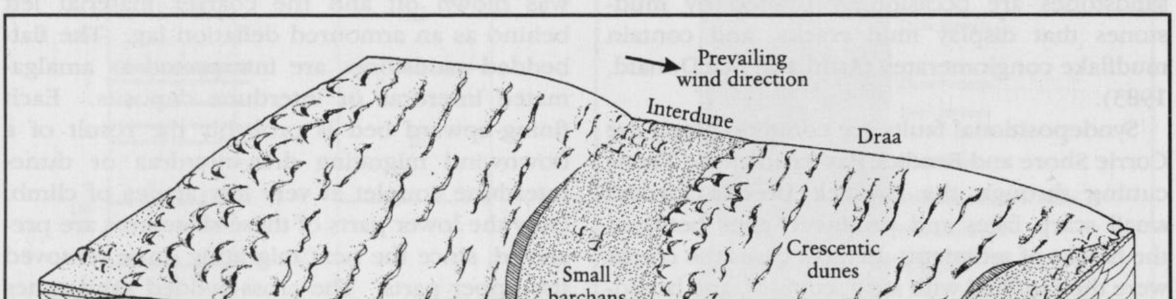


Figure 2.9 Palaeoenvironmental reconstruction for the Corrie Sandstone erg. Mainly slipfaceless draas with superimposed crescentic dunes alternated with interdune flats, the latter associated with small barchans. (From Clemmensen and Abrahamsen, 1983.)

and tabular cross-bedding suggests that the dominant flow direction was to the south (Astin and MacDonald, 1983).

Conclusions

Corrie Shore is a key locality for the understanding of Permian palaeoenvironments and palaeogeography. The Corrie Sandstones formed in a marginal desert environment where fluvial sediments were reworked by aeolian processes, and the overlying Brodick Breccia was the result of major high-energy transfer of sediment from surrounding uplands, perhaps assisted by syndepositional faulting and basinal subsidence. The fulgurites, recording lightning strikes, are an added novelty of the site, and provide a rare vignette on contemporary meteorological conditions.

HAPLAND BURN, DUMFRIES AND GALLOWAY (NS 887 023–NS 889 025)

Introduction

In the Thornhill Basin, the small stream sections of Hapland Burn, and nearby water courses such as Carron Water, expose a continuous section from the Lower to Middle Permian Carron Basalt Formation, upwards through the breccias of the Durisdeer Formation, and the succeeding Thornhill Sandstone Formation, into the Locherben Breccia Formation. The deposits comprise a relatively thin sequence of coarse-grained sediments with boulders up to 1 m in diameter, followed by a fining-upward sequence of sandstones and sporadic siltstones and mudstones. Hapland Burn is the type locality for the Durisdeer Formation. The site encompasses exposures of a succession from high-energy fluvial deposits at the base to aeolian deposits near the top. The Hapland Burn sections form part of the Carron Water and Hapland Burn Site of Special Scientific Interest (SSSI).

The Permian succession of the Thornhill Basin has been described by Simpson and Richey (1936), Craig (1965), Brookfield (1978, 1981, 1984, 2000), McMillan and Brand (1995), and Stone (1996).

Description

The basal unit of the Permian sequence is the Carron Basalt Formation, a series of weathered, olivine-rich, amygdaloidal basalts interbedded with sandstones, greywackes, and breccias. The basal bed is a sandy, fine-grained breccia containing many clasts of basalt and greywacke. It is succeeded by three basalt flows, which have lower aphanatic and upper amygdaloidal layers. The tops of the flows are marked by substantial cracks, infilled with the overlying laminated sandstones and fine breccias. In the southern part of the Thornhill Basin the Carron Basalt Formation directly overlies Carboniferous sediments (Brookfield, 1978, 1980).

The Durisdeer Formation consists of approximately 70 m of tabular sandy breccias, medium-to fine-grained sandstones, and subordinate siltstones and mudstones (Figure 2.10). Small lenses of aeolian sandstones have also been recorded within this sequence. The breccias commonly contain large numbers of amygdaloidal basalt clasts up to 0.8 m in diameter and commonly with well-developed wind-faceted and polished surfaces (Brookfield, 1978, 1980). Other clast types include greywacke, chert, mudstone, acidic intrusive igneous material, limestone, and contact metamorphic rocks (slate and hornfels). The matrix of the breccias includes up to 10% aeolian sand grains. The breccias occur in beds approximately 1 m thick and commonly display graded bedding, rare clast imbrication, and cut-and-fill structures. Individual beds of breccia are overlain by thin layers of poorly sorted, granular, silty sandstone, or by particularly coarse breccias, comprising material reworked from the underlying bed. The fine- and medium-grained sandstones are arranged in tabular units and show a range of sedimentary structures, including parallel and low-angle cross-laminations.

The Durisdeer Formation grades upwards into the Thornhill Sandstone Formation (Brookfield, 1978). The latter comprises a basal coarse-grained, laminated, red-green quartz sandstone which grades up into a well-sorted, fine-grained, cross-stratified quartz sandstone arranged in tabular and wedge-shaped cross-stratified sets; beds of coarse- and fine-grained sandstone occur throughout the sequence.

The Locherben Breccia Formation consists of approximately 10 m of reddish, sandy breccia. The sediments are arranged in tabular units between 0.2 and 0.5 m thick, and are generally massive. Some of the beds preserve rare examples of pebble imbrication and cut-and-fill structures. The breccia clasts are from 0.02 to 0.1 m in diameter, and comprise fragments of

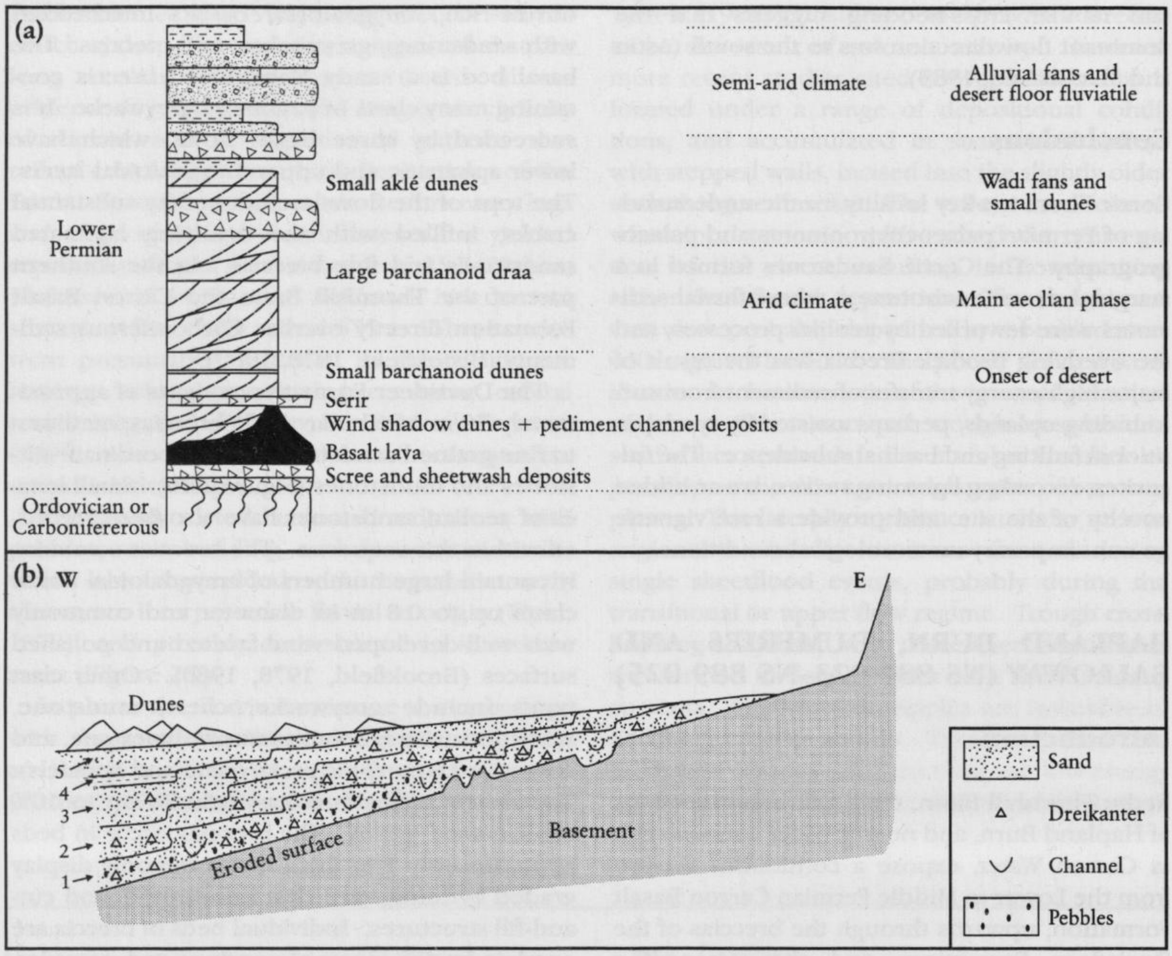


Figure 2.10 Sedimentology of the Hapland Burn locality. (a) Generalized sedimentary log, with palaeoenvironmental interpretations. Either Ordovician or Carboniferous rocks are present beneath the unconformity at different parts of the site. (b) Reconstructed cross-section of the main units through the east side of the Thornhill Basin. In (b), main palaeoenvironments are numbered: 1, braided stream, sandy breccia, and trough cross-beds; 2, sheet flood; 3, ephemeral stream; 4, temporary lake/siltstone; 5, aeolian sand. (After Brookfield 1980, 1984.)

greywacke, argillite, and purple amygdaloidal basalt. The matrix is composed of subangular to well-rounded quartz grains and some 'millet seed' sand (Brookfield, 1978).

Interpretation

The sandstones and breccias of the Durisdeer Formation represent episodic deposition during a series of sheetflood events, and more long-term deposition in a complex pattern of braided stream channels (Brookfield, 1978, 1980). These sediments are interbedded with very well-sorted and well-rounded sandstones that indicate aeolian processes, and possibly represent the localized development of wind shadow dunes, which may have formed on the lee side of upstanding masses of basalt of the Carron Basalt Formation.

The overlying sediments record a change in sedimentary environment from braided streams to sheetflood events and desert floor ephemeral sheetflood deposits. Aeolian sandstones are interbedded throughout the fluviatile succession, and represent more arid climatic phases. Eventually the pediment was buried by aeolian and fluviatile materials (Brookfield, 1980, 2000).

The Thornhill Sandstone Formation, typified by well-sorted, well-rounded coarse- to fine-grained quartz sandstones with tabular and cross-bedded units, represents aeolian dune sedimentation, though it is not clear which type of desert dune forms are represented (Brookfield, 1978).

The Locherben Breccia Formation, comprising reddish, sandy breccias with few sedimentary structures, is thought to represent fluid debris flows and sheetflood deposits that are commonly associated with wadis. The finer-grained deposits from the upper part of this formation were deposited in low-sinuosity braided streams (Brookfield, 1978).

Conclusions

The exposures in the banks of Hapland Burn provide an excellent section across the boundary between the Carron Basalt Formation and the lower Permian Durisdeer Formation breccias. The sedimentary succession preserves details of a complex desert environment, including evidence of pediment breccias with cross-bedded sandstones and silty mudstones indicative of flooding episodes, interdune temporary lakes and overbank flood deposits. Sandstones with aeolian characteristics are interbedded with the breccias and fluvial sediments.

LOCHARBRIGGS NORTH QUARRY, DUMFRIES AND GALLOWAY (NX 990 810)

Introduction

The three quarries at Locharbriggs expose an excellent section through lower Permian sediments. Locharbriggs North Quarry is the type locality for the Locharbriggs Sandstone Formation. The 20 m-thick sedimentary sequence is dominated by well-sorted fine- to medium-grained sandstones. Sedimentary structures such as large-scale cross-bedding are well preserved at this site. The sediments have been interpreted as having formed in a substantial dune field. A number of hierarchical bounding surfaces are identified between the individual dune sets and indicate the migration of predominantly transverse dunes over larger-scale bed forms (draas). This is a key site for the understanding of Permian palaeoenvironments, and a classic location for aeolian sedimentology.

The Locharbriggs Permian succession has been described by Harkness (1850), Cameron Smith (1925), Mykura (1965), Brookfield (1977, 1978, 1980, 2000), and Stone (1996).

Description

The Locharbriggs quarries are located 5 km to the north-east of Dumfries, just north of the village of Heathall, in the north-eastern corner of the Dumfries Basin (Figure 2.11a). The three quarries are aligned from north-west to south-east (Figure 2.11b): the northern one is Knowehead Quarry (NX 988 814), the middle one is Locharbriggs North Quarry (NX 990 810), and the southern one is Locharbriggs South Quarry (NX 992 808). The southern quarry is still being worked, and produces building and ornamental stone (Stone, 1996). Locharbriggs North Quarry is selected as the GCR site.

Smith *et al.* (1974) termed the sequence at Locharbriggs the 'Dumfries Sandstone'. However, Brookfield (1978) noted that the sediments in the vicinity of Dumfries consist predominantly of coarser-grained breccias, conglomerates, and sandstones, and that the term 'Dumfries Sandstone' had already been applied to a different stratigraphical unit (Horne and Gregory, 1916). He introduced the formal term, 'Locharbriggs Sandstone Formation', for the unit at this site.

Sedimentology

The sediments exposed in the Locharbriggs quarries belong to the middle part of the Locharbriggs Sandstone Formation, which extends over much of the northern and eastern regions of the Dumfries Basin. The sediments consist of medium- and fine-grained, unimodal or polymodal sandstones (Brookfield, 1977, 1978, 1979, 2000). Grain sorting within individual beds is good, but grain size varies between beds, and clasts on the erosion surfaces tend to be slightly coarser grained. Clasts, dominated by quartz, within the finer-grained beds are generally subangular and those in the coarser-grained beds are very well rounded. Smaller grains are mainly quartz, although a small proportion are composed of highly altered feldspar and lithic fragments, including basalt and cemented siltstones. Frosted grains are present, although the original surface textures are frequently obscured by diagenetic quartz overgrowths (Brookfield, 1979). The rock is cemented by silica and contains iron oxide, which gives the sediments a rich red colour.

The sandstones show well-developed cross-beds, which generally have a concave-up form,

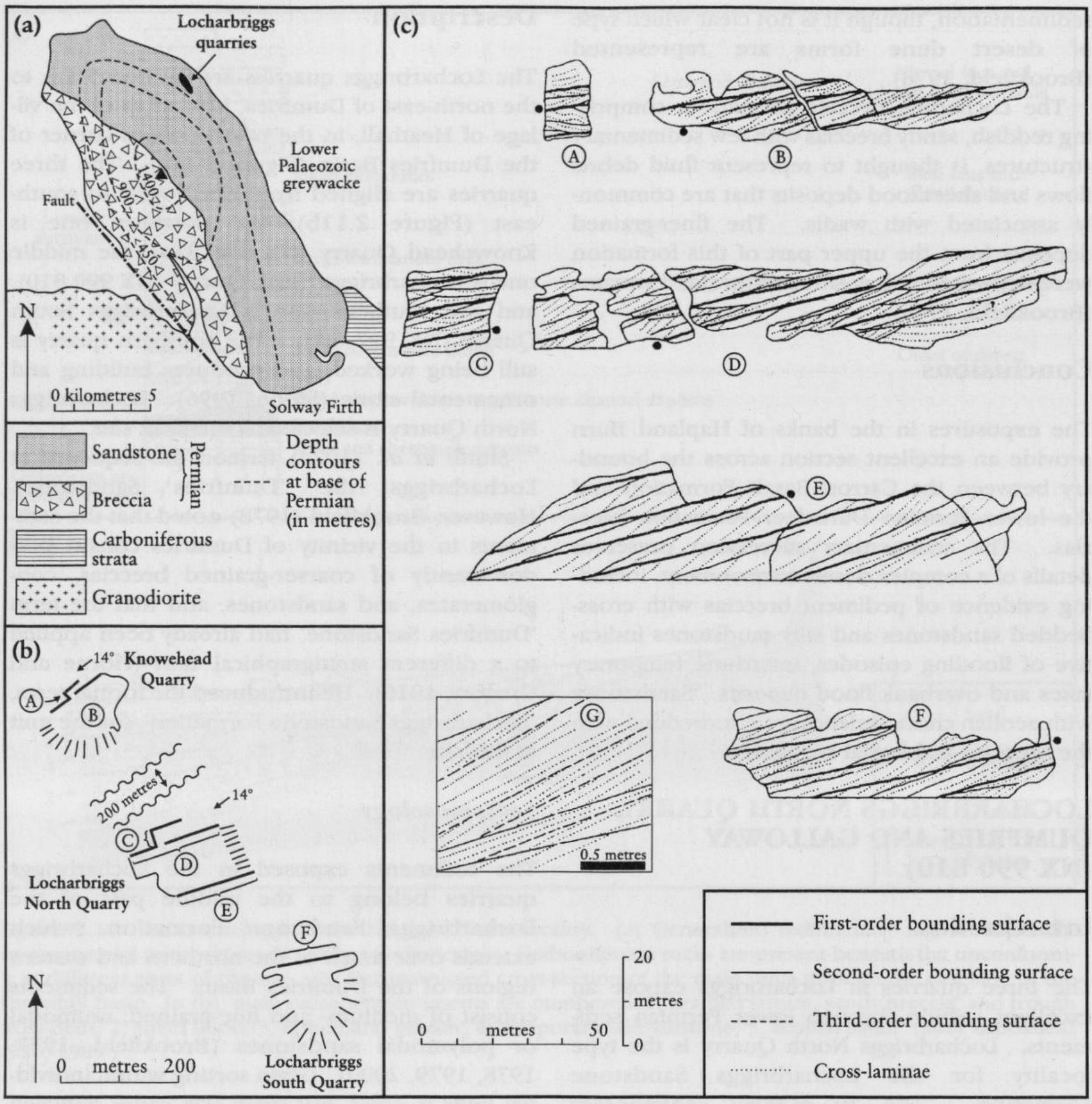


Figure 2.11 Sedimentology of the Locharbriggs Sandstone Formation in the Locharbriggs Quarries. (a) The Dumfries Basin, showing location of the Locharbriggs Quarries (arrow). (b) Plan view of the three quarries, the middle one of which is the GCR site. (c) Sketches of the exposures of the cross-bed sets and bounding surfaces in the three quarries; (A) to (F) correspond to the faces marked on the plan views in (b). (All from Brookfield, 1977.)

and occur in planar and wedge-shaped sets from 0.5 to 2.0 m thick (Figure 2.11c). Individual beds are 0.1 to 10 m thick, and dip at angles between 10 and 30° to the south-west. Trough cross-bedding is apparent in lower parts of the sequence, but it is rare higher up.

Bounding surfaces are common and clearly defined in the quarry faces; three orders have been recognized (Figures 2.11c and 2.12). The first-order surfaces can be traced across many quarry faces, and typically dip south-west at angles of 13° to 15°. These were formed as sub-horizontal surfaces. The second-order bounding surfaces are sub-parallel and planar, and are often associated with accretion laminae and small ripples. The second-order surfaces are cut by the first-order surfaces. Third-order surfaces cut across sequences of laminae (Brookfield,

Figure 2.12 The working area of Locharbriggs North Quarry (see also Figure 2.11b). (Photo: C. MacFadyen.)

1977, 1979).

Smaller-scale sedimentary structures are also common. In many cases the bounding surfaces are covered with small ripples. Laminae are common, and typically consist of very well-sorted grains. Towards the bases of the foresets the tangential sand laminae may be interbedded with silt laminations (Brookfield, 1977, 1978).

Palaeontology

Vertebrate tracks, thought to have been made by dicynodonts and pelycosaurs, have been described from the Lower Permian sediments at Locharbriggs Quarry and nearby Corncockle Muir, Annandale (Sarjeant, 1974), but are rare at both localities. Many of the footprints are well preserved, and occur in thin beds of clay-rich silt or fine sandstone (Sarjeant, 1974; McKeever, 1991, 1994). They have been assigned to four species of the ichnogenus *Chelichnus*, *C. duncani*, *C. gigas*, *C. bucklandi*, and *C. titan*, which differ in shape and in the length of the print (10–25 mm, 25–75 mm, 75–125 mm, and more than 125 mm respectively) in the four forms (McKeever and Haubold, 1996).

Interpretation

The Locharbriggs Sandstone Formation was deposited under continental conditions. Palaeomagnetic data indicate that southern Scotland lay about 10° north of the palaeoequator during early Permian times (Brookfield, 1979).

The well-sorted and polished sand grains are typical of aeolian processes. The large-scale cross-bedding, characterized by tabular sets and foresets with a uniform angle of dip, indicates transverse dunes that were associated with larger-scale features such as transverse draa dunes (Brookfield, 1978, 1979). It is thought that the draa dune was between 110 and 250 m high and had a wavelength of between 1.2 and 3 km. The SW-dipping sandstone wedges indicate that the dominant palaeowind direction was from the north-east.

Certain deposits and structures common in many ancient desert sequences have not been recorded in the Locharbriggs sequence; these include interdune clay deposits, lag sediments, interbedded fluvial deposits, and rain drop imprints. The scarcity of these features suggests that the area experienced little or no rainfall (Brookfield, 1979, 2000).

The first-order bounding surfaces are interpreted as the result of migration of the largest, draa dunes. The second-order surfaces were produced by the migration of small-scale structures, for example small dunes, which may be found superimposed on the surfaces of the draa dunes. The third-order bounding surfaces are interpreted as re-activation surfaces, and may have been produced when the direction of dune migration changed (probably a periodic phenomenon, which may reflect the daily change in wind direction common in modern deserts, or seasonal fluctuations), or when the forwards migration of one dune overtook another (Brookfield, 1979).

The clay-rich sandstones on which the vertebrate tracks were impressed are an unusual feature for desert environments. It is likely that the clays were introduced into the system either by the infiltration of rainwater, or by the settling of dust clouds (McKeever, 1991). The interbedded silt laminae common at the bases of the foresets may also have formed as dust settled out of suspension in the lee of the dunes (Brookfield, 1978).

Conclusions

The quarries at Locharbriggs expose an excellent section through the continental lower Permian Locharbriggs Sandstone Formation. These predominantly arenaceous sediments were deposited in a desert and comprise the remains of large transverse dunes or draas with subsidiary dunes climbing up their backs. This graphic example of large desert structures, on the scale of hundreds of metres long, is unique in Britain. The Locharbriggs site is of considerable importance for the understanding of early Permian aeolian environments and palaeogeography, and for its ichnofauna.

THE PERMIAN RED BEDS OF NORTH-EAST ENGLAND

INTRODUCTION

The Permian succession of north-east England lies within the Zechstein Sea Basin, the deposits at the western edge of which are exposed from Durham south to Nottinghamshire. The succession in Durham begins with 0–9 m of basal breccia, followed by the Yellow Sands, which are overlain by the Marl Slate at the base of the marine Zechstein sequence.

The thin basal breccia is a piedmont deposit, associated with uplift and erosion of underlying Carboniferous sediments. The Yellow Sands are predominantly aeolian in origin, and are either coeval with, or younger than, the basal breccias. There is no independent evidence for the age of these units, but they are generally considered to be Mid Permian, since they underlie the Marl Slate (Smith *et al.*, 1974). The Marl Slate was traditionally dated as Ufimian, or Wordian, on the basis that it overlies the Rotliegendes units which include the major Illawara magnetic reversal; in the Jin Yugan *et al.* (1997) stage succession, this reversal is considered to occur in the highest Wordian (Middle Permian Series; see Figure 1.3). However, Smith (1995) suggested that the whole of the Zechstein may be younger, Wuchiapingian or Changhsingian. If this is the case, the basal breccia and the Yellow Sands in Durham, Yorkshire, and Nottinghamshire, could be late-Mid Permian in age.

One GCR site only, Crime Rigg, is selected to illustrate the Permian red-bed facies of north-east England. The remainder of the Permian succession, the marine Zechstein, is represented by marine Permian GCR sites (Smith, 1995).

CRIME RIGG QUARRY, COUNTY DURHAM (NZ 344 416)

Introduction

Crime Rigg Quarry exposes an excellent section through the Yellow Sands Formation and the overlying Marl Slate and Raisby Formation ('Lower Magnesian Limestone'). Large faces in the quarry show the Yellow Sands with typical complex interdigitating cross-bedding. The unit has been interpreted as deposits of seif dunes that were aligned NE–SW, parallel to the dominant wind direction. The crests of these dunes show soft-sediment deformation structures comparable with those in the Weissliegendes of Germany and the southern North Sea.

The Yellow Sands of Durham have been described by Lebour (1902), Versey (1925), Hodge (1932), Shotton (1956), Raymond

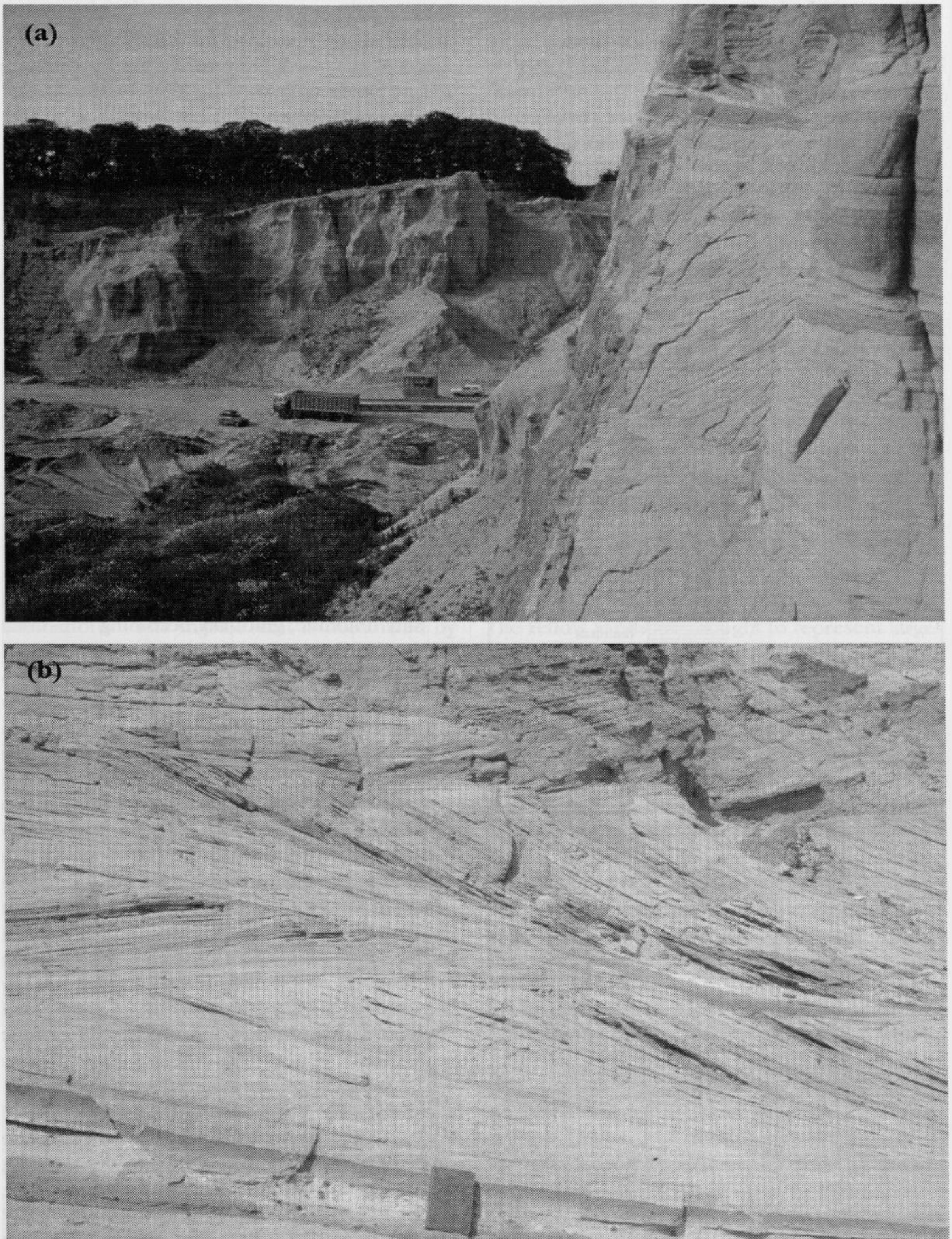


Figure 2.13 The sequence of the Yellow Sands and overlying Zechstein deposits in the western part of Sherburn Hill Sand Pit, Crime Rigg. (a) General overview and (b) close up. The face in (b) shows a transverse section through a linear mound or draa. Foresets dip to the left and right, and there are numerous third-order bounding surfaces. Exposed thickness of the Yellow Sands here is about 25 m. (Photo: L. B. Clemmensen.)

(1961), Smith and Francis (1967), Pryor (1971), Smith (1974, 1979, 1994, 1995), Kent (1975), Turner *et al.* (1978), Bell *et al.* (1979), Steele (1983), Mader and Yardley (1985), Smith *et al.* (1986), Clemmensen (1989), Price (1996), and Turner and Smith (1997); these authors describe aspects of the geology of Crime Rigg and the neighbouring Sherburn Hill quarries.

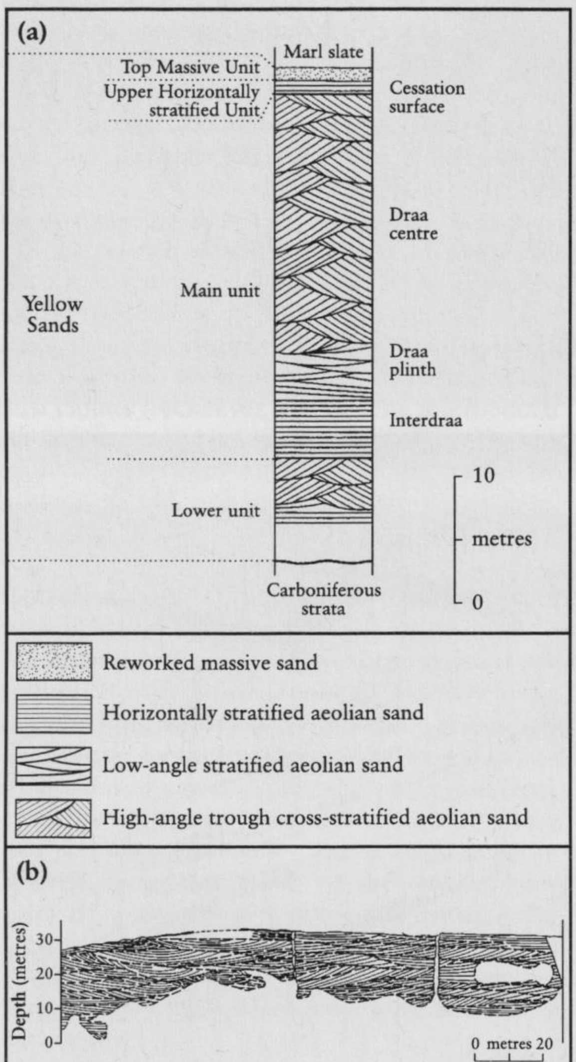


Figure 2.14 Sedimentology of the Yellow Sands at Crime Rigg. (a) Summary log through the sequence; (b) drawing of the west face at Sherburn Hill Sand Pit (NZ 344 417), showing a trough-cross-bedded dune set, with part of the face (from 0 to 50 m) transverse to the palaeocurrent, and the other part (from 60 to 140 m) sub-parallel to the palaeocurrent. (From Clemmensen, 1989).

Description

Crime Rigg Quarry is currently worked for the Yellow Sands and for dolomites of the Raisby Formation ('Lower Magnesian Limestone'). The site is part of the Crime Rigg Quarry and Sherburn Hill Quarries Site of Special Scientific Interest (SSSI). The quarry is situated between the villages of Sherburn Hill and Shadforth, and contains unvegetated quarry faces cut into the Yellow Sands, Marl Slate, and Raisby Formation (Figure 2.13).

A summary section at Crime Rigg Quarry, based on an unpublished Regionally Important Geoligical/Geomorphological Site (RIGS) report, is given below:

	Thickness (m)
Superficial deposits	
Dark carbonaceous soil	0.60
Pale brown calcareous soil with round grit fragments	0.40
Don Group: *Raisby Formation* ('Lower Magnesian Limestone')	
Thickly bedded (0.2–0.3m), massive silty dolomite, gradually becoming more dolomitic upwards	10.8
Silty dolomite, with vugs	~8
Don Group: Marl Slate	
Thin-bedded, blocky, fissile sandstone, weathering pale yellow and with many dolomitic, faintly laminated concretions along the bedding planes	1.8
Dark grey and carbonaceous laminated flaggy siltstone	0.05
Brown mudstone, with the texture of fudge	0.14
Yellow Sands Formation	
Cemented sandstones	1.1
Dune bedded sandstone, with large-scale cross-bedding	~25

The base of the Permian succession here is marked by the Yellow Sands Formation, which rests unconformably on Coal Measures (Figure 2.14a). Offshore, a 1–2 m unit of sandstone, siltstone and mudstone lies beneath the Yellow Sands, but this has not been detected onshore (Turner and Smith, 1997). The Yellow Sands are up to 68.7 m thick (Smith, 1994), and comprise well-sorted, medium- to fine-grained, unconsolidated sands, with generally well-rounded grains and occasional angular and subangular clasts, and large-scale cross-bedding. At outcrop, the sandstones are yellow, although unweathered samples collected from boreholes may be bluish, greenish, or grey. Petrographical analysis of the Yellow Sands from nearby Sherburn Hill Sand Pit (NZ 343 417) shows that the majority of the clasts consist of quartz, with small amounts of feldspar (including orthoclase and microcline), lithic fragments (including chert and sandstone), and rare clay clasts (Pryor, 1971); frosted grains are common. Generally the sandstones are poorly cemented, although the top metre or so is strongly cemented by sparry calcite, and dolomite may be present in lower beds (Pryor, 1971). In places, the interaction between the carbonate cement and sediment produces small spherical concretions (Smith and Francis, 1967). Mineral overgrowths of secondary quartz, carbonate minerals, and clays are commonly observed on many of the clasts.

Steele (1983) subdivided the Yellow Sands into three units, of which only the middle one is seen at Crime Rigg. The lower unit, up to 3 m thick, is characterized by gently dipping and flat-lying sand beds, with wind-ripple and sand-sheet laminations. The middle unit is dominated by large-scale trough cross-bedding in sets typically 4 to 6 m thick, but up to 11 m, and up to 60 m wide (Figures 2.13b and 2.14b). The sets are divided by clearly defined bounding surfaces; a first-order horizontal bounding surface occurs at the base of the section, and common second-order bounding surfaces, typically low- to medium-angle, curved and straight surfaces, are present (Pryor, 1971). Smaller-scale sedimentary structures preserved within the cross-bedded units are wind-ripple, sandflow, and grainfall laminations. Of minor importance are flat-laminated sands. The upper unit is characterized by planar bedding with wind-ripple and sand-sheet lamination. The top of the Yellow Sands is marked by a thin bed of bioturbated fossiliferous sand with a maximum thickness of 0.3 m.

The cross-bedded sets immediately below the Marl Slate are covered by a thin layer of reworked aeolian sand that may display surface-parallel laminations. Small-scale deformation structures are scattered throughout the Yellow Sand sequence; they are generally found towards the top of the aeolian units and are associated with inclined beds located close to the dune axis (Glennie and Buller, 1983).

The overlying Marl Slate is the basal unit of the Zechstein succession (Smith *et al.*, 1986), and there is a well-marked boundary. The Marl Slate is a thin deposit, consisting of laminated, grey ferroan dolomicrite and black or brown bitumen, with some discontinuous bands of siltstone and sandstone, especially near the base (Smith and Francis, 1967). The unit becomes progressively paler upwards as the bitumen content decreases, and crystalline dolomite and rarer calcite occur in thin laminae. At Sherburn Hill Sand Pit the relationship between the Yellow Sands and the Marl Slate is clearly seen. Here, the latter ranges in thickness from 1 and 4 m (Pryor, 1971), commonly infills the hollows in the upper surface of the Yellow Sands, and is absent or thins out on the tops of ridges on that surface.

The Yellow Sands have not yielded many fossils, although isolated ***Lingula*** valves are known from the thin, bioturbated sandstone bed at the top of the unit, presumably introduced through burrowing from the overlying Marl Slate (Steele, 1983).

Interpretation

The Yellow Sands are thought to represent large-scale seif dunes; the overlying Marl Slate was deposited under predominantly marine conditions, and represents the beginning of the Zechstein transgression.

Although it is now widely accepted that the Yellow Sands are a product of aeolian processes, there has been some debate concerning their origin (Turner, 1980). Early interpretations supported the aeolian theory (for example Dalglish and Forster, 1864; Versey, 1925; Hodge, 1932). More recent analyses of the petrography and geometry of the sandstone units suggested a shallow marine origin. Pryor (1971) considered that the texture of the sandstones, the presence of angular clasts, etched and pitted surfaces, and overgrowths of various clay minerals, as well as carbonates and silica, were evidence against an aeolian mode of deposition. He interpreted the Yellow Sands as deposits of submarine tidal current ridges, but subsequent workers have strongly favoured an interpretation of aeolian deposition.

The dunes in the Yellow Sands have been interpreted as longitudinal draa dunes (Steele, 1983), longitudinal seif dunes (Glennie and Buller, 1983), or complex linear features (Clemmensen, 1989). Steele (1983) and Clemmensen (1989) showed that the Yellow Sands in north-east England form nine huge elongate linear features, 20 m thick, 1.5 to 3.5 km wide and more than 13 km long, that are separated by interdune corridors 0.8 to 2 km wide (Figure 2.15). Clemmensen (1989) identified the flat-bedded sands as interdraa and draa plinth deposits in the draa ridges. The interdraa deposits are generally the most coarse-grained, and they are gradationally overlain by low-angle draa plinth deposits. The contact between draa plinth and overlying trough-cross-bedded draa centre deposits is frequently gradational, but can also be characterized by deep aeolian scours. Each draa ridge contains two interdraa–draa plinth–draa centre units, which record an early phase of lateral migration of the draa field followed by a second phase of vertical accretion

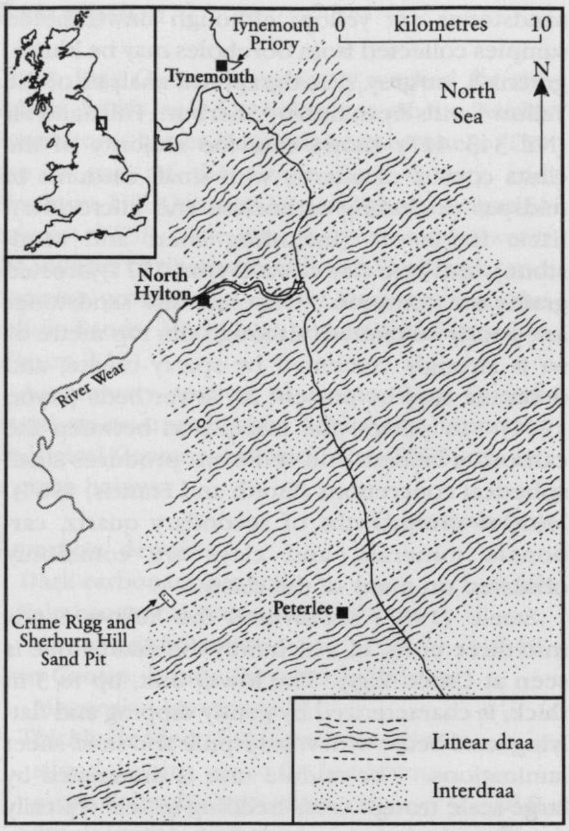


Figure 2.15▸ Palaeogeographical map of north-east England during the time of deposition of the Yellow Sands, showing the position of the nine major SW–NE-trending draa ridges. These ridges are wider and more closely spaced than in modern examples of parallel draa ridges, possibly because of the coarse-grain size of the Yellow Sands. (Based on Steele, 1983; and Clemmensen, 1989.)

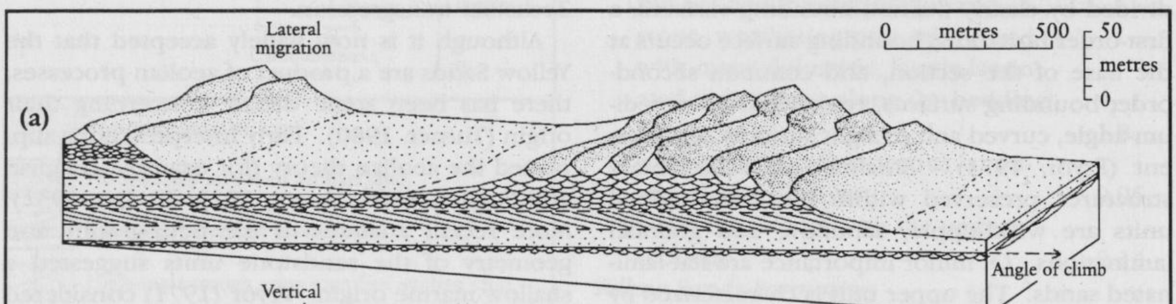


Figure 2.16 Proposed structure of the Yellow Sands draas and dunes, showing two stages in their evolution, (a) initial lateral migration, followed by (b) vertical accretion. The vertical scale is exaggerated for illustrative purposes. (After Clemmensen, 1989).

(Figure 2.16). During the lateral migration phase, the draa–interdraa systems, some 3.1 km across on average, migrated broadly towards the south-east. This movement generated a sequence of basal interdraa, middle draa plinth, and upper draa centre deposits over a basal erosion surface (seen as a first-order bounding surface). Because of lateral migration, only one flank of the draa is preserved. During the vertical accretion phase, additional trough-cross-bedded deposits were formed by the continued down-draa migration of superimposed linear dunes. The migration direction, parallel to the draa ridges, was roughly south-west (Figures 2.15 and 2.16). Finally, the draa ridges were eroded to some extent, and then covered by sand sheet deposits.

It is worth noting some aspects of the Marl Slate, which immediately overlies the Yellow Sands at Crime Rigg Quarry, since there are possible interactions between the two. The Zechstein Sea probably transgressed rapidly (Smith, 1970, 1979, 1995). The evidence for this rapid inundation comes from the similarity between the lithologies and faunal assemblages on both the topographical highs and lows preserved on the underlying Yellow Sands, although the Marl Slate is generally thinner on the highs than in the lows. Even though the transgression may have been rapid, it did not cause dramatic erosion: the unconsolidated dunes of the underlying Yellow Sands were not destroyed by the encroaching water (Smith, 1979; Steele, 1983), and only a thin layer of reworked sand has been found associated with the sand dunes (Glennie and Buller, 1983). The complex sedimentary structures of the soft and porous Yellow Sands were not destroyed because of the presence of infiltrated clays within the pore spaces between sand grains (Price, 1996).

Conclusions

The sediments exposed in Crime Rigg Quarry and the adjacent Sherburn Hill Sand Pit are of Permian age. At the base of the sections the desert sand dunes of the Yellow Sands Formation are clearly exposed. Overlying this unit is the Marl Slate, a marine deposit which infills depressions in the upper surface of the Yellow Sands. The Marl Slate marks the beginning of the inundation of the region by the Zechstein Sea, and the continuation of marine conditions is indicated by the succeeding Raisby Formation ('Lower Magnesian Limestone'). This locality is of regional, national, and international importance for illustrating the end of continental red-bed conditions and the onset of the Zechstein transgression.

THE PERMIAN RED BEDS OF WEST CUMBRIA

INTRODUCTION

The Permian strata of west Cumbria reflect the offshore geology of the Irish Sea Basin (Jackson *et al.*, 1987, 1995; Jackson and Johnson, 1996; Akhurst *et al.*, 1997; Meadows *et al.*, 1997). The succession begins with the Brockram, a breccia unit, which is followed by the Cumbrian Coast Group, comprising marine sediments, the St Bees Evaporites Formation, overlain by the St Bees Shale Formation and the St Bees Sandstone Formation, which is of presumed Early Triassic age, and forms part of the Sherwood Sandstone Group (see Chapter 3). (The Barrowmouth Mudstone Formation is the offshore equivalent to the St Bees Shale Formation (Akhurst *et al.*, 1997); Jackson *et al.*, 1997, follow this scheme). The Brockram rests unconformably on Carboniferous sediments, which are often reddened; it is traceable throughout the Irish Sea basin (Jackson *et al.*, 1987). The base of the marine deposits is equated with the basal Zechstein, dated as Late Permian (Smith, 1995). Palynomorphs from a borehole in unit BS4 in the Irish Sea Basin, equivalent to the Barrowmouth Mudstone Formation, only 18 m below the St Bees Sandstone Formation, gave a Kazanian–Tatarian date (Jackson *et al.*, 1987, p. 198).

Onshore in west Cumbria, one GCR site, at Saltom Bay, has been selected to illustrate the Permian succession and its passage into the Triassic succession.

SALTOM BAY, CUMBRIA (NX 958 159–NX 957 155)

Introduction

The foreshore at, and adjacent to, Saltom Bay provides the best exposure of the Permian succession in west Cumbria. A basal breccia, the Brockram, rests unconformably on the

Whitehaven Sandstone Formation (Carboniferous), and passes upwards into the St Bees Evaporite Formation, represented by the Saltom Dolomite, a marine carbonate. The overlying St Bees Shale Formation was deposited in a mudflat environment, and is succeeded by the St Bees Sandstone Formation (?Lower Triassic Series), which represents a range of fluvial environments. This site has the best exposure of the Permian succession of west Cumbria, and it is critical for understanding the geology of the extensive contiguous offshore Irish Sea Basin.

The first description of the geology of the region was published by Sedgwick (1832), and later accounts include Binney (1855), Harkness (1862), Smith (1924), Eastwood *et al.* (1931), Meyer (1965), Arthurton and Hemingway (1972), Macchi and Meadows (1987), and Akhurst *et al.* (1997).

Description

The exposures at Saltom Bay form part of the St Bees Head Site of Special Scientific Interest (SSSI), which comprises five GCR sites – essentially the same area has been selected independently for both its marine Permian (Smith, 1995) and red bed features, and the continuation to St Bees Head has been selected for its Triassic red beds (see Chapter 3); the 'Westphalian' and 'Quaternary of Cumbria' GCR Blocks are also represented here.

Sedimentology

The Permian section in Saltom Bay (Figure 2.17) comprises (Akhurst *et al.*, 1997, p. 67):

Sherwood Sandstone Group (Lower Triassic Series)
- St Bees Sandstone Formation

Cumbrian Coast Group (?Upper Permian)
- St Bees Shale Formation
- St Bees Evaporite Formation (includes Saltom Dolomite)

Appleby Group (?Lower Permian)
- Brockram (= Basal Breccia)

Whitehaven Sandstone Formation (Upper Carboniferous)

The Whitehaven Sandstone Formation (Westphalian C–D) is a trough-cross-bedded sandstone unit with reddish or purplish stains. The joints have been widened and infilled with material from the overlying Brockram.

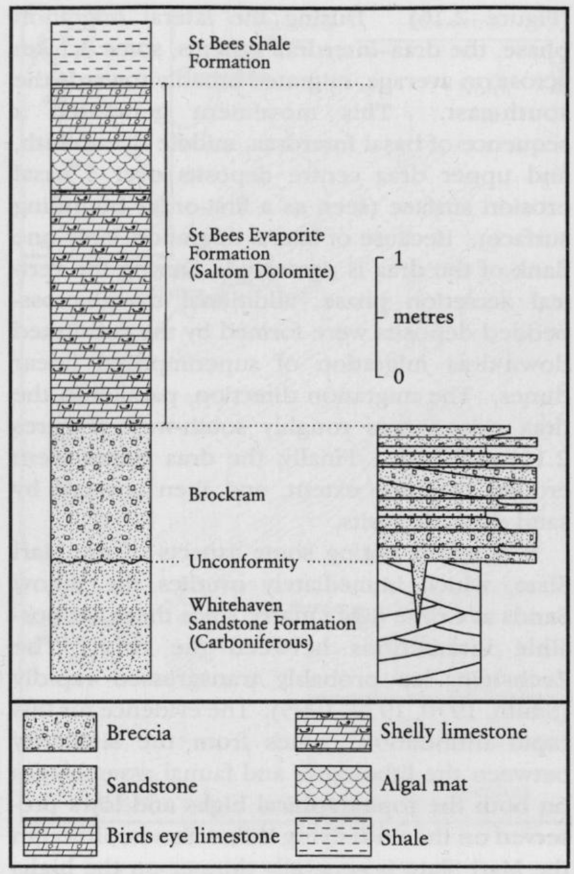


Figure 2.17 Simplified sedimentary log of the succession at Saltom Bay, with the Permian Brockram resting unconformably on the Carboniferous Whitehaven Sandstone Formation and succeeded by the St Bees Evaporite and St Bees Shale formations. A graphical facies log of the Basal Breccia is shown. Note the deep, weathered fissure in the top of the sandstone filled with brockram. (After Macchi and Meadows, 1987.)

The Brockram rests unconformably upon the Whitehaven Sandstone; it ranges from 1.5 to 3 m in thickness, and thins towards the south-west, where, at low water, it is seen to be only 0.2 m thick (Eastwood *et al.*, 1931). The unit is much thicker offshore, reaching 150 m in some boreholes (Akhurst *et al.*, 1997). The Brockram is a coarse, poorly bedded to moderately sorted, generally massive, matrix- or clast-supported breccia. Clasts range from granule to cobble grade, but are mostly pebble-sized. Many of the clasts are local in origin and are subangular to angular; rounded to subrounded clasts are rare. The clasts consist of Carboniferous sandstone, siltstone, and limestone, and Ordovician slates,

Figure 2.18 The Saltom Dolomite of the St Bees Evaporite Formation resting on the uneven top surface of the Brockram, at the south-west end of Barrowmouth Beach, Saltom Bay. The hammer is 0.33 m long. (Photo: D. B. Smith.)

sandstones, vein quartz, tuffs, and lavas. The lower parts of the breccia contain abundant quartz sandstone matrix, while the upper parts show evidence of reworking, followed by cementation with dolomite (Macchi and Meadows, 1987). Sedimentary structures are generally limited to poorly developed bedding, although there are patches of low-angle cross-bedding and clast imbrication. The top surface of the breccia is marked by vertical cracks that form large polygons infilled with fine- to medium-grained sand (Arthurton and Hemingway, 1972). The Brockram is laterally equivalent to the Collyhurst Sandstone Formation of the offshore East Irish Sea Basin (Jackson *et al.*, 1987, 1995; Akhurst *et al.*, 1997), the two units being included in the Appleby Group.

The Brockram is succeeded by the marine St Bees Evaporite Formation, which has been described in the GCR volume *Marine Permian of England* (Smith, 1995, pp. 15–18). At Saltom Bay only part of this formation, the Saltom Dolomite, formerly known as the 'Magnesian Limestone' (Arthurton and Hemingway, 1972), is exposed. The lowest metre of the basal division of this unit, a shelly dolomite, contains fragments of the underlying breccia, which were incorporated during a phase of sediment reworking (Figure 2.18).

The St Bees Shale Formation at Saltom Bay comprises a few metres of reddish siltstones and mudstones with some beds of fine-grained, calcareous sandstone. The sediments are commonly cross-laminated, and also display load casts, slumps, and desiccation cracks; they include gypsum nodules and veins, mudstone rip-up clasts, and a few rock fragments (Arthurton and Hemingway, 1972). The top of the formation is placed below the first significant sandstone bed of the St Bees Sandstone Formation (Barnes *et al.*, 1994), and the contact appears to be gradational. The St Bees Shale Formation and its offshore equivalent, the Barrowmouth Mudstone Formation, is better represented in boreholes (Akhurst *et al.*, 1997).

Palaeontology

The Brockram has not yielded fossils. The Saltom Dolomite, representing the St Bees

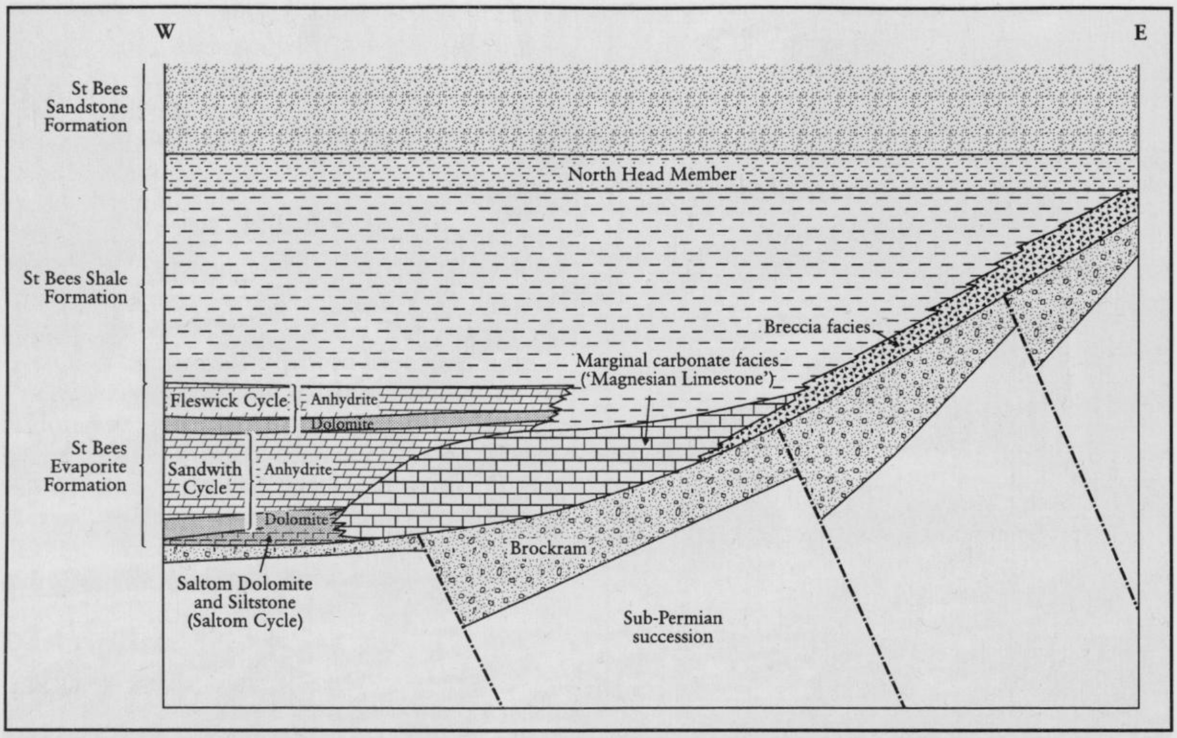


Figure 2.19 Diagram of stratigraphical relationships of the sub-Permian strata, and the Permian Brockram and higher breccia facies and basinal marine deposits in the Appleby and Cumbrian Coast groups, west Cumbria. (After Akhurst *et al.*, 1997.)

Evaporite Formation, contains a fauna of bivalves (Pattison, 1970), including ***Bakevellia binneyi***, ***Permophorus costatus***, and ***Schizodus obscurus***. Miospores have been recovered from the basal unit in this formation; these include ***Falcisporites zapfei***, ***Klausipollenites schaubergeri***, and ***Taeniaesporites labdacus***, and indicate a Late Permian age (Warrington in Arthurton and Hemingway, 1972).

Interpretation

Detailed mapping, and borehole information from onshore and offshore areas, allowed Akhurst *et al.* (1997) to compile a schematic cross-section of the Permian succession of the East Irish Sea–west Cumbria coast area (Figure 2.19). The Carboniferous basement formed a surface that was undergoing faulting and differential uplift and subsidence as the Brockram was deposited. This explains the great variations in thickness of this unit, from less than 1 m in places to 150 m in some boreholes. The Brockram is succeeded by evaporite, carbonate, and breccia units in different parts of the basin. The marine units are partly laterally equivalent to the St Bees Shale Formation, which also overlies them. The lower Triassic St Bees Sandstone Formation (basal unit, the North Head Member) succeeds the Permian uniformly across the basin.

The reddening of the Carboniferous Whitehaven Sandstone Formation, at the base of the succession, was probably caused by deep weathering during arid early Permian times when the contemporary water table would have been at a low level (Jackson *et al.*, 1987).

The Brockram has been interpreted as the deposits of a series of alluvial fans comprising material eroded and transported from the Carboniferous uplands to the east (Figure 2.20a). Syndepositional faulting maintained those uplands and produced the differences in relief necessary for the accumulation of large alluvial fans. The textures and sedimentary structures of the Brockram show that it formed in alluvial fans comparable with those now forming from debris-flow processes. The debris flows followed periods of heavy rainfall that created flash floods and resulted in rapid erosion and

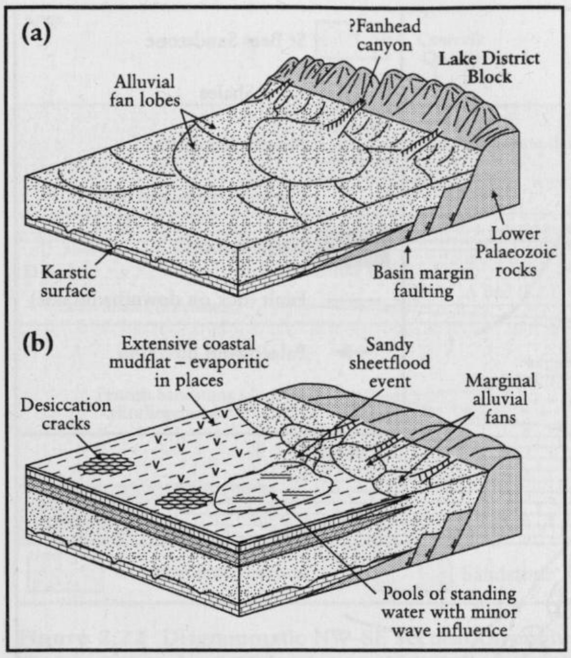


Figure 2.20 Block reconstructions of major sedimentary environments represented by (a) the Brockram, and (b) the St Bees Shale Formation. (From Akhurst *et al.*, 1997.)

transport of debris from upland areas. Finer-grained sediments indicate waning flood conditions.

The Saltom Dolomite of the St Bees Evaporite Formation represents the initiation of a marine transgression, with carbonate sedimentation on a shallow coastal shelf that supported a restricted marine bivalve fauna. These marginal carbonates are succeeded by the St Bees Shale Formation, comprising fine-grained clastic material presumably washed in from the basin margins. Rising sea level then led to the deposition of dolomite. Later, halite and anhydrite were deposited in the centre of the basin. Alluvial fans prograded into the basin from its margins throughout this marine phase (Figure 2.19).

The St Bees Shale Formation represents a reversion to continental conditions. The depositional environment was essentially a mudflat with slow accretion of sediment transported by wind and sheet floods (Figure 2.20b). The occurrence of small pools of water is recorded by evidence of minor wave influence. The mudflats dried out from time to time, producing mud cracks and evaporites. Coarse-grained alluvial fans built up around the margins of the basin.

Conclusions

The sediments exposed in the cliffs and on the wave-cut platform at Saltom Bay are Permian in age, and include the Brockram, the St Bees Evaporite Formation, the St Bees Shale Formation, and the lower beds of the St Bees Sandstone Formation. This is the best exposure through the Permian succession in west Cumbria and it illustrates a major change in palaeoenvironment, from terrestrial piedmont breccias to marine carbonate shoals, following a marine transgression, and then a reversion to continental conditions. The Saltom Bay section is critical for understanding of the Permian history of the Irish Sea Basin, and for broad-scale palaeogeographical reconstruction.

THE PERMIAN RED BEDS OF THE VALE OF EDEN

INTRODUCTION

The Vale of Eden is an isolated depositional basin (Figure 2.21) located midway between the East Irish Sea–west Cumbria Basin and the North Sea Basin. The 50-km-long basin was initiated in the Devonian, re-activated at the end of the Variscan Orogeny (Bott, 1974, 1978; Holliday, 1993) and was filled with up to 1 km of mainly continental Permo–Triassic red bed sediments. The sedimentology and stratigraphy of the Permian deposits of the Vale of Eden have been described by Sedgwick (1832), Binney (1855, 1857), Harkness (1862), Murchison and Harkness (1864), Nicholson (1868), Eccles (1870–71), Goodchild (1881, 1893), Dakyns *et al.* (1897), Kendall (1902), Versey (1939), Hollingworth (1942), Eastwood (1953), Burgess (1965), Meyer (1965), Waugh (1965, 1970a,b, 1978), Burgess and Wadge (1974), Smith *et al.* (1974, pp. 14–15), Arthurton *et al.* (1978), Taylor *et al.* (1978), Burgess and Holliday (1979), Arthurton and Wadge (1981), and Younger and Milne (1997).

The Vale of Eden succession includes a complex series of continental sediments, the continental breccias ('Brockrams') and water-laid and aeolian (Penrith) sandstones (Figure 2.22), which share broad characters with the red beds of the southern Scottish basins (see above). Breccias and water-laid sandstones are the dominant rock types near the margin of the basin,

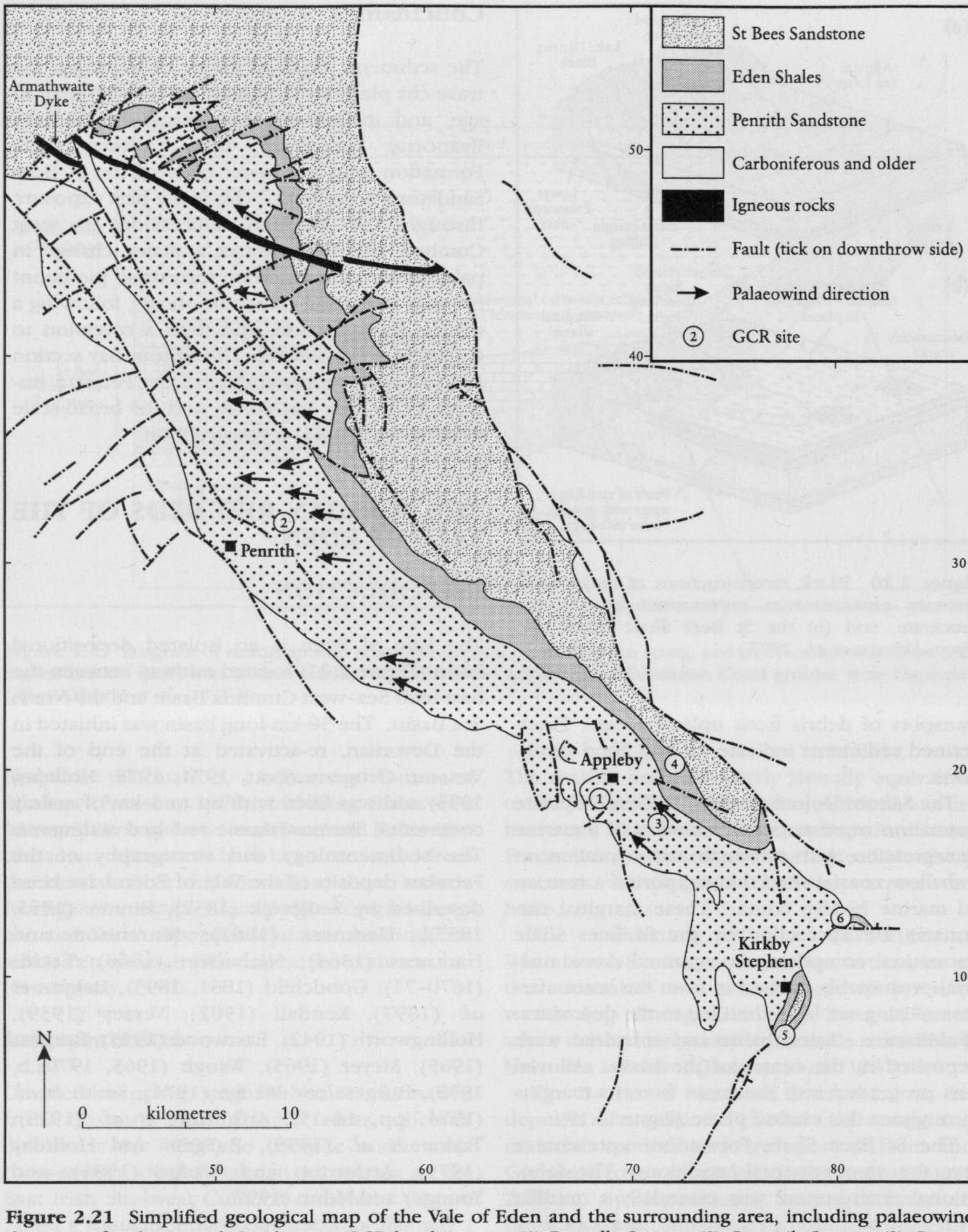


Figure 2.21 Simplified geological map of the Vale of Eden and the surrounding area, including palaeowind directions for the Penrith Sandstone. GCR localities are: (1) Burrells Quarry; (2) Cowraik Quarry; (3) George Gill; (4) Hilton Beck; (5) Stenkrith Beck; (6) River Belah. Based on Waugh (1970b), Burgess and Holliday (1974), and Younger and Milne (1997).

and they interdigitate with aeolian sands and marginal marine evaporite and dolomite units towards its centre.

The Penrith Sandstone comprises two distinct facies: in the northern part of the basin it is mainly a coarse, dune-bedded, red sandstone,

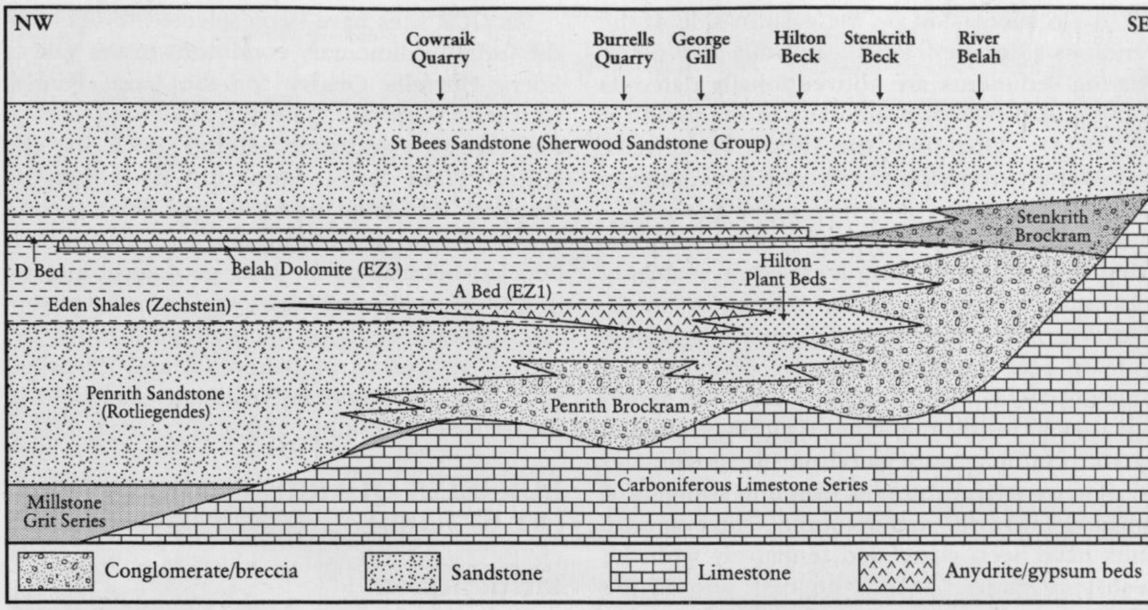


Figure 2.22 Diagrammatic NW–SE section through the Vale of Eden basin, showing the Permian succession. The section is about 55 km long. (After Arthurton *et al.*, 1978.)

while in the south and around the margins of the basin it interfingers with the brockrams and more poorly sorted fluvial sediments. The maximum exposed thickness is 460 m, but the unit probably reaches a thickness of 900 m in the centre of the basin (Bott, 1974). The Penrith Sandstone is mainly an aeolian facies, attributed to crescentic barchans moving through a large sand sea (erg). Palaeowinds blew mainly to the west (Figure 2.21), except in the south of the basin where they blew to the north-west. Silicified layers occur throughout, and these may be incipient silcretes, desert soils (Waugh, 1970a; Younger and Milne, 1997). Reptilian footprints from high in the aeolian facies near Penrith are of Permian aspect (Hickling, 1909), although they are hard to match precisely with those from the south of Scotland (see above).

The lowermost Penrith Sandstone south of Appleby, and around Kirkby Stephen (Figure 2.21), is a breccia known colloquially as the 'brockram'. This is typically a clast-supported breccia, with a few red, cross-bedded, channel sandstones (Macchi, 1990). Clasts are mainly limestone, and range from 10 to 400 mm in diameter. The clasts and the medium-grained sand matrix are reddened. Small channel fills, up to 0.5 m thick, are composed predominantly of lithic fragments, and fine upwards from a conglomerate lag into sandstones. Both the breccias and the sandstones are extensively cemented by calcite.

The Eden Shales overlie the Penrith Sandstone and comprise shales, siltstones, and sandstones, with several beds of evaporite and a thin dolomite (Arthurton, 1971). They include some marginal breccias, such as the Stenkrith Brockram, which continued to be deposited through late Permian times. In central areas of the basin, alternating continental and estuarine marine sediments (red beds, evaporites, carbonates, grey clastics) were deposited, and reached a total thickness of 160 m, but thin to 0 m at the margins (Figure 2.22). The Vale of Eden Basin was occupied during late Permian times by an elongate, almost flat, sedimentary plain flanked by slightly elevated rocky desert; from time to time the sub-facies of the plain included alluvial fans, continental sabkhas, deflation surfaces, playas, and minor dunefields.

The Late Permian marine transgression was apparently accompanied by a change in climate from arid to more humid, and the spread of plants over the land surface. Abundant plant remains are found in grey lagoonal clastic deposits at the southern end of the trough, and represent vegetation that apparently stabilized the uplands, since wind-blown clastic debris diminishes sharply at this level in the sequence. The plants are similar to those from the lower

Zechstein succession on the eastern side of the Pennines (Stoneley, 1958), and the grey plant-bearing sediments are conventionally dated as Mid Permian (Wordian–Ufimian) in age (Smith *et al.*, 1974). One unit, the Hilton Plant Beds, immediately overlying the Penrith Sandstone in Hilton Beck, is especially rich in plant debris.

Correlation of the succeeding divisions of the Eden Shales (Figure 2.22) is based on matching individual evaporite units, termed A to D. However, the evaporites are poorly exposed, and are seen best in boreholes (Burgess and Holliday, 1974). The evaporite units are generally 1 to 30 m thick, and are typically separated by 10 to 60 m of variegated purple, green, and grey laminated mudstones, with thin stringers of gypsum, anhydrite, and dolomite. The evaporite units have been correlated tentatively with the Zechstein succession on the east side of the Pennines, on the assumption that they formed in response to wide-ranging climatic changes (Smith *et al.*, 1974, p. 15). Some additional evidence comes from a restricted fauna from the Belah Dolomite, which is correlated tentatively with the Seaham Formation of east Durham and the Brotherton Formation of Yorkshire (Burgess, 1965; Pattison, 1970; Burgess and Holliday, 1979), both of which units occur at the base of the Teesside Group or cycle EZ3 (Smith, 1995). The Belah Dolomite apparently marks the only marine incursion into the Vale of Eden Basin, when the Zechstein Sea entered the southern part of the basin.

The Belah Dolomite is succeeded by two continental units. The first, more than 30 m of brick-red, massive sandstone and blocky, argillaceous siltstone, was probably deposited by aeolian processes on the damp surface of an inland sabkha. The second, comprising 20–30 m of brick-red, finely cyclic mudstones, siltstones, and sandstones, was probably deposited on an alluvial plain. These sediments are comparable with the St Bees Shale Formation of the west Cumbria coast (see above).

The Vale of Eden Basin is confluent to the north with the Carlisle Basin, a branch of the East Irish Sea Basin that runs under the Solway Firth. Brockram deposits in the south-eastern margin of the Carlisle Basin are overlain by aeolian sandstones of Penrith Sandstone-type, which were redistributed by water action in their uppermost 10 m, and pass up by interdigitation into the St Bees Sandstone Formation of the Sherwood Sandstone Group (Triassic System).

Six GCR sites have been selected to illustrate the varied sedimentary conditions in the Vale of Eden: Burrells Quarry for the basal Penrith Brockram, Cowraik Quarry and George Gill for the Penrith Sandstone, Hilton Beck for the Hilton Plant Beds, Stenkrith Beck for the Stenkrith Brockram, and the River Belah section for the Belah Dolomite. The GCR coverage is detailed because of the long geological interest in this unusual small basin, and in order to represent the diversity of the geological units; the marine sequences of Bakevellia and Zechstein provinces are described in detail elsewhere in the GCR Series (Smith, 1995).

BURRELLS QUARRY, CUMBRIA (NY 677 180)

Introduction

Burrells Quarry is stratigraphically the lowest of the Vale of Eden GCR sites, and it provides one of the finest exposures of the Penrith Brockram, which rests unconformably on Carboniferous sandstones and limestones. The breccias frequently show trough cross-bedding, and were deposited by sheetflood processes on an alluvial fan. The main facies consists of fine to very coarse breccias in tabular sheets, which are usually less than one metre thick. Cross-bedding indicates sediment transport direction consistently towards the north-east. This is a well-known locality for studies of the coarse basal Permian sediments of Cumbria.

Articles dealing specifically with the sedimentology and stratigraphy of the Penrith Brockram and Burrells Quarry include Waugh (1970b), Macchi and Meadows (1987, pp. 83–6), and Macchi (1990).

Description

The Penrith Brockram at Burrells Quarry (Figure 2.23) has many features in common with comparable breccia facies at nearby localities, but there are three important differences: it consists purely of breccio-conglomeratic sediments with no associated sandstones; a wider range of sedimentary structures are present; and the sediments are very hard, being well cemented by calcite, and containing non-dolomitized Carboniferous Limestone clasts (Macchi and Meadows, 1987).

The breccio-conglomerates are generally

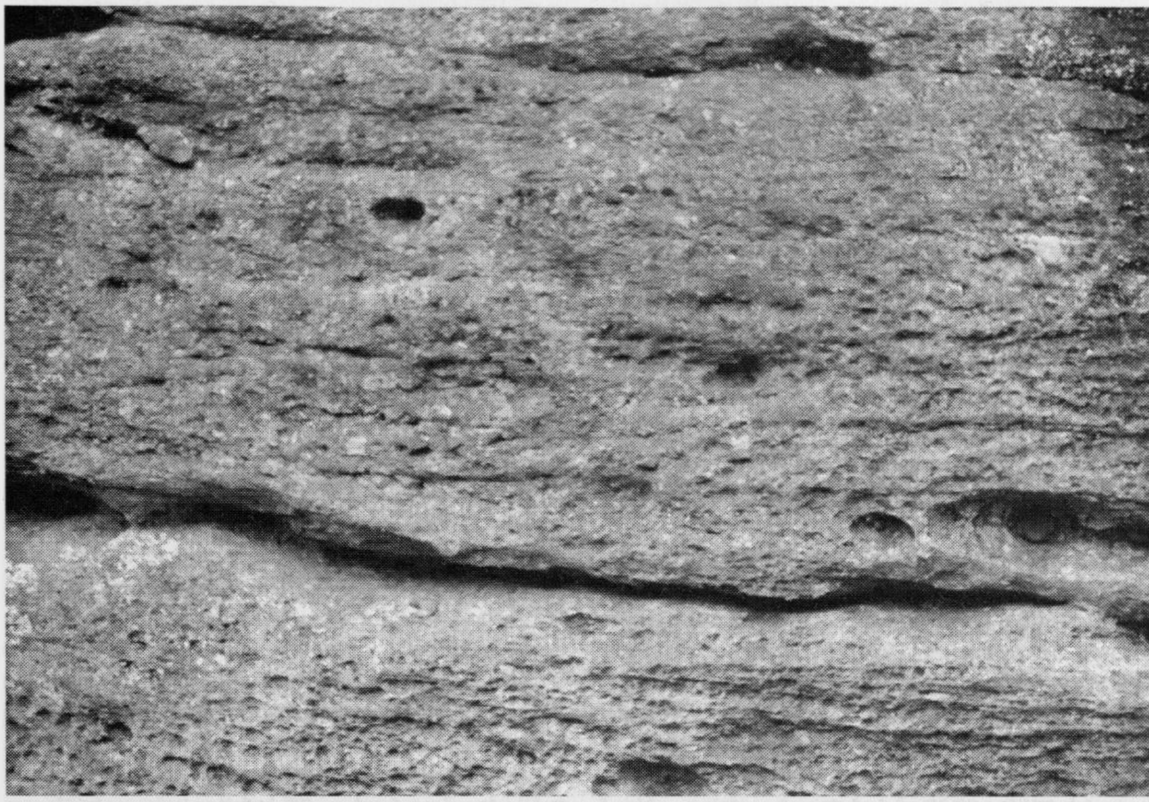


Figure 2.23 Penrith Brockram at Burrells Quarry; a poorly sorted, clast-supported breccio-conglomerate. (Photo: P. Turner.)

poorly sorted and clast-supported (Figure 2.23). Coarser-grained lag-type deposits occur at the bases of some of the units, and some show weakly defined normal graded bedding. The clasts range from less than 10 mm to over 1 m in diameter, and the larger clasts appear to be most common in the thicker beds; clast shapes range from angular to well rounded. Clast imbrications and parallel orientations of elongate clasts are common (Macchi and Meadows, 1987) and indicate a flow direction to the north-east. The clasts are composed of unweathered Carboniferous Limestone, with subordinate Carboniferous sandstone and chert (Waugh, 1970b).

The breccio-conglomerates preserve many examples of trough cross-bedding, which generally occurs as festoon-shaped scour infills. Bedding planes are laterally continuous and erosive, and separate the sediments into broadly sheet-like bodies 2 to 3 m thick. The beds persist laterally for several tens of metres before wedging out at the depositional limit of the bed or because of truncation by the overlying unit. The contact surfaces between the beds may form channel-like features. Rarely, erosional surfaces are preserved within individual beds (Macchi and Meadows, 1987).

Interpretation

The Penrith Brockram was deposited on large alluvial fans situated at the margin of the contemporaneously subsiding basin on the site of the Vale of Eden (Waugh, 1970b; Bott, 1974), probably as a result of high-energy flash floods that originated in the surrounding uplands, particularly to the south-west. Stream and channel sediments form only a minor part of the Penrith Brockram, and probably resulted from deposition in small braided stream systems that developed on the alluvial fan surfaces (Macchi and Meadows, 1987).

Conclusions

The exposures in Burrells Quarry, and natural exposures in the vicinity, provide excellent sections through the lower Permian Penrith Brockram. These sediments are very coarse grained (a breccio-conglomerate), and were deposited on a large, complex alluvial fan, probably situated towards the margin of an actively subsiding depositional basin. Sediment transport was to the north-east from uplands at the south-west of the basin. This is the best site to show the earliest phases of filling of the Vale of Eden Basin.

COWRAIK QUARRY, CUMBRIA (NY 542 310)

Introduction

Cowraik Quarry exposes the lower Permian Penrith Sandstone, and shows many of the characteristic features of that unit, including large-scale aeolian dune foresets, which show a variety of lamination types, and indicate palaeowind directions towards the west. The sandstones include sand wedges composed of very coarse, well-rounded grains, with normal graded lamination. The lower part of the sequence is unsilicified, while the upper part has been silicified through the process of authigenic quartz precipitation. This is a key locality for the study of lower Permian aeolian sand dunes.

The Penrith Sandstone has been described by Arthurton and Wadge (1981), Macchi (1981), Steele (1981), and Mader and Yardley (1985, pp. 186–7), and its petrological features by Versey (1939) and Waugh (1965, 1970a,b, 1978).

Description

Cowraik Quarry is situated on the margins of the wooded southwards-facing escarpment of Beacon Edge, close to the northern outskirts of Penrith. Though the quarry is currently disused, good sections are exposed. The regional dip is about 5° to the east.

Along the southern margin of the quarry, the lower faces expose foresets that dip towards the north-west at about 25°. The sandstone is generally friable and consists of well-rounded coarse grains ('millet seed grains'), and finer more angular grains. The exposure is cut by many small granulation seams.

The northern wall of the quarry exposes better sections. At the eastern end of this face, the sandstones are well cemented, and a suite of sedimentary structures is visible. For example, a bounding surface exists between the cross-bedded sandstone and an overlying unit, 100 to 150 mm thick, of laminated sandstones, which, in turn, are overlain by sandstones with steeply dipping foresets. Towards the top of this face a second, less well-defined, bounding surface is seen.

At the western end of the face, the highest part of the exposed sequence, comprising red, well-cemented sandstones, is seen. Most of the grains are quartz, although there are small quantities of feldspar and reworked rock fragments (Waugh, 1970b). The cement is siliceous, and often occurs as overgrowths in optical continuity with the quartz grains. Overgrowths are also found around the feldspar grains. The red coloration is caused by a thin layer of haematite covering each grain (Waugh, 1965, 1970a,b, 1978). Farther up the face, large-scale, steeply dipping cross-bedding surfaces are clearly visible. The upper parts of the foresets are cut by a bounding surface, marked by a lag of coarse sand grains.

The cross-stratification fabric of the Penrith Sandstone is mainly composed of large-scale to very large-scale tabular-planar and trough sets, which are separated by horizontal or curved bounding surfaces. The foresets are built up mainly of amalgamated coarse grain-flow tongues, which give rise to massive sandstones without distinct internal laminations (Mader and Yardley, 1985, p. 186).

Interpretation

The Penrith Sandstone in the Vale of Eden Basin ranges from 0 to 500 m thick and was deposited in an inland erg (desert sand sea) by winds blowing over a predominantly dry landscape. The erg developed in the middle of the Vale of Eden basin, and the Penrith Sandstone was deposited contemporaneously with 'brockram' alluvial fans along the basin margins. The sediments in Cowraik Quarry contain very well-rounded and frosted sand grains, which are indicative of aeolian deposition.

The large-scale cross-bedding represents single migrating straight- or sinuous-crested transverse dunes. The presence of bounding surfaces throughout the succession indicates that the upper sections of the dunes were eroded away during dune migration and fine-grained material was blown away, leaving a deflation lag of coarser material. The presence of coarse-grained sandstone on some of the bounding surfaces suggests that these may have supported small-scale wind ripples. Analysis of the orientations of the cross-bedded units indicates that palaeowind directions were towards the west.

Conclusions

Cowraik Quarry exposes good sections of the Penrith Sandstone in which sets of cross-bedded sediments, interpreted as being deposited in a series of migrating sand dunes, are separated by many examples of bounding surfaces. Cowraik Quarry is one of the best sites for study of the Penrith Sandstone, a significant aeolian unit of Early to Mid Permian age.

GEORGE GILL, CUMBRIA (NY 719 189)

Introduction

George Gill provides a series of natural crag exposures in the higher part of the lower Permian Penrith Sandstone. About 10 m of aeolian dune-bedded sandstones are visible and include up to five superimposed dune sets separated by gently inclined bounding surfaces. The sandstones are generally friable and show well-developed sand-flow laminae; cross-beds reflect a palaeowind direction from the east. The aeolian beds overlie fluvially deposited flat-lying beds lower in the Gill. Isolated brockrams in George Gill include one that is famous for containing dolerite clasts, possibly from the Whin Sill. This is a key site for understanding the Vale of Eden Basin, and for a wider understanding of early Permian palaeoenvironments in northern England.

The Penrith Sandstone and George Gill have been described by Burgess and Wadge (1974), Burgess and Holliday (1979), Arthurton and Wadge (1981), Macchi (1981), Steele (1981), Mader and Yardley (1985, pp. 186–7), Macchi and Meadows (1987, pp. 80–2), and Macchi (1990), and its petrological features by Versey (1939) and Waugh (1965, 1970a,b, 1978).

Description

George Gill is a narrow glacial valley that drains into the Hilton Beck. It is situated along the southern margin of Appleby golf course. The sandstones are cut by a complex system of conjugate fractures manifest as intersecting bands of hard sandstone composed of granulated quartz. The fractures offset the sedimentary structures by 4 mm, and are orientated parallel the Pennine faults, with a trend of 165° (Macchi and Meadows, 1987).

The Penrith Sandstone at this locality is red, somewhat friable, coarse-grained, and composed of well-sorted, well-rounded 'millet seed' grains, which are cemented by calcite and some

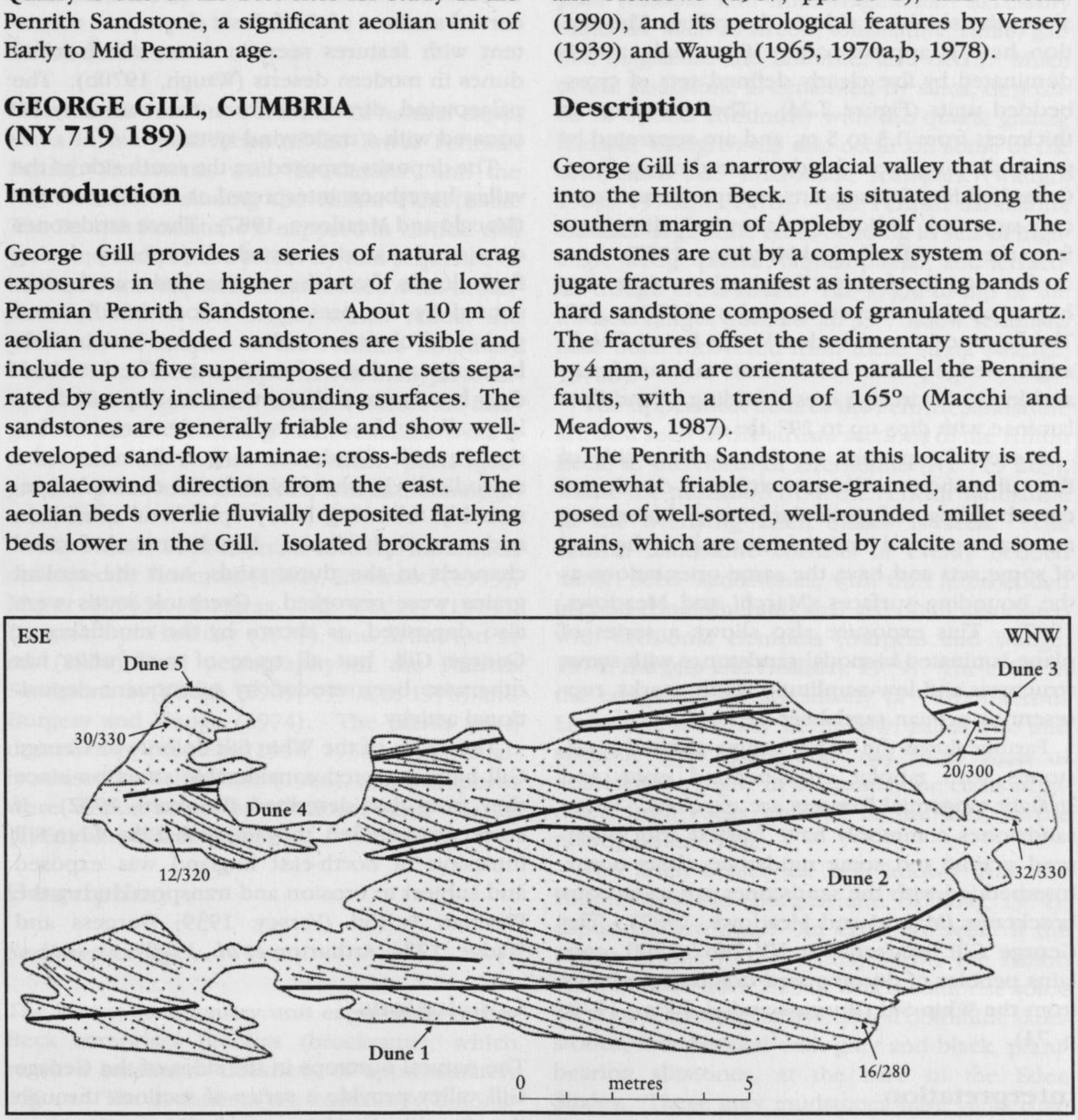


Figure 2.24 The Penrith Sandstone at George Gill, showing aeolian dune cross-bedding (lighter line) and bounding surfaces (heavier line), as exposed in crags on the southern side of the valley. Dune foreset orientations are indicated (dip in degrees/dip direction, degrees from north). (After Macchi and Meadows, 1987.)

silica (Versey, 1939). The red coloration is produced by a thin layer (pellicle) of iron oxide coating each grain. Approximately 95% of the grains are quartz, which may be unicrystalline or polycrystalline, derived from veins, metaquartzites, gneisses, and schists. The subordinate constituents include feldspar (orthoclase and microcline) and lithic fragments (Waugh, 1970a,b, 1978). Of particular note are large grains of the accessory mineral rutile (Versey, 1939).

The Penrith Sandstone is exposed in crags along the southern side of the valley. The section here is approximately 10 m high, and is dominated by five clearly defined sets of cross-bedded units (Figure 2.24). The sets range in thickness from 0.3 to 5 m, and are separated by gently dipping second-order bounding surfaces. Cross-bedding foresets are asymptotic and concave-up, and indicate palaeowind directions from the east (Macchi and Meadows, 1987). Low in the sets, the foresets have a low angle, but higher up they steepen to angles of 20° to 33°. The large-scale cross-beds take the form of high-angle, wedge-planar, subordinate tabular-planar, and lenticular trough cross-bedding. Sand-flow laminae with dips up to 29° are seen.

A second exposure, on the northern side of the valley, shows sediments with well-developed cross-bedding. Of particular note in this section are coarse-grained laminae that occur at the base of some sets and have the same orientations as the bounding surfaces (Macchi and Meadows, 1987). This exposure also shows a series of plane-laminated bi-modal sandstones with scour structures and low-amplitude ripple marks, representing aeolian sandsheet deposition.

Farther down the valley, coarse-grained sandstones with tabular cross-bedded units and straight tangential foresets are exposed. These sandstones commonly have frosted and millet-seed grains, and some mudstone clasts occur. Interbedded with the sandstones are rudaceous brockrams (Macchi and Meadows, 1987). The George Gill brockram, at NY 7167 1900, contains pebbles of decomposed dolerite, probably from the Whin Sill (Burgess and Holliday, 1979, p. 71).

Interpretation

The Penrith Sandstone consists of variable thicknesses of aeolian sands deposited in an erg in the centre of the Vale of Eden Basin. George Gill shows both the classic aeolian cross-bedded dune facies of the Penrith Sandstone, as well as associated water-laid beds.

The succession exposed in the southern side of the George Gill valley is interpreted as comprising aeolian sand dune deposits; diagnostic features are the type of cross-bedding and well-rounded frosted grains. Five sand dune sets are seen separated by bounding surfaces, representing erosion surfaces that formed when transverse dunes migrated over each other. The unidirectional distribution of the foresets, and the curved surfaces of the foreset slopes, are consistent with features seen in crescentic barchan dunes in modern deserts (Waugh, 1970b). The palaeowind directions from the east may be equated with a trade-wind system.

The deposits exposed on the south side of the valley have been interpreted as fluvial in origin (Macchi and Meadows, 1987). These sandstones consist of material reworked, probably during flash floods, from the aeolian beds, as demonstrated by the presence of frosted millet-seed grains of obvious aeolian origin, and include large rip-up clasts of mudstone. The interbedded brockram sediments were deposited on large alluvial fans. These units demonstrate that the Penrith Sandstone erg was intersected episodically by short-lived fluvial channels, presumably following heavy ephemeral rainfall in and around the basin. Rapid outwash formed channels in the dune sands, and the aeolian grains were reworked. Overbank muds were also deposited, as shown by the mudflakes at George Gill, but all trace of such units has otherwise been eroded by subsequent depositional activity.

The clasts of the Whin Sill dolerite at George Gill have attracted considerable attention since they were first described (Dunham, 1932). If correctly identified, they imply that the Whin Sill intrusion of north-east England was exposed and subject to erosion and transport during the Permian Period (Versey, 1939; Burgess and Wadge, 1974; Arthurton *et al.*, 1978).

Conclusions

The natural outcrops in the sides of the George Gill valley provide a series of sections through the Penrith Sandstone. Sediments present include a sequence of migrating sand dunes and aeolian sand sheets, river deposits (probably deposited during flash floods), and alluvial fan deposits represented by 'brockrams' deposited on the margins of the Vale of Eden Basin. George Gill is critically important for understanding aspects of the aeolian sedimentology of the Penrith Sandstone, and for showing its rare fluvial facies and yielding clasts of the Whin Sill. It is a key site for understanding lower Permian palaeogeography and palaeoenvironments in the north of England.

HILTON BECK, CUMBRIA (NY 720 206)

Introduction

Hilton Beck contains a number of natural exposures in marginal facies of the lower Permian Penrith Sandstone, with 'brockrams', and the Eden Shales, including the Hilton Plant Beds. The Penrith Sandstone is exposed in vertical cliff faces and comprises a relatively thin sequence of aeolian dune deposits, interbedded with brockrams of alluvial fan origin, which reflect the proximity of this site to the Pennine Boundary Fault. Hilton Beck is important as the type locality of the Hilton Plant Beds, a series of fine-grained sands containing plant remains. This is a key site for studies of Permian palaeogeography, palaeoenvironments, and the contemporary flora.

The Hilton Beck Permian sections have been described by Harkness (1862), Eastwood (1953), Meyer (1965), Burgess and Wadge (1974), Burgess and Holliday (1979), and Arthurton *et al.* (1978), and petrography of the Penrith Sandstone by Waugh (1965, 1970a,b, 1978) and Burgess and Wadge (1974). The plants were described by Stoneley (1956, 1958), and partially revised by Schweitzer (1986), and miospores were documented by Chaloner and Clarke (1961) and Clarke (1965b).

Description

Sedimentology

The lowest sedimentary unit exposed in Hilton Beck comprises breccias (brockrams), which reach a maximum thickness of approximately 150 m. The sediments are commonly dolomitized and contain a range of clast types, dominantly Carboniferous Limestone, though Roman Fell Quartzite is also a significant component and indicates a provenance in the nearby Pennine escarpment area (Waugh, 1970b; Arthurton *et al.*, 1978; Burgess and Holliday, 1979). The breccias are generally arranged in wedge-shaped units.

The overlying Penrith Sandstone has a distinctive red coloration and is a texturally and chemically mature sandstone. Individual grains are well rounded, may have frosted surfaces, and have a thin coating of iron oxide, giving the rock its characteristic colour. Between 90 and 95% of the grains are quartz, and the remainder comprise feldspar and lithic fragments. Accessory minerals, such as zircon, tourmaline, rutile, garnet, magnetite and limonite, also occur. Much of the sandstone is cemented by silica, deposited in optical continuity with the quartz grains; feldspar overgrowths also occur on some of the orthoclase and microcline feldspars (Waugh, 1965, 1970a,b, 1978). The Penrith Sandstone exhibits large-scale cross-bedding in sets of high-angle wedge-planar, tabular-planar, and lenticular trough cross-strata. The angle of dip of the foresets ranges from 20° to 33°. A few ventifacts have been recovered from these strata (Waugh, 1970b).

The uppermost beds of the Penrith Sandstone are best seen in the stream sections of the Hilton Beck, to the north of Ellerholme (NY 715 203), where the transition from the Penrith Sandstone to the overlying Eden Shales is seen. The Penrith Sandstone consists of evenly bedded 'millet seed' sandstones, with thin interbedded breccio-conglomerates that are often associated with erosional channels (Burgess and Wadge, 1974; Burgess and Holliday, 1979). The clasts in the conglomerate are mostly of Carboniferous Limestone and may be hollow; sandstone and siltstone also occur, and may show signs of imbrication. Many of the sandstone clasts originated from rocks exposed to the east, in the nearby Roman Fell.

The Eden Shales are best known from the Hilton borehole (Burgess and Holliday, 1974); exposures are poor. An exposure west of the Hilton Bridge (NY 719 205) shows the Hilton Plant Beds (Figure 2.25a), which comprise some 30 m of yellowish, thinly bedded dolomitic sandstones, interbedded with grey and black, plant-bearing siltstones, at the base of the Eden Shales. These grey mudstones have yielded an extensive flora and microflora (Stoneley, 1956, 1958; Chaloner and Clarke, 1961; Clarke, 1965b; Burgess and Holliday, 1979, p. 73; Schweitzer, 1986).

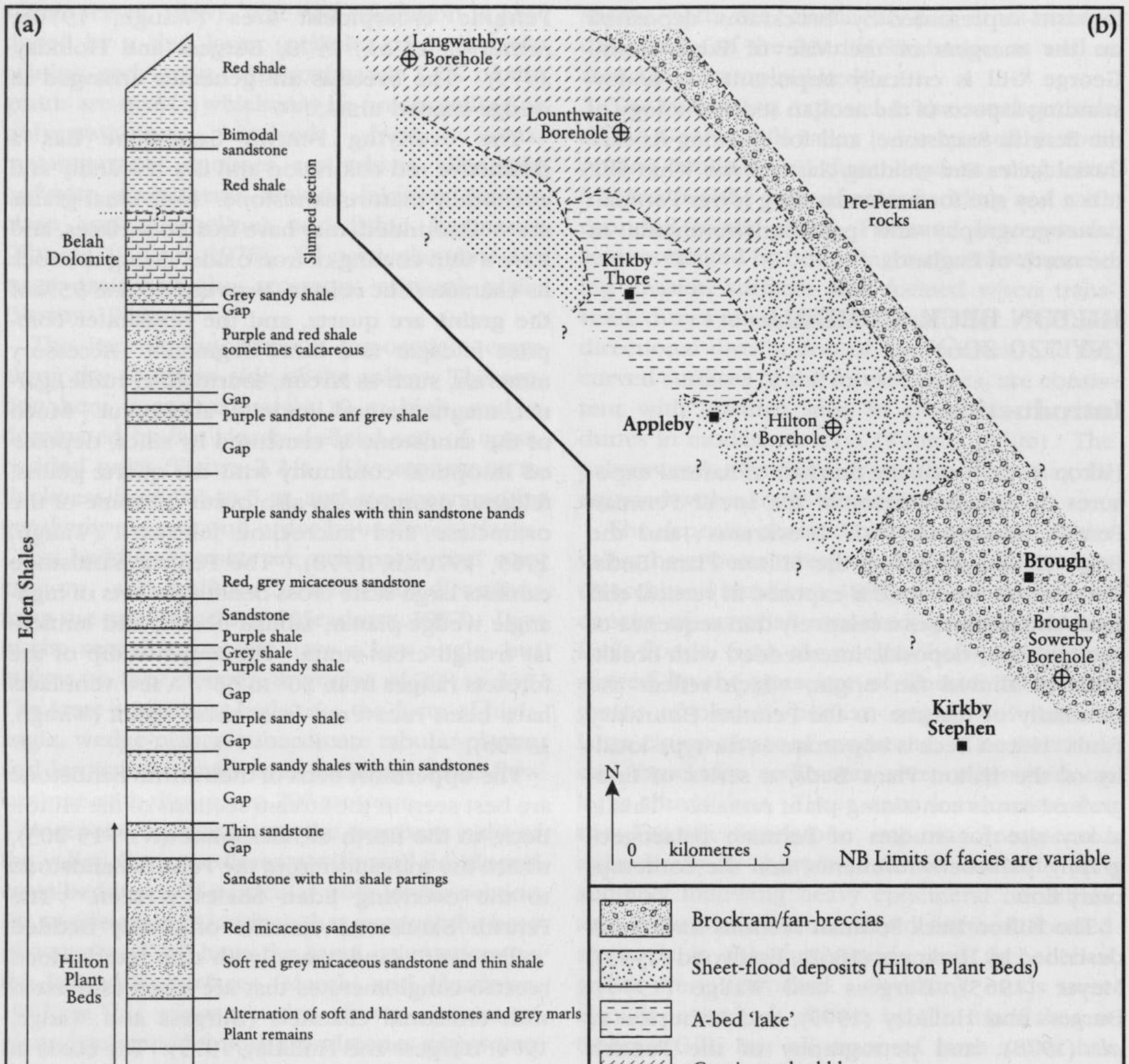


Figure 2.25 The geology of the Eden Shales. (a) Sedimentary log taken in Hilton Beck. (b) Palaeogeography of the southern end of the Vale of Eden during deposition of the Hilton Plant Beds. (After Clarke, 1965b, and Burgess and Holliday, 1979.)

The Hilton Plant Beds are overlain by 50 m of purple or wine-coloured sandy mudstone and shale. Above these is the Belah Dolomite, some 5 m thick, and well exposed in the stream sections. It is succeeded by collapse breccias thought to represent the D-Bed gypsum-anhydrite proved in the Hilton Borehole but dissolved out at outcrop. The overlying strata are poorly exposed but comprise perhaps 40 m of red sandstone with green reduction spots, composed of well-rounded frosted 'millet seed' clasts in a red argillaceous matrix. The top of this sandstone is well cemented with calcium carbonate. The top of the Eden Shales at this locality consists of red, thinly bedded, rippled sandstones and siltstones, which are overlain in places by the lower Triassic St Bees Sandstone Formation (Burgess and Wadge, 1974; Burgess and Holliday, 1979).

The term 'Hilton Plant Beds' has had a variety of meanings. At first it was applied to all of the Eden Shales below the Belah Dolomite (Goodchild, 1893; Stoneley, 1958), or to all of the beds below the 'B dolomite' (Hollingworth, 1942). It is now generally restricted simply to the plant-bearing strata (Meyer, 1965; Burgess and Holliday, 1979).

Palaeontology

Plant remains, including leaves, wood, and cones, are recorded from the grey or yellowish shales and sandstones of the Hilton Plant Beds (Harkness, 1862; Stoneley, 1958; Schweitzer, 1986). Taxa include *Sphenopteris* cf. *bipinnata*, '*Strobilites bronni*', *Lepidopteris martinsi*, *Pseudovoltzia liebeana*, *Ullmannia bronni*, and *Ullmannia* cf. *frumentaria*. The microflora recovered from the Hilton Plant Beds resembles assemblages from Zechstein sequences in Nottinghamshire and Germany (Clarke, 1965b), indicating a uniform Europe-wide parent flora.

A few marine fossils, the bivalve *Schizodus obscurus* and calcispheres (Burgess and Holliday, 1979, p. 69), recovered from the Belah Dolomite at Hilton Beck, confirm equivalence in age to the Seaham Formation of the Teesside Group (EZ3) in the Zechstein sequence in north-east England.

Interpretation

The succession exposed in the Hilton Beck sections illustrates a series of changes in depositional conditions. The Penrith Sandstone was deposited in a large desert area in a contemporaneously subsiding sedimentary basin. The sediments show many features indicative of aeolian processes, for example large-scale cross-bedding and well-rounded grains with frosted surfaces (Waugh, 1970a,b). The associated interbedded brockram facies was deposited by periodic flash floods discharging on to large alluvial fans, on the edges of the sedimentary basin (Figure 2.25b).

The succeeding Eden Shales represent a change from aeolian desert sedimentation to continental sabkhas, which are also characteristic of arid climates (Figure 2.25b). The grey and reddish, thinly bedded sandstones and siltstones, with associated gypsum–anhydrite evaporites, are typical of sabkha regions (Burgess and Wadge, 1974; Arthurton *et al.*, 1978). The Belah Dolomite represents a period of marine incursion, and probably equates with the Seaham Formation (EZ3; Arthurton *et al.*, 1978; Smith *et al.*, 1986). The lower part of the Belah Dolomite was deposited under supratidal conditions, and the upper part represents an intertidal environment (Burgess and Holliday, 1974). This was followed by a return to continental sabkha conditions. 'Millet seed' grains in these sediments were probably reworked from the Penrith Sandstone around the margins of the sabkha plain (Burgess and Wadge, 1974; Arthurton *et al.*, 1978).

The Eden Shales succession is hard to interpret in natural exposures since the evaporite units dissolve out and leave gaps. A borehole at Hilton Beck (NY 7284 2056) proved the complete sequence, including the anhydrite and gypsum beds (Burgess and Holliday, 1974, 1979).

Conclusions

The exposures along Hilton Beck provide an important source of information concerning Permian palaeogeography and environments. The sediments reflect a change from an aeolian desert, with sandstones and fluvial fan breccio-conglomerates of the Penrith Sandstone, to continental sabkhas, subject to brief marine incursions, represented by the Eden Shales. The Hilton Plant Beds at this locality provided material for the principal study of British late Permian plants, and for early work on the palynology of the Late Permian Epoch. This site is critically important for documenting the continental and marine successions of the Vale of Eden Basin during the Mid and Late Permian epochs.

STENKRITH BECK, CUMBRIA (NY 773 075)

Introduction

Stenkrith Beck is the type locality for the highest of the Permian brockrams, the Stenkrith Brockram. At this locality, these beds are overlain by the alternating red sandstones and shales of the St Bees Sandstone Formation (Triassic in age). This outcrop, near the southern margin of the Vale of Eden Basin (Figure 2.21), is in an area dominated by alluvial fan breccias (brockrams) and fluvial sands. The brockram is probably the lateral equivalent of the Belah Dolomite and D-bed gypsum-anhydrite farther north. The Stenkrith Brockram is made up of sheet-like units of breccia with angular to rounded limestone clasts. Trough cross-bedding indicates transport to the north. This is an important locality for the examination of the coarse fan-sediments of the Permian System.

Details of the sedimentology of localities close to Stenkrith Beck and the River Eden have been given by Sedgwick (1832), Binney (1855), Harkness (1862), Burgess (1965), Macchi and Meadows (1987, pp. 73–5), and Macchi (1990).

Description

The Upper Permian Stenkrith Brockram is exposed at several sites, generally in stream banks and small gorges, around Kirkby Stephen and Stenkrith. These localities include High Stenkrith (NY 771 073), Stenkrith Park (NY 775 075), and the banks of the River Eden. The Permo–Triassic rocks of this area occupy a small, approximately north–south-trending, syncline (Burgess, 1965).

The Stenkrith Brockram is approximately 19 m thick and comprises a series of laterally persistent sheets of rudaceous material, which vary from less than 0.1 m up to 1 m in thickness. The breccias are clast-supported and composed of large (0.3 m in diameter) clasts of yellowish Carboniferous Limestone, all sourced from the local area, and rarer clasts of reddish sandstone and chert. The matrix consists of red, well-rounded silty grains derived from the Penrith Sandstone.

Although the majority of the beds are traceable over 500 m or more (Figure 2.26), a few wedge out over as little as 10 m; in many cases this is associated with local developments of scours and other evidence of erosion. Most of the beds are characterized by parallel bedding, although examples of low-angle trough cross-bedding occur; some beds show crudely defined graded bedding, and sequences of beds may also

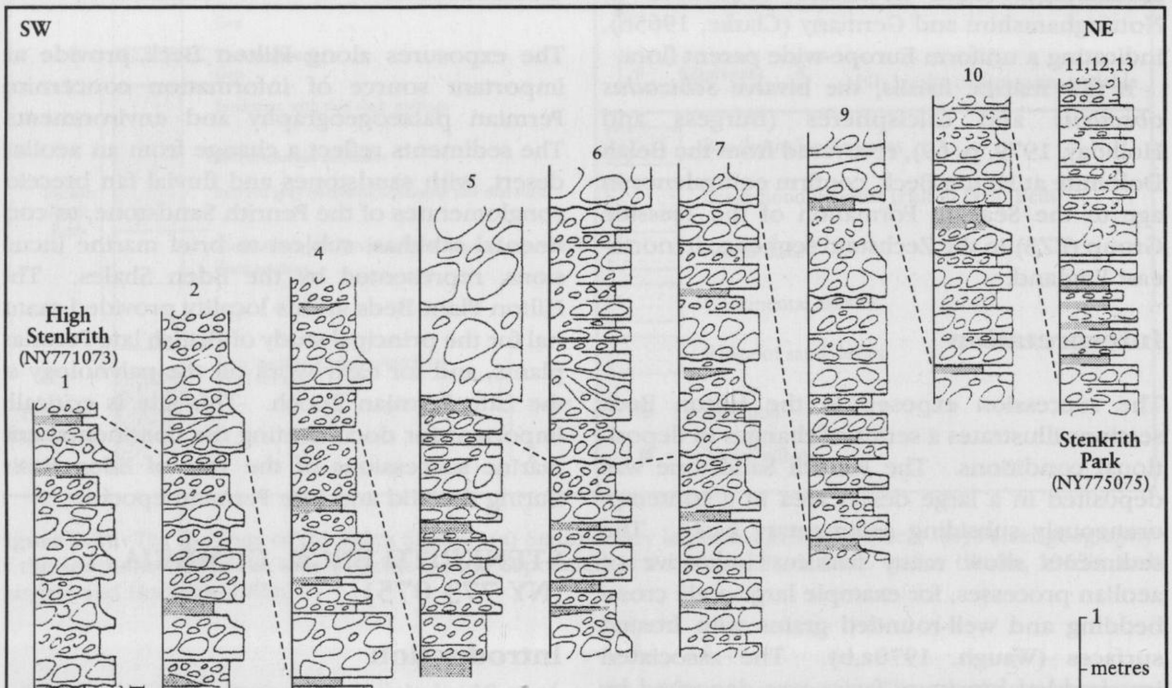


Figure 2.26 The Stenkrith Brockram, recorded in a series of logs from High Stenkrith to Stenkrith Park, along Stenkrith Beck. (After Macchi and Meadows, 1987.)

show a fining-upwards series. Imbrication and parallel alignment of the clasts is common (Macchi and Meadows, 1987).

The Stenkrith Brockram passes laterally into reddish and grey mudstones and sandstones, more typical of the Eden Shales (Macchi and Meadows, 1987). Occasional thin beds of micaceous sandstone are found throughout the sequence, and become more common towards the top, where there is a passage upwards into the St Bees Sandstone Formation. Grains of well-rounded quartz similar to those found in the Penrith Sandstone have been recovered from one of these sandstone units towards the base of the Eden Shales (Burgess, 1965). In the Stenkrith area the shales have a maximum thickness of approximately 3 m. However, most of the sections through the Permian sediments in the Vale of Eden show thicknesses of at least 15 m, overlying a thin brockram (Burgess, 1965).

Interpretation

The Stenkrith Brockram was deposited in alluvial fans and as wadi deposits close to the margins of the Vale of Eden Basin (Waugh, 1970b), having been derived from the areas of high ground bordering the basin to the south and south-west.

The Eden Shales, generally characterized by reddish or grey, fine-grained mudstones, siltstones and sandstones, were deposited under lacustrine and coastal sabkha-type conditions (Arthurton *et al.*, 1978; Macchi and Meadows, 1987). At Stenkrith, the locally occurring Stenkrith Brockram interdigitates with the Eden Shales (Figure 2.22) and hence it is younger than the other brockrams seen in the Vale of Eden Basin, which lie below the Belah Dolomite level or are equivalent in age to the Penrith Sandstone.

Lithostratigraphical evidence from this site indicates that the Stenkrith Brockram is equivalent in age to, or younger than, the Belah Dolomite, and hence probably also equivalent in age to the D-bed gypsum-anhydrite farther north in the basin (Figure 2.22).

Conclusions

Stenkrith Beck, the type locality for the Stenkrith Brockram, is a regionally and nationally important site for understanding the Permian palaeogeography of north-west England. The sections expose excellent examples of the deposits of fluvial fans that reflect active erosion around the margins of the Vale of Eden Basin until late in the Permian Period, and of contemporary sabkha environments.

RIVER BELAH, CUMBRIA (NY 799 123)

Introduction

The River Belah section exposes the Penrith Sandstone, showing aeolian and fluvial facies interbedded with alluvial fan conglomerates. The Penrith Sandstone is overlain by the Eden Shales, which consist of fluvial and continental sabkha deposits. The Belah Dolomite contains a marine fauna and represents an incursion of the late Permian Bakevellia sea. This is therefore an important site for the study of Permian palaeogeography and palaeoenvironmental change.

The petrology of the Penrith Sandstone has been described by Versey (1939) and Waugh (1965, 1970a,b, 1978), the Eden Shales, including the Belah Dolomite, have been described by Eccles (1870–1871), Meyer (1965), Burgess and Wadge (1974), Burgess and Holliday (1974, 1979), Arthurton *et al.* (1978), Macchi and Meadows (1987, pp. 76–9), and Macchi (1990).

Description

Several localities in the vicinity of the River Belah, in the southern part of the Vale of Eden (Figure 2.21), have exposures with sections through the Permian succession (Figures 2.27 and 2.28); the best sites include Belah Bridge (NY 7935 1210) and Belah Scar (NY 7965 1215). The Belah Scar exposure is cut by a series of major and minor faults that may be syndepositional.

Sedimentology

The Penrith Sandstone is a brownish-red, texturally mature orthoquartzite, with some yellowish bands and mottles (Versey, 1939), and interbedded grey, green, or brown siltstones. The sandstones are coarse-grained and well sorted, and are cemented by secondary quartz that occurs as overgrowths in optical continuity with the generally well-rounded grains. The overgrowths may be unicrystalline or polycrystalline,

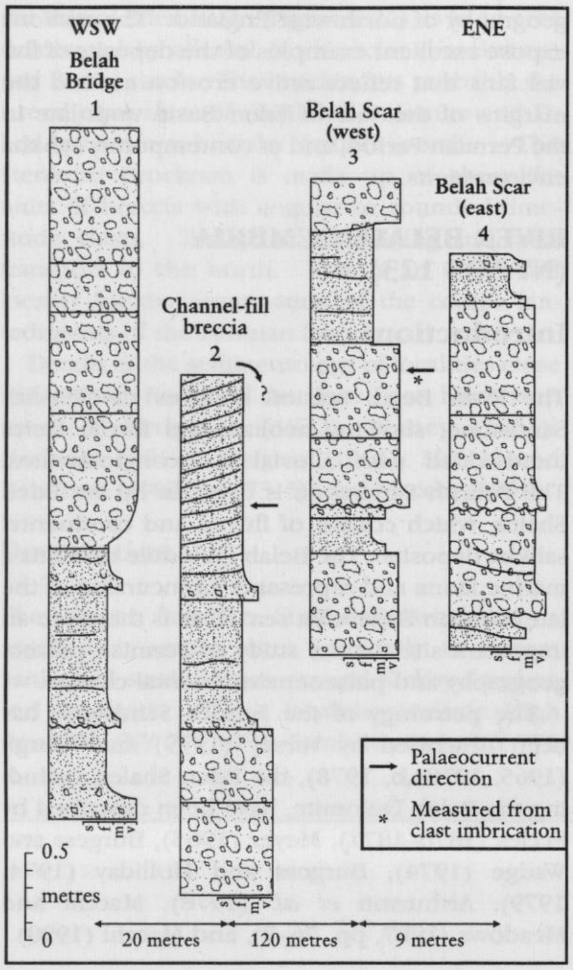


Figure 2.27 Sections through the Penrith Sandstone exposed between Belah Bridge (1) and Belah Scar (4). (After Macchi and Meadows, 1987.)

and may include fragments of derived vein quartz, metaquartzite, gneiss, and schist. Grains are dominantly quartz (90% to 95%), with minor feldspar (5% to 8%) and lithic fragments (2% to 5%). Rarely, the orthoclase and microcline feldspar grains have feldspar overgrowths. Accessory minerals, such as zircon, tourmaline, rutile, garnet, limonite, and magnetite, are also present. Many of the quartz grains have frosted surfaces. Ventifacts occur sporadically (Waugh, 1970a,b, 1978).

Sedimentary structures are clearly defined and well preserved in the Penrith Sandstone. Large-scale cross-bedded units occur, mostly with sets of high-angle wedge-planar cross-bedding, but also with some tabular-planar and lenticular trough cross-strata. The angle of inclination of the foresets ranges from 20° to 33° (Waugh, 1970b).

The exposure at Belah Bridge comprises 1 m of parallel-bedded sandstones overlain by a 2.5 m-thick bed of poorly sorted conglomerate (Figure 2.27, part 1). The sandstone sequence contains thin, laterally discontinuous beds of gritty or pebbly, dolomitized limestone conglomerate overlying erosion surfaces. The breccio-conglomerate facies (the brockram) is clast-supported, and consists of granule- to boulder-sized fragments of Carboniferous Limestone and reddish sandstone in a matrix of red, medium- to coarse-grained sand and clay.

North of Belah Bridge, *c.* 1 m of breccio-conglomerates, with erosional or channelled bases (Burgess and Holliday, 1979), is overlain by *c.* 2 m of sandstones (Figure 2.27, part 2). In the sandstones, a lower unit has a basal breccia overlain by parallel and sub-parallel bedded sands. It is succeeded by a second sandstone unit, also with a basal breccio-conglomerate, but with well-preserved cross-bedding structures, with several re-activation surfaces overlain by tangential foresets. Downcurrent, the tangential foresets are replaced by foresets with asymptotic bases. Grain sizes on the foresets have a bi-modal distribution typical of fine- and coarse-grained alternating laminations. The foresets dip at 27° towards the west. It is likely that these sandstones are the lateral equivalents of the rudaceous sediments at Belah Bridge (Macchi and Meadows, 1987).

Above the Penrith Sandstone, *c.* 12 m of the Eden Shales are seen and comprise brown and green siltstones, with thin sandstone interbeds and a prominent collapse breccia at their base. These siltstones are overlain by the Belah Dolomite, *c.* 5 m of thinly bedded, pale grey or yellowish dolomite and dolomitic limestone; the upper part of this unit contains solution cavities and calcite veins (Burgess and Holliday, 1979).

At Belah Scar (NY 7965 1215), the Penrith Sandstone interfingers with brockram (Figure 2.27, part 3). The sandstones are dark red in colour, medium- to coarse-grained, and moderately well-sorted. They are massive or parallel-laminated; individual beds have sharp planar or erosive boundaries. Many of the erosion surfaces support a thin drape of argillaceous material. Small limestone pebbles commonly occur in the lower parts of the sandstone beds. At the eastern end of Belah Scar (Figure 2.27, part 4) these become more common, occur through a

Figure 2.28 Permian sediments on Belah Scar: Penrith Sandstone with brockram lenses cut by an extensional fault downthrowing to the west. The cliff is about 6 m high. (Photo: P. Turner.)

greater thickness, and may show evidence of soft-sediment deformation (sub-vertical and vertical clasts). Lenses, thin beds, and desiccation horizons of red mudstone occur throughout the sandstone sequence (Macchi and Meadows, 1987).

The conglomerates in the upper part of the section are poorly sorted and show crude horizontal bedding; their boundary with the underlying sandstone is sharp and has considerable erosional relief, with conglomerate commonly infilling deep scours and incised channel-margin contacts. The beds fine upwards, and basal lags are common. Clasts show evidence for imbrication, but are more commonly aligned parallel to the inferred current direction (Macchi and Meadows, 1987).

The uppermost part of the Permian section exposed around the River Belah comprises the Eden Shales, and includes the Belah Dolomite. The Eden Shales are red and grey sandstones and mudstones with discontinuous beds of evaporites. The Belah Dolomite is a carbonate horizon with marine fossils (Arthurton *et al.*, 1978).

Palaeontology

Fossils are rare in the Belah Dolomite, but a restricted marine fauna, including an alga (cf. *Calcinema permiana*), foraminifera (cf. *Glomospira* sp.), bivalves (*Liebea squamosa*, *Schizodus obscurus*), ostracods (possibly bairdiids), and calcispheres, has been recovered from the River Belah section at NY 8008 1225 (Burgess and Holliday, 1979, p. 69).

Interpretation

The succession along the River Belah (Figure 2.27) may be correlated with that at Hilton Beck by noting the position of the Penrith Sandstone–Eden Shales contact, and of the Belah Dolomite. The latter unit was formerly identified as the 'Magnesian Limestone' (e.g. Meyer, 1965), but lateral comparisons with sections farther north in the Vale of Eden Basin allow the evaporite units A–D to be employed as markers. Anhydrite unit D lies immediately above the Belah Dolomite, which allows this dolomite unit to be traced extensively through the basin.

The Penrith Sandstone accumulated in continental desert environments. The well-sorted nature of the sediments, and the presence of frosted grains and ventifacts are characteristic features of aeolian sedimentation and erosion processes. The large-scale cross-bedded units have unidirectional foreset slopes, and in places the foreset surfaces are smoothly curved and concave, features consistent with formation in crescentic barchan dunes. Palaeowind directions were dominantly from the east or south-east (Waugh, 1970b). The cross-bedded sediments exposed at Belah Bridge and in the middle of Belah Scar are the only confirmed aeolian facies at this locality. The remainder originated as aeolian sands, but were reworked by fluvial activity (Macchi and Meadows, 1987).

The arenaceous facies of the Penrith Sandstone is interbedded with coarse-grained breccias, the 'brockram'. These wedge-shaped units of rudaceous sediments, with planar and lenticular trough cross-bedding, are the products of ephemeral flash floods on alluvial fans and in wadis at the margins of the Vale of Eden sedimentary basin (Waugh, 1970b). Their distribution and geometry indicate that the wadi channels were steep-sided, long, and aligned ENE–WSW. Sedimentary structures, such as imbricated pebbles, indicate that sediment transport was from the north-east (Macchi and Meadows, 1987).

The Belah Dolomite represents a period of marine deposition, caused by a marine incursion, possibly from the east, through the Stainmore Depression. The associated sediments of the Eden Shales were deposited under dominantly terrestrial conditions, in lagoons or on sabkha flats (Arthurton *et al.*, 1978).

The fossil assemblage confirms that the Belah Dolomite is a marine unit and provides important evidence for correlation: the assemblage of *Liebea*, *Schizodus*, and *Calcinema* (Burgess, 1965; Pattison, 1970) indicates a correlation with the Seaham Formation (cycle EZ3) of the Durham Zechstein sequence.

Conclusions

The Permian sediments in the vicinity of the River Belah provide important information on palaeoenvironmental and palaeogeographical change. Sandstones and conglomerates were deposited in and around large alluvial fans. The sandstones were deposited by aeolian processes, although many of the resulting sand dunes were then reworked by rivers. The conglomerates were deposited on the alluvial fans and in wadis. The overlying Eden Shales were deposited under sabkha-type conditions, with the Belah Dolomite representing a period of marine incursion.

THE PERMIAN RED BEDS OF THE ENGLISH MIDLANDS

INTRODUCTION

A series of basins opened up from Lancashire to Warwickshire in latest Carboniferous times (Figure 1.5), and were filled by presumed Early Permian red-bed continental sediments. Most of the basins were actively subsiding during early Permian times as a result of intermittent movement along boundary faults, and this is shown by non-sequences and unconformities in the sedimentary successions.

Each basin shows a distinctive sequence. In the Warwickshire Basin, the base of the Permian System is placed at the base of the Kenilworth Sandstone Formation on the basis of rare occurrences of a fossil amphibian, *Dasyceps*, the pelycosaur reptiles *Sphenacodon* and *Haptodus* (Paton, 1974, 1975), and the conifer *Lebachia* (= *Walchia*), all of which appear to be more Permian than Carboniferous in aspect. By analogy, the base of the Permian succession in the Worcester, West Shropshire, Staffordshire–Worcestershire, and South Staffordshire basins, where fossils are absent, is drawn where the Haffield, Abberley, Enville, Clent, and Nechells breccias unconformably overlie mainly Upper Carboniferous sediments (Smith *et al.*, 1974). In all cases, these breccias, ranging in thickness from 50 m to more than 200 m, are accumulations of debris transported from the Welsh and Mercian highlands to the west and east respectively. Clasts of Precambrian and Palaeozoic rock types were deposited from braided streams on top of alluvial fans and in wadis at the edges of the subsiding basins, while sandstones, siltstones, and, more rarely, mudstones were transported farther downstream and accumulated in basin centres.

In the West Shropshire and Staffordshire–Worcestershire basins, the basal breccia units are succeeded, above an unconformity, by up to 650 m of aeolian sandstone, the Bridgnorth Sandstone Formation. This formation displays desert dune features including large dune sets, hierarchical bounding surfaces marking deflation processes on several different scales, and typical dune-sand petrography. It is interpreted as a desert sand that accumulated in large-scale transverse draa bedforms bearing superimposed smaller-scale transverse dunes (Mader and Yardley, 1985). The Bridgnorth Sandstone Formation may be laterally equivalent to the Collyhurst Sandstone of the East Irish Sea Basin and the Penrith Sandstone of the Vale of Eden Basin (see above). In the South Staffordshire Basin, different clastic units, the Quartzite Breccia, Barr Beacon Beds, and Hopwas Breccia, overlie the basal breccias unconformably, and apparently represent a later phase of debris accumulation, as residual lags formed by reworking of older alluvial fan sediments on a mature desert pavement.

Three GCR sites have been selected to represent the Permian red beds of the English Midlands: Sling Common in the South Staffordshire Basin for the basal Clent Breccia; Osebury Rock in the Worcester Basin for the basal Haffield Breccia overlain by the Bridgnorth Sandstone; and Kinver Edge in the South Staffordshire Coalfield Basin for the Bridgnorth Sandstone.

SLING COMMON, HEREFORD AND WORCESTER (SO 946 781)

Introduction

Sling Common gravel pits expose the Lower Permian Clent Breccia overlain unconformably by the Lower Triassic Kidderminster Formation (formerly 'Bunter Pebble Beds'). The Clent Breccia is composed of abundant fragments of older volcanic rock, deposited rapidly in a marginal alluvial fan. The clasts can be identified as late Precambrian and Lower Palaeozoic rocks derived from the Welsh Uplands to the west. The Kidderminster Formation is, by contrast, a mature conglomerate deposited from braided rivers. This is a key site for the study of the Clent Breccia, and for understanding the palaeoenvironments and palaeogeography of the English Midlands in the Early Permian Epoch.

The Permian and Triassic rocks around Sling Common have been described by Eastwood *et al.* (1925), Wills (1948, 1970a), and Garrett *et al.* (1958), and the sedimentological characteristics of the Clent Breccia by King (1893), Whitehead and Pocock (1947), and Glover and Powell (1996).

Description

Sling Common forms part of the Sling Gravel Pits Site of Special Scientific Interest (SSSI), and consists of a series of faces in three disused and partially infilled quarries. Much of the original area of the quarries has been infilled, and the remaining faces were partially obscured by talus and vegetation at the time of writing. Small patches of exposure are seen towards the top of the 5 m-high obscured sections in the south-facing part of the quarry. A second exposure, which consists of a low strip in front of Calcothill Farm (between SO 9439 7804 and SO 9464 7831) and is partially covered by debris and vegetation, forms the boundaries to fields created during the landfill.

At the back of the disused pit, a fault brings the Triassic Kidderminster Formation into contact with the Clent Breccia. The Clent Breccia rests unconformably on a conglomerate of probable Stephanian (Late Carboniferous) age; it is poorly sorted and contains angular clasts ranging in diameter from 0.005 to 0.3 m. The clasts include igneous and pyroclastic rocks, quartzites, sandstones, and limestones (King, 1893); both sandstones and limestones may be fossiliferous. The matrix is a sandy mudstone or sandstone. In places the breccias show poorly defined cross-bedding.

Most of the small-scale exposures in the gravel pits also provide sections through the Lower Triassic Kidderminster Formation. This is a conglomerate that is texturally submature and consists of generally very well-rounded clasts but is commonly poorly sorted and includes both grain- and matrix-supported fabrics. The clasts range in size from 0.005 to 0.05 m and consist mainly of grey and liver-brown quartzite and vein quartz, with some weathered igneous rocks, sandstones, cherts, tourmaline (schorl), and fossiliferous Ordovician and Devonian quartzites. A few mudstone or sandstone intercalations, some with thin beds of pebbles or scattered pebbles, occur within the conglomerate (Wills, 1970a). This unit is described in more detail in Chapter 3 from its occurrence at other sites.

Interpretation

The Clent Breccia, showing angular clasts and cross-bedding structures, was deposited on an alluvial fan located on the margins of the sedimentary basin, probably by a series of flash floods that cut wadi channels proximally, and spread out distally into the subsiding basin (cf. Glover and Powell, 1996, fig. 8D). The clasts have, for the most part, been identified as local in origin and include Lickey Quartzite, Llandovery sandstones, and late Precambrian volcanic rocks (Whitehead and Eastwood, 1927). This suggests that the breccia is composed of material eroded from the neighbouring uplands to the east and south-east.

Elsewhere in the South Staffordshire Basin, the Clent Breccia is conformably overlain by the Quartzite Breccia, the Barr Beacon Beds, and the Hopwas Breccia. These units are not known from the Sling Common area, and a substantial period of non-deposition or erosion is represented by the unconformity between the Clent Breccia and the Kidderminster Formation.

The age of the Clent Breccia is unknown, but it is dated as earliest Permian (Smith *et al.*, 1974) on the basis of lithological similarities with other breccias in the other Midlands basins, and the evidence that the Kenilworth Sandstone Formation of the Warwickshire Basin is, from its contained tetrapod and plant remains, thought to be earliest Permian in age. In addition, breccia formations occur at the base of the succession in each of the basins in the English Midlands, and their approximate age equivalence is suggested by the likelihood that the basins all began to subside at the same time, in response to a regional extensional tectonic phase.

Conclusions

The sediments exposed at Sling Common provide an important record of the changes in environmental and geomorphological conditions affecting the English Midlands during the Early Permian Epoch. Of particular interest is the Clent Breccia, deposited in large-scale alluvial fans in a subsiding basin on the margin of the Welsh uplands. This is a key site for the study of Lower Permian basinal development, red-bed facies, and the palaeogeography in central England.

OSEBURY ROCK, HEREFORD AND WORCESTER (SO 737 554)

Introduction

Osebury Rock provides significant exposures of Permian sediments at the western margin of the Worcester Basin. The Haffield Breccia, comprising texturally immature ephemeral stream conglomerates, was the product of marginal alluvial fans developed along the fault-bounded eastern margin of the Malvern Hills. Overlying the Haffield Breccia is the Bridgnorth Sandstone Formation, an aeolian dune sandstone. This site shows the best Permian succession in the Worcester Basin, and illustrates different aspects of basin fill in arid desert conditions during the Early Permian Epoch.

The Permian rocks of the Malvern Hills, and Osebury Rock, are mentioned *en passant* by Whitehead and Pocock (1947), Mitchell *et al.* (1961), Phipps and Reeve (1967), Penn and French (1971), and Barclay *et al.* (1997). The 'Haffield Conglomerate' was initially described by Phillips (1848); it was renamed the 'Haffield Breccia' by Groom (1902), and was described in detail by Blackith (1956).

Description

Osebury Rock is a natural, 500-m-long linear exposure that runs along the top of a small, wooded hillside, and is located at the edge of the Birmingham Plateau Natural Area. The exposure faces north-west, and overlooks the River Teme. At the south-western end of the cliffs the sequence is dominated by the Haffield Breccia, and towards the north-eastern end the Bridgnorth Sandstone Formation is exposed.

The oldest unit exposed at Osebury Rock is the Haffield Breccia, which reaches a maximum thickness of some 120–140 m here, and rests unconformably on rocks of Silurian age. In the surrounding area, the Haffield Breccia is seldom more than 30 m thick (Phipps and Reeve, 1967). The sediments are very coarse grained, poorly sorted, and generally composed of subangular fragments. Several clast types have been identified, including Malvernian rocks (mainly sheared pinkish-brown granite and dark green dolerite), and Silurian and Old Red Sandstone rock fragments, all with a thin, dark reddish-brown coating of haematite. The matrix is dominantly argillaceous, and purple or dark brown. The clasts are generally less than 0.1 m in diameter, although there are occasional larger blocks up to 0.45 m. In places, there are lenses of coarse-grained sandstone (Blackith, 1956; Phipps and Reeve, 1967). The Haffield Breccia frequently occurs as lenses, which may infill depressions in the surface of the underlying rocks.

Sedimentary structures are common, and frequently well preserved. Individual beds are well defined, and may be lenticular in overall form. Some of the beds rest on erosional or scoured surfaces with a relief of as much as 0.3 m.

The overlying Bridgnorth Sandstone Formation appears to succeed the Haffield Breccia conformably and with no evidence of lateral passage from one to the other. It comprises reddish-brown, medium- to coarse-grained, well sorted sandstones, with rounded or subrounded sand grains. The dominant grain type is quartz. The reddish-brown colour is caused by a coating of haematite around each sand grain, but there is little interstitial cement, and the sandstone is soft and friable, and readily weathers to a sandy soil. The Bridgnorth Sandstone Formation here shows many fine examples of large-scale cross-bedding, with individual sets up to 15 or 20 m thick, and with foresets, approximately 4 m thick, which dip to the south and south-west.

Interpretation

The Lower Permian sediments at Osebury Rock are an important source of palaeogeographical and palaeoenvironmental information on the western margin of the tectonically controlled Worcester Basin. The Haffield Breccia and the Bridgnorth Sandstone Formation were deposited under continental conditions in an arid, desert-type climatic regime. The proto-Malvern Hills to the immediate west of the Worcester Basin were probably undergoing uplift in Late Carboniferous and Early Permian times, while the basin was subsiding as a result of contemporary fault movements. Material was eroded from the hills and washed down into the neigbouring basinal areas, forming alluvial fans. Later, a vast sand sea, represented by the Bridgnorth Sandstone Formation, spread over much of the Midlands. Much of this unit was subsequently eroded, and it is now seen only around the periphery of the basin.

The Haffield Breccia, with large pebbles and erosive, scoured bases to individual beds, was deposited in braided streams on large alluvial fans, located along the margins of the proto-Malvern Hills (Phipps and Reeve, 1967). It is likely that most of the sediment accumulation took place during periodic flood events, when large amounts of debris were transported and reworked from the surrounding local area. The source of pebbles was probably the Worcester Horst to the east, which was uplifted at the time, and has since been eroded (Barclay *et al.*, 1997).

It has been suggested that the Haffield Breccia may be correlated with the Clent Breccia, which crops out over substantial areas of South Staffordshire (Fleet, 1927; Smith *et al.*, 1974). Evidence for this correlation comes from the analysis of heavy minerals (Phipps and Reeve, 1967) and from lithological and regional evidence that all the basal breccias in the Permo–Triassic basins in the English Midlands are probably roughly coeval (Smith *et al.*, 1974). Whether the Haffield Breccia is Early Permian or Late Carboniferous in age is, however, unclear. Barclay *et al.* (1997, p. 48) note the possibility that the Haffield Breccia pre-dates the rifting and formation of the Worcester Graben, since it is found west of the East Malvern Fault (Figure 1.5), and hence may be Late Carboniferous in age.

The Bridgnorth Sandstone Formation, consisting of uniform, well-sorted sandstone displaying large-scale cross-beds, is interpreted as the product of large dune systems migrating south and south-west through a desert (Mader and Yardley, 1985).

Conclusions

The natural crags of Osebury Rock preserve one of the best sections through the Lower Permian Haffield Breccia and the overlying Bridgnorth Sandstone Formation in the English Midlands. The sequence exposed here provides critically important information on the Permian palaeogeography and palaeoenvironments of the Worcester Basin.

KINVER EDGE, STAFFORDSHIRE (SO 828 820–SO 837 836)

Introduction

The Lower Permian Bridgnorth Sandstone Formation is seen in superb three-dimensional exposure on Kinver Edge. The formation displays large-scale, high-angle cross-bedding, which records palaeowinds blowing from the east. A number of other characteristic aeolian features are well displayed, including hierarchical bounding surfaces between individual dunes, various lamination types, and very well-rounded sand grains. These sedimentary features make this an important site for the elucidation of Permian environments in the English Midlands.

The Permian sediments exposed on Kinver Edge have been described briefly by Shotton (1937), Whitehead and Pocock (1947), Smith *et al.* (1974), and Mader and Yardley (1985).

Description

Kinver Edge is a ridge of high ground with three separate outcrops, Vale's Rock, Nanny's Rock, and Holy Austin Rock, arranged in a SSW–ENE line. The crags expose the Lower Permian Bridgnorth Sandstone Formation, formerly the 'Lower Bunter', 'Lower Mottled Sandstone', or the 'Dune Sands' (Wills, 1948; Smith *et al.*, 1974), which is capped by the Kidderminster Formation, formerly the 'Bunter Pebble Beds' (Warrington *et al.*, 1980).

The Bridgnorth Sandstone Formation on and around Kinver Edge rests unconformably on the Upper Carboniferous Enville Breccia. It is characterized by a brick-red or reddish-brown colour and irregular pale green mottles. The sandstone is medium- or fine-grained, and the grains are generally well rounded. In places, the rock has a 'millet seed' texture, although the smaller grains may tend towards angular or subangular; pebbles are rare. Sedimentary structures include large-scale, high-angle cross-bedding arranged mainly in trough-cross-bedded sets, with minor planar-cross-bedded sets (Figure 2.29a). The cross-beds are divided by a complex system of bounding surfaces (Figure 2.29b), divisible into a hierarchy of as many as four levels.

The base of the overlying Kidderminster Formation channels deeply into the top of the Bridgnorth Sandstone Formation. The Kidderminster Formation comprises sandstones and pebbly sandstones, which are generally brownish-red in colour. The basal bed, exposed on the top of Kinver Edge, reaches a maximum thickness of 0.6 m; it contains subrounded and subangular clasts in a soft sandy or marly matrix that is locally calcareous. The clasts consist predominantly of quartzite, although Carboniferous limestone, chert, and volcanic rocks are present. The marly or sandy breccio-conglomerate is, in places, overlain by a unit of pebbly grit (Whitehead and Pocock, 1947).

Interpretation

The Bridgnorth Sandstone Formation, characterized by large-scale cross-bedding and well-sorted, polished 'millet seed' sands grains, is a classic aeolian deposit, as recognized by Shotton (1937). The orientations of the foresets of the dunes indicate palaeowind directions from the east. Shotton (1956) interpreted the unit as the deposits of large-scale, crescentic barchan dunes.

Mader and Yardley (1985) suggested that the complex hierarchy of bounding surfaces (Figure 2.29b) demonstrates that the Bridgnorth Sandstone Formation is a compound system consisting of major draa bedforms bearing superimposed smaller-scale transverse dunes. The sinuous-crested transverse dunes migrated partly obliquely down the lee side of essentially inactive draa bodies. The four elements of the hierarchy of bounding surfaces reflect, respectively, draa migration, draa modification, dune migration, and dune modification. Here and there, individual cross-bed sets pinch out laterally, which indicates cut-off by succeeding migrating dunes. The apparent absence of interdune deposits points to a sand-saturated system with closely spaced aeolian bedforms (both draas and dunes) separated by only narrow interdune corridors that are represented by minor disconformities. This is in contrast with, for example, the Corrie Sandstone of Arran, where interdune beds are a major part of the record (see above).

In a study of the Bridgnorth Sandstone Formation around Bridgnorth, Karpeta (1990) presented evidence for three major facies associations: transverse draas, barchanoid draas, and dome dunes, with long-term winds blowing from the east (controlling the shape of the transverse draas and dome dunes), and seasonal winds blowing from the north-east (controlling the shape of oblique crescentic dunes on the lee face of the transverse draas and the barchanoid draas). This study depended on detailed mapping and recording of all sedimentary structure orientations; such work has yet to be done on the Bridgnorth Sandstone Formation of the Worcester Basin.

The overlying Kidderminster Formation comprises breccio-conglomerates deposited on large alluvial fans at the margins of the sedimentary basin (Whitehead and Pocock, 1947), probably where deeply incised wadis opened onto the

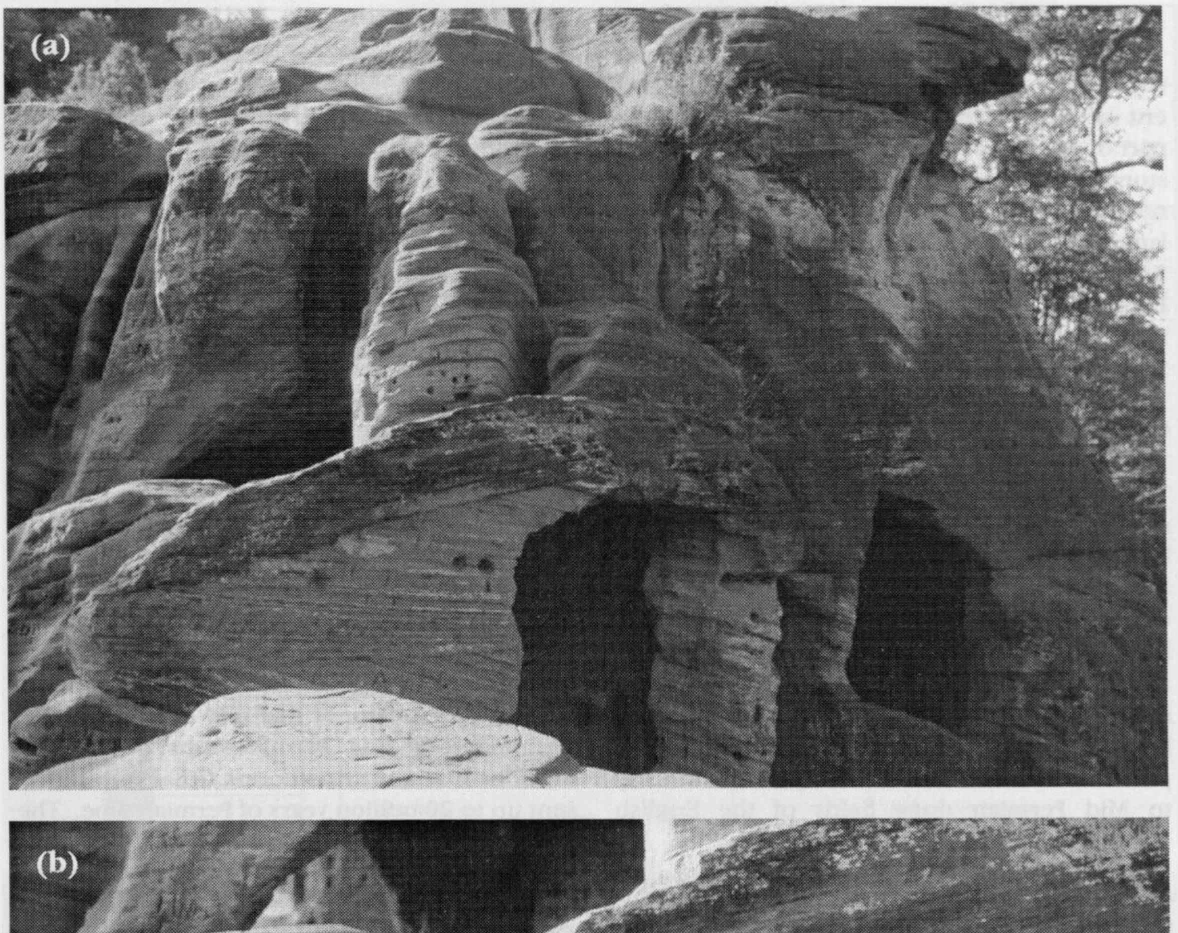


Figure 2.29 The Bridgnorth Sandstone at Kinver Edge, showing (a) large-scale barchanoid aeolian dune bedding, and (b) a close up of the aeolian bounding surfaces. The hammer is about 300 mm long. (Photos: P. Turner.)

more even relief of the sedimentary basin.

The Bridgnorth Sandstone Formation contains no fossils, nor has it yielded any independent evidence of age. However, it appears to be part of a widespread series of thick aeolian sandstones deposited over much of central and northern England, and has been broadly correlated with the Collyhurst Sandstone of the Irish Sea Basin, the Penrith Sandstone of the Vale of Eden, and the Quartzite Breccia, Barr Beacon Beds, and Hopwas Breccia of the North Staffordshire Basin (Smith *et al.*, 1974, p. 26).

Conclusions

The natural crags on Kinver Edge provide a series of small, but informative sections through Permo–Triassic sequences. The Bridgnorth Sandstone Formation consists of large-scale dune cross-beds, and the exposures show excellent three-dimensional detail that allow the ancient compound dune forms to be reconstructed. This is a key site for understanding Early Permian palaeogeography and the palaeoenvironments at the margins of the Early to Mid Permian dune fields of the English Midlands.

THE PERMIAN RED BEDS OF DEVON

INTRODUCTION

The Permian deposits in Devon occur in a number of sedimentary basins and are extensively exposed on the coast. A broad outcrop extends southwards from Somerset to Devon (Figures 2.1 and 2.31), and then under the English Channel (Figure 1.5). The Permian succession, dipping east at low angles, continues beneath the Triassic and Jurassic strata of east Devon and Dorset into the Wessex Basin, where it is detected in boreholes (Holloway, 1985a; Holloway *et al.*, 1989). The total thickness of the Devon Permo–Triassic red-bed succession is perhaps 2.75 km (Laming, 1965) but varies locally.

The stratigraphy of the Permo–Triassic red beds of Devon has proved immensely complex (Smith *et al.*, 1974, pp. 27–30; Warrington *et al.*, 1980). Datable fossils (fishes, amphibians, and reptiles) from the Otter Sandstone Formation in eastern Devon are Anisian (Mid Triassic) in age, and the underlying Budleigh Salterton Pebble Bed is generally accepted as Triassic, and is placed in the Lower Triassic Series (see Chapter 3). A lower limit on the age of the red-bed succession is provided by the fact that it rests unconformably upon clearly Carboniferous rocks up to Westphalian C in age (Laming, 1965). The succession of red beds from that level up to the basal Budleigh Salterton Pebble Beds was generally regarded as Permian in age.

Formal stratigraphical units for the Permian succession around Exeter were introduced by Bristow and Scrivener (1984), new palaeontological evidence for the age of some of the units was provided by Warrington and Scrivener (1988, 1990), and the information was formalized by Edwards *et al.* (1997) and Edwards and Scrivener (1999) in thorough revisions of the stratigraphy of the Permo–Triassic around Exeter, and in the Crediton Trough to the west (Figure 2.30). The Permian succession comprises most of the Exeter Group, an 800-m-thick sequence of breccias and subordinate sandstones and mudstones that may represent latest Carboniferous and Permian time, but which includes a major unconformity that may represent up to 20 million years of Permian time. The Cadbury Breccia in the Crediton Trough overlies the Carboniferous Bude Formation unconformably. It contains mostly locally derived Carboniferous clasts, with only rare fragments from the Devonian of north Devon. The Cadbury Breccia can be dated only as post-Westphalian, and may span the Permo–Carboniferous boundary or be entirely Early Permian in age.

The succeeding Bow Breccia rests unconformably on the Cadbury Breccia. It contains clasts of Carboniferous sandstone, as well as shale and hornfels and sporadic igneous rock fragments including quartz-porphyry; it is succeeded by the Knowle Sandstone in the western Crediton Trough, and is partly coeval with the Thorverton Sandstone in the eastern Crediton Trough. Around Exeter, the Permo–Triassic red-bed succession begins with a thin representative of the Knowle Sandstone. The Bow Breccia, and the Knowle and Thorverton sandstones are associated with thin lamprophyric and basaltic lavas which have been dated radiometrically and yielded ages in the range 291–282 Ma, hence placing these units low in the Lower Permian Series. The base of the Permian succession may be dated as about 298 Ma (Edwards *et al.*, 1997) or 291 Ma (Wardlaw, 2000).

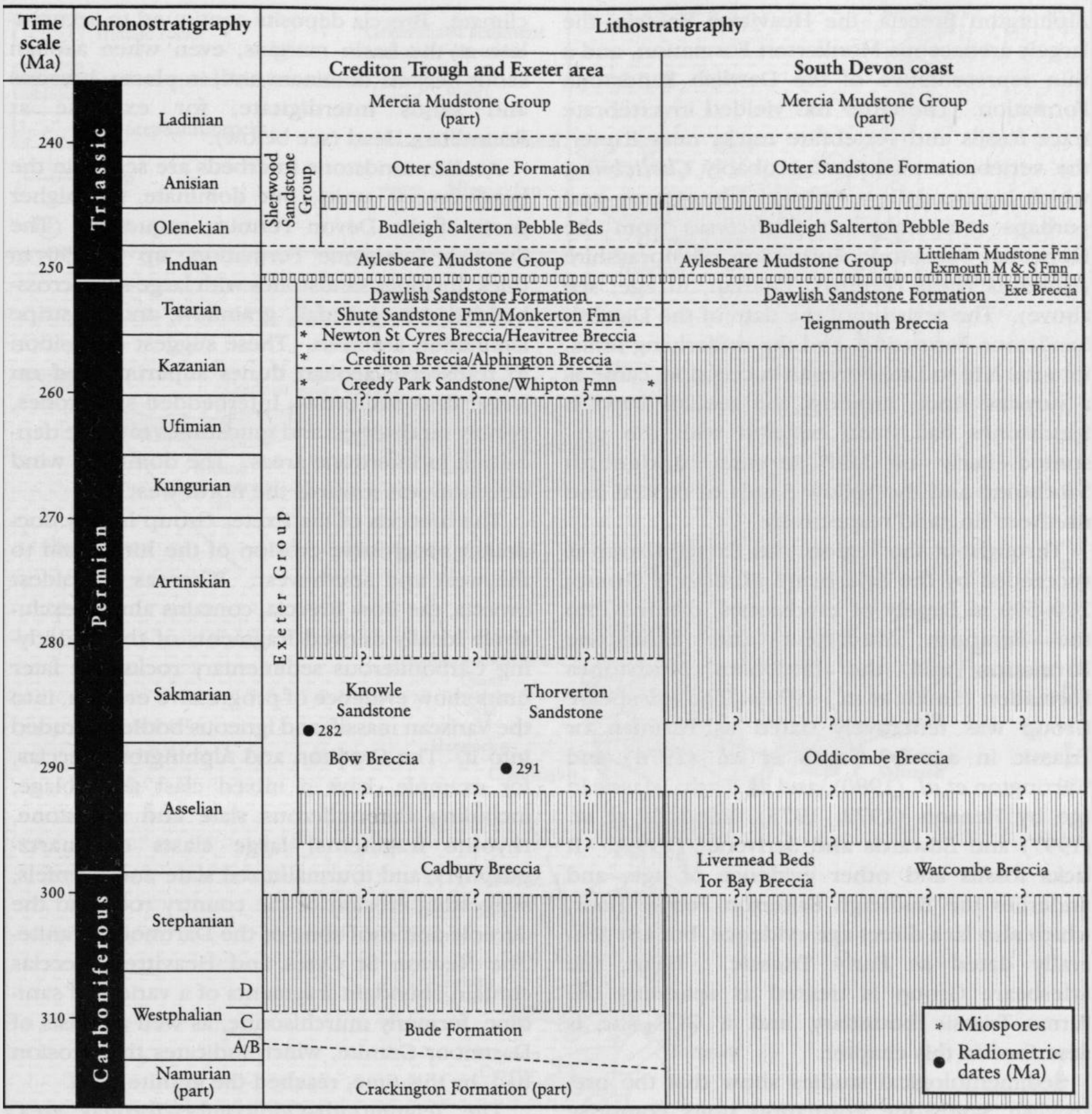


Figure 2.30 Stratigraphy of the Permian successions of the East and South Devon basins. Formal divisions for the Crediton Trough and Exeter area are from Edwards *et al.* (1997), and the successions around Torquay and Teignmouth are updated tentatively from Smith *et al.* (1974), Selwood *et al.* (1984), and Warrington and Scrivener (1990).

After a long hiatus, the Knowle and Thorveton sandstones were succeeded by younger Permian sandstones and breccias (Figure 2.30). In the western Crediton Trough, mudstone units in the Creedy Park Sandstone and the Crediton and Newton St Cyres breccias have yielded miospores that indicate a Mid to Late Permian age. The Crediton Breccia interfingers with the Yellowford Formation, composed mainly of mudstones, in the eastern Crediton Trough, and these units are succeeded by the Shute Sandstone, which is probably equivalent in age to the Newton St Cyres Breccia, and is, in turn, succeeded by the Dawlish Sandstone Formation. Around Exeter, the basal Whipton Formation, equivalent in age to the Creedy Park Sandstone, has also yielded miospores that indicate a Mid to Late Permian age. It is succeeded by the

Alphington Breccia, the Heavitree Breccia, the largely arenaceous Monkerton Formation, and a thin representative of the Dawlish Sandstone Formation. The latter has yielded invertebrate trace fossils and vertebrate tracks near Exeter; the vertebrate tracks are probably *Chelichnus*, which is essentially a Permian ichnogenus, and perhaps comparable to *Chelichnus* from the Hopeman Sandstone Formation of Morayshire (dated as latest Permian, Tatarian, in age; see above). The revision of the date of the Dawlish Sandstone Formation, and the underlying units, into the Mid to Late Permian succession, came as a surprise since, hitherto, the aeolian Dawlish Sandstones had been equated with the presumed Early or Mid Permian Bridgnorth Sandstone and the Yellow Sands of central and northern England respectively.

Throughout the region, the Exeter Group is succeeded by the Aylesbeare Mudstone Group, 200–500 m largely of mudstones, divided into the Exmouth Mudstone and Sandstone Formation and the Littleham Mudstones Formation (Smith *et al.*, 1974). The Aylesbeare Group was tentatively dated as Permian or Triassic in age by Smith *et al.* (1974) and Warrington *et al.* (1980), and as ?Early Triassic in age by Henson (1972, 1973), Edwards *et al.* (1997) and Edwards and Scrivener (1999). It lacks fossils and other evidence of age, and underlies the Budleigh Salterton Pebble Beds, which also lack direct age evidence, but are generally dated as Early Triassic. Here, the Aylesbeare Group is treated as spanning the Permo–Triassic boundary, and a GCR site is described in this chapter.

Sedimentological studies show that the pre-Dawlish Sandstone Formation units comprise deposits of alluvial fan systems that were active for long periods. Deep channels were incised into the pre-Permian uplands around the depositional basins, and breccias were deposited in wadi channels and in braided streams on top of the fans. The active basins were complex in shape, some, such as the Crediton Trough, being long and narrow, others broad (Figure 2.31). Palaeocurrent directions, assessed from imbrication patterns in the breccias, cross-stratification, and other evidence, show a broad range of downslope orientations. The clast types allow fan systems to be distinguished (Laming, 1966), but individual fan lobes cannot be mapped because of poor exposure. The evidence suggests rapid erosion and deposition in a semi-arid climate. Breccia deposits continued to accumulate at the basin margins, even when aeolian sands became dominant and, in places, breccias and sands interdigitate, for example at Roundham Head (see below).

Aeolian sandstone interbeds are scarce in the basal breccia units, but dominate the higher parts of the Devon Permian sequence. The Dawlish Sandstone Formation, up to 350 m thick, includes sandstones with large-scale cross-bedded sets; grainfall, grainflow, and pinstripe lamination are seen. These suggest deposition in transverse aeolian dunes superimposed on larger draa bedforms. Interbedded sandstones, pebbly sandstones, and mudstones indicate deposition in interdune areas. The dominant wind direction was towards the north-west.

The breccias of the Exeter Group largely document progressive erosion of the hinterland to the west and south-west. Whereas the oldest breccia, the Bow Breccia, contains almost exclusively locally derived fragments of the underlying Carboniferous sedimentary rocks, the later units show evidence of progressive erosion, into the Variscan massif, and igneous bodies intruded into it. The Crediton and Alphington breccias, for example, have a mixed clast assemblage, including Carboniferous slate and sandstone, rhyolite fragments, large clasts of quartz-porphyry, and tourmalinized slate and hornfels, suggesting erosion of the country rock and the aureole and roof zone of the Dartmoor Granite. The Newton St Cyres and Heavitree breccias contain abundant fragments of a variety of sanidine, formerly murchisonite, as well as clasts of Dartmoor Granite, which indicates that erosion had, by this time, reached the granite itself.

The Teignmouth–Oddicombe–Torquay area, to the south of Exeter, displays a corresponding Permian succession largely exposed along the coast (Laming, 1966, 1968, 1969; Smith *et al.*, 1974; Selwood *et al.*, 1984) (Figure 2.30). There are several seemingly separate basins, or cuvettes, from south to north, the Paignton, Marldon, and Teignhead cuvettes, into which breccias and coarse sands were transported from uplands to the west. In the Paignton Cuvette, the basal Tor Bay Breccia rests unconformably on Devonian rocks and fines upwards into the Livermead Beds. In the deepest part of the Teignhead Cuvette, fine slate breccias of the Watcombe Breccia, rest unconformably on Devonian limestones and slates and are succeeded by the Oddicombe Breccias, up to 350 m

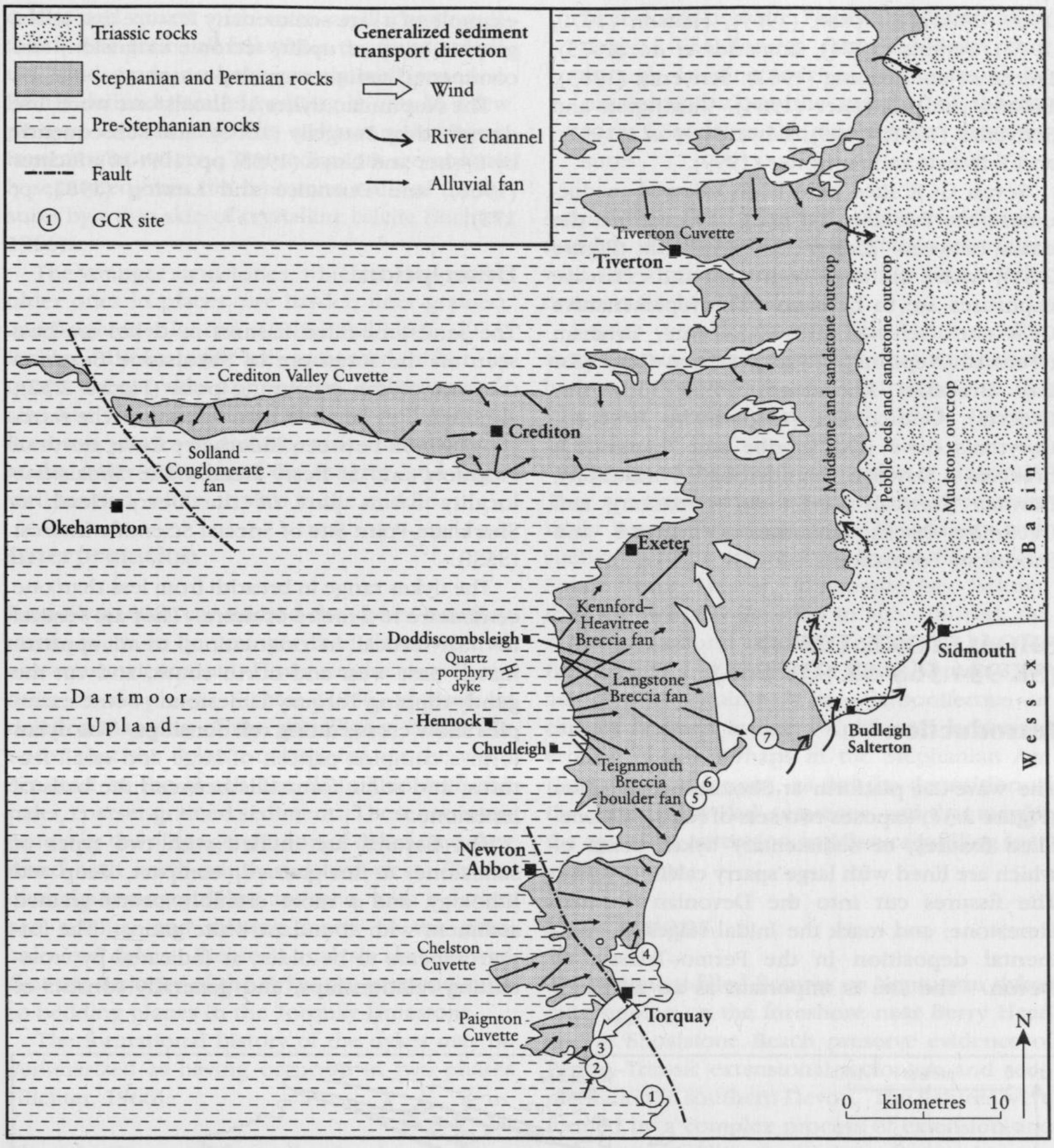


Figure 2.31 Depositional basins and sediment transport trends in the Permian of Devon. GCR sites are: (1) Shoalstone; (2) Saltern Cove; (3) Roundham Head; (4) Oddicombe Beach; (5) Coryton's Cove; (6) Dawlish; (7) Orcombe Rocks. (After Laming, 1982.)

thick, which contain abundant cobbles and pebbles of Devonian limestones. In different parts of this basin, the Oddicombe Breccias are followed by the Netherton and Ness formations, up to 45 and 67 m thick respectively. The Ness Formation comprises interbedded breccias composed alternately of units dominated by limestone and slate clasts, and by sandstone and porphyry clasts. These are in turn followed by the Teignmouth Breccia, some 115 m thick, with sandstone and porphyry clasts.

The geology of the Permian succession of Devon has been described by Whitaker (1869), Ussher (1875, 1876, 1878, 1902, 1913), Irving (1888), Hull (1892), Ussher and Lloyd (1933), Scrivenor (1948), Laming (1965, 1966, 1968, 1969, 1982), Simpson (1969), Henson (1970, 1972), Perkins (1971), Edmonds *et al.* (1975), Durrance and Laming (1982), Scrivener (1983), Bristow and Scrivener (1984), Warrington and Scrivener (1988, 1990), Edwards *et al.* (1997), and Edwards and Scrivener (1999).

Seven GCR sites have been selected to document the Permian red beds of Devon on the coast between Torbay and Exmouth (Figure 2.31), where the most consistent and extensive exposures are to be seen. The representative GCR sites selected are Shoalstone, Brixham (?Permian Neptunian dykes), Saltern Cove (Tor Bay Breccia), Roundham Head (Tor Bay Breccia), Oddicombe (Oddicombe Breccia), Coryton's Cove (Oddicombe and Teignmouth breccias, Dawlish Sandstone Formation), Dawlish (Dawlish Sandstone Formation), and Orcombe Rocks (Exmouth Mudstone and Sandstone Formation).

SHOALSTONE, DEVON (SX 934 568–SX 939 568)

Introduction

The wave-cut platform at Shoalstone, Brixham (Figure 2.31) exposes two sets of red sandstone-filled fissures, or sedimentary dykes, some of which are lined with large sparry calcite crystals. The fissures cut into the Devonian Torquay Limestone, and mark the initial stages of continental deposition in the Permo–Triassic of Devon. The site is important as an excellent example of a rare sedimentary feature that tells a graphic story of uplift, tectonic extension, and continental sedimentary deposition.

The Neptunian dykes at Shoalstone were first described by Pengelly (1866), and subsequently by Ussher and Lloyd (1933, pp. 109–10), Richter (1966), and Durrance and Laming (1982, p. 175).

Description

The sandstone-filled fissures or dykes are best seen on the foreshore of Shoalstone Beach to the east of the swimming pool (Figure 2.32), although they occur in many places on the wave-cut platform between Elderberry Cove, north of Paignton, and at Berry Head. The Shoalstone locality forms part of the Berry Head to Sharkham Point Site of Special Scientific Interest (SSSI).

The dykes range in breadth from less than one centimetre to a metre or more. They are vertical to near-vertical in orientation, trend approximately east–west and north–south, and cut the gently dipping Torquay Limestone. Some examples show cross-cutting relationships. The dykes form a complex pattern of large and small features, and some form sills between the beds of limestone.

The fissures are infilled with two types of sandstone: a fine-grained, compact, deep red lithology, and a more crumbly, coarse-grained sediment with abundant white grains. The former appears to be older, as indicated by cross-cutting relationships, and generally consists of

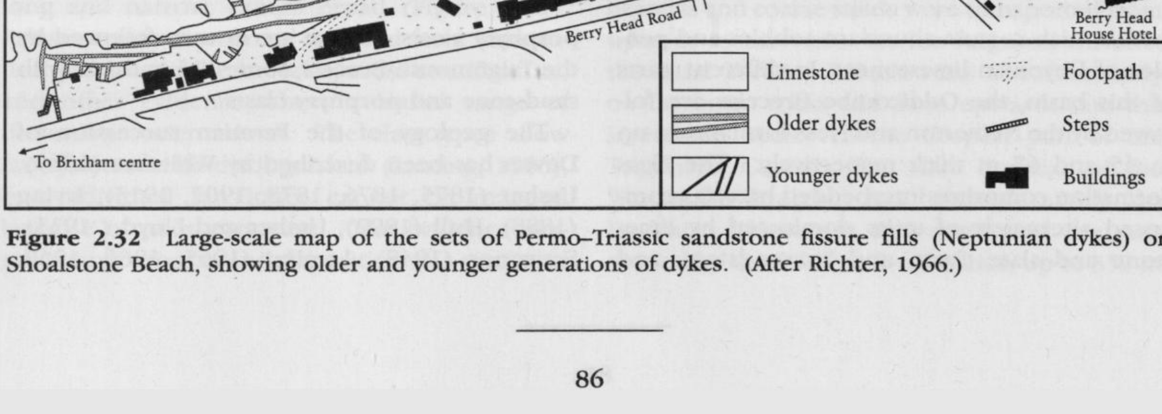


Figure 2.32 Large-scale map of the sets of Permo–Triassic sandstone fissure fills (Neptunian dykes) on Shoalstone Beach, showing older and younger generations of dykes. (After Richter, 1966.)

calcite and quartz with some argillaceous sediment. The grains all fall within the fine to medium sand grade and are mostly well rounded. Poorly defined parallel bedding is seen in a few places. Occasionally the sediments are conglomeratic in nature. The sediments are normally separated from the limestone walls of the fissures by a thin skin of crystalline calcite (Richter, 1966).

The younger sandstones, which cut across the older ones in places, are harder, finer grained, and brighter coloured (Ussher and Lloyd, 1933; Richter, 1966), and are cemented either by quartz overgrowths or by calcite. Calcite crystals also line the sides of the fissures, and show at least two phases of growth, with brown crystals at the outer margins of the fissures, and large, well-formed, white crystals in the middle.

Interpretation

Pengelly (1866) considered the dykes trending north–south to be younger than those with an east–west orientation. However, the story is not quite so simple, as Richter (1966) showed by detailed mapping of the site (Figure 2.32). He noted that the dykes outcropping on the western part of the beach are all infilled with the paler, coarser-grained sediment. These are interpreted as the older generation of dykes, and they trend both north–south and east–west. To the east, the younger dykes are seen, with a darker red colour, and cutting many of the pale-coloured dykes. Richter's analysis also showed that the majority of the dykes are perpendicular to bedding planes in the Torquay Limestone.

The formational history of the dykes may be summarized as having occurred in two phases (Richter, 1966):

Phase 1. Fissures formed in the Torquay Limestone as a result of north–south tectonic extension. These cracks were infilled with sediment, probably by a combination of fluvial (surface and subsurface flow) and aeolian activity, and the sediment was cemented by calcium carbonate. The cementation of the sediment probably occurred quite quickly as this sediment was itself fractured and the resulting cracks infilled with sediment of a similar age.

Phase 2. An episode of broadly east–west tectonically induced fracturing took place. These fractures cut both the Torquay Limestones and the Phase-1 sediment-filled dykes. The fissures remained open long enough to allow calcium carbonate to be precipitated along the margins of the fissures. Sand was also washed into these fissures.

A third, less clearly defined, phase of deformation has also been identified, and is associated with the formation of silica rather than calcite cements (Richter, 1966).

Similar vertical fissures infilled with reddish sandstone are also seen on the coast at Brixham harbour (SX 935 557), and Churston Cove (SX 919 570) (Ussher and Lloyd, 1933; Richter, 1966).

The age of the Shoalstone dykes is uncertain. They are clearly post-Devonian, and almost certainly Permo–Triassic in age. By analogy with similar, but less impressive, fissure fills in the South Devon area at Oddicombe (see below), they are probably Permian in age. Indeed, the sediments around Brixham and Torbay, the Tor Bay Breccia and Livermead Beds (Figure 2.30) are almost certainly Permo–Carboniferous or earliest Permian in age. Uplift and landscape erosion began perhaps in the Stephanian Age (latest Carboniferous), as did the deposition of the Devon 'New Red' sequence, and that may be the age of the extension and fissure infilling seen at Shoalstone.

Conclusions

The sediment-filled fissures or Neptunian dykes outcropping on the foreshore near Berry Head and at Shoalstone Beach preserve evidence of Permo–Triassic extensional tectonism and sedimentation in southern Devon. The fissures were formed by a complex process of extension and subsequent infilling by both aeolian and water-borne sediments. The sediments were then cemented by calcite and silica. This is a key site to examine an unusual and spectacular sedimentary phenomenon, and for an insight into the Permian palaeogeography and topography of the Devon area.

SALTERN COVE, DEVON (SX 894 591–SX 896 586)

Introduction

The sea cliffs and foreshore exposures at Saltern

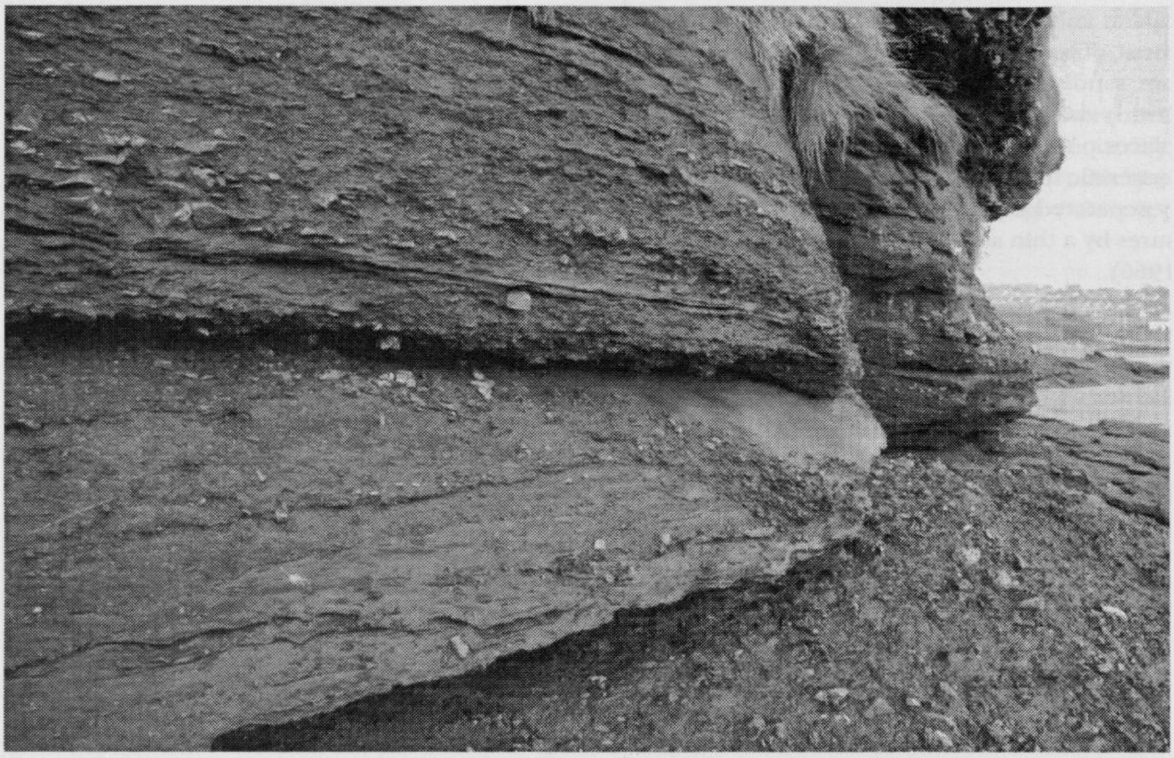


Figure 2.33 The Tor Bay Breccia in Saltern Cove. (Photo: D. Evans.)

Cove and the adjacent headland to the north expose the unconformity between Devonian slates and the Lower Permian Tor Bay Breccia. The breccia contains much locally derived material and comprises poorly organized, fining-upwards sequences. The coarsest Permian beds occur immediately above the unconformity. The site is notable also for the occurrence of large fossil burrows, possibly excavated by tetrapods.

The Saltern Cove section has been described by Ussher and Lloyd (1933), Laming (1966, 1982), and Perkins (1971), and the trace fossils by Ridgeway (1974) and Pollard (1975).

Description

The coastal section between the southern end of Crystal Cove (SX 985 579) and the northern margin of Waterside Cove (SX 896 587) exposes sandstones and breccias of the Tor Bay Breccia.

This GCR site is part of the more extensive Saltern Cove Site of Special Scientific Interest (SSSI) comprising two GCR sites – the area was selected for the GCR both for Permian red beds and, independently, for marine Devonian stratigraphy and sedimentology.

Sedimentology

At Waterside Cove, also known as 'Oyster Cove', the unconformable boundary between the Lower Devonian Meadfoot Beds and Permian Tor Bay Breccia is clearly exposed. Here, the purple Devonian slates have a reddened zone that extends below the contact for approximately 3 m. The surface of the Devonian rocks is an eroded landscape, but there is no evidence of soil formation.

The Tor Bay Breccia consists of interbedded sandstones, sandy breccias, and coarser breccias (Figure 2.33). The breccias are poorly sorted and contain clasts, at most 0.2 m across, primarily of locally derived Devonian limestones and shales; smaller clasts include shale and slate. The breccia contains a high proportion of medium-grained sand matrix that is well cemented by calcite. The sediments preserve a variety of sedimentary structures, including bedding (indicated by alignment of clasts), low-angle trough cross-bedding, planar bedding, rare channels, and pebble imbrication (Perkins, 1971; Laming, 1982). Larger pebbles are imbricated and smaller clasts are aligned parallel to the bedding.

The sediments in Saltern Cove are cut by at least three faults. The headland that separates Saltern Cove and Waterside Cove is fault-bounded. Other faults cut the cliffline, and affect the Devonian limestones and volcanic rocks (Perkins, 1971). At Crystal Cove, outside the GCR site boundary, the Permian sediments have been affected by extensive calcite mineralization, associated with the Crystal Cove Fault Zone. The calcite crystals are found scattered across the cliff faces, and are especially common in the shatter zone (Laming, 1982).

Palaeontology

At Waterside Cove (SX 895 588) large burrows (Figure 2.34) have been recorded from interbedded sandstones and sandy breccias in the Tor Bay Breccia. Individual burrows are up to 0.15 m wide and up to 1.7 m long and are infilled with sediment, which is tightly packed, forming nests of curved meniscus structures (Ridgeway, 1974). Early reports of these burrows claimed that they were made by worms (Scrivenor, 1948; Laming, 1969), but they may have been produced by burrowing reptiles or amphibians as nesting or aestivation structures (Ridgeway, 1974; Pollard, 1975).

Interpretation

The red-bed succession at Saltern Cove was deposited under predominantly terrestrial conditions in a semi-arid climate (Laming, 1966). The eroded basal surface and absence of soil shows that the currents that carried the clasts scoured the underlying Devonian sediments and discharged their load directly on the eroded surface.

The interbedded sandstones and breccias of the Tor Bay Breccia were deposited in one of the many alluvial fans that characterize Permian deposition in South Devon. The sediments accumulated through a combination of sheet and channel flows associated with periodic torrential rainfall. The sediment-rich flood waters flowed through channels and wadis until they reached the open areas of the fans. Here, the flood waters were able to expand and cover a larger area, resulting in a decrease in current velocity and the deposition of the sediment load. At Saltern Cove, the beds of imbricated pebbles indicate that the dominant direction of flow was from the south and west (Figure 2.31; Laming, 1982). The coarser-grained materials are more characteristic of the proximal areas of the fans, and the sandstones were deposited in the distal areas.

It is unclear whether the Tor Bay Breccia should be regarded as entirely latest Carboniferous (Stephanian; Laming, 1965, 1968, 1982), as spanning the Permo–Carboniferous boundary, or as entirely Early Permian in age. By analogy with the basal breccias of the Exeter and Crediton areas (Edwards *et al.*, 1997; Edwards and Scrivener, 1999), they are here regarded as probably spanning the Permo–Carboniferous boundary, on the assumption that the cycle of red-bed deposition began at the same time throughout Devon.

The large burrows indicate that life was pres-

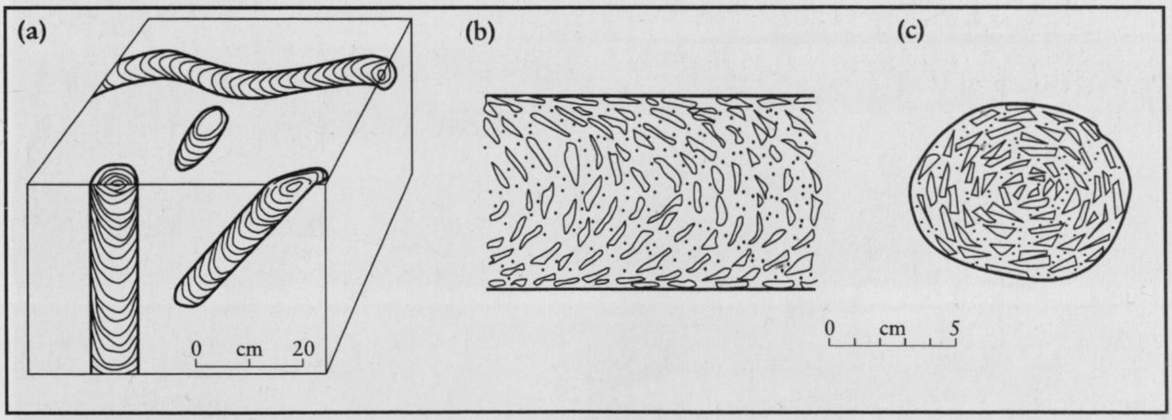


Figure 2.34 Burrows from the Tor Bay Breccia of Waterside Cove, shown as a reconstruction (a), in vertical section, with meniscate packing structures (b), and in horizontal section, with oriented clasts (c). (After Ridgeway, 1974.)

ent, despite the climate being semi-arid. The presence of reptiles or amphibians implies availability of water bodies and abundant vegetation and insect life, for example. Burrows of vertebrates are unusual in the fossil record, and may have been constructed for nesting purposes, so that the eggs and developing young are sheltered from the sun and potential predators. Alternatively, they may have been constructed by adult animals that themselves merely sought protection, or as aestivation structures (Pollard, 1975), dug as resting chambers in which the inhabitants went into a torpid state during the summer months.

Conclusions

The Tor Bay Breccia exposed in the cliff and foreshore section in Saltern Cove comprises a sequence of interbedded sandstones, breccias and coarse-grained breccias. These sediments rest unconformably on the Lower Devonian limestones, shales and tuffs of the Meadfoot Beds. The Tor Bay Breccia was deposited in a large alluvial fan complex, from periodic floods in the Permian deserts. Key features in Saltern Cove are the basal unconformity, the breccia composition, and the unusual burrows. This site provides important information for the reconstruction of the palaeogeography of Devon during around the beginning of the Permian Period.

ROUNDHAM HEAD, DEVON (SX 896 603–SX 894 598)

Introduction

The sea cliffs and foreshore exposures at Roundham Head are the type locality for the Tor Bay Breccia; this unit includes fluvial breccias, most of which were deposited by formed during ephemeral sheet floods. On the south side of the headland are interbedded aeolian sands, with cross-bedding indicating a palaeowind direction towards the north-west, contrary to the prevailing direction to the south-west (cf. Figure 2.31). This contrasts with the direction of *fluvial* transport, deduced from sedimentary structures such as imbrication and cross-bedding in the breccias, which was towards the south-east (cf. Figure 2.31 where the prevailing direction is

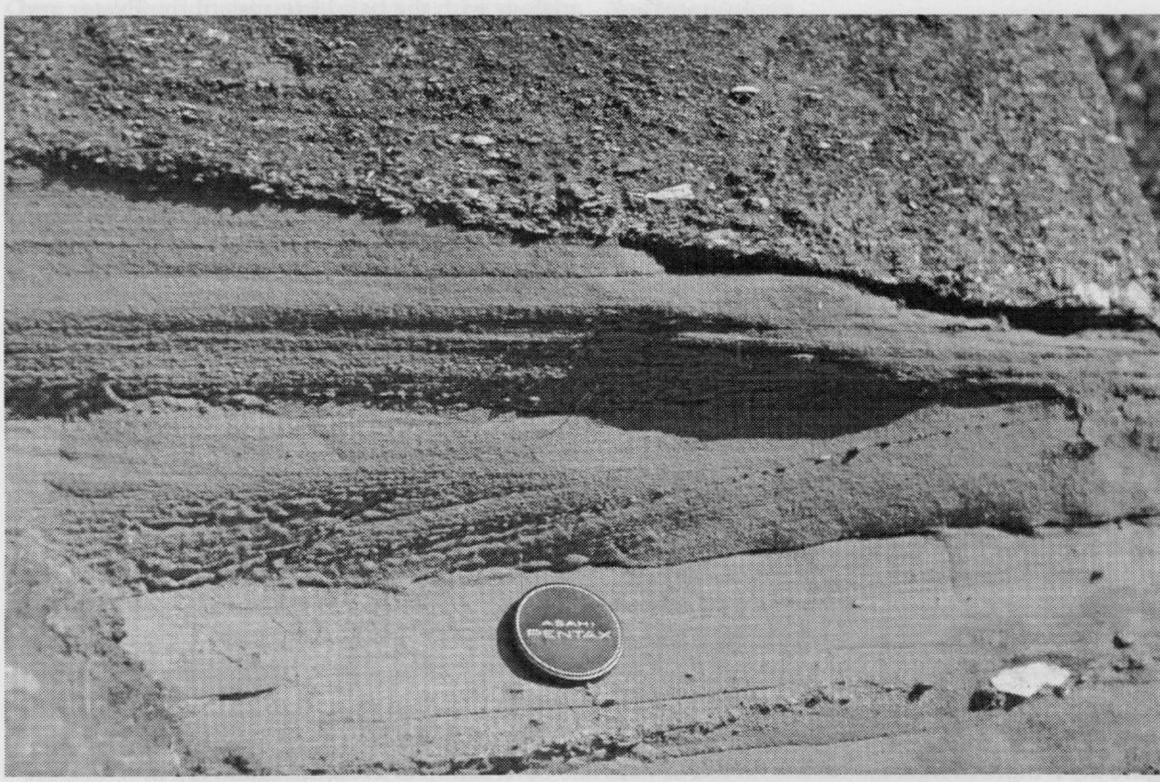


Figure 2.35 The Tor Bay Breccia at Roundham Head. (a) Contact between sandstone and breccia. (Photo: P. Turner.)

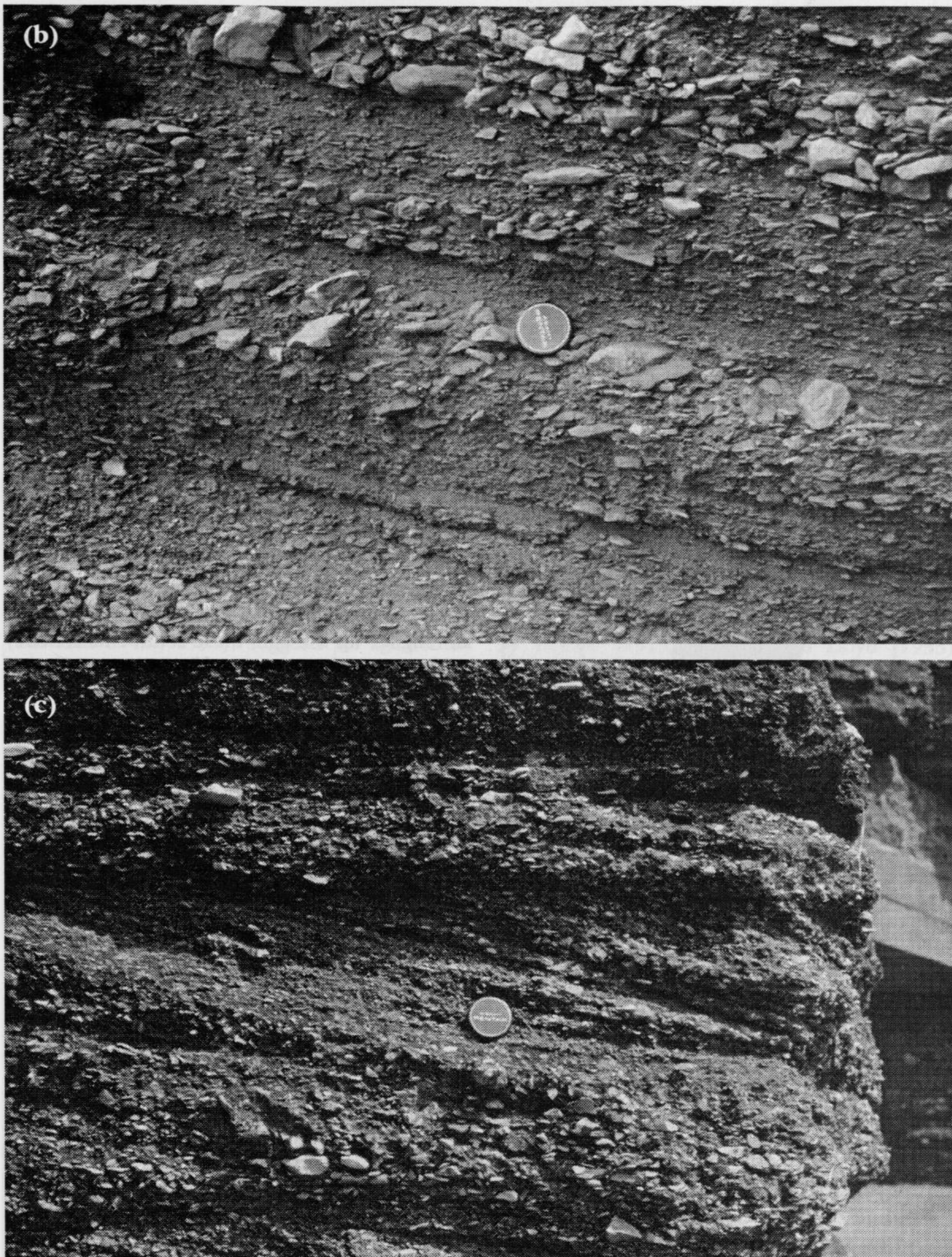


Figure 2.35 – *contd*. The Tor Bay Breccia at Roundham Head. (b) Coarse, imbricated, red, sandy fan breccia composed of locally derived angular clasts of Devonian rocks, mainly limestone. (c) Crudely stratified gravels interbedded with finer-grained cross-stratified gravel. In both (b) and (c) the palaeoflow direction is to the right (west). (Photos: P. Turner.)

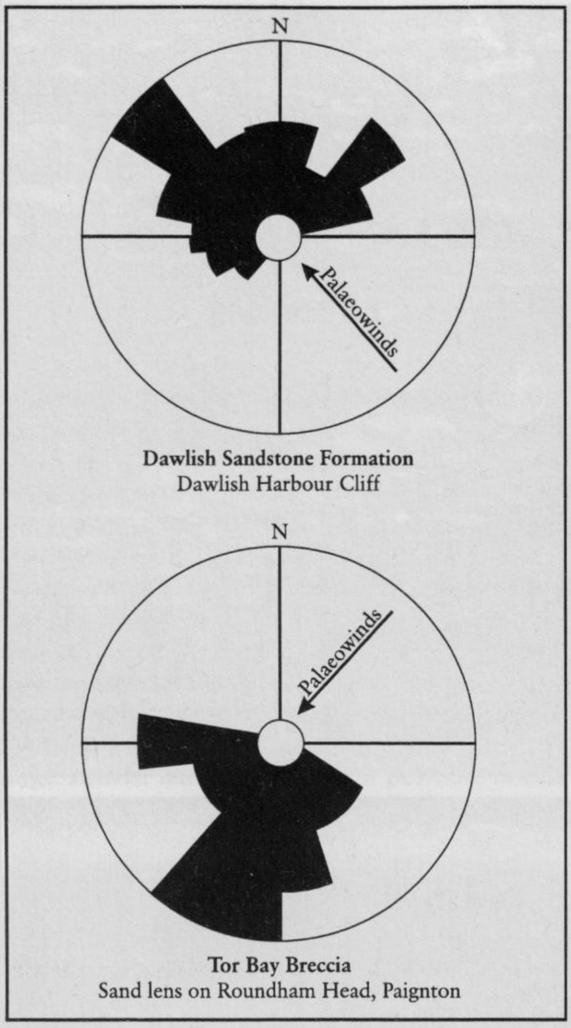


Figure 2.36 Rose diagrams of palaeowind directions from aeolian foreset orientations for the Tor Bay Breccia and the Dawlish Sandstone Formation. (From Laming, 1982.)

to the north-east).

The red-bed succession at Roundham Head has been described by Ussher and Lloyd (1933), Laming (1966, 1969, 1982) and Perkins (1971).

Description

The Tor Bay Breccia at Roundham Head (Figure 2.35a), and on the adjacent wave-cut platform, comprises some 80 m of interbedded sandstones, sandy breccias, and breccias, which are poorly sorted and contain clasts, up to 0.2 m in diameter, of porphyry, quartzite, and Devonian limestones and sandstones. Smaller clasts consist largely of shale and slate. The matrix is a medium-grained sandstone, and is well-cemented by calcite (Laming, 1969).

Sedimentary structures in the Tor Bay Breccia include planar bedding and trough cross-bedding, both highlighted by clast orientations and by grading of clast sizes. The smaller plate-like fragments of slate and shale are frequently orientated parallel to the bedding planes (Figure 2.35b,c) and the larger limestone and sandstone clasts may display coarse imbrication, although they are frequently randomly oriented. The imbrication indicates fluvial transport to the south-east.

The Tor Bay Breccia at Roundham Head includes a 6-m-thick lens of sandstone, composed primarily of well-rounded, polished lithic clasts (mostly slate), all with a thin haematite coating, indicative of aeolian processes. Cross-bedding preserved in the lens indicates a predominantly south-westwards palaeowind direction (Figure 2.36).

The Tor Bay Breccia grades up into the Livermead Beds, which comprise soft cross-bedded sandstones, mudstones, and sparse units of breccia containing fragments of igneous material. Higher up the cliff, these sediments are succeeded by planar-bedded mudstones, whose exposed surface is cut by many sub-vertically orientated sandstone ribs, which are the vertical expression of desiccation cracks (Laming, 1966, 1969; Perkins, 1971).

Interpretation

The sediments at Roundham Head were deposited under terrestrial conditions in an area that was experiencing a semi-arid climatic regime (Laming, 1966, 1968, 1982). The Tor Bay Breccia was deposited on a large-scale alluvial fan complex, initiated during periodic floods. Initial transport was through canyons and channels cut into the margins of the surrounding highland areas and the top of the alluvial fans. On reaching the more open areas of the fans, the waters dispersed over a wider area, causing the velocity to decrease and sediment to be deposited. The coarser-grained breccias and sandy breccias were deposited on the proximal areas of the fan, the sandstones in more distal parts.

The well-rounded polished grains and cross-bedding in the large sandstone lens are characteristic of aeolian deposits, and of crescentic barchan dunes in particular. The presence of this facies suggests that there was a period when flooding declined significantly, allowing purely aeolian processes to predominate, and fluvial sands to be reworked by wind action. Analysis of the dominant orientations of the dune foresets indicates that the prevailing winds blew to the south-west.

The Livermead Beds comprise interbedded sandstones and mudstones that were deposited on the extreme distal portions of the alluvial fan complex. After a flood, water that had soaked into the more permeable gravels of the proximal zone of the fans formed small resurgent streams at the fan margins and fine-grained sediment carried by these streams was deposited in a series of small-scale fans at those margins. Desiccation of the argillaceous layers produced mud flakes and polygons.

The Tor Bay Breccia and Livermead Beds form the base of the red-bed succession in the Paignton Cuvette. There is no direct evidence of dating, other than that they are clearly post-Devonian and pre-Triassic in age. Laming (1965, 1968, 1982) and Perkins (1971) suggested a latest Carboniferous (Stephanian) age, while comparison with the Exeter Group farther north (Edwards *et al.*, 1997), suggests an age tentatively spanning the Carboniferous–Permian boundary.

Conclusions

Roundham Head provides the best section through the Tor Bay Breccia on the Devon coast. These sediments consist of interbedded sandstones and breccias and represent deposition on a large alluvial fan complex. The overlying Livermead Beds are finer-grained sandstones and mudstones, and were deposited on the downstream margins of the alluvial fans. This site is important for understanding the geological history and palaeogeography of Devon around the beginning of the Permian Period.

ODDICOMBE BEACH, DEVON (SX 927 660)

Introduction

The sea cliffs behind Oddicombe Beach expose sections through the Lower Permian Oddicombe Breccia, for which this is the type locality. The breccias are faulted against the Devonian limestones of Petit Tor. The breccias are poorly sorted sediments arranged in crude sheet-like units that fine upwards, and were deposited from ephemeral floods. Imbrication of clasts in some of the finer-grained breccia units indicates fluvial transport towards the east. Permian sandstones and siltstones also infill a cavity and fissure system cut into the underlying Devonian limestone.

The Oddicombe Breccia has been described by Ussher (1913), Ussher and Lloyd (1933), Laming (1966, 1982), Perkins (1971), and Selwood *et al.* (1984).

Description

The cliffs behind Oddicombe Beach expose the Oddicombe Breccia and Devonian rocks, including the dolerites, shales, and limestones best seen on Babbacombe Downs (Figure 2.37). Potential foreshore exposures are obscured by thick deposits of white limestone and quartz

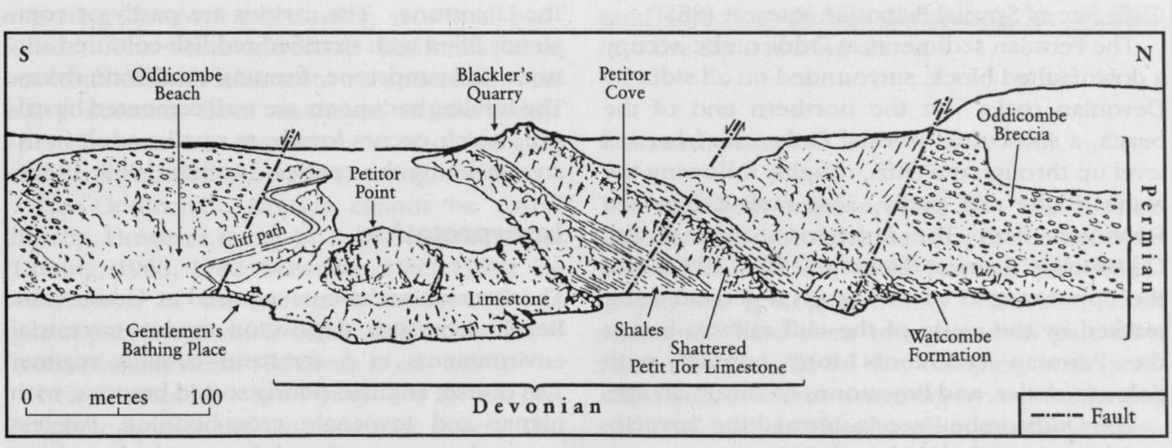


Figure 2.37 The cliff section at Petitor and Oddicombe, showing the three faults that bring the Devonian and the Permian sediments into direct contact. (From Laming, 1982.)

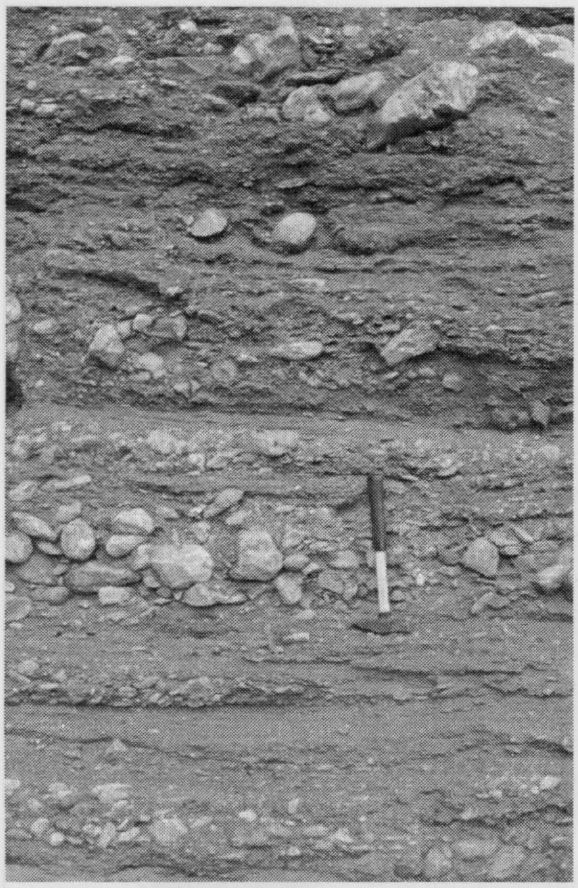


Figure 2.38 The Oddicombe Breccia at Oddicombe Beach, showing intercalated coarse sands and breccias, with imbrication of the pebbles. (Photo: P. Turner.)

debris that has been introduced by longshore drift (Perkins, 1971). The sea cliffs surrounding Oddicombe Bay form part of the Babbacombe Cliffs Site of Special Scientific Interest (SSSI).

The Permian sediments at Oddicombe occupy a downfaulted block, surrounded on all sides by Devonian rocks. At the northern end of the beach, a substantial normal fault runs from sea level up through the cliffs, roughly following the route of the cliff path. This fault brings the Devonian Petit Tor Limestone against the Oddicombe Breccia (Laming, 1969, 1982). At the opposite end of the beach a second fault, marked by the route of the cliff railway, brings the Permian sediments into contact with dolerite, shales, and limestones of Devonian age.

The Oddicombe Breccia, termed the 'breccio-conglomerates' by Ussher (1913), has a maximum exposed thickness here of approximately 350 m. The unit comprises a series of breccia beds, which range in thickness from 0.15 to 0.5 m, interbedded with thinner units of coarse, pebbly cross- and planar-bedded sandstone (Figure 2.38; Laming, 1966). The breccio-conglomerate clasts are rounded, and have an average diameter of 0.15 m, although some are as much as 1.5 m across. The clasts consist mainly of Devonian limestones (possibly the Chercombe Bridge and East Ogwell limestones from south-west of Newton Abbot), with smaller amounts of sandstone and quartz-feldspar-porphyries (Selwood *et al.*, 1984). Finer-grained breccias composed of arkosic sandstone clasts enclosing clay clasts are similar to the Devonian Ugbrooke Sandstone, and therefore reflect a local origin for this material (Selwood *et al.*, 1984). The matrix is reddish-brown, haematitic, silty sand composed of quartz, lithic fragments, and mudstone. The Oddicombe Breccia is very well cemented.

Sedimentary structures are commonly preserved within the Oddicombe Breccia, and include pebble imbrication, planar bedding associated with graded bedding, and low-angle cross-bedding. Rarer sedimentary structures include channels and trough cross-bedding (Laming, 1966, 1982; Selwood *et al.*, 1984). At Maidencombe Cove (SX 928 685), large blocks and joint surfaces of the Oddicombe Breccia display individual and interfering trough cross-bedded units and less common subordinate planar bedding. The cross-bedding grades between isolated cut-and-fill trough cross-bedding and grouped cut-and-fill scoops (Laming, 1966).

Towards the northern end of Oddicombe Beach, cavities and open fissures are seen in the top metre or so of the massive Devonian Petit Tor Limestone. The cavities are partly or completely filled with stratified reddish-coloured siltstone and sandstone, forming sandstone dykes. The infilling sediments are well cemented by calcite, which occurs locally as small nodules and crystals lining the cavities (Laming, 1969, 1982).

Interpretation

The Permian sediments exposed at Oddicombe Beach represent deposition under terrestrial environments in a semi-arid climatic regime. The coarse, angular, poorly sorted breccias, with planar and low-angle cross-bedding, suggest accumulation on alluvial fans, with deposition from sheet floods and from floods channelled through canyons incised in the upper surface of

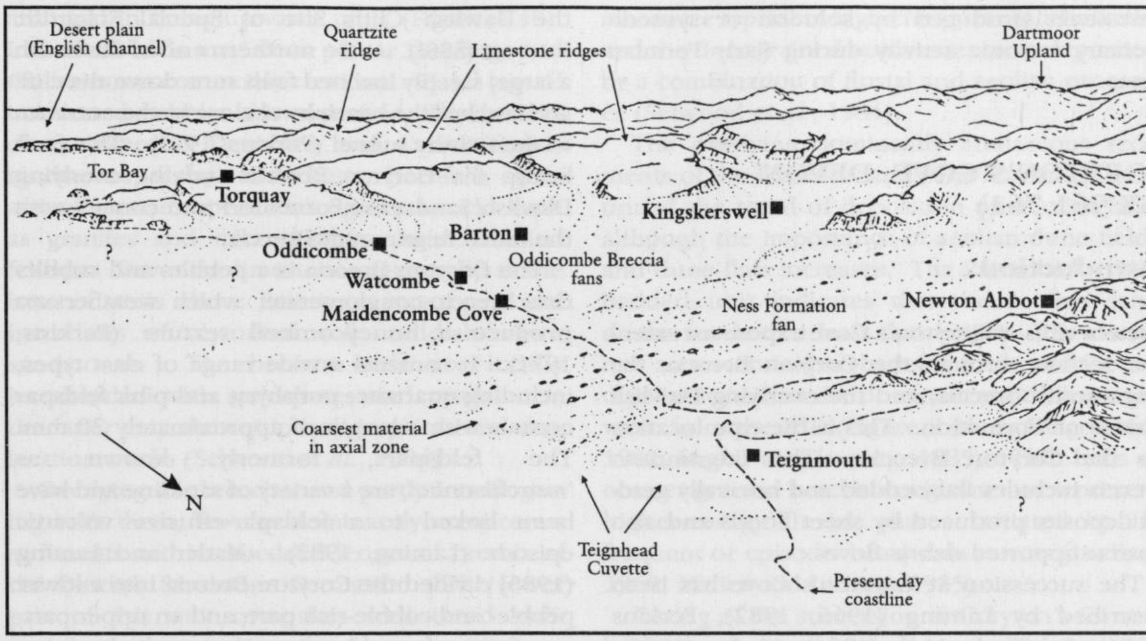


Figure 2.39 Palaeogeography of South Devon during the Early–Mid Permian epochs, showing the mountainous hinterland of uplifted Devonian and Carboniferous sediments, the main depositional basins, and the present-day coastline. (After Laming, 1982.)

the fans (Laming, 1982). The rounded nature of the clasts in the Oddicombe Breccia indicates that they had been transported some distance from the uplands to the west and north-west (Figure 2.39).

The isolated cut-and-fill troughs and the grouped cut-and-fill scoops exposed at Maidencombe Cove (Figure 2.39) have been interpreted as evidence for current eddies migrating downstream, causing erosional bedforms. The scour-and-scoop bedforms have been infilled with sediments transported by less active currents from upstream of the eddy. These features are characteristic of converging streams in braided channels (Laming, 1966).

The Oddicombe Breccia cannot be dated directly. However, it may be Early Permian in age (Laming, 1968, 1982; Selwood *et al.*, 1984), by comparison of the included clasts, such as quartz porphyry, which occur also in the Bow Breccia farther north (Edwards *et al.*, 1997).

Two theories have been proposed for the origin of the fissures and the sandstone dykes. The first is that fissures and cavities within the Petit Tor Limestone are solution features produced by exposure and karstification of the limestones during the Permian Period (Laming, 1982). The fissures were then filled with a mixture of red sandstone and silt, grey limy silt, and small fragments of limestone, presumably washed into the cracks. The alternative view is that the fissures were formed through a combination of desiccation and loading associated with flooding events (Selwood *et al.*, 1984). The red sediment may then have been emplaced from below by quicksand injection during dewatering, or washed into the fissures from above.

Conclusions

The excellent exposures of the Oddicombe Breccia at Oddicombe Beach provide valuable information on the early Permian palaeogeography and geological history of Devon. These sediments have been interpreted as part of a regional-scale alluvial fan complex, with sediment accumulation occurring by a combination of fluvial, and, to a lesser extent, aeolian processes. The site is the type location for the Oddicombe Breccia. Notable also are the cracks and fissure infills in the underlying Devonian limestones produced by solution or synsedimentary tectonic activity during Early Permian times.

CORYTON'S COVE, DEVON (SX 961 761)

Introduction

The sea cliffs at Coryton's Cove expose an extensive section through the Coryton Breccia, the Teignmouth Breccia, and the overlying Dawlish Sandstone Formation. This is the type location for the Coryton Breccia. The Teignmouth Breccia includes flat-bedded and normally graded deposits produced by sheet floods and also matrix-supported debris flows.

The succession at Coryton's Cove has been described by Laming (1966, 1982), Perkins (1971), Selwood *et al.* (1984), Mader (1985), and Mader and Laming (1985).

Description

The outcrops around Coryton's Cove are part of the Dawlish Cliffs Site of Special Scientific Interest (SSSI). At the northern end of the beach a large, steeply inclined fault runs down the cliff, and reaches the beach level close to the entrance to the railway tunnel (Perkins, 1971). This fault brings the Coryton Breccia and the overlying Dawlish Sandstone Formation into contact with the older Teignmouth Breccia.

The Coryton Breccia is a pebble- and cobble-rich breccio-conglomerate, which weathers to produce a honeycombed texture (Perkins, 1971). It contains a wide range of clast types, including quartzite, porphyry, and pink feldspar crystals with a length of approximately 20 mm. The feldspars, formerly known as 'murchisonite', are a variety of sanidine and have been linked to a feldspar-effusive volcanic episode (Laming, 1982). Mader and Laming (1985) divided the Coryton Breccia into a lower pebble- and cobble-rich part, and an upper part, consisting of sandstones and sporadic breccias. Dewatering structures comprising sand-filled cracks that open upwards into breccia units are present (Mader, 1985, p. 29).

The Teignmouth Breccia comprises coarse- and finer-grained rudaceous sediments, often

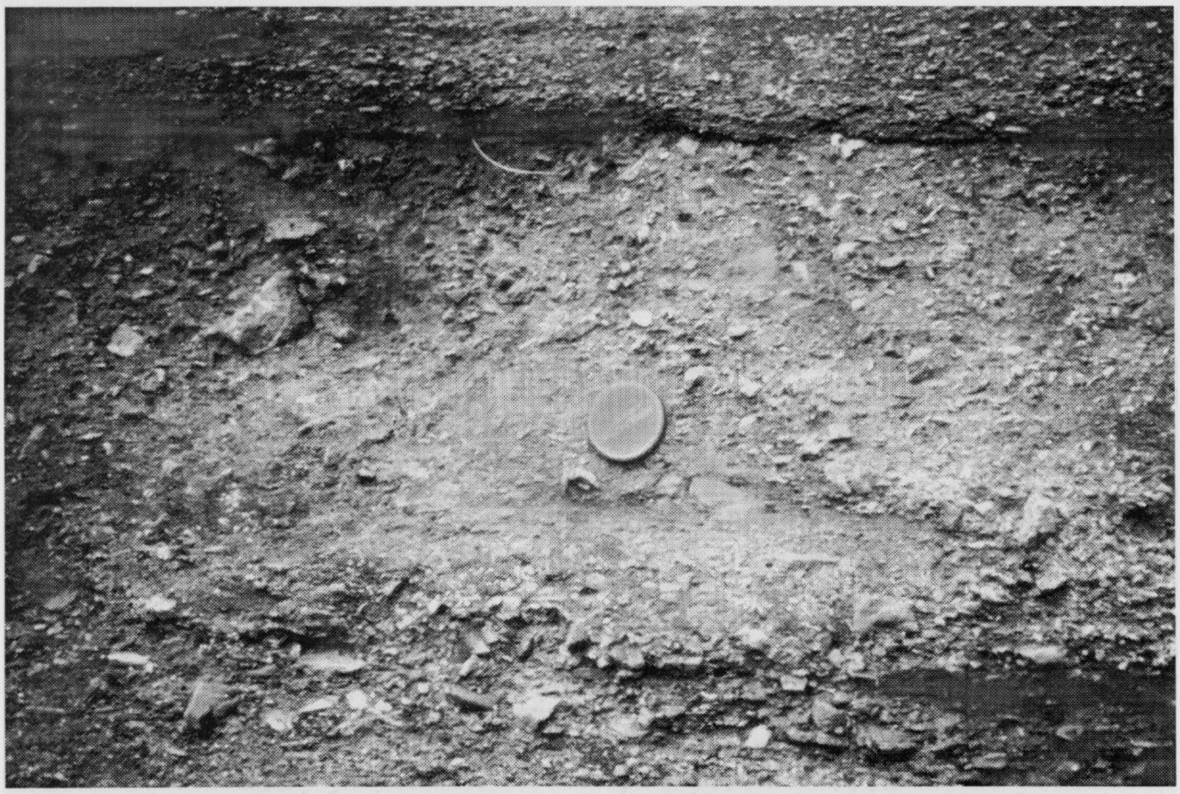


Figure 2.40 Debris flow in the Teignmouth Breccia at Coryton's Cove. Near the top of the photograph is a sharp transition to an overlying sheetflood deposit. (Photo: P. Turner.)

arranged in fining-upwards units (Figure 2.40). Individual beds may show planar bedding, and the bases are commonly erosional. Basal lags of imbricated pebbles are common. The breccia clasts comprise Devonian and Carboniferous sandstones, slates, and cherts, hornfels, slate, aureole metamorphic rock, igneous rocks such as granites and micrograntes, 'murchisonite' feldspar, Devonian limestones (generally at the base of units above limestone outcrops), and intraclasts of reworked soft, reddish-brown sandstones. The breccia beds are locally interbedded with sandstones and mudstones; the latter may show raindrop imprints and desiccation cracks (Selwood *et al.*, 1984).

Overlying the breccias, and partly interfingering with them, are the dominantly arenaceous sediments and interbedded lenses of breccia of the Dawlish Sandstone Formation. The lower part of this unit comprises well-sorted sediments, composed primarily of quartz with frosted surfaces and thin coatings of haematite. Minor constituents of the sandstones include orthoclase and plagioclase feldspars and lithic fragments. Large-scale cross-beds with asymptotic bases are common, and are arranged in large wedge-shaped units separated by planar bounding surfaces. The upper part of the Dawlish Sandstone Formation consists of sandstones reworked from the lower, aeolian, parts of the formation, and preserves cross-bedding, and breccia-filled channels and scours (Laming, 1966, 1982; Selwood *et al.*, 1984).

Interpretation

The Permian breccio-conglomerates and sandstones exposed at Coryton's Cove were deposited by terrestrial processes under semi-arid climatic conditions. The breccio-conglomerates were deposited on aeolian fans, and the sandstones accumulated through a combination of aeolian and fluvial processes (Laming, 1968; Mader and Laming, 1985).

The breccias indicate high-energy deposition on alluvial fans. The lower pebble- and cobble-rich unit of the Coryton Breccia was presumably deposited on the medial and distal regions of alluvial fans with little or no reworking of aeolian dune deposits (Mader and Laming, 1985). The overlying upper unit was deposited on the distal parts of a fan complex, and shows reworking of aeolian sediments. In the Teignmouth Breccia, the coarser-grained sediments are typical of high-energy fluvial channels, and the finer-grained sandstones were deposited by a combination of fluvial and aeolian processes (Selwood *et al.*, 1984).

The overlying dominantly arenaceous sediments of the Dawlish Sandstone Formation continued the trend of deposition on alluvial fans, although the importance of aeolian dune fields and dune flats increases. The 20-m-thick cross-bedded unit indicates that the aeolian sand dunes reached at least that height. The dunes had a crescentic (barchanoid) form, and foreset dips indicate that the dominant wind directions were from the SSE (Figure 2.36; Laming, 1966, 1982; Mader and Laming, 1985). Thin beds of coarser-grained breccio-conglomerate represent higher-energy fluvial phases initiated by infrequent or episodic heavy rain storms (Laming, 1968; Mader and Laming, 1985).

Dating of the succession at Coryton's Cove is based on circumstantial evidence. The presence of 'murchisonite' in both the Coryton and Teignmouth breccias may be a useful stratigraphical indicator (G. Warrington, pers. comm., 2001). In the clast succession demonstrated in the Exeter Group around Exeter (Edwards *et al.*, 1997) this mineral appears in the Newton St Cyres and Heavitree breccias that underlie the Dawlish Sandstone Formation (Figure 2.30). Its appearance in the Coryton and Teignmouth breccias may indicate correlation with those more northerly units, and hence a comparable Mid to Late Permian age.

The Dawlish Sandstone Formation partially overlies the Teignmouth Breccia, and partially interfingers with it. In the Exeter region, the Dawlish Sandstone Formation follows a succession of sandstones and breccias dated by miospores as Late Permian and is assigned a latest Permian age (Edwards *et al.*, 1997).

Conclusions

The sequence exposed in the cliffs at Coryton's Cove includes the Coryton Breccia, the Teignmouth Breccia, and the Dawlish Sandstone Formation, all probably Mid to Late Permian in age. The breccias were deposited within a major alluvial fan complex, where sediment was occasionally reworked by aeolian processes. The overlying Dawlish Sandstone Formation is largely aeolian in origin. Coryton's Cove is critical for understanding of Permian palaeoenvironments and palaeogeography in the Devon region.

DAWLISH, DEVON (SX 966 768–SX 979 782)

Introduction

The site shows one of the finest continuous exposures in the country of interbedded aeolian sands and water-laid breccia-filled fluvial channels of Permian age. The sediments belong to the Dawlish Sandstone Formation, of which this is the type section. At the northern end of the section, Langstone Rock is the type location of the Exe Breccia, a coarse alluvial fan unit intercalated within dune sandstones. This is a classic site for the study of aeolian bedforms and for understanding the palaeogeographical evolution of the Devon region during Permian times.

The Dawlish Sandstone Formation in its type area has been described by Laming (1966, 1982), Selwood *et al.* (1984), Mader (1985), Mader and Laming (1985), Mader and Yardley (1985), Clemmensen *et al.* (1994), and most recently by Newell (2001).

Description

The sea cliff exposures around Dawlish are part of the Dawlish Cliffs Site of Special Scientific Interest (SSSI). A complete section through the Dawlish Sandstone Formation is exposed in the cliffs around the town, in particular beside the railway line east of Dawlish (Figure 2.41). This unit consists primarily of aeolian and fluvial sandstones, with some interbedded breccias and breccio-conglomerates (Laming, 1982; Selwood *et al.*, 1984; Mader, 1985). The breccia horizons contain some large blocks of reworked aeolian sandstone. This alternation between breccias and sandstones grades upwards into sandstones with occasional mudstone beds. Towards the top of the sequence, the sandstones are incised by channels infilled with breccia (Laming, 1966, 1982; Mader, 1985).

The sandstones at the base of the Dawlish Sandstone Formation are generally well sorted and composed of well-rounded grains, which commonly have frosted surfaces and thin coat-

Figure 2.41 Aeolian dune sands in the Dawlish Sandstone Formation. The large-scale cross-bedded unit in the middle of the section represents an eastwardly migrating barchanoid draa. It is interbedded with fluvial sheet-flood sands and gravels (Photo: P. Turner.)

ings of haematite. Quartz grains dominate (65–80%), although pinkish sanidine feldspar ('murchisonite') crystals up to 20 mm long are present (20%), as well as lithic fragments (10%) (Laming, 1966, 1982). The sedimentary structures are mainly large-scale planar-wedge dune sets, some 0.7 m thick and 5 m wide, with minor planar-tabular cross-bedded sets and trough sets (Figure 2.41; Mader and Yardley, 1985). The bounding surfaces are predominantly planar and horizontal, as well as gently inclined to create the wedge-shaped sets. The foreset laminae are generally slightly concave-downwards and asymptotic at the base, and they indicate a predominant wind direction towards the north-west (Figure 2.36). Some truncation planes are lined with thin deflation lag veneers consisting of fine gravel. Intercalated breccia lenses from 0.05 to 4 m thick rest on erosion surfaces and fine- upwards into planar-bedded sandstones with scattered gravel clasts.

The top 120 m of the Dawlish Sandstone Formation comprises sandstone with thin beds of breccia (Figure 2.41). Quartz grains dominate, and appear to have been reworked from the underlying aeolian sediments. Cross-bedding is present, but is generally not very well preserved. Large channels and 'washouts' cut into the underlying sandstone are also recorded, and are infilled with medium-grained breccias with quartzite and porphyry clasts (Laming, 1966, 1982).

The overlying Exe Breccia (Selwood *et al.*, 1984, p. 94), formerly the Langstone Breccia, is seen towards the northern end of the beach at Langstone Rock (SX 979 780). The Exe Breccia overlies and partially interdigitates with the Dawlish Sandstone Formation, and is succeeded unconformably by the Exmouth Mudstone and Sandstone Formation of the Aylesbeare Mudstone Group (Figure 2.30). It comprises up to 85 m of poorly cemented, pebbly breccio-conglomerates composed primarily of angular clasts of sandstone, with some fragments of aureole metamorphic rocks (slate) and porphyry (Laming, 1982; Mader and Laming, 1985). The clasts are generally less than 0.15 m across and are contained in a haematite-stained sand and silt matrix. Graded bedding is recognizable, and cross-bedded and planar-bedded sandstone sets are common at the tops of breccia units. Sets and cosets of cross-bedded breccia up to 0.3 m thick, comprising clasts 20–40 mm in diameter in a silty sand matrix, occur towards the top of the formation.

Interpretation

The Dawlish Sandstone Formation was deposited by aeolian and fluvial processes in a semi-arid climate (Laming, 1966; Selwood *et al.*, 1984; Mader, 1985). Mader and Laming (1985) divided the formation into lower, middle, and upper parts, which were in turn subdivided into eleven units. The lower part comprises interbedded sandstones and breccias, representing deposition in alluvial fans, which pass upwards into deposits of an aeolian dune field. The alluvial fan sediments show some degree of reworking by aeolian processes.

The middle part of the sequence represents a continuation of deposition in the aeolian dune field and in dune flats, with a varying degree of fluvial activity, resulting in sandy braidplains and alluvial fans, and reworking of the aeolian sediments. Hierarchical bounding surfaces indicate that the dune sediments were periodically reworked and redeposited in subsequent generations of dunes. Fluvial incursions are represented by sandy sediments that lack well-defined sedimentary bedding and contain mudstone lenses and layers, interpreted as accumulating on distal parts of alluvial fans (Laming, 1982). Channels incised into the sandstone indicate that during some of the flooding episodes the more common sheet floods were replaced by high-energy erosive channelled flows. The channels were formed when sheet floods were forced into narrow areas between the dunes, and may reflect changes in the climatic regime of the British Isles towards the end of the Permian Period.

The cross-bed sets indicate that the dunes were straight- to sinuous-crested transverse dunes that migrated in essentially one direction, to the NNW. There is evidence for some slight variation in palaeowind direction (Figure 2.36), possibly caused by topographical wind deflection as winds blew across the lowland area of the erg and encountered surrounding mountain chains (Mader and Yardley, 1985). The upper part of the sequence reflects a change to deposition on an alluvial fan complex consisting of small-scale, pebbly, distal fans, sandy braidplains, and rarer dune facies.

The Exe Breccia comprises lower and upper parts (Mader and Laming, 1985). The lower part is generally coarse-grained, with a large proportion of pebbles, and has been interpreted as representing the medial and distal portions of an alluvial fan. The upper part is more sandy, and represents the more distal areas of an alluvial fan. Deposition of the breccias may have resulted from an increase in rainfall associated with climatic change towards the close of the Permian Period.

Fossils are absent throughout the Dawlish section, and the Dawlish Sandstone Formation is dated on circumstantial evidence. Footprints, which suggest a Late Permian age, have been found in the unit near Exeter, (Edwards *et al.*, 1997; Edwards and Scrivener, 1999). In addition, around Exeter, the Dawlish Sandstone Formation occurs above sandstones and breccias that have been dated by miospores as Mid to Late Permian (Figure 2.30). Furthermore, at Dawlish, the Dawlish Sandstone Formation interfingers with the Teignmouth Breccia (assigned a Mid to Late Permian age – see GCR site report for Coryton's Cove). The assignment of a this later Permian age to the formation (Edwards *et al.*, 1997; Edwards and Scrivener, 1999) is a substantial shift from the traditionally assigned Early or Mid Permian age (Laming, 1968, 1982).

Conclusions

The excellent exposures of the Dawlish Sandstone Formation and the Exe Breccia in the vicinity of Dawlish reflect important changes in sedimentary conditions during the Late Permian Epoch. The lower part of the Dawlish Sandstone Formation represents aeolian sedimentation in dune fields, with occasional incursions of fluvial sandstones and breccias. The upper part of the formation is characteristic of a fluvially dominated system, which reworked much of the aeolian sequence. The Exe Breccia was deposited in an alluvial fan environment. This is a critical site for understanding aeolian sedimentation processes and for reconstruction of the Permian palaeogeography of Devon.

ORCOMBE ROCKS, DEVON (SY 018 797–SY 023 795)

Introduction

The site is an excellent coastal section in the sandstones, siltstones, and mudstones of the Permo–Triassic Exmouth Mudstone and Sandstone Formation. The sandstones are fluvial in origin and show trough and planar-tabular cross-bedding, which indicate that the rivers that deposited these sediments flowed towards the north. The mudstones represent deposition in fluvial overbank (floodplain) and playa-lake environments, and contain sporadic plant fossils. This is an important site for the elucidation of Permo–Triassic palaeoenvironments in the south of England.

The Exmouth Mudstone and Sandstone Formation has been described by Irving (1888), Ussher (1902, 1913), Carus-Wilson (1913), Laming (1966, 1982), Henson (1970, 1972, 1973), Smith *et al.* (1974), Bristow and Scrivener (1984), Selwood *et al.* (1984), Mader and Laming (1985), Clemmensen *et al.* (1994), Edwards *et al.* (1997), and Edwards and Scrivener (1999). Harrison (1975) documented the geochemistry of the concretions found within the argillaceous and arenaceous sediments exposed around Orcombe Point.

Description

Orcombe Rocks form part of the Exe Estuary Site of Special Scientific Interest (SSSI) and part of the Dorset and East Devon Coast World Heritage site (established December, 2001).

The Permo–Triassic sediments are faulted and comprise mudstones, with thick interbedded sandstones. Most of the faults follow the line of strike (Harrison, 1975; Selwood *et al.*, 1984, pp. 104–5).

The cliffs and foreshore expose the Exmouth Mudstone and Sandstone Formation of the Aylesbeare Mudstone Group (Figure 2.42). The upper formation of the Group, the Littleham Mudstone, crops out to the east between Littleham Cove and Budleigh Salterton. These formations, which are equivalent to the former 'Lower Marls' (Ussher, 1875, 1876, 1913) were established by Laming (1966, 1968) and Henson (1970) and were united in the Aylesbeare Mudstone Group, introduced by Smith *et al.* (1974, pp. 38–9). Henson (1972, 1973) referred to the 'Exmouth Sandstones and Mudstones' and the 'Littleham Mudstones', and these were formalized as the Exmouth Sandstone and Mudstone Formation and the Littleham Mudstone Formation by Warrington *et al.* (1980, p. 43). The more inclusive unit term was transmogrified into the Aylesbeare Mudstone Formation by Bristow and Scrivener (1984) and

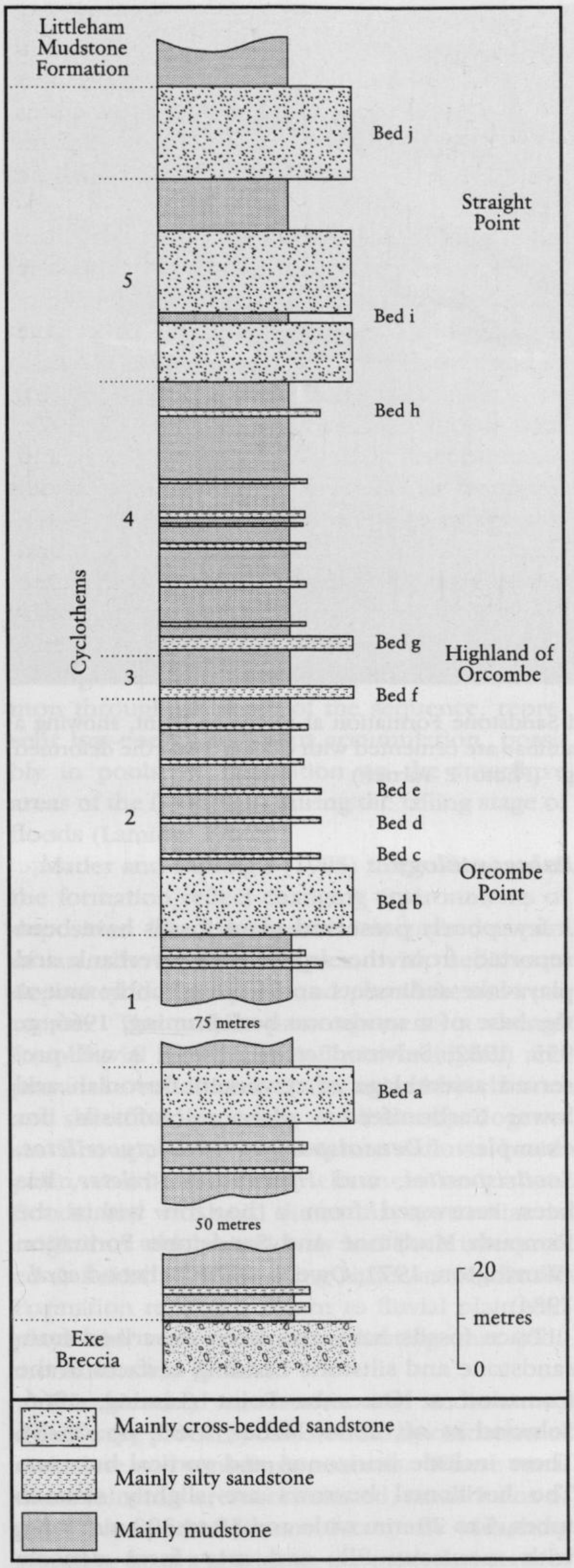


Figure 2.42 Summary log through the Exmouth Mudstone and Sandstone Formation in the coast section between Orcombe Point and Straight Point, east of Exmouth. (From Selwood *et al.*, 1984.)

Warrington and Scrivener (1990), and the two constituent subunits became members. These units were restored to higher rank by Edwards *et al.* (1997) who refer to the 'Aylesbeare Mudstone Group' (Figure 2.30), equivalent in rank to the underlying Exeter Group (essentially all the Devon Permian strata), and the overlying Sherwood Sandstone, Mercia Mudstone, and Penarth groups of the Triassic succession (see Chapter 3).

Sedimentology

The Exmouth Mudstone and Sandstone Formation at Orcombe consists of some 255 m of red and green sandstones interbedded with structureless reddish siltstone and blocky mudstones (Figure 2.42). This unit succeeds the Dawlish Sandstone Formation or the Exe Breccia unconformably (Selwood *et al.*, 1984; Edwards *et al.*, 1997). The mudstones are dark red and have a blocky texture; in the past, they were described as 'marls', although the carbonate content is too low for this term to apply. The sandstones typically infill large channels cut into the interbedded thin sandstones and mudstones, and may be laterally extensive over distances of approximately 200 m. They form discrete lenses that overlie scoured surfaces and preserve evidence of internal planar and trough cross-bedding; the foresets are generally concave-up and gently curving. Mudstone lenses are common throughout the sandstone bodies, and the sandstone may be interbedded with siltstone lenses. The sandstones associated with the siltstones are frequently pale green in colour, and may be mottled (Laming, 1966, 1982; Henson, 1970).

Three distinct sedimentary facies have been distinguished in the Exmouth Mudstone and Sandstone Formation (Henson, 1970).

1. Poorly sorted, locally impersistent, green sandstone beds, 0.15 to 1.0 m thick, interbedded with mudstones. Sedimentary structures include small-scale cross-bedding and small channels cut into the underlying sediments.
2. Red and green, cross-bedded sandstones with mudstone lenses, arranged in fining-upwards sequences, with trough and planar cross-bedding, and a few intraformational mud-pellet conglomerates. The lenses are between 1.25 and 3.0 m thick, and generally rest on erosion surfaces cut into the underlying silts.

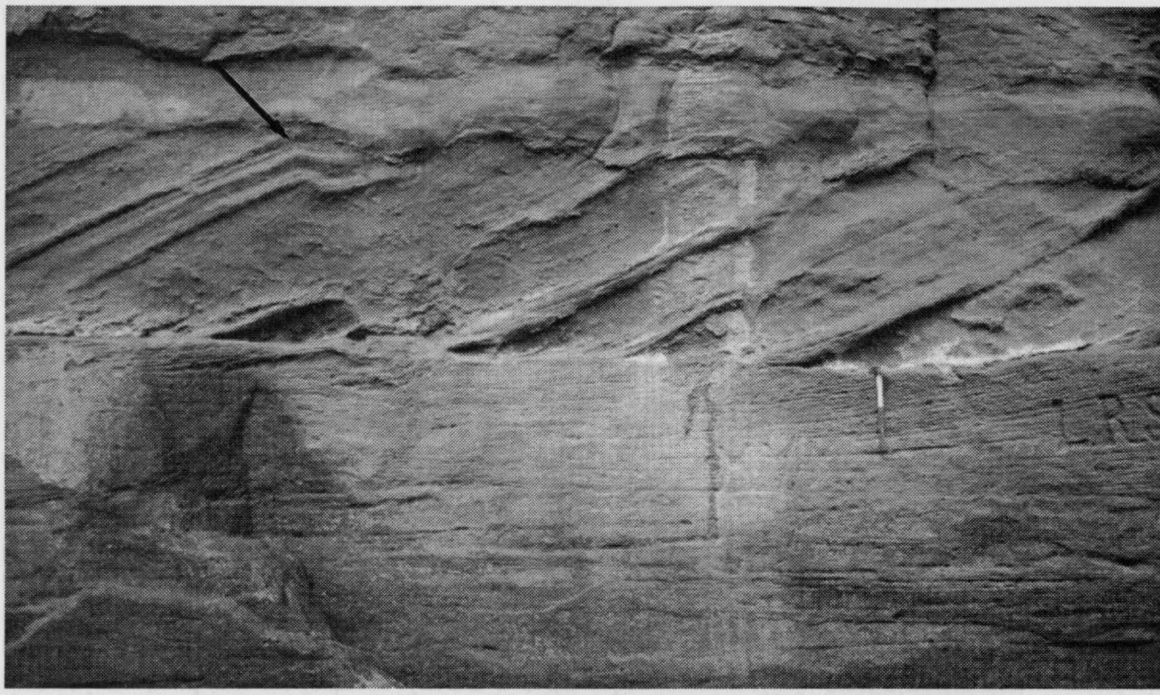


Figure 2.43 Sandstones of the Exmouth Mudstone and Sandstone Formation at Orcombe Point, showing a transition from planar to tabular cross beds. Prominent laminae are cemented with calcite. Note the deformed foresets, upper left (arrowed). The hammer is 0.3 m long. (Photo: P. Turner.)

3. Red and green sandstone beds, with mudstone beds and lenses. Large- and small-scale cross-bedding structures and fining-upwards sequences are common (Figure 2.43). Thicker units may display sun cracks and bioturbation. The clay lenses have well-developed small-scale cross-bedding and pipes and burrows infilled with sandstone.

A more detailed sequence of facies divisions has been outlined by Mader and Laming (1985), who divided the formation into lower, middle, and upper parts. The middle and upper parts are further divided into five and four units respectively. These authors note channels, sheet floods, some development of sand dunes, and limited pedogenesis in the upper units.

At Orcombe Point, bleached sandstone beds are present, with grey-green sandstone dykes radiating from them and penetrating the underlying reddish-brown marls to a depth of 0.1 to 0.2 m. The bleaching is associated with malachite (Carus-Wilson, 1913). Clay minerals in the sandstones include kaolinite, swelling chlorite, and mixed-layer illite. Euhedral calcite crystals, rare dolomite, and possible gypsum crystals have also been noted (Henson, 1973).

Palaeontology

A few poorly preserved plant fossils have been reported from the argillaceous overbank and playa-lake sediments and from a rubbly unit at the base of a sandstone bed (Laming, 1966, p. 955, 1982; Selwood *et al.*, 1984). A well-preserved assemblage of reworked Devonian and lower Carboniferous plant microfossils, for example *Densoisporites*, *Dictyotriletes*, *Savitrisporites*, and *Hymenozonotriletes*, has been recovered from a horizon within the Exmouth Mudstone and Sandstone Formation (Warrington, 1971; Owens, 1972; Selwood *et al.*, 1984).

Trace fossils have also been described from sandstone and siltstone bedding surfaces in the formation at Orcombe Point (Laming, 1966; Selwood *et al.*, 1984; Mader, 1985, pp. 23–5). These include horizontal and vertical burrows. The horizontal burrows are slightly sinuous tubes, 5 to 20 mm wide and 30 to 300 mm long, with meniscus fill, and may form densely packed, complex cross-cutting structures that thoroughly rework the sediment. Vertical tubes reach depths of 10 mm and may be up to 20 mm wide; they are either isolated or tightly packed, and are filled with massive medium- to coarse-grained sand. Less distinct bioturbation traces are also visible in mudstone units in the Aylesbeare Mudstone Group formations.

Interpretation

The Exmouth Mudstone and Sandstone Formation was interpreted as representing predominately fluvial sedimentation in low-sinuosity braided streams in a semi-arid climate (Laming, 1968; Henson, 1970, 1973; Selwood *et al.*, 1984).

The first facies association (see above) with poorly sorted, greenish, laterally discontinuous sandstone beds, was interpreted as overbank deposits with evidence of crevasse splays and the gradual accumulation of fine-grained material. The red and green, cross-bedded sandstones of the second and third facies were interpreted as being deposited in river channels, probably on large-scale point bars. The mudstones, common throughout much of the sequence, represent low-energy sediment accumulation, possibly in pools, or deposition on the interfluve areas of the floodplain during the falling stage of floods (Laming, 1966).

Mader and Laming's (1985) three divisions of the formation reflect changing environments of deposition The lower part is interpreted as part of an alluvial fan complex, with sediments deposited in floodplain and playa-lake environments. The middle part represents a change from fluvial braidplain to fluvial braidplain and playa-lake conditions, characterized by channel and sheetflood processes and limited pedogenesis. The upper part sees a return to fluvial braidplain conditions, with channels and sheet floods, and with sand dunes that are aeolian in origin but which previously had been interpreted as fluvial. The overlying Littleham Mudstone Formation reflects a return to fluvial plain and playa-lake environments, indicating that sedimentation was cyclical.

The bleached sandstones and sedimentary dykes were probably discoloured by oxidation of malachite and vanadium minerals. Where vanadium minerals are concentrated, small halos of paler bleached sediment occur, the bleaching resulting from a change in the oxidation state of iron minerals within the sediment, from ferric to ferrous oxides (Carus-Wilson, 1913; Harrison, 1975). Laming (1966, p. 955) suggested that the malachite might have been a weathering product of diagenetic copper mineralization, probably chalcocite, nucleated around plant debris.

The proportions of clay minerals in the mudstones of the Exmouth Mudstone and Sandstone Formation confirm that the environment of deposition was fluvial and thus corroborate the sedimentological interpretation. The euhedral calcite crystals, rare dolomite, and possible gypsum crystals suggest that evaporation of ephemeral lakes and ponds took place, forming bodies of hypersaline water (Henson, 1973).

The poorly preserved, sporadic plant fossils offer little information, other than to confirm that the sediments include terrestrial elements. The burrows appear to have been produced by invertebrates rather than amphibians or reptiles, in contrast with much larger meniscate burrows at Saltern Cove (see GCR site report, this volume). They were classified as dwelling structures by Henson (1970), but they occur so densely in the fluvial sandstones (Mader, 1985, p. 23) that they are more likely to be feeding traces of animals churning the river-bed sediments as they consumed organic debris.

The Aylesbeare Mudstone Group may be entirely Permian in age (Laming, 1968, 1982), or it may span the Permo–Triassic boundary (Smith *et al.*, 1974; Warrington *et al.*, 1980), or be entirely Early Triassic in age (Edwards *et al.*, 1997; Edwards and Scrivener, 1999); there is no evidence yet to confirm which of these views is correct. Its age is poorly constrained by the position between Late Permian Exeter Group below (Figure 2.30) and by the possibly Early Triassic Budleigh Salterton Pebble Beds above.

Conclusions

The Permo–Triassic sediments exposed at Orcombe Rocks show evidence for deposition in a range of fluvial and playa-lake environments. The section consists of a thick sequence of red and greenish-grey sandstones and siltstones with mudstones. The thick beds of coarser-grained sediments represent channel deposits such as bars, or, in some cases, aeolian dunes; the thinly bedded sandstones and mudstones accumulated in overbank areas and in playa lakes. This is a key site for understanding the palaeogeography of south-west Britain around the time of the Permian–Triassic transition.