# *The Old Red Sandstone of Great Britain*

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# Chapter 3

# The Midland Valley of Scotland and adjacent areas

## INTRODUCTION

*M.A.E. Browne and W.J. Barclay*

The Midland Valley of Scotland (Figure 3.1) is an elongate NE-trending tectonic feature lying between the Highland Boundary Fault to the north and the Southern Upland Fault to the south (Cameron and Stephenson, 1985). It extends from under the North Sea (Forth Approaches Basin) south-westwards across Scotland and under the Irish Sea into Ireland. Usually described as a rift (or graben), the 'valley' contains substantial hilly and upland areas. Reflecting its origin as part of a collage of tectonically juxtaposed crustal fragments, it is also referred to as the 'Midland Valley Terrane' (Bluck, 2001, 2002).

The strata exposed today in the Midland Valley range from Ordovician to Palaeocene in age, but are mainly of Devonian and Carboniferous age. The Devonian strata are represented by volcanic and Old Red Sandstone sedimentary rocks, laid down in semi-isolated basins. The succession is divided into informal lithostratigraphical units (Lower Old Red Sandstone (LORS) and Upper Old Red Sandstone (UORS)) that have loosely defined age connotations and correlation with the Lower (Early) and Upper (Late) Devonian respectively. The Lower Old Red Sandstone

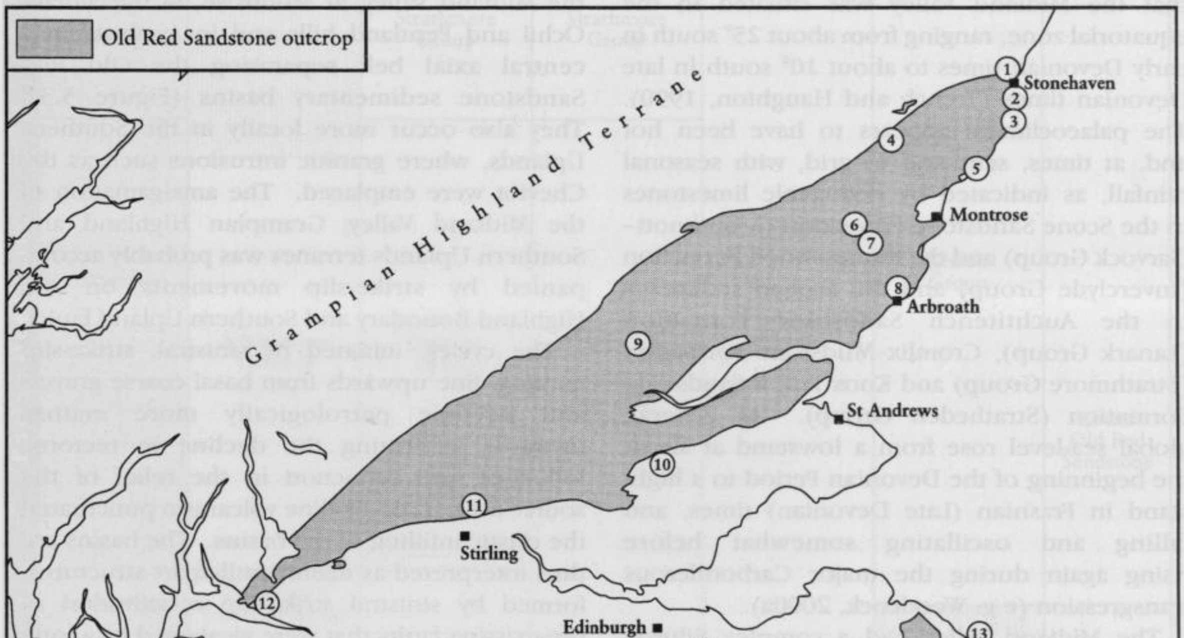



**Figure 3.1** Old Red Sandstone outcrops in the Midland Valley, showing locations of GCR sites: (1 – The Toutties; 2 – Dunnottar Coast Section; 3 – Crawton Bay; 4 – North Esk River; 5 – Milton Ness; 6 – Aberlemno Quarry; 7 – Tillywhandland Quarry; 8 – Whiting Ness; 9 – Tay Bank; 10 – Glen Vale; 11 – Wolf's Hole Quarry; 12 – Auchensail Quarry; 13 – Siccar Point to Hawk's Heugh; 14 – Largs Coast, Ayrshire; 15 – North Newton Shore, Arran). After British Geological Survey 1:625 000 Solid Geology Map, UK North Sheet, 4th edn (2001).

spans the Wenlock–Ludlow to Emsian (middle Silurian to lower Devonian) stages and the Upper Old Red Sandstone is Famennian (Late Devonian) to Courceyan (early Carboniferous) in age. The lithostratigraphy of the Old Red Sandstone used in this account is based on a recent review by the British Geological Survey (Browne *et al*., 2002) (Figure 3.2). Bluck (2002) provides a recent, comprehensive summary of the Old Red Sandstone of the Midland Valley.

Devonian palaeogeography of the British Isles is illustrated and summarized in Cope *et al*. (1992). Recent models of the palaeogeography of the Midland Valley were given by Bluck (2000, 2001), Woodcock (2000a) and Trewin and Thirlwall (2002). Palaeomagnetic data suggest that the Midland Valley was situated in the equatorial zone, ranging from about 25° south in early Devonian times to about 10° south in late Devonian times (Trench and Haughton, 1990). The palaeoclimate appears to have been hot and, at times, semi-arid to arid, with seasonal rainfall, as indicated by pedogenic limestones in the Scone Sandstone Formation (Arbuthnott–Garvock Group) and the Kinnesswood Formation (Inverclyde Group) and the aeolian sediments in the Auchtitench Sandstone Formation (Lanark Group), Cromlix Mudstone Formation (Strathmore Group) and Knox Pulpit Sandstone Formation (Stratheden Group). In general, global sea-level rose from a lowstand at about the beginning of the Devonian Period to a high-stand in Frasnian (Late Devonian) times, and falling and oscillating somewhat before rising again during the major Carboniferous transgression (e.g. Woodcock, 2000a).

The Midland Valley had a complex Siluro–Devonian geological history involving multiple phases of transcurrent strike-slip faulting, sediment deposition, igneous activity, uplift and erosion (e.g. Smith, 1995). This followed its collision with the Laurentian continental margin in Ordovician times (e.g. McKerrow *et al*., 1991), with deposition of the Old Red Sandstone succession taking place after the amalgamation of terranes that were previously widely separated (see 'Old Red Sandstone palaeogeography', Chapter 1). The closure of the Iapetus Ocean resulted in sinistral strike-slip fault re-activation, crustal compression, uplift, granitic intrusion, andesitic volcanicity and low-grade metamorphism. The Midland Valley and Grampian Highland terranes amalgamated by late Silurian time, after which strike-slip movements between them appear to have been of the order of only tens of kilometres (Trench and Haughton, 1990). The compression in the Laurentian crust, of which the Scottish Highlands were part, was accompanied by the intrusion of large volumes of granitic rocks and the extrusion of predominantly andesitic volcanic rocks. The latter were probably extensive, their eroded remnants being seen at Ben Nevis, Glen Coe, Lorn and immediately north of the Highland Boundary Fault. Volcanic rocks also crop out extensively within the Midland Valley, at Montrose, in the Sidlaw, Ochil and Pentland hills and in Ayrshire, in a central axial belt separating the Old Red Sandstone sedimentary basins (Figure 3.3). They also occur more locally in the Southern Uplands, where granitic intrusions such as the Cheviot were emplaced. The amalgamation of the Midland Valley, Grampian Highland and Southern Uplands terranes was probably accompanied by strike-slip movements on the Highland Boundary and Southern Upland faults.

The cycles, initiated by sinistral, strike-slip faulting, fine upwards from basal coarse gravels and become petrologically more mature upwards, reflecting the decline in tectonic influence and reduction in the relief of the source area. Calc-alkaline volcanism punctuated the clastic infilling of the basins. The basins are thus interpreted as mainly pull-apart structures, formed by sinistral strike-slip re-activation of pre-existing faults that were weakened by a long history of igneous activity (e.g. Phillips *et al*., 1998; Bluck, 2000). However, when regional crustal shortening and intrusion of buoyant granitic magma had caused uplift of the Caledonian mountain chain, gravitational collapse of the orogen and extensional spreading may also have been a factor (e.g. Woodcock, 2000a). Transpressive movements subsequently inverted the basins, resulting in the recycling of the basin-fills and providing weak points for continuing volcanic extrusion (Bluck, 2000).

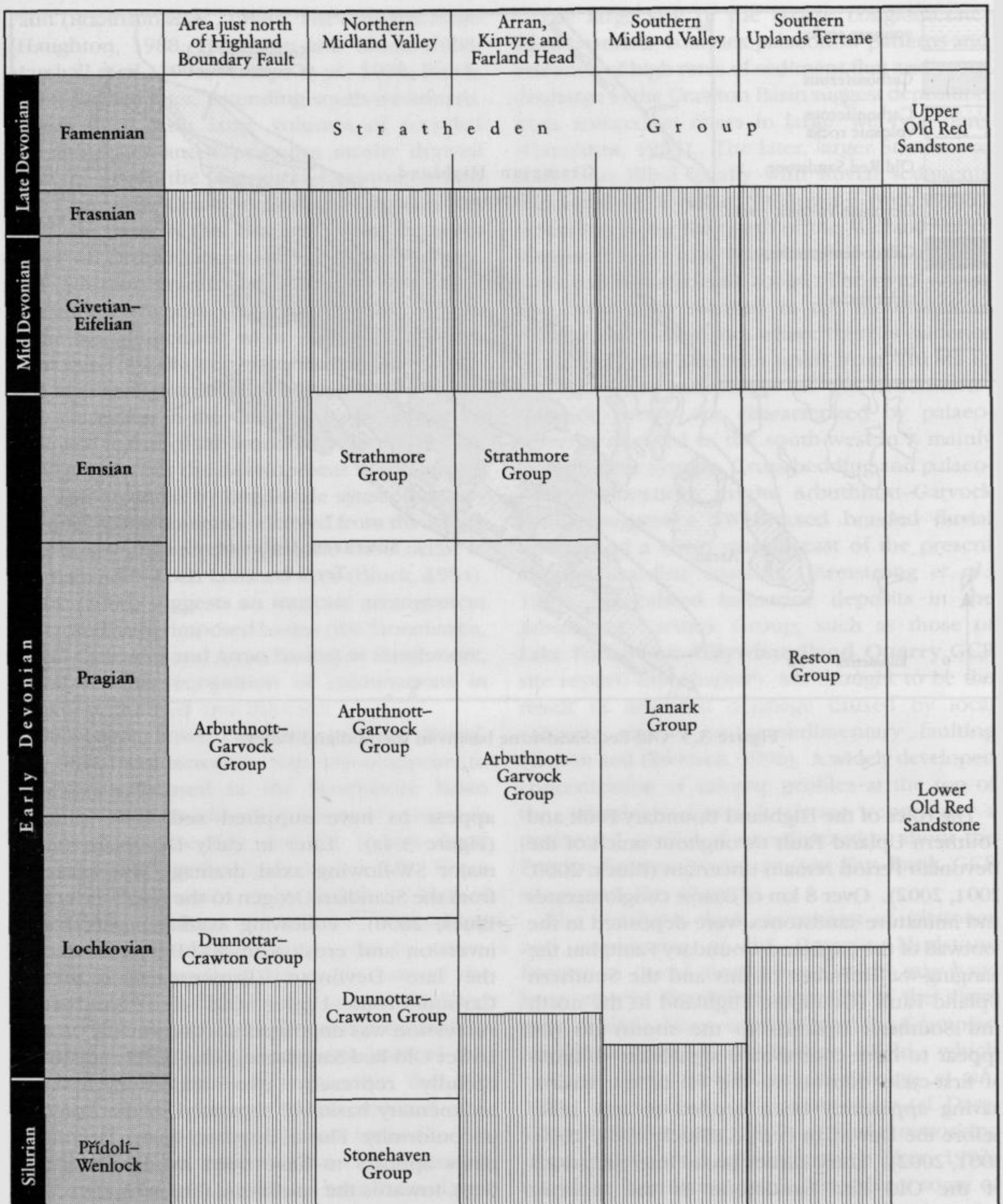



**Figure 3.2** Lithostratigraphical groups of the Old Red Sandstone of the Midland Valley. After Browne *et al.* (2002).

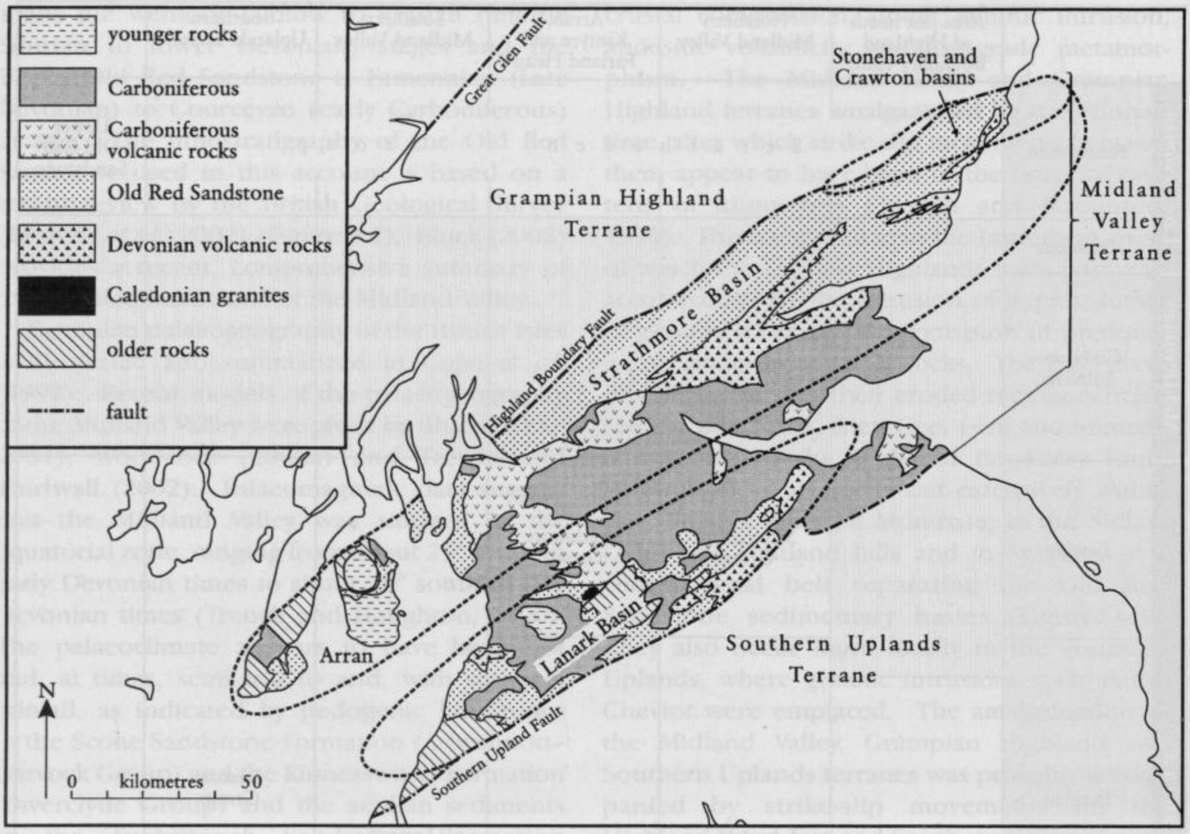



**Figure 3.3** Old Red Sandstone basins in the Midland Valley.

The roles of the Highland Boundary Fault and Southern Upland Fault throughout much of the Devonian Period remain uncertain (Bluck, 2000, 2001, 2002). Over 8 km of coarse conglomerates and immature sandstones were deposited in the footwall of the Highland Boundary Fault, but the hanging-wall terranes of this and the Southern Upland Fault (Grampian Highland to the north and Southern Uplands to the south) do not appear to have contributed significant volumes of first-cycle detritus to the fill of the basins, having apparently been eroded to low relief before the Devonian Period (Bluck, 1984, 2000, 2001, 2002). Thus, earlier broad interpretations of the Old Red Sandstone as the molasse deposits of the Caledonian mountain chain have been refined (e.g. by Haughton, 1988; Phillips *et al.*, 1998; Bluck, 2000). However, the source of much of the sediment is enigmatic; a now-concealed flysch terrane under the Midland Valley (Haughton, 1988; Bluck, 1992), and a limestone-covered metamorphic–volcanic arc terrane between the Midland Valley and Southern Uplands (Armstrong and Owen, 2000) appear to have supplied sediment initially (Figure 3.4a). Later in early Devonian times, major SW-flowing axial drainage was sourced from the Scandian Orogen to the north-east (e.g. Bluck, 2000). Following Acadian uplift, basin inversion and erosion in Mid-Devonian times, the late Devonian (Famennian) to early Carboniferous Upper Old Red Sandstone succession was deposited unconformably on the Lower Old Red Sandstone. The LORS and UORS broadly represent two major cycles of sedimentary basin-fill, separated by the Acadian unconformity. Fluvial dispersal in late Devonian times appears to have been mainly from the west, towards the north-east (Figure 3.4f).

The main graben development started in Wenlock times in the north-east, with the small Stonehaven and Crawton basins (see **The Toutties** GCR site report, this chapter) forming as a result of sinistral shear along the Highland Boundary Fault Zone. The sediments of the Stonehaven Group were sourced to the south-west and include medium-grade metamorphic clasts from south of the Highland Boundary

Fault (Robinson *et al.*, 1998). The Crawton Basin (Haughton, 1988; Haughton and Bluck, 1988; Marshall *et al.*, 1994; Phillips *et al.*, 1998; Bluck, 2000) formed later, extending south-westwards. It was filled with large volumes of recycled conglomerates and sandstones mostly derived from the north (the Dunnottar–Crawton Group) (see **Dunnottar Coast Section** and **Crawton Bay** GCR site reports, this chapter). These contain clasts of Ordovician muscovite-biotite granite, late Silurian granitoids and staurolite-grade metamorphic rocks (Haughton *et al.*, 1990). Some conglomerates were southerly derived, from outcrops of deep-water sedimentary rocks and high-level granite within the Midland Valley. The succession in the Crawton Basin appears to be linked to that of the Stonehaven Basin (Phillips *et al.*, 1998), but the development of the former was accompanied by large-scale synsedimentary faulting. Conglomerates, derived from the south-east, containing recycled quartzite clasts occur in the Callander–Loch Lomond area (Bluck, 1984). Bluck (2000) suggests an intricate arrangement of stacked, superimposed basins (the Stonehaven, Crieff–Callander and Arran basins) in Strathmore, based on the recognition of culminations in thickness at Edzell and Balmaha.

Subsequent Lower Old Red Sandstone alluvial-fan, fluvial and lacustrine deposition appears to have been focused in the Strathmore Basin (Arbuthnott–Garvock and Strathmore groups) in the north (Figure 3.5) and the Lanark Basin (Lanark Group) in the south (Figure 3.6). These basins were separated by an ill-defined high of little-known geology, but possibly comprising an Ordovician volcanic arc intruded by micro-granitic bodies such as that at the base of the Salsburgh No. 1 Well in the central Midland Valley. The cryptic flysch terrane proposed by Haughton (1988) may have been part of this block. Farther west, it is possible that the Strathmore and Lanark basins merged and continued south-westwards into Ireland. The calc-alkaline lavas and associated intrusions in the Lower Old Red Sandstone have been dated at about 410 Ma (Thirlwall, 1988). However, volcanism may have started earlier in the north, as minor amounts of acid/intermediate lava occur in the Stonehaven Group. Thick piles of lavas accumulated in composite centres and strato-volcanoes in the Dunnottar–Crawton and Arbuthnott–Garvock groups, as well as thinner, but quite widespread ignimbrites and other volcaniclastic deposits.

The large size of the coarse conglomerate-filled channels, complex palaeoflow patterns and evidence of high rates of sediment flux and water discharge in the Crawton Basin suggest deposition from antecedent rivers in large 'wet-type' fans (Haughton, 1989). The later, larger Strathmore Basin was filled axially with fluvial sediments deposited by a major SW-flowing river system extending along the north of the Midland Valley (Figure 3.4c,d) and interstratified calc-alkaline lavas and volcaniclastic rocks. The river system may have been sourced in the mountains of Norway and Greenland, where there is evidence of considerable Scandian uplift from 410 Ma to 380 Ma. The sandstones of the Arbuthnott–Garvock Group are characterized by palaeo-currents directed to the south-west in a mainly braided river system. Cross-bedding and palaeo-current directions in the Arbuthnott–Garvock Group suggest a SW-directed braided fluvial system and a basin margin east of the present Angus/Kincardine coastline (Armstrong *et al.*, 1985). Localized lacustrine deposits in the Arbuthnott–Garvock Group, such as those of Lake Forfar (see **Tillywhandland Quarry** GCR site report, this chapter), are thought to be the result of impeded drainage caused by local volcanic activity or synsedimentary faulting (Trewin and Davidson, 1996). A widely developed concentration of calcrete profiles at the top of the Arbuthnott–Garvock Group represents a prolonged period of non-deposition about the Pragian–Emsian boundary (see **Tay Bank** GCR site report, this chapter).

The overlying thick succession of siltstones and mudstones of the Cromlix Mudstone Formation (basal Strathmore Group) may have been alluvial floodplain deposits of the distal parts of alluvial fans, sourced from the Grampian Highland Terrane or farther afield, which escaped fluvial reworking (Armstrong *et al.*, 1985). Alternatively, an aeolian origin (cf. Dare-Edwards, 1984; Yang, 1997) or fluvial reworking of pedogenic mud aggregates (e.g. Ékes, 1993) may have been responsible for at least some of the argillaceous rocks. Cross-bedded and ripple-laminated sandstones up to 2 m thick are interpreted as the overbank deposits of large river systems (Haughton and Bluck, 1988). Thick arenaceous fluvial deposits (the Teith Sandstone Formation) occur widely in the Strathmore Basin above the Cromlix Mudstone Formation. Local, thick fanglomerates were still being deposited close to the Highland Boundary Fault at that time,

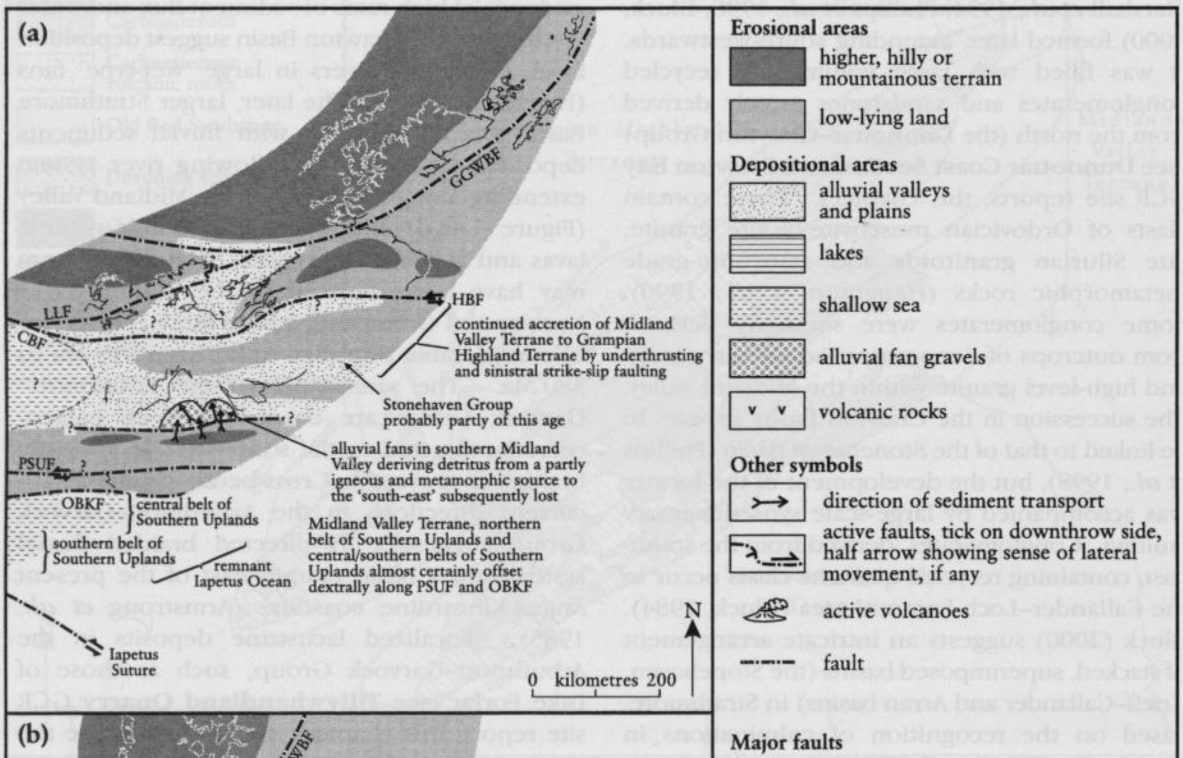



**Figure 3.4** Palaeogeographical development of the Midland Valley and adjacent areas. (a) Early Wenlock; (b) Mid-Přídolí. (a) after Bassett *et al.* (1992); (b) after Bluck *et al.* (1992). Continued on page 133.

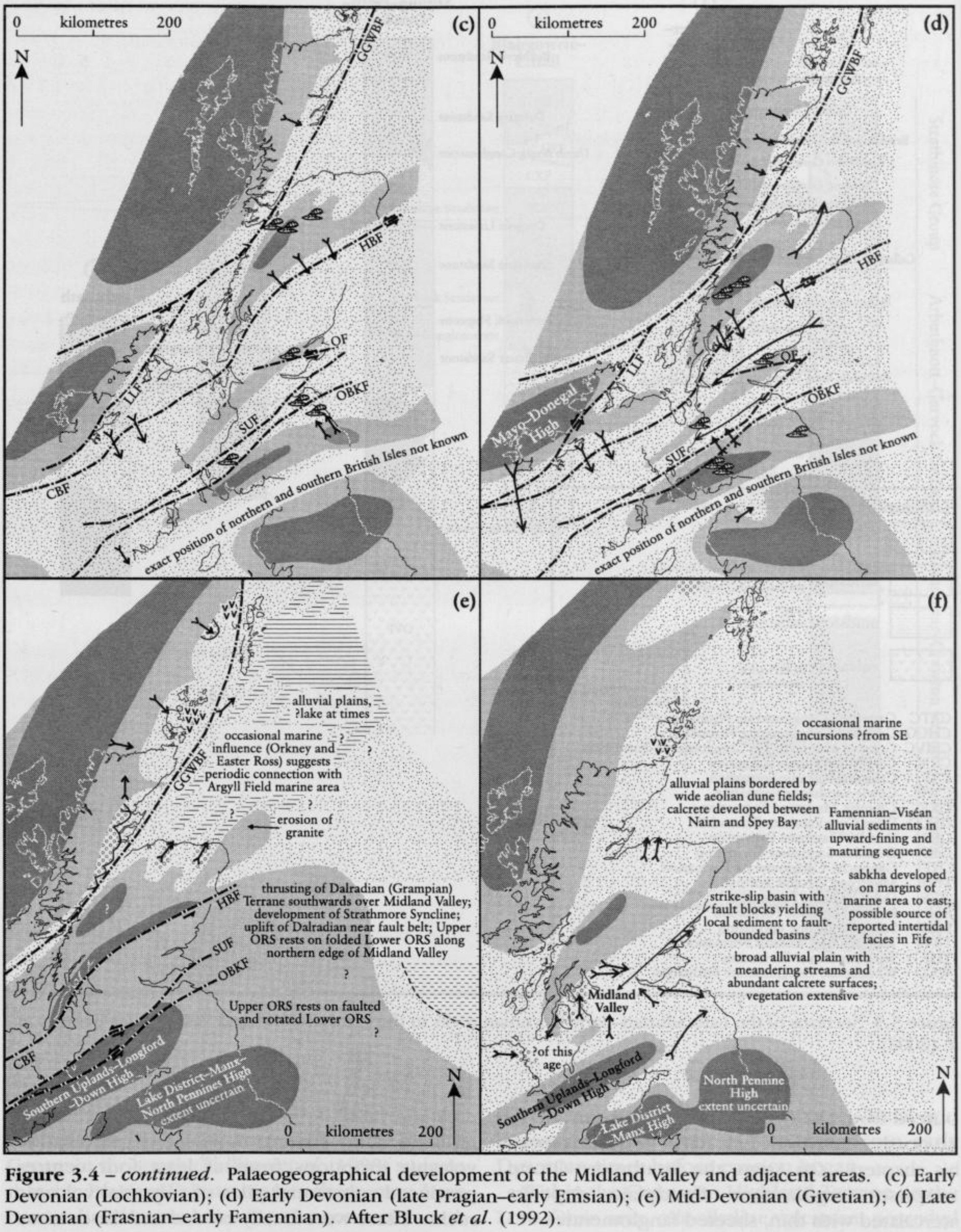



**Figure 3.4** – *continued*. Palaeogeographical development of the Midland Valley and adjacent areas. (c) Early Devonian (Lochkovian); (d) Early Devonian (late Pragian–early Emsian); (e) Mid-Devonian (Givetian); (f) Late Devonian (Frasnian–early Famennian). After Bluck *et al*. (1992).

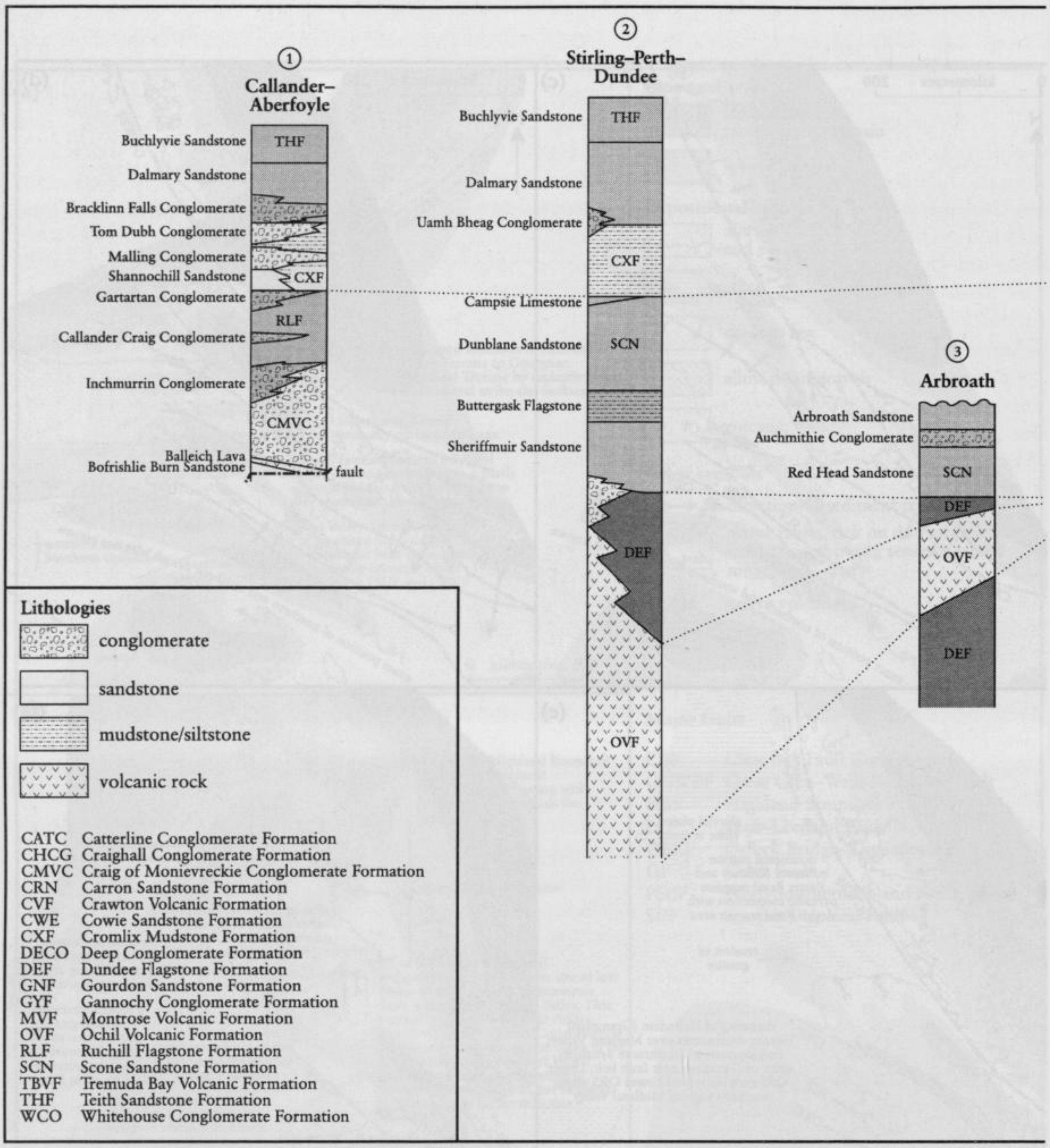
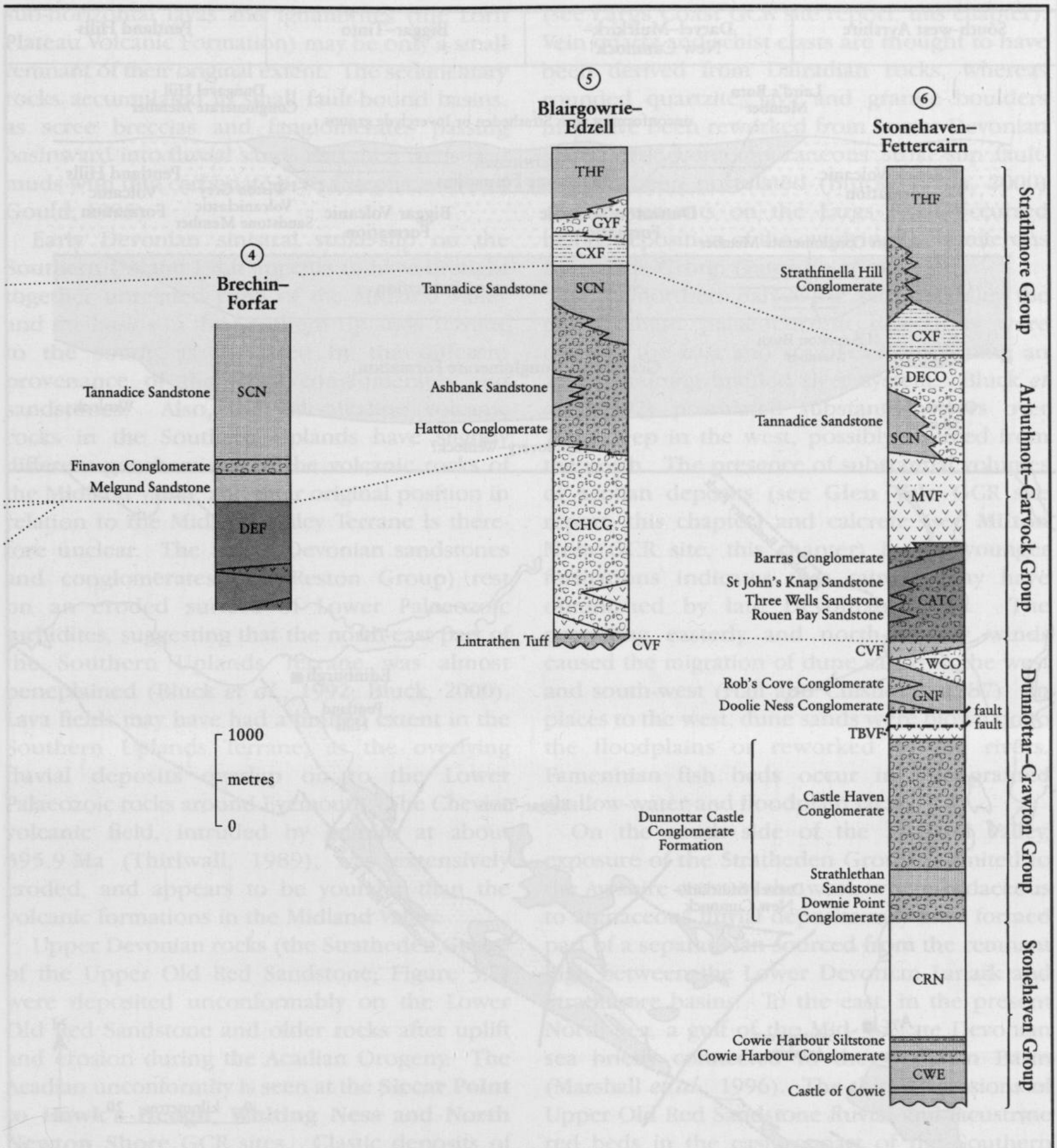



**Figure 3.5** Sections of the Late Silurian–Early Devonian rocks in the northern Midland Valley. After Browne *et al.* (2002).

sourced from the Grampian Highland Terrane to the north (see **North Esk River** GCR site report, this chapter). On Arran, the Strathmore Group comprises argillaceous floodplain deposits intercalated with thin, sheeted fanglomerates.

In the Lanark Basin, alluvial-fan gravels generally fine upwards into fluvial sandstones. The detritus is thought to have been derived from horsts of flysch to the east (Syba, 1989) created by strike-slip fault movements within the Midland Valley Terrane. A period of calc-alkaline volcanic eruptions from at least four centres produced substantial piles of subaerial volcanic rocks. These were locally eroded and the detritus reworked by rivers which also carried quartzose metamorphic detritus from a more distant source to the north-east. Lithological similarities between the upper part of the Arbuthnott–Garvock




Group in the north of the Midland Valley and the Auchtitench Sandstone Formation of the Lanark Group in the south (Phillips *et al*., 1998) suggest that by Pragian–Emsian times, there may have been a link between the Strathmore and Lanark basins, at least in the west. Along the southern margin of the Midland Valley, the Lower Palaeozoic marine basin, now represented by rocks of the Pentland Hills, Hagshaw Hills and Lesmahagow inliers, was inverted, with terrestrial fluvial and lacustrine sedimentation continuing into early Devonian times before erosion began.

Within the Grampian Highland Terrane, in the Lorn–Oban area, calc-alkaline volcanism preceded the deposition of fossiliferous sedimentary rocks of Přídolí to Lochkovian age on peneplained Dalradian basement (Marshall, 1991; Durant, 1999a,b; Bluck, 2000). The area of preserved

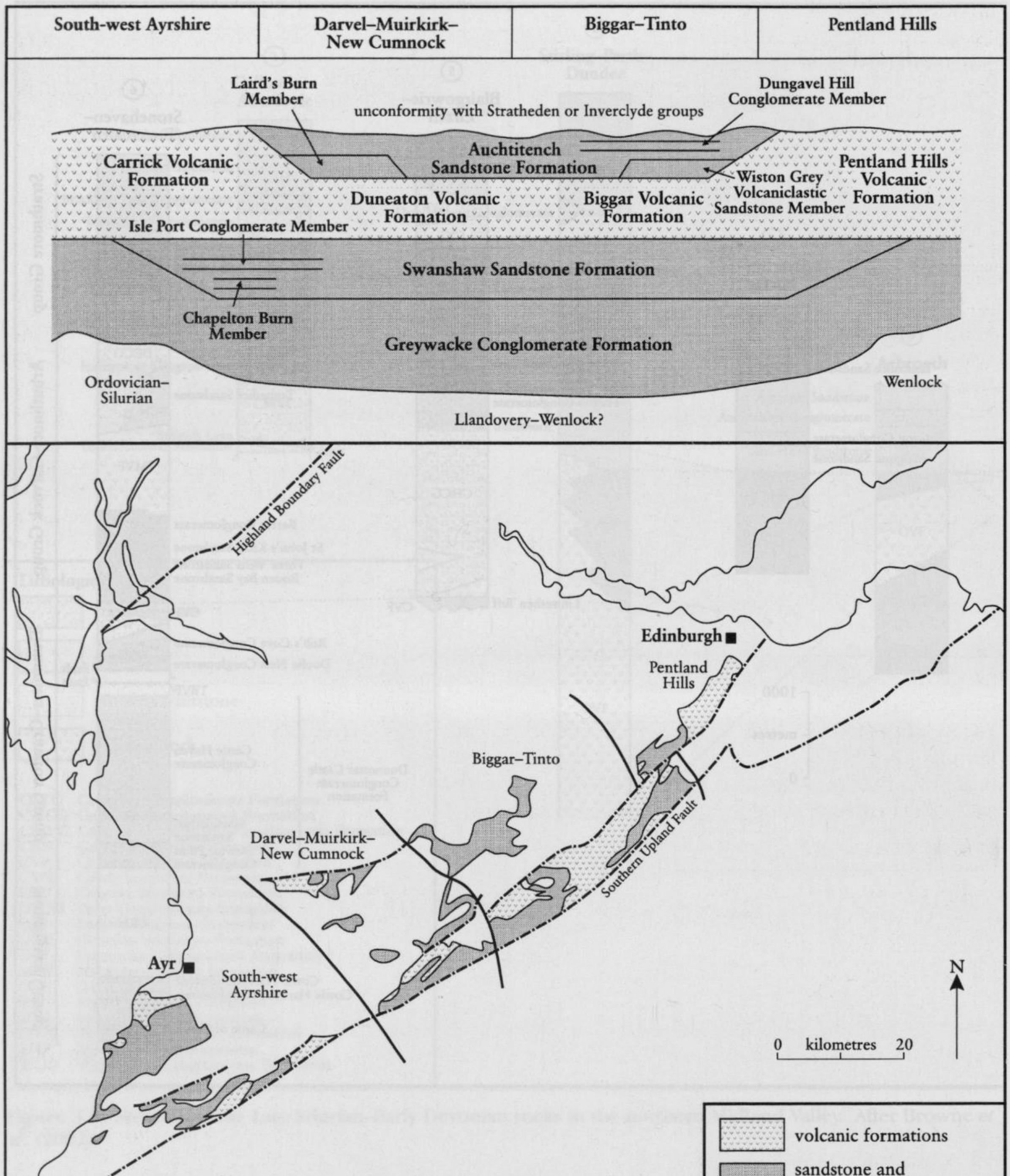



**Figure 3.6** Outcrops of the Lanark Group in the southern Midland Valley and schematic cross-section. After Browne *et al.* (2002).

sub-horizontal lavas and ignimbrites (the Lorn Plateau Volcanic Formation) may be only a small remnant of their original extent. The sedimentary rocks accumulated in small fault-bound basins, as scree breccias and fanglomerates passing basinward into fluvial sands and then lacustrine muds with thin carbonate beds (Stephenson and Gould, 1995).

Early Devonian sinistral strike-slip on the Southern Upland Fault appears to have brought together unrelated parts of the Midland Valley and the basins in the Southern Uplands Terrane to the south, as indicated by the different provenance of the basal conglomerates and sandstones. Also, the calc-alkaline volcanic rocks in the Southern Uplands have slightly different geochemistry to the volcanic rocks of the Midland Valley, and their original position in relation to the Midland Valley Terrane is therefore unclear. The Lower Devonian sandstones and conglomerates (the Reston Group) rest on an eroded surface of Lower Palaeozoic turbidites, suggesting that the north-east part of the Southern Uplands Terrane was almost peneplained (Bluck *et al.*, 1992; Bluck, 2000). Lava fields may have had a limited extent in the Southern Uplands Terrane, as the overlying fluvial deposits overlap on to the Lower Palaeozoic rocks around Eyemouth. The Cheviot volcanic field, intruded by granite at about 395.9 Ma (Thirlwall, 1989), was extensively eroded, and appears to be younger than the volcanic formations in the Midland Valley.

Upper Devonian rocks (the Stratheden Group of the Upper Old Red Sandstone; Figure 3.7) were deposited unconformably on the Lower Old Red Sandstone and older rocks after uplift and erosion during the Acadian Orogeny. The Acadian unconformity is seen at the **Siccar Point to Hawk's Heugh**, **Whiting Ness** and **North Newton Shore** GCR sites. Clastic deposits of fluvial and aeolian origin predominate, tending to be generally finer grained than the Lower Old Red Sandstone. A single, major ENE-trending basin has been modelled towards the north of the Midland Valley (e.g. Hall *et al.*, 1998). The deposits in the western and northern parts of this basin are thicker and coarser than those in the south and east, braided fans of relatively mature detritus prograding from the west and north (see **Largs Coast** GCR site report, this chapter). Vein quartz and schist clasts are thought to have been derived from Dalradian rocks, whereas rounded quartzite, lava and granite boulders may have been reworked from Lower Devonian strata. Penecontemporaneous strike-slip faulting has been postulated (Bluck, 1980a, 2000) and movements on the Largs Fault occurred before deposition of the overlying Carboniferous Inverclyde Group (Paterson *et al.*, 1990).

In the northern part of the Midland Valley, the predominant palaeocurrent directions were towards the east and south-east, indicating an axially-draining braided river system. Bluck *et al.* (1992) postulated substantial rivers over 10 m deep in the west, possibly sourced from the north. The presence of substantial volumes of aeolian deposits (see **Glen Vale** GCR site report, this chapter) and calcrete (see **Milton Ness** GCR site, this chapter) in the younger formations indicates that rainfall may have diminished by late Devonian times. The prevailing easterly and north-easterly winds caused the migration of dune sands to the west and south-west (Hall and Chisholm, 1987). In places to the west, dune sands were blown on to the floodplains or reworked by the rivers. Famennian fish beds occur in finer-grained shallow-water and floodplain facies.

On the south side of the Midland Valley, exposure of the Stratheden Group is limited to the Ayrshire coast in the west, where rudaceous to arenaceous fluvial deposits may have formed part of a separate fan sourced from the remnant high between the Lower Devonian Lanark and Strathmore basins. To the east, in the present North Sea, a gulf of the Mid- to Late Devonian sea briefly connected to the Orcadian Basin (Marshall *et al.*, 1996). The thin successions of Upper Old Red Sandstone fluvial and lacustrine red beds in the eastern part of the Southern Uplands (including the Cockburnpath–Pease Bay outcrops) may have been deposited in a basin separate from the Midland Valley. However, in both the Midland Valley and Southern Uplands, alluvial gravels and fluvial/lacustrine beds pass up into fluvial sandstones with pedogenic carbonate of the Carboniferous Kinnesswood Formation. Leeder (1973) postulated internal drainage in a Scottish Border

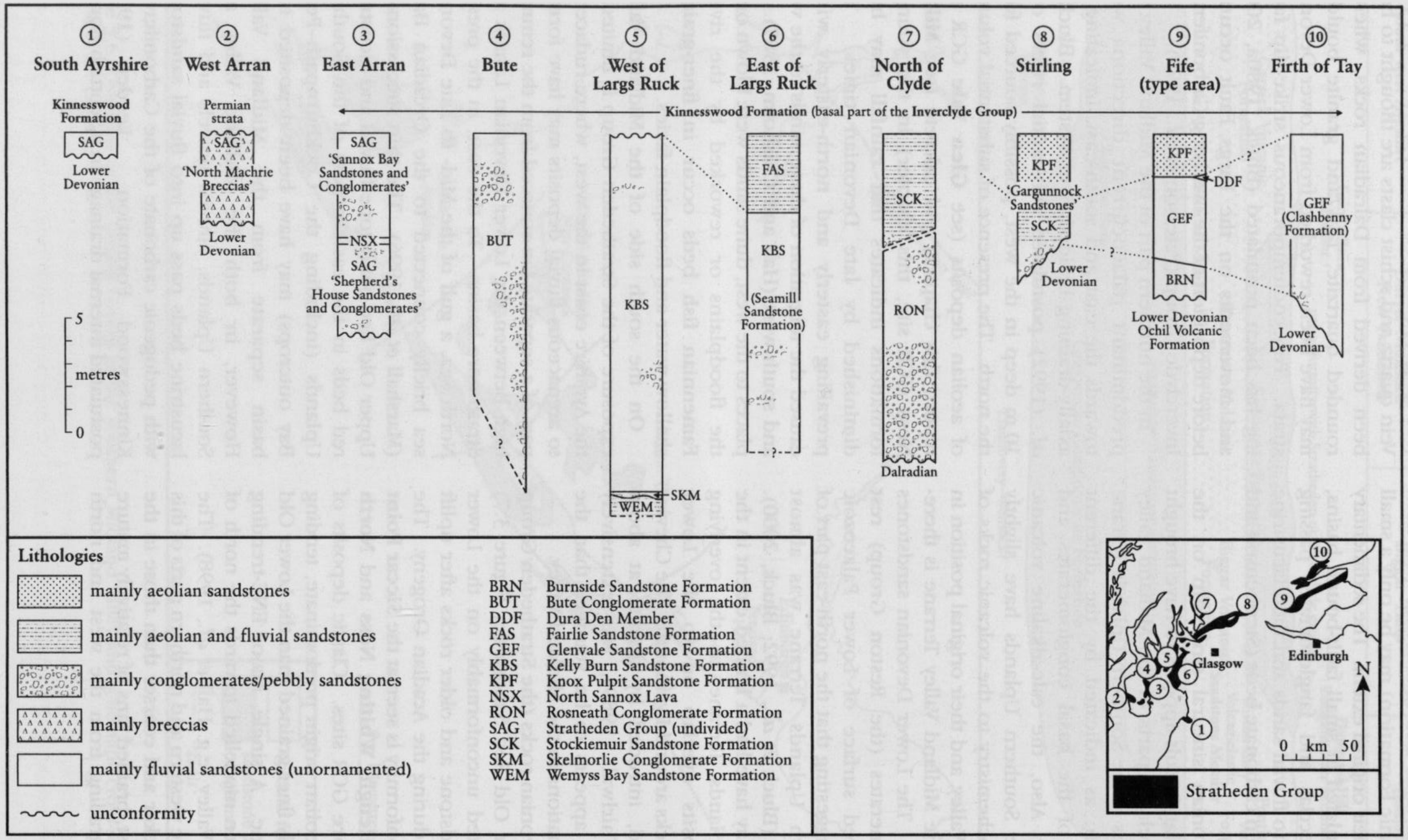



**Figure 3.7** Sections of the Late Devonian Stratheden Group in the Midland Valley showing stratigraphical positions of GCR sites. Inset shows outcrop of Stratheden Group and locations of sections. After Browne *et al.* (2002).

basin in the Jedburgh area, but the overall pattern can be explained by an easterly flowing river system (Paterson *et al.*, 1976) which may have connected with the Northumberland Basin farther east. In the central North Sea, red sandstones of relatively mature fluvial systems are assigned a Frasnian age, but may extend into the early Carboniferous (Gatliff *et al.*, 1994).

Some of the Caledonian igneous rock GCR sites in and adjacent to the Midland Valley, described by Stephenson *et al.* (1999), include Old Red Sandstone sedimentary rocks (Table 1.5, Chapter 1). These are not described in this volume. The sedimentary rocks of the Montrose Volcanic Formation at the Scurdie Ness to Usan Harbour and Black Rock to East Comb sites (Smith, 1999a) are clast-supported conglomerates and coarse-grained, locally cross-bedded sandstones consisting of volcanic detritus with varying amounts of non-igneous components. The Balmerino to Wormit, Sheriffmuir Road to Menstrie Burn, and Tillicoultrie sites (Browne, 1999) are in the Ochil Volcanic Formation. The main sedimentary rocks at these sites are volcaniclastic conglomerates, commonly matrix-supported and of debris-flow origin. At Balmerino to Wormit, the lavas and volcaniclastic conglomerates are interbedded with fluvio-lacustrine sandstones and minor mudstones of the Dundee Flagstone Formation. The mudstones have yielded fish, arthropod and plant fossils, providing palaeontological evidence of an early Devonian (Lochkovian) age to complement local radiometric ages of 410.5 ± 5.6 Ma. GCR sites in Ayrshire with Old Red Sandstone rocks are Port Schuchan to Dunure Castle, Culzean Harbour and Turnberry Lighthouse to Port Murray (Durant, 1999a). The principal feature of these sites is the interaction of unconsolidated, finely laminated, sandy sediments and andesitic igneous rocks formerly regarded as lava flows, but re-interpreted by Kokelaar (1982) as high-level andesitic sill intrusions. In the Scottish Borders, volcaniclastic conglomerates with some sandstones are interbedded with lava flows of the St Abb's Volcanic Formation at the Pettico Wick to St Abb's Harbour GCR Site (Stephenson, 1999). In the Grampians, sedimentary rocks are present on the island of Kerrera, around Oban, in Allt a'Mhuilinn (Ben Nevis) and Glencoe.

At Kerrera (Durant, 1999b), Lower Old Red Sandstone conglomerates and sandstones (the Kerrera Sandstone Formation of Browne *et al.*, 2002) underlie the Lorn Plateau Volcanic Formation (dated as 424–415 Ma) locally. They have yielded fossil fish and arthropod remains, as well as spores of late Silurian to early Devonian age (*tripapillatus-spicula–micrornatus-newportensis* biozones) (Marshall, 1991). In the central down-faulted block of the Ben Nevis igneous complex, mudstone/siltstone laminites with non-volcaniclastic interbeds (the Allt a'Mhuilinn Mudstone Formation) rest unconformably on Dalradian metasedimentary rocks and are overlain by volcaniclastic sediments (McGarvie, 1999a). The deposits are interpreted as lacustrine, playa-lake deposits. In Glencoe, sedimentary rocks underlie the volcanic complex and are sandwiched locally between volcanic rocks (McGarvie, 1999b). Basal conglomerates locally infill channels and canyons incised into the underlying Dalradian metasedimentary rocks. Within the central caldera, 20 m of finely laminated, greenish grey mudstones and sandstones (Group 6 of the caldera succession) are interpreted as caldera lake deposits. At the base of Stob Dearg (NN 224 547), a sequence of breccias, conglomerates, well-bedded, quartzose sandstones, red, laminated sandstones and fissile mudstones underlies the volcanic complex. *Psilophyton* and *Pachytheca* were obtained from a mudstone slab, and spore assemblages indicate a mid-Lochkovian (*micrornatus-newportensis* Biozone) age (Wellman, 1994; McGarvie, 1999b). The overlying lavas are dated at 421 ± 4 Ma (Thirlwall, 1988).

Several Old Red Sandstone GCR sites are described in the companion GCR volume on fossil fishes (Dineley and Metcalf, 1999; Table 1.2, Chapter 1). Of these, the Whitehouse Den GCR site (NO 426 397) near Dundee, is not described in this volume. It is one of three localities at which the Tealing Fish Bed has been identified. Poorly exposed sandstones and black lacustrine mudstone laminites of the Dundee Flagstone Formation (Arbuthnott–Garvock Group) have yielded fish and plant fossils, and arthropod remains and tracks.

GCR Old Red Sandstone fossil plant sites are described in the companion GCR volume on Palaeozoic palaeobotany (Cleal and Thomas, 1995; Table 1.3, Chapter 1). Of these, Ballanucater Farm, Callander is not described in this volume. There, plant remains in grey, coarse-grained sandstones and blue-green mudstones are typical of the Lower Devonian (Emsian) Teith Sandstone Formation (Strathmore Group).

## THE TOUTTIES, ABERDEENSHIRE (NO 881 866)

## Potential ORS GCR site

*M.A.E. Browne and W.J. Barclay*

## Introduction

The Toutties GCR site on the foreshore at Cowie Harbour north of Stonehaven, Aberdeenshire (Figure 3.8) has been long known for the fossil fish specimens from the Cowie Harbour Fish Bed and the arthropods from the overlying mudstones. The fish are described in the companion GCR volume on fossil fishes (Dineley and Metcalf, 1999). The site has recently gained international prominence with the discovery of fossil terrestrial millipedes, including a new air-breathing species, *Pneumodesmus newmani* (Wilson and Anderson, 2004). Traditionally referred to the 'Downtonian' (Přídolí), recent palynological evidence (Marshall, 1991; Wellman, 1993) suggests a mid-Silurian (Late Wenlock–Early Ludlow) age for the beds. Although controversial (Dineley, 1999b), this dating makes the strata among the oldest Old Red Sandstone lithofacies in Britain and the terrestrial diplopod the earliest air-breathing animal of any kind recorded in the geological column. The strata are near-vertical to overturned, lying on the north-west limb of the asymmetric Strathmore Syncline. They belong to the Cowie Sandstone Formation and Carron Sandstone Formation of the Stonehaven Group (Figure 3.9).

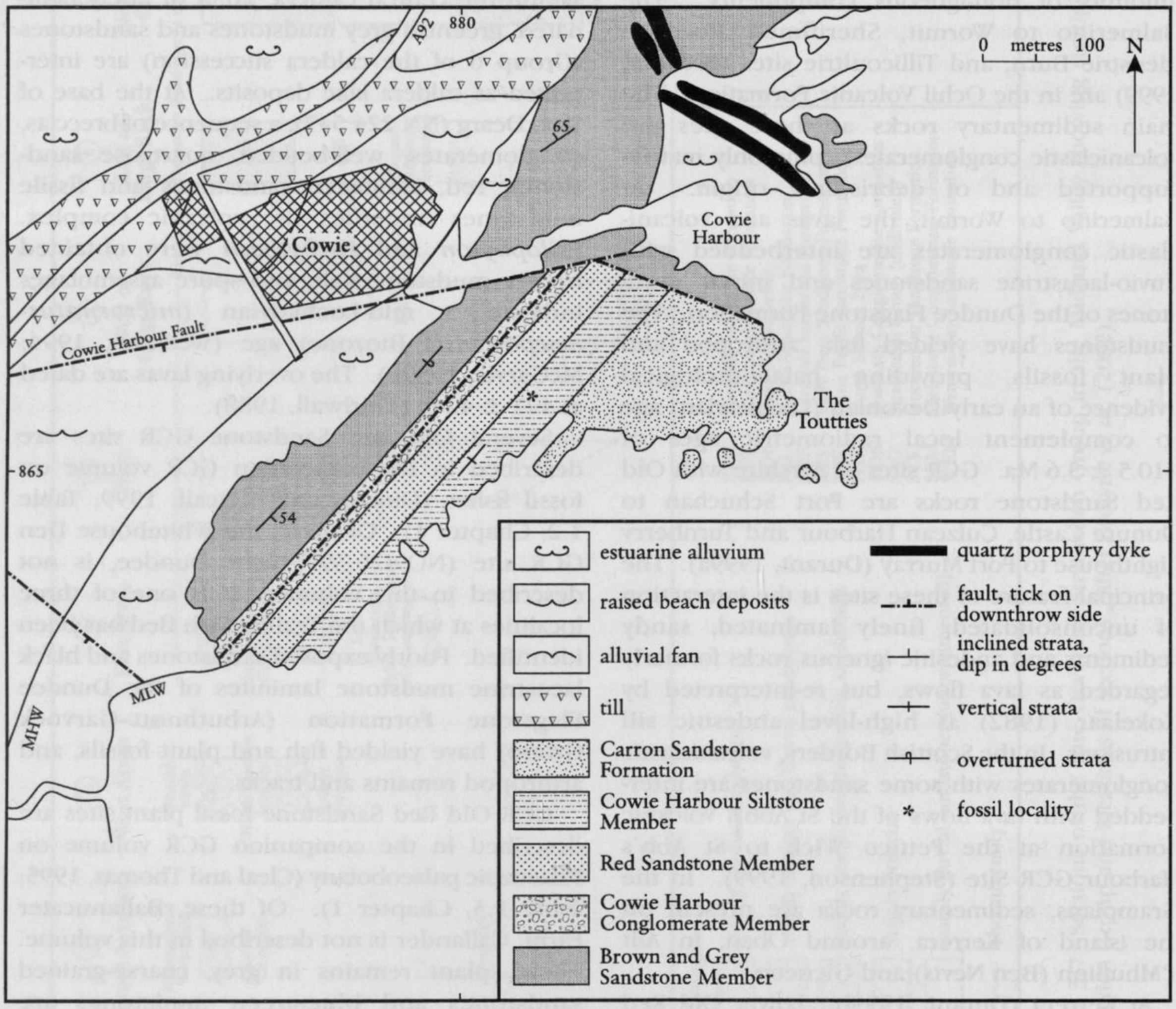



**Figure 3.8** Geological sketch map of the area of The Toutties GCR site. After British Geological Survey, 1: 10 000 Manuscript Map NO 88NE (1996).

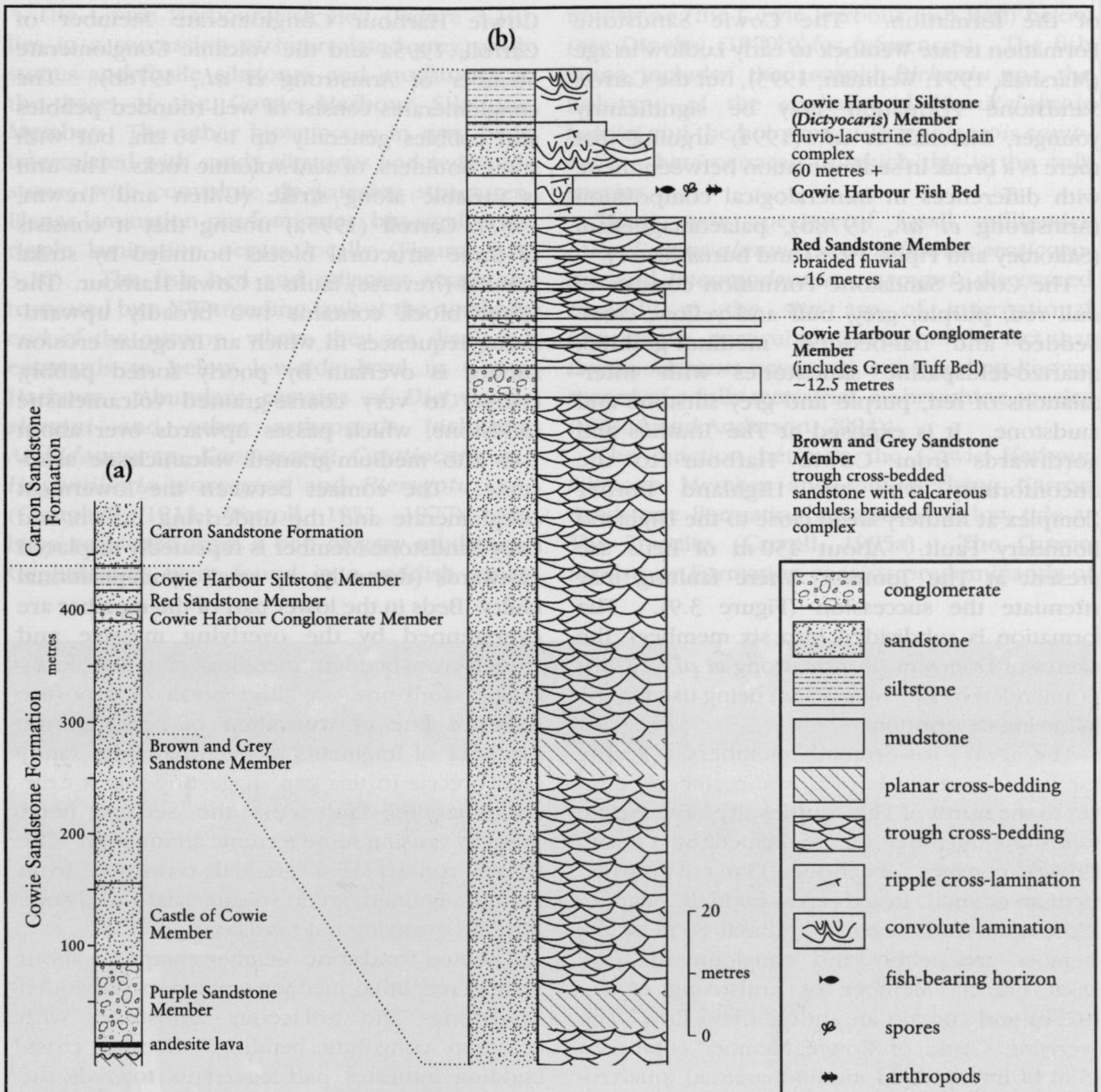



**Figure 3.9** (a) Vertical section of the Cowie Sandstone Formation; and (b) detailed section at The Toutties. Based on Armstrong *et al*. (1978b) and Dineley (1999b).

## Description

The geology of the site has been described by Armstrong *et al*. (1978b), Gillen and Trewin (1987) and Carroll (1995a). Trewin and Thirlwall (2002) provided a summary. Dineley (1999b) described the fossil fishes and summarized the early work on the fauna. The Cowie Sandstone and Carron Sandstone formations consist mainly of cross-bedded and horizontally laminated, quartzo-feldspathic sandstones. There are numerous intercalations of silty mudstone and siltstone in the Cowie Sandstone Formation and abundant fragments of volcanic rock in the overlying Carron Sandstone Formation. Robinson *et al*. (1998) reported that the sandstones in both formations show a dominant palaeocurrent direction to the north-west and contain detrital garnets indicating a metamorphic source terrane to the south-east. In contrast, Gillen and Trewin (1987) reported palaeocurrent indicators in the Cowie Sandstone Formation showing transport to the ESE near the base and to the south-west in the remainder of the formation. The Cowie Sandstone Formation is late Wenlock to early Ludlow in age (Marshall, 1991; Wellman, 1993), but the Carron Sandstone Formation may be significantly younger, Marshall *et al.* (1994) arguing that there is a break in sedimentation between them, with differences in mineralogical composition (Armstrong *et al.*, 1978b), palaeomagnetism (Sallomey and Piper, 1973) and burial history.

The Cowie Sandstone Formation consists of dull red, purple, grey, buff and yellow, cross-bedded and flat-bedded, medium-grained, quartzo-feldspathic sandstones with intercalations of red, purple and grey siltstone and mudstone. It is exposed at The Toutties and northwards from Cowie Harbour to the unconformity with the Highland Border Complex at Ruthery Head close to the Highland Boundary Fault. About 450 m of beds are present at The Toutties, where faulting may attenuate the succession (Figure 3.9). The formation is subdivided into six members, the names of Donovan (in Armstrong *et al.*, 1978b) as amended by Carroll (1995a) being used in the following description.

The two lowermost members (Purple Sandstone and Castle of Cowie members) crop out to the north of The Toutties site. The Purple Sandstone Member (as re-defined by Carroll, 1995a) consists of about 93 m of purple, medium-grained, trough cross-bedded, quartzo-feldspathic sandstones. The basal 60 m of the member are pebbly and conglomeratic (the Basal Breccia Member of Armstrong *et al.*, 1978b) and contain an andesite lava flow. The overlying Castle of Cowie Member comprises 75 m of interbedded medium-grained, quartzo-feldspathic sandstones, red siltstones and sandy siltstones.

Within and just to the north of the site, over 240 m of soft, brown, grey and green, locally pebbly, trough cross-bedded, quartzo-feldspathic sandstones with common calcareous nodules constitute the Brown and Grey Sandstone Member. The sandstones contain a greater proportion of lithic clasts in comparison with the sandstones of the underlying members. Lenses of breccia containing rip-up siltstone clasts up to cobble size are locally abundant and volcaniclastic material makes its first appearance in the succession.

The Brown and Grey Sandstone Member is overlain by 12.5 m of conglomerates and interbedded green tuffaceous sandstone (the Cowie Harbour Conglomerate Member of Carroll, 1995a and the Volcanic Conglomerate Member of Armstrong *et al.*, 1978b). The conglomerates consist of well-rounded pebbles and cobbles generally up to 10 cm, but with some boulders, of acid volcanic rocks. The unit is variable along strike (Gillen and Trewin, 1987), Carroll (1995a) noting that it consists of three structural blocks bounded by strike parallel (?reverse) faults at Cowie Harbour. The lower block contains two broadly upward-fining sequences in which an irregular erosion surface is overlain by poorly sorted pebbly, coarse- to very coarse-grained volcaniclastic sandstone, which passes upwards over about 7 m into medium-grained volcaniclastic sandstone. The contact between the lowermost conglomerate and the underlying Brown and Grey Sandstone Member is repeatedly displaced eastwards (dextrally) by small syndepositional faults. Beds in the lower part of the member are overstepped by the overlying massive and trough-cross-bedded medium-grained volcaniclastic sandstone. A short break in exposure marks a line of truncation of bedding, the presence of fragments of fractured, soft, sandy fault breccia in this gap suggesting that a near-strike-parallel fault cuts the section here, possibly causing some tectonic attenuation. The upper contact is a gradual transition from medium-grained, green volcaniclastic sandstone into the overlying red sandstone.

The Red Sandstone Member comprises about 16 m of red, lithic, medium-grained, cross-bedded sandstones and tuffaceous sandstones with common convolute bedding. Trough cross-bedding indicates palaeocurrents towards the south-west. In the western part of the Stonehaven area, westwards from Tewel (NO 826 855), a thicker succession of massive and thinly planar-bedded, medium-grained, lithic sandstone may be an indication of varying rates of subsidence across the basin (Carroll, 1995a).

The Cowie Harbour Siltstone Member of Carroll (1995a) (the *Dictyocaris* Member of Armstrong *et al.*, 1978b) consists of interbedded sandy siltstone and planar-bedded, fine-grained sandstone. Both lithologies are predominantly planar laminated, but small-scale cross-lamination is also present, mainly in asymmetrical, current-generated ripples. Symmetrical, wave-generated ripples and convolute de-watering structures occur on the upper surfaces of sandstone beds directly overlain by siltstone.

The Cowie Harbour Fish Bed (Figure 3.10) lies in a succession of intercalated grey sandstones and fissile siltstones and mudstones at the base of the Cowie Harbour Siltstone Member. The other biota occur in grey beds intercalated with sandy siltstones and red sandstones with convolute de-watering structures. Planar lamination predominates, but small-scale ripple lamination occurs locally (Figures 3.9, 3.10). The fish bed and adjacent strata are truncated by a NW-trending fault at the northern end of the outcrop, where they are displaced eastwards to below low-tide level in Cowie Harbour. Abundant remains of *Dictyocaris slimoni* and other arthropods including *Archidesmus* sp., *Kampecaris*?, *Ceratiocaris* sp., *Hughmilleria norvegica* and *Pterygotus* sp. (Campbell, 1913; Westoll, 1951, 1977) have been recovered from a bed of grey mudstone. Cephalaspids were found in a reddish sandy mudstone (the Cowie Harbour Fish Bed) below (see Dineley (1999b) for references). The fish fauna includes the anaspid *Birkenia* sp., the holotype of the cephalaspid *Hemiteleaspis heintzi* and the holotype of *Traquairaspis campbelli*, a heterostracan of which this is the only species.

Three new species of fossil millipedes (*Albadesmus almondi*, *Cowiedesmus eroticopodus* and *Pneumodesmus newmani*) discovered recently at the site are of international importance, particularly in view of the fact that *Pneumodesmus newmani* is the earliest-known record of a fully terrestrial, air-breathing species (Wilson and Anderson, 2004).

The junction between the Cowie Harbour Siltstone Member and the overlying Carron Sandstone Formation is exposed at low tide at The Toutties (Carroll, 1995a). The Carron Sandstone Formation consists predominantly of

**Figure 3.10** Cowie Harbour Fish Bed (NO 8813 8667). Fissile mudstones and siltstones with thin ripple-laminated sandstone. (Photo: BGS No. D2455, reproduced with the permission of the Director, British Geological Survey, © NERC.)

brown, dull reddish brown and grey, locally pebbly, medium-grained, lithic sandstones with a substantial volcanic content locally. The sandstones are thinly bedded and weakly planar laminated in the lower part of the formation in and adjacent to the GCR site, and trough cross-bedded in the upper part near Downie Point to the south of Stonehaven Harbour.

## Interpretation

The Stonehaven Group is interpreted as the fill of a pull-apart basin (the Stonehaven Basin) controlled by strike-slip faulting (Bluck, 2000, 2001). In contrast to the Crawton and Strathmore basins, there is no broad upward-fining trend to the sedimentary basin-fill and conglomerates are rare. Vitrinite reflectivities of the Stonehaven Group (represented here by the Cowie Sandstone Formation) are compatible with a maximum burial of 3–5 km (Marshall *et al.*, 1994). This, along with the distinctive structure, sediment dispersal pattern, petrography and palaeomagnetism, supports the suggestion of Marshall *et al.* (1994) that the Cowie Sandstone Formation was the fill of a separate strike-slip sub-basin, and not part of the general fining-upward Lower Old Red Sandstone megacycle of which the Carron Sandstone Formation is a part. In this interpretation, the junction between the Cowie Sandstone and Carron Sandstone formations is a major structural and stratigraphical discontinuity (Trewin and Thirlwall, 2002). However, Carroll (1995a) and Phillips and Carroll (1995) record a transitional boundary, invoking the development of forced folds by continuous sedimentation and deposition in a strike-slip basin (cf. Christie-Blick and Biddle, 1985; Serrane, 1992). In this model, the bedding in the older deposits adjacent to the basin margin is progressively rotated, resulting in them retaining a structurally high position. Hence the Cowie Sandstone Formation could have been marginal to the supposed Crawton Basin deposits, as indicated by present outcrop distribution, and have been buried at shallow depth, as indicated by the vitrinite reflectivity data of Marshall *et al.* (1994).

The sandstones of the Purple Sandstone Member and Brown and Grey Sandstone Member are interpreted as the deposits of a braided river complex (Armstrong *et al.*, 1978b). Phillips and Carroll (1995) interpreted the sediments to have been laid down by small, bedload-dominated, braided streams on the lower part of alluvial fans, with some sheet-flood deposits in the Purple Sandstone Member. Based on palaeocurrents, the drainage was lateral (towards the ENE) in the Purple Sandstone Member and longitudinal (south or SSW) in the Brown and Grey Sandstone Member. The interbedded sandstones and argillaceous rocks of the Castle of Cowie Member are interpreted as the channelized and floodplain deposits respectively of a sinuous (?meandering) river system with longitudinal flow to the south-west. The Cowie Harbour Conglomerate Member was deposited from bedload-dominated, braided streams either on a distal alluvial-fan or braidplain, with transport to the ENE. Marked scouring at channel bases suggests higher flow energies than those of the streams that deposited the other members of the formation. Phillips and Carroll (1995) suggested that deposition of this thin unit might be linked to the appearance of a small volcanic cone on the braidplain. A return to a bedload-dominated, braided stream environment is suggested by the Red Sandstone Member. Palaeocurrents indicate derivation from the north-east (Gillen and Trewin, 1987; Phillips and Carroll, 1995). Sedimentation by fluvial channel, floodplain and lacustrine processes were responsible for the deposition of the Cowie Harbour Siltstone Member. Phillips and Carroll (1995) interpreted the horizontally laminated and cross-bedded sandstones that form most of the member as distal deposits of turbidity currents that introduced fluvial sediment into the lake. The finer-grained, carbonaceous siltstones lack wave ripples and trace fossils, suggesting that the lake was deep and stratified periodically, with anoxic bottom conditions.

The fish and arthropod fauna of the Cowie Harbour Fish Bed were formerly considered to be of late Silurian–early Devonian ('Downtonian') age (now the Přídolí Series) (Campbell, 1913; Denison, 1956; Westoll, 1951, 1977). However, Lamont (1952) advised caution in the age dating and correlation of the fauna, on the basis of similar faunas of probable late Llandovery to early Wenlock age in the southern part of the Midland Valley. Hanken and Størmer (1975) later suggested an early Ludlow age for the eurypterid arthropods. Marshall (1991) and

Wellman (1993) provided palynological evidence of a late Wenlock or early Ludlow (mid-Silurian) age. On this basis, the site is only one of two, the other being in Pennsylvania, that has yielded late Wenlock palynomorphs from continental Old Red Sandstone facies.

The Toutties site is important because it is comparable with the red-bed successions of the Silurian inliers in the southern Midland Valley, in which the Silurian rocks are overlain unconformably by Lower Old Red Sandstone of latest Silurian to early Devonian age. A late Wenlock (Homerian) to Ludlow (Gorstian) age for the Cowie Harbour Siltstone (*Dictyocaris*) Member, as proposed by Marshall (1991) and Wellman (1993), implies that *Traquairaspis campbelli* is substantially older than had previously been thought, and of similar age to the heterostracans of the Cape Phillips Formation and Cape Storm Formation in the Canadian Arctic (Dineley, 1999b). It also implies that the site provides, in the discovery of the fully terrestrial millipede *Pneumodesmus newmani*, the earliest evidence of air-breathing in any animal of any kind (Wilson and Anderson, 2004).

## Conclusions

The site's international importance lies in its freshwater fauna of fish, arthropods and newly discovered millipedes, and in its late Wenlock to early Ludlow palynomorphs, which date the rocks as some of the oldest Old Red Sandstone facies recorded. The unique heterostracan fish *Traquairaspis campbelli* is unknown elsewhere, with similar heterostracans providing a link with the Canadian and Baltic provinces. Recent discoveries of new species of fossil millipedes add a new dimension to the site's importance, particularly in the presence of the oldest record anywhere in the world of a fully land-based, air-breathing animal.

The section is also important in the evidence it provides into an understanding of the early development of the Midland Valley. The Stonehaven Basin appears to have been an early pull-apart basin formed before the development of the larger Strathmore Basin. The site offers opportunity for further research into its unique fauna and microflora and into the relationship between the Cowie Sandstone Formation and the overlying Carron Sandstone Formation.

# DUNNOTTAR COAST SECTION, ABERDEENSHIRE (NO 883 853–NO 882 839)

## Potential GCR site

*M.A.E. Browne and W.J. Barclay*

## Introduction

The dramatic cliffs and foreshore of the coastline extending southwards from Downie Point, south of Stonehaven Harbour to Dunnottar Castle and beyond for 1 km to Tremuda Bay (Figure 3.11) expose a Lower Old Red Sandstone succession dominated by conglomerates. This potential GCR site includes the topmost beds of the Carron Sandstone Formation (of the middle Silurian Stonehaven Group) and the type section of the Dunnottar Castle Conglomerate Formation (of the upper Silurian to lower Devonian Dunnottar–Crawton Group) (Figure 3.5, Section 6). The northern limit of the outcrop of the Tremuda Bay Volcanic Formation marks the southern limit of the potential site. The strata lie on the steeply dipping to overturned north-west limb of the asymmetric, NE-trending Strathmore Syncline.

## Description

Descriptions of the site were given by Gillen and Trewin (1987), Carroll (1995a,b) and MacGregor (1996a). Haughton and Bluck (1988) carried out a detailed analysis of the conglomerates in the section. Trewin and Thirlwall (2002) provided a summary of the succession and its depositional environments. The Stonehaven Group crops out northwards from Downie Point (Figure 3.11; see **The Toutties** GCR site report, this chapter) and comprises at least 1800 m (Carroll, 1995a) of cross-bedded and horizontally laminated, quartzo-feldspathic sandstones. The lower part of the group (the Cowie Sandstone Formation) has numerous mudstone/siltstone interbeds. The upper part (the Carron Sandstone Formation) is rich in volcanic detritus, has predominantly NW-directed palaeocurrents and contains detrital garnets indicating a metamorphic source to the south-east (Robinson *et al.*, 1998).

In this area, the sandstones of the Carron Sandstone Formation range from fine-grained to pebbly, gritty and lithic. They are predominantly

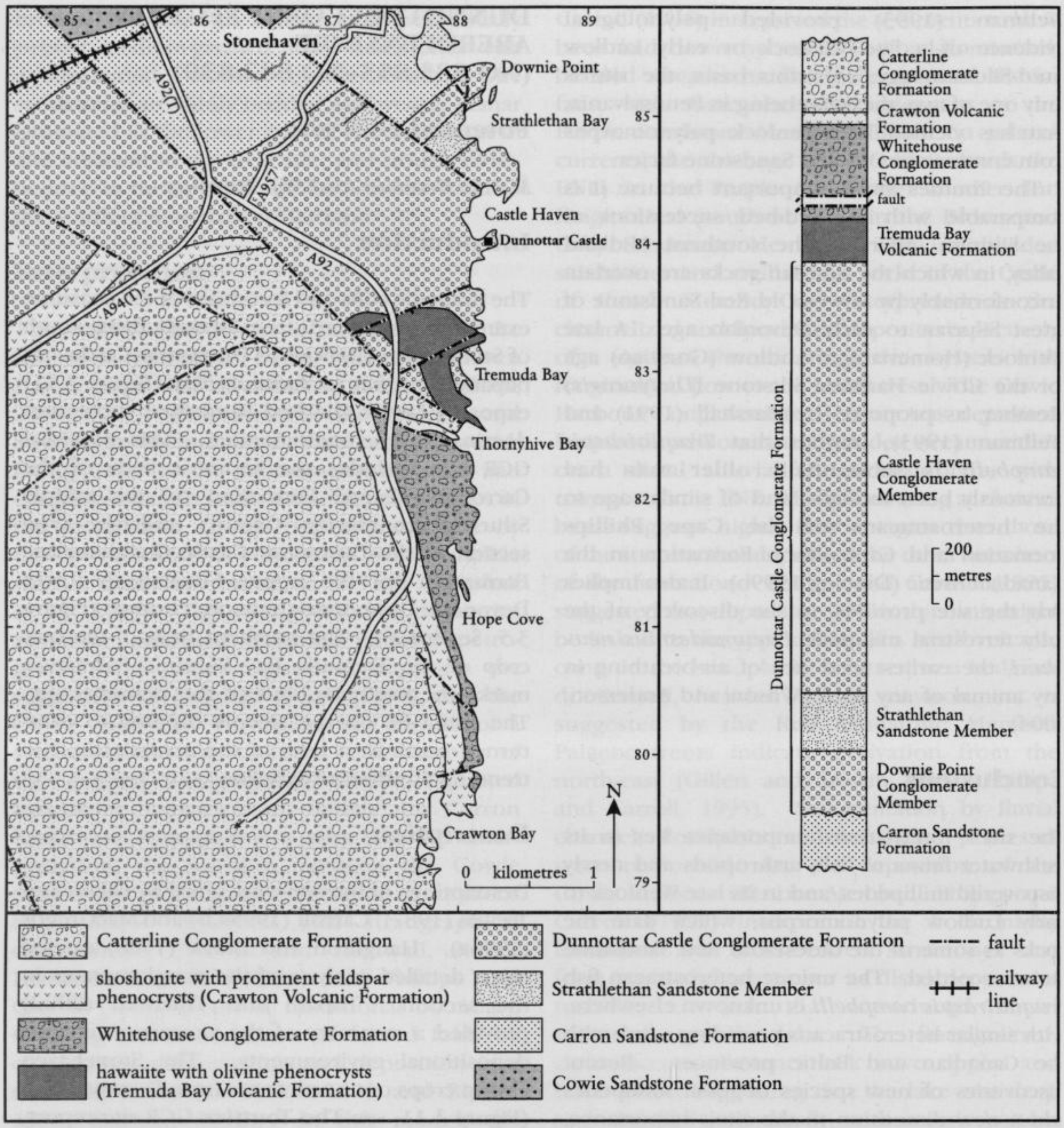



**Figure 3.11** Geological map of the area of the Dunnottar Coast Section, from Downie Point to Crawton Bay, with generalized vertical section of the strata. After British Geological Survey 1:50 000 Sheet 67 (Scotland), Stonehaven (1999).

red to purple, with some pink, orange and yellow beds. Both tabular and trough cross-bedded sets (over 1 m thick) and planar laminated units occur, the former with convolute de-watering structures locally. Some of the sandstones are micaceous, others are tuffaceous, the latter being associated with conglomerates dominated by acid volcanic clasts. There are a few beds of red sandy mudstone up to 0.3 m thick, but little evidence of upward-fining cycles, with argillaceous overbank rocks being a minor component and largely confined to pale lilac rip-up mudstone clasts in some of the sandstones. The rare conglomeratic beds and the pebbly sandstones contain clasts of chert, jasper, schistose grit, quartzite, vein quartz and rhyolite.

The Carron Sandstone Formation is overlain unconformably by thick, clast-supported conglomerates (the Downie Point Conglomerate Member), which form the basal part of the Dunnottar Castle Conglomerate Formation (of the Dunnottar–Crawton Group; Browne *et al.*, 2002) at Downie Point. The Downie Point Conglomerate Member comprises 180–225 m of strongly jointed, bimodally sorted, clast-supported cobble to boulder (generally less than 0.6 m) conglomerate with a matrix of coarse-grained sandstone (Carroll, 1995a). Massive, thickly bedded and cross-bedded units occur. The largest, well-rounded boulders are up to 1 m and mainly of resistant 'Highland' quartzites and psammites. They account for 30–60% of the coarse fraction, the remainder being largely of igneous lithologies (mostly andesitic lava, with rare granite and feldspar-phyric microgranite). A few pebbles of Highland Border Complex rocks (metabasalt, serpentinite and red chert) are also present. Beds of sandstone less than 1 m thick occur locally. The basal unconformity is seen particularly well in the quarry north-west of Downie Point (Gillen and Trewin, 1987; MacGregor, 1996a), where there appears to be about 2 m of relief on the erosion surface.

The Strathlethan Sandstone Member overlies the Downie Point Conglomerate Member, its base resting on an irregular surface that is markedly oblique to bedding, cutting down into the Downie Point Conglomerate Member from west to east. The member crops out in Strathlethan Bay and consists mainly of grey and grey-green, medium-grained, cross-bedded, locally pebbly, lithic sandstones. A thin basal bed of red, massive, medium- to coarse-grained volcaniclastic sandstone contains angular clasts of felsite and andesitic lava with rarer, rounded clasts of quartzite. Thin planar beds with normal grading are present locally, but sedimentary structures are destroyed towards the north-east of the exposures by a 1 cm-spaced parting sub-parallel to the bedding. The top of the bed is transitional with the overlying green, locally pebbly, lithic sandstone in places, but in others there is a sharp, highly convolute junction. Foreshore exposures at the north end of Strathlethan Bay show spectacular disruption in a 100 m-thick zone. Disruption is most intense at the base of the Strathlethan Sandstone Member, with rotated and partly rounded blocks of grey-green sandstone in a volcaniclastic sandstone matrix with a streaky, foliated fabric (Gillen and Trewin, 1987; Robertson, 1987). The zone apparently thickens from west to east and some of the rotated sandstone blocks are up to 30 m long. At the top of the zone, 'flames' of massive sandstone extend up into the overlying undisturbed beds.

Trough cross-bedding in sets of 1–2 m are typical of the undisturbed upper beds and in coherent blocks within the disturbed zone. Lenses of clast-supported pebble conglomerate and very poorly sorted volcaniclastic sandstone and thin beds of mudstone with desiccation cracks are interbedded with the lithic sandstones in the topmost 20–30 m near the sea stack of Carlin Craig (NO 880 847) at the southern end of Strathlethan Bay, in a rapidly upward-coarsening transition into the Castle Haven Conglomerate Member.

The Castle Haven Conglomerate Member (Browne *et al.*, 2002) consists of massive and weakly bedded, clast-supported conglomerate with lenses of horizontally laminated, medium-grained sandstone. This member forms most of the Dunnottar Castle Conglomerate Formation and is almost continuously exposed in the cliffs and foreshore from Dunnicaer (NO 8825 8473) to Tremuda Bay (NO 880 830) 1 km south of Dunnottar Castle. The conglomerate is of essentially 'Highland' type, its pebble suite dominated by andesitic lavas, quartzite and psammite. There are more clasts of 'granite' and porphyritic microgranite than in the underlying conglomerates, as well as a diverse suite of lithologies including vein quartz, chert, metabasalt, gabbro, migmatitic 'gneiss' and flow-banded rhyolite (Haughton 1989). Gillen and Trewin (1987) noted a quartzite-dominated clast assemblage with jasper and jasper-rich grit pebbles typical of the Highland Border Complex from the base of the member near the southern end of Strathlethan Bay.

At the north end (NO 880 842) of its type locality of Castle Haven, exposures of the Castle Haven Conglomerate Member on the wave-cut platform show well-sorted conglomerates with current imbrication of the pebbles and thin sandstone interbeds, cross-bedding in the sandstones indicating mainly SSW flow (Gillen and Trewin, 1987).

A conglomerate at the south end of Castle Haven (NO 880 840) marks the first appearance of clasts typical of the Dalradian Southern Highland Group (Gillen and Trewin, 1987). They are less well-rounded and of cleaved, low-grade metamorphic rocks. An unusual displacive sparry calcite carbonate cement may be of pedogenic origin. Sparse cross-bedding data indicate ESE flow. The succeeding conglomerate (NO 8800 8404) is also distinctive in consisting mainly of matrix-supported red, weathered andesitic lava boulders and pebbles in a matrix of argillaceous siltstone/very fine-grained sandstone with convolute laminations. The conglomerates between this unit and Dunnottar Castle (Figure 3.12) contain clasts of apparent Dalradian lithologies.

Red, coarse-grained, medium-bedded, volcaniclastic sandstone up to 30 m thick in the upper part of the member are composed largely of coarse-grained, angular clasts of fine-grained 'felsitic' material. These are present around Old Hall Bay (NO 8799 8370) just south of Dunnottar Castle, where the dip of the strata decreases from 70° to 40° to the south-east.

The overlying Tremuda Bay Volcanic Formation crops out in the cliffs southwards from Maiden Kaim (NO 882 834) to Tremuda Bay. It is 170 m thick (Carroll, 1995a) and consists of a number of lava flows of microporphyritic, olivine-bearing hawaiite (Thirlwall, 1979; Le Maitre, 1989). The basal bed of the formation is a thin, fine-grained, sandstone-to-mudstone, fining-upward unit.

## Interpretation

The cliff sections between Downie Point and Tremuda Bay expose superb examples of conglomerates of Old Red Sandstone lithofacies that are interpreted as the deposits of a large braided stream system and alluvial fans (Figure 3.13; Haughton and Bluck, 1988). The scale of

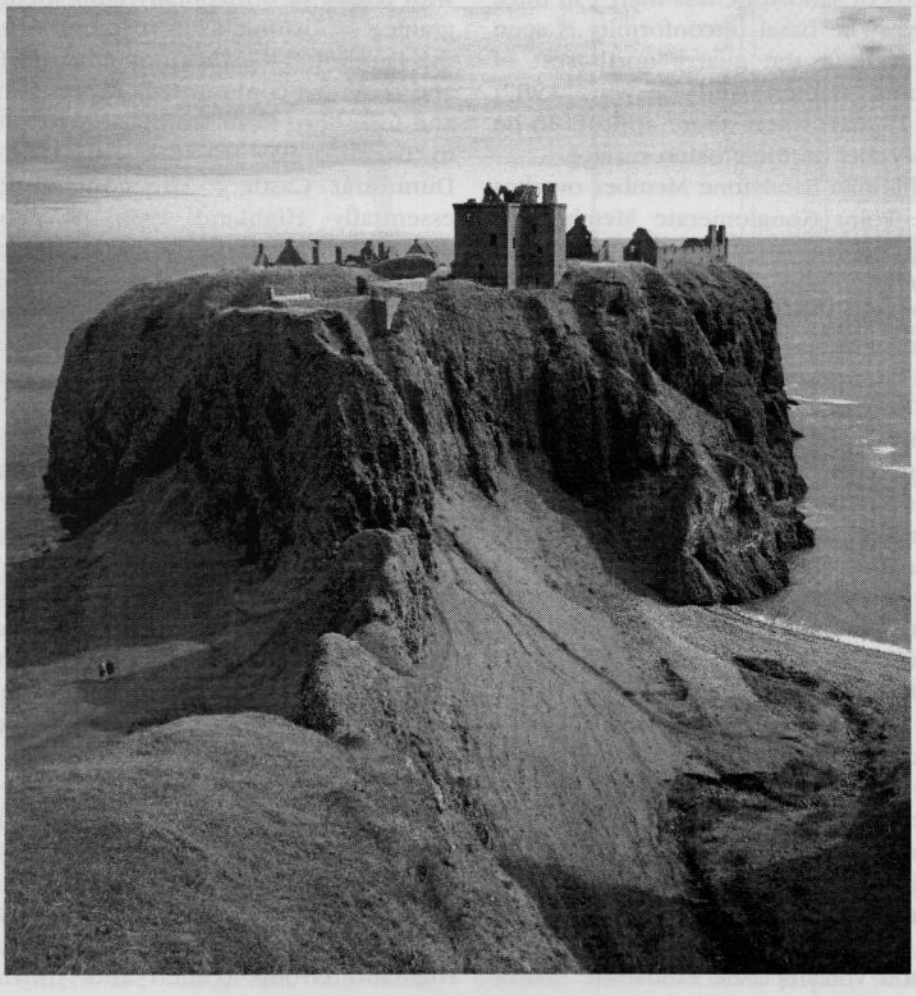


**Figure 3.12** Sub-vertical conglomerates of the Castle Haven Conglomerate Member of the Dunnottar Castle Conglomerate Formation at Dunnottar Castle (NO 882 839). (Photo: BGS No. D5187, reproduced with the permission of the Director, British Geological Survey, © NERC.)

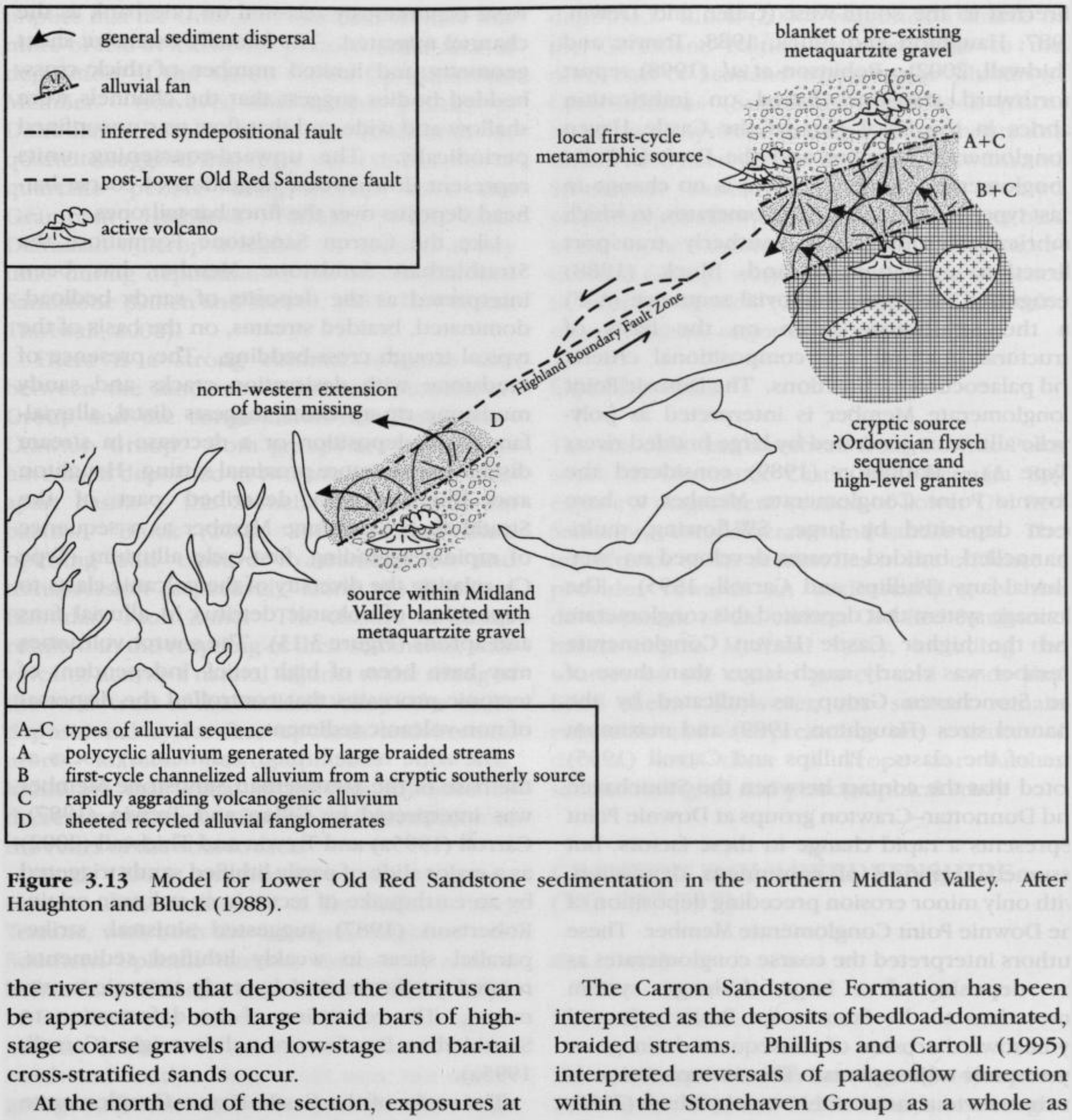



**Figure 3.13** Model for Lower Old Red Sandstone sedimentation in the northern Midland Valley. After Haughton and Bluck (1988).

the river systems that deposited the detritus can be appreciated; both large braid bars of high-stage coarse gravels and low-stage and bar-tail cross-stratified sands occur.

At the north end of the section, exposures at Downie Point show the unconformable relationship between the sediments laid down during mid- to late Silurian times in the Stonehaven Basin (the Carron Sandstone Formation) and those in the later Crawton Basin (the Dunnottar Castle Conglomerate Formation). However, the time represented by the unconformity at Downie Point, and whether the Carron Sandstone Formation has more in common with the Dunnottar–Crawton Group than with the Cowie Sandstone Formation in the Stonehaven Group, remain matters of debate (Gillen and Trewin, 1987; Carroll, 1995a; Trewin and Thirlwall, 2002). The sources of some of the detritus are also unclear.

The Carron Sandstone Formation has been interpreted as the deposits of bedload-dominated, braided streams. Phillips and Carroll (1995) interpreted reversals of palaeoflow direction within the Stonehaven Group as a whole as reflecting the interaction of transverse and longitudinal drainage systems within a fault-controlled basin. Contemporaneous tectonic activity may also have changed the local palaeoslope. Convolute bedding structures also point to rapid deposition, liquefaction and de-watering in a tectonically active basin (Trewin and Thirlwall, 2002). The topmost beds of the formation were probably braidplain deposits laid down by moderate- to high-energy streams flowing to the south-west.

The Downie Point Conglomerate Member represents a sudden influx of coarse detritus and uplift, probably to the north-east, as palaeocurrents in a large braided river system are directed to the south-west (Gillen and Trewin, 1987; Haughton and Bluck, 1988; Trewin and Thirlwall, 2002). Robinson *et al.* (1998) report northward transport based on imbrication fabrics in the basal part of the Castle Haven Conglomerate Member and the Downie Point Conglomerate Member. There is no change in clast types in the higher conglomerates, in which imbrication indicates a southerly transport direction. Haughton and Bluck (1988) recognized six types of alluvial sequence (A–F) in the Strathmore Basin on the basis of structural, textural and compositional criteria and palaeocurrent directions. The Downie Point Conglomerate Member is interpreted as polycyclic alluvium generated by large braided rivers (Type A). Haughton (1989) considered the Downie Point Conglomerate Member to have been deposited by large, SW-flowing, multichannelled, braided streams developed on 'wet' alluvial-fans (Phillips and Carroll, 1995). The drainage system that deposited this conglomerate and the higher Castle Haven Conglomerate Member was clearly much larger than those of the Stonehaven Group, as indicated by the channel sizes (Haughton, 1989) and maximum size of the clasts. Phillips and Carroll (1995) noted that the contact between the Stonehaven and Dunnottar–Crawton groups at Downie Point represents a rapid change in these factors, but assumed a period of continuous deposition, with only minor erosion preceding deposition of the Downie Point Conglomerate Member. These authors interpreted the coarse conglomerates as the deposits of a large drainage system antecedent to the Stonehaven Basin, captured by headward erosion of consequent drainage or by tectonic adjustments. This interpretation is in contrast to a more recent one by Bluck (2000, 2001), in which the Stonehaven Group is envisaged as the fill of an older, pull-apart basin separate from that in which the Dunnottar–Crawton Group was deposited. The presence of volcaniclastic sandstones in the upper part of the Castle Haven Conglomerate Member was interpreted by Phillips and Carroll (1995) to be due to the introduction of large volumes of volcanic detritus during periods when the more general coarse gravel deposition was overwhelmed. Although largely of braided stream origin, high-concentration flood deposits and debris flows are also present. Haughton and Bluck (1988) envisaged deposition of the conglomerates mainly as gravel braid bars that were continuously accreted on one bank as the channel migrated. The laterally extensive sheet geometry and limited number of thick cross-bedded bodies suggest that the channels were shallow and wide and that flow was unconfined periodically. The upward-coarsening units represent downstream migration of coarse bar-head deposits over the finer bar-tail ones.

Like the Carron Sandstone Formation, the Strathlethan Sandstone Member has been interpreted as the deposits of sandy bedload-dominated, braided streams, on the basis of the typical trough cross-bedding. The presence of mudstone with desiccation cracks and sandy mudstone rip-up clasts suggests distal, alluvial-fan, flood deposition or a decrease in stream discharges in a more proximal setting. Haughton and Bluck (1988) described part of the Strathlethan Sandstone Member as a sequence of rapidly aggrading, first-cycle alluvium (Type C), relating the diversity of the volcanic clasts to deposition of volcanic detritus in alluvial fans and aprons (Figure 3.13). The source volcanoes may have been of high relief, independent of tectonic processes that controlled the dispersal of non-volcanic sediment.

The zone of deformed sedimentary rocks at the base of the Strathlethan Sandstone Member was interpreted by Gillen and Trewin (1987), Carroll (1995a) and Trewin and Thirlwall (2002) as a major slide of partly lithified sands triggered by an earthquake of tectonic or volcanic origin. Robertson (1987) suggested sinistral, strike-parallel shear in weakly lithified sediments, rotated to the vertical by early tectonic movements. The restriction of the deformation to Strathlethan Bay favours a slide origin (Carroll, 1995a).

The rocks of the Castle Haven Conglomerate Member were interpreted by Haughton (1989) as the deposits of large braided streams flowing south or south-west on extensive alluvial-fans. Phillips and Carroll (1995) recognized debris flow and hyperconcentrated flood deposits in the volcaniclastic sandstones, introduced when large volumes of volcanic detritus, possibly of local origin, flooded the basin. One matter of debate concerns the change in clast composition recognized by Gillen and Trewin (1987), from conglomerates sourced from the Highland Border Complex at the base of the Castle Haven Conglomerate Member at the south end of Castle Haven to Dalradian-sourced conglomerates (not recognized by Bluck, 1984) to the south. This implies that the Grampian Highland Terrane was more-or-less in its current position at the time of deposition of the Castle Haven Conglomerate Member. However, the relative paucity of Dalradian clasts and the predominance of quartzite suggests that there was a thick cover of quartzite pebble conglomerate over the Grampian Highland Terrane, with little Dalradian outcrop available for erosion at any time during deposition of the Lower Old Red Sandstone (Gillen and Trewin, 1987; Trewin and Thirlwall, 2002).

There is a strong contrast in grain size between the sandstone-dominated Stonehaven Group and the conglomerate-rich Dunnottar–Crawton Group. Both groups are thought to have been deposited in two small, separate pull-apart basins – the Stonehaven and Crawton basins. Bluck (2000, 2001) related their opening and closure to transtension and transpression respectively, along the Highland Boundary Fault Zone. The closure of basins resulted in the recycling of their sediments, with volcanic activity a natural adjunct to the rifting of the weak crust of the Midland Valley. The major depositional cycles fine upwards and become more mature petrographically upwards, indicating that initial rifting was followed by decreasing tectonic influence and a reduction in the relief of the source area.

Bluck (2000) commented on the enigmatic sources of the sediments in the Midland Valley Terrane, with both the Grampian Highland and Southern Uplands terranes extensively eroded before latest Silurian times. The Midland Valley of Scotland was therefore not a post-orogenic molasse basin, with mountainous areas to the north and south. These areas were not undergoing sufficient uplift to provide the huge volume of sediment preserved in the Lower Old Red Sandstone succession, nor were there slopes of sufficient gradient to supply much of the coarse gravels. The thick coarse conglomerates, such as those at Dunnottar, may therefore have been the product of recycling of sediment from a locally inverted, pop-up basin, or from older sedimentary cover in the area of the Highlands to the north. A now-hidden flysch below the centre of the Midland Valley to the south may also have contributed to the fill of the Dunnottar–Crawton Basin (Haughton, 1988). However, whereas local drainage may have accounted for the coarse gravels, it could not have supplied the huge volume of sands deposited. Bluck (2000) suggested a source in the Greenland–Baltica collision zone to the north-east of Scotland where major Silurian to Carboniferous (Scandian) uplift took place. Major river systems draining these mountains would have been able to enter the Crawton and Strathmore basins when relief was lowered sufficiently to allow them access. Large river bars in the Scone Sandstone Formation (Arbuthnott–Garvock Group) west of Perth provide evidence to support Bluck's (2000) model of a distant source of these major distributaries.

## Conclusions

The sea cliffs and foreshore from Downie Point south to Dunnottar Castle and Tremuda Bay expose a magnificent section of Lower Old Red Sandstone conglomerates and sandstones. The importance of the section lies in the evidence it provides towards an understanding of the development of the earliest Old Red Sandstone basins in the Midland Valley, including the sources of the coarse gravels and sands that filled them. However, the sources remain enigmatic and interpretations are a matter of debate, and there is scope for further sedimentological and petrographical study.

# CRAWTON BAY, ABERDEENSHIRE (NO 897 797)

***R.A. Smith***

## Introduction

The coastline of Crawton Bay (Figure 3.14) exposes a succession of Lower Old Red Sandstone conglomerates and is the type locality of the Crawton Volcanic Formation, the youngest formation in the Dunnottar–Crawton Group (Browne *et al.*, 2002). This formation is Late Silurian to Early Devonian in age and comprises olivine basalts, basaltic andesites and interbedded conglomerates, described in the GCR volume on the Caledonian igneous rocks (Smith, 1999b). The underlying alluvial conglomerates, intercalated volcaniclastic beds and overlying boulder conglomerates are the subjects of this description. The cliff sections, particularly at Crawton Ness and Trollochy, show superb examples of large braid bars with high-stage coarse gravels and low-stage cross-stratified sands. The braided stream character and the

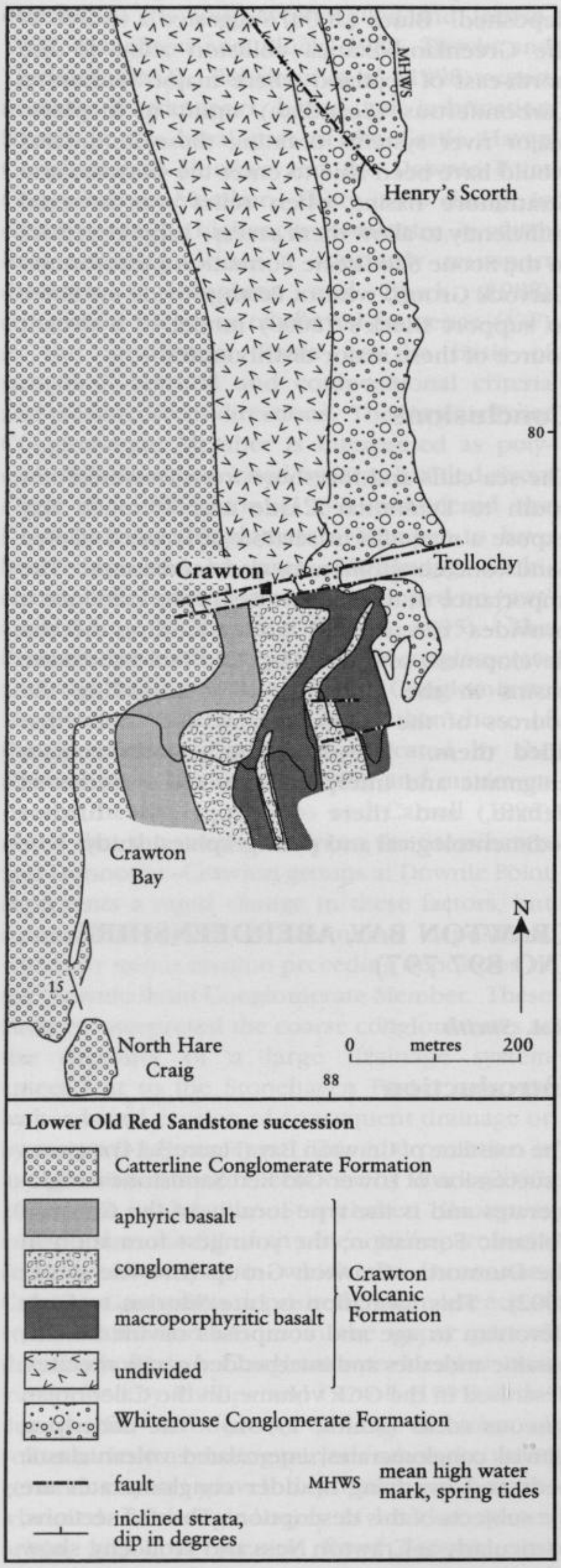



**Figure 3.14** Geological sketch map of the Crawton Bay area. After Stephenson *et al.* (1999, fig. 9.19).

large scale of the river system that deposited the detritus in the Midland Valley of Scotland can be appreciated at this locality. The large proportion of quartzite and granite clasts in the conglomerates, in contrast to the clast types in the conglomerates elsewhere in the Dunnottar–Crawton Group (Haughton, 1988), suggests that the source was the Grampian Highland Terrane to the north. This evidence contributes to our knowledge of the unroofing history of the Grampian Highland Terrane and the development of the Midland Valley.

## Description

The inter-relationships between the lava flows and the intercalated sedimentary rocks of 'Highland origin' were first noted by Geikie (1897). The locality has since been described in detail by Campbell (1913), Trewin (1987b), Carroll (1995b) and MacGregor (1996a). Carroll (1995b) divided the section, in ascending sequence, into the Whitehouse (Fowls Heugh) Conglomerate Formation (exposed at Crawton Ness), the Crawton Volcanic Formation (interbedded conglomerates and lavas) and the Catterline Conglomerate Formation, which is the basal formation of the Arbuthnott–Garvock Group. The provenance of the clasts in the conglomerates of the Dunnottar–Crawton Group conglomerates at the site has been studied by Haughton *et al.* (1990).

The oldest conglomerates at the site belong to the Whitehouse Conglomerate Formation of Browne *et al.* (2002) (the Fowls Heugh Conglomerate Formation of Carroll, 1995b), which dips gently to the WSW below the Crawton Volcanic Formation. The cliffs to the north and south of Trollochy (NO 881 798), the inlet east of Crawton, are eroded along ENE-trending faults cutting the Whitehouse Conglomerate Formation (Figure 3.14). The conglomerates of the formation are clast-supported and have weak bedding picked out by grain-size differences. Intercalated sandstone lenses are trough- and planar cross-bedded, moderately well-sorted and locally scoured below conglomerate beds. At the base of the cliff on the north side of Trollochy, sandstone rests on an inclined surface of conglomerate, and cross-stratification can be seen in the conglomerates nearby. A few metres up the cliff, a conglomerate that originally had open interstices, is now cemented by micritic calcite

(Trewin, 1987b). Coarse conglomerates immediately below the Crawton Volcanic Formation (NO 881 798) occur in units that coarsen upwards overall (Haughton *et al.*, 1990) and have imbricate fabrics indicating palaeoflow from the north. Clast types depend on their sizes, which range up to 1 m. Volcanic rocks similar to those in the Crawton Volcanic Formation predominate, with lesser amounts of psammites, granites, granodiorites, hypabyssal rocks, quartzites and vein quartz. Of the granitic rocks, biotite-muscovite granite, porphyritic granite and equigranular red granite are the commonest in the boulder-size fraction, other granitoids and porphyries are common in the cobble to pebble fraction. Rb–Sr muscovite whole-rock ages for biotite-muscovite granite boulders from the top of the Dunnottar–Crawton Group are 473–457 Ma; a U–Pb age of 475 ± 5 Ma was obtained from a monazite in one of the clasts (Haughton *et al.*, 1990). A Rb–Sr biotite age of 412 ± 4 Ma was obtained from a clast of porphyritic biotite granite. Mica whole-rock ages for the accompanying psammitic clasts suggest that their source included metamorphic rocks that were uplifted at the same time as the intrusion of the granites. Haughton *et al.* (1990) concluded that the source resembled the Grampian Highland Terrane of north-east Scotland, and that the north Midland Valley Terrane was juxtaposed within tens of kilometres of its present position with the Grampian Highland Terrane at the time of deposition. South of Trollochy (NO 8805 7970), laminated sandstone and mudstone immediately below the first lava flow are locally disrupted and baked by the lava (Trewin, 1987b).

The Crawton Volcanic Formation, which is up to 70 m thick (Carroll, 1995b), has conglomerates above the first and third lava flows. There is evidence of penecontemporaneous erosion of the third lava flow where it was partly eroded and potholed prior to deposition of the thick overlying conglomerates (Figure 3.15). These are clast- and matrix-supported, and consist of well-rounded clasts ranging from pebbles to boulders about 1 m set in a coarse-grained, poorly sorted, volcaniclastic sandstone matrix. The clasts comprise macroporphyritic andesite lava, psammite and quartzite, with lesser amounts of metabasalt, felsite, chert and greywacke. The coarse fraction of the clast suite is of broadly 'Highland' provenance (i.e. Highland Border Complex and probably some Grampian Highland Terrane), with a significant component of local lavas.

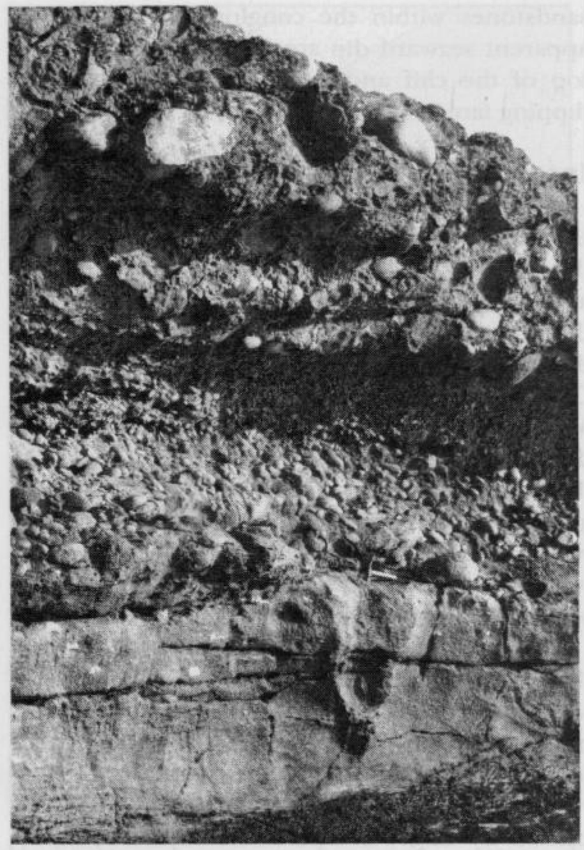


**Figure 3.15** Coarse conglomerates of the Crawton Volcanic Formation resting on the eroded top of the third lava. (Photo: N.H. Trewin.)

The overlying Catterline Conglomerate Formation is exposed in a steep cliff on the west side of Crawton Bay (NO 877 796). It comprises red-brown and grey, thickly bedded, pebble- to boulder-grade conglomerates that show weak grain-size stratification. They are mainly clast-supported, with well-rounded pebbles set in a matrix of less well-rounded, volcaniclastic, coarse sand grains and granules. Volcanic pebbles are more common than in the underlying conglomerates, and include massive basalt and vesicular and porphyritic andesites, probably of local derivation. Quartzite, vein quartz, greywacke sandstone, granitic rocks, jasper and metabasalt are also present. The last two rock types are typical of the Highland Border Complex and the greywacke sandstone has a spaced cleavage similar to that in the Dalradian Southern Highland Group north of the Highland Boundary Fault. Cross-bedded sandstones within the conglomerates with an apparent seaward dip are exposed towards the top of the cliff and form part of a southerly dipping fan (Trewin, 1987b).

## Interpretation

Earlier models for Lower Old Red Sandstone deposition (Bluck, 1978) suggested that axial alluvial sedimentation in an elongate basin was dominant over lateral, coarse alluvial-fan deposition. Detailed work on the Dunnottar–Crawton Group (Haughton, 1988, 1989; Marshall *et al.*, 1994) showed that other depositional packages, with clastic material derived from sources within the Midland Valley and the penecontemporaneous volcanic rocks, were present in the Crawton Basin, together with the polycyclic alluvium from a 'Highland' source (Haughton and Bluck, 1988).

The alluvial gravel overlying the top of the third lava flow (Figure 3.15) indicates that a short period of erosion removed any hematized bole, such as that developed between the second and third flows, but not all of the vesicular top to the lava. The gravels were carried by large, complex river systems from both local and distant 'Highland' sources. The large size of the cobbles and coarsening-upward units in the river gravels suggest that the sporadic, relatively thin and sheet-like Crawton lavas only temporarily diverted these powerful rivers.

All the conglomerates at this site contain varying proportions of locally derived volcanic rocks and northerly derived 'Highland' rocks. This contrasts with conglomerates derived from the south and east within the Midland Valley Terrane (Haughton, 1988), which contain first-cycle clasts of lithic arenite, granodioritic rocks and metagreywacke, as well as limestone clasts with Early Ordovician faunas. This cryptic Midland Valley source is distinct from the Southern Uplands Terrane and may have originally comprised displaced fore-arc slivers to the south of the Laurentian continental margin.

Carroll (1995b) considered the Crawton Volcanic Formation to be Late Silurian in age. This was based on an earliest Devonian age (on palynological evidence) for the overlying Arbuthnott–Garvock Group (Richardson *et al.*, 1984) and a date of 415 ± 5.8 Ma for a dacitic ignimbrite (the Lintrathen Tuff Member) north of the Highland Boundary Fault (Thirlwall, 1988; Bluck, 2000). This is correlated with the Glenbervie 'Porphyry' at the top of the Crawton Volcanic Formation, and because it crops out north of the Highland Boundary Fault, Trench and Haughton (1990) considered that the relative lateral movement between the northern Midland Valley and the Grampian Highland terranes from Early Devonian time onwards could have been only of the order of tens of kilometres. This has an important bearing on the provenance of the intercalated sedimentary clasts. The Lower Old Red Sandstone lavas appear to have accumulated in a subsiding rift basin close to the Highland Boundary Fault, with the Grampian Highland Terrane to the north-west of the fault providing a source of coarse clastic detritus. The succeeding Arbuthnott–Garvock Group lacks any clasts known to be derived from the cryptic Midland Valley source and heralds the development of the more extensive Strathmore Basin. Further work on the provenance of the sedimentary rocks, including dating studies of heavy mineral suites, may identify more precisely the clastic sources. Geochemical studies may reveal the extent of the contribution from local volcanic, as opposed to other volcanic, sources. Sedimentological studies will refine our understanding of the relationship between the high-energy alluvial deposition and the penecontemporaneous volcanic eruptions. The development of the Crawton Basin, including syndepositional fault control on its subsidence, is a further topic of future research.

## Conclusions

The Crawton Bay GCR site provides the best exposures of the Crawton Volcanic Formation and its type section. This is a significant marker horizon at the top of the Dunnottar–Crawton Group, and its relationship with the conglomerate formations above and below can be seen at the site. The intercalated lavas and conglomerates here have been studied since the late 19th century, because of the fine exposures, which demonstrate the relationship between volcanic and sedimentary rocks in a rifted marginal basin. The sedimentary rocks provide important evidence for the large size of the river systems, which were interrupted by calc-alkaline volcanic outpourings in Late Silurian to Early Devonian times. The Crawton Basin was the precursor to the larger Strathmore Basin that developed within the northern Midland Valley. However, unlike the Crawton Basin, the Strathmore Basin lacks clasts derived from cryptic sources within the Midland Valley.

## NORTH ESK RIVER, ABERDEENSHIRE (NO 595 719–NO 604 703)

***R.A. Smith***

### Introduction

The North Esk River section in the Gannochy Gorge (Figure 3.16) is in the Strathmore Group of the Lower Old Red Sandstone in the northern Midland Valley, about 500 m south-east of the Highland Boundary Fault. The Strathmore Group is the youngest Lower Devonian succession of the area and comprises a sequence of alluvial siltstones, sandstones and conglomerates. This GCR site provides the best sections in which to examine the variations in lithology and thickness of the strata, as well as the pebble content of the conglomerates. The change in clast content along the gorge reflects movements along the Highland Boundary Fault and the history of erosion of the Dalradian Supergroup, which formed land to the north during this part of the Devonian Period. This is also an important section for understanding the tectonic development of the Midland Valley and its relationship to the Grampian Highland Terrane at that time. The sedimentology and fluvial architecture of the succession can be studied in this impressive gorge, which is 20 m to 30 m deep.

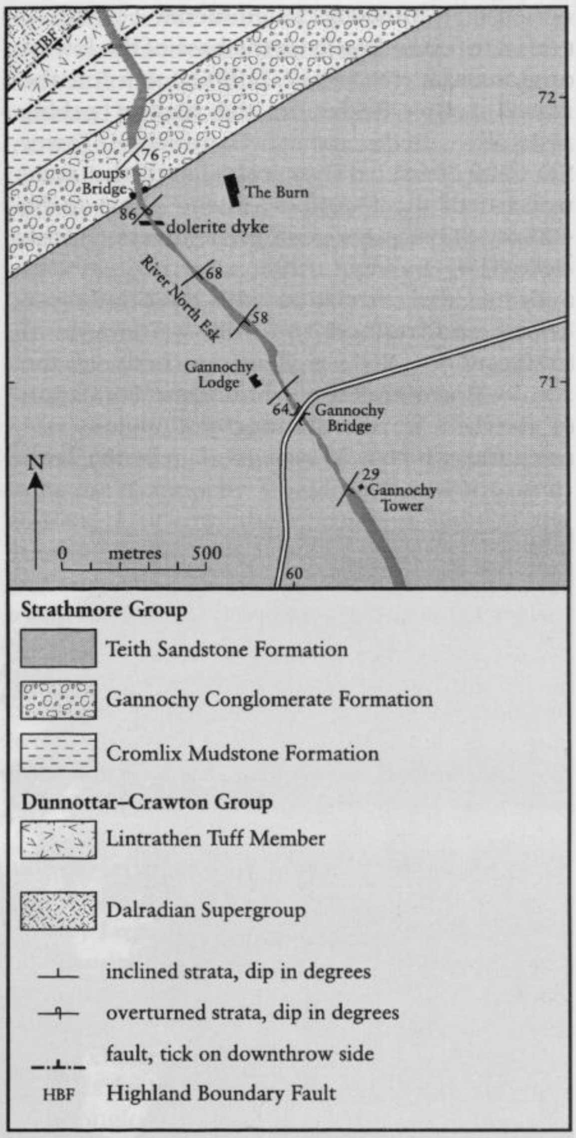



**Figure 3.16** Geological sketch map of the North Esk River section.

### Description

The North Esk River cuts through the Strathmore Group on the steep north-west limb of the Strathmore Syncline. To the north of the site, poorly exposed, reddish brown siltstones and poorly sorted fine- to medium-grained, argillaceous sandstones are correlated with the coarser-grained facies of the Cromlix Mudstone Formation, which is truncated against the Highland Boundary Fault. The Cromlix Mudstone Formation is the basal formation of the Strathmore Group and because it is relatively soft it is generally poorly exposed. To the south, the formation passes conformably up into the 250 m-thick Gannochy Conglomerate Formation, which is more resistant and forms the northern part of the gorge.

The sandstones and conglomerates upstream of Gannochy Tower (NO 6021 7065) were formerly correlated with the Garvock Group (Campbell, 1913; MacGregor, 1968), but later re-assigned to the Strathmore Group on the faulted north-west limb of the Strathmore Syncline (Armstrong and Paterson, 1970; MacGregor, 1996b). Armstrong and Paterson defined the Gannochy Conglomerate Formation at this site, extending from the base of the lowest conglomerate (NO 5947 7199) north of the disused Loups Bridge to the highest pebbly sandstone beds near Gannochy Tower (NO 6020 7064). They calculated the total thickness of the formation in the gorge to be 1400 m. Subsequent geological surveys (British Geological Survey, 1995; Carroll, 1995c) confirmed the correlation with the Strathmore Group, and refined the lithostratigraphical classification. Red, argillaceous beds of the Cromlix (formerly Edzell) Mudstone Formation are overlain by the Gannochy Conglomerate Formation, which is in turn overlain by the Teith (formerly Edzell) Sandstone Formation (Browne *et al.*, 2002). Carroll (1995c) re-defined the Gannochy Conglomerate Formation in the North Esk River, placing the top of the formation at the top of the clast-supported orthoconglomerate beds immediately downstream of Loups Bridge (NO 5948 7164).

The clast-supported conglomerates of the Gannochy Conglomerate Formation (Figure 3.17) appear to occur in lenses within pebbly sandstones, which dip almost vertically in this section. Locally, 50 m north of an E–W-trending Permo–Carboniferous dolerite dyke (NO 5951 7156), the beds are overturned, dipping 86° to the north-west. The conglomerates

**Figure 3.17** Coarse clast-supported orthoconglomerate of the Gannochy Conglomerate Formation at Loups Bridge, North Esk River. (Photo: BGS No. D5347, reproduced with the permission of the Director, British Geological Survey, © NERC.)

are weakly stratified and poorly sorted, and contain rounded to subrounded pebbles in a medium- to coarse-grained sandstone matrix. Cross-bedded pebbly sandstone lenses occur within the conglomerate lenses and some of the sandstone bodies have basal, pebbly lags. Conglomerates continue south of Loups Bridge (NO 5948 7164), and are conformably overlain by fine- to medium-grained, pebbly sandstones of the Teith Sandstone Formation. The conglomerates have a decreasing proportion of quartzite and quartz pebbles in their upper part (MacGregor, 1968, 1996b).

The Teith Sandstone Formation forms the bulk of the gorge section and is relatively coarse-grained, containing several thick conglomerates within red-brown sandstones and mudstones. The sandstones are commonly trough cross-bedded, pebbly to medium-grained and include large detrital micas. Red mudstone beds up to 2.5 m thick and dipping about 60° to the south-east are well exposed about 230 m north of Gannochy Bridge. The conglomerate interbeds are polygenetic and although quartzite is the most common pebble type, vein quartz, porphyry, andesite, granite, gneiss, felsite and sedimentary types are also present (MacGregor, 1968, 1996b). The overlying part of the Teith Sandstone Formation south of Gannochy Tower, and about 270 m downstream from Gannochy Bridge, consists of mainly fine- to medium-grained, red sandstones, with some coarse-grained to pebbly sandstones with mudstone intraclasts. The beds dip about 30° to the south-east. Some of the finer-grained sandstones are cross-bedded or ripple cross-laminated, and there are thick, planar-bedded, silty sandstones with very thin mudstone interbeds (Carroll, 1995c).

## Interpretation

The sequence of sandstones and conglomerates north of Gannochy Tower was originally placed in the Garvock Group (Campbell, 1913), but Armstrong and Paterson (1970) re-assigned it to the Strathmore Group on structural grounds, considering its position on the north-west limb of the Strathmore Syncline. The Strathmore Group exposed in Gannochy Gorge is coarser grained than that on the south-east side of the Strathmore Syncline, probably due to its proximity to the source of the detritus to the north.

The depositional environment of the Cromlix Mudstone Formation has been inferred from exposures at Mid Mains of Balfour (NO 624 740), a few kilometres to the north-east, to be an alluvial floodplain that periodically dried out, as indicated by local desiccation cracks. Trace fossils include *Skolithos*, *Arenicolites* and *Beaconichnus* (Carroll, 1995c), indicating a habitat suitable for burrow-feeders, possibly close to a lake shoreline. The Gannochy Conglomerate Formation marks the progradation of a high-energy alluvial-fan system, with reduced fluvial energies being represented by the overlying Teith Sandstone Formation. Only the lower part of the Teith Sandstone Formation is seen in this section, but it appears to fine upwards overall. Its base is probably coarser grained here, as it is gradational from the Gannochy Conglomerate Formation, and the facies on the north-west limb of the Strathmore Syncline is typically laterally variable and coarser grained than the more distal facies to the south-east. In the younger parts of the formation exposed elsewhere, the plant remains *Arthostigma* sp. and *Psilophyton* sp. are locally common, indicating plant colonization of the less active floodplains. Spores from plant beds in the Strathmore Group indicate an Early to Mid-Emsian age (Richardson *et al.*, 1984).

Haughton and Bluck (1988) recognized two alluvial styles in the Strathmore Group. Fine-grained alluvium was deposited in axial systems by very large rivers that probably drained areas of Scandian uplift. First-cycle conglomerates were deposited in fans close to the Highland Boundary Fault and derived from the north-west. The textural immaturity of the conglomerates suggests flash-flood deposition. The Strathfinella Hill Conglomerate Member, which crops out to the north-east, contains clasts of metamorphic rock of garnet- and higher grades. Haughton and Bluck (1988) related these grades to the Barrovian zones in the adjacent Dalradian rocks of the Grampian Highland Terrane to the north-west, inferring little displacement on the Highland Boundary Fault since Emsian times. Comparison of Lower Old Red Sandstone sequences immediately to the north and south of the Highland Boundary Fault (Bluck, 2000) suggests that the Grampian Highland Terrane pushed southwards, either during or after Lower Old Red Sandstone deposition, effectively removing the northern part of the Strathmore Basin and generating the steep northern limb of the Strathmore Syncline.

Peacock (1961) suggested that significant uplift of the source area caused the influx of conglomerates of the Gannochy Conglomerate Formation and noted a decrease in its maturity upwards (MacGregor, 1968, 1996b). The upper, less mature conglomerates contain gneisses (about 25%), as well as 'porphyry', 'granite' and sedimentary pebbles, presumed to have been derived from the highlands to the north. Armstrong and Paterson (1970) considered that the Gannochy Conglomerate Formation continued north-eastwards to link with the Strathfinella Hill Conglomerate Member, but detailed mapping by Carroll (1995c) indicates that they are the deposits of separate alluvial fans. The Lintrathen Tuff Member (Dunnottar–Crawton Group), which is exposed in a faulted wedge within the Highland Boundary Fault Zone farther north in the North Esk River section, also occurs to the north-west of the fault zone. Its presence there has been interpreted (Trench and Haughton, 1990) as confirmation that only a limited amount of lateral movement on the Highland Boundary Fault has occurred since the tuff erupted at 415.5 ± 5.8 Ma (Thirlwall, 1988).

## Conclusions

The North Esk River GCR site is the best-exposed section through the Strathmore Group on the north-western side of the Strathmore Syncline and the type section for the Gannochy Conglomerate Formation. It provides good exposures of the conglomerate formation, as well as the underlying and overlying finer-grained formations. The pebbles in the conglomerate are mainly from the Grampian Highland Terrane to the north-west, in contrast to the older Lower Old Red Sandstone rocks sourced from more distant areas of Scandian uplift. The depositional model envisaged for these sedimentary rocks comprises an interplay of a large, axially draining alluvial system flowing to the south-west and the lateral build up of alluvial-fans draining south-east across the Highland Boundary Fault Zone during Emsian times. Because of its proximity to the clastic source, the facies of the Strathmore Group in this section is coarser grained than that on the south-east limb of the Strathmore Syncline. Detailed sedimentological and provenance studies at the site, compared to studies at Strathfinella, would test this simple model and provide important data on fault control on sedimentation and the timing of exhumation of the Grampian Highland Terrane.

# MILTON NESS, ABERDEENSHIRE (NO 766 650–NO 771 648)

## Potential GCR site

*W.J. Barclay*

## Introduction

The coast section at Milton Ness near Montrose (Figure 3.18) provides the best example of mature Old Red Sandstone carbonate soil (calcrete) development in Scotland. The calcrete occurs in the Upper Devonian–Lower Carboniferous (Upper Old Red Sandstone) Kinnesswood Formation (of the Inverclyde Group), in a down-faulted block of predominantly fluvial sedimentary rocks. The near-horizontal rocks crop out in a wave-cut cliff up to 10 m high and about 500 m long, providing excellent lateral exposure. This has allowed a detailed examination of the morphology and development of a mature calcrete at the top of the section by Balin (2000). Palaeokarst cavities, reworked hardpan calcrete and rhizoliths were recognized by Balin for the first time in the Old Red Sandstone at this locality. In addition to the features commonly seen in Quaternary calcretes, the Milton Ness horizon preserves some features that are unusual in calcretes of any age. The

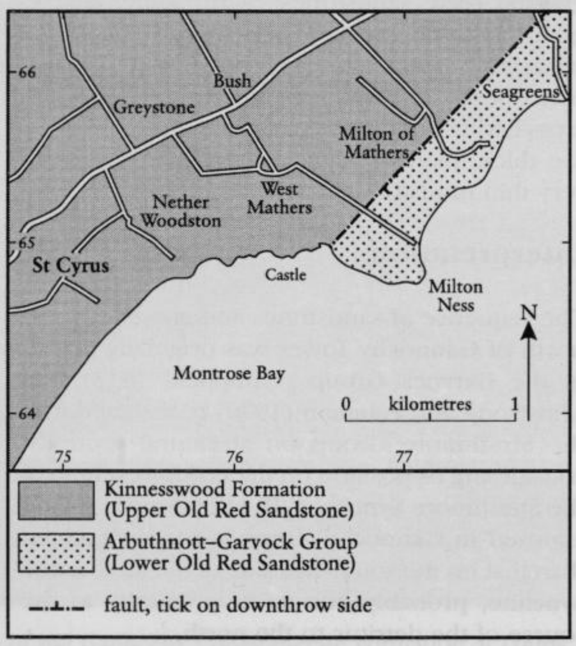



**Figure 3.18** Location and geological map of the Milton Ness area. After Trewin (1987c).

rhizoliths are some of the finest examples seen in Palaeozoic rocks. Mature calcrete development is largely restricted to the Kinnesswood Formation in Scotland, with minor amounts in the Lower Old Red Sandstone of the Orcadian Basin and almost none in the Middle Old Red Sandstone.

## Description

The geology of Milton Ness (NO 766 650–NO 771 648) was described in a field guide by Trewin (1987c). The Upper Old Red Sandstone is down-faulted against Lower Old Red Sandstone lavas and conglomerates by a NE-trending fault at Rock Hall (Figure 3.18). The cliffs from here south-eastwards to Milton Ness expose an interesting succession of mudstones, sandstones, conglomerates and calcretes (Figure 3.19). Trewin (1987c) recognized three fining-upward cycles in the 10 m section. Intraformational conglomerate lenses form the base of the cycles, resting on the underlying scoured surface, locally filling the bases of channels and containing calcrete clasts. Cross-bedded and parallel-bedded sandstones overlying the conglomerates contain sporadic *Beaconites* burrows and calcified root tubules (rhizoliths). The tops of the cycles comprise red siltstones/mudstones with an abundance of carbonate nodules ('cornstone' of the older literature) interpreted as immature calcrete horizons. The nodules at the top of the uppermost cycle (Cycle 3, Figure 3.19) increase in abundance and size upwards and are capped by the laminated, brecciated and karstified calcrete described by Balin (2000).

Balin (2000) noted significant lateral variation in the amount and type of pedogenic alteration throughout the calcrete horizon, but locally,

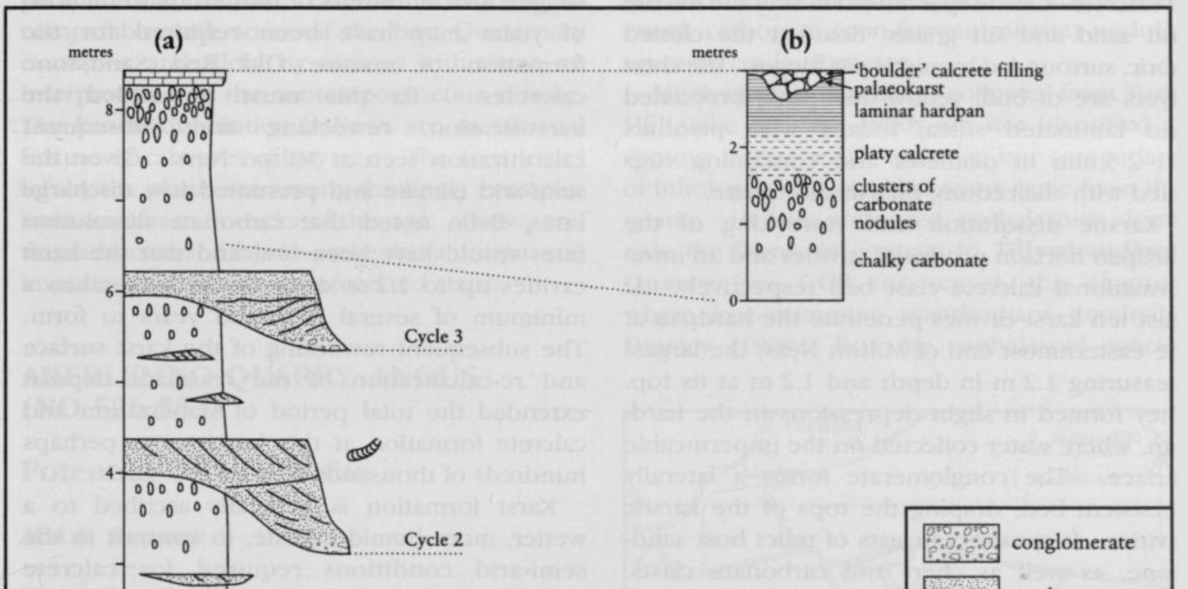



**Figure 3.19** Log of the section at Milton Ness. (a) After Trewin (1987c); (b) idealized calcrete profile after Balin (2000).

development of the profile shows an idealized vertical zonation comprising: upper compact crust or hardpan (70 cm); platy, sheet-like carbonate (70 cm); clusters of carbonate nodules (120 cm); uniformly distributed chalky carbonate (55 cm); unaltered host mudstone. At the eastern end of the outcrop, karst cavities and reworked, intraformational calcrete-clast conglomerate represent additional stages, with a subsequent period of calcretization completing the development of the profile.

The hardpan layer is up to 1.5 m thick at the eastern end of the section, where it crops out as a resistant ledge extending for 150 m and forms the topmost part of a 4 m-thick calcrete profile. It is a brecciated limestone with irregular, sub-horizontal carbonate layers, horizontal, wavy to irregular chert layers and relicts of the original sandstone. Much of the limestone is an irregularly mottled dark and pale grey micrite, the latter grading to microspar, in a 'clotted' fabric typical of calcrete. Calcite spar fenestrae vein the micrite and sand and silt grains 'float' in the clotted fabric, surrounded by microspar fringes. The chert layers are of buff, yellow and pink, brecciated and laminated silica, locally with pisolites 0.1–2.5 mm in diameter and containing vugs filled with chalcedony, quartz and calcite.

Karstic dissolution and reworking of the hardpan horizon produced cavities and an intraformational calcrete clast bed respectively. At least ten karst cavities penetrate the hardpan at the easternmost end of Milton Ness, the largest measuring 1.2 m in depth and 1.2 m at its top. They formed in slight depressions in the hardpan, where water collected on the impermeable surface. The conglomerate forms a laterally persistent bed, draping the tops of the karstic cavities. It consists of clasts of relict host sandstone, as well as chert and carbonate clasts. Abrasion of the small chert pebbles indicates some transport and not in-situ modification of the underlying calcrete. Balin (2000) referred to the bed as a 'boulder calcrete', to denote clasts derived from the break-up of a hardpan calcrete during weathering, although later calcretization of the bed precludes determination of the original clast size.

## Interpretation

The succession at Milton Ness is interpreted as a series of channel deposits built by laterally migrating river systems on an alluvial plain (Trewin, 1987c). Much of the Upper Old Red Sandstone in this part of the Midland Valley represents the distal part of an east-flowing axial drainage system. However, palaeocurrents at Milton Ness and nearby Boddin Point are south-directed, suggesting a tributary system in which the relatively small catchment area would have contributed to the low sedimentation rates necessary for calcrete formation (Balin, 2000).

The presence of calcrete in the finer-grained floodplain deposits points to a hot, semi-arid, seasonally wet climate. The laminated hardpan top to the calcrete at the top of the section represents a maturity (Stage IV of Machette, 1985) very rarely seen in Old Red Sandstone calcretes. Balin (2000) discussed the probable timescale of the horizon's formation, noting that Leeder (1975) proposed a minimum of 10 000 years for calcrete of similar maturity, but that a considerably longer period seems probable. Recent studies (e.g. Marriott and Wright, 2004) suggest that hundreds of thousands to millions of years may have been required for the formation of mature Old Red Sandstone calcretes. To this must be added the karstification, reworking and subsequent calcretization seen at Milton Ness. Given the semi-arid climate and presumed low discharge rates, Balin noted that carbonate dissolution rates would have been low, and that the karst cavities up to 1.2 m deep would have taken a minimum of several thousand years to form. The subsequent reworking of the karst surface and re-calcification of the resultant deposit extended the total period of stabilization and calcrete formation at this horizon, to perhaps hundreds of thousands of years.

Karst formation is generally ascribed to a wetter, more humid climate, in contrast to the semi-arid conditions required for calcrete formation. However, Balin (2000) interprets the Milton Ness example as the result of water collecting in hollows on the impervious hardpan surface under constant semi-arid conditions, possibly with tree-like roots initiating and contributing to the dissolution process.

The presence of rhizoliths in the sandy parts of the alluvial cycles suggests that the environment on the floodplain some distance from the rivers was less hospitable to plant growth because of a low water-table, or that the floodplain mudrocks were impermeable (Balin, 2000). The presence of horizontal, ramifying networks of rhizoliths rather than vertical tap roots points to plant colonization of sandy point bars. The large size of some of the tubules at Milton Ness (over 3 cm) points to relatively large, shrub- or tree-like plants, confirming that plant development was well advanced by Late Devonian times (Balin, 2000). The *Beaconites* trace-fossil burrows were probably made by arthropods that burrowed into the channel sands to escape the arid, dry season conditions (Trewin, 1987c).

## Conclusions

The coast section at Milton Ness provides superb lateral exposure for about 500 m of a mature fossil carbonate soil (calcrete) in the Upper Old Red Sandstone. This is one of the best sections of Old Red Sandstone calcrete in Scotland, and one of very few in the Old Red Sandstone of Great Britain where soil development to a stage of laminated hardpan is recorded. The excellent preservation of the calcrete textures are comparable with some of the best Quaternary examples, and allow, by analogy with these, an interpretation of the contemporaneous climate. The karstic dissolution hollows are an unusual feature of calcretes of any age. The root traces left by the plants are among the finest examples seen anywhere in rocks of this age. These, and the carbonate soil fabrics make this a unique and important site worthy of protected status.

# ABERLEMNO QUARRY, ANGUS (NO 526 551)

## Potential ORS GCR site

***M.A.E. Browne***

## Introduction

Aberlemno Quarry is one of a number of quarries (including Tillywhandland Quarry) worked on and around Turin Hill near Forfar, Angus for Arbroath Paving Stone during the eighteenth and nineteenth centuries (Mackie, 1980). Of these, Aberlemno Quarry and Clocksbriggs (or Wemyss) Quarry are well-known fossil plant localities, and Aberlemno is (as 'Turin Hill') already a confirmed GCR site for its Palaeozoic palaeobotany (Cleal and Thomas, 1995) and for its fossil osteostracan fish fauna (Dineley and Metcalf, 1999).

## Description

Descriptions of the quarry were provided by Armstrong *et al.* (1978b), Cleal and Thomas (1995) and Dineley (1999c). It lies on the north-east flank of Turin Hill, forming an elongate entrenchment alongside a minor road (Figure 3.20). About 9.5 m of strata belonging to the Dundee Flagstone Formation and the overlying Scone Sandstone Formation (both of the Arbuthnott–Garvock Group) are exposed (Figures 3.21, 3.22). The succession exposed in a 300 m-long face is remarkably persistent laterally and comprises about 7.5 m of red-brown, medium- to coarse-grained, trough cross-bedded sandstones (Melgund Sandstone Member of the Scone Sandstone Formation) overlying about 2 m of fish-bearing, fine-grained sandstones and greyish green, fissile, laminated siltstones and mudstones (Dundee Flagstone Formation). The latter show much syn-sedimentary deformation and contain many ovoid, carbonate (non-ferroan micrite) nodules up to 30 cm in diameter.

Much of the fish remains collected from Turin Hill since the late 1800s are not identified as coming from specific quarries, but comparison of lithologies suggests that many came from this quarry. Heavily armoured cephalaspids dominate the fauna, in contrast to **Tillywhandland Quarry** (see GCR site report, this chapter) where free-swimming acanthodians dominate. Dineley (1999c) lists the cephalaspid species

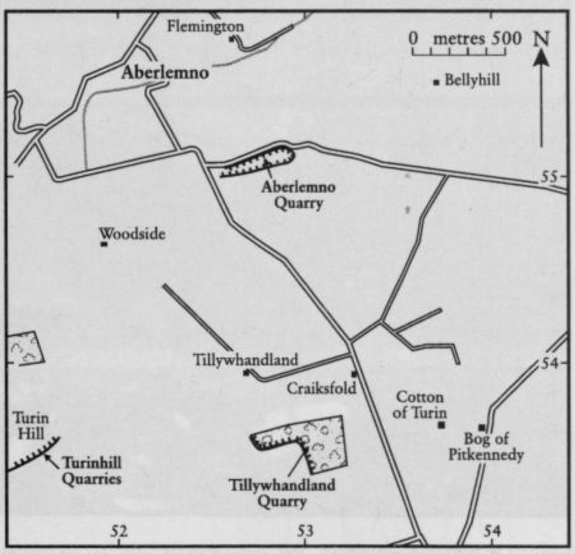



**Figure 3.20** Locations of Aberlemno, Tillywhandland and Turin Hill quarries

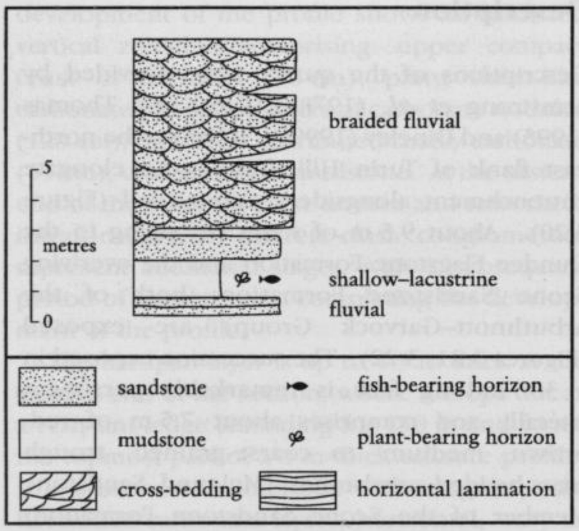



**Figure 3.21** Section of Aberlemno Quarry. Based on Dineley (1999c) and Armstrong *et al.* (1978b).

that are most likely to have been collected from Aberlemno, but only *Cephalaspis pagei* is definitely attributed to the quarry. Acanthodian spines have been recorded, as well as the arthropod *Dictyocaris* and the eurypterids *Pterygotus* and *Erieopterus*.

The fossil plants in the basal laminated beds are particularly renowned and belong to the *Zosterophyllum* Zone of Banks (1980). Cleal and Thomas (1995) described them in detail. The commonest are impressions picked out by iron staining, but some coalified compressions and petrifactions also occur. *Prototaxites forfarensis*, *Parka decipiens*, *Pachytheca* sp., *Cooksonia caledonica* and *Zosterophyllum myretonianum* have been identified. Most significant are the well-preserved specimens of the alga or early land-plant *Parka*, the early vascular plant *Zosterophyllum* and the holotype of *Cooksonia caledonica*.

**Figure 3.22** Aberlemno Quarry. Strike section in flaggy sandstones of the Dundee Flagstone Formation. (Photo: C.J. Cleal.)

## Interpretation

The laminated beds at the base of the quarry were interpreted by Armstrong *et al*. (1978b) as the deposits of a shallow lake. The overlying sandstones of the Scone Sandstone Formation have a varied internal geometry consistent with deposition in a braided stream complex flowing to the west, and probably marking a switch from small local drainage systems to a larger regional one (Bluck, 2000). The switch was diachronous and transitional, the uppermost part of the Dundee Flagstone Formation interdigitating with the lowermost part of the Scone Sandstone Formation. This may have been due to blocking of local drainage by lava flows and the establishment of shallow lakes.

Armstrong and Paterson (1970) correlated the Aberlemno fish bed with No. iv of the eight (i to viii) fossil fish horizons they identified in the Arbuthnott–Garvock Group; five beds (i–v) lie in the Dundee Flagstone Formation. The flora recorded from the Arbuthnott–Garvock Group belong to the *Zosterophyllum* Zone (Banks, 1980) and suggest a Gedinnian (Lochkovian) or early Siegenian (Pragian) age (Edwards, 1980; Edwards and Fanning, 1985). Palynological and fish evidence supports an early Gedinnian age (Edwards, 1980; Edwards and Fanning, 1985). The fish and eurypterids indicate an age not older than the base of the Dittonian of the Anglo-Welsh Basin (Westoll, 1977). Richardson *et al*. (1984) correlated the Aberlemno horizon with the middle subzone of the *micrornatus-newportensis* Zone (= Lochkovian Stage) of the Anglo-Welsh Basin. A radiometric age of 407 ± 6 Ma was determined by Thirlwall (1983) for the lower part of the Arbuthnott–Garvock Group.

## Conclusions

Aberlemno Quarry is of international importance for its fossil plant flora, having yielded one of the best *Zosterophyllum* Zone assemblages in the world. It is also important in being one of the two quarries on Turin Hill (the other being **Tillywhandland Quarry**) that remain open. A rich fossil fish fauna is dominated by the armoured cephalaspids, in contrast to the free-swimming acanthodians that dominate the fauna at Tillywhandland. The site's conservation value lies in providing an opportunity for further excavation and collection of its fauna and flora.

# TILLYWHANDLAND QUARRY, ANGUS (NO 528 537)

## Potential ORS GCR site

***M.A.E. Browne***

## Introduction

Tillywhandland Quarry on Turin Hill near Forfar (Figure 3.23) is one of the best Early Devonian fossil fish sites in Scotland; it is an established GCR site for fossil fishes (Dineley and Metcalf, 1999). The site also provides a reference section for the Dundee Flagstone Formation, allows the detailed examination of the lithofacies and sedimentation of a typical Early Devonian fish bed, and is unique in the Midland Valley in exposing a clastic–carbonate–organic laminite similar to those of the Mid-Devonian Orcadian Basin. Trewin and Davidson (1996) provided a detailed description of the quarry, summarized by Dineley (1999c). The fauna includes a rich assemblage of primitive acanthodians, with some cephalaspids, collected from this and other quarries on Turin Hill, which worked the sandstones of the Dundee Flagstone Formation for over 200 years. Richardson and MacGregor (1986) ascribed the beds to the *micrornatus-newportensis* Zone of early Lockhovian age.

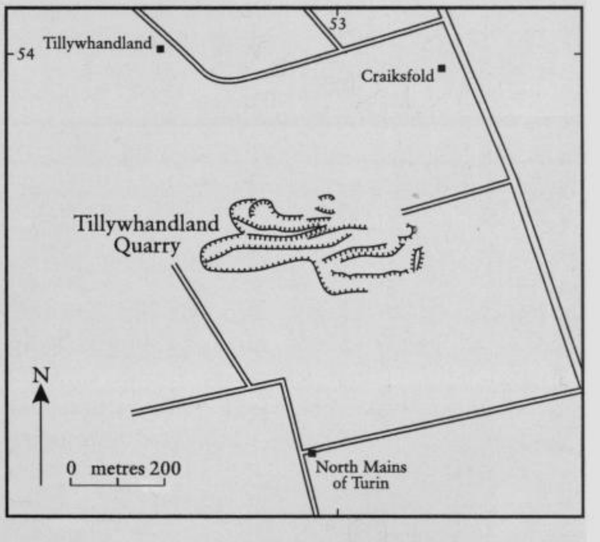



**Figure 3.23** Location of Tillywhandland Quarry, Angus.

## Description

Tillywhandland Quarry exposes beds of the Dundee Flagstone Formation (of the Arbuthnott–Garvock Group). Working probably ceased over 100 years ago and the quarry at the time of writing was overgrown. The Dundee Flagstone Formation consists mainly of medium- to coarse-grained, cross-bedded, fluvial sandstones. Numerous distinctive deltaic and lacustrine units up to 30 m thick of thinly bedded sandstones and intercalated siltstones and mudstones are particularly characteristic of the formation. They include a number of fish beds, including the one exposed in this quarry, that have also yielded arthropods and plant remains (Lang, 1927; Westoll, 1951).

The quarry exposes a fish-bearing laminite (Figure 3.24) and underlying sandstone, having worked the latter for building stone. Powrie (1861, 1864) first described the laminite (the Forfarshire Fish Bed), considering it to be the only such horizon and correlating it with similar occurrences elsewhere. However, later workers (Hickling, 1912; Armstrong and Paterson, 1970) envisaged several discrete beds. Armstrong *et al.* (1978b) provided a brief description of the quarry. Trewin and Davidson (1996) recorded a detailed section of the fish bed and adjacent strata (Figure 3.25), and the following account is a summary of their work. Dineley's (1999c) summary emphasizes the fish fauna and its palaeoecology, Wilson and Anderson (2004) describe the invertebrate fauna.

About 3 m of red to pale brown, medium- to coarse-grained sandstone are exposed beneath the fish bed. The lowest beds exposed are massive and trough cross-bedded in sets up to 0.5 m thick, with two pebble-lined erosion surfaces. The massive sandstones contain scattered pebbles and soft-sediment de-watering structures. The topmost 1 m of sandstone are parallel-laminated with primary current lineation. Sandstone dykes penetrate up to 0.5 m into the overlying laminite; they are up to 0.1 m wide at their base and folded by soft-sediment compaction. The fish-bearing laminite has a sharp contact with the underlying sandstone, is about 1.3 m thick and contains a 60 mm-thick pale green to buff, sticky bentonitic clay 1 m above its base. The laminites comprise a stacked sequence of repeated quadruplets of clastic siltstone, carbonate, organic matter, and green claystone averaging about 5 mm in thickness.

**Figure 3.24** Part of Tillywhandland Quarry, showing lacustrine laminites. (Photo: M.A.E. Browne.)

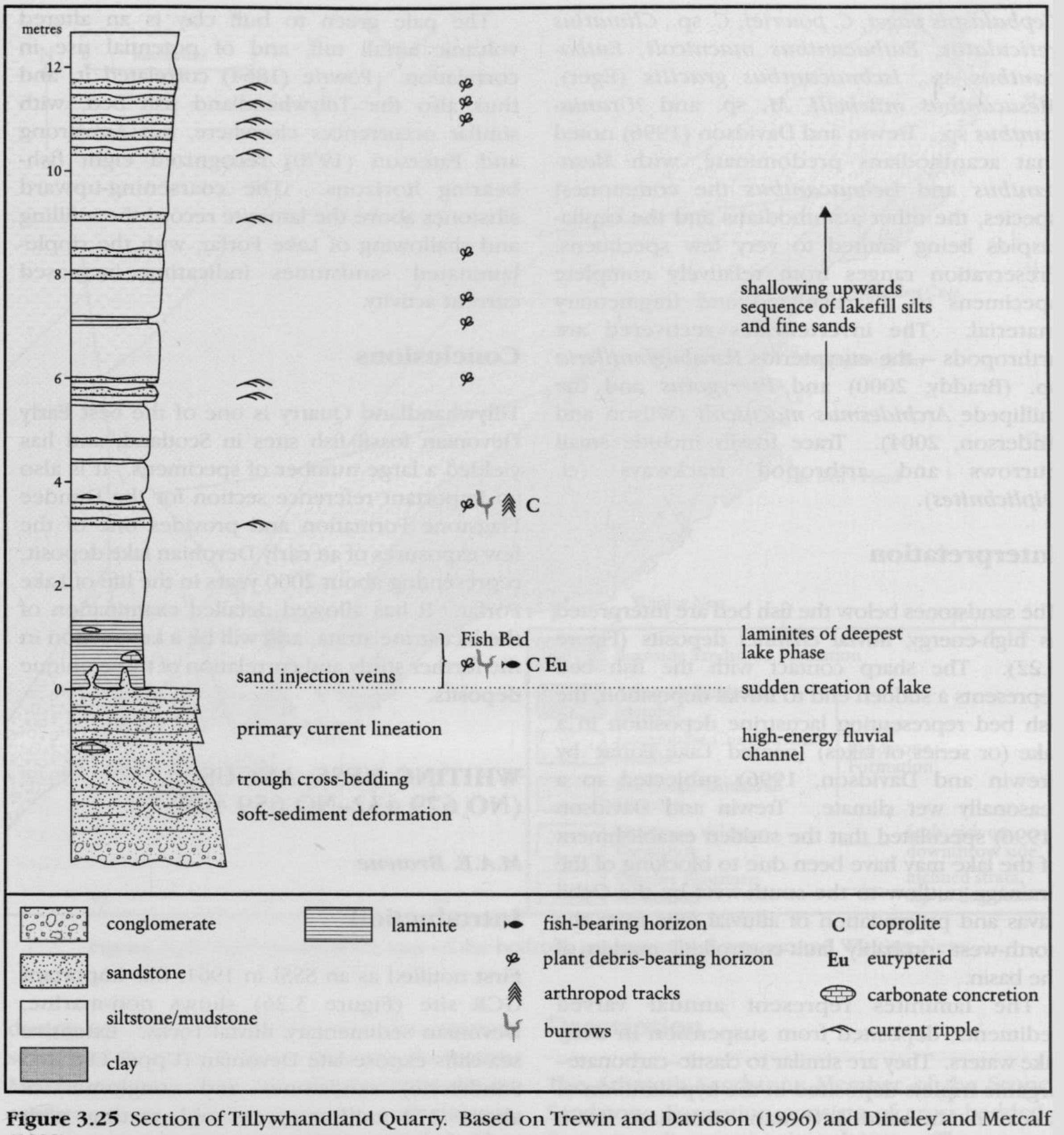



**Figure 3.25** Section of Tillywhandland Quarry. Based on Trewin and Davidson (1996) and Dineley and Metcalf (1999).

Their colour varies from brown to green depending on the proportion of green claystone laminae present and the amount of carbonate and organic matter. Soft-sediment deformation produced folding and slide planes locally and there are some carbonate concretions. A very thin (0.01 mm) organic lamina commonly overlies the carbonate laminae and contains most of the fish fragments, with a few remains occurring also in the carbonate concretions. Coprolites appear to be concentrated in the organic-rich laminae and the finest laminae. The laminite grades upwards into green siltstones, which contain minor laminites with a few organic laminae. The sequence coarsens upwards generally to coarse siltstone–fine sandstone, with thin (up to 20 cm) sheets of fine-grained, muddy, current ripple-laminated sandstone that are commonly rich in plant debris.

Dineley (1999c) gave full details and classifications of the fish fauna recovered from the site. It comprises *?Brachyacanthus scutiger*, *Cephalaspis pagei*, *C. powriei*, *C.* sp., *Climatius reticulatus*, *Euthacanthus macnicoli*, *Euthacanthus* sp., *Ischnacanthus gracilis* (Eger), *Mesacanthus mitchelli*, *M.* sp. and ?*Uraniacanthus* sp.. Trewin and Davidson (1996) noted that acanthodians predominate, with *Mesacanthus* and *Ischnacanthus* the commonest species, the other acanthodians and the cephalaspids being limited to very few specimens. Preservation ranges from relatively complete specimens to disarticulated and fragmentary material. The invertebrates recovered are arthropods – the eurypterids *Parahughmilleria* sp. (Braddy, 2000) and *Pterygotus* and the millipede *Archidesmus macnicoli* (Wilson and Anderson, 2004). Trace fossils include small burrows and arthropod trackways (cf. *Diplichnites*).

## Interpretation

The sandstones below the fish bed are interpreted as high-energy, fluvial channel deposits (Figure 3.22). The sharp contact with the fish bed represents a sudden end to fluvial deposition, the fish bed representing lacustrine deposition in a lake (or series of lakes) (named 'Lake Forfar' by Trewin and Davidson, 1996) subjected to a seasonally wet climate. Trewin and Davidson (1996) speculated that the sudden establishment of the lake may have been due to blocking of the drainage outflow to the south-west by the Ochil Lavas and progradation of alluvial fans from the north-west, probably fault-controlled, margin of the basin.

The laminites represent annual varved sediments, deposited from suspension in deep lake waters. They are similar to clastic–carbonate–organic triplets deposited in the hypolimnion of lakes in the Mid-Devonian Orcadian Basin (Donovan, 1980; Trewin, 1986), except that the green claystone laminae have not been seen in the Orcadian Basin and the dolomite laminae present there are absent in Lake Forfar. A period of about 2000 years is represented by the Tillywhandland laminite. The origin of the coarser laminae, whether by aeolian or distant fluvial input to the lake, remains unclear. The carbonate laminae were precipitated as a result of phytoplankton photosynthetic activity, the organic laminae were the product of seasonal decay of the phytoplankton, which settled on the lake bed to produce an organic sludge and the most anoxic bottom conditions.

The pale green to buff clay is an altered volcanic airfall tuff, and of potential use in correlation. Powrie (1864) correlated it, and thus also the Tillywhandland fish bed, with similar occurrences elsewhere, but Armstrong and Paterson (1970) recognized eight fish-bearing horizons. The coarsening-upward siltstones above the laminite record the infilling and shallowing of Lake Forfar, with the ripple-laminated sandstones indicating increased current activity.

## Conclusions

Tillywhandland Quarry is one of the best Early Devonian fossil fish sites in Scotland, and has yielded a large number of specimens. It is also an important reference section for the Dundee Flagstone Formation and provides one of the few exposures of an early Devonian lake deposit, representing about 2000 years in the life of Lake Forfar. It has allowed detailed examination of the lacustrine strata, and will be a key section in the further study and correlation of these unique deposits.

# WHITING NESS, ANGUS (NO 679 432–NO 659 409)

*M.A.E. Browne*

## Introduction

First notified as an SSSI in 1961, this important GCR site (Figure 3.26) shows non-marine, Devonian sedimentary fluvial rocks. Extensive sea-cliffs expose late Devonian (Upper Old Red Sandstone) sandstones and conglomerates about 370 million years old resting with irregular unconformity on early Devonian (Lower Old Red Sandstone) sandstones about 410 million years old belonging to the Scone Sandstone Formation of the Arbuthnott–Garvock Group. The site shows the contrast between the far-travelled, early Devonian sandy alluvium and the locally derived pebbles in the late Devonian rocks. The basal breccias of the Upper Old Red Sandstone contain combinations of bedding types that show the control of topography of the underlying unconformable surface on braided stream morphology. The site is important in demonstrating that the Old Red Sandstone of the Midland Valley was formed

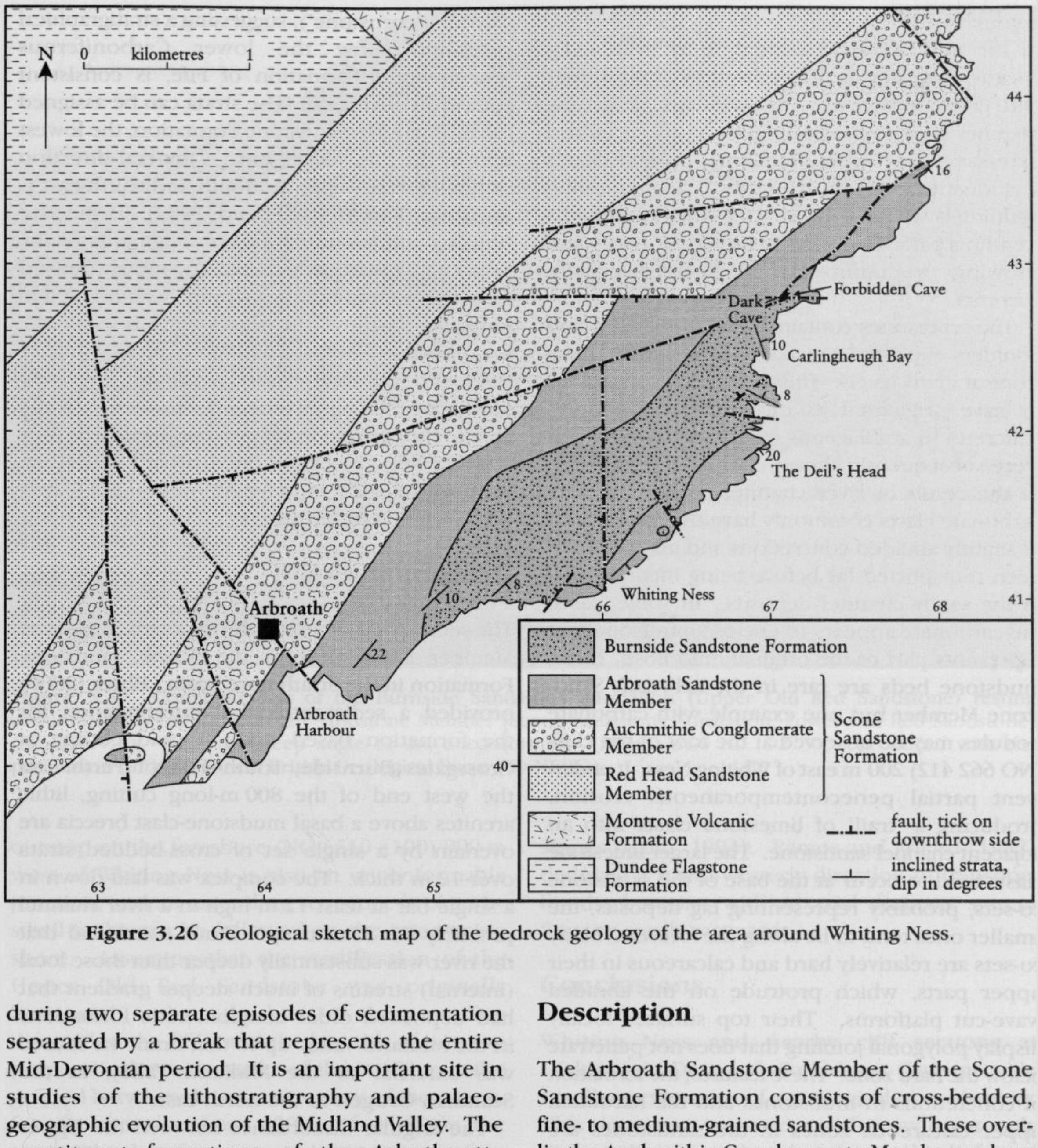



**Figure 3.26** Geological sketch map of the bedrock geology of the area around Whiting Ness.

during two separate episodes of sedimentation separated by a break that represents the entire Mid-Devonian period. It is an important site in studies of the lithostratigraphy and palaeogeographic evolution of the Midland Valley. The constituent formations of the Arbuthnott–Garvock Group consist mainly of cross-bedded sandstones. These contain clasts of metamorphic and igneous rocks, as well as soil carbonate (calcrete) clasts of intrabasinal origin (cf. Balin, 2000; see **Milton Ness** GCR site report, this chapter), which are especially characteristic of the upper part of the group. There are interbedded conglomerates in the Arbroath area, and the topmost unit in Strathmore (the Scone Sandstone Formation) contains a persistent conglomeratic horizon with lenticular beds of nodular calcrete.

## Description

The Arbroath Sandstone Member of the Scone Sandstone Formation consists of cross-bedded, fine- to medium-grained sandstones. These overlie the Auchmithie Conglomerate Member and are the youngest known strata of early Devonian age on the south-east limb of the Sidlaw Anticline. Named by Hickling (1908) and given formational status by Armstrong and Paterson (1970), the Arbroath Sandstone is now accorded member status (Browne *et al.*, 2002). It is at least 365 m thick, and consists of bright purple-red sandstones on the coast near Arbroath, where it is overlain with marked unconformity by the Upper Old Red Sandstone. Near Carnoustie, however, 3 km to the south-west, the sandstones are generally green or purplish grey. The red colour at Arbroath may be due to the proximity of the mid-Devonian unconformity, with deep weathering prior to the deposition of the Upper Old Red Sandstone. The Arbroath Sandstone Member dips to the south-east at about 20° on extensive wave-cut platforms north-east of Carnoustie and at Arbroath. Trough-cross-bedding is well displayed, with elongate troughs trending parallel to the strike of the rocks and showing predominantly SW-directed palaeocurrents.

The sandstones contain abundant pebbles and boulders (up to 0.3 m across) of nodular limestone at many levels. These clasts are considered to have originated as carbonate soil nodules (calcrete) in argillaceous overbank deposits that were subsequently almost completely destroyed as the result of river channel migration. The carbonate clasts commonly have the appearance of slightly abraded concretions and may not have been transported far before being incorporated in the sandy channel deposits. In some clasts, the carbonate appears to enclose mudstone that represents part of the original mud host. Intact mudstone beds are rare in the Arbroath Sandstone Member but one example with carbonate nodules may be observed at the foot of the cliffs (NO 662 412) 200 m east of Whiting Ness. It underwent partial penecontemporaneous erosion, producing a 'trail' of limestone clasts into an adjacent channel sandstone. The larger limestone clasts tend to occur at the base of the sandstone co-sets, probably representing lag deposits, the smaller ones tend to lie along the foresets. Many co-sets are relatively hard and calcareous in their upper parts, which protrude on the abraded wave-cut platforms. Their top surfaces locally display polygonal jointing that does not penetrate below the hard zone. These features, the formation of concretions in mudstones and the hardened upper calcareous zones in the sandstones are attributed to pedogenic processes in response to fluctuations in water-table levels.

East of Arbroath, in the general neighbourhood of Whiting Ness, a sequence of mainly red-brown and yellow conglomerates with subordinate sandstone beds and basal and marginal breccias rests with striking unconformity on the Arbroath Sandstone Member (Figure 3.27; Hickling, 1908). These beds are unfossiliferous, but the sandstones resemble those in the fossiliferous Late Devonian Stratheden Group in Stratheden and the Carse of Gowrie, and a Late Devonian age seems probable. The absence of calcrete ('cornstone'), suggesting a stratigraphical position below the lower Carboniferous Kinnesswood Formation of Fife, is consistent with this conclusion. The strata can be assigned to the Burnside Sandstone Formation, the lowest unit in the Fife succession. A general direction of transport towards the south and south-east is apparent (Ramos and Friend, 1982). Distinctive breccias composed of angular fragments of the Arbroath Sandstone Member, and clearly derived from the ancient bedrock slopes, accumulated in lenticular bodies. In places they rest on the unconformity, but elsewhere occur at a higher level and are intercalated with the overlying sandstones, or fill channels cut in them. In the area of the Steeple Rock (NO 6585 4095) SSW of Whiting Ness, blocks of the Arbroath Sandstone Member up to 2.5 m in length occur immediately above the unconformity.

## Interpretation

The sedimentary rocks of the Arbroath Sandstone Member are typical of the Scone Sandstone Formation in the Strathmore Basin. Bluck (2000) provided a sedimentological interpretation for the formation based upon a road cutting at Crossgates–Burnside, south-west of Perth. At the west end of the 800 m-long cutting, lithic arenites above a basal mudstone-clast breccia are overlain by a single set of cross-bedded strata over 12 m thick. The complex was laid down in a single bar at least 12 m high in a river channel probably 15–20 m deep. Bluck concluded that the river was substantially deeper than those local (internal) streams of much steeper gradient that had deposited older conglomeratic formations in the Midland Valley up to that time. Its source was external to the Midland Valley, in the Scandian Orogen to the north-east.

The angular discordance between the Upper and Lower Old Red Sandstone strata at Whiting Ness is marked. The Lower Old Red Sandstone dips south-east at about 25°, whereas the Upper Old Red Sandstone dips approximately ESE at 10°. The latter was deposited against steep slopes forming part of the sub-late Devonian land surface, as can be seen in the cliffs (NO 6510 4100) on the east side of the Horse Shoe east of Whiting Ness. It is probable, however, that the palaeorelief of the unconformity seen in the irregular surface near Whiting Ness is small compared to that elsewhere in this area. The western limit of the Upper Old Red Sandstone

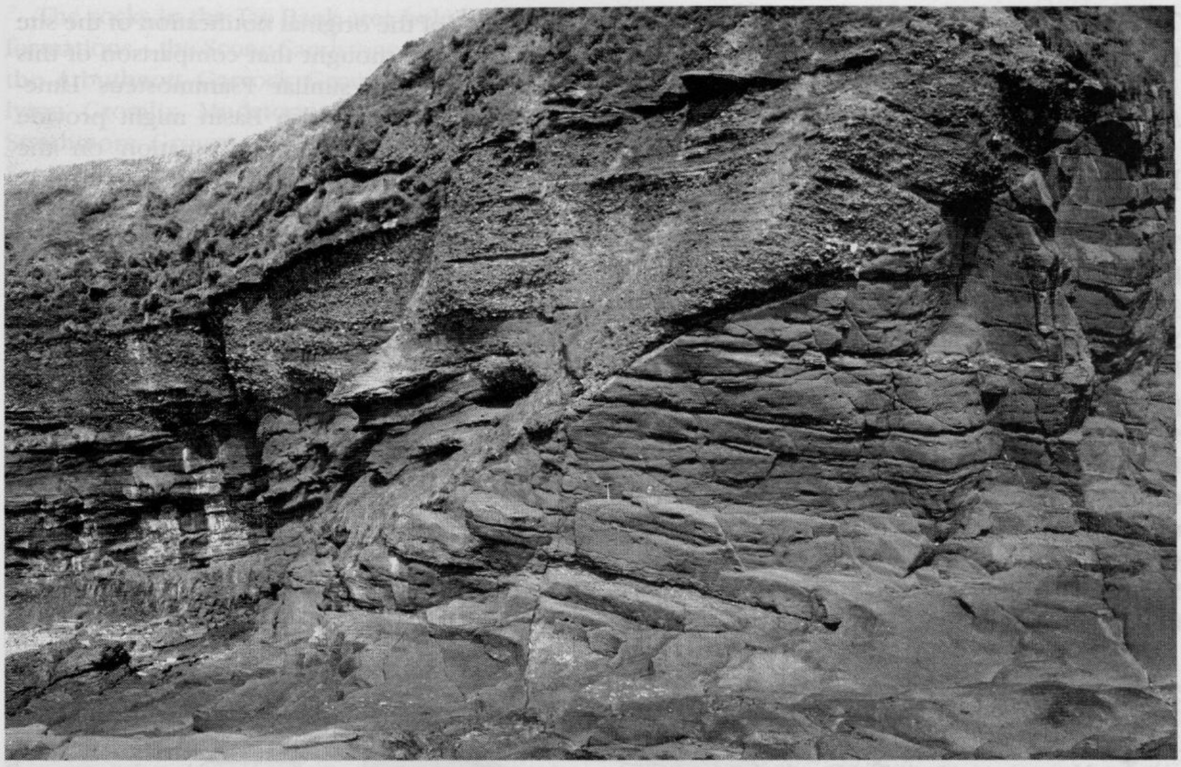


**Figure 3.27** Conglomerates of the Burnside Sandstone Formation (Upper Old Red Sandstone) resting unconformably on the Arbroath Sandstone Member (Scone Sandstone Formation; Lower Old Red Sandstone) (NO 660 412). Note the steep angle of the unconformity. (Photo: BGS No. D2730, reproduced with the permission of the Director, British Geological Survey, © NERC.)

outcrop on the foreshore (NO 6510 4100) 900 m west of Whiting Ness is also an unconformable junction, and an ascending sequence broken by small faults can be followed on the intervening shore. Assuming that the stratification of the Upper Old Red Sandstone was originally horizontal, and on the basis of the prevailing dip (10° to the ESE) and the breadth of outcrop perpendicular to the strike of about 450 m in the ground between the two exposures of the unconformity, there is about 100 m of relief on the ancient land surface.

Most of the Upper Old Red Sandstone sediments appear to have accumulated in braided channels as lateral bars in the active part of an alluvial plain covered with sand and gravel. White, flat-bedded, fine-to medium-grained sandstones of sheet-flood type were laid down preferentially in topographically protected areas close to the steeper slopes on the surface of the unconformity near Whiting Ness (Ramos and Friend, 1982). Steep-sided gullies up to 1.5 m deep cutting into these beds are mostly filled with breccia derived from the adjacent steep slopes (Balin, 1993). Ramos and Friend (1982) deduced a south-westerly direction of transport for the breccias, with an axial drainage system flowing south-eastwards.

## Conclusions

Whiting Ness and nearby cliff sections at Dickmont's Den and Forbidden Cave provide excellent exposures of a geological unconformity. This represents an ancient surface with a steeply dissected topography; the observed relief is of the order of 6 m, but is calculated to reach 100 m locally. The sections also show indurated braided river deposits of the Arbroath Sandstone Member that were uplifted, weathered and eroded in a semi-arid climate during mid-Devonian earth movements. Tropical weathering at that time probably caused the reddening of the strata. The overlying Burnside Sandstone Formation was mainly laid down by braided rivers flowing south and south-east, but contains breccias that were deposited by streams flowing south-west at the basin margin.

## TAY BANK, PERTH AND KINROSS (NO 125 328)

***M.A.E. Browne and W.J. Barclay***

### Introduction

This important site on the east bank of a meander loop of the River Tay south of Campsie (Figure 3.28) exposes Early Devonian (Lower Old Red Sandstone) sedimentary rocks and concretionary limestones of pedogenic origin (calcretes). It provides the type section of the Campsie Limestone Member and the best exposure of the Stanley Limestone, a group of calcretes in this member named from this locality. A concentration of mature calcrete soil profiles is developed at this stratigraphical level across the Midland Valley of Scotland, marking a period of river downcutting, floodplain stability and reduced sedimentation.

At the time of the original notification of the site in 1976, it was thought that comparison of this horizon with the similar Psammosteus Limestone in the Anglo-Welsh Basin might provide regional correlation and information on the climatic evolution of the British Isles during early Devonian times. The Stanley Limestone is, however, younger and may correlate with the Abdon limestones of the Anglo-Welsh Basin.

### Description

The Lower Old Red Sandstone of the Strathmore region was described by Armstrong and Paterson (1970) and a compiled section of the rocks exposed in the river bed and both banks at the Tay Bank site was given by Armstrong *et al.* (1985). The lithostratigraphical classification of the succession was revised recently by Browne *et al.* (2002).

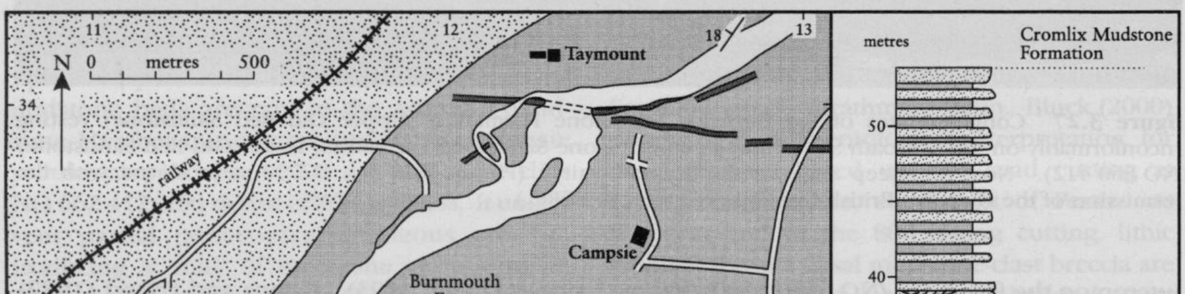



**Figure 3.28** Geological sketch map of the area around the Tay Bank section and log of the Campsie Limestone Member exposed. After Armstrong *et al.* (1985).

The rocks in the Tay Bank area belong to two formations – the Scone Sandstone Formation (of the Arbuthnott–Garvock Group) and the overlying Cromlix Mudstone Formation (of the Strathmore Group). The 2000 m-thick Scone Sandstone Formation consists largely of grey, yellow, brown, red, purplish and red-brown, medium- to coarse-grained, cross-bedded, arkosic to lithic sandstones characteristically containing intraformational mudstone and limestone clasts. Pebbles of metasedimentary and volcanic rocks are also present. Reddish brown or greenish grey silty mudstone and siltstone occur as impersistent interbeds, some more than 0.5 m thick. Pale grey, fine-grained limestone of pedogenic origin occurs as thin, lenticular beds, but more abundantly as reworked clasts, throughout the formation. Lava flows occur locally, as around Laurencekirk and west of Perth.

The Campsie Limestone Member forms the topmost part of the Scone Sandstone Formation. It is characterized by mature calcrete beds (the Stanley Limestone and equivalent Pittendriech Limestone) and conglomerates with intraformational and exotic clasts.

The Cromlix Mudstone Formation consists predominantly of bright red to brownish red, purplish brown and green, poorly sorted, soft, sandy and silty mudstones and siltstones. There are minor, poorly sorted, very fine-grained, argillaceous sandstones, and all of the mudstones and sandstones contain green reduction spots. The beds are typically massive and appear blocky as a result of pervasive fracturing, although weak planar bedding is common. Also present are thin beds of medium- to coarse-grained sandstone, and conglomerate sheets that pass into localized, very thick alluvial-fan bodies.

The Campsie Limestone Member, including the Stanley Limestone (Figure 3.29), is exposed on the banks of an incised meander in the River Tay just east of the village of Stanley (Figure 3.28). The strata lie on the north-west limb of an anticlinal inlier affected by minor NW-trending faults, the exposed beds dipping mainly about 20° to the north-west. The strata are accessible on the banks of the river, and in its bed when the water-level is low. The section compiled from the exposures by Armstrong *et al.* (1985) is shown graphically in Figure 3.28. The lowermost beds of the Campsie Limestone Member, including conglomerates, sandstones and calcretes (the Stanley Limestone), are best seen

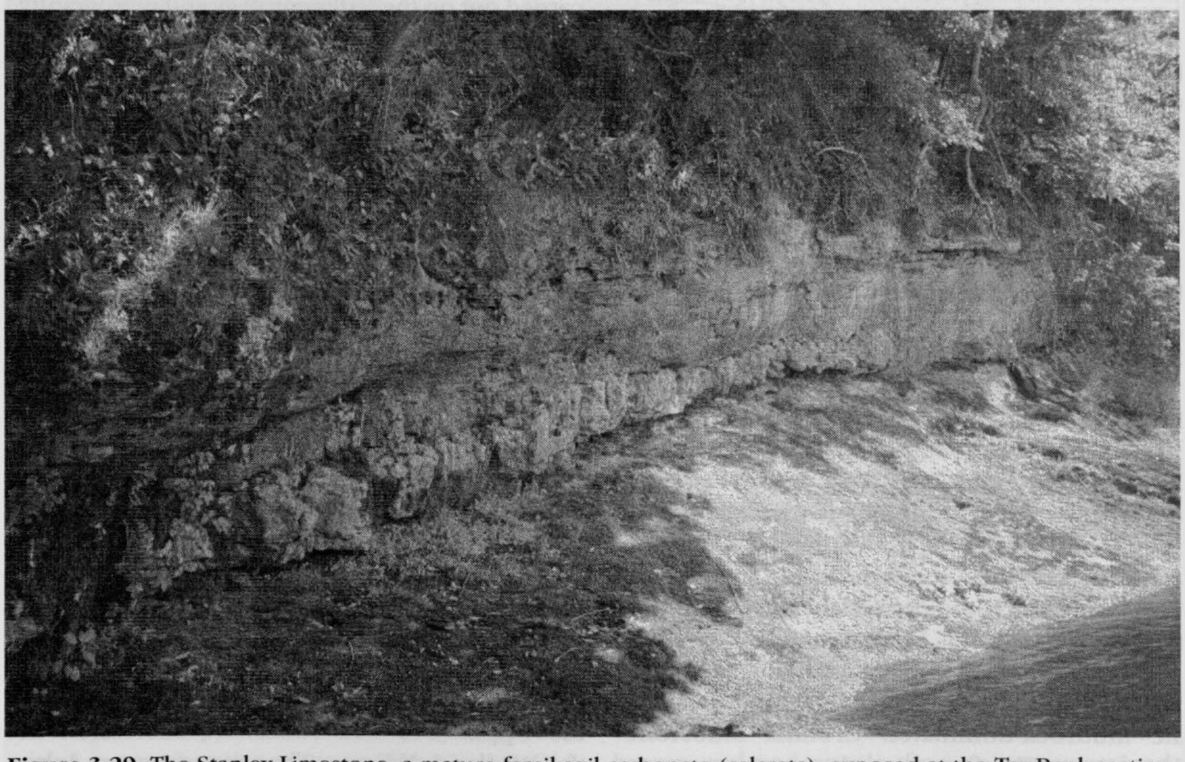


**Figure 3.29** The Stanley Limestone, a mature fossil soil carbonate (calcrete), exposed at the Tay Bank section. (Photo: M.A.E. Browne.)

in the river bed and in the east bank (NO 124 327). The clasts in the 7.5 m-thick conglomerate at the base of the Campsie Limestone Member include quartzite, felstone, greenstone, porphyrite, syenite and jasper (Armstrong *et al.*, 1985; J. Geikie, unpublished data). Geikie recognized a southerly direction of transport of the sediments based on imbrication of the clasts. The calcretes mainly occur in sandstone host rock, and are fine-grained, white, pale grey, pale greenish grey and pink, nodular limestones.

The uppermost beds of the Campsie Limestone Member, comprising intercalated sandstones and mudstones, dip below the basal beds of the Cromlix Mudstone Formation and are best seen on the west bank below Inchbervis Castle (NO 120 328). On the north side of the peninsula made by the meander loop, the basal argillaceous strata of the Cromlix Mudstone Formation are exposed along the river bank for about 500 m upstream of their junction with the Campsie Limestone Member. About 200 m from the junction, the mudstones are cut by a 0.5 m-wide, ENE-trending basaltic dyke, and thin, irregular basaltic intrusions up to 0.3 m thick occur a little farther east.

## Interpretation

The sandstones of the Scone Sandstone Formation were deposited in a SW-flowing river system and are characterized by the presence of intraformational limestone clasts. The carbonate formed as concretionary soil (calcrete) nodules in floodplain silts and muds, reflecting a hot, seasonally wet, semi-arid climate appropriate to a location 10–20° south of the equator (Balin, 1993, 2000). Penecontemporaneous reworking of the floodplain deposits in migrating channels released the resistant carbonate nodules to become incorporated in the sandstones as clasts. However, the Campsie Limestone Member is rare in that the nodules and beds of calcrete in a horizon about 20 m thick largely escaped reworking, except for one or two conglomerate beds. Armstrong *et al.* (1978b) suggested that the calcretes formed during prolonged weathering when the previously well-developed axial river system was bypassed.

Further evidence of significant change in the basin's dispersal systems lies in the switch to the mudrock-dominated Cromlix Mudstone Formation. The formation does not appear to have been subjected to appreciable fluvial reworking (Armstrong *et al.*, 1978b). However, Phillips and Aitken (1998) suggested that the typical structureless silty mudstones in the formation are comparable with aeolian clay pellet deposits formed in landlocked basins in arid and semi-arid parts of south-east Australia (Dare-Edwards, 1984; Yang, 1997; Gibling *et al.*, 1998). The pellets form as pedogenic mud and silt aggregates in arid to semi-arid desert environments and are blown and deposited by winds.

## Conclusions

This site is important in providing the best section of the Stanley Limestone and the type section of the Campsie Limestone Member, a regional marker horizon that defines the boundary between the Arbuthnott–Garvock and Strathmore groups. The Stanley Limestone is a concentration of carbonate soil (calcrete) profiles that developed at this stratigraphical level across the Midland Valley of Scotland. The soils represent shut-down of the basin and mark an important change in sedimentation patterns, the earlier river systems being replaced by predominantly arid to semi-arid floodplain environments. Little detailed work has been carried out on the sedimentology and petrography of the rocks at this site and further study is warranted.

# GLEN VALE, FIFE (NO 171 068–NO 195 072)

## Potential GCR site

*M.A.E. Browne and W.J. Barclay*

## Introduction

The stream sections and crag exposures in the Glen Vale area, Fife and Kinross (Figure 3.30), are reommended for the GCR for the Upper Old Red Sandstone windblown (aeolian) facies sandstones that are exposed. The importance of these sandstones, which belong to the Upper Devonian Knox Pulpit Sandstone Formation (of the Stratheden Group), lies in their aeolian origin, in contrast to the fluvial origin of most of the Upper Old Red Sandstone succession in the Midland Valley. The exposures at John Knox's Pulpit (NO 1891 0582) and Dow Craig

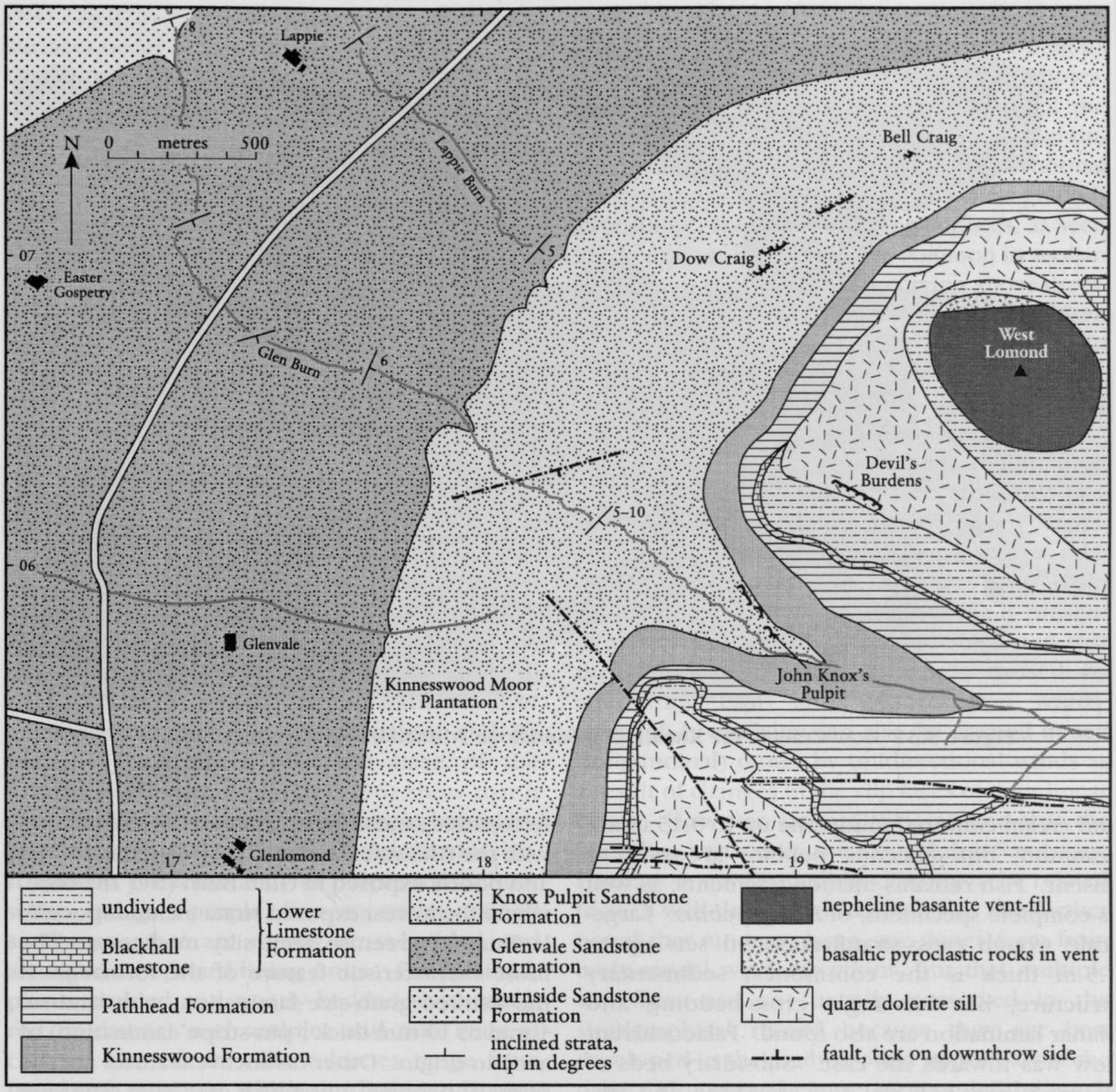



**Figure 3.30** Geological map of the Glen Vale area showing limits of the potential GCR site.

(NO 1892 0702) (Figure 3.31) allow a three-dimensional study of many of the key sedimentological features of the formation. In the Glen Vale area, the Upper Old Red Sandstone succession comprises, in ascending order, the Burnside Sandstone, Glenvale Sandstone and Knox Pulpit Sandstone formations. The site thus allows the aeolian facies rocks to be placed in stratigraphical context, between the underlying Glenvale Sandstone Formation and the overlying lower Carboniferous Kinnesswood Formation (of the Inverclyde Group). Chisholm and Dean (1974) gave a comprehensive account of the Upper Old Red Sandstone succession in the area. Although they noted that an aeolian origin could not be discounted for the Knox Pulpit Sandstone Formation, these authors favoured a shallow marine origin. Subsequently, an aeolian origin was recognized (McAlpine, 1978; Mader and Yardley, 1985; Hall and Chisholm, 1987).

## Description

The lowermost beds within the proposed site boundary belong to the Glenvale Sandstone Formation. This consists of white, yellow, brown, red and purple, fine- to coarse-grained, feldspathic sandstones. Clasts of red, green

**Figure 3.31** Dow Craig in the Knox Pulpit Sandstone Formation. (Photo: J.I. Chisholm.)

and cream-coloured mudstone up to 0.15 m are common, but siliceous pebbles are rare to absent. Fish remains include fragments, as well as complete specimens, of *Holoptychius*. Large-scale trough cross-stratification, in sets up to 1.5 m thick is the commonest sedimentary structure, but low-angle cross-bedding and planar lamination are also found. Palaeocurrent flow was towards the east. Subsidiary beds of greenish grey and red silty claystone and siltstone are also present, some forming the upper parts of upward-fining cycles. The transitional junction with the underlying Burnside Sandstone Formation is exposed in the Glen Burn (NO 170 076) north of the site boundary, west of Lappie Farm. It is placed at the point above which the siliceous pebbles that are characteristic of the Burnside Sandstone Formation are absent. The formation includes the well-known Dura Den Fish Bed, which elsewhere has yielded abundant *Bothriolepis* (including *B. hydrophila*), *Glyptopomus* and *Holoptychius*. This fauna indicates a Famennian age (e.g. Westoll, 1977).

The Knox Pulpit Sandstone Formation consists of 130–180 m of soft, weakly cemented, white, buff and yellow, very fine- to coarse-grained, feldspathic sandstones. The transitional junction with the Glenvale Sandstone Formation is faulted and poorly exposed in Glen Burn (NO 181 063), where the lowest exposed strata include sporadic laminae of greenish grey, silty mudstone. The most characteristic feature of the formation is the marked grain-size lamination, with laminae 1 mm to 10 mm thick ('pin-stripe' lamination) of aeolian origin. Other distinctive features are the rarity of pebbles, a greenish grey, silty claystone near the base, ochreous, decomposed calcrete nodules near the top, and an absence of clastic mica flakes that are common in the other Upper Old Red Sandstone formations in the Midland Valley. Bedding forms include tabular planar cross-bedding and planar wedge-shaped cross-bedding, planar lamination and convoluted bedding. The cross-bedding sets are mainly about 1 m or less, with foresets dipping at 20° to 30°, although some sets in the lower part of the formation at Dow Craig are up to 2.5 m. The cross-bedding is predominantly directed to the west and north-west, but bi-modal, east- and west-directed palaeocurrents are also present. Herringbone pattern is seen locally, as at Dow Craig (NO 1892 0702), John Knox's Pulpit (NO 1891 0582) and Kilgour Craigs

(NO 226 078). Erosional, first-order bounding surfaces occur between some sets at Dow Craig. Convolutions affect the larger (up to 2.5 m) sets towards the base of the formation (Chisholm and Dean, 1974). Ripple lamination is rare, except near the top. Well-rounded millet seed grains are common in the coarser laminae. Trace fossils referred to *Skolithos* are most common towards the top of the formation, where they occur in ripple-bedded sandstones as simple, vertical tubes up to 2 cm across and 7–30 cm long. Concentrations of up to 1000 per $m^2$ are recorded, although they are generally much sparser.

The Kinnesswood Formation is the basal formation of the Inverclyde Group, which is characterized by the presence of sandstones with pedogenic carbonate ('cornstones') and by mudstones with thin beds of dolomite and limestone ('cementstone'). The base of the formation is placed at the appearance of carbonate-bearing strata. The junction with the Knox Pulpit Sandstone Formation is seen in the Glen Burn, at the lip of a small waterfall (NO 1908 0570), where there is a transition over a few metres. Miospores of Tournaisian (LN–PC biozones) age from near the base of the formation elsewhere (Smith, 1996) show that it straddles the Devonian–Carboniferous boundary, but that most of it is of early Carboniferous age. It consists predominantly of purple-red, yellow, white and grey-purple, fine- to coarse-grained sandstones that are mostly cross-bedded and arranged in upward-fining units. Fine-grained, planar bedded and poorly bedded sandstones, red mudstones and nodules and thin beds of calcrete also occur. The calcretes range from immature types, in which the host sandstones have a patchy carbonate matrix with ill-defined concretions, to mature types, in which well-defined nodules (glaebules) are elongate perpendicular to the bedding and overlain by laminar and pisolitic beds. Some of the laminar calcrete, in which the laminae are bedding-parallel, is brecciated and the carbonate is replaced by chert.

## Interpretation

The Knox Pulpit Sandstone Formation was initially interpreted as marine in origin (Chisholm and Dean, 1974). However, compelling evidence for an aeolian origin was provided by Balin (1993), drawing on earlier aeolian interpretations by McAlpine (1978), Mader and Yardley (1985) and Hall and Chisholm (1987). The types of planar cross-bedding and heights of the sets are typical of modern aeolian dunes. Some are 2.5 m high in the lower part of the formation at Dow Craig (Figure 3.31). The grain-size lamination may be formed by grainfall (normal graded) and grainflow avalanche (reverse graded) deposition. Inter-set bounding surfaces, as seen for example at Dow Craig, are common in aeolian sands, with coarser sands occurring above them. They may be caused by shifts in wind direction, often accompanied by a slight increase in wind velocity, which introduces coarser sand (Balin, 1993). The planar lamination is produced by traction currents at high wind velocities.

The convoluted, soft-sediment deformation and the opposed (bi-modal) cross-bedding directions (including herringbone cross-bedding) in the sandstones suggested a tidal origin to Chisholm and Dean (1974). Balin (1993) noted that contorted bedding is present in all types of aeolian dune and suggested that the bi-modal cross-bedding was caused by alternating east- and west-directed winds, although bi-modality can also be created in seif (longitudinal) dunes by unidirectional winds as a result of changes in the slip faces of their linear crests. However, Balin (1993) argued that the bounding surfaces in the Knox Pulpit Sandstone Formation are too shallow-dipping to be related to such well-developed steep crests. She further noted that modern, large star dunes form from multi-modal wind directions, but that multiple slip faces are not usually preserved in the stratigraphical record because they are best developed in the easily eroded upper part of the dune. However, they are surrounded by much smaller crescentic and reversing dunes, which form where larger crescentic and linear dunes (the precursors to the star forms) advance into areas affected by variable wind directions. On this basis, Balin concluded that the bi-modal foreset was due to deposition in reversing dunes by opposing wind directions. Adjusting the palaeocurrent data for polar rotation (about 25° anti-clockwise), Balin (1993) found that the prevailing wind direction was to the WSW, with a secondary direction to the south-east. Neither direction is compatible with the presumed north-west trade wind direction, and Balin suggested that an exposed early Devonian volcanic terrane in the Ochil Hills exerted a topographic and orographic influence. Rapid heating of dark volcanic rocks in the daytime may have generated the main winds, with the weaker opposing winds produced by rapid air cooling over the hills at night.

Wavy lamination, small-scale convex-up lamination, climbing translatent ripple lamination (in co-sets up to 2 cm) and the *Skolithos* burrows were interpreted by Balin (1993) as features of interdune sedimentation. Thin wavy laminae are thought to have formed in wet interdune areas as a result of weak, variable wind conditions or falling water-table, leading to modification of the ripples. The convex-up laminae may be adhesion warts, formed where small mounds of sand adhere to a damp substrate. The climbing translatent ripple forms show slight upward coarsening of grain size and lack internal foreset lamination, which are apparently only associated with a dry substrate. These suggest aeolian, rather than waterlain, deposition. *Skolithos* is generally regarded as a marine trace fossil, and its presence was used by Chisholm and Dean (1974) to argue for a tidal origin for the Knox Pulpit Sandstone Formation. Balin (1993) favoured a wet interdune habitat.

The strata below (Glenvale Sandstone Formation) and above (Kinnesswood Formation) the Knox Pulpit Sandstone Formation are of fluvial origin. The cross-bedded sandstones of the Kinnesswood Formation were deposited in river channels and the fine-grained sandstones and mudstones were formed on the adjacent flood-plains. Evidence of an arid to semi-arid palaeoclimate and inhospitable terrestrial environments includes desiccation cracks, pedogenic carbonates, the scarcity of fauna (other than fish) and an almost total absence of micro- and macro-floral remains. It is difficult to assess the aridity of the climate, since it is unclear as to how evolved the terrestrial vegetational cover was in the Midland Valley during Late Devonian times. However, large rhizoliths in pedogenic carbonates in the Kinnesswood Formation elsewhere in the Midland Valley (Balin, 2000; see **Milton Ness** GCR site report, this chapter) demonstrate the presence of substantial trees in Late Devonian to Early Carboniferous times. The Knox Pulpit Sandstone Formation shows evidence of hot desert environments, with higher water-table conditions in the interdune areas. The presence of small, ochreous carbonate nodules in the upper part of the formation may herald a less arid climate, the pedogenic carbonates in the Kinnesswood Formation showing that the climate during its deposition was semi-arid, with seasonal (?monsoonal) rainfall.

## Conclusions

The natural stream sections in the Glen Burn and nearby crag exposures, including John Knox's Pulpit and Dow Craig, are proposed for GCR site status. The crags provide fine exposures of the Upper Devonian (Famennian) Knox Pulpit Sandstone Formation. This formation represents strata that were deposited by winds, in contrast to most of the Old Red Sandstone succession of the Midland Valley, which is of fluvial origin. The underlying (Glenvale Sandstone) and overlying (Kinnesswood) fluvial formations are well exposed in Glen Burn. The site is therefore important in providing evidence of the changing sedimentary environments of Late Devonian to Early Carboniferous times and in interpretation of the climate and palaeogeography at that time.

# WOLF'S HOLE QUARRY, STIRLINGSHIRE (NS 790 981)

## Potential ORS GCR site

*M.A.E. Browne and W.J. Barclay*

## Introduction

The importance of Wolf's Hole Quarry, at Bridge of Allen in Stirlingshire (Figure 3.32), lies mainly in the fossil fish specimens recovered from a coarse-grained, pinkish brown quartz- and feldspar-rich arkose. It is already an established GCR site for its fossil fishes (Dineley and Metcalf, 1999) and only a brief summary is provided here. No fossils have been found recently, but the lithology of museum specimens matches the sandstones in the basal and middle parts of the section exposed today. The strata belong to the basal part (the Sheriffmuir Sandstone Member) of the Scone Sandstone Formation of the Arbuthnott–Garvock Group. A thin, porphyritic, andesitic lava flow at the top of the quarry is the highest occurrence of lava (of the Ochil Volcanic Formation) on the southern side of the Strathmore Basin.

No fossils have been found since the quarry closed in 1898, most of the fish specimens being found in the 1860s and 1870s when the sandstones were worked for building stone. The fish may have been preserved in one or more lenses, in a similar fashion to the preservation of some cephalaspids and pteraspids in the Welsh Borderland (Dineley,

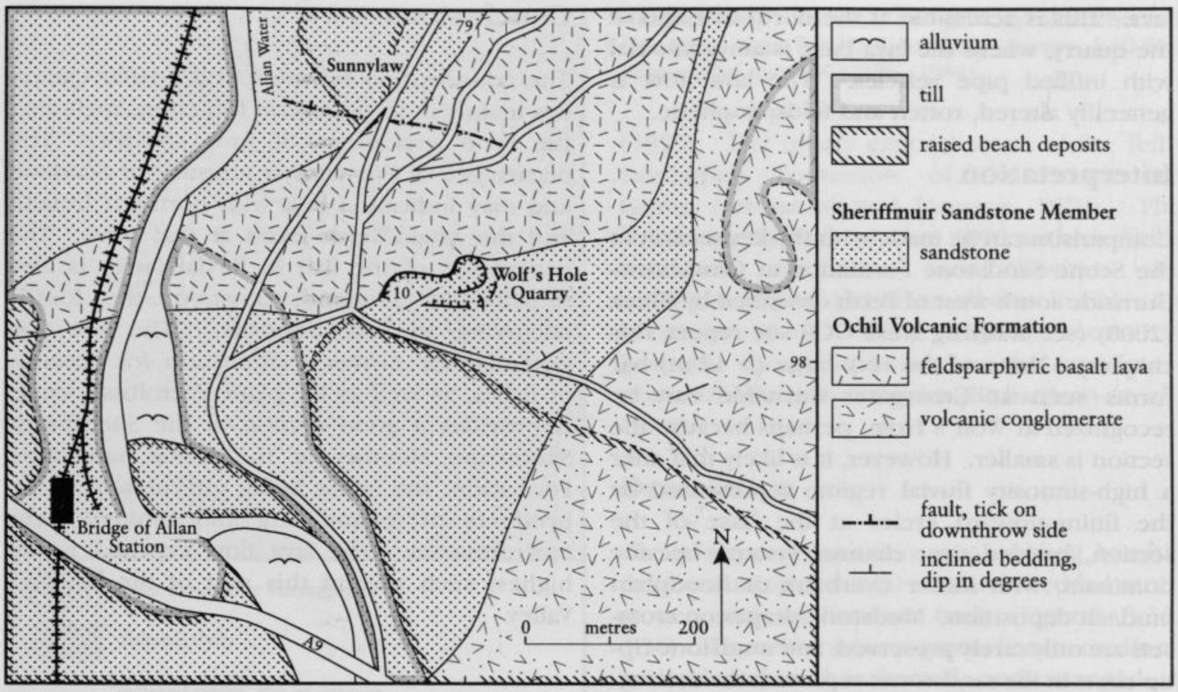



**Figure 3.32** Geological map of the area around Wolf's Hole Quarry. After British Geological Survey 1:10 560 Sheet NS 79NE (1976).

1999c). The quarry is primarily selected as a GCR site for its small, but unique fish assemblage, including the type specimens of four agnathan species. Dineley (1999c) summarized the details of the fauna, which includes *Pteraspis mitchelli*, *Cephalaspis scotica*, *Securiaspis waterstoni* and *Securiaspis caledonica*.

## Description

Wolf's Hole Quarry (Figure 3.33) exposes 25 m of cross-bedded sandstones with some siltstones, overlain by a flow of basaltic-andesite amygdaloidal lava (Francis *et al.*, 1970). The lowest 6 m of strata exposed in the quarry comprise several fining-upward sandstone–siltstone–mudstone cycles, each about 2–3 m thick and grading upwards from gritty, cross-bedded sandstones to siltstones and then green mudstones. The base of each unit rests on an erosion surface veneered by intraformational conglomerate. Sandstones become more dominant upwards, the cyclic beds passing into 10 m of cross-bedded sandstones. Within these, a persistent, thin (50–150 mm) grey mudstone can be traced across the width of the quarry face. At the top of the section 2 m of flaggy sandstones are truncated at the uneven base of the overlying

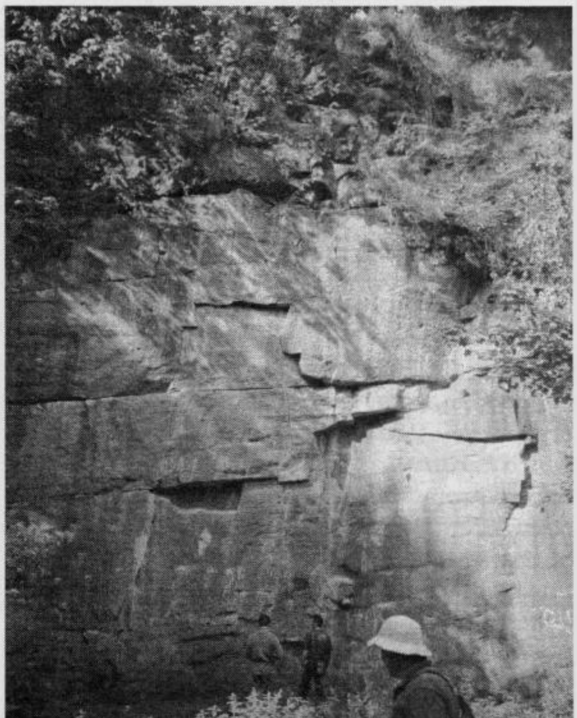


**Figure 3.33** Wolf's Hole Quarry. A lava flow at the top of the section rests on thick-bedded sandstones. (Photo: M.A.E. Browne.)

lava. This is accessible at the north-east end of the quarry, where the lava base is amygdaloidal with infilled pipe vesicles. The lava flow is generally altered, rotten and feldspar-phyric.

## Interpretation

Comparison can be made with the key section in the Scone Sandstone Formation at Crossgates–Burnside south-west of Perth described by Bluck (2000) (see **Whiting Ness** GCR site report, this chapter). None of the very large (> 12 m) bar forms seen at Crossgates–Burnside can be recognized at Wolf's Hole, perhaps because the section is smaller. However, it is likely that after a high-sinuosity fluvial regime represented by the fining-upward cycles at the base of the section, braided river channel systems became dominant, with minor overbank or floodplain mud/silt deposition. Mudstone drapes on cross-sets are only rarely preserved, and mudstone rip-up clasts in the sandstones represent the destruction and reworking of most of the fine sediment. The uneven basal surface of the lava may reflect the palaeotopography, the flow appearing to infill channels locally. The flow may have been emplaced from the 'south', from the volcanic terrane represented by the Ochil Volcanic Formation.

Dineley (1999c) discussed the fossil fishes fauna, its affinities and habitat. *Pteraspis mitchelli* is a very rare pteraspid occurrence in Scotland, although pteraspids are common in the Dittonian of the Welsh Borderland. The taxonomy of *Pteraspis mitchelli* remains in some doubt, Blieck (1981, 1984) noting affinities with *Protopteraspis* and similarities to *Pteraspis rostrata*. The affinity with *P. rostrata* suggests a connection with the Fintona Beds of County Fermanagh (Harper and Hartley, 1938), from which *P. rostrata* is recorded, the only pteraspid known from Ireland. *Securiaspis* is confined elsewhere to the Dittonian (Lochkovian–Pragian) of the Welsh Borderland and Spitsbergen, and this is the only occurrence in Scotland. The fauna as a whole suggests a correlation with the Dittonian of the Anglo-Welsh Basin. Palynological investigation of the grey and green beds at Wolf's Hole may offer a further correlation. The preservation of the fish in fluvial facies is also more akin to the Anglo-Welsh Basin occurrences, unlike the predominantly lacustrine facies in which most of the Lower and Middle Old Red Sandstone fossil fish of Scotland are found.

## Conclusions

The conservation value of Wolf's Hole Quarry lies mainly in its important fish fauna, including the type specimens of four species. The occurrence of *Pteraspis* is unusual for Scotland and may indicate a link with northern Ireland and the Anglo-Welsh Basin at that time. The occurrence of the fish in fluvial facies is also unusual in Scotland, most of the fossils occurring in lake deposits. The site has potential for further examination for remains of fishes, as well as for plant microfossil study. It provides a good section of the Sheriffmuir Sandstone Member of the Scone Sandstone Formation, the strata being interpreted as the products of meandering and braided river environments. The lava flow exposed is the highest such unit in this part of the Midland Valley.

# AUCHENSAIL QUARRY, WEST DUNBARTONSHIRE (NS 342 799)

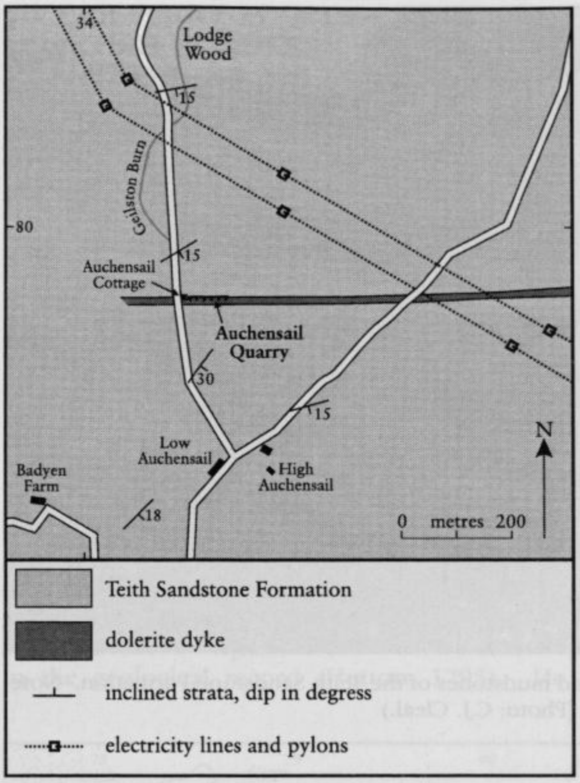
## Potential ORS GCR site

***M.A.E. Browne and W.J. Barclay***

## Introduction

Auchensail Quarry (Figure 3.34) near Cardross, West Dunbartonshire exposes sandstones and mudstones/siltstones of the Teith Sandstone Formation (Strathmore Group) of the Lower Old Red Sandstone. It has yielded some of the best-preserved plant fossils of Emsian (Early Devonian) age in Britain (Morton, 1976; Scott *et al.*, 1976). The sandstones contain an abundance of plant material, including exceptionally well-preserved examples of *Sawdonia* and the youngest examples of *Prototaxites* known in Britain, some of which reveal considerable anatomical detail (Rayner, 1983, 1984, 1995). The site is already an established GCR site for its Palaeozoic palaeobotany (Cleal and Thomas, 1995) and a brief summary is presented here. In plant material of similar age from Ballanucater Farm GCR site, the outer protective skin (cuticle) of the plants is preserved (Rayner, 1995).

The geology of the quarry was described by Scott *et al.* (1976) and summarized by Rayner




**◂Figure 3.34** Location and geology of Auchensail Quarry. After British Geological Survey 1:10 560 manuscript map NS 37NW (1984).

(1995). The quarry exposes strata of the Teith Sandstone Formation of the Strathmore Group (Armstrong and Paterson, 1970). The strata are typical of the 1000 m-thick Teith Sandstone Formation, and illustrate the sedimentological character of this fluvial unit (Paterson *et al.*, 1990). Spores recovered from the formation belong to the ***annulatus-sextantii*** Biozone (Emsian) (Richardson *et al.*, 1984).

## Description

The quarry exposes a thin, east-trending, basaltic dyke intruding about 20 m of interbedded sandstones and argillaceous beds (Figures 3.35, 3.36). The sandstones are green, fine- to medium-grained and well indurated, and arranged in upward-fining units up to 2 m thick, some with trough cross-bedding and lateral accretion surfaces. They have conglomeratic bases with

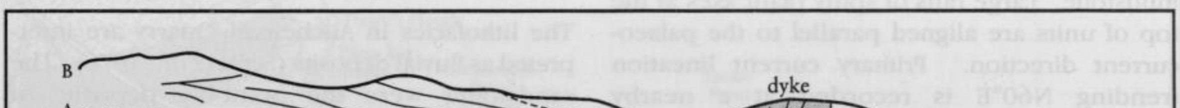



**Figure 3.35** Sketch of Auchensail Quarry and its facies associations. After Scott *et al.* (1976), reproduced by Cleal and Thomas (1995).

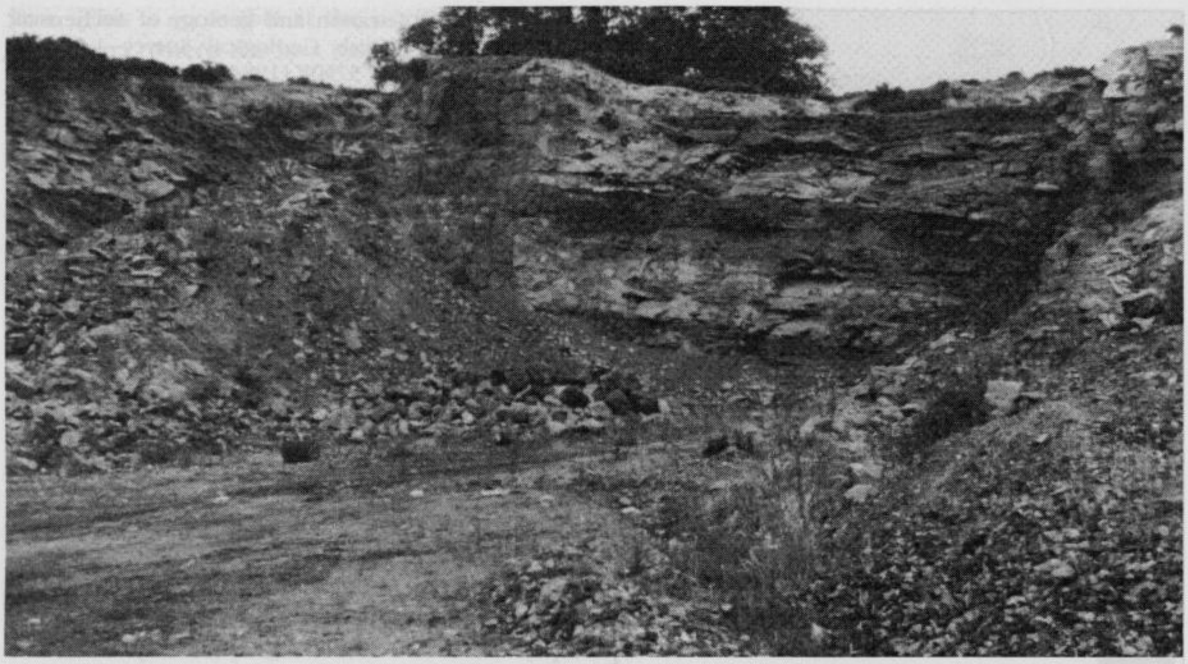


**Figure 3.36** Auchensail Quarry: sandstones, siltstones and mudstones of the Teith Sandstone Formation. Note the igneous dyke just to the left of centre of the quarry. (Photo: C.J. Cleal.)

cobbles and pebbles of intraformational red mudstone. Large rafts of spiny plant axes at the top of units are aligned parallel to the palaeocurrent direction. Primary current lineation trending N60°E is recorded at a nearby exposure. Plant fossils are abundant in the sandstones. Mats of coalified plant compressions occur mainly within the upper part of the sandstone units, whereas discrete pyrite petrifactions occur throughout. The floral assemblage comprises *Drepanophycus spinaeformis*, *Dawsonites* sp., *Prototaxites* sp., *Sawdonia ornata*, ?*Sporogonites* sp. and *Zosterophyllum* sp.. It is typical of the Emsian Strathmore Group and similar to those in grey, coarse-grained sandstones and blue-green mudstones at Ballanucater Farm, Callander. A discussion on the plant fossil assemblages is given by Rayner (1995).

The argillaceous beds are of red siltstone and mudstone up to 2 m thick, comprising stacked fining-upward units 0.2–0.3 m thick. Most of the units are tabular, but some lenticular ones fill abandoned palaeochannels. No plants are preserved in this facies, but a single specimen of the trace fossil *Beaconites* Vyalov is recorded in a loose block and fish remains are recorded nearby. Desiccation-cracked bedding surfaces are common.

## Interpretation

The lithofacies in Auchensail Quarry are interpreted as fluvial deposits (Scott *et al.*, 1976). The sandstones were the point-bar deposits of medium-size, meandering rivers; the mudrocks were floodplain deposits. The plants occur only in the sandstones, suggesting that they lived within the margins of the river channels, perhaps on the point bars. No plants occur in growth position. However, post-depositional oxidation may account for their absence in the red floodplain beds. *Beaconites* has been interpreted as the locomotory or temporary resting burrow of amphibians or reptiles. The burrows may be similar to those in the beds of wet-dry, seasonal streams in modern deserts, such as the dry season burrows of the lungfish (Scott *et al.*, 1976).

## Conclusions

Auchensail Quarry is accorded GCR site status because it has yielded an exceptionally well-preserved suite of Early Devonian (Emsian) land plants. The quarry also provides a good section of the interbedded sandstones and mudstones/siltstones of the Teith Sandstone Formation, the youngest Early Devonian formation in the Midland Valley of Scotland.

# SICCAR POINT TO HAWK'S HEUGH, SCOTTISH BORDERS (NT 813 710–NT 790 714)

*M.A.E. Browne and W.J. Barclay*

## Introduction

Accorded SSSI status in 1961, the Siccar Point unconformity (known as 'Hutton's unconformity') is an internationally famous place of geological pilgrimage. It is of great historical importance in the development of the science of geology. Although James Hutton had previously observed unconformities in Arran (see **North Newton Shore** GCR site report, this chapter) and Jedburgh (see Figure 4.2, Chapter 4), the unconformity at Siccar Point is the most spectacular. It was here in 1788 that Hutton, accompanied by James Hall and John Playfair, was the first person to appreciate the significance of unconformities in the geological record (Hutton, 1795). He used the locality to demonstrate the cycle of deposition, folding, erosion and further deposition that the unconformity represents. He understood the implication of unconformities in the evidence that they provided for the enormity of geological time and the antiquity of the earth, in contrast to the biblical teaching of the creation of the Earth (Repcheck, 2003). All three of 'Hutton's unconformities' have been proposed as Global Geosites on the basis of their historical importance in the development of geology (Cleal *et al.*, 2001). A casting of the Siccar Point unconformity is housed in the American Museum of Natural History, New York.

Field guides to Siccar Point were provided by Craig (1960, 1986) and Greig and Davies (1978). Greig (1988) and Balin (1993) gave detailed accounts, from which the following description is largely derived. The geology of Siccar Point is placed into a wider context of the geology of the area between Redheugh and the Hawk's Heugh SSSI to the west (Figure 3.37), including

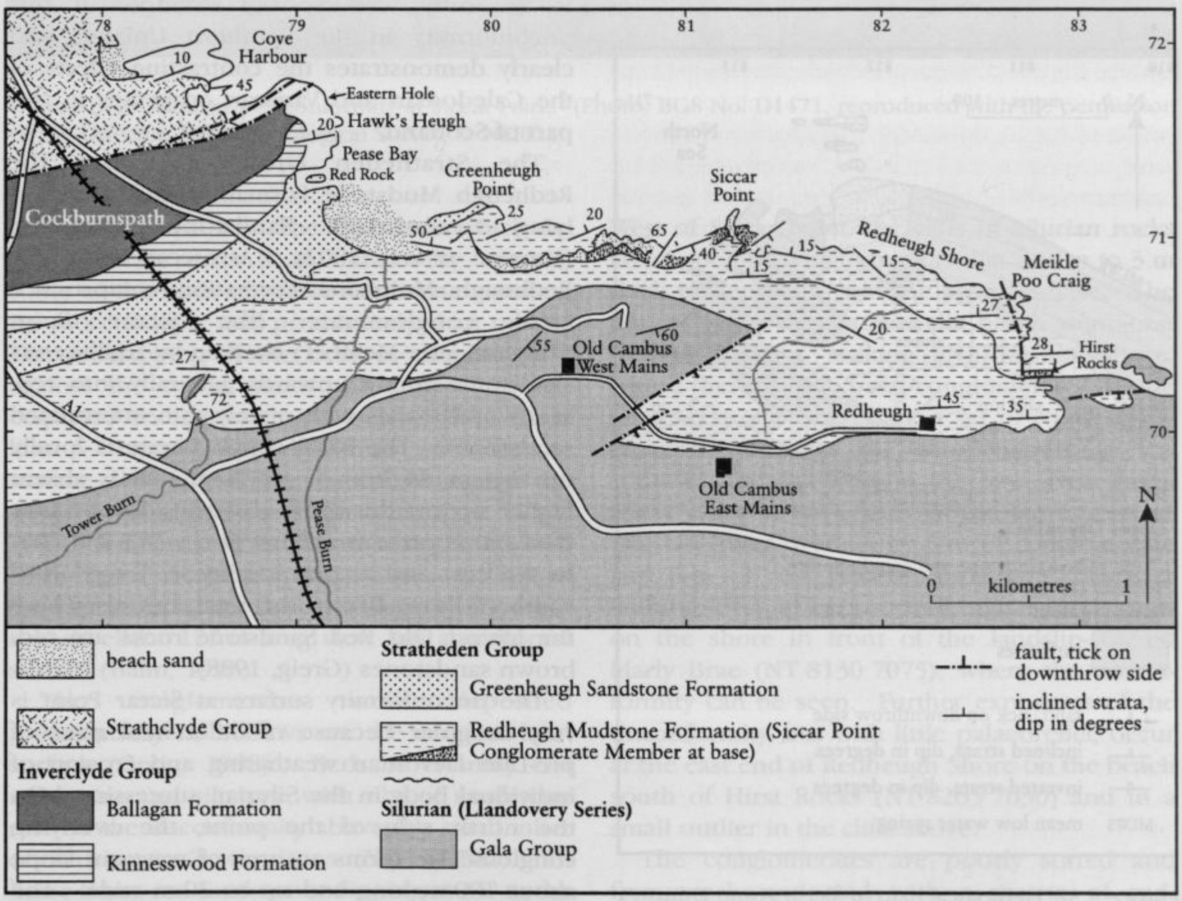



**Figure 3.37** Geological map of the area around Siccar Point, from Cove Harbour to Hirst Rocks. After British Geological Survey 1:50 000 Sheet 34 (Scotland), Eyemouth (1982).

the superb cliff sections of Upper Old Red Sandstone in Pease Bay (Craig, 1960; Greig and Davies, 1978; Fyfe, 1985; Clarkson, 1986; Greig, 1988; Salter, 1992; Balin, 1993). The 4 km coast section from Siccar Point westwards to Hawk's Heugh and Cove Harbour provides a unique, magnificently exposed transect through the succession of Upper Devonian to Lower Carboniferous rocks and merits protected status in its entirety. The uppermost part of the transect lies within the Cove GCR site and is described in the GCR volume on Lower Carboniferous stratigraphy (Cossey *et al.*, 2004)

## Description

### *Siccar Point*

Siccar Point (Figure 3.38) is a coastal promontory of gently dipping Upper Devonian (Upper Old Red Sandstone) beds resting discordantly on folded, vertical, Lower Palaeozoic strata. The latter are turbiditic, dark grey, fine-grained

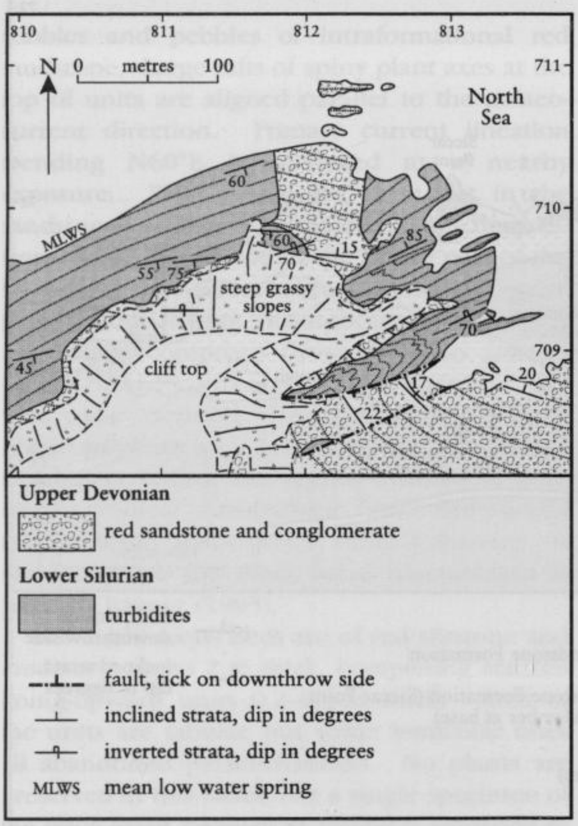



**Figure 3.38** Geological map of Siccar Point: Hutton's Unconformity. After Greig (1988).

wacke sandstones and interbedded finely laminated, fissile mudstones of the Gala Group, of early Silurian (Llandovery Series) age. The sandstone beds are up to 0.4 m thick and the mudstones are up to 0.15 m. The beds are locally contorted by tight folds and cut by closely spaced, parallel fractures produced by intense compressive stresses during the Caledonian Orogeny. In the south-east of the outcrop, the beds dip to the north-west at almost 90°, but a synclinal axis results in dips to the south-east of about 60° in the north-west of the site. They are truncated by the sharp, angular unconformity, which is overlain by Upper Devonian strata comprising reddish brown conglomerates and sandstones of the Redheugh Mudstone Formation of the Stratheden Group (Figure 3.39). These beds were deposited in the Oldhamstocks Basin (Lagios, 1983), which was possibly a sub-basin of the Scottish Border Basin. The beds are undeformed, with only a gentle inclination produced during the later, here less intense Variscan Orogeny. Siccar Point is the only well-exposed example of this unconformity in the Southern Uplands and clearly demonstrates the contrasting effects of the Caledonian and Variscan orogenies in this part of Scotland.

The Stratheden Group comprises the Redheugh Mudstone Formation and the overlying Greenheugh Sandstone Formation (Browne *et al.*, 2002). At Siccar Point, the Redheugh Mudstone Formation comprises a basal conglomerate (the Siccar Point Conglomerate Member) overlain by argillaceous sandstones fining upwards generally into red, sandy mudstones with mainly thin intercalated sandstones. The basal conglomerate is locally up to 6 m thick at Siccar Point, but is absent higher up on the south-eastern side of Siccar Cove. It is present at Hirst Rocks (NT 830 705) to the east and at one locality in Tower Burn south of Pease Bay to the west, but elsewhere the lowest Old Red Sandstone rocks are red-brown sandstones (Greig, 1988).

The unconformity surface at Siccar Point is very irregular because of differential rates of pre-Late Devonian weathering and erosion of individual beds in the Silurian succession. On the north side of the point, the overlying conglomerate forms an area of wave-cut slope about 100 m long and up to 20 m wide. The conglomerate dips seawards (north-west)

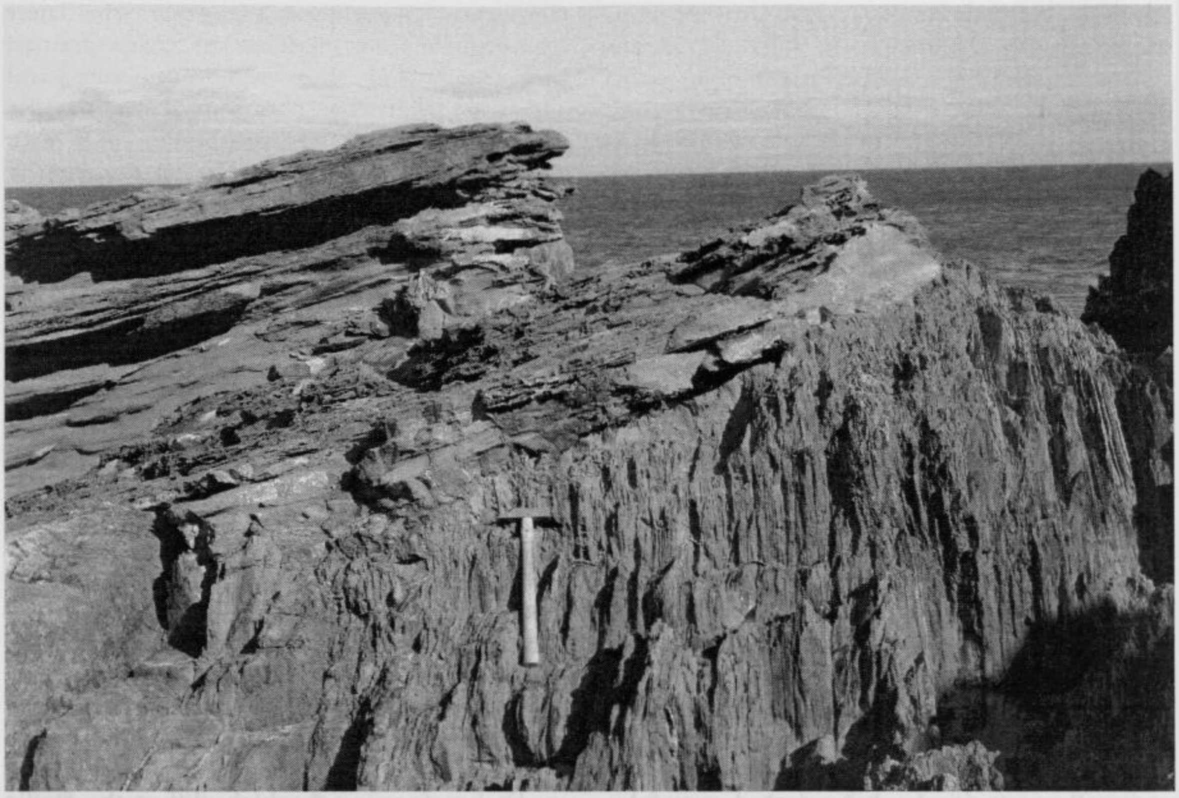


**Figure 3.39** Hutton's Unconformity at Siccar Point. (Photo: BGS No. D1471, reproduced with the permission of the Director, British Geological Survey, © NERC.)

between 15° and 20°. The surface on which the conglomerate rests is in detail very uneven, some of the beds of wacke sandstone standing up more sharply and prominently than others. The overlapping of the beds of conglomerate against the wacke sandstone surface is well displayed on centimetre- to metre-scale, with at least 3–10 m of palaeorelief on the unconformity surface. Relief of 10 m is observable towards the western margin of the main outcrop at Siccar Point. Similar relief is also seen in the faulted, 60 m-high cliff face forming the eastern limit of the exposure, where the unconformity in part of this excellent 125 m-long view has a scalloped surface (Balin, 1993).

The conglomerates were deposited preferentially in hollows on the original land surface (Greig, 1988). Beds of crumbly red mudstone and siltstone with ribs of sandstone rest on the unconformity above the small inlier of Silurian in Tower Burn (NT 758 702). In Pease Burn, red sandstones dipping at 35° to the north rest unconformably on Silurian rocks. West of Siccar Point, the cliffs of Silurian rocks are capped by conglomerates that are up to 3 m thick in depressions in the palaeosurface. The unconformity descends to the beach south-east of Kirk Rigging, striking ENE on the shore, where there is little basal conglomerate. To the south-east of Siccar Point, a set of NE-trending faults downthrows the conglomerate to the south-east to sea level in the bay. Near high-water mark in the corner of the bay is a small Silurian inlier overlain by 5 m of conglomerate and 6 m of red, pebbly sandstones. Further faulting leads to exposure of higher sandstones on the shore in front of the landslip-scarred Marly Brae (NT 8130 7075), where the unconformity can be seen. Further exposures of the unconformity, but with little palaeorelief, occur at the east end of Redheugh Shore on the beach south of Hirst Rocks (NT 8265 7030) and in a small outlier in the cliffs above.

The conglomerates are poorly sorted and framework-supported with a matrix of red, medium- to coarse-grained sandstone. The angular, generally tabular clasts are of grey, wacke sandstone of pebble- to boulder-grade up to 0.56 m, with a few vein quartz pebbles up to 0.07 m (Balin, 1993). Greig (1988) noted strong imbrication indicating transport by south- to SE-flowing palaeocurrents. Individual beds are sheet-like and range from about 0.9 m to 2 m in thickness, with apparently planar tops and bases, except where adjacent to basement channel margins. Weak normal and reverse grading are present locally. The sandstones that overlie the conglomerates, and locally lie within them, are horizontally laminated and trough cross-bedded. The laminated beds are up to 1.6 m thick and comprise centimetre-scale laminae with scattered cobbles. The trough cross-bedded sandstones comprise sets up to 0.5 m high and over 1 m wide, commonly stacked into multi-storey units. Palaeocurrents are mainly to the south-west, as also inferred from most of the pebble imbrication in the conglomerate. There are also a few tabular sheets of cross-bedded sandstone about 0.15 m thick with low-angle foresets.

The Siccar Point Conglomerate Member passes up into the main, mudrock-dominated part of the Redheugh Mudstone Formation. The formation is about 200 m thick and comprises red-brown, sandy mudstones interbedded with mainly thin, red-brown, pale yellowish grey, green, purple and cream sandstones that become more numerous and massive upwards. One bed contains calcareous concretions up to 1 m in diameter (Greig, 1988). The proportion of mudstone to sandstone is of the order 3:1 at Meikle Poo Craig (NT 822 708) 1.5 km east of Siccar Point. Fossil fish remains indicating a Famennian age include *Bothriolepis hicklingi* found in loose blocks at Redheugh, Siccar Point and Greenheugh Point, and fragments of *Grossilepis brandi*, *Bothriolepis* sp. and *Holoptychius* sp. from Hazeldean Burn (NT 8138 7019) (Miles, 1968).

### *Pease Bay*

Pease Bay, 2 km west of Siccar Point (Figure 3.37) is a sandy bay dramatically rimmed by cliffs of Upper Old Red Sandstone strata that dip 25°–35° to the north (Clarkson, 1986). At its eastern end, Greenheugh Point (NT 800 711), the transition between the Redheugh Mudstone Formation and overlying Greenheugh Sandstone Formation is exposed. The latter comprises mainly medium- to coarse-grained sandstones and thin, red, mudstone and siltstone interbeds. About 70 m of the formation is present at Greenheugh Point, with a further 25 m at Red Rock (NT 791 711) on the west side of Pease Bay. Salter (1992) and Balin (1993) gave detailed sedimentological accounts of the beds. The sandstones are mainly red-brown, but with some pale yellow and pale green beds. Fragments of *Bothriolepis* have been found in the lower sandstones and scales of *Holoptychius nobilissimus* have been found in abundance (Dineley, 1999d). A large fallen block crowded with intact specimens of *Bothriolepis* was recorded by Clarkson (1986), the fish probably washed out of a river channel during flooding and stranded in a drying pool.

Red, medium- to coarse-grained, cross-bedded sandstones at Red Rock have silty mudstone interbeds containing yellowish green ribs and coarse sandy layers. In the corner of the bay 150 m to the north, the highest mudstone is exposed on the shore and is succeeded by red sandstones forming the high cliff at the Deil's Hole. These dip 17° to the north and comprise alternating parallel-bedded and cross-bedded sandstone bodies with well-rounded grains. The basal beds of the sandstone are trough cross-bedded, the troughs trending south. Above, both fluvial and aeolian facies (Figure 3.40) have been identified (Salter, 1992).

### *Hawk's Heugh (NT 790 714)*

About 240 m north of Red Rock (NT 7910 7134) three E–W-striking faults, seen particularly well in the cliff, throw down to the north, bringing in the Kinnesswood Formation (the Cockburnspath Formation of Balin, 1993). This formation is exposed in an extensive wave-cut platform and high cliff at Hawk's Heugh and is characterized by the presence of calcrete. Accorded protected status because of the occurrence of *Remigolepis*, the only British example of this fish (Dineley, 1999d), the site provides superb exposures of this calcrete-rich topmost part of the Upper Old Red Sandstone. Strongly cross-bedded sandstones at the base of the section contain an abundance of veins and layers of bright red and purple-brown, iron-stained carbonate nodules, the latter commonly aligned along the horizontal

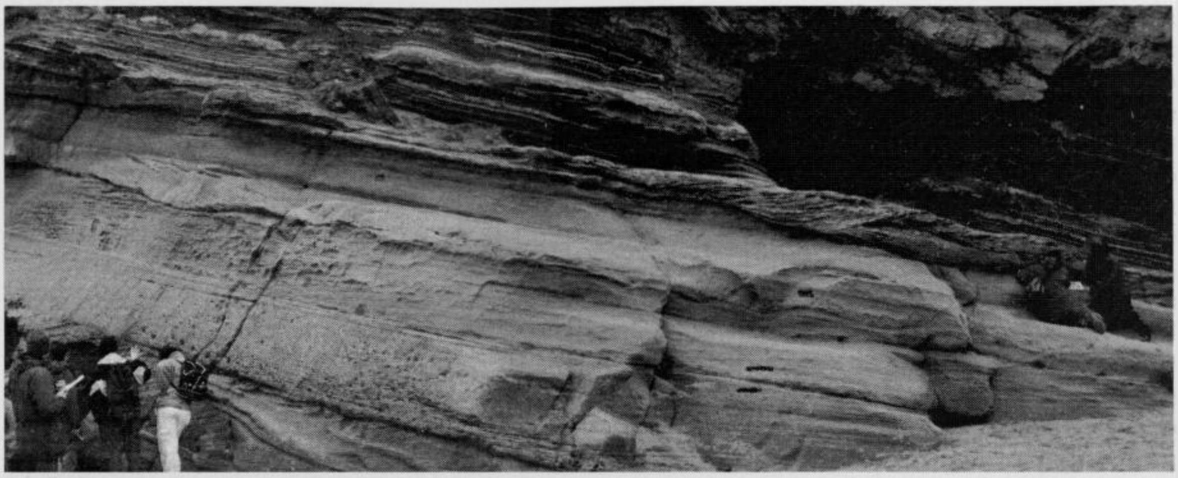


**Figure 3.40** Interbedded fluvial and aeolian sandstones at Red Rock, Pease Bay. The aeolian sandstones show sandflow and wind ripple lamination, the fluvial sandstones are sheet-flood deposits (Photo: B.P.J. Williams).

bedding planes. Above, grey beds appear locally in the red beds and there is an increasing upwards abundance of carbonate in the form of red-brown, iron-stained irregular lenses and layers of nodules that form prominent ridges trending seawards across the wave-cut platform. Vertical, cylindrical concretions also occur. The sandstones are predominantly red, particularly in the lower part of the formation; many of the higher beds are greyish white with red flecks of ferroan dolomite. The sandstones occur in trough cross-bedded, tabular cross-bedded and massive bodies. Intraformational calcrete-clast conglomerates are interbedded in the succession and thin, red-white mottled, locally micaceous, argillaceous interbeds occur sporadically (Balin, 1993).

The Hawk's Heugh SSSI is described in the companion GCR volume on fossil fishes (Dineley and Metcalf, 1999). *Remigolepis* was found in a loose block of intraformational conglomerate similar to a bed in the cliff above about 6 m below the top of the Kinnesswood Formation. *Holoptychius* and *Bothriolepis* are also recorded from the bed.

The top of the Kinnesswood Formation is in Eastern Hole (NT 7900 7157), the bay to the north of Hawk's Heugh. It was placed at the top of a prominent deep-red, 0.9 m-thick calcrete with cream chert veins and lenses by Salter (1992), and 1–1.5 m above it by Greig (1988) and Balin (1993), at the top of a bed of trough cross-bedded sandstone of Old Red Sandstone facies that overlies the calcrete. Above this, yellow and dark green, plant-bearing mudstones and ferroan dolostones (cementstones) of the Ballagan Formation make their first appearance. Described as a sandstone by Greig (1988), the calcrete is a silty mudstone with coarse, ferroan, dolomite crystals (Andrews *et al.*, 1991). A cementstone with layers of conglomerate containing yellow, angular dolomite clasts and fish fragments (the Eastern Hole Conglomerate) lies about 13 m above.

## Interpretation

James Hutton was probably the first natural philosopher to recognize and understand the significance of the relationships between rocks separated by an angular unconformity. He understood the long time-period represented by the unconformity and also, to a degree, the events that led to the formation of the observed features. The first of the unconformities he studied was at **North Newton Shore** on Arran in 1786 (see GCR site report, this chapter), followed by the one at Inchbonny, Jedburgh (formerly known as 'Aller's Mill', now a RIGS site; Figure 4.2, Chapter 4). Hutton and John Playfair were obviously struck by the significance of the exposure at Siccar Point – 'the mind seemed to grow giddy by looking so far into the abyss of time' (Playfair, 1805).

The planar-bedded conglomerates and interbedded sandstones above the unconformity at Siccar Point were interpreted by Balin (1993) as sheet-flood deposits, formed mainly by ephemeral floods, which created pulses of sediment-charged water that spread out from the mouth of a channel. Localized thickening of the conglomerate beds results from the infilling and draping of the uneven basement topography at the unconformity surface. Balin (1993) considered that the coarse grain-size of all the Late Devonian lithofacies at Siccar Point was consistent with deposition by high-velocity, high-gradient flows. Framework-supported gravels are laid down by high-energy water flow that prevents, or partially prevents, deposition of sand from suspension. This fact, together with the clast imbrication and the framework-supported structure of the conglomerates, suggests deposition from traction currents or as flash-flood sheets. Reduced-flow regime allowed sand to settle in the spaces in the gravels and deposition of the plane-bedded sandstone lithofacies (Balin, 1993).

The generally impermeable bedrock contributed to the high velocity of the flood discharges. Also important was the bedrock topography, the steep-sided gully at the western side of Siccar Point, for example, being responsible for the local SE-directed imbrication (Balin, 1993). Pipe-like burrows, about 1 cm wide and 10 cm long, in the planar-bedded sandstones at Hirst Rocks suggest periods of lower flow-energy and non-deposition. The conglomerates form part of an upward-fining succession, suggesting that uplift of the source area ceased. With complete draping of the palaeotopography and burial of remnant highs, floodplain mud- and silt-dominated deposition became established and the remainder of the Redheugh Mudstone Formation was laid down widely in the Scottish Border Basin.

The Greenheugh Sandstone Formation has been interpreted as entirely fluvial by Balin (1993) and as mixed fluvial and aeolian by Salter (1992). The basal part of the formation at Greenheugh Point was interpreted by Salter (1992) as the deposits of shallow, braided streams and overbank sheet-flooding across a broad, flat alluvial-plain. Balin (1993) noted that the absence of vegetation resulted in easily eroded channel banks, facilitating the migration of stream channels. Silts were deposited in ephemeral lakes on the floodplain at the terminations of some channels. Minor aeolian reworking of exposed fluvial bar forms also occurred. The sandstone-dominated succession at Red Rock was interpreted by Salter as the product of deposition in ephemeral, shallow channels that became the sites of aeolian deflation during periods of increased aridity. Salter also suggested that stabilized aeolian dune-fields formed during times of maximum aridity, resulting in aeolian bedforms up to 2 m high at Red Rock (Figure 3.40). Balin (1993) favoured an entirely fluvial origin, but noted that the textures of some grains (Fyfe, 1985) suggest that they may have been involved in a phase of aeolian transport. The presence of pin-stripe lamination and the alternation of laminae with marked contrast in grain size is regarded as characteristic of aeolian deposition.

Calcrete palaeosol development in the upper part of the Upper Old Red Sandstone (the Kinnesswood Formation) is seen throughout the Midland Valley of Scotland and Southern Uplands. The carbonate concretions at Hawk's Heugh are interpreted as pedogenic calcrete, their formation along foresets, bedding planes and desiccation cracks being aided by increased groundwater permeability. The vertical, cylindrical concretions are interpreted by Balin (1993) as rhizocretions formed around plant roots. The 0.9 m-thick calcrete close below the top of the Kinnesswood Formation contains horizontal, cream-coloured chert lenses, indicating a mature stage of palaeosol development (Stage 4 of Leeder, 1975; Stage VI of Machette, 1985), and a period of formation of up to 1.5 million years (Salter, 1992). Low sedimentation rates and a semi-arid climate are requisite for calcrete formation, although the climate may have been less arid than during deposition of the Greenheugh Sandstone Formation. The prolonged period of tectonic stability during formation of the mature calcrete near the top of the Kinnesswood Formation preceded a major change in palaeogeography when coastal floodplain deposition of the Ballagan Formation was introduced. Eustatic sea-level rise at the start of the Carboniferous Period, a wetter climate and tectonic factors may all have contributed to the change.

The fish from Pease Bay (*Bothriolepis* and *Holoptychius*) point to a Famennian age for the Greenheugh Sandstone Formation (Dineley, 1999d). *Remigolepis* from the Kinnesswood Formation at Hawk's Heugh occurs elsewhere in the world in strata ranging from Frasnian to

Early Carboniferous in age. The position of the Devonian–Carboniferous boundary at the Hawk's Heugh GCR site is not clear. The base of the Eastern Hole Conglomerate and the basal cementstone beds have variously and arbitrarily been taken as the boundary in the past, but late Tournaisian (CM Zone) spores have been recovered from the lowermost cementstones (Andrews *et al.*, 1991). The Devonian–Carboniferous boundary may therefore lie at a level lower than its previous, arbitrary position, within or near the base of the Kinnesswood Formation (Browne *et al.*, 1999).

## Conclusions

Siccar Point is a world-renowned site forever associated with James Hutton, in particular, but also with Sir James Hall and Professor John Playfair. It is arguably the most important SSSI in Scotland and a place of international geological pilgrimage. In addition to its main, historical, importance, it is also important in providing excellent exposures of the Silurian and Late Devonian sedimentary rocks that lie below and above Hutton's unconformity respectively. The unconformity is beautifully displayed in three dimensions at Siccar Point, providing one of the best exposures of an angular unconformity in Scotland.

The coastline from Siccar Point westwards through Pease Bay to the Hawk's Heugh fossil fishes GCR site and the Cove Lower Carboniferous Stratigraphy GCR site presents a magnificently exposed, complete transect of the entire Late Devonian (Famennian) succession and the transition into the overlying strata of Early Carboniferous (Courceyan) age. Both river and wind-borne sediments are beautifully displayed in the cliffs and foreshore and the beds have yielded important fish remains, including the only occurrence of *Remigolepis* at Hawk's Heugh and complete specimens of *Bothriolepis* from Pease Bay. The whole section is frequently visited by students and professional geologists. It is an important teaching resource in terms of the sedimentary and contemporaneous pedogenic structures displayed, and the depositional environments they represent. There is also the potential for future fossil fish discoveries, and the section between the two existing GCR sites at Siccar Point and Cove is eminently worthy of protected status.

# LARGS COAST, NORTH AYRSHIRE (NS 191 633–NS 192 619)

*A.A. Monaghan*

## Introduction

The section of Late Devonian rocks on the west coast of Scotland north of Largs (Figure 3.41) is an important GCR site for understanding the internal structures of Upper Old Red Sandstone braided river deposits. Outcrops of intercalated pebbly sandstones and finer-grained sandstones with thin silty mudstone interbeds are well exposed along the shore. These rocks demonstrate the lateral and vertical facies variations and the scale of bar forms in a braided river channel, and the relationship of the bar forms to the river floodplain deposits.

The sedimentology and tectonic setting of the Largs section and others along the coast of the Firth of Clyde have been studied by Bluck (1967, 1978, 1980a,b, 1986, 1992, 2000). This account is based on Bluck's detailed analysis of the geometry of the sandbodies at the site. He is one of a group of workers who have made major advances in the understanding of Old Red Sandstone fluvial facies, sedimentary processes and environments by comparing the rocks with modern analogues.

The Upper Old Red Sandstone rocks north of Largs belong to the Kelly Burn Sandstone Formation of the Stratheden Group (British Geological Survey, 1990; Paterson *et al.*, 1990; Browne *et al.*, 2002). The base of the Kelly Burn Sandstone Formation is transitional with the Skelmorlie Conglomerate Formation. Its top is a sharp, possibly disconformable junction with the Lower Carboniferous Kinnesswood Formation. The Late Devonian age of the Stratheden Group is constrained by a rare Fammenian fish fauna (Browne *et al.*, 2002), the Tournaisian age of the overlying Kinnesswood Formation (Browne *et al.*, 1999) and the Early Devonian age of the underlying Lower Old Red Sandstone.

The Midland Valley of Scotland is interpreted to have been delimited in Late Devonian times by the Highland Boundary Fault in the north and the Southern Upland Fault to the south, with a central, western high (Bluck, 1978; Browne *et al.*, 1985). In the Firth of Clyde area, extensional half-grabens formed by sinistral strike-slip movement on the Highland Boundary Fault are thought to have controlled sediment dispersal

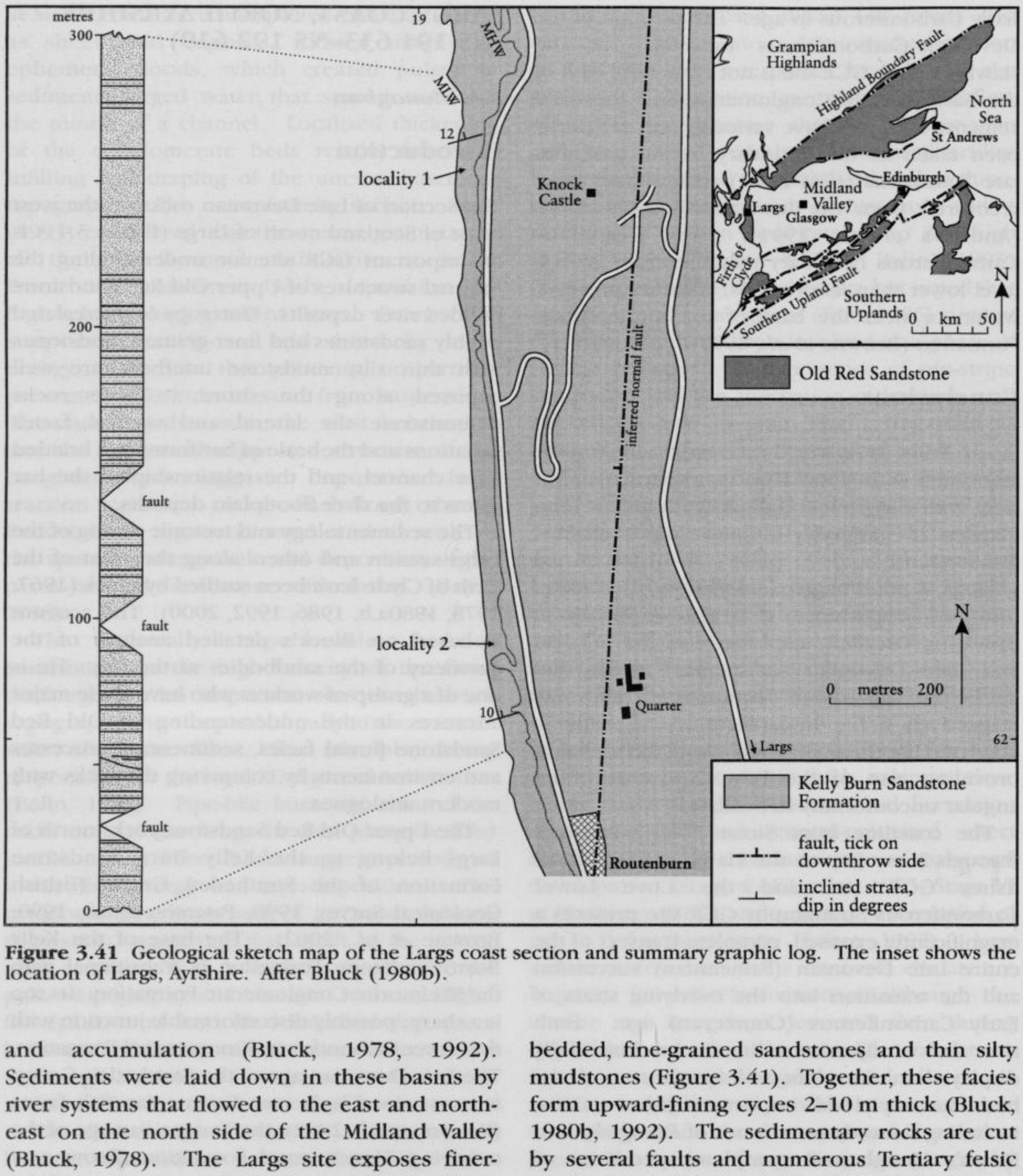



**Figure 3.41** Geological sketch map of the Largs coast section and summary graphic log. The inset shows the location of Largs, Ayrshire. After Bluck (1980b).

and accumulation (Bluck, 1978, 1992). Sediments were laid down in these basins by river systems that flowed to the east and north-east on the north side of the Midland Valley (Bluck, 1978). The Largs site exposes finer-grained sedimentary facies that are distinct from the proximal, coarser conglomerates of the underlying Skelmorlie Conglomerate Formation (Bluck 1967, 1992; Browne *et al*., 2002).

## Description

The Largs coast section, 3 km WNW of the town of Largs, comprises approximately 300 m of cross-stratified sandstones, pebbly sandstones and conglomerates interbedded with planar bedded, fine-grained sandstones and thin silty mudstones (Figure 3.41). Together, these facies form upward-fining cycles 2–10 m thick (Bluck, 1980b, 1992). The sedimentary rocks are cut by several faults and numerous Tertiary felsic alkaline and dolerite dykes (British Geological Survey, 1990).

A typical cycle begins with coarse-grained, pebbly, cross-stratified sandstone that rests on an erosion surface cut in the underlying fine-grained sandstone. The coarse-grained sandstone is generally overlain by finer-grained sandstones with complex sedimentary structures, lateral facies variations and numerous internal erosion surfaces. Two examples of such cycles are described in detail.

### *Locality 1. West of Knock Castle (NS 1913 6303)*

This outcrop (Figure 3.42) commences with an upward-coarsening unit 2.8 m thick resting on a basal erosion surface and comprising 0.5–1 m-thick beds of cross-stratified, pebbly sandstone. The foresets of the cross-stratification have a comparatively low spread of dip directions. Above this, a 4 m-thick, upward-coarsening unit consists of four facies that interfinger down-dip and have transitional boundaries. The facies are:

1. An eastward-thinning sandstone wedge with soft-sediment folding and re-folding structures.
2. A cross-stratified sandstone that thins to the east and has converging dips.
3. A sheet of upward-coarsening, coarse-grained, pebbly sandstone that caps the outcrop.
4. A coarse-grained sandstone of uncertain affinity.

Cross-bedding indicates a north-westerly palaeoflow and the whole outcrop becomes finer-grained in that direction.

### *Locality 2. WNW of Quarter (NS 1917 6215)*

Two groups of facies can be observed at this locality. The lower group comprises alternations of planar sheets of sandstones and thin, subordinate, silty mudstones with desiccation cracks. The sandstones exhibit cross-stratification, low-angle cross-stratification and parallel lamination, and locally rest on erosion surfaces. These beds dip in the same direction as the coarser overlying group and have similar north-easterly palaeocurrents.

An erosion surface separates the two groups. The basal part of the upper group comprises pebbly sandstones with large-scale cross-stratification that dips radially outwards. Smaller-scale cross-stratification migrates along and down the larger foresets. Above this, a mudstone bed grades laterally to the east and north into clay-rich sandstones and westwards into a wedge of pebbly sandstones. In turn, these partly interfinger with, and are overlain by, pebbly sandstones that form a tabular cross-stratified unit with much internal re-activation and ripple cross-lamination.

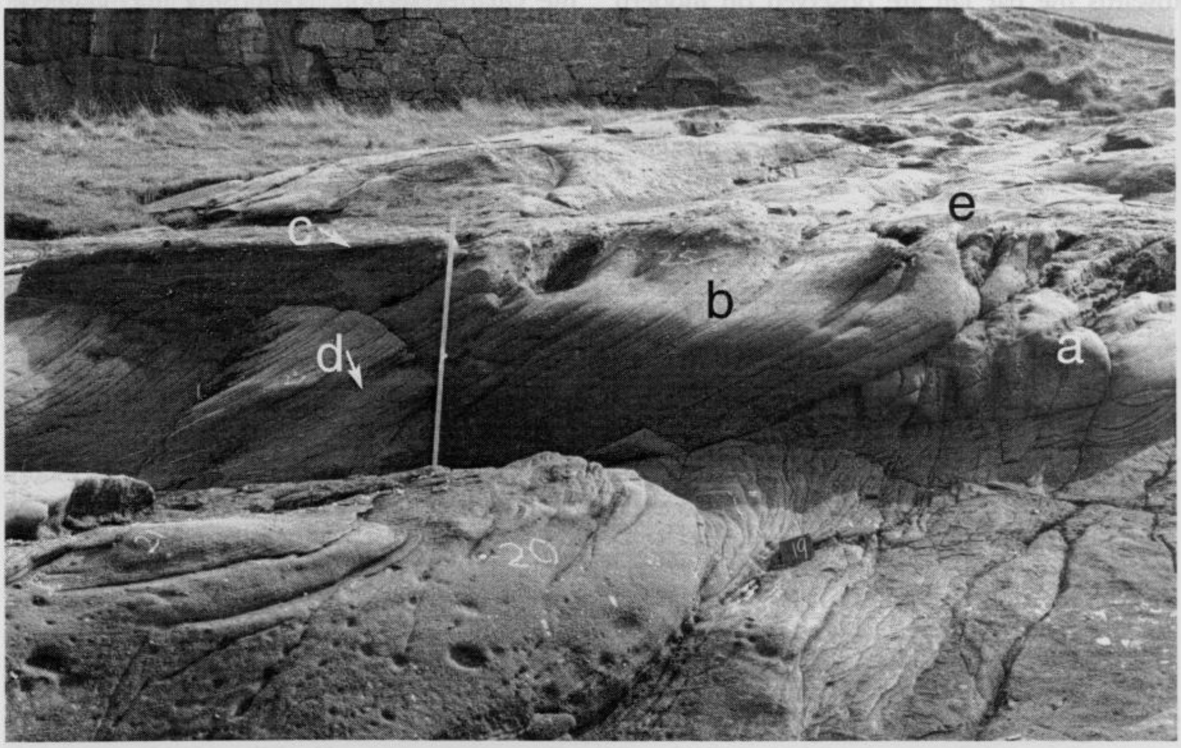



**Figure 3.42** Cross-bedded sandstones, west of Knock Castle (NS 1913 6303). An upward-coarsening unit interfingering between coarse sediment (e) and fine sediment (d) at (a); gradational contact between coarse and fine sediment at (b); sharp, erosive contact at (c), and counter-current ripples at (d); scale rule 1 m. (Photo: B.J. Bluck.)

## Interpretation

A key feature in the recognition of bar form in braided river systems is the upward coarsening of the sands from a sharp base, caused by the downstream migration of the coarse-grained head of the bar over the finer-grained tail (Bluck, 1992; Figure 3.43). Also, braided pebbly alluvium has palaeocurrents that vary laterally and vertically and a facies distribution that indicates the influence of the bar form on river flow (Figure 3.43; Bluck, 1980b; Miall, 1996). The Knock Castle section and the upper part of the Quarter section can be interpreted as different types of braided river-bar deposits. At the Knock Castle outcrop, the consistent dips and volume of coarse-grained, cross-stratified sandstones in the lower part are attributed to bedform deposition within a river channel (Bluck, 1980b). The upper part is interpreted as a mid-channel bar form, where the bar head (represented by the coarse-grained, pebbly sandstone sheet) migrated north-west over the bar tail (represented by the deformed sandstone; see Figure 3.43). The converging palaeocurrents in the cross-stratified sandstones towards the bar tail are observed on modern bar forms that have channels to each side (Bluck, 1980b, 1992). The variability of facies and palaeocurrents implies that the bar split the flow of the river and was subject to variations in water-level. The bar sequence thickens downstream and indicates a minimum water depth of about 3 m. The Knock Castle outcrop is therefore an overall fining-upward cycle interpreted as the growth of a mid-channel bar over an earlier mid-channel bedform (Bluck, 1980b).

At the outcrop WNW of Quarter, the structure and palaeocurrents of the lower pebbly sandstones indicate a linguoid bar within the river (Bluck, 1980b; Figure 3.44, Stage 1). The facies arrangements and geometry in the upper part of the section suggest that the linguoid bar later acted as a lateral bar at least 1 m high, separated from the bank by an abandoned channel in which muds accumulated (Bluck, 1980b; Figure 3.44, Stage 2). During flood events, the lateral bar acted as a 'chute bar' when the river flowed across it. The direction of bar migration, as indicated by the sandstone sheets, was normal to the general flow of the river (Figure 3.44). In addition to the bar facies, the lower part of the Quarter section, comprising finer-grained,

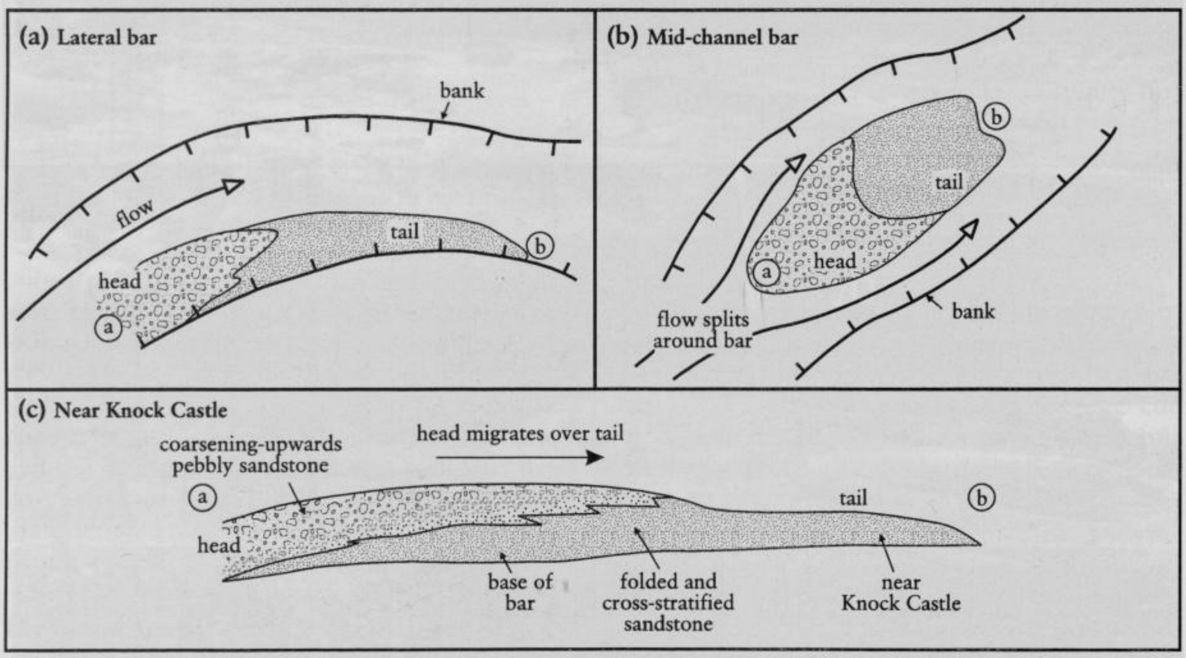



**Figure 3.43** (a) Flow around lateral bar; and (b) mid-channel bar; (c) cross-section through a bar. After Bluck (1992).

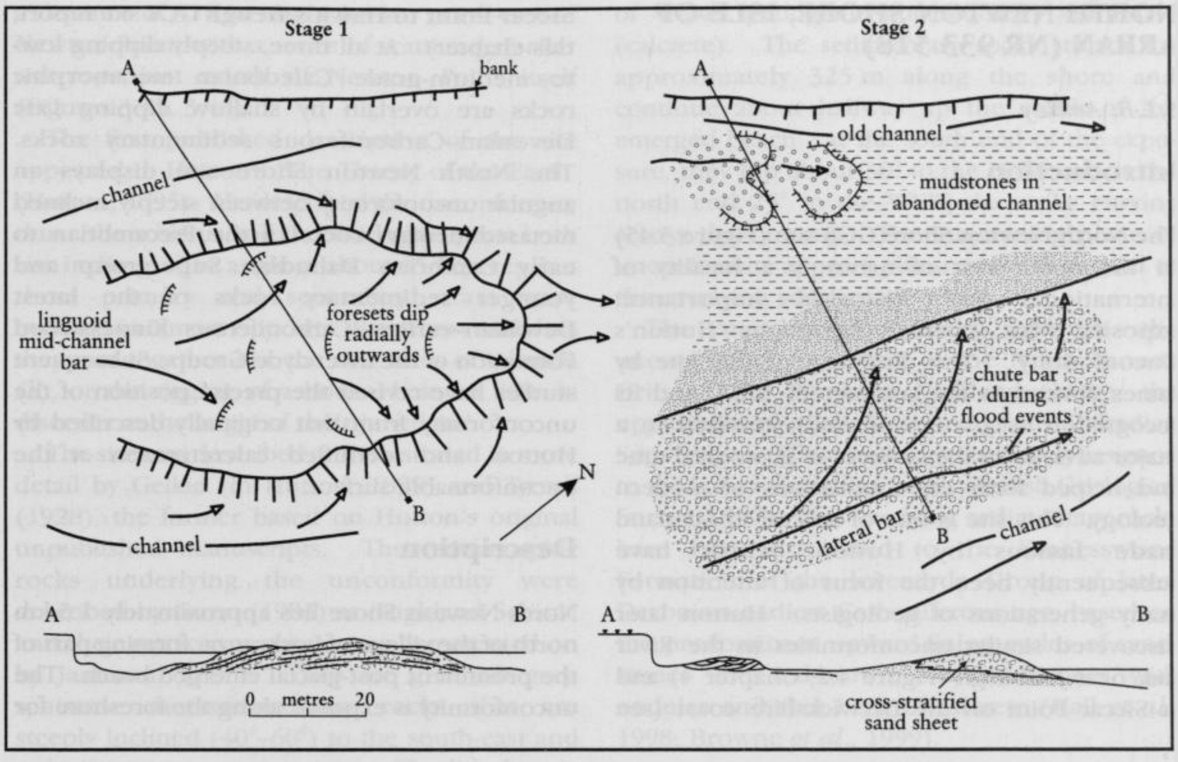



**Figure 3.44** Plan and cross-sectional views (A–B) of the interpreted development of bars at Locality 2, WNW of Quarter. Stage 1 records the growth of a linguoid mid-channel bar, Stage 2 records the development into a lateral and chute bar. After Bluck (1980b).

planar sheet-like sandstones and thin mudstones, is interpreted as the deposits of a floodplain that was periodically subaerially exposed (Bluck, 1980b). The sandstones were ripple-topped, lobate sand sheets deposited by decelerating flows. Palaeocurrents suggest that the sheet flooding occurred on a broad floodplain, with flows in the same direction as the channel and no levees to the channel. Preservation of fine lamination and the lack of iron reduction suggest that that the floodplain had a meagre plant cover or was unvegetated (Bluck, 1980b).

The sedimentary rocks of the Largs section occur in fining-upward cycles with sharp, basal erosion surfaces, and are interpreted as the deposits of a braided river system (Bluck, 1967). The cyclicity is thought to result from the migration of the active river channel over the floodplain. The overall dip of cross-stratification implies flow to the north-east, but the accretion directions of bars and bedforms are commonly to the north-west. The Largs site is therefore interpreted to have been at the north-west margin of a 'cone' of sediment prograding to the ENE (Bluck, 1980b).

## Conclusions

The well-exposed Largs Coast GCR site is a key locality for observing and understanding the typical three-dimensional structures and processes of sediment deposition in an ancient braided stream system. Detailed sedimentological study at the site has allowed the reconstruction of a braided river system subject to changing water-levels and channel switching. Of the two sections discussed in detail, one illustrates the change from a channel bedform to a migrating mid-channel bar, and the other shows the transition from a linguoid mid-channel bar to a lateral bar at the side of the river channel (Figures 3.43, 3.44). Floodplain deposits are identified between the barforms. The thickness of the bars suggests a minimum water depth of 1–3 m at this locality.

## NORTH NEWTON SHORE, ISLE OF ARRAN (NR 933 518)

*S.L.B. Arkley*

### Introduction

The North Newton Shore GCR site (Figure 3.45) in the north-west of Arran is a locality of international and historical importance, exposing what is widely known as 'Hutton's Unconformity'. The discovery of this site by James Hutton in the summer of 1787, and its recognition as an unconformity, resulted in a major advance in the concept of geological time and helped form the foundations of modern geology. This site is one of several in Scotland made famous by Hutton, which have subsequently been the focus of attention by many generations of geologists. Hutton later discovered similar unconformities in the River Jed, near Jedburgh (Figure 4.2, Chapter 4) and at Siccar Point on the Berwickshire coast (see **Siccar Point to Hawk's Heugh** GCR site report, this chapter). At all three, steeply dipping low- to medium-grade Caledonian metamorphic rocks are overlain by shallow dipping Late Devonian–Carboniferous sedimentary rocks. The North Newton Shore site displays an angular unconformity between steeply inclined metasedimentary rocks of the Precambrian to early Cambrian Dalradian Supergroup and younger sedimentary rocks of the latest Devonian–earliest Carboniferous Kinnesswood Formation of the Inverclyde Group. Subsequent studies have revised the precise position of the unconformity from that originally described by Hutton, and identified calcretization at the unconformable surface.

### Description

North Newton Shore lies approximately 1.5 km north of the village of Lochranza, forming part of the prominent post-glacial emerged beach. The unconformity is exposed along the foreshore for

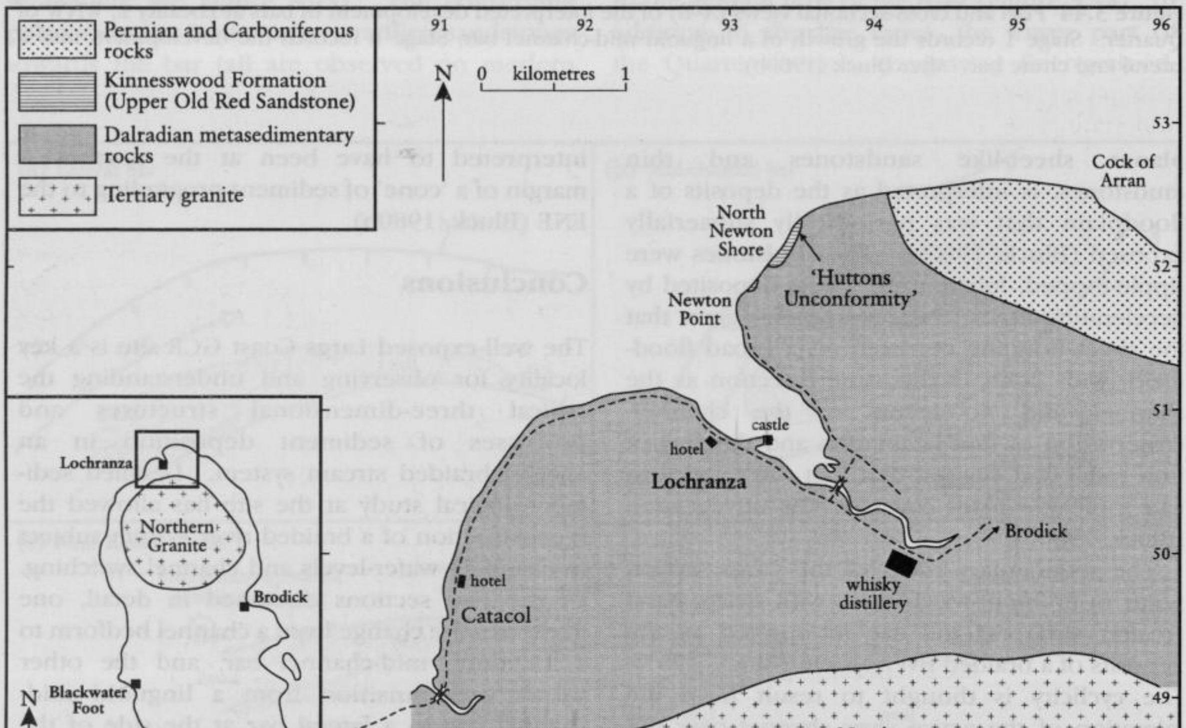



**Figure 3.45** Geological map of the area of North Newton Shore and Hutton's Unconformity, Isle of Arran. Inset shows location of map.

a distance of 325 m, about 0.5 km north-east of Newton Point, with a series of scattered smaller outcrops just north of Newton Point itself (Figures 3.45, 3.46).

The first published description of the site appeared in Hutton's 'The Theory of the Earth' (Hutton, 1795). He described the unconformity thus: 'the schistus and the sandstone strata both rise inclined at an angle of about 45 degrees; but these primary and secondary strata were inclined in almost opposite directions; and thus they met together like the two sides of a lamda (λ), or the rigging of a house, being a little in disorder at the angle of their junction.'

The site was described and illustrated in more detail by Geikie (in Hutton, 1899) and Tyrrell (1928), the former based on Hutton's original unpublished manuscripts. The metamorphic rocks underlying the unconformity were described by Gunn (1903) as 'Highland Schists' and their micaceous nature was commented on by Jameson (1800). They are greenish grey, schistose metasedimentary rocks that are steeply inclined (40°–60°) to the south-east and contain common quartz veins. The lithology is dominantly a greywacke grit, with bands of finer-grained, more micaceous, chloritic slaty material. The metamorphic rocks are overlain by red and yellowish sandstones containing lenticular calcareous beds, breccias and distinctive beds of white, pedogenic concretionary carbonate (calcrete). The sedimentary rocks stretch for approximately 325 m along the shore and continue about halfway up the width of the emerged beach. At the south end of the exposure, they dip about 30° to the NNW and at the north end 25° to the WNW, the strike curving across the outcrop. The intervening plane of unconformity appears planar and sub-parallel to the overlying sedimentary rocks.

The metamorphic rocks beneath the unconformity form part of the North Sannox Grits of the Southern Highland Group, the uppermost stratigraphical unit of the Dalradian Supergroup. These rocks are tentatively assigned to the Lower Cambrian Series (British Geological Survey, 1987). The overlying sedimentary rocks have been attributed to the Kinnesswood Formation of the Inverclyde Group of latest Devonian–earliest Carboniferous age, based on the predominant upward-fining cycles of sandstones and red-brown, silty mudstones with nodules and thin beds of calcrete (Hall *et al.*, 1998; Browne *et al.*, 1999).

## Interpretation

North Newton Shore is one of the most important localities in the development of modern geology. Hutton recognized that the juxtaposition of two

**Figure 3.46** Hutton's Unconformity. Steeply dipping Dalradian metasedimentary rock in the foreground (lower half of image), overlain by more gently inclined thicker-bedded Upper Old Red Sandstone sedimentary rocks dipping towards the sea. (Photo: S.L.B. Arkley.)

lithological units displaying very different geological characteristics could not be explained by normal continuous rock-forming processes. This led him to propose that a gap in deposition had occurred, during which erosion took place, prior to deposition of the overlying rock mass. This interpretation and the concept of 'unconformability' eventually became widely accepted by the geological community, and unconformities are recognized as fundamental to the study of geology and geological time.

Several workers examined the site during the twentieth century, resulting in a re-assessment of the precise location of the plane of the unconformity. Anderson (1944, 1954) established that the lower 1.2 m of the calcareous sedimentary rocks were in fact 'calcitised' grits belonging to the underlying metamorphic rocks, thereby re-positioning the plane of unconformity at the base of the overlying 0.6 m-thick calcrete (cornstone) that underlies the calcareous, red, pebbly sandstones. This was subsequently confirmed and illustrated by Tomkeieff (1953) (Figure 3.47).

More recently, the importance of the 'calcitised' horizon has been recognized and it has been re-interpreted as having formed by carbonate pedogenesis during Late Devonian to Early Carboniferous times. Intensive fragmentation of the metamorphic rocks at and below the unconformity surface resulted from displacive and replacive carbonate formation, which is strongly developed along the schistosity planes in a bed up to 50 cm thick (Bucheit *et al.*, 1997; Donovan *et al.*, 1998). This zone of altered and calcretized metamorphic rock is parallel to the overlying unconformable surface. Interpreted by earlier workers as a 'sedimentary' cornstone deposit containing clasts of gritty material, it is a calcified regolith. Donovan *et al.* (1998) identified two higher calcretized horizons. The lower overlies the calcified regolith and is a 25 cm-thick calcretized schist pebble breccia containing angular clasts up to 8 cm in length, supported within a carbonate matrix dominated by dolomite spar. The uppermost pedogenic layer is a calcretized quartz pebble conglomerate containing abundant rounded clasts up to 3 cm in diameter, and a few schist clasts.

The geological features exposed at the site provide clear evidence for a time interval between the formation of the underlying deformed and metamorphosed Dalradian rocks and the deposition of the overlying latest Devonian–earliest Carboniferous sedimentary rocks. In addition, the unconformity exhibits features that indicate the geological environment and climate immediately prior to deposition of the overlying sediments. The interpretation of the carbonate-rich horizons as calcretized regolith and pedogenic horizons invokes a long period of subaerial weathering in a semi-arid environment with seasonal rainfall prior to the deposition of the mineralogically mature alluvial deposits of the Kinnesswood Formation.

## Conclusions

The North Newton Shore GCR site is recognized internationally as an important site in the history of geology, discovered by James Hutton in the 18th century. The site provides a superb example of an angular unconformity where the age relationships between two distinct superimposed rock masses can be demonstrated

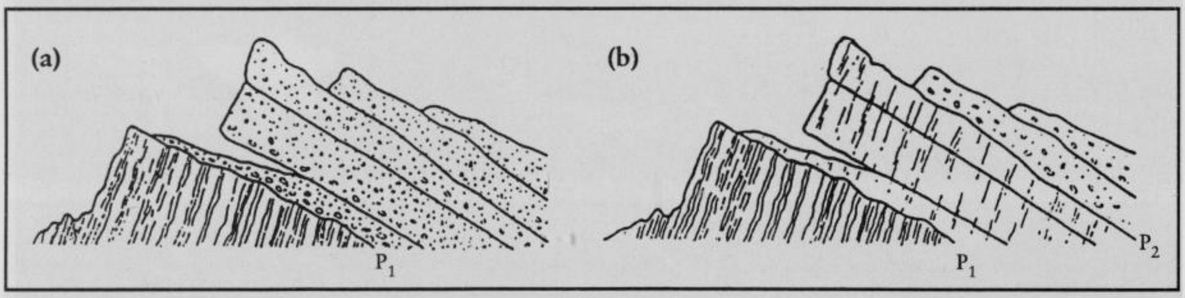



**Figure 3.47** Sketches of Hutton's Unconformity at North Newton Shore from Tomkeieff (1953) showing his re-interpretation of the precise contact between the two rock formations. Height of illustrated exposure is about 1 m. (a) – position of plane of unconformity as placed by Hutton ($P_1$); (b) – new position as suggested by Tomkeieff ($P_2$).

clearly. The steeply inclined Caledonian metasedimentary rocks of the Dalradian Supergroup are directly overlain by much younger sedimentary rocks belonging to the latest Devonian–earliest Carboniferous Kinnesswood Formation. The more recent recognition of a calcrete horizon at the unconformity has resulted in the re-positioning of the unconformable surface and increased the understanding of the pedogenic processes that occurred at the surface during a prolonged period of non-deposition. 'Hutton's Unconformity' has long been used as a teaching site to demonstrate a typical angular unconformity, first recognized over two centuries ago. The site has provoked some controversy and has been the subject of evolving interpretation of the detail of the unconformable junction ever since.