Chapter 4 Silesian and Early Permian volcanic rocks of Scotland

Introduction

D. Stephenson

Volcanism continued intermittently throughout Dinantian time in the Midland Valley of Scotland, but as the sedimentary basins developed and the palaeogeography changed from fluvial plains with lakes to deltas, estuaries and shallow seas, so the nature of the volcanism changed. The vast subaerial lava plateaux and linear eruptive centres that dominated earlier Dinantian times were replaced in later Dinantian and Namurian times by more localized, short-lived, central vent complexes, characterized by more explosive, phreato-magmatic eruptions. Pyroclastic deposits are a major product of these eruptions and the lavas are almost exclusively basaltic (of micro-porphyritic 'Dalmeny' and 'Hillhouse' types); many are silica-undersaturated alkali olivine basalts and basanites. Basaltic hawaiites are rare, and the more fractionated rocks that are a feature of many early Dinantian successions, are absent.

These volcanic conditions were already widely established by the beginning of Namurian time and continued intermittently until at least mid-Westphalian times in the eastern Midland Valley, though at an overall less productive level than in Dinantian times. In the western Midland Valley, volcanism ceased following a major outpouring of lavas in late Namurian to earliest Westphalian times. Since there are no strata of Stephanian age preserved in Scotland we cannot be certain if there was any volcanism at this time. Large volumes of tholeiitic magma were intruded as dykes and sill-complexes during early Stephanian times (see Chapter 6) but, according to the model of Francis (1982), the magma was under insufficient pressure to reach the surface and there is no evidence of it having done so. Volcanism did resume in latest Stephanian or very early Permian times, when conditions had once again become continental, with localized outpourings of alkali basalt and basanite lavas in western and south-western areas and possibly also in the eastern Midland Valley where some sub-volcanic plugs and necks have late Stephanian to Early Permian radiometric ages.

Most of the Silesian volcanic rocks are interbedded with well-established, commonly fossiliferous, shallow-water sedimentary successions, and it is relatively easy to trace their strati-graphical development (Figure 4.1).

Lavas dominate volcanic successions in the early Namurian rocks of the Bathgate Hills, the late Namurian rocks of north Ayrshire and the Early Permian rocks of south-west Scotland (Figure 4.2). Other eruptions were predominantly of pyroclastic rocks and these are represented only by sub-volcanic necks and beds of ash-fall tuff. However, throughout Silesian times, large volumes of magma solidified at depth as sill-complexes (see Chapter 5). It is likely that the increasing thickness of geotechnically weak sediments in the rapidly developing Silesian basins would be of too low density to support columns of magma, which spread laterally as sills (Francis, 1991). Magma that did have sufficient energy to rise to shallower levels reacted with groundwater and wet sediment to produce violent, phreatomagmatic eruptions. Such eruptions took place largely in areas of shallow water close to low-lying coastal plains. Here, accumulations of sediment and volcanic rocks broadly kept pace with subsidence, but periodically the volcanic rocks would build up above sea level where they were subjected to subaerial weathering, lateritization, erosion and re-deposition as volcaniclastic sediments. As the balance between rates of eruption, erosion and subsidence changed, so the relationships between the volcanic rocks and sediments within the preserved successions varied (Francis, 1961a,b, 1991). Since many of these successions include coal-bearing strata, studies of the volcanic rocks have had vital economic implications. Accumulations of volcanic rocks are commonly surrounded by shoals of volcaniclastic sand, and together these locally 'interrupt' the continuity of otherwise widespread contemporaneous coal seams. They also continued to influence the subsequent development of coal seams due to differential compaction, which led to marked attenuation above the relatively incompressible volcanic piles.

Bathgate Hills, Saline Hills and Kincardine Basin (late Visean to mid Namurian)

The most continuous volcanic activity from late Dinantian through to mid Namurian times occurred in the area around the Bathgate Hills (Peach *et al.,* 1910; Cadell, 1925; Macgregor and Haldane, 1933; Smith *et al.,* 1994; Stephenson in

Cameron *et al.,* 1998). Here, a 600 m-thick succession of basaltic pyroclastic rocks and lavas, the Bathgate Hills Volcanic Formation, extends from the upper part of the Hopetoun Member, West Lothian Oil-shale Formation, to just above the Castlecary Limestone at the base of the Passage Formation. Unfortunately, there are no reliable radiometric dates for this prolonged sequence, which spans the Dinantian–Silesian boundary; some precise Ar-Ar determinations would have clear international value. This important and extensive sequence is not represented at present by a GCR site.

Borehole and mining information to the west of the outcrop suggests that the volcanic deposits are restricted to a sub-circular area, 20–25 km in diameter, that coincides with spectacular positive gravity and magnetic anomalies. The source of these anomalies has been the subject of much debate, as the combined thickness of volcanic rocks (Bathgate Hills and earlier volcanic formations) is insufficient to generate the observed anomalies. Current interpretations favour up to 1 km of volcanic rocks, intruded in their lower part by a large basic mass extending to a depth of about 8 km, and all sited upon a WNW-trending structural high that may have acted as a focus for the igneous activity (Rollin in Cameron *et al.,* 1998). Several necks and plugs that cut older strata to the east of the main outcrop of volcanic rocks give some idea of the former eastward extent of the volcanic field, prior to erosion.

The basal part of the volcanic sequence, up to the base of the Lower Limestone Formation, is predominantly of pyroclastic rocks, except for some more persistent lavas in the Riccarton–Longmuir area. Sporadic graded bedding and load casts suggest subaqueous deposition in places, but numerous seatclays indicate frequent emergence. Layers of chert and spherulitic carbonate within the freshwater East Kirkton Limestone, famous for its terrestrial vertebrate, arthropod and plant fossils (Rolfe *et al.,* 1994; Dineley and Metcalfe, 1999) , have been interpreted as evidence of hot spring activity associated with the volcanism (McGill *et al.,* 1990, 1994). From the top of the Lower Limestone Formation upwards, lavas become dominant at outcrop, although in boreholes to the west, thick, proximal pyroclastic deposits suggest the presence of a long-lived volcanic centre or centres in this area. The petrography of the lavas has been described by Falconer (1906) and Flett (in Peach *et al.,* 1910). They are all alkali olivine basalts or basanites, and are microporphyritic with phenocrysts of olivine and variable amounts of augite ('Dalmeny' and 'Hillhouse' type). Kaolinized or reddened flow tops indicate subaerial eruption.

The overall picture of the Bathgate Hills area is of a low-lying, heavily vegetated coastal plain in late Dinantian times, giving way periodically to shallow marine conditions in Lower Limestone and Upper Limestone formation times. Volcanoes accumulated above sea level to form islands surrounded by coastal plains, restricted lagoons and a variety of carbonate reefs, all neatly modelled by Jameson (1987) (see Petershill Quarry GCR site report in the *British Lower Carboniferous Stratigraphy* GCR volume — Cossey *et al.,* in prep). Carbonaceous mudstones and argillaceous limestones, interpreted as having formed in back-reef lagoons, contain synsedimentary Pb-Zn mineralization related to the volcanism (Stephenson, 1983).

The Saline Hills of western Fife are broadly along strike to the NNE of the Bathgate Hills along the Bo'ness High, a zone of relatively low subsidence that forms the eastern margin of the Silesian Kincardine Basin (Read, 1988). Here, thick tuffs, volcaniclastic sedimentary rocks and rare thin basalt flows occur in the Limestone Coal Formation and parts of the Upper Limestone Formation (Francis, 1961a). The succession is cut by several necks and plugs. Within the Kincardine Basin, boreholes and mine workings have revealed distal tuffs at various levels in the Limestone Coal Formation and Upper Limestone Formation that may correlate with the volcanism in the Bathgate Hills to the south (Francis *et al.,* 1961). These are mostly on the eastern side of the basin, on the flank of the Bo'ness High, where several necks have also been recognized (Francis, 1957, 1959; Barnett, 1985). However, a borehole at Tillicoultry in the centre of the basin revealed proximal agglomerates and some lavas in the top part of the Upper Limestone Formation. Rippon *et al.* (1996) have suggested that these were related to the NNE-trending Coalsnaughton Fault which may have been an active extensional fault parallel to the Bo'ness Line.

South-west Scotland (Namurian)

In the west of the Midland Valley, basic pyroclastic rocks are interbedded with sedimentary strata throughout the Limestone Coal Formation and to a lesser extent the Upper Limestone Formation to the west of Dalry; they are known mainly from borehole records (Richey *et al.,* 1930). All may have been derived from necks that cut older strata to the west.

A major episode of volcanism is represented in the upper part of the Passage Formation by the Troon Volcanic Member. This is recognizable over an area that extends from Ayrshire south to Stranraer and west to Arran, Kintyre and possibly to Northern Ireland (Richey *et al.,* 1930, fig. 25), but the main development occurs beneath the Coal Measures of the Ayrshire Basin (Monro, 1999). Outcrops of lava occur on the northern and southern flanks of the basin and the thickest development of over 160 m is just to the north of the town of Troon (Figure 4.3). Isopachs suggest contemporaneous movements along the Inchgotrick and Dusk Water faults. Specific volcanic centres have not been identified and may lie offshore. Miospores from interbedded sedimentary rocks constrain the biostratigraphical age to the KV zone (Kinderscoutian to early Marsdenian) and a minimum K-Ar radiometric age of 305 ± 6 Ma has been estimated by De Souza (1982). More precise Ar-Ar determinations would clearly be very useful at this well-defined point in time, just prior to the development of the major coalfield basins. The volcanic member is represented by the Ardrossan to Saltcoats Coast GCR site (see GCR site report).

The Troon Volcanic Member is composed almost entirely of subaerial basaltic lavas (olivine-microphyric, 'Dalmeny' type) with some interbedded sedimentary rocks. Petrographical details were given by MacGregor (in Richey *et al.,* 1930; in Eyles *et al.,* 1949). Like the earlier, Dinantian lavas, these are transitional in nature and range from hypersthene- to nepheline-normative; a few are basanites (Macdonald *et al.,* 1977; Wallis, 1989).

The lavas are generally decomposed, commonly with a characteristic red speckled appearance due to sideritic alteration. More advanced decomposition produces pseudostratified greenish-blue clays, thought to be the result of penecontemporaneous subaerial weathering. This weathering is particularly well developed at the top of the member, and on the northern side of the Ayrshire Basin it grades upwards into aluminous clayrocks interbedded with laminated mudstones, seatclays and coals that together comprise the Ayrshire Bauxitic Clay Member (Wilson, 1922; Eyles *et al.,* 1949; Monro, 1999) (see High Smithstone Quarry GCR site report in the *British Upper Carboniferous Stratigraphy* GCR volume — Cleal and Thomas, 1996). This complex member is up to 20 m thick in places, but is more typically 2–4 m thick and has been extracted as a source of alum and specialist refractory clay. It contains some of the highest quality fireclay in Britain, with up to 42% Al_2O_3. Whilst the basal parts were undoubtedly formed by the weathering of basalt *in situ,* there has been much debate about additional sedimentary and diagenetic processes that may have operated (Monro *et al.,* 1983). Bauxitic laterites only form in tropical climates and require a significant time to build up any thickness. A variety of clastic clayrocks demonstrate the local reworking of the weathered crust and, in the absence of any other sediment input, we can deduce that the topography of the underlying lava surface was low. Coals, seatrocks and plant remains, including tree trunks, are abundant and, together with the presence of at least one marine band, suggest that the area was reduced to a heavily vegetated, flat, low-lying coastal plain when the volcanism ended at the close of Namurian time.

To the west of the main outcrop, on the Isle of Arran, a thin succession of red tuff and basaltic lava overlain by bauxitic clays and Middle Coal Measures occurs in the Merkland Burn, near Brodick Castle. Tuffs with thin lavas occur in two outcrops to the west and WSW of Lamlash: in the Benlister Burn, bauxitic clays are found and in the larger outcrop at the head of the Sliddery Water, tuffs are overlain by red mudstones with mussels of Middle Coal Measures type (Leitch, 1942). Both occurrences have been assigned to the Passage Formation. Farther west, in Kintyre, about 100 m of thick basaltic lavas with thin tuffs and red lateritic mudstones are known only from boreholes at Machrihanish. The highest lavas have been weathered to bauxitic clay and there is a marked non-sequence beneath the overlying Lower Coal Measures. In Galloway, a single thin flow of basaltic lava near Kirkcolm, on the west side of Loch Ryan, occurs within a sequence of mottled sandstones, mudstones and seatclays that is overlain unconformably by Permian breccias.

Fife (mid Namurian to Early Permian)

Evidence of volcanicity in the form of interbedded tuffs and tuffaceous sedimentary rocks is widespread in the Silesian successions of Fife, south of the East Ochil Fault. Basaltic lavas are rare. Much of the information comes from underground coal mining and boreholes, both onshore and offshore, though there are some good exposures, particularly in coast sections. The area is renowned for its numerous, mainly small necks, many with plugs of alkali olivine basalt or basanite. These are particularly abundant in East Fife where over 100 are recorded, and are represented by the East Fife Coast GCR site. Here, the continuing influence of deep-seated Caledonian structures is well illustrated by the NE-trending Ardross Fault, along which ten or more necks are sited over a distance of 4 km (Francis and Hopgood, 1970). On the opposite side of the Firth of Forth, Howells (1969) recorded high-level vent structures near Longniddry that cut Namurian strata and lie directly on the projected north-eastwards continuation of the Southern Upland Fault, which may have controlled the rise of magma during Visean time (see Chapter 2). The East Fife necks are also renowned as some of the most productive sources in Scotland of megacrysts and/or rock clasts of deep-seated igneous material or metamorphic basement (e.g. Colvine, 1968; Chapman, 1974, 1976; Macintyre *et al.,* 1981; Donaldson, 1984) (see Chapter 1).

Onshore outcrops of interbedded volcanic rocks are concentrated mainly in two areas. Around the former Westfield opencast coal site in central Fife, there are five flows of basaltic pillow lava with associated tuffs and hyaloclastites in the top of the Upper Limestone Formation and the basal Passage Formation. The large complex necks of Largo Law and Rires in East Fife are surrounded by bedded tuffs and a few lavas that seem to be interbedded with the Upper Limestone Formation and Passage Formation, though in many places it is difficult to separate them from pyroclastic rocks within the necks (Forsyth and Chisholm, 1977). Offshore, boreholes in the Firth of Forth have proved pyroclastic rocks and rare basalt lavas, ranging from the topmost Passage Formation up into the Middle Coal Measures.

The necks cut almost the full local age range of Dinantian and Namurian strata and it is likely that some are the source of the Namurian bedded tuffs. A few necks cut Coal Measures strata. The Viewforth Neck contains foundered blocks of tuffaceous sedimentary rocks that have yielded Langsettian spores, and the Lundin Links Neck cuts (Duckmantian) Middle Coal Measures. Some necks are thus of Duckmantian age or younger and it has been suggested that blocks of quartz-bearing dolerite in several necks (e.g. Ardross, St Monance, Viewforth, Lundin Links) are derived from the early Stephanian tholeiitic intrusive suite, though this has not been proved. The most reliable K-Ar radiometric dates from four of the necks are within a range of 295–288 Ma, which dates their time of emplacement as close to the Stephanian–Permian boundary (Wallis, 1989). The highly silica-undersaturated nature of plugs and other minor intrusions (basanites, olivine nephelinites and olivine analcimites) within many of the vents is characteristic of the latest magmatism elsewhere in the Carboniferous–Permian Igneous Province of northern Britain, especially the undoubted Early Permian lavas and associated necks of south Ayrshire (see below), and hence is compatible with the age estimates.

The morphology and physical volcanology of the Fife volcanoes and their relationships to surrounding contemporaneous sedimentation have been studied more intensively than in any other part of the Carboniferous–Permian Igneous Province of northern Britain. Much of this work has been by E.H. Francis, building upon earlier Geological Survey work and making extensive use of boreholes and mine sections (Francis, 1960, 1961b,c, 1968a,b, 1970b; Francis *et al.,* 1961; Francis and Ewing, 1961; Francis and Hopgood, 1970; Francis in Forsyth and Chisholm, 1977).

The bedded tuffs consist of a mixture of basaltic and comminuted sedimentary debris and are often well graded, indicative of ash fall into shallow water. Thin distal representatives have been traced for up to 30 km from their implied vents and have correlation value as effective time-planes (Francis, 1961c, 1968a). Many of these thin tuffs have been altered diagenetically to kaolin, especially in, or near to, coal seams, and have been likened to the 'tonsteins' of north-west European coalfields (Francis *et al.,* 1961; Francis, 1969, 1985). Most of the necks appear to be funnel-shaped tuff-pipes filled by varying proportions of basaltic material and country rock. Initial updoming, with associated radial and concentric fracturing, was probably followed by gas-fluxioning and wall-rock stoping, prior to the rise of basaltic magma that interacted with groundwater and surface water in explosive, phreatomagmatic eruptions. Many of the larger necks contain inward-dipping bedded pyroclastic rocks and sediments, with fragments of fossil wood that show that they accumulated at the surface. The inward dips were generated by inward collapse of the areas surrounding the initial vent during the eruption, possibly along ring-fractures, and by immediate post eruptive subsidence (Francis, 1970b). Such features, together with the interpretation of cross-bedding and large-scale slumping as the results of base-surge eruptions, led Francis (in Forsyth and Chisholm, 1977) to compare the volcanoes with modern Surtseyan ash-rings of wide diameter and low height, which are typical of basaltic eruptions into shallow water. Magmas failing to reach the surface were emplaced as a variety of minor intrusions. Details, as illustrated by individual necks, are given in the East Fife Coast GCR site report.

East Lothian (?late Stephanian to Early Permian)

The volcanic rocks interbedded with the sedimentary succession of East Lothian are undoubtedly of Dinantian age, as are most of the closely related vents (see North Berwick Coast GCR site report). However, some of the associated intrusions are basanitic or foiditic and it seems reasonable to suggest that these may represent a south-eastern continuation of the East Fife late Stephanian to Early Permian volcanic field, from which they are separated by only 15 km. Available K-Ar whole-rock dates are equivocal, but suggest minimum ages in the range 295–229 Ma (Snelling and Chan in McAdam and Tulloch, 1985, recalculated; Wallis, 1989). Notable examples of these intrusions occur at Oldhamstocks, Kidlaw, Limplum, Gin Head, Yellow Man, Yellow Craig Plantation and North Berwick Abbey, and it is probable that some of the breccia-filled necks in the area belong to this late phase of activity.

A large plug of nepheline basanite at Southdean, south of Jedburgh, is anomalous among the Dinantian plugs of south-east Scotland (see Chapter 3) and may be an isolated Early Permian occurrence.

Mauchline, Sanquar and Thornhill basins (Early Permian)

Bedded volcanic rocks of Early Permian age crop out in south Ayrshire, in an elliptical outcrop around the overlying aeolian sandstones of the Mauchline Basin, and in the NNW- to NW-trending, fault-controlled Sanquhar and Thornhill basins, within the Southern Uplands. Together these mid-Carboniferous-Permian basins define a broad NW-trending lineament that continues to the south-east through the Permian sedimentary basins at Dumfries, Lochmaben and the Vale of Eden. Contemporaneous necks and sub-volcanic intrusions within and around the Mauchline lavas and in the Sanquhar Basin extend the known limits of the volcanic fields, but it is not known if they were ever interconnected.

The Mauchline Volcanic Formation, represented by the Howford Bridge GCR site, is up to 238 m thick and rests unconformably but with no marked discordance upon the 'Barren Red Beds' of the Upper Coal Measures. Plant debris found near the base of the volcanic sequence suggests an earliest Permian age (Wagner, 1983) and K-Ar whole-rock dates around 286 ± 7 Ma are Early Permian (De Souza, 1982). Palaeo-magnetic measurements have also indicated pole positions close to those of Carboniferous-Permian boundary time (Du Bois, 1957; Harcombe-Smee *et al.,* 1996). The lavas are predominantly microporphyritic olivine basalts ('Dalmeny' type), but basanites are common and some strongly silica-undersaturated olivine nephelinites are present. However, analyses include some hypersthene-normative transitional basalts (Macdonald *et al.,* 1977; Wallis, 1989). Pyroclastic rocks comprise a large part of the succession, becoming more abundant in the thicker, eastern parts. Sedimentary rocks within the volcanic sequence contain wind-rounded sand grains, indicating that the lavas were erupted in predominantly desert conditions, but fluvial sandstones and mudstones imply spasmodic sheet-floods and ephemeral lakes.

Over 60 necks are known, mostly within a 20–30 km radius of the centre of the Mauchline Basin, but also extending to West Kilbride in the north (Alexander *et al.,* 1986), Muirkirk in the east and Dalmellington in the south (Figure 4.2). Numerous lines of evidence suggest that these necks are contemporaneous with the lavas and hence delimit the former extent of the volcanic field. Necks are known to cut the Coal Measures succession, post-Coal Measures alkali dolerite sills and the Mauchline Volcanic Formation, but not the overlying Mauchline Sandstone Formation. Many of the necks contain wind-rounded sand grains and some include large subsided blocks of aeolian and fluvial sandstones. Plugs and other vent intrusions are predominantly of highly silica-undersaturated olivine analcimite or monchiquite, but camptonite, basanite and alkali dolerite are also known. Monchiquite dykes, common in the Irvine Valley and the Patna area, are assumed to be related. Xenolithic megacrysts and ultramafic nodules in many of the vent intrusions yield valuable information on the upper mantle source area of the magmas.

In the Thornhill Basin, the Carron Basalt Formation, represented by the Carron Water GCR site, is up to 50 m thick and rests unconformably on reddened Coal Measures and Lower Palaeozoic rocks. It comprises subaerial olivine-microphyric basalts and basanites similar to those of the Mauchline Basin and interbedded sedimentary units. Conglomeratic sandstones and breccias below the lavas, and beyond the present lava outcrop, contain angular fragments of basalt indicating earlier, possibly more extensive, flows. Although some basalts incorporate wind-blown sand in their matrix, the sedimentary rocks interbedded with and overlying the volcanic rocks are predominantly fluvial. Aeolian desert conditions did not become fully established here until well after the volcanic period. Small outliers of olivine basalt rest upon Middle Coal Measures at the southeast end of the Sanquhar Basin and five small necks pierce the Coal Measures nearby.

Across the North Channel, in a borehole at Larne in Northern Ireland, over 600 m of basic volcanic rocks were proved at a depth of over 2000 m, beneath an undoubted Permo-Triassic succession (Penn *et al.,* 1983). A K-Ar whole- rock date of 245 ± 13 Ma is almost certainly too young and the authors suggested an Early Permian age. However, there are marked petrological differences between these lavas (which have possible tholeiitic affinities) and those of south-west Scotland. They occupy a separate sedimentary basin and are certainly a separate lava field.

Offshore

In the centre of the East Irish Sea Basin, a borehole has penetrated 45.5 m of altered basalts overlain by 22 m of volcaniclastic rocks at the base of the Permian succession (Jackson *et al.,* 1995, 1997). These Tormentil Volcanics occur on a high that trends north-east towards south Cumbria, where clasts of olivine-dolerite and vesicular basalt are abundant in basal Permian conglomerates in the Humphrey Head Borehole (Adams and Wadsworth, 1993). The source of these clasts is not known, but they are likely to be Carboniferous to Early Permian in age and relatively local. Thin subaerial basaltic flows are also recorded from the Lower Permian rocks of the North Sea Basin (Dixon *et al.,* 1981).

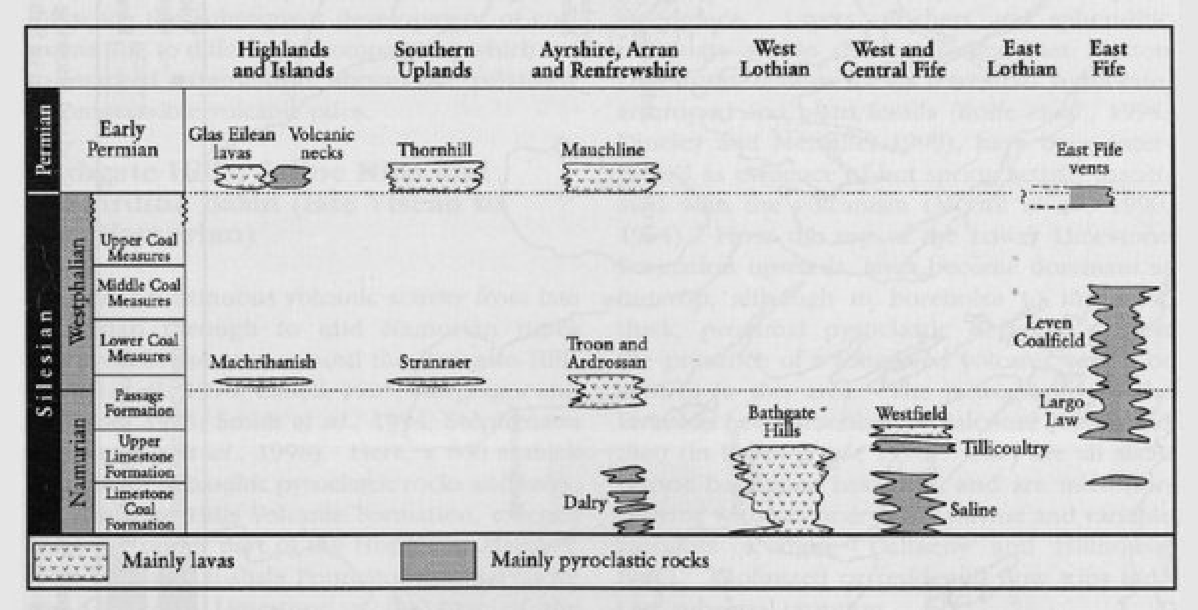
Highlands and Islands (Early Permian)

On the Isle of Arran, the sequence at the head of the Sliddery Water that includes possible Passage Formation volcanic rocks (see above), passes up into gritty feldspathic sandstones and slaggy basaltic lavas with thin tuffs that have been assigned to the base of the Permian succession on the current British Geological Survey 1:50 000 map (1987).

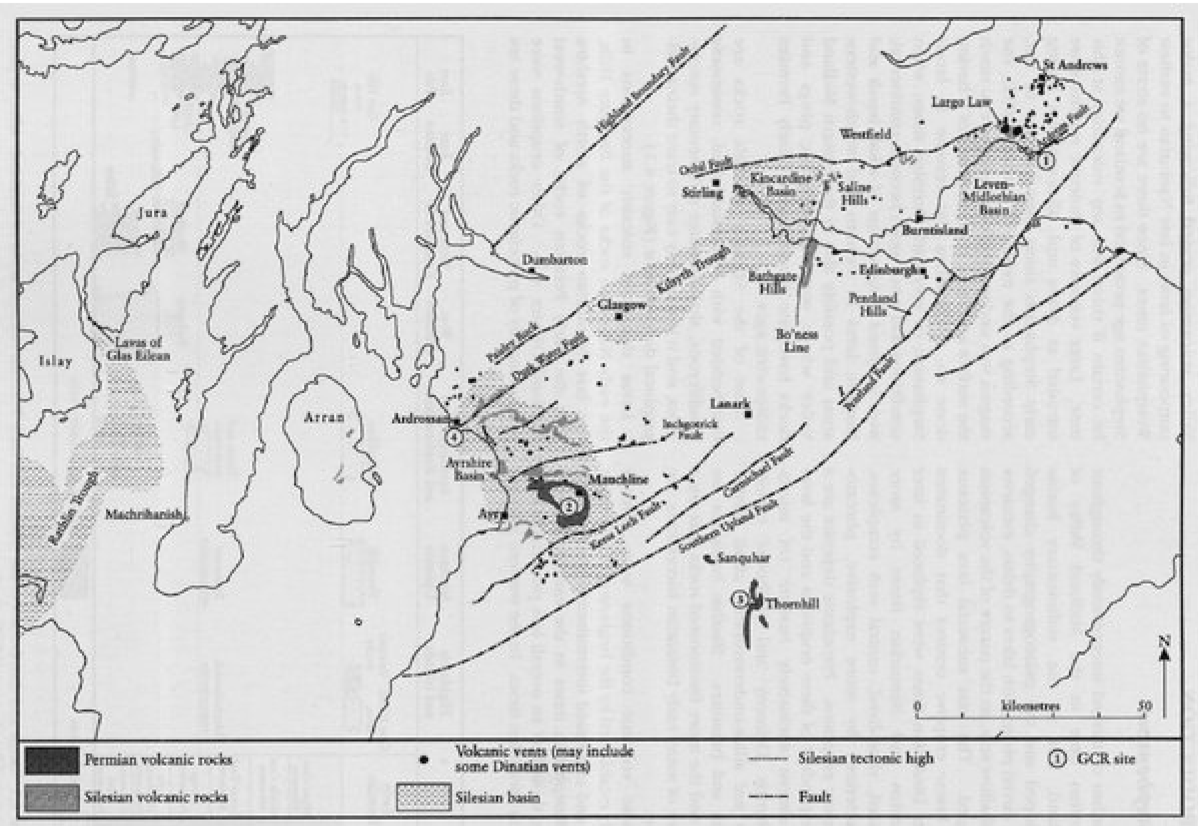
A 120 m-thick Permian succession is exposed on the small island of Glas Eilean in the Sound of Islay, between the Isles of Islay and Jura (Pringle and Bailey, 1944; Upton *et al.,* 1987) (Figure 4.2). Above a basal conglomerate and sandstone (7 m thick), which contain basaltic clasts, most of the succession comprises sub-aerial basaltic lavas. There are many individual flows, up to 2 m thick and with slaggy amygdaloidal tops. The flow thickness decreases upwards as intercalations of shallow-water sedimentary rocks increase. The lavas are all mildly alkaline olivine-microphyric basalts that are hypersthene- or nepheline-normative and the lower flows are relatively primitive with high MgO, Ni and Cr contents. The succession appears to overlie Dalradian rocks unconfor-mably to the ENE, and dips WSW at *c.* 30°, towards an inferred NNW-trending fault along the sound. It therefore seems to occupy a hall graben, a possible transverse extension off the northern end of the Rathlin Basin, which may have been active at the time of the sedimentation and volcanism (Fyfe *et al.,* 1993; Anderson *et al.,* 1995). A K-Ar whole-rock date of 285 ± 5 Ma appears to confirm the Early Permian age.

Evidence of more widespread Early Permian volcanism in the Highlands and Islands comes from the distribution of small sub-volcanic necks (Figure 4.4), composed largely of explosion breccia, but characterized by the presence of monchiquite, either as clasts, or as a magmatic matrix, or in associated minor intrusions (Rock, 1983). They are thus correlated petrographically with the even more widespread camptonite and monchiquite dykes swarms that are well established as being of Early Permian age (see Chapter 5; (Figure 5.2)). Nine necks, including that at Stob a'Ghrianain (Hartley and Leedal, 1951), seem to define a NW-trending lineament between Coire na Ba, near Kinlochleven (Wright in Bailey and Maufe, 1960) and Toscaig, near Applecross (Rock, 1982). Most others form a cluster around south-east Orkney (Mykura, 1976) which includes the neck at Duncansby Ness, dated at around 270 Ma by K-Ar whole-rock dating (Macintyre *et al.,* 1981). Like the dykes, many of the necks are a valuable source of inclusions derived from the lower crust and upper mantle (e.g. Chapman, 1975) (see Chapter 1).

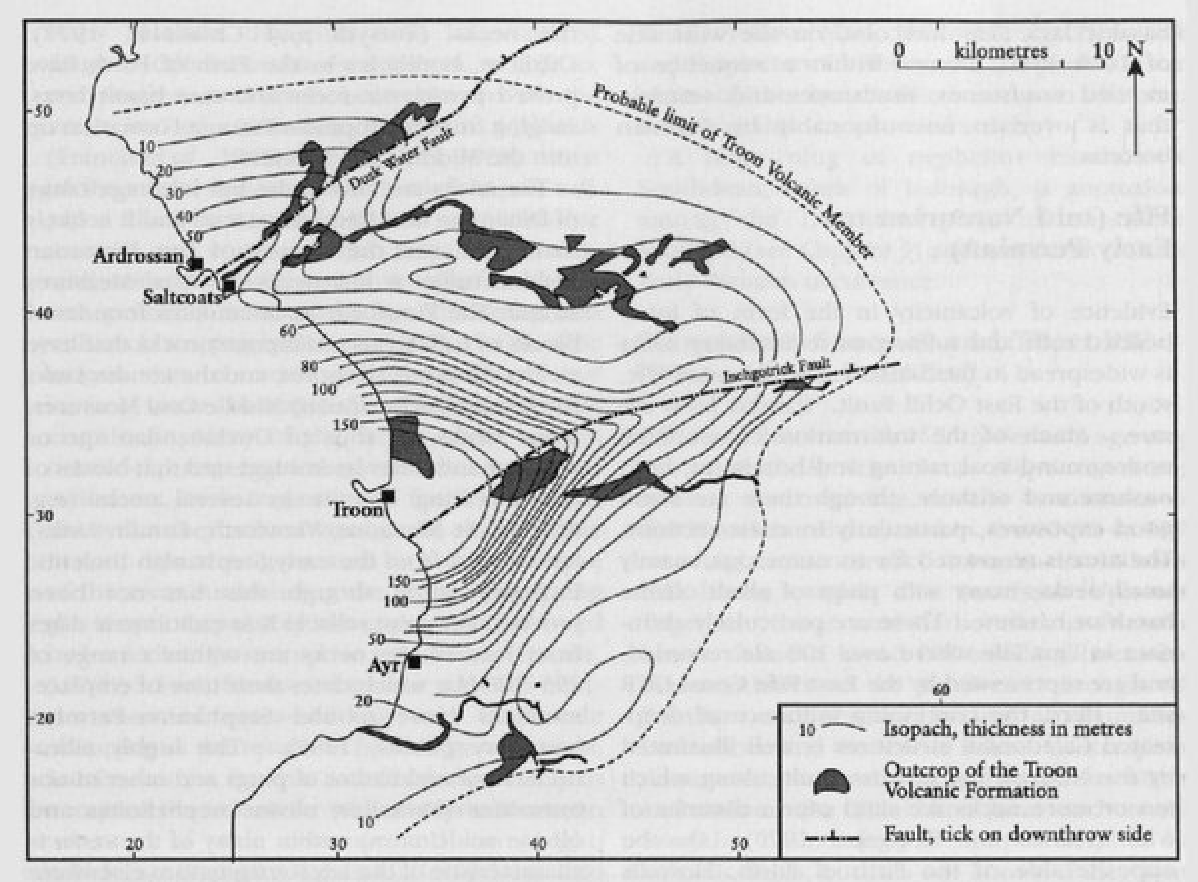
References



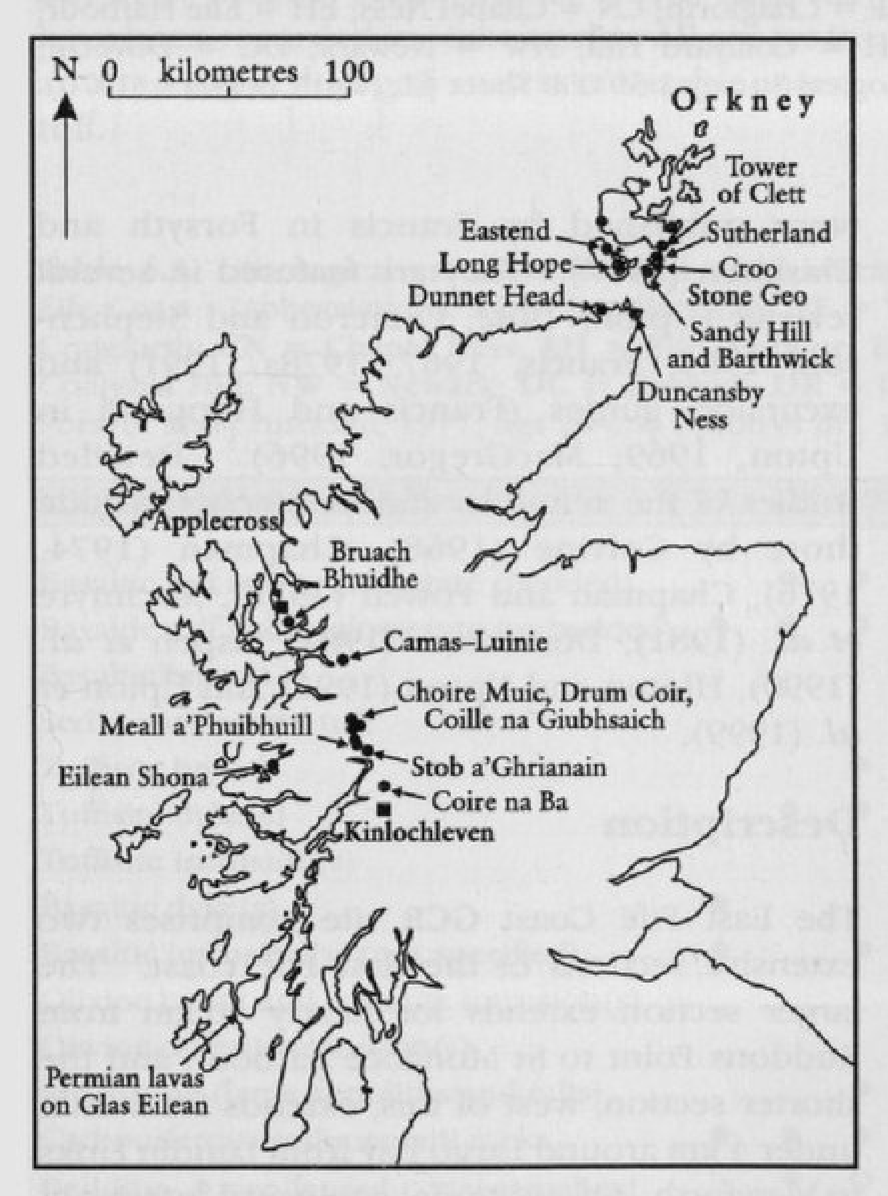
(Figure 4.1) Range and distribution of the Silesian and Early Permian volcanic rocks of Scotland. After, in part, Cameron and Stephenson (1985).



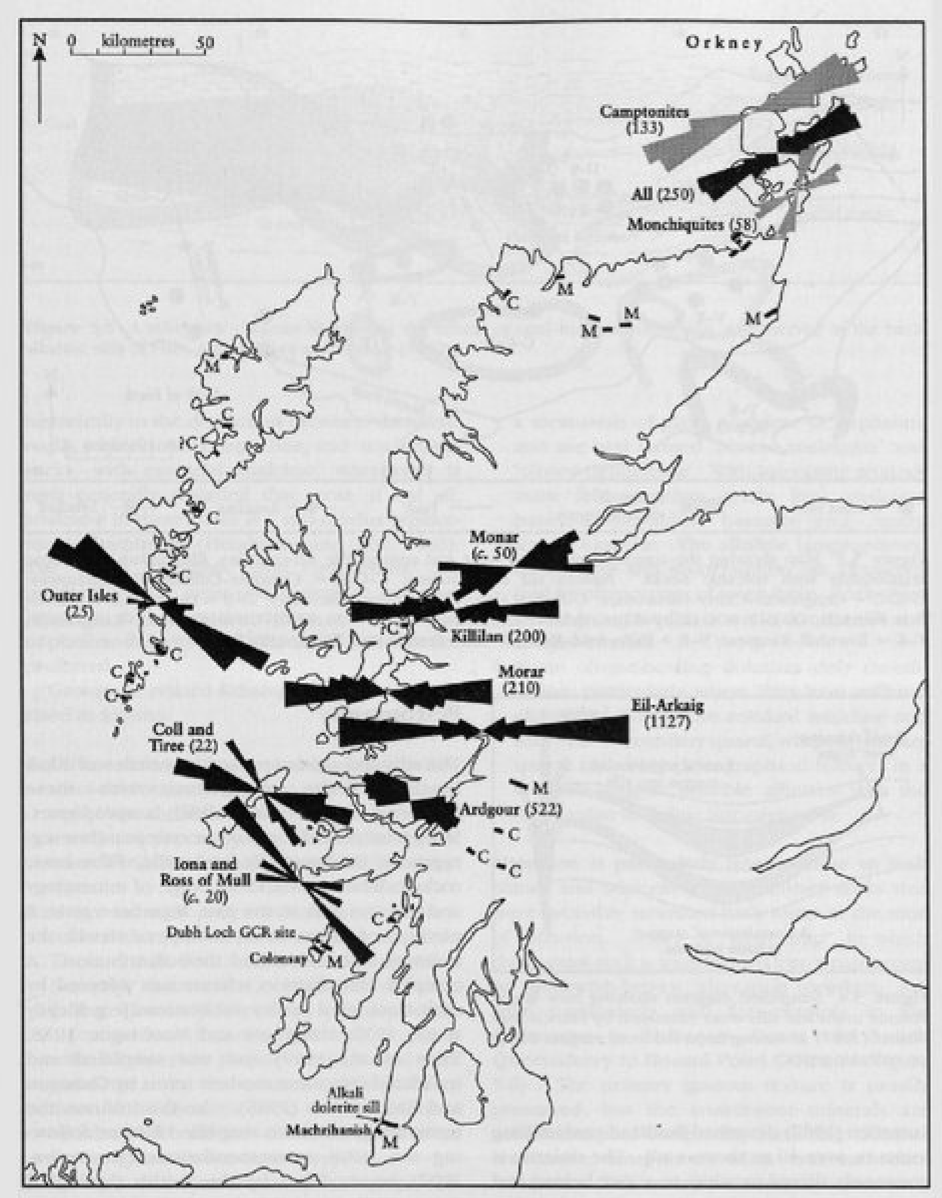
(Figure 4.2) Map of central and southern Scotland showing the main outcrops of Silesian and Permian volcanic rocks. GCR sites: 1 = East Fife Coast; 2 = Howford Bridge; 3 = Carron Water; 4 = Ardrossan to Saltcoats Coast. Information from published sources, including Cameron and Stephenson (1985); Francis (1991); Read (1988); and Rippon et al. (1996).



(Figure 4.3) Map showing areas of outcrop, and thickness variations, of the Troon Volcanic Member. After Monro (1999); Geological Survey 1:50 000 sheets 14' Ayr (1978); 14E, Cumnock (1976); and British Geological Survey 1:50 000 Sheet 22E, Kilmarnock (1999).



(Figure 4.4) Map showing the location of plugs and vents of Carboniferous to Permian age in the Highlands. The Early Permian lavas of Glas Eilean are also indicated. After Rock (1983).



(Figure 5.2) Map showing the location and azimuth distribution of the main alkaline lamprophyre (camptonite and monchiquite) dyke-swarms of the northern Highlands. Azimuth distributions are presented as total percentage of dykes in each swarm with a particular orientation; thus long arms indicate swarms trending more uniformly than short ones. The number of dykes recorded in each swarm is shown in brackets. Isolated occurrences of monchiquite and camptonite are shown by M and C respectively. After Rock (1983).