Chapter 3 The Midland Valley of Scotland and adjacent areas

Introduction

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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 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).

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 3.4)a. 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 3.4)f.

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 southwest 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 southeast, 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 microgranitic 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 3.4)c,d and interstratifled 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 palaeocurrents directed to the south-west in a mainly braided river system. Cross-bedding and palaeocurrent 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. Ekes, 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 dose to the Highland Boundary Fault at that time, 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 Lom-Oban area, calc-alkaline volcanism preceded the deposition of fossiliferous sedimentary rocks of P■ídolí to Lochkovian age on peneplained Dalradian basement (Marshall, 1991; Durant, 1999a,b; Bluck, 2000). The area of preservedsub-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 Borderbasin 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

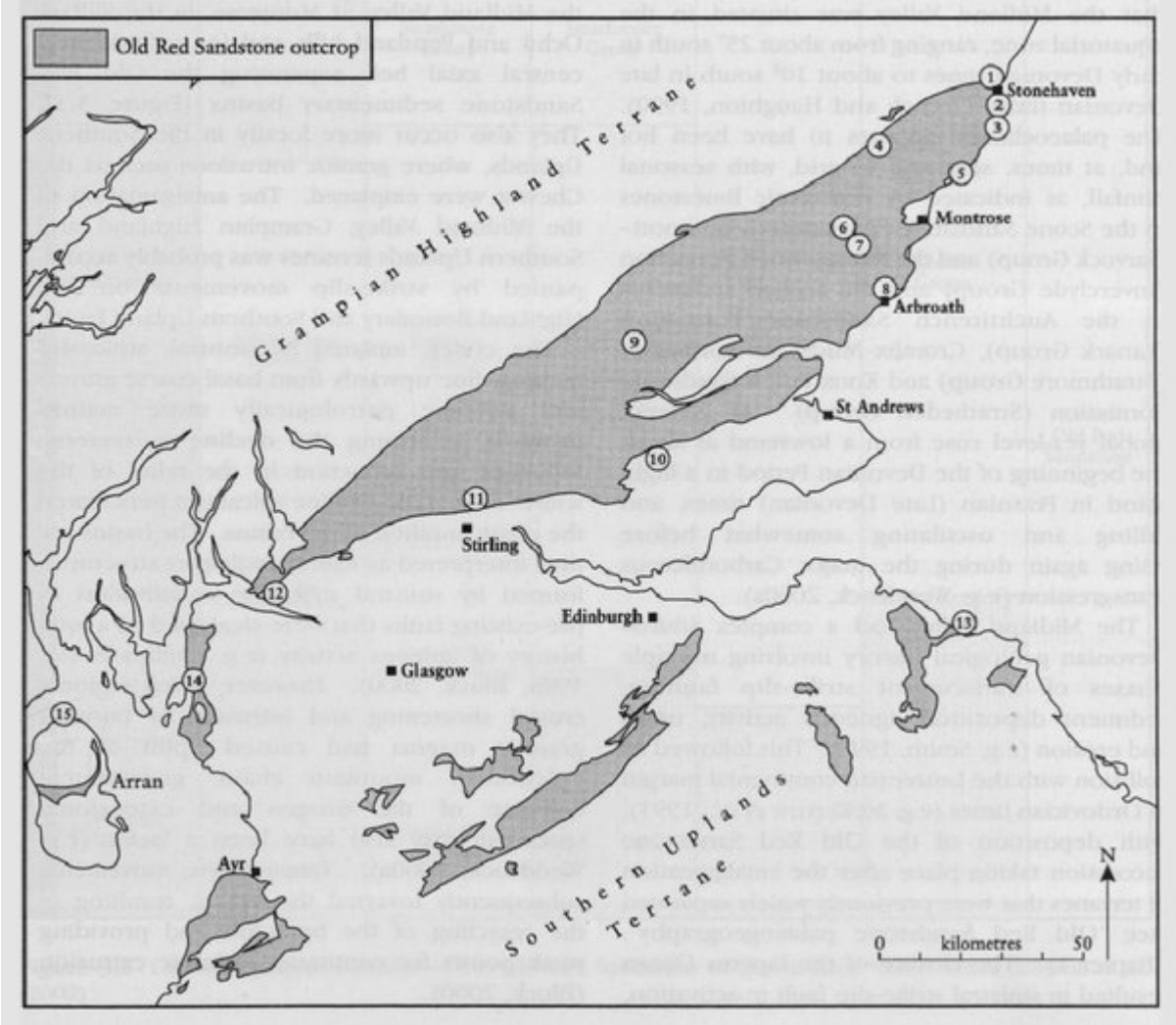
unconsolidated, finely laminated, sandy sediments and andesitic igneous rocks formerly regarded as lava flows, but re-interpreted by Kokelaar (1982) as high-level andesitic sill intrusions. In the Scottish Borders, volcaniclastic conglomerates with some sandstones are interbedded with lava flows of the 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).

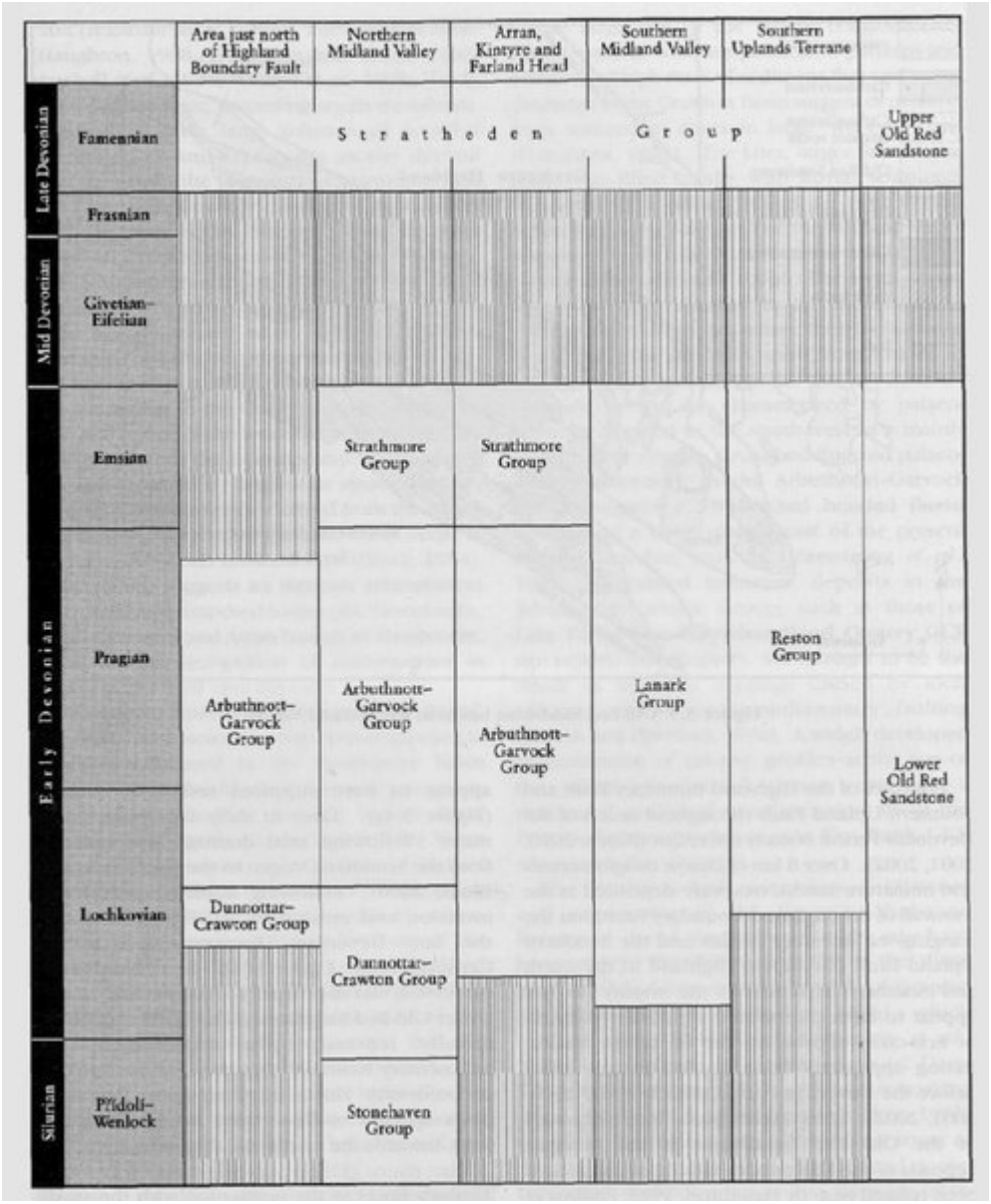
Several Old Red Sandstone GCR sites are described in the companion GCR volume on fossil fishes (Dineley and Metcalf, 1999; (Table 1.2), Chapter 1). Of these, the Whitehouse Den GCR site [NO 426 397] near Dundee, is not described in this volume. It is one of three localities at which the Tealing Fish 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 (Cleat 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).

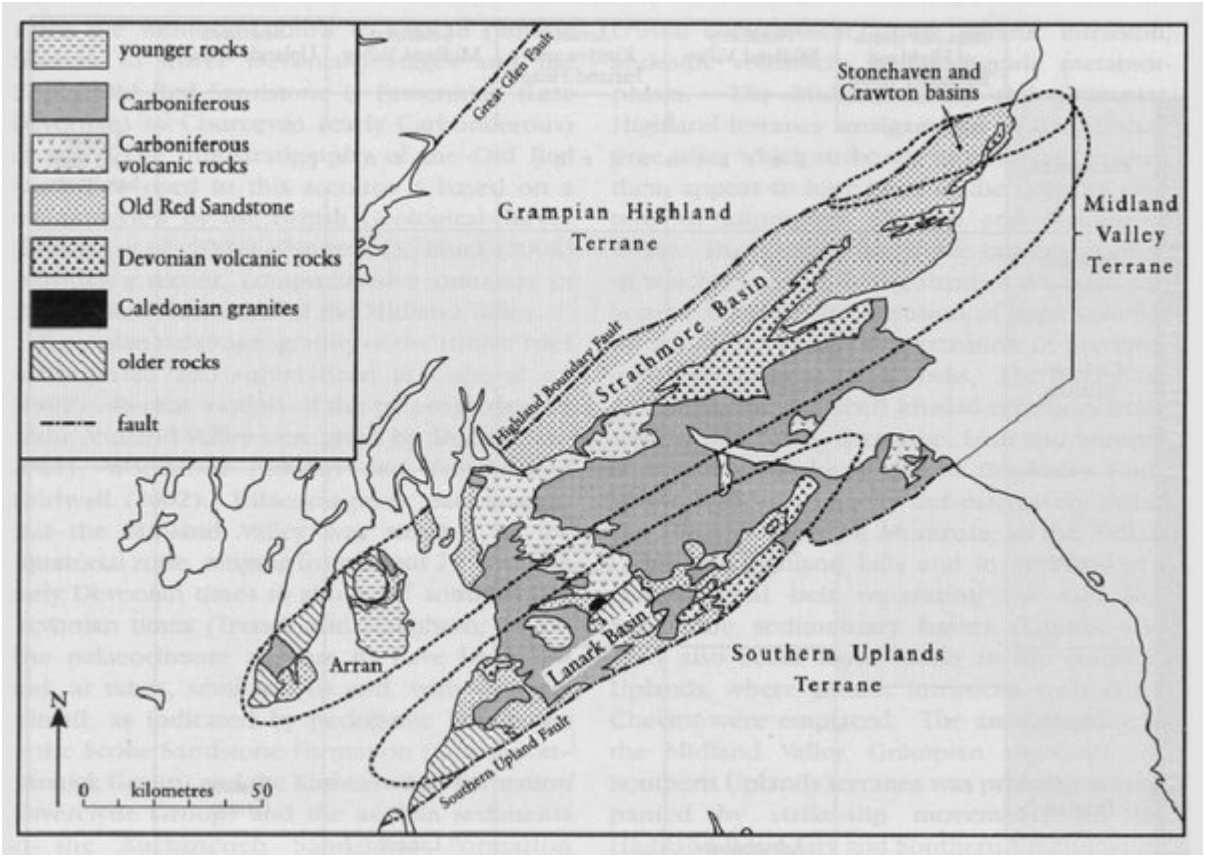
References



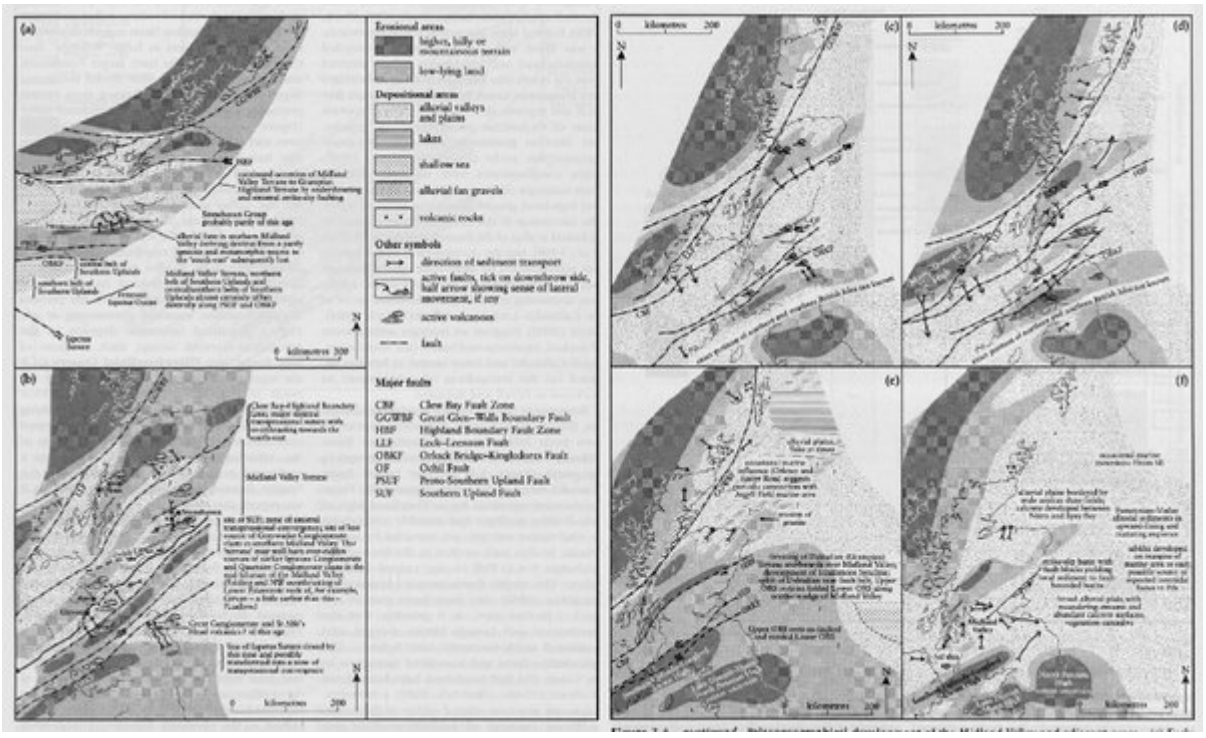
(Figure 3.1) Old Red Sandstone outcrops in the Midland Valley, showing locations of GCR sites: (1 — The Touties; 2 — Dunnottar Coast Section; 3 — Crawton Bay; 4 — North Esk River; 5 — Milton Ness; 6 — Aberlemno Quarry; 7 — Tillywhandland Quarry; 8 — Whiting Ness; 9 — Tay Bank; 10 — Glen Vale; 11 — Wolf's 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).



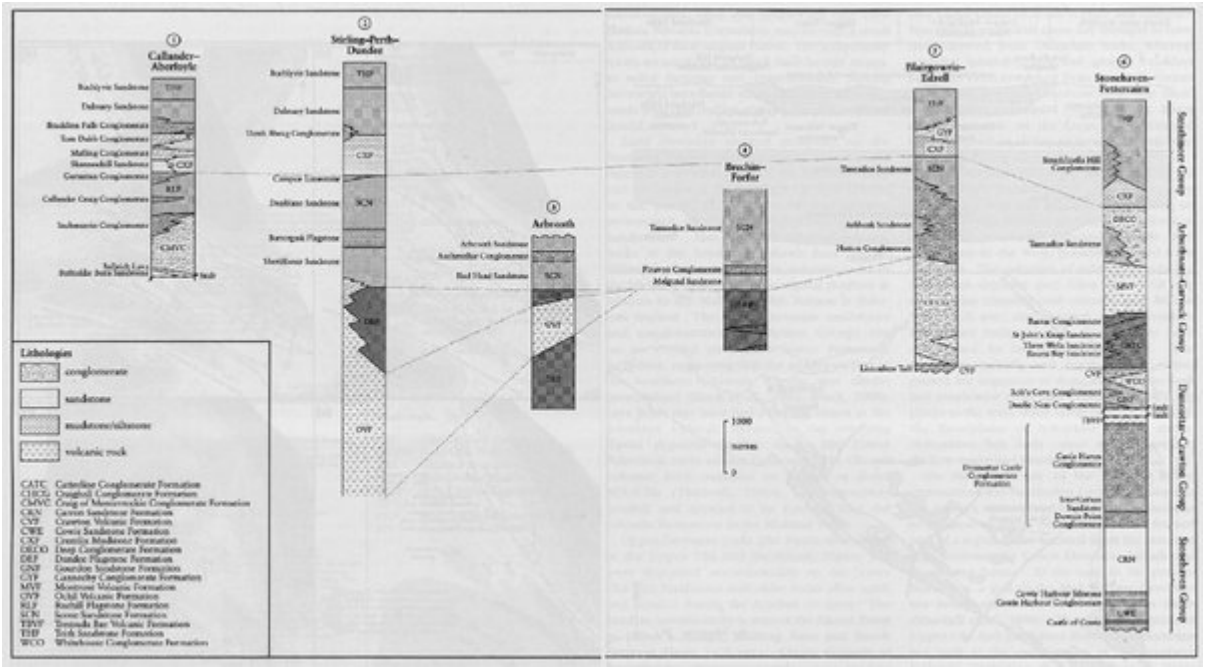
(Figure 3.2) Lithostratigraphical groups of the Old Red Sandstone of the Midland Valley. After Browne et al. (2002).



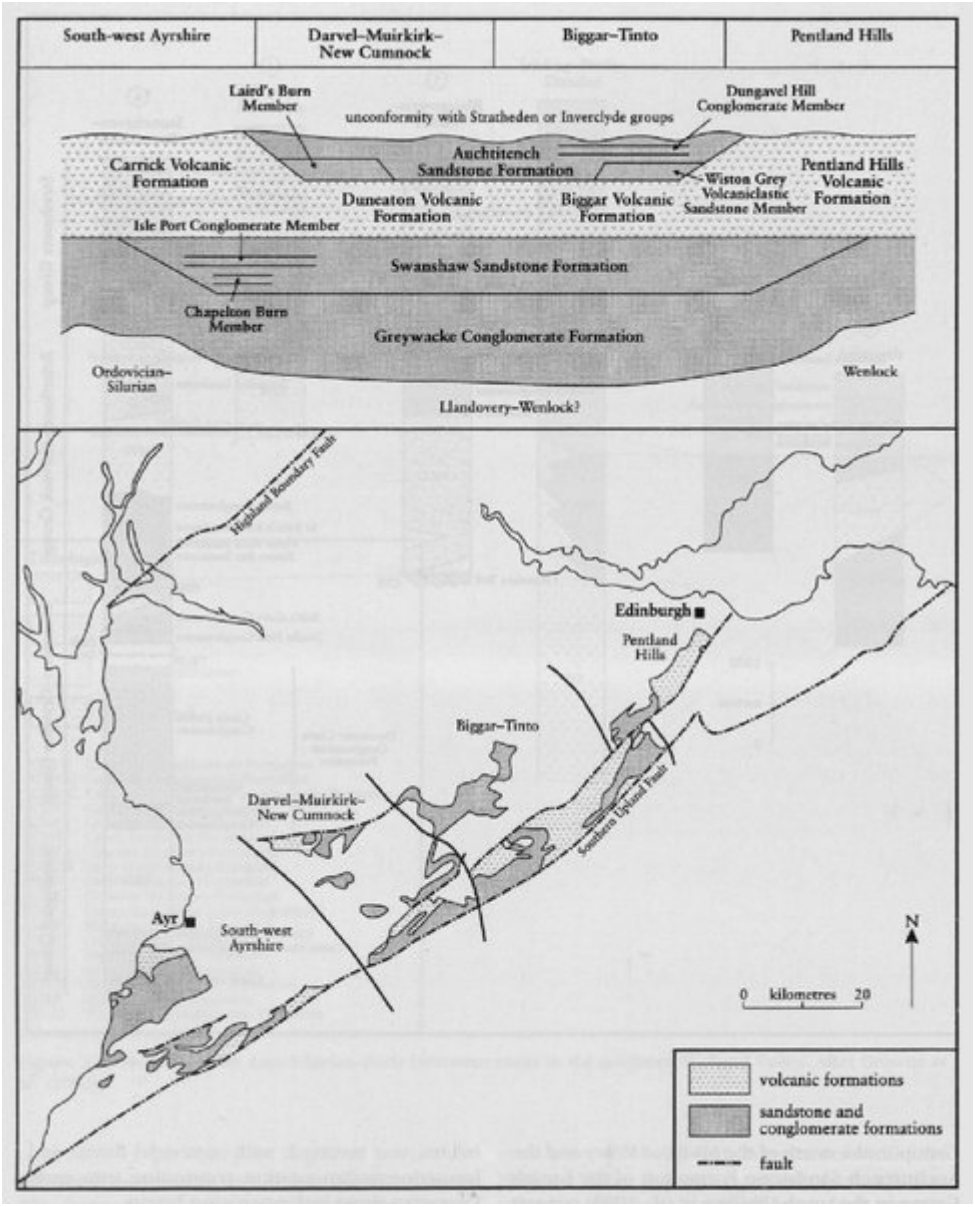
(Figure 3.3) Old Red Sandstone basins in the Midland Valley.



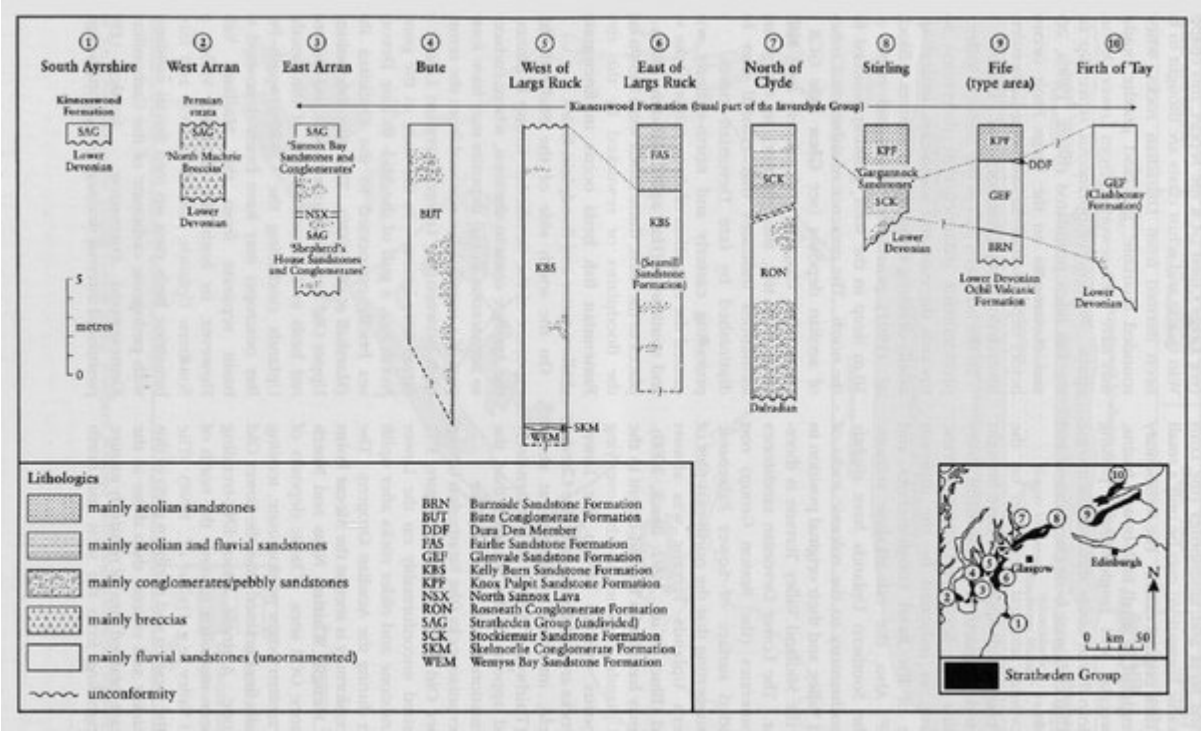
(Figure 3.4) Palaeogeographical development of the Midland Valley and adjacent areas. (a) Early Wenlock; (b) Mid-P■ídolí. (a) after Bassett et al. (1992); (b) after Bluck et al. (1992). Palaeogeographical development of the Midland Valley and adjacent areas. (c) Early Devonian (Lochkovian); (d) Early Devonian (late Pragian–early Emsian); (e) Mid-Devonian (Givetian); (t) 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).



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



(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).

Site	Stratigraphy/ radiometric age	GCR selection criteria
Eshaness Coast	Mid-Devonian	Representative of Eifelian Eshaness volcanic succession, NW Shetland.
Ness of Clousta to the Brigs	Mid-Devonian	Representative of Givetian Clousta volcanic rocks, Walls, Shetland.
Point of Ayre	Mid-Devonian	Representative of Givetian Deerness Volcanic Member, mainland Orkney.
Too of the Head	Mid-Devonian	Representative of Givetian Hoy Volcanic Formation, Isle of Hoy, Orkney.
South Kerrera	Late Silurian to Early Devonian	Representative of Lorn Plateau Volcanic Formation. Exceptional examples of subaerial lava features and interaction of magma with wet sediment.
Ben Nevis and Allt a'Mhuilinn	Mid-Silurian 425 Ma	Representative of Ben Nevis Volcanic Formation. Exceptional intrusive tuffs. Internationally important as example of exhumed root of caldera, and historically for development of cauldron subsidence theory.
Stob Dearg and Cam Ghleann	Mid-Lochkovian 421 ± 4Ma	Representative of succession in eastern part of Glencoe caldera, including basal sedimentary rocks. Exceptional rhyolites, ignimbrites and intra-caldera sediments. Possible international importance for radiometric dating in conjunction with palaeontology close to Silurian–Devonian boundary.
Crawton Bay*	Late Silurian–Early Devonian	Representative of Crawton Volcanic Formation.
Scurdie Ness to Usan Harbour	Early Devonian	Representative of 'Ferrydean' lavas and 'Usan' lavas, comprising lower part of Montrose Volcanic Formation.
Black Rock to East Comb	Early Devonian	Representative of 'Ethie' lavas, comprising upper part of Montrose Volcanic Formation.
Balmerino to Wormit	Early Devonian (Lochkovian) 410.6 ± 5.6 Ma	Representative of eastern succession of Ochil Volcanic Formation. Possible international importance for radiometric dating in conjunction with palaeontology close to Silurian–Devonian boundary.
Sheriffmuir Road to Menstrie Burn	Early Devonian 416 ± 6.1 Ma	Representative of western succession of Ochil Volcanic Formation. Exceptional topographic expression of Ochil fault-scarp.
Tillycoultrie	Early Devonian 415–410 Ma	Representative of diorite stocks, intruded into Ochil Volcanic Formation, surrounded by thermal aureole and cut by radial dyke swarm. Exceptional examples of diffuse contacts due to metasomatism and contamination, with 'ghost' features inherited from country rock.
Port Schuchan to Dunure Castle	Early Devonian	Representative of Carrick Hills volcanic succession. Exceptional features resulting from interaction of magma with wet sediment are of international importance.
Culzean Harbour	Early Devonian	Representative of inlier of Carrick Hills volcanic succession. Exceptional features resulting from interaction of magma with wet sediment are of international importance.
Turnberry Lighthouse to Port Murray	Early Devonian	Representative of most southerly inlier of Carrick Hills volcanic succession. Exceptional features resulting from interaction of magma with wet sediment are of international importance.
Pettico Wick to St Abb's Harbour	Early Devonian *c.* 400+ Ma	Representative of volcanic rocks in the SE of the Southern Uplands. Exceptional vent agglomerates, block lavas, flow tops and interflow high-energy volcaniclastic sediments.

* described in this volume

(Table 1.5) GCR sites with Old Red Sandstone sedimentary rocks described in the Caledonian igneous rocks volume. After Stephenson et al. (1999).

Site	Stratigraphy	Criterion	Treatment in this volum Full description FD Summary description SD Not described ND
Orcadian Basin			
Westerdale Quarry	Mid-Devonian; Eifelian	One of oldest fish-bearing horizons in Orcadian Basin; complete specimens	ND
Achanarras Quarry	Mid-Devonian; Eifelian–Givetian boundary	Richest Old Red Sandstone fish site in Britain	FD
Crusday Quarry	Mid-Devonian; Eifelian–Givetian boundary*	Best Old Red Sandstone fish site in Orkney	ND
Black Park, Edderton	Mid-Devonian; Eifelian–Givetian boundary*	Fish well preserved in three dimensions	ND
Den of Findon, Gamrie	Mid-Devonian; Eifelian–Givetian boundary*	Prolific fish fauna	SD
Tynet Burn, Elgin	Mid-Devonian*	Rich fish fauna and historically important	FD
Melby	Mid-Devonian; Eifelian–Givetian boundary*	Northernmost occurrence of Achanarras horizon	FD
Papa Stour	Mid-Devonian; Eifelian–Givetian boundary*	Fish in sedimentary rocks in predominantly volcanic sequence	ND
Dipple Brae	Mid-Devonian	Fish fauna younger than that of the Achanarras horizon	ND
Spittal Quarry	Mid-Devonian	Rare fish fauna, including only Mid-Devonian cephalaspid	ND
Bannisklirk Quarry	Mid-Devonian	First ORS site to yield fishes	ND
Holborn Head Quarry	Mid-Devonian; mid-Givetian	10–11 fish species, including *Osteolepis panderi*	ND
Weydale Quarry	Mid-Devonian	Well-preserved *Osteolepis panderi* and *Dipterus valenciennesi*	ND
Pennyland	Mid-Devonian; Givetian	Many fish specimens from several fish-bearing horizons	FD
John o'Groats	Mid-Devonian; late Givetian	Youngest fish fauna in Caithness	SD
The Cletts, Eunaboe	Mid-Devonian; late Givetian	Northernmost late Givetian fish site	FD
Sumburgh Head	Late Mid-Devonian; late Givetian	Possibly youngest fish fauna of the Orcadian Basin	ND
Midland Valley of Scotland			
The Tounties	Late Wenlock	Oldest Old Red Sandstone facies rocks in Scotland; unique fish fauna	FD
Tillywhandland Quarry	Early Devonian	One of best Early Devonian fish sites in Scotland	FD
Aberlemno Quarry	Early Devonian	Best surviving of the famous Turin Hill fish sites; also a fossil plant GCR site (Table 1.3)	FD
Wolf's Hole Quarry	Early Devonian	Unique pteraspid fish fauna	FD
Whitehouse Den	Early Devonian	Fossil acanthodian fish	ND
Grampian Highlands			
Ardmore–Gallanach	Late Silurian–Early Devonian	Unique early fish fauna in sediments associated with Lorne lavas	ND
Bogmore, Muckle Burn	Earliest Late Devonian (Frasnian)	Diverse fish fauna with over 15 species	ND
Scaat Craig	Late Devonian	Diverse late Devonian fish fauna and a distinctive tetrapod	ND
Southern Uplands			
Otterdean Burn	Late Devonian	Abundant fragments of *Bothriolepis*	ND
Hawk's Heugh	Late Devonian	Only British occurrence of *Remigolepis*	FD
Anglo-Welsh Basin			
Ludford Lane and Ludford Corner	Silurian; Přídolí	Internationally renowned for rich fish fauna; see also Table 1.4	ND
Ledbury cutting	Silurian; Přídolí	Historical site yielding complete specimens of *Auchenaspis* and *Hemicyclaspis*	ND
Temeside, Ludlow	Silurian; Přídolí	Historical site in Temeside Mudstone Formation yielding a rich fish fauna including *Hemicyclaspis murchisoni*	ND
Tite's Point (Purton Passage)	Silurian; Ludlow–Přídolí	*Thelodus parvidens* fish fauna, allowing correlation with Ludlow Bone Bed, and source of *Cyathaspis*	ND
Lydney	Late Přídolí–Early Devonian	Sequence of vertebrate faunas, including specimens of *Sabrinacanthus*	FD
Downton Castle area (network of 4 sites)	Early Přídolí	Several quarries in Downton Castle Sandstone yielding vertebrate remains	ND
Bradnor Hill Quarry	Late Přídolí	Late Přídolí thelodont fauna	ND
Devil's Hole	Přídolí–Lochkovian	Fish fauna straddling Downtonian–Dittonian boundary	SD
Oak Dingle, Tugford	Lochkovian (Dittonian)	Near-strike section of fish-bearing beds; earliest record of *Weigeltaspis*	SD
Cwm Mill	Lochkovian (Dittonian)	Unique preservation of complete cephalaspids, including three new species; also specimens of *Rhinopteraspis crouchi*	ND
Wayne Herbert Quarry	Lochkovian (Dittonian)	Well-preserved, diverse fish fauna	ND
Besom Farm Quarry	Lochkovian (Dittonian)	Rich, diverse fish fauna, including 7 type specimens and sole occurrence of 5 of them	ND
Heol Senni Quarry	Lochkovian–Pragian	Only occurrence of *Althaspis senniensis*	FD
Portishead	Late Devonian	Unique fish fauna, including only British occurrence of *Groenlandaspis*	FD
Prescott Corner	Late Devonian (Frasnian)	Extensive Late Devonian fish fauna	ND
Afon y Waen	Late Devonian	*Bothriolepis* and *Holoptychius* in Upper Old Red Sandstone	FD

* Achanarras Fish Bed horizon