Chapter 5 Alkaline basic sills and dykes of Scotland

Introduction

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Sub-volcanic minor intrusions, such as plugs, dykes and sills, form an integral part of all eruptive centres and a genetic association is usually clear from close geographical links and from petrological similarities. Descriptions of such intrusions within the Scottish volcanic fields are included, where relevant, in chapters 2, 3 and 4. More-extensive sill-complexes and regional dyke-swarms, representing voluminous injections of alkaline basic magma, are also widespread in parts of Scotland. Some may well be contemporaneous with local extrusive events, but others occur well outside known volcanic fields or are demonstrably younger than any local volcanic rocks.

Most of the major sill-complexes and regional dyke-swarms are of Namurian age or younger and hence post-date the most voluminous outpourings of lava that occurred during Visean time, but they are coeval with intermittent, more localized volcanic events that continued until Early Permian times. The tectonic development of the region during this period is described in Chapter 1. It has been argued that the increasing thicknesses of geotechnically weak sediments in the rapidly developing Silesian basins of the Midland Valley were of too low density to support columns of magma, which were unable to rise to the surface, and hence they spread laterally to form sills (Francis, 1991). Their distribution throughout the Midland Valley is shown on (Figure 5.1). Associated regional dyke-swarms of alkaline basic rocks are not recognized in the Midland Valley, except in the Ayrshire Basin where alkali dolerite dykes, some of which may be contemporaneous with the sills, occupy a wide range of fracture directions. In contrast, in the more competent 'basement' rocks of the north-west Highlands, and to a much lesser extent in the Southern Uplands, there are several alkaline basic dyke-swarms but no sills (Figure 5.2).

The alkaline intrusions represent a major component of Carboniferous–Permian igneous activity in Scotland; Macdonald (1980) has estimated a total volume of 1200–1500 km^3. Most of these are probably post-Dinantian in age, and hence their volume significantly exceeds the known volume of Silesian and Permian extrusive rocks — less than 500 km^3, according to the calculations of Tomkeieff (1937) — and probably increased only moderately by newer information from mining and boreholes.

Emplacement mechanisms

The large sill-complexes in Scotland were almost all emplaced into developing sedimentary basins, and in many cases the greatest sill thicknesses have been shown to occur in the deepest parts of the basins (Francis and Walker, 1987). From a detailed study of Namurian sills in western and central Fife, Francis and Walker (1987) concluded that magma had flowed down bedding planes that were already dipping inwards at up to 5° at the time of intrusion. Magma accumulated in the bottoms of the basins and in some cases flowed up-dip on the opposite side, due to hydrostatic pressure. In this respect the model is similar to that proposed by Francis (1982) for the later tholeiitic sill-complex (see Chapter 6). However, whereas the tholeiitic magma rose along dykes that extended above the sills without reaching the surface and hence provided the head of magma, there are no known dykes associated with the alkali sills. Instead, there is a close geographical and petrological association with volcanic necks that mark the sites of conduits for surface eruptions (Figure 5.3). Francis and Walker (1987) suggested that it was degassed magma in the volcanic pipes that provided the feeders for the alkali sills, bursting out along radial and concentric minor fractures to flow down-dip when the pipes became plugged following an eruption (Figure 5.4). Synsedimentary extensional faults within the basins acted as structural controls of sill emplacement; they limited the extent of some sills and acted as near-vertical channels by which the sills changed level by up to 400 m.

Most of the volcanism at this time was phreato-magmatic, driven by the interaction of magma and water within the sedimentary pile (see Chapter 4). The effects of this interaction are well exhibited at the advancing edges of some sills, where peperitic textures occur, such as isolated blobs of magma within reconstituted sediment and plastically deformed inclusions of vesiculated, heterogeneous sediment within dolerite (Walker and Francis, 1987). The contact effects are particularly dramatic where sills have been emplaced along planes of weakness created by seams of wet lignite (now coal), a common feature of the Scottish coalfields (e.g. Mykura, 1965). At one contact, Walker and Francis (1987) recorded compositionally banded tuffisites, rich in basalt clasts and coal fragments, and identical to those seen in some volcanic pipes (Figure 5.5) and Lumsden (1967) described fluidized coal infilling joints to over 40 m above a sill. The dolerite is commonly altered to 'white trap' (see below) and productive coal seams may be totally replaced or 'burnt' (i.e. coked). In contrast, some seams close to sills have been converted to a higher grade of coal (anthracite), so enhancing their economic value (see Benbeoch GCR site report).

Petrography

The sills and dykes are mostly varieties of alkali basalt, dolerite or gabbro, with some basanites, foidites and alkali lamprophyres. More fractionated rocks occur only as minor segregations in essentially basic sills. The basic rocks exhibit a remarkable range of mineralogy and textures and, in the past, have been given a plethora of names in an attempt to classify the varieties and understand their distribution. A complex classification scheme was adopted by early Geological Survey publications (e.g. Richey *et al.,* 1930; Macgregor and MacGregor, 1948; Eyles *et al.,* 1949) and was simplified and translated into more modern terms by Cameron and Stephenson (1985). In this volume the terminology has been simplified further, following the IUGS recommendations (Le Maitre, 2002), as modified by the British Geological Survey (Gillespie and Styles, 1999). Many names have been shown subsequently to have little or no petrogenetic significance and hence do not aid interpretation (Henderson *et al.,* 1987). In particular, much significance has been given historically to the distinction between 'theralitic' rocks, with essential nepheline, and 'teschenitic' rocks, with essential analcime, whereas it is now generally regarded that most, if not all, analcime in these rocks is a sub-solidus replacement of nepheline (Henderson and Gibb, 1983). The terms 'theralitic' and 'teschenitic' are retained to aid cross-referencing to previous literature, but more descriptive names such as nepheline-dolerite and analcime-dolerite are preferred.

Groups of related lithologies can be summarized as follows:

1. Olivine-dolerite, basalt and basanite, mildly silica-undersaturated, but with no modal nepheline and little analcime. These are commonly microporphyritic (olivine ± augite), resembling local basaltic lavas of 'Dalmeny' type.
2. More strongly silica-undersaturated basic rocks with modal nepheline and/or analcime. These include analcime-dolerite/gabbro (formerly 'teschenite), nepheline-dolerite/gabbro (formerly 'theralite) and nepheline-monzogabbro (formerly 'essexite'), together with olivine-rich picritic variants and rare peridotite. In the western Midland Valley, most of the theralitic rocks are characterized by abundant olivine (10–40%) and were formerly classified as 'kylitic' types.
3. Strongly silica-undersaturated, highly alkaline, feldspar-poor or feldspar-free rocks, mostly fine-grained basanite, foidites and alkaline lamprophyres (all formerly classified as 'monchiquitic' types). Typically they comprise phenocrysts of olivine and augite in a mesostasis of glass, analcime or nepheline and are best termed 'olivine analcimite' and 'olivine nephelinite'. With increasing groundmass feldspar they grade into analcime basanite, nepheline basanite and, rarely, leucite basanite. The alkaline lamprophyres, camptonite and monchiquite, are characterized by phenocrysts of amphibole. Rock-types of this group tend to occur in thinner sills and in dyke-swarms.
4. Some olivine-bearing dolerites defy classification, particularly where they have suffered alteration. Some have residual analcime and many have secondary quartz, whereas primary quartz and other petrographical features in a few sills suggest possible affinities with the Stephanian tholeiitic intrusive suite.

Alteration is particularly intense close to fault planes and adjacent to sedimentary rocks that were probably saturated with water at the time of intrusion. Zones of 'white trap', in which the normal rock is transformed into a pale-cream or yellowish-brown alteration product, are seen particularly well for example in the Ardrossan to Saltcoats Coast and South Queensferry to Hound Point GCR sites (Figure 5.8). The primary igneous texture is usually preserved, but the constituent minerals are pseudomorphs, comprising kaolinite, chlorite, leucoxene, amorphous silica and carbonate minerals. 'White trap', commonly containing solid or viscous hydrocarbons on joint surfaces, is particularly widespread in dolerites that are associated with carbonaceous mudstones, coals or oil-shales. It has been suggested that the alteration was caused by volatiles released during the distillation of such rocks by heat from the intrusions (Day, 1930a; Mykura, 1965).

The alkaline sills of the Midland Valley in particular have been the subject of many detailed petrological and geochemical studies that have contributed greatly to developing theories for the origin and evolution of alkaline basic magmas. The wide variety of rock-types within composite or differentiated intrusions such as the Lugar and Saltcoats Main sills in Ayrshire (see Lugar and Ardrossan to Saltcoats Coast GCR site reports) and the Braefoot Outer Sill in Fife attracted many early petrologists, such as Flett (1930, 193 la,b, 1932), Campbell *et al.* (1932, 1934), Patterson (1945, 1946), Higazy (1952) and Tyrrell (1917b, 1948, 1952), with more recent work on the Benbeoch Sill (Dreyer and MacDonald, 1967) and the sills of Fife (Walker, 1986). The observed ranges in lithology have been variously attributed to differentiation *in situ* aided by gravitational settling of crystals; to multiple injections of magma; to enrichment in residual liquid and volatiles; or to some combination of these. Most modern interpretations invoke multiple pulses of progressively more primitive magma from a deeper, fractionating magma chamber, followed by limited further fractionation *in situ* (e.g. Henderson and Gibb, 1987). Further details on the mode of emplacement of these heterogeneous intrusions are discussed in the Benbeoch, Lugar and Ardrossan to Saltcoats Coast GCR site reports.

Eastern Midland Valley

Major alkali dolerite sills are widespread throughout Fife and the Lothians, where there are also numerous minor intrusions associated with the local volcanic centres. In the Lothians, the major sills cut strata as low as the Ballagan Formation and extend up to the Lower Limestone Formation, whereas in west and central Fife they extend up to the Upper Limestone Formation ((Figure 1.2), Chapter 1). They are not present in the overlying Passage Formation, nor in the Coal Measures, and it has been suggested therefore that they are of late Visean to Namurian age, contemporaneous with volcanism at Burntisland, the Bathgate Hills and western Fife. In the latter area, many of the sills seem to be located along the same hinge lines that control the volcanic necks (see Chapter 4) and there is field and borehole evidence to suggest that sills were emplaced into near-surface Namurian sediments that were still saturated with water and not fully consolidated (Francis and Walker, 1987; Walker and Francis, 1987). Some individual sills and the marginal facies of others are of olivine-microphyric basalt or basanite, with strong petrographical and geochemical similarities to the local lavas ('Dalmeny' type) (Walker, 1986). However, many of the thicker sills are of analcime-dolerite ('teschenite) that is more silica-undersaturated and may comprise a separate, slightly later group. A possible upper age limit is provided by quartz-dolerite dykes of the Stephanian tholeiitic swarm that cut analcime-dolerite sills on the island of Inchcolm and near Linlithgow.

The few available K-Ar whole-rock radiometric dates must be treated with caution. Four determinations from Lothian sills fall within the range 317 ± 9 Ma to 308 ± 7 Ma (De Souza, 1974, 1979, recalculated by Wallis, 1989), suggesting that the intrusive activity may have continued into mid Westphalian times. However, recent Ar-Ar dates on biotite separated from three of these sills give late Visean ages in the range 332–329 Ma (A.A. Monaghan and M.S. Pringle, pers. comm., 2002). Five determinations from East Fife fall in the range 310 ± 6 Ma to 280 ± 8 Ma (Forsyth and Rundle, 1978, recalculated by Wallis, 1989), suggesting that although some of the larger sills may be Namurian to Westphalian in age, others may be of Early Permian age, coeval with the minor intrusions in volcanic necks of this area (see Chapter 4). Unfortunately, the petrographical divisions of the sills and the clear geochemical divisions on the basis of silica-saturation and incompatible elements, recognized by Wallis (1989), show no meaningful correlation with currently available age determinations.

Analcime-dolerite sills, up to 137 m thick, are widespread in East and West Lothian and within the city of Edinburgh, but are absent from the Midlothian Basin. Detailed descriptions were given in earlier Geological Survey memoirs by Bailey (in Clough *et al.,* 1910) and Flett (in Peach *et al.,* 1910), and summaries and updates were given in subsequent editions, in particular McAdam and Tulloch (1985) and Davies *et al.* (1986). There have also been numerous studies on individual intrusions, which are given below. They are represented in this volume by the Salisbury Craigs Sill in the Arthur's Seat Volcano GCR site and the Mons Hill Sill in the South Queensferry to Hound Point GCR site (Walker, 1923; Flett, 1930). Other major 'teschenitic' sills include those at Ravensheugh (Day, 1930f), Gullane (Young, 1903; Day, 1914), Gosford Bay, Point Garry (Day, 1932a), Blackness (Flett, 1931b, 1934), Blackburn, Corstorphine Hill and Stankards (Flett, 1932). The last three are noted for their thick picritic layers. One of the thickest sills recorded in the eastern Midland Valley (114.5 m) is an olivine basalt, porphyritic in parts with augite and olivine phenocrysts, that was penetrated in the

Spilmersford Borehole (McAdam, 1974).

In the Firth of Forth, sills of analcime-dolerite form the Isle of May (Walker, 1936) and Inchcolm island, where there is a marked picritic facies (Campbell and Stenhouse, 1908).

In west and central Fife, sills of olivine-dolerite and analcime-dolerite are well known from coal workings and boreholes as well as from extensive surface outcrops. Most of the sills lie within an area limited to the north and south by the Ochil and Rosyth faults, and to the east and west by major sedimentary basins. These constitute a major sill-complex, extending over 750 km^2 and having a total volume of 7.25 km^3 (Francis and Walker, 1987). Francis and Walker have correlated the many individual leaves and recognized nine component sills, some of which may originally have been joined (Figure 5.3). Walker (1986) also recognized distinctive geochemical signatures, based particularly on incompatible trace-element ratios such as Zr/Nb and the pyroxene geochemistry, which represent at least three separate pulses of magma injection, not necessarily widely separated in time.

The Craigluscar–Cluny–Glenrothes Sill is the most extensive and also possibly the oldest, having geochemical affinities with the late Visean Kinghorn Volcanic Formation of the Burntisland area. Intrusive relationships of one leaf of this sill were described in detail by Walker and Francis (1987). The Dunnygask–Steelend and Oakley–Kinneddar–Parklands sills were both correlated with basanitic plugs associated with the early Namurian Saline Hills volcanic rocks, and the Cairnfold–Dollar–Tillicoultry Sill was correlated with mid-Namurian basalts just north of Saline. The second most extensive and thickest sill, at 190 m, is the Parkhill–Cowdenbeath–Kinglassie Sill. Others are the Valleyfield–Kinneil Sill, the Crombie–Cairneyhill–Bellknowes Sill, the Townhill–Kingseat Sill, and the Fordell Sill, which has an atypical nepheline basanite petrography (Allan, 1931) and a unique geochemical signature (Walker, 1986).

At lower stratigraphical levels in the core of the Burntisland Anticline, the Raith–Galliston Sill (Allan, 1924) may be a lower leaf of the Craigluscar–Cluny–Glenrothes Sill, but the Braefoot Outer Sill occurs much lower in the succession, near the base of the Visean Series. The latter is well documented petrologically on account of its layered structure attributable to gravitational sinking of olivine, a pegmatitic dolerite facies and well-developed chilled margins (Campbell *et al.,* 1932, 1934; Higazy, 1952). Layering in part of the Oakley–Kinneddar–Parklands Sill was attributed by Flett (1931a) either to gravitational sinking after emplacement, or to separation of olivine crystals by elutriation in a feeder conduit.

In East Fife, more than 30 sill-like bodies of alkali dolerite, up to 115 m thick, have been recorded, forming a sill-complex of considerable extent (Forsyth and Chisholm, 1977, fig. 16). There is a wide range of petrographical varieties, a feature that was commented upon by Balsillie (1922), who was also the first to recognize the major distinction between the alkaline olivine-dolerites and the tholeiitic quartz-dolerites. Forsyth and Chisholm (1977) recognized a crude zonal distribution to the sills, but this is independent of any obvious geological structure and hence the significance is not apparent. Ophitic, non-ophitic and olivine-microphyric olivine-dolerites form sills at Balcarres, Kilbrackmont, Baldutho, Gilston, Drumcarrow, Gathercauld, Greigston and Wilkieston. More silica-undersaturated 'teschenitic' types, which include analcime-dolerite, analcime basanite, picrite and analcime-monzogabbro, occur at Lathones, Crossgates, Radernie, Craighall,

Kingask and Lingo. Considerable vertical differentiation is recorded in 'teschenitic' sills at Higham, Dunotter, Lochty and Kinaldy and is probably present elsewhere (Forsyth and Chisholm, 1968).

Western Midland Valley

A wide petrographical range of alkali dolerites occurs as both sills and dykes in the Ayrshire Basin and analcime-dolerite ('teschenite') sills are abundant in the Glasgow–Paisley area. Although individual intrusions cut strata as low as the Lawmuir Formation, just above the Clyde Plateau Volcanic Formation, representatives of most types cut Coal Measures and many cut Upper Coal Measures. Thus, although some individuals may be coeval with the Namurian volcanism of north Ayrshire (see Chapter 4), most are of late Westphalian age or younger.

In the Ayrshire Basin, most of the transitional to mildly silica-undersaturated olivine-dolerites ('Dalmeny' type) have a petrographical and spatial association with the Troon Volcanic Member and only cut rocks of that member and older; they are probably Namurian in age. The more strongly silica-undersaturated dolerites, basanites and foidites (former 'teschenitie, 'kylitic' and 'monchiquitic' types) cut Coal Measures, but none cut the Mauchline Sandstone Formation that overlies the Early Permian Mauchline lavas. They are all therefore assumed to be slightly older than, or broadly coeval with, the Early Permian volcanism. The most reliable K-Ar radiometric dates on separated minerals from these last types are within the range 303–278 ± 7 Ma (late Westphalian to earliest Permian) (De Souza, 1979, recalculated by Wallis, 1989). More-precise Ar-Ar ages within this range have also been obtained: 288 ± 6 Ma from the Lugar Sill (Henderson *et al.,* 1987), and 295.2 ± 1.3 Ma and 298 3 ± 1.3 Ma from sills at Carskeoch and Ardrossan (A.A. Monaghan and M.S. Pringle, pers. comm., 2002).

There is also some field evidence that, within this latest group of intrusions, there are significant age differences. For instance, underground records have revealed that most sills post-date most faults apart from a late NW- to WNW-trending set, but that there are some sills that post-date all major faults (Eyles *et al.,* 1949; Mykura, 1967). Some sills are cut by necks and dykes associated with the Early Permian volcanic rocks, and their rock-types occur as blocks in the necks. However, the most strongly silica-undersaturated and alkaline intrusions of the Ayrshire Basin have strong petrographical and geochemical similarities with these volcanic rocks and hence have to be regarded as comagmatic and coeval. Palaeomagnetic data on some of the sills also support a Permian age (Armstrong, 1957).

Much of the early general work on the alkali intrusions of the western Midland Valley was by Tyrrell (1909a, 1912, 1923, 1928a,b) and details of the Ayrshire sills are given in Geological Survey memoirs (Richey *et al.,* 1930; Eyles *et al.,* 1949; Monro, 1999). Unlike in the eastern Midland Valley, only a few of the sills have been studied in detail, but these have acquired international recognition. Several are composite and have provided continuous sections, variously interpreted as showing sequential intrusion of differentiates from an alkali basalt magma and/or differentiation of the magma *in situ.* The earliest study was by Tyrrell (1917b) on the Lugar Sill, which was followed by that of Patterson (1945, 1946) on the Saltcoats Main Sill and by further definitive work on the Lugar Sill that took advantage of two continuous borehole cores (Tyrrell, 1948, 1952). These studies became textbook examples and prompted further work (e.g. Phillips, 1968), culminating in the comprehensive model of Henderson and Gibb (1987), which is based on a further 49 m continuous core through the Lugar Sill. According to this model, the sill formed by up to four multiple injections of progressively less evolved alkali basalt magma, followed by a large pulse of olivine-rich magma that differentiated *in situ.* Upward enrichment of residual liquids and volatile fractions gave rise to late-stage veins. These key intrusions are represented in this chapter by the Lugar and Ardrossan to Salt-coats Coast GCR sites. The latter site includes several other sills that exhibit a wide variety of field relationships and petrographical features. Other notably composite sills occur at Carskeoch, Kilmein Hill and Craigens–Avisyard.

The Benbeoch Sill (Benbeoch GCR site) is one of a dense cluster of sills in the Patna–Dalmellington–Cumnock area, between the Kerse Loch and Southern Upland faults, and is one of the thickest sills at over 65 m. It was the type locality for the 'kylitic' types of sill, characterized by olivine-rich nepheline-dolerite, and typically contains about 35% olivine, rising to 55% in picritic layers (Dreyer and MacDonald, 1967). Other notably picritic sills occur at Craigdonkey and Benquhat. A further concentration of sills occurs in the Dundonald area, between Galston and Troon, where dolerite crops out over some 16 km^2 and has been quarried extensively. Most of the outcrops are part of two large sills, the Caprington Sill of analcime-dolerite and the 58 m-thick Hillhouse Sill, dominantly of nepheline-dolerite.

Sills of the strongly silica-undersaturated 'monchiquitic' types are never more than 2 m thick and are all closely associated with volcanic necks of the Mauchline lava field (see 'Introduction' to Chapter 4). Notable examples occur at Meikleholm Glen, Dunaskin Glen and Carskeoch.

Numerous dykes of alkali dolerite and basalt, with a variety of trends, are exposed in coastal sections of Ayrshire and were recorded in underground workings. They are clearly younger than the Coal Measures and some must be late Westphalian to Early Permian in age, but many are members of the extensive Palaeogene dyke-swarms that cross the area. Some attempt has been made to divide the dykes on the basis of their trends and cross-cutting relationships with other dykes and with faults (Eyles *et al.,* 1949; Mykura, 1967), but with only limited success. It is assumed that most of the NW-trending dykes are of Palaeogene age, though some near West Kilbride are cut by other dykes orientated east–west. In this area, dykes of all ages can be very fresh and petrography is not a reliable indicator of age, except for the alkali lampro-phyres and foiditic types, which can be compared with the Early Permian volcanic rocks. Hence it is seldom possible to assign an age to an individual dyke with any confidence in the absence of radiometric or palaeomagnetic dates, or of diagnostic trace-element and isotope ratio data (Palaeogene magmas were generally depleted in incompatible elements relative to earlier magmas in the same area; e.g. Thompson, 1982). Many dykes are analcime-bearing olivine-rich dolerites with coarsely ophitic titanaugite, such as are very common in the Palaeogene swarms. However, few have sufficient analcime or nepheline to compare with the 'teschenitie sills, which has led to general statements that there is no dyke-swarm associated with the late Westphalian to Early Permian alkali dolerite sills (e.g. Cameron and Stephenson, 1985). However, Richey *et al.* (1930) have described east- to ESE-trending dykes that appear to rise from a 'teschenitie sill and are not present in coal workings below.

In the Glasgow–Paisley area, four major sill-complexes, some consisting of up to three leaves and up to 80 m thick, can he traced over wide areas (Clough *et al.,* 1925; Hall *et al.,* 1998). These occur in the Johnstone–Howwood area; between Paisley and the River Clyde at Scotstoun (the Hosie and Hurlet sills); around Cathcart; and between the Necropolis Hill, Glasgow and Easterhouse. All are 'teschenitic' analcime-dolerites and some contain appreciable amounts of nepheline in addition to analcime. A particularly striking melanocratic nepheline-dolerite at Barshaw has abundant titanaugite and red-brown alkali amphibole (kaersutite); it was formerly classified as a 'bekinkinite' by comparison with a similar rock from Madagascar (Tyrrell, 1915). Three of these sills have yielded K-Ar radiometric dates, based on separated amphibole or biotite, that are tightly grouped in the range 279 ± 9 Ma to 276 ± 8 Ma (De Souza, 1979, recalculated by Wallis, 1989) implying an association with the Early Permian volcanism of Ayrshire. However, an Ar-Ar re-determination of one of these gives a more precise but significantly older age of 292.1 ± 1.1 Ma (A.A. Monaghan and M.S. Pringle, pers. comm., 2002). Two plug-like intrusions, close to the Campsie Fault at Lennoxtown, are of a distinctive augite-phyric nepheline-monzogabbro (Clough *et al.,* 1925; Forsyth *et al.,* 1996), similar to that of the Crawfordjohn dyke in the Southern Uplands (see Craighead Quarry GCR site report). One of the plugs has been dated at 276 ± 7 Ma (De Souza, 1979, recalculated by Wallis, 1989), suggesting an Early Permian age for both the Lennoxtown and the Crawfordjohn intrusions, but the Lennoxtown intrusion also gives a significantly older date of 292 ± 2.7 Ma by Ar-Ar (A.A. Monaghan and M.S. Pringle, pers. comm., 2002). Alkali dolerite dykes are rare in this area, which lies well to the north-east of the sharply defined limit of the main Palaeogene dyke-swarms (Cameron and Stephenson, 1985). Hence, the few very fresh olivine-dolerite dykes that are present are probably related to the Early Permian sills.

Highly altered sills around Milngavie, up to 30 m thick, consist of olivine-free dolerite with small patches of quartz (probably secondary), but their mafic minerals (purplish augite, red-brown amphibole and biotite) are of the type found in the alkali dolerites (Clough *et al.,* 1925; Hall *et al*., 1998).

Southern Uplands

In the Sanquhar Basin, thin sills of analcime-dolerite cut Coal Measures (Simpson and Richey, 1936). Most are altered, commonly to 'white trap', but some have been described as 'camptonitic' and presumably contain abundant alkali amphibole. A few NW-trending dykes of 'monchiquite' and 'camptonitic dolerite' are also recorded in the coalfield, and both dykes and sills are presumed to be related to the Early Permian volcanic rocks that are preserved as small outliers in the basin (see 'Introduction' to Chapter 4 (Figure 4.2)).

The Lower Palaeozoic rocks of the Southern Uplands are cut by rare 'monchiquite' dykes and by two 'essexites' near Wanlockhead and Abington. The latter, an attractive nepheline-gabbro that was formerly well known as the Crawfordjohn 'Essexite' (Scott, 1915), is represented in this volume by the Craighead Quarry GCR site. It is very similar petrographically to the nepheline-monzogabbro at Lennoxtown, north of Glasgow which has been dated radiometrically at 292 Ma. Most of the dykes are NW-trending, although a NE-trending 'monchiquite' has been recorded in Lauderdale (Walker, 1925). The area is also cut by NW-trending dykes of the Palaeogene regional swarm, but this swarm is not known to include strongly silica-undersaturated rocks such as the 'monchiquites' and nepheline-gabbros.

Highlands and Islands

North-west of the Highland Boundary Fault, Early Permian extrusive rocks occur only in the Sound of Islay, but sub-volcanic necks occur in a linear zone between Kinlochleven and Applecross and in a cluster around south-east Orkney (see (Figure 4.4), Chapter 4). A 60 m-thick sill of alkali olivine-dolerite intruded into Coal Measures at

Machrihanish is probably of similar age. Much more widespread are dykes of alkaline lamprophyre (camptonite and monchiquite), with subordinate associated foidite, basanite and basalt (Figure 5.2), which have long been assumed to be of Carboniferous to Permian age (rather than of Caledonian or Palaeogene age) on petrographical grounds (e.g. Richey, 1939). In the western Highlands, camptonite dykes cut quartz-dolerite dykes of the Stephanian suite (see Chapter 6).

The Orkney dykes have been described in great detail by Flea (in Wilson *et* al., 1935; Flett, 1900) and those of the Eil-Arkaig, Monar and Ardgour areas were described by Leedal (1951), Ramsay (1955) and Gallagher (1963) respectively. Several individual dykes have been studied, largely because of their varied content of mantle and crustal inclusions (see below) (Walker and Ross, 1954; Praegel, 1981; Upton *et al.,* 1992, 1998, 2001). In a major review of the whole suite, Rock (1983), recognized over 3000 dykes which he divided into nine swarms, with a few widely scattered individual dykes elsewhere (Figure 5.2). There are three principal trends: north-west-south-east, dominant in the western and south-western Highlands and Islands; east-west, dominant in the central part of the northern Highlands; and WSW–ENE in the Orkneys.

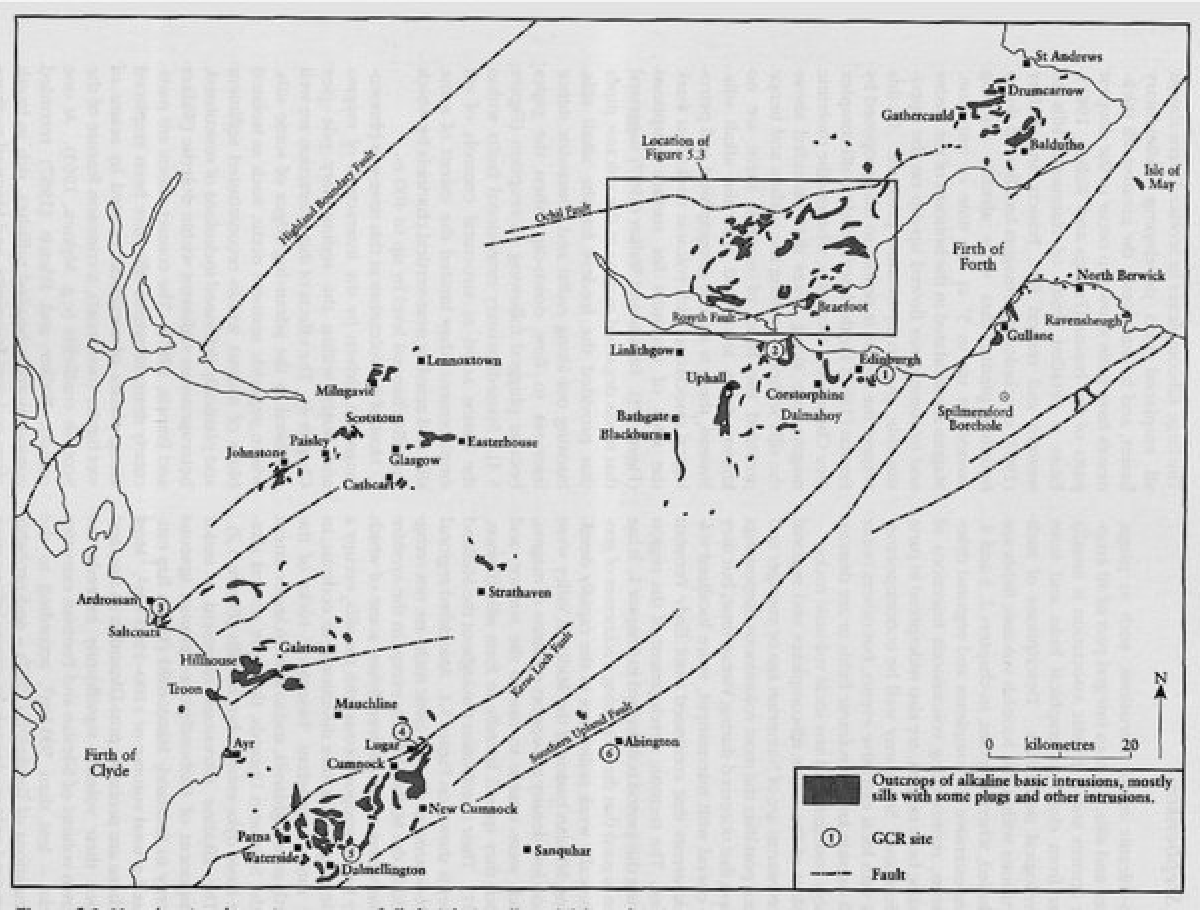
The age of these dyke-swarms was the subject of one of the first ever radiometric studies, by Urry and Holmes (1941), who determined the age of two monchiquite dykes on Colonsay by the pioneering Helium Method. One of these dykes now represents the suite in this chapter (see Dubh Loch GCR site report). Subsequently many K-Ar studies appeared to confirm a Late Carboniferous to Permian age (Beckinsale and Obradovich, 1973; Brown, 1975; Mykura, 1976; Halliday *et al.,* 1977; De Souza, 1979; Speight and Mitchell, 1979). A review of these works, together with further K-Ar determinations, by Baxter and Mitchell (1984) led to the suggestion that the three trends may represent three separate tectonomagmatic events:

1. late Visean age (326 Ma, measured on the E–W-trending Morar and Eil–Arkaig swarms). A comparable date for these swarms was obtained by palaeomagnetic measurements (Esang and Piper, 1984)
2. late Stephanian to Early Permian age (290 Ma, measured on the NW-trending Ardgour Swarm). A NNW-trending dyke on Mull has yielded an Ar-Ar age of 268 ± 2 Ma (Upton *et al.,* 1998)
3. Late Permian age (250 Ma, measured on the WSW-trending Orkney Swarm).

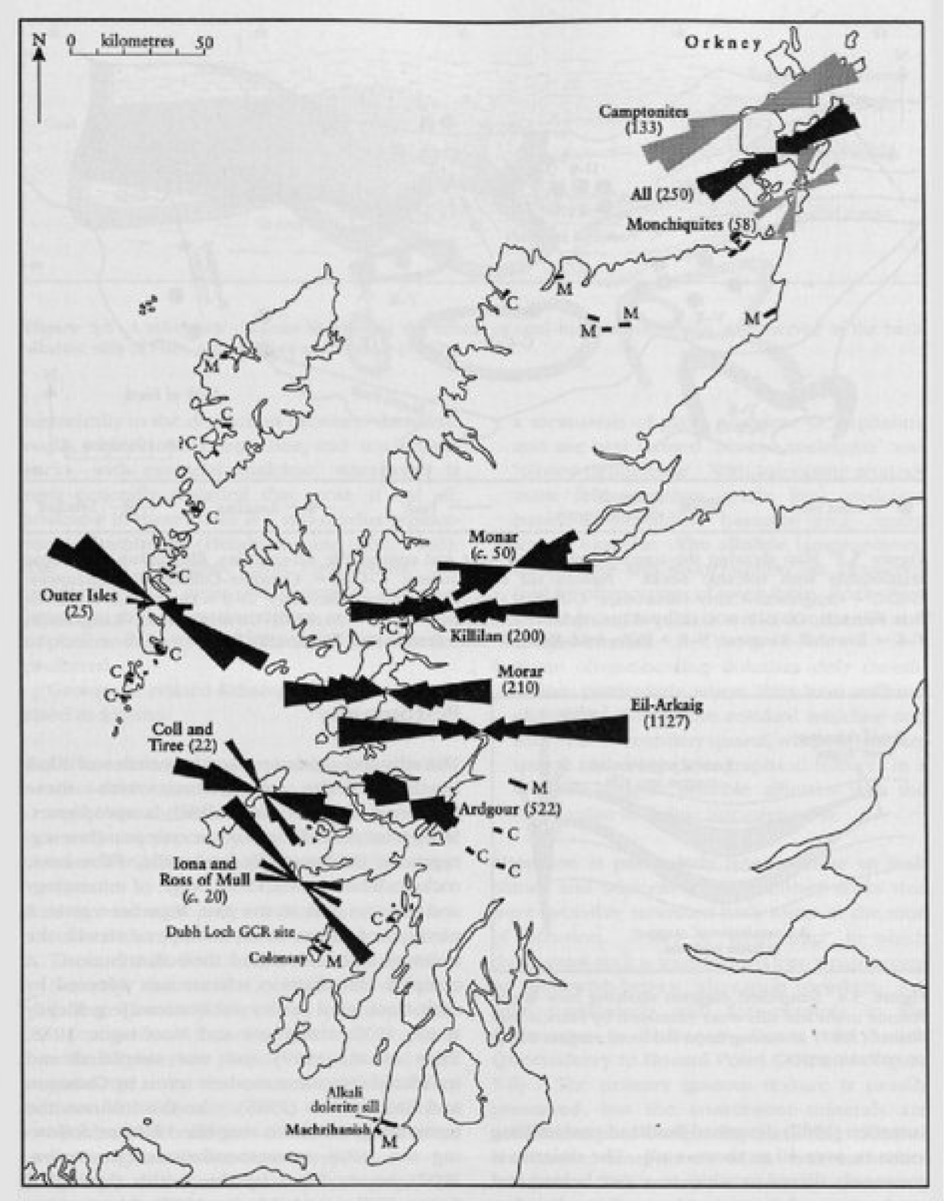
This correlation of trend with age may be broadly applicable in terms of the various swarms, but individual dykes commonly follow pre-existing structures and hence it cannot be applied to individual dykes. The problem is compounded in Ardgour and the Inner and Outer Hebrides, where swarms of Caledonian calc-alkaline lamprophyres and Palaeogene alkali olivine-dolerites cross the same area as the Ardgour Swarm and occupy the same fracture sets (Morrison *et al.,* 1987). Criteria for distinguishing the dykes of various ages are listed by Rock (1983).

Collectively, these dykes are the most silica-undersaturated, the most highly alkaline and the most primitive suite of basic igneous rocks recorded anywhere in Britain. They are a vital source of information on late Visean to Permian magma genesis and the nature of the upper mantle over a far wider area than that sampled by the more voluminous magmatism of the Midland Valley of Scotland (Baxter, 1987; Upton *et al.,* 1992). They commonly contain xenoliths and xenocrysts from their source region, but also include material from the overlying litho-spheric upper mantle and lower crust. Together with the coeval volcanic necks, the dykes are the most prolific source of such material, which is discussed in detail in Chapter 1.

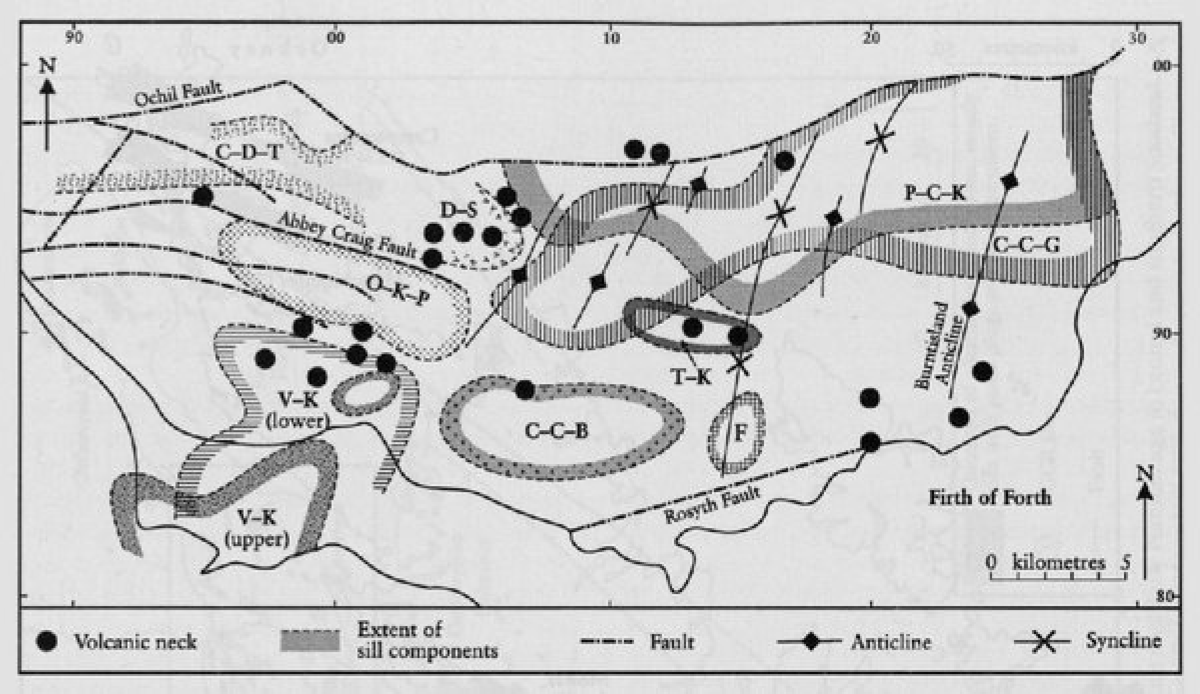
References



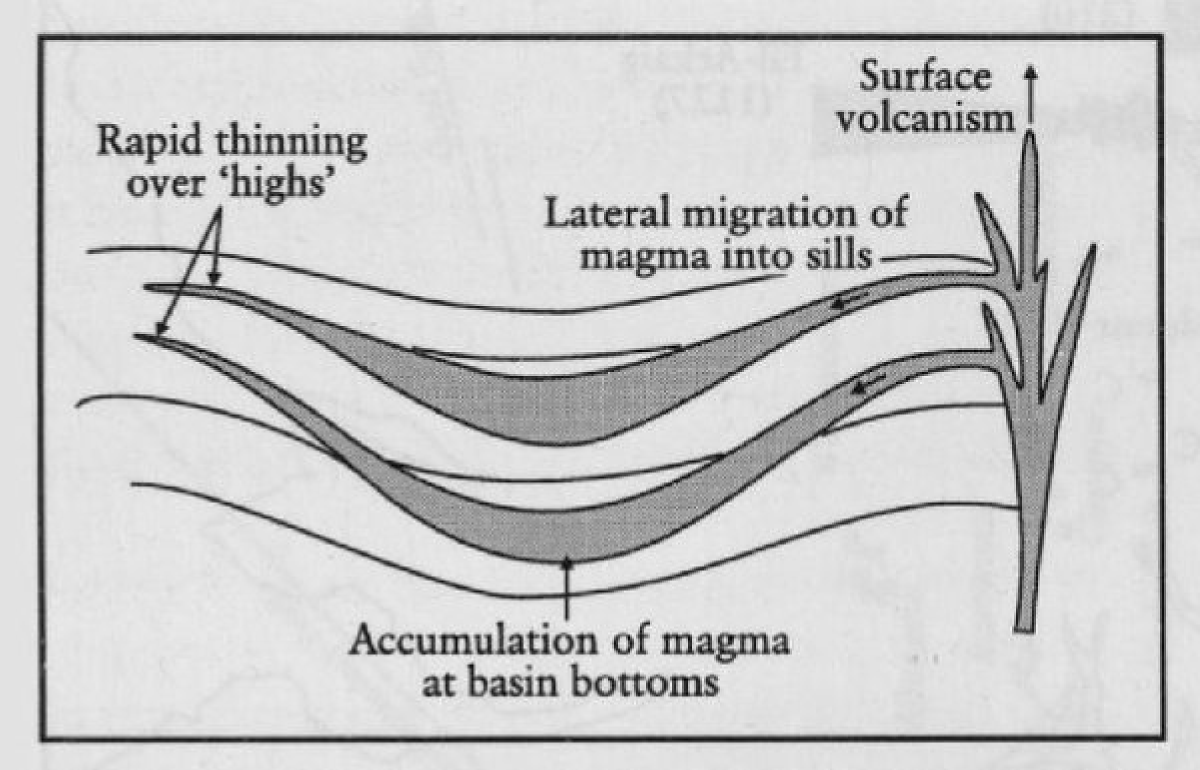
(Figure 5.1) Map showing the main outcrops of alkali dolerite sills and dykes of Carboniferous and Early Permian age in central and southern Scotland. GCR sites: 1 = Arthur's Seat Volcano (Salisbury Craigs Sill); 2 = South Queensferry to Hound Point (Mons Hill Sill); 3 = Ardrossan to Saltcoats Coast; 4 = Lugar; 5 = Benbeoch; 6 = Craighead Quarry. The Dubh Loch GCR site lies outside the range of this map (see (Figure 5.2)). After Cameron and Stephenson (1985).



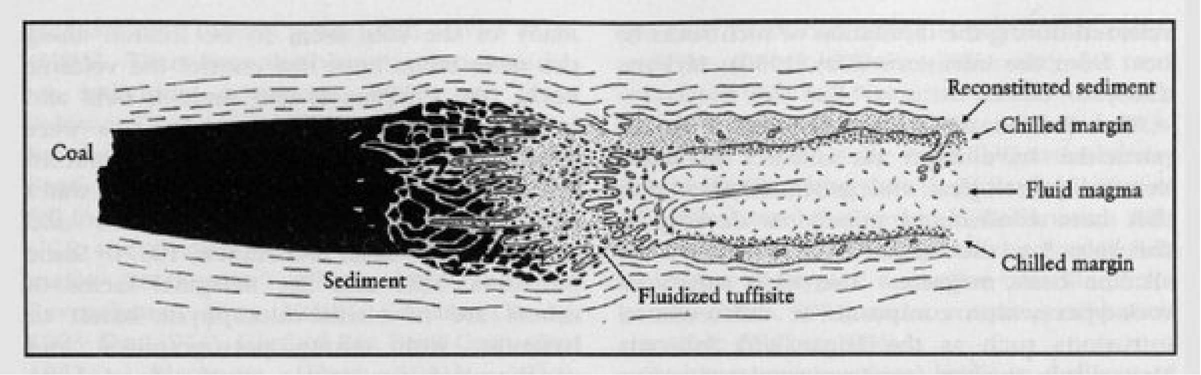
(Figure 5.2) Map showing the location and azimuth distribution of the main alkaline lamprophyre (camptonite and monchiquite) dyke-swarms of the northern Highlands. Azimuth distributions are presented as total percentage of dykes in each swarm with a particular orientation; thus long arms indicate swarms 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).



(Figure 5.3) Map showing the components of the west and central Fife sill-complex, illustrating their close relationship with volcanic necks. Named sill components: C–C–B = Crombie–Cairneyhill–Bellknowes; C–C–G = Craigluscar–Cluny–Glenrothes; C–D–T = Cairnfolds–Dollar–Tillicoultry; D–S = Dunnygask–Steelend; F = Fordell; O–K–P = Oakley–Kinneddar–Parklands; P–C–K = Parkhill–Cowdenbeath–Kinglassie; T–K = Townhill–Kingseat; V–K = Valleyfield–Kinnell. After Francis and Walker (1987).

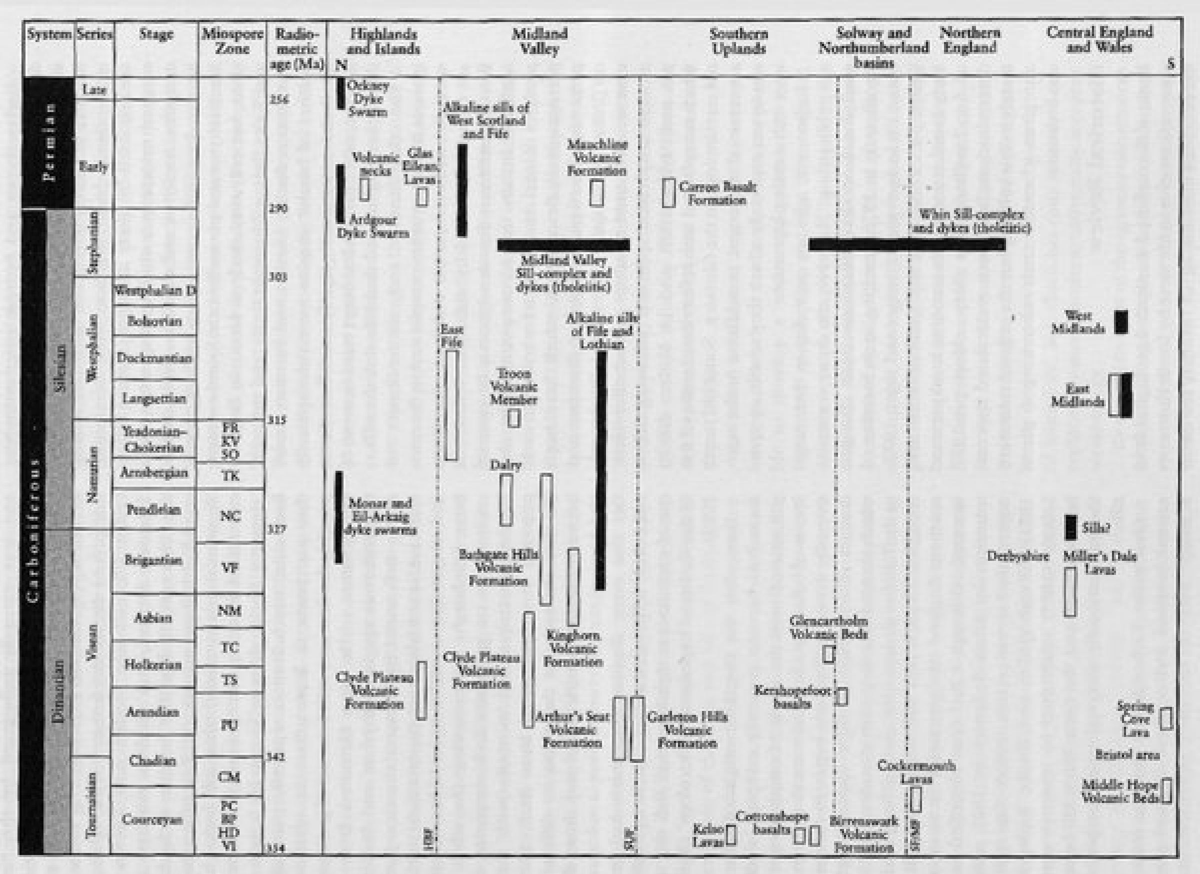


(Figure 5.4) Simplified diagram showing how large-volume multi-leaf sills were envisaged by Francis and Walker (1987) as having been fed from magma rising up volcanic pipes.

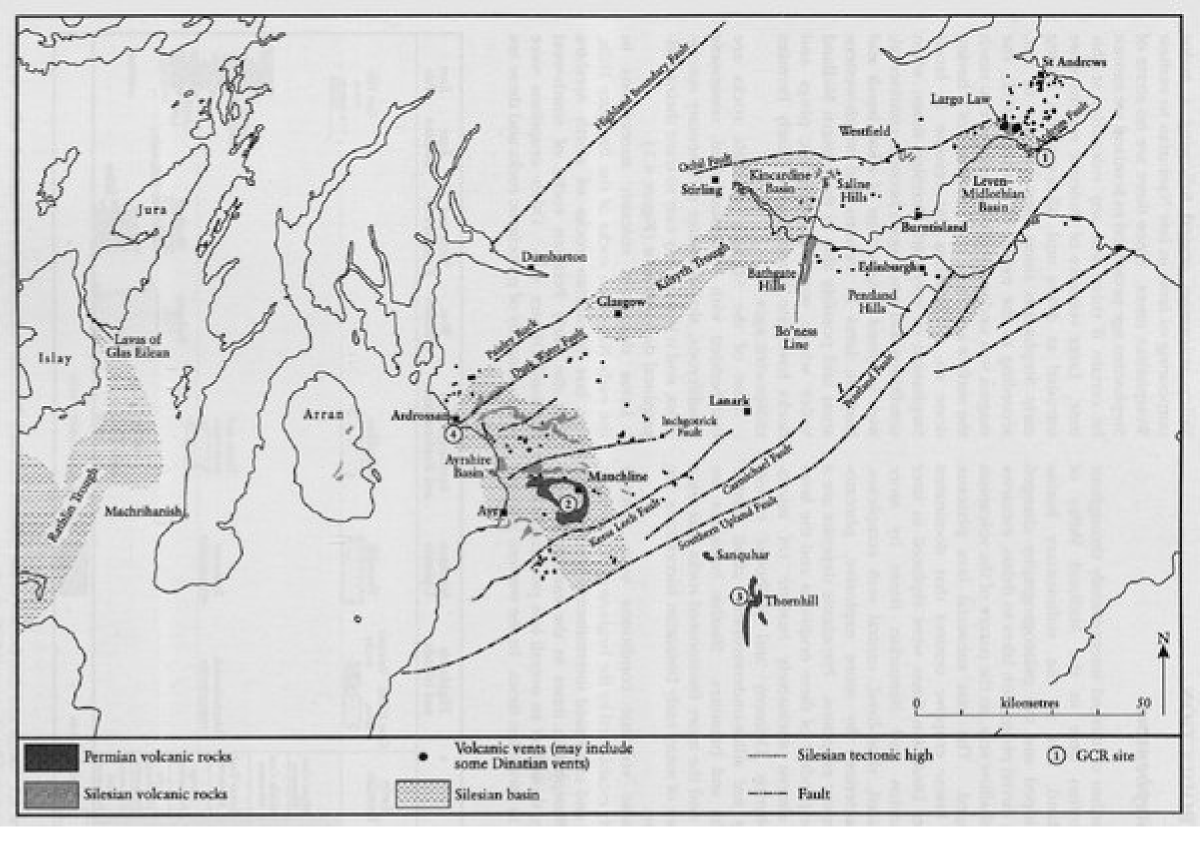


(Figure 5.5) A schematic diagram illustrating the effects of coal–magma interaction, as observed in the basic alkaline sills of Fife. After Walker and Francis (1987).

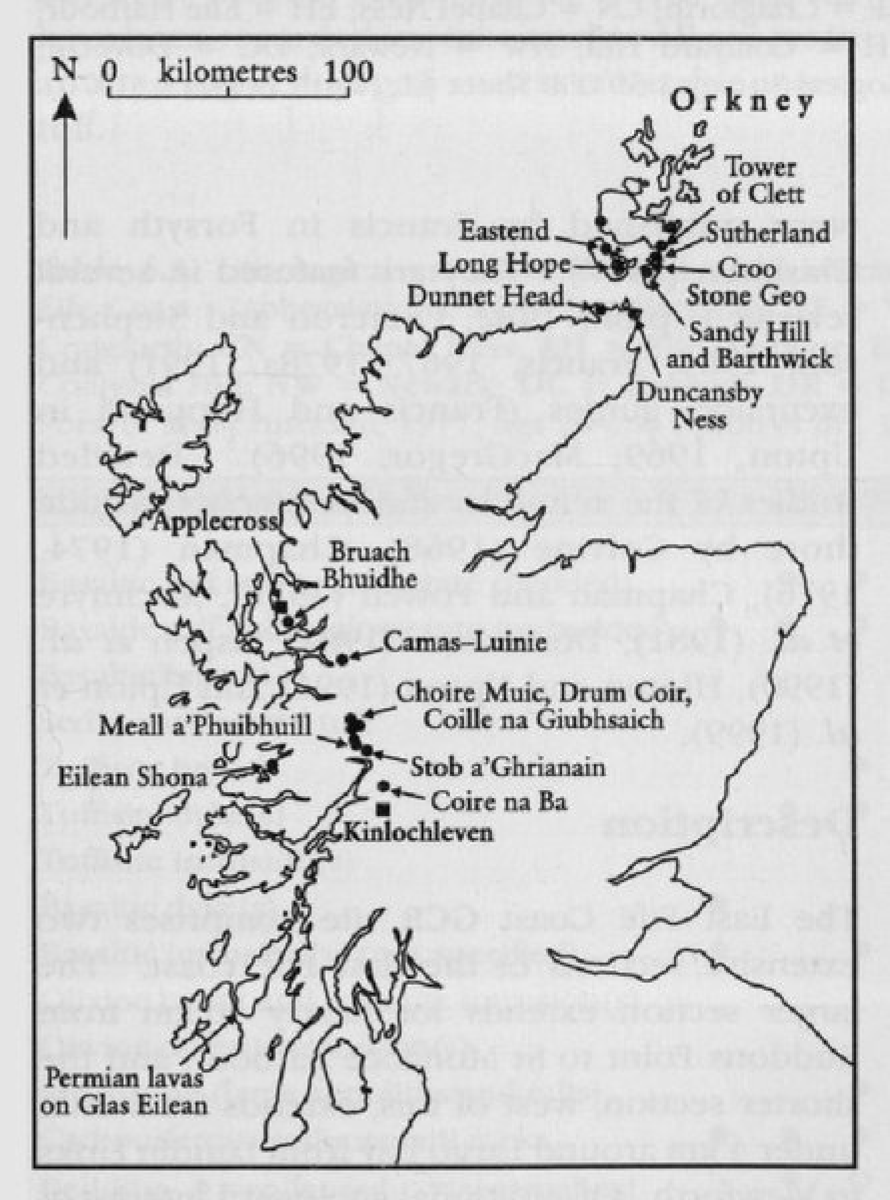
(Figure 5.8) Basic sill intruding and transgressing sedimentary rocks of the West Lothian Oil-shale Formation and altered to 'white trap', South Queensferry shore. The hammer shaft is about 35 cm long. (Photo: A.D. McAdam.)



(Figure 1.2) Stratigraphical distribution of British Carboniferous and Permian extrusive rocks (open bars) and intrusive rocks (solid bars). Timescale after Gradstein and Ogg (1996). See individual chapters for more detailed stratigraphical charts. (HBF = Highland Boundary Fault; SUF = Southern Upland Fault; SF = Stublick Fault; MF = Maryport Fault.)



(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 4.4) 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).