Chapter 9 Late Silurian and Devonian volcanic rocks of Scotand

Introduction

D. Stephenson

The most voluminous phase of magmatism within the Caledonian Igneous Province of Scotland took place during the later stages of orogenesis, following the collision of Eastern Avalonia with Laurentia along the line of the Iapetus Suture. The 'Newer Granites' (described in Chapter 8), were emplaced during or following the ensuing late tectonic uplift, which ultimately gave rise to the Caledonian mountain chain. Overlapping in age with pluton emplacement was a widespread development of essentially calc-alkaline volcanic rocks and swarms of minor intrusions. On mainland Scotland the products of this volcanism are restricted to the upper Silurian and Lower Devonian, but in Orkney and Shetland they occur in the Middle Devonian, and show geochemical transitions away from calc-alkaline towards both tholeiitic (Shetland) and alkaline (Orkney) compositions. Both the plutonic and the volcanic rocks contributed greatly to the construction of the Caledonian mountain chain; many of the more dramatic mountains of the Scottish Highlands are carved out of the plutons, while the volcanic rocks also form many of the more prominent hill ranges of lowland Scotland.

The locations of all significant outcrops of late Caledonian volcanic rocks in Scotland are shown on (Figure 9.1). The volcanic province extends south-westwards into Antrim, Tyrone and Roscommon in Ireland and similar volcanic rocks may have been exposed formerly to the east of the Grampian Highlands, contributing material to volcaniclastic sediments in the lower part of the Lower Old Red Sandstone succession of the northern Midland Valley. They are absent from the area NW of the Great Glen Fault, apart from in Orkney and Shetland, possibly because of significant lateral and/or vertical movements on this fault. All are associated with Old Red Sandstone sedimentary sequences of continental molasse facies. Most are now preserved in fault-bound basins and their original extent may have been far more extensive prior to erosion from the intervening uplifted areas. In some cases the volcanicity was intimately associated with high-level plutons. Volcanic rocks occur in small down-faulted blocks as a result of 'cauldron subsidence' at Glen Coe and within the Ben Nevis pluton. Elsewhere plutons have risen through volcanic sequences, as at Glen Etive and Cruachan where the Etive pluton cuts earlier lavas, and also far to the south in the Cheviot Hills, where an extensive lava field is intruded by a granite pluton.

The stratigraphical age of the volcanic rocks, and consequently of the continental Old Red Sandstone successions, was originally poorly defined, being based on a few fragmental fish, arthropod and plant remains (House *et al.,* 1977; Rolfe, 1980), although many more precise determinations are now available as a result of spore data (e.g. Richardson *et al.,* 1984; Marshall, 1991; Wellman, 1994). Published radiometric ages are of variable quality in these rocks, which are in general notorious for their secondary alteration, and many conflicting and confusing interpretations have been presented. All methods of radiometric age determination require critical interpretation of their analytical precision and petrological significance (i.e. as to which crystallization or alteration event is actually being dated). Even where radiometric dates appear to be confirmed by more than one independent method, good geological and palaeontological evidence should not be ignored, and in this volume this always takes precedence, where it is available (e.g. see (Figure 1.2) and (Figure 9.2)). However, radiometric age determinations by several methods have been reviewed objectively by Thirlwall (1988), who has shown that the radiometric ages of the volcanic rocks and closely related intrusions vary systematically across the strike of the Scottish Caledonides (Figure 9.2). In the Grampian Highlands the volcanicity ranges from 424 to 415 Ma (early to mid Ludlow), although related plutonism extends to a minimum of 408 Ma. In the Midland Valley the range of most volcanic rocks and intrusions is 415–410 Ma (late Ludlow to early P■ídolí, although Thirlwall does not rule out the possibility of unexposed older igneous rocks in this area, coeval with those of the Highlands. In the north-western Southern Uplands, intrusions range from 413 to 407 Ma (late Ludlow to early Lochkovian), but intrusions and volcanic rocks in the south-eastern Southern Uplands and the Cheviot Hills, closest to the Iapetus Suture, are notably younger at 398–391 Ma (late Lochkovian to late Pragian), contemporaneous with the youngest granites in the Lake District.

These radiometric dates are very important in reconstructing the sequence of tectonic, magmatic and stratigraphical events in the late stages of the Caledonian Orogeny and, since the volcanic activity spans the Silurian–Devonian boundary, they have assumed great international significance in the construction of the Geological Time Scale. The most commonly accepted date for the base of the Devonian at the time of writing is around 409 Ma (e.g. Harland *et al.,* 1990, as used in this volume), which implies that most of the volcanicity, and consequently much of the Lower Old Red Sandstone sedimentary succession is of late Silurian rather than Early Devonian age. Thirlwall himself suggested 412 Ma on the basis of his dates on Scottish lavas, and a more recent rationalization of the British dates and spore evidence (in particular from Glen Coe and the northern Midland Valley) has resulted in a considerable revision of the estimated date of the Silurian–Devonian boundary to 417 Ma (Tucker and McKerrow, 1995). If this boundary date becomes accepted, as has been proposed by Gradstein and Ogg (1996), most of the volcanicity will be regarded as Early Devonian (Figure 9.2). The only exception will be that of the Grampian Highlands (Glencoe and Lorn), which has given slightly earlier dates of 424–421 Ma, in contradiction with the presence of Lower Devonian fish and arthropods, but within the range of recent spore estimates of latest Silurian to Early Devonian (Marshall, 1991; Wellman, 1994).

The late Silurian and Devonian age volcanic rocks of Scotland and the north of Ireland have been reviewed by Stillman and Francis (1979), Elliot (1982) and Fitton *et al.* (1982) and there have been several detailed studies of the petrology and geochemistry of lava sequences in individual areas (Taylor, 1972; Gandy, 1972, 1975; Groome and Hall, 1974; Slater, 1977; French *et al.,* 1979). However, it was the comparative study of lavas from across the whole province by Thirlwall (1979, 1981a, 1982) which led to a significant advance in the understanding of the origin and evolution of the magmas and a controversial unifying theory of their tectonic setting, related to the subduction of Iapetus oceanic lithosphere beneath the Laurentian continental margin.

The volcanic rocks comprise a high-K calc-alkaline suite, with particularly high K_2O (relative to silica) in such areas as the Sidlaw Hills, the western Ochil Hills and Lorn, suggesting affinities with the 'shoshonitic' suites of active continental margins. Compositions range from basalt to rhyolite, although in most of the more widespread sequences basaltic andesites and andesites predominate. The more acid magmas were erupted from local centres, commonly as pyroclastic material, and ignimbrites are common in several centres.

Most of the lavas are quartz-normative with SiO_2 ranging from 52 to 63% and alumina is generally high. High levels of Mg, Ni, Cr and V in the more basic rocks are taken by most authors to indicate that these are derived from primitive magmas that originated by partial melting of upper mantle material. However, the generally high levels of Ba, Sr, Rb, K, light rare earth elements (LREE) and other incompatible elements are difficult to derive by fractionation of mantle material, which generally has low levels of such elements. It is therefore necessary to invoke an additional source, such as partial melting of the lower continental crust (Groome and Hall, 1974) or subducted, hydrous, oceanic lithosphere (Taylor, 1972). Thirlwall (1982, 1983b, 1986) discussed the origin of the magmas in more detail, based upon a regional study of the trace element geochemistry, together with Sr, Nd and Pb isotopes. He invoked the mixing of melts from two primary sources: primitive mantle, giving the high Ni and Cr levels; and subducted Lower Palaeozoic greywackes, giving the high content of incompatible lithophile elements. The same study concluded that contamination by continental basement material is not likely and that most of the more evolved compositions were probably derived by closed-system fractional crystallization at high crustal levels. Most other authors have also invoked varying degrees of fractional crystallization to produce the more evolved compositions. For example high-pressure melting experiments on lavas from the Sidlaw Hills by Gandy (1975) suggested a multistage model involving fractionation during the ascent of a picritic magma to give a range of high-alumina basalts, followed 'by further low-pressure fractionation of olivine, plagioclase and ilmenite.

In his original study, Thirlwall (1979, 1981a) concentrated on the more primitive basalts and andesites with high Mg, Ni and Cr. He found that these rocks show pronounced spatial chemical variations, with Sr, Ba, K, P, LREE and the ratio La/Y in particular showing up to a six-fold increase north-westwards from the Southern Upland Fault across the Midland Valley and Grampian Highlands, perpendicular to the main Caledonian structural trend (Figure 9.3). The more evolved rocks show similar increases, but their regional pattern is complicated by the effects of fractional crystallization. Broadly similar spatial chemical changes are shown by the late Caledonian plutonic suites (Stephens and Halliday, 1984; see Chapter 8). These spatial variations, coupled with the overall geochemical and petrographical features of the volcanic rocks, are typical of calc-alkaline suites associated with subduction at continental margins. Hence Thirlwall postulated the former presence of a WNW-dipping subduction zone beneath present-day Scotland that originated on the SE margin of the Laurentian continent during closure of the Iapetus Ocean. Compositional stratification in the mantle source, with depleted overlying enriched mantle, is considered to be the cause of the observed spatial variation, which reflects the depth of melting of the primitive source above the subduction zone (Thirlwall, 1982).

Although the subduction model is attractive in that it explains and unites many of the observed features of the late Caledonian igneous activity, it is beset by serious problems related to the overall timing of tectonic events and the distribution of some of the magmatism. For instance, it is now generally accepted from a wide range of evidence that the Iapetus Ocean had closed by the end of Wenlock time, and hence that active subduction had all but ceased, before the onset of volcanicity in the early Ludlow, and prior to the emplacement of most late Caledonian granitic plutons. A further problem is that the volcanic and plutonic rocks of the south-eastern Midland Valley and Southern Uplands are very close to the projected line of the Iapetus Suture relative to rocks of comparable composition in modern subduction settings.

The relationships of the later, Mid-Devonian volcanism in Orkney and Shetland to the main part of the volcanic province have been the subject of some debate. Thirlwall (1981a) and Fitton *et al.* (1982) argued that the trace elements and general transitional calc-alkaline to tholeiitic characteristics of the Shetland and some Orkney lavas suggest a relatively close proximity to the surface trace of the proposed subduction zone. Hence they proposed a curved suture, convex to the SE, which follows the regional Caledonian strike and passes close to the east of Shetland. However, Astin (1983) advocated caution in interpreting the Orkney and Shetland data in terms of subduction, and it has subsequently become accepted that the Middle Devonian sediments and volcanic rocks of this area developed in an extensional basin (McClay *et al.,* 1986; Enfield and Coward, 1987; Astin, 1990). The Shetland lavas and the Deer-ness lavas of Orkney do have geochemical characteristics that may be a relict of earlier subduction, but 'it cannot be stated with certainty that they are closely related to the rest of the province' (Thirlwall, 1981a); furthermore, the alkaline nature of the Hoy lavas could be seen as marking the start of the Carboniferous intra-plate alkaline volcanism (Francis, 1988).

Since the subduction model depends upon the evidence of several suites of Caledonian igneous rocks, it has been discussed, with alternative interpretations, in Chapter 1 in the context of the tectonomagmatic setting of late Caledonian magmatism in general.

Grampian Highlands

The most extensive development of volcanic rocks in the Grampian Highlands is the Lorn Plateau sequence, which extends over some 300 km^2 and is up to 800 m thick, comprising mainly flows of basalt and andesite, with rare acid lavas and ignimbrites. The whole Lorn sequence is 'shoshonitic' (enriched in potassium and other incompatible elements) and the flows on the island of Kerrera are the most shoshonitic in the whole province. The South Kerrera GCR site illustrates a range of features in these lavas, which rest upon fluvial sedimentary rocks containing macro- and microfossils of latest Silurian to earliest Devonian age. Lavas of the Lorn sequence are also seen in the Cruachan Reservoir GCR site (Chapter 8), where they are preserved in a down-faulted screen within the margin of the Etive pluton.

Volcanic rocks are also preserved in cylindrical down-faulted blocks in the classic settings of Ben Nevis and Glen Coe, which illustrate the relationships between surface volcanicity sub-volcanic complexes and underlying granitic plutons. It was in these areas that the concept of 'cauldron subsidence' was first developed by E. B. Bailey and others of the Geological Survey almost a century ago. The model has subsequently been applied worldwide but these original sites, which provide spectacular three- dimensional exposures of the roots of central volcanos, have continued to stimulate teaching and research to the present day. The Ben Nevis and Allt a'Mhuilinn GCR site represents the Ben Nevis pluton (cf. Chapter 8), within which is a subsided block of sedimentary rocks and, largely volcaniclastic, andesitic volcanic rocks, some 650 m thick. The Glencoe volcanic sequence comprises over 1500 m aggregate thickness of fluvial, graben-controlled sedimentary rocks, andesitic lavas and high-level sills, rhyolitic lavas and ignimbrites, and a variety of other volcaniclastic rocks, all enclosed by a later ring fracture and granitic ring intrusion. The complex is represented by five GCR sites. The Bidean nam Bian site gives the most complete section through the volcanic sequence and exposes relationships with the underlying land surface of Dalradian metasedimentary rocks. At Stob Dearg and Cam Ghleann, sedimentary rocks below the volcanic sequence are particularly well developed and have yielded Lower Devonian plant remains and spores. Buachaille Etive Beag exhibits three thick pyroclastic flow units of ignimbrite, separated by erosional surfaces and fluvial sedimentary sequences. Two branches of the ring fault and the ring intrusion are exposed at Stob Mhic Mhartuin and contrasting expressions of these features, together with good exposures of the Dalradian rocks below the volcanic sequence are seen at Loch Achtriochtan.

Elsewhere in the Grampian Highlands there is only sparse evidence of volcanic activity. A 20 m-thick flow of andesite lava in the Lower Old Red Sandstone outlier at Rhynie is closely associated with siliceous sinters that include the internationally renowned plant-bearing 'Rhynie Chert' and significant gold mineralization (Rice and Trewin, 1988; Trewin and Rice, 1992). Single exposures of vesicular andesite in the Cabrach outlier and in the Gollachy Burn, near Buckle have been interpreted as lavas, but could equally be intrusive.

Highland Border

At several places along the Highland Border, Lower Old Red Sandstone rocks of the Strathmore sequence overlap the Highland Boundary Fault to give a series of small faulted outliers resting on Dalradian rocks (Armstrong and Paterson, 1970). Several of these outliers contain basaltic and andesitic lavas and a distinctive dacitic ignimbrite, the 'Lintrathen Porphyry', forms a stratigraphical marker at the top of the Crawton Group on both sides of the fault (Paterson and Harris, 1969). This ignimbrite has been dated at around 416 Ma (Thirlwall, 1988) and is potentially a significant marker close to the Silurian–Devonian boundary. In Kintyre, Lower Old Red Sandstone conglomerates contain boulders of 'lava', possibly derived from the north, thin acid tuffs occur locally and three vents at Southend are very close to the projected position of the Highland Boundary Fault (Friend and Macdonald, 1968). An andesite lava, overlain by conglomerates containing lava pebbles, also occurs in the Lower Old Red Sandstone just south of the fault on Arran.

Northern Midland Valley

In the northern Midland Valley volcanic rocks are present throughout most of the lower part of the Lower Old Red Sandstone Strathmore succession (Figure 9.2), between the Highland Boundary and Ochil faults (Armstrong and Paterson, 1970). Volcaniclastic conglomerates first appear in the middle of the Stonehaven Group, possibly in the late Wenlock to early Ludlow (Marshall, 1991), above which they become a major part of the succession. The earliest lava occurs in the middle of the Dunottar Group and several flows of basalt comprise the Tremuda Bay Volcanic Formation at the top of this group. Isolated flows of andesite occur in the lower parts of the Crawton Group and the top of the group is marked by several flows of basalt and basaltic andesite that comprise the Crawton Volcanic Formation. The latter is well exposed in the Crawton Bay GCR site, where most flows are of the distinctive 'Crawton type' with large flow-orientated plagioclase phenocrysts.

The volcanic activity reached a peak during deposition of the Arbuthnott Group, which is regarded as early Lochkovian on palynological grounds and which has several radiometric age determinations around 412 Ma (Thirlwall, 1988; Tucker and McKerrow, 1995). The group contains two diachronous formations dominated by volcanic rocks. In the NE, the Montrose Volcanic Formation comprises several separate volcanic developments, all of which are thought to have emanated from a centre now covered by the North Sea. The Scurdie Ness to Usan Harbour GCR site represents the lower part of the formation, which comprises two sequences, informally termed the 'Ferryden lavas' (predominantly basaltic andesites) and the 'Usan lavas' (predominantly basalts). The Black Rock to East Comb GCR site exposes the basaltic andesites of the 'Ethie lavas' in the upper part of the formation. The Ochil Volcanic Formation forms the Ochil Hills (Francis *et al.,* 1970) and the Sidlaw Hills (Harry 1956, 1958) and has a maximum thickness of over 2400 m. Olivine basalts and pyroxene andesites predominate throughout the formation, but minor trachyandesites, dacites and rhyodacites also occur. Pyroclastic rocks are thickest, coarsest and most common close to the Ochil Fault suggesting that the main centre of eruption lay to the south of the fault and is now concealed beneath younger strata. Two GCR sites provide sections through typical sequences of basaltic to andesitic lavas and intercalated volcaniclastic sedimentary rocks; Balmerino to Wormit in the eastern Ochils is a coastal section through a 350 m-thick sequence that has also provided radiometric and palaeontological age dating evidence, and Sheriffmuir Road to Menstrie Burn in the western Ochils exposes a 600 m-thick sequence in the dramatic Ochil Fault scarp. Rare acidic lavas are represented by the rhyodacite of the Craig Rossie GCR site and a suite of diorite stocks that cut the volcanic sequence within a wide thermal aureole show a variety of interesting contact relationships in the Tillicoultry GCR site.

The youngest volcanic activity in the northern Midland Valley is recorded by a few local flows of basalt and andesite in the upper part of the Garvock Group, south of Laurencekirk. The succeeding Emsian, Strathmore Group contains no primary volcanic rocks.

Southern Midland Valley

On the SE side of the Midland Valley volcanic rocks occur in a series of generally poorly exposed Lower Old Red Sandstone outcrops, separated by major NE–SW faults, in a 10 km-wide zone parallel to the Southern Upland Fault. At the NE end of this zone, the Braid Hills and Pentland Hills expose up to 1800 m of lavas and pyroclastic rocks with compositions ranging from olivine basalt to rhyolite (Mykura, 1960), that have been dated at *c.* 412 Ma by Thirlwall (1988). Farther to the SW major outcrops occur between West Linton and Douglas (the 'Biggar Centre' of Geikie, 1897), SE of Muirkirk (the Duneaton Volcanic Formation; Phillips, 1994; Smith, 1995), and in the Straiton–Dalmellington area (Eyles *et al.*, 1949). Sequences in the SW are almost entirely of olivine basalt and basaltic andesite, although acid rocks are present in several large sills and laccoliths, such as that of Tinto hill (Read, 1927) which has yielded precise isotope dates of *c.* 412 Ma by both Sm-Nd and 39Ar-^{40}Ar methods (Thirlwall, 1988). Intercalated volcaniclastic sedimentary rocks are common in the south-western outcrops but pyroclastic rocks and recognizable vents are rare.

Other outcrops of volcanic rocks in the Lower Old Red Sandstone occur to the NW of this zone near Galston and in the Carrick Hills. In the latter area a sequence of 300–450 m, consisting almost entirely of olivine basalts and andesites with intercalated fluvial and lacustrine sedimentary rocks, is particularly well exposed on the coast. Three GCR sites at Port Schuchan to Dunure Castle, Culzean Harbour and Turnberry Lighthouse to Port Murray exhibit a variety of sedimentary inclusions, infillings and intercalations within the igneous rocks, which suggest that the magmas were emplaced as shallow sub-volcanic sills within unconsolidated wet sediment (Kokelaar, 1982). Such features have subsequently been recognized in many other parts of the Old Red Sandstone province, and also within Ordovician sequences (Chapters 4 and 6) where many parts of the lava sequences have now been re-interpreted as high-level sill complexes.

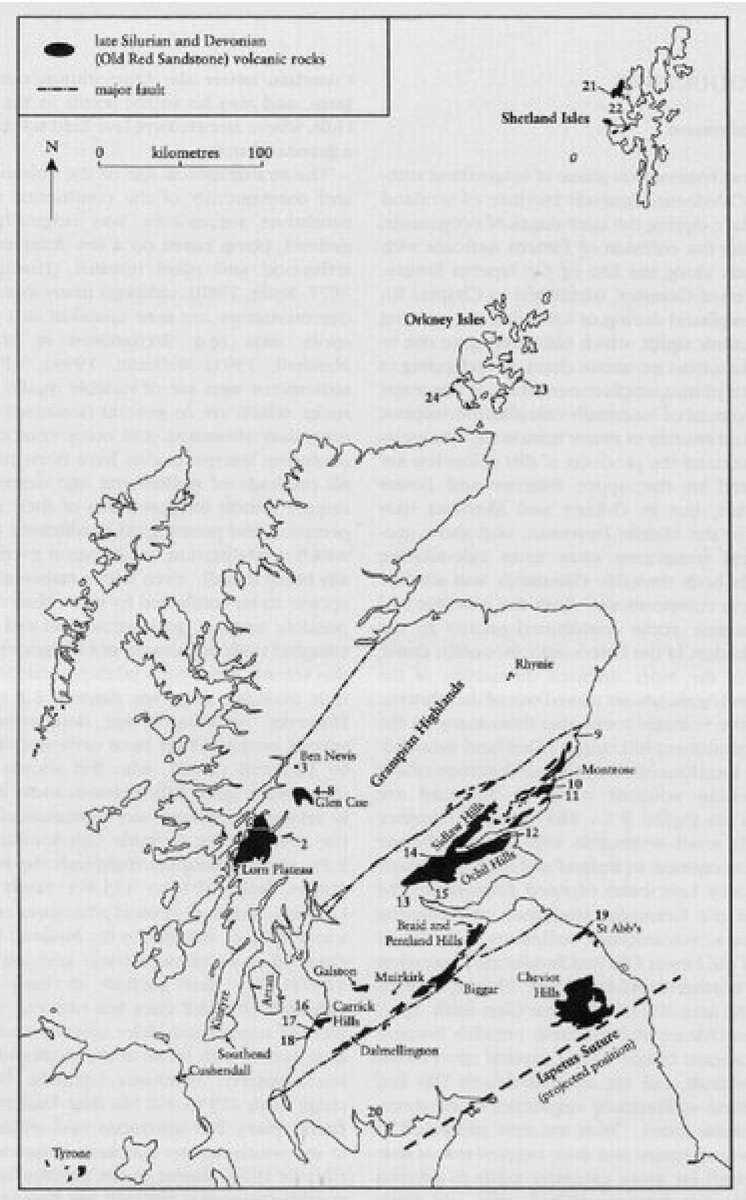
Southern Uplands

South-east of the Southern Upland Fault an extensive lava field in the Cheviot Hills is the most south-easterly expression of the Siluro-Devonian volcanicity (Carruthers *et al.,* 1932; Thirlwall, 1979, 1981a). A poorly exposed sequence of over 500 m, consisting almost entirely of acid andesites and dacites with only local pyroclastic interbeds, is located over the projected line of the Iapetus Suture. Some 25 km to the north, the somewhat smaller outcrop around St Abb's and Eyemouth is magnificently exposed on the coast at the Pettico Wick to St Abb's Harbour GCR site. Here, a 600 m-thick sequence of basalt and basaltic andesite lavas, with interbedded volcaniclastic sedimentary rocks, exhibits a variety of flow features, pre served by rapid burial in a high-energy volcano-sedimentary environment. Volcanic activity farther to the SW in the Southern Uplands is suggested by the presence of a number of subvolcanic vents in Kirkcudbrightshire that are represented by the Shoulder O'Craig GCR site. This coastal locality exposes an intrusion breccia, a basalt intrusion and a series of slightly younger lamprophyre dykes that are part of an important regional swarm (Rock *et al.,* 1986b; see Chapter 8, Introduction).

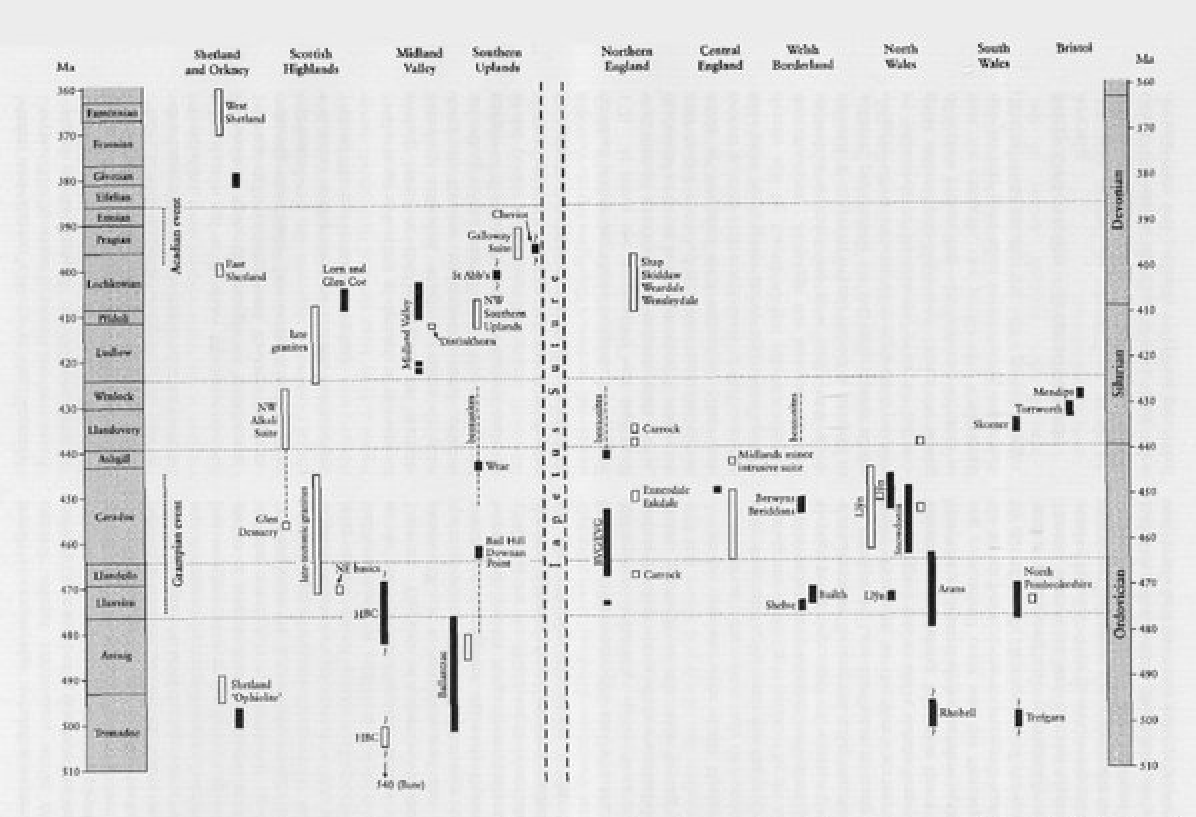
Shetland and Orkney

In Shetland and Orkney volcanic activity occurred during late Mid-Devonian time, significantly later than in mainland Scotland, and it is not certain whether it originated in the same tectonomagmatic setting. The most extensive outcrops are in west Shetland at Melby, Papa Stour and Eshaness, all of which are thought to be of similar late Eifelian age, as are thin tuffs in the Upper Stromness Flags of Hoy, Orkney. The Eshaness GCR site illustrates a sequence of lavas, shallow sills and pyroclastic rocks of olivine basalt to andesitic composition, and a rhyolitic ignimbrite, all exposed by spectacular coastal erosion. Volcanic rocks of Givetian age occur on the Walls Peninsula of Shetland (the Clousta volcanic rocks), and on Orkney at Hoy (the Hoy Volcanic Member) and at Deerness, Shapinsay and Copinsay (the Deerness Volcanic Member). The Clousta volcanic rocks are represented by the Ness of Clousta to the Brigs GCR site, which is notable for its well-bedded pyroclastic rocks, intercalated with alluvial deposits and well preserved beneath a penecontemporaneous basaltic shallow sill. The pyroclastic rocks have been interpreted as the products of phreatic and phreatomagmatic eruptions that emanated from maars and tuff-rings. The Hoy Volcanic Member comprises basaltic breccias, tuffs and lavas of nepheline-normative alkali olivine basalt and hawaiite; they are represented by the Too of the Head GCR site. Although some of the lavas of the Deerness Volcanic Member also show alkaline characteristics, this is regarded as a secondary effect. The member is represented by the Point of Ayre GCR site, where the margin of a basalt lava flow is exposed, together with an underlying air-fall tuff and lacustrine sediments that show synsedimentary deformation associated with the volcanicity.

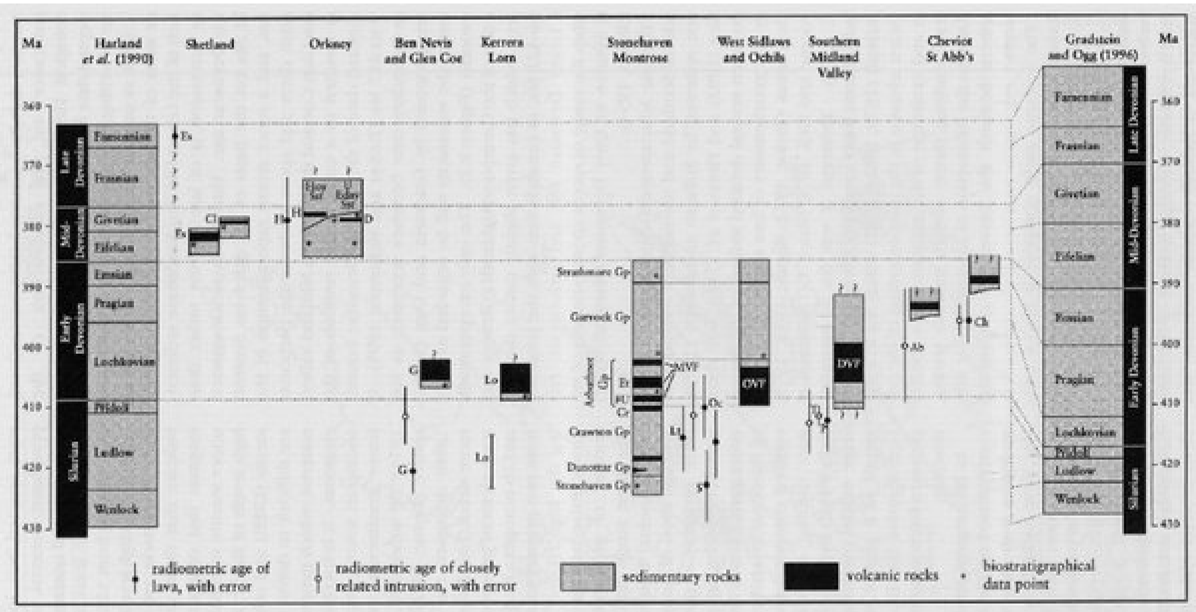
References



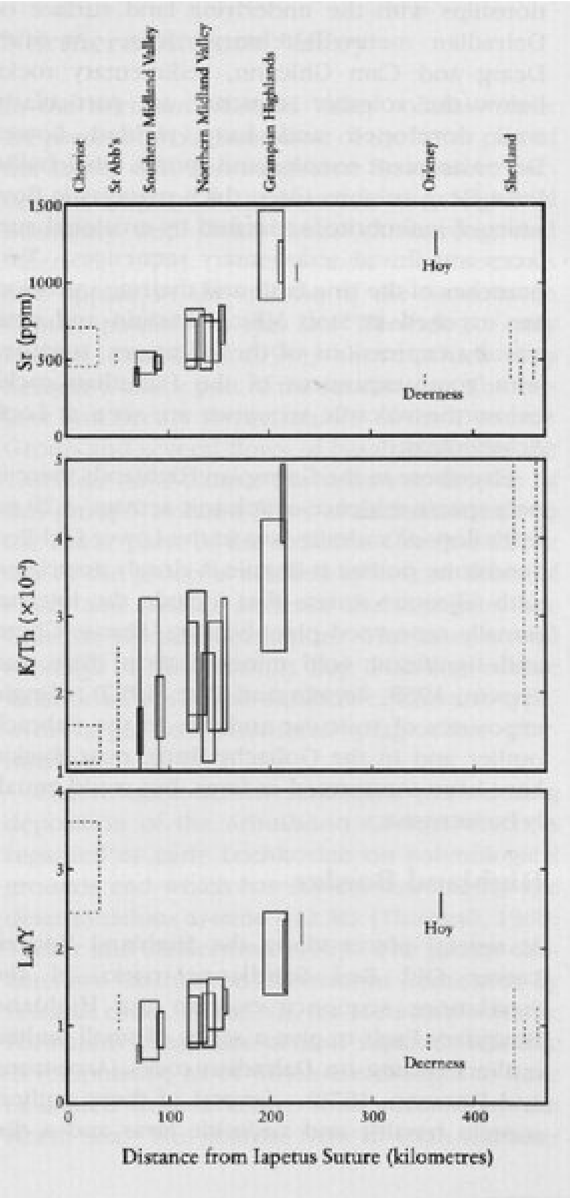
(Figure 9.1) Location of late Silurian and Early- to Mid-Devonian age volcanic rocks of northern Britain. GCR sites: 1, South Kerrera; 2, Cruachan Reservoir (Chapter 8); 3, Ben Nevis and Allt a'Mhuilinn; 4, Bidean nam Bian; 5, Stob Dearg and Cam Ghleann; 6, Buachaille Etive Beag; 7, Stob Mhic Mhartuin; 8, Loch Achtriochtan; 9, Crawton Bay; 10, Scurdie Ness to Usan Harbour; 11, Black Rock to East Comb; 12, Balmerino to Wormit; 13, Sherriffmuir Road to Menstrie Burn; 14, Craig Rossie; 15, Tillicoultry; 16, Port Schuchan to Dunure Castle; 17, Culzean Harbour; 18, Turnberry Lighthouse to Port Murray; 19, Pettico Wick to St Abb's Harbour; 20, Shoulder O'Craig; 21, Eshaness Coast; 22, Ness of Clousta to The Brigs; 23, Point of Ayre; 24, Too of the Head.



(Figure 1.2) Stratigraphical distribution of Caledonian extrusive rocks (solid bars) and intrusions (open bars) in the various terranes of the British Caledonides. The timescale is after Harland et al. (1990); horizontal lines indicate descriptive time units as used in the main text. Wherever possible the extrusive rocks are plotted according to their biostratigraphical range, as are the intrusions of Wales. Other intrusions have little or no biostratigraphical control and hence are plotted according to their currently accepted radiometric ages. This leads to some unavoidable discrepancies, in particular in the upper Silurian to Lower Devonian suites of Scotland, where intrusions and volcanic rocks in the same area are probably much closer in age than the diagram shows (see Chapter 9, Introduction). See individual chapter introductions for more detailed stratigraphical distribution charts.



(Figure 9.2) Stratigraphical relationships and ages of late-Silurian to Mid-Devonian age volcanic rocks of northern Britain. Biostratigraphical ages (where known) are given precedence and are plotted relative to the time-scale of Harland et al. (1990) (on the left). Note the consistent discrepencies between the biostratigraphical ages and the radiometric ages, which are not present if the time-scale of Gradstein and Ogg (1996) (on the right) is used. Where there is no biostratigraphical control (i.e. Southern Midland Valley, St Abb's and Cheviot), the volcanic sequences are projected from *the radiometric dates. For example Cheviot at 396 Ma is early Emsian on the Gradstein and Ogg timescale, so it is plotted in the early Emsian position on the Harland et al. time scale. Ab, St Abb's; Ch, Cheviot; Cl, Clousta; Cr, Crawton; D, Deerness; DVF, Duneaton Volcanic Formation; Es, Eshaness, Papa Stour and Melby; Et, Ethie; FU, Ferryden and Usan; G, Glen Coe; F1, Hoy; Lo, Lorn; Lt, Lintrathen; MVF, Montrose Volcanic Formation; Oc, Ochil Hills; OVF, Ochil Volcanic Formation; P, Pentland Hills; S, Sidlaw Hills; T, Tinto.*



(Figure 9.3) Ranges of whole-rock Sr, K/Th and La/Y from late Silurian and Devonian volcanic rocks of northern Britain, plotted against projected distance from the Iapetus Suture of Phillips et al. (1976). Adapted from Fitton et al. (1982, fig. 9). The heights of rectangles and bars represent the range of values within geographically related outcrops; the width of the rectangles represents each outcrop width. Southern Midland Valley: Pentland Hills and Lanarkshire, Ayrshire Coast, Straiton; Northern Midland Valley: Ochil Hills, north Fife hills, Sidlaw Hills, Montrose, Highland Border; Grampian Highlands: Ben Nevis, Glen Coe, Lorn Plateau; Orkney: Deerness, Hoy; Shetland: Eshaness, Papa Stour, Clousta; Note the anomalous values (dotted lines) from the Cheviot and St Abbs outcrops, close to the proposed line of suture, and from the Deerness outcrops of Orkney and all of the Shetland outcrops (see text for discussion).