Carboniferous and Permian Igneous Rocks of Great Britain

North of the Variscan Front

D. Stephenson*,

S.C. Loughlin*,

D. Millward*,

C.N. Waters+

and

I.T. Williamson+

*British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA.

+British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG.

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Chapter 5

Alkaline basic sills and dykes of Scotland

INTRODUCTION

D. Stephenson

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 phreatomagmatic, 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

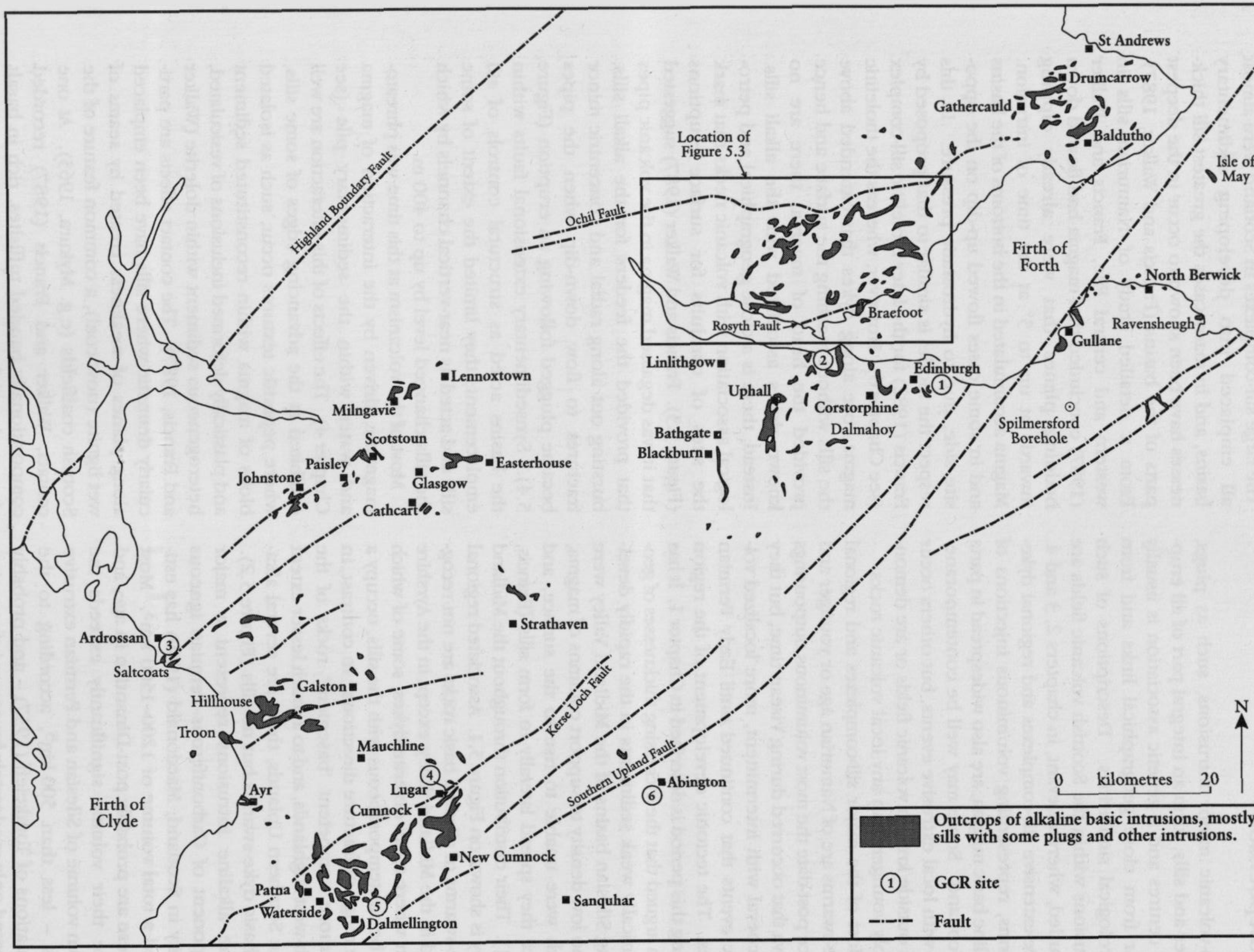

Figure 5.1 Map showing the main outcrops of alkali dolerite sills and dykes of Carboniferous and Early Permian age in central and southern Scotland. GCR sites: 1 = Arthur's Seat Volcano (Salisbury Craigs Sill); 2 = South Queensferry to Hound Point (Mons Hill Sill); 3 = Ardrossan to Saltcoats Coast; 4 = 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).

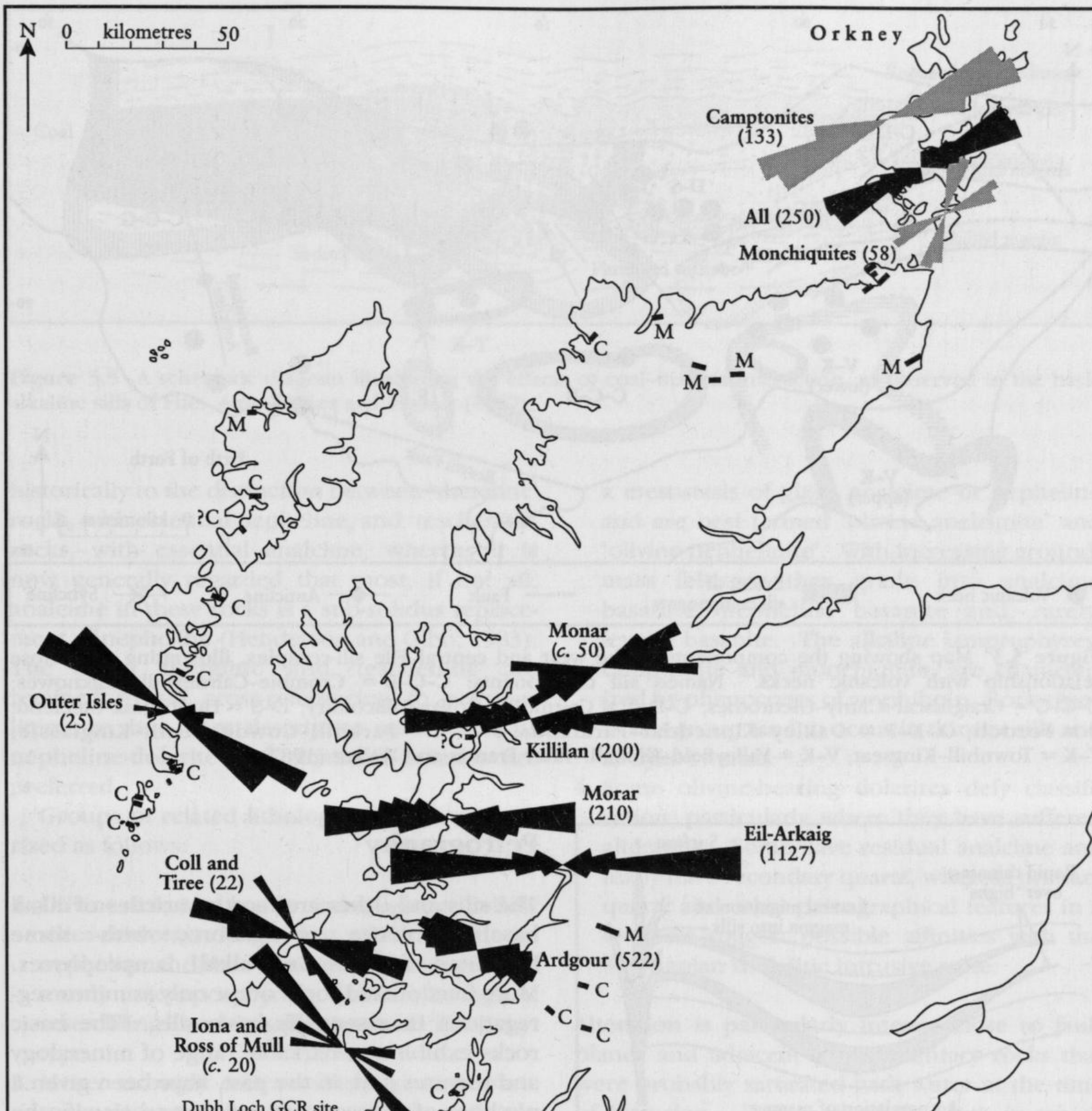

Figure 5.2 Map showing the location and azimuth distribution of the main alkaline lamprophyre (camptonite and monchiquite) dyke-swarms of the northern Highlands. Azimuth distributions are presented as total percentage of dykes in each swarm with a particular orientation; thus long arms indicate swarms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

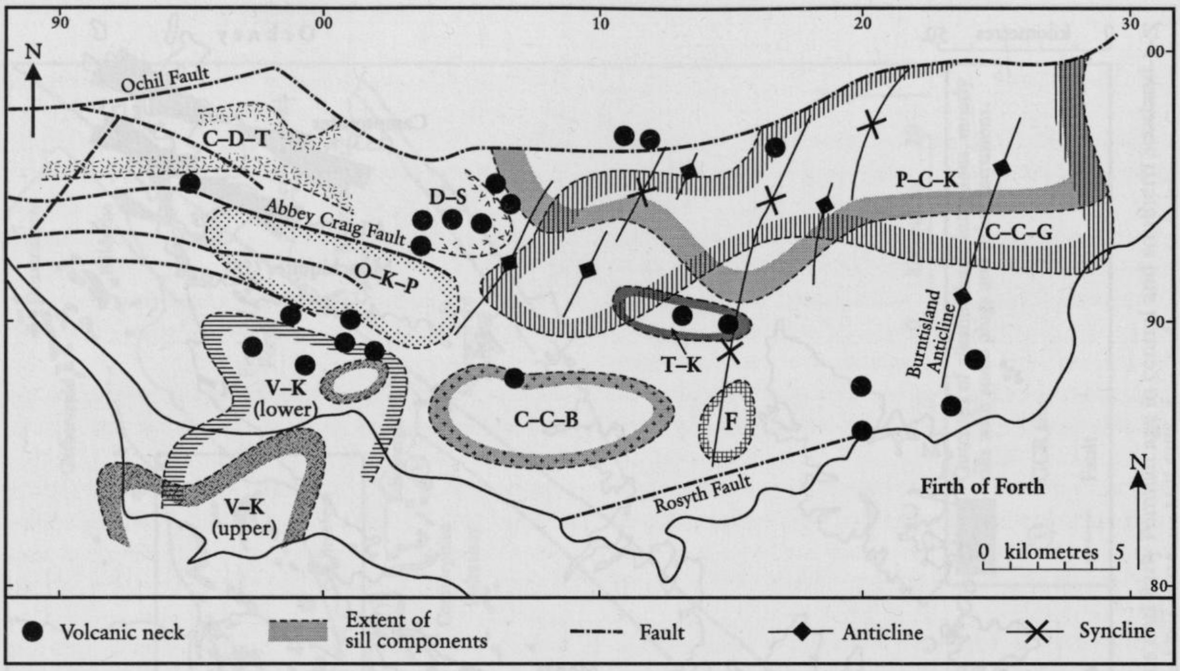

Figure 5.3 Map showing the components of the west and central Fife sill-complex, illustrating their close relationship with volcanic necks. Named sill components: C–C–B = Crombie–Cairneyhill–Bellknowes; C–C–G = Craigluscar–Cluny–Glenrothes; C–D–T = Cairnfolds–Dollar–Tillicoultry; D–S = Dunnygask–Steelend; 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).

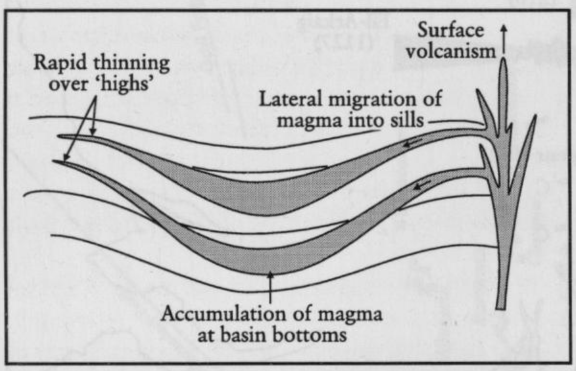

Figure 5.4 Simplified diagram showing how large-volume multi-leaf sills were envisaged by Francis and Walker (1987) as having been fed from magma rising up volcanic pipes.

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

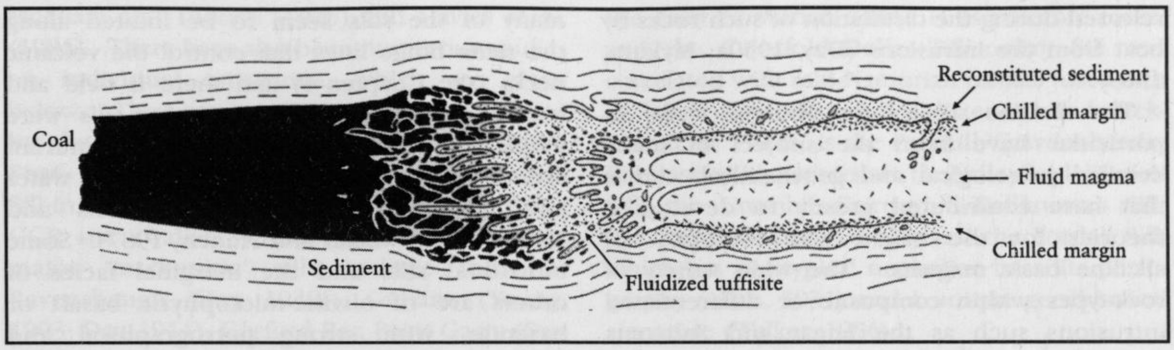

Figure 5.5 A schematic diagram illustrating the effects of coal–magma interaction, as observed in the basic alkaline sills of Fife. After Walker and Francis (1987).

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, 1931a,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 (Drever 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 'teschenitic', '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 Saltcoats 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 (Drever 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 lamprophyres 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 'teschenitic' 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 'teschenitic' 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 be 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 Flett (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 lithospheric 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.

SOUTH QUEENSFERRY TO HOUND POINT, CITY OF EDINBURGH (NT 137 784–NT 159 794)

S.C. Loughlin and I.T. Williamson

Introduction

Major basic sills of both alkaline and tholeiitic affinity are prominent within many parts of the Midland Valley of Scotland. The southern shore of the Firth of Forth, to the east of the famous railway bridge, provides a unique opportunity to examine both types of sill in close proximity, where they intrude mudstones and sandstones of the Gullane Formation (Strathclyde Group). The superb exposures and great diversity of features make this a valuable site for educational purposes and it is a favoured field excursion venue (e.g. MacGregor, 1973; McAdam in McAdam and Clarkson, 1986).

The site has been a source of interest and debate since the 19th century. Some of the more important early studies include Howell and Geikie (1861), Geikie (1880, 1897), Stecher (1888), Flett (in Peach *et al.*, 1910) and Walker (1923). The alkaline Mons Hill Sill, formerly classed as a 'teschenite', exhibits considerable petrographical variation but mainly comprises analcime-dolerite. It shows many features characteristic of other alkali dolerite sills in the eastern Midland Valley (e.g. Flett, 1930, 1931a,b, 1932; Campbell *et al.*, 1932, 1934; Higazy, 1952), but also has slight petrographical differences that are of academic interest. The tholeiitic Hound Point Sill comprises mainly quartz-dolerite and is a component of the Midland Valley Sill-complex (see Chapter 6). It is petrographically and geochemically similar to other quartz-dolerite sills in the eastern Midland Valley (e.g. Falconer, 1906; Tyrrell, 1909b; Bailey in Clough *et al.*, 1911) and shows typical features such as the development of a coarse-grained and slightly evolved facies just above mid-height, and segregation veins. Near the railway bridge smaller doleritic sills, intruded into a sequence of carbonaceous mudstones and oil-shales, have been altered to a distinctive rock-type known as 'white trap' (Day, 1930a). 'White trap' is relatively common in the Edinburgh district but this is a particularly well-exposed example.

There is no precise field evidence for the age of the sills within the South Queensferry to Hound Point GCR site, or for their age relative to each other. Alkaline basic sills were emplaced during various magmatic episodes from Visean to Early Permian times. In Fife and the Lothians many olivine-dolerites may be Visean or Namurian, as they are petrographically and geochemically similar to neighbouring extrusive rocks of that age (e.g. the Bathgate Hills Volcanic Formation). Some radiometric dates confirm this correlation (De Souza, 1979, 1982). The distinctive 'teschenitic' sills (analcime-dolerites) were thought to be younger, possibly Namurian to Westphalian in age, as appeared to be confirmed by a K-Ar whole-rock date of 308 ± 7 Ma on the Mons Hill Sill (De Souza, 1979, recalculated by Wallis, 1989). However, a re-determination of this sample by Ar-Ar dating has yielded a latest Visean age of 329.3 ± 1.3 Ma (A.A. Monaghan and M.S. Pringle, pers. comm., 2002). Radiometric dates on the tholeiitic Midland Valley Sill-complex elsewhere suggest a Stephanian age on current timescales (see Chapter 6).

Description

Walker (1923) mapped this site in some detail (Figure 5.6), slightly modifying the linework of the 1910 edition of the Geological Survey one-inch Sheet 32 on which some quartz-dolerite

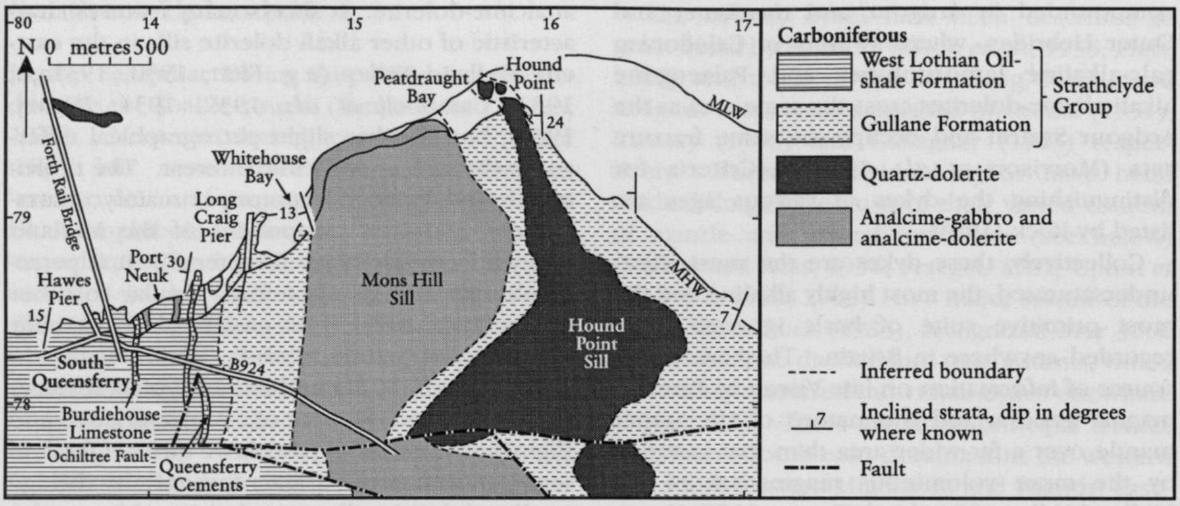

Figure 5.6 Map of the area around the South Queensferry to Hound Point GCR site. After McAdam (in McAdam and Clarkson, 1986).

outcrops had been mapped as 'teschenite'. He recognized that the quartz-dolerite commonly shows spheroidal weathering and crude columnar jointing whereas the analcime-dolerite does not have such distinctive weathering but does have well-developed, sharp-edged columnar joints. In addition, analcime-dolerite is more leucocratic in appearance than quartz-dolerite and ferromagnesian minerals are usually fresher. Analcime-dolerite commonly contains irregularly shaped cavities (druses) into which euhedral crystals of the rock project.

The section is described from east to west, up the succession.

The Hound Point Sill (tholeiitic)

Hound Point, at the eastern extremity of the site (NT 158 796), and rocks on the shore to the north, are composed of a gently westward-dipping (*c.* 15°) quartz-dolerite sill. Here the sill is 20–30 m thick, but it thickens inland. Crude columnar jointing is developed and pale-grey, curvi-planar segregation veins are well displayed locally as a result of differential weathering. The sill intrudes sandstones and black mudstones belonging to the Gullane Formation (formerly part of the 'Queensferry Beds').

The base of the sill is exposed on the east side of Hound Point, where it lies on indurated mudstones and sandstones. The more arenaceous beds are baked to quartzite, whereas black carbonaceous mudstone has been altered to a cordierite-bearing hornfels. The cordierite is commonly pseudomorphed by calcite or altered to micaceous material and gives the altered mudstones a spotted appearance (Flett in Peach *et al.*, 1910; Day, 1928b). Two thin sheets of quartz-dolerite with chilled margins occur below the main body of the sill (MacGregor, 1973). These are probably apophyses from the main sill. The sill becomes finer grained towards its base and has a chilled margin. At one place the base of the main sill has wedged into the bedded sediments producing a transgressive contact (Figure 5.7) that resembles Hutton's famous locality at Salisbury Craigs (see **Arthur's Seat Volcano** GCR site report). Above this contact a thin sheet-like body of quartzite within the sill, which superficially resembles a quartzo-feldspathic segregation vein, has chilled basalt on each side.

Basalt exposed in reefs close to the low-water mark north-west of Hound Point is presumed to represent the chilled margin at the top of the sill.

The Mons Hill Sill (alkaline)

Just above the horizon of the Hound Point Sill the Gullane Formation is intruded by another major basic sill known as the 'Mons Hill Sill' (e.g. Flett in Peach *et al.*, 1910; Walker, 1923; MacGregor, 1973). Virtually the whole thickness of the sill is seen in well-exposed sections from

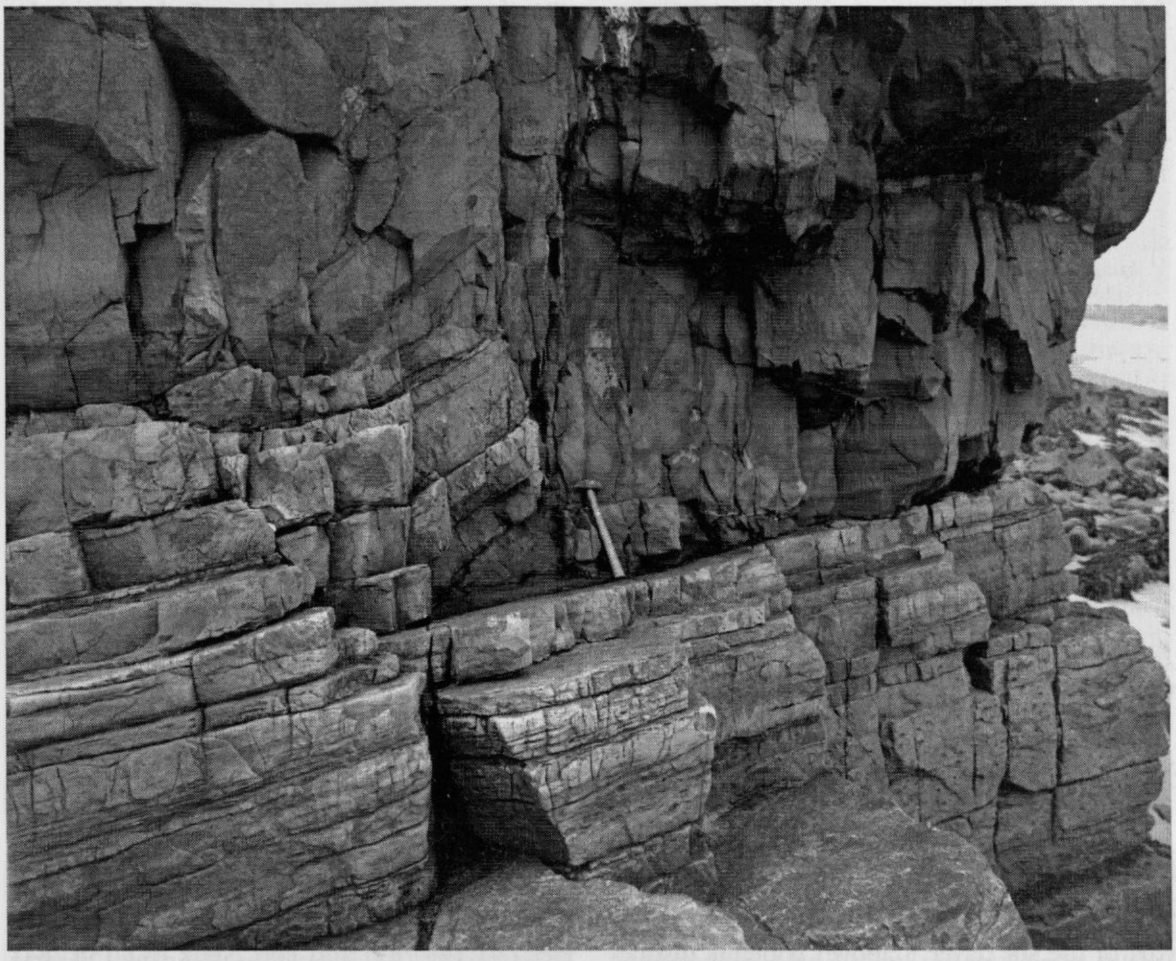

Figure 5.7 Base of the Hound Point quartz-dolerite sill at Hound Point, forcing up the underlying beds of sandstone. The hammer shaft is about 35 cm long. (Photo: British Geological Survey, No. D1917, reproduced with the permission of the Director, British Geological Survey, © NERC.)

the west side of Peatdraught Bay (NT 154 794) to Whitehouse Point (NT 147 789). Inland, the sill forms the upstanding ridge of Mons Hill, from which it takes its name, and it is seen in several, now disused, quarries. Jointing in the sill suggests a dip of about 11° to the west, more-or-less conformable with the country-rock strata, which here dip westwards at 13°–19°. Original estimates of the thickness were 150–155 m, but undulations in the dip, suggested by the jointing, mean that it may be thinner (McAdam and Clarkson, 1986).

The basal contact of the sill is obscured by sand and the upper contact is accessible only during exceptionally low tides. The upper few metres of the sill are vesicular and well jointed. Contact-altered spotted mudstones and indurated sandstones of the Gullane Formation are exposed close to the supposed locations of both contacts and a good section through these beds is exposed intermittently for 25–35 m along the top of the beach on the east side of Whitehouse Bay (MacGregor, 1973).

This 'teschenitic' sill is composed mainly of analcime-dolerite and analcime-gabbro, with some nepheline-dolerite. In common with other alkaline sills of the Midland Valley, internal contacts separate a number of distinct sheets showing variations in texture, petrography and chemical composition. The description of the coastal section (see below), is based largely on Walker (1923), who distinguished what he termed 'modifications', but apparently was unable to give precise thicknesses.

Top
1. **Nepheline-dolerite**, dark, medium grained with idiomorphic kaersutite needles, black and pink segregation veins and a vesicular top; angular jointing

Contact fairly sharp but not chilled
2. **Analcime-dolerite**, compact, medium grained, sub-ophitic, fresh with mottled appearance and no segregation veins

Sharp contact seen at Whitehouse Point
3. **Analcime-gabbro**, coarse grained and very coarse-grained, mottled; large ophitic titaniferous augite crystals, plagioclase partly altered to analcime, much chlorite; pink segregation veins; calcite-filled cavities and conspicuous zeolitic drusy cavities; rounded jointing. Forms the bulk of the sill, between a point 300 m west of Peatdraught Bay and Whitehouse Point

Sharp contact
4. **Analcime-dolerite**, dark, medium grained, sub-ophitic; angular jointing

Uncertain contact
5. **Nepheline-dolerite**, pale, medium grained, with small kaersutite needles

Merging contact
6. **Kaersutite analcime-gabbro**, coarser grained than the nepheline- and analcime-dolerites above. Seen just east of a small sea-stack

Sharp contact, not chilled
7. **Analcime-dolerite**, dark, medium grained, idiomorphic titaniferous augite; angular jointing

Base

The analcime-gabbro that comprises the main part of the sill (layer 3 above) contains distinctive ophitic titaniferous augites measuring up to 2 cm × 15 cm and enclosing strongly zoned plagioclase that is partially replaced by analcime. Chlorite is also prominent and there are rare pseudomorphs after olivine. Alkali feldspar, analcime, natrolite and large skeletal ilmenite occur as prominent accessories along with some biotite and apatite. The kaersutite analcime-gabbro towards the base of the sill (layer 6 above) contains sub-ophitic titaniferous augite and variably sized kaersutite prisms. There is much chloritization and no nepheline.

The analcime-dolerite (layers 2 and 4 above) contains sub-ophitic titaniferous augite and plagioclase, most of which is altered to analcime. Pseudomorphs after olivine are common, as is biotite but there is no kaersutite. A variety of analcime-dolerite with idiomorphic rather than ophitic titaniferous augite comprises layer 7.

The nepheline-dolerite (layers 1 and 5 above) is dominated by idiomorphic kaersutite and green-rimmed (presumably slightly sodic) titaniferous augite. In layer 5 the kaersutite forms prominent needles. The groundmass comprises zoned plagioclase (labradorite to oligoclase), alkali feldspar, analcime, nepheline (mostly altered), titaniferous magnetite and pyrite with accessory apatite and biotite. There are also rare pseudomorphs after olivine.

Distinctive pink segregation veins occur in layers 1 and 3. They are medium grained, non-porphyritic and contain biotite, alkali feldspar, analcime and rare euhedral nepheline. Two varieties of black fine-grained segregation vein occur in layer 1: a ferromagnesian-rich variety with ocellar structure, and a modification of this with large phenocrysts of plagioclase and titaniferous augite.

The inland continuation of the Mons Hill Sill was proved in two boreholes sunk during the early decades of the 20th century, one at Easter Dalmeny (*c.* NT 150 775) and the other about 320 m farther west (Flett, 1930). These boreholes proved a layered sequence of over 85 m that includes analcime-gabbro and, notably, some picritic (olivine-rich) variants that are not present in the coastal section of the sill. In neither case was the top of the intrusion seen.

'White trap'

The rocky shoreline between Long Craig Pier (NT 144 789) and Port Neuk (NT 138 784) comprises a succession of mudstones, siltstones, sandstones, oil-shales and ferroan dolostones ('cementstones') belonging to the Calders Member of the West Lothian Oil-shale Formation. Within this succession, there are two thin, slightly transgressive sills, roughly 100 m apart, which have been altered to a light-coloured calcareous clay-rich material known as 'white trap' (Figure 5.8). The eastern sill, 60 cm thick, is a cream-coloured rock with brown margins; the western sill, 90 cm thick, is pale grey and weathers buff-brown. The margins of both sills are indistinct in places because the host sandstones are of a similar pale colour, but the sills may be distinguished by their polygonal jointing. Carbonaceous mudstones, even where bleached, are slightly darker and hence contacts with them are quite distinct; they may be brecciated or smooth (MacGregor, 1973; McAdam and Clarkson, 1986).

The 'white trap' sills are composed almost entirely of calcium-magnesium-iron carbonates, kaolin, muscovite and quartz. Relict igneous

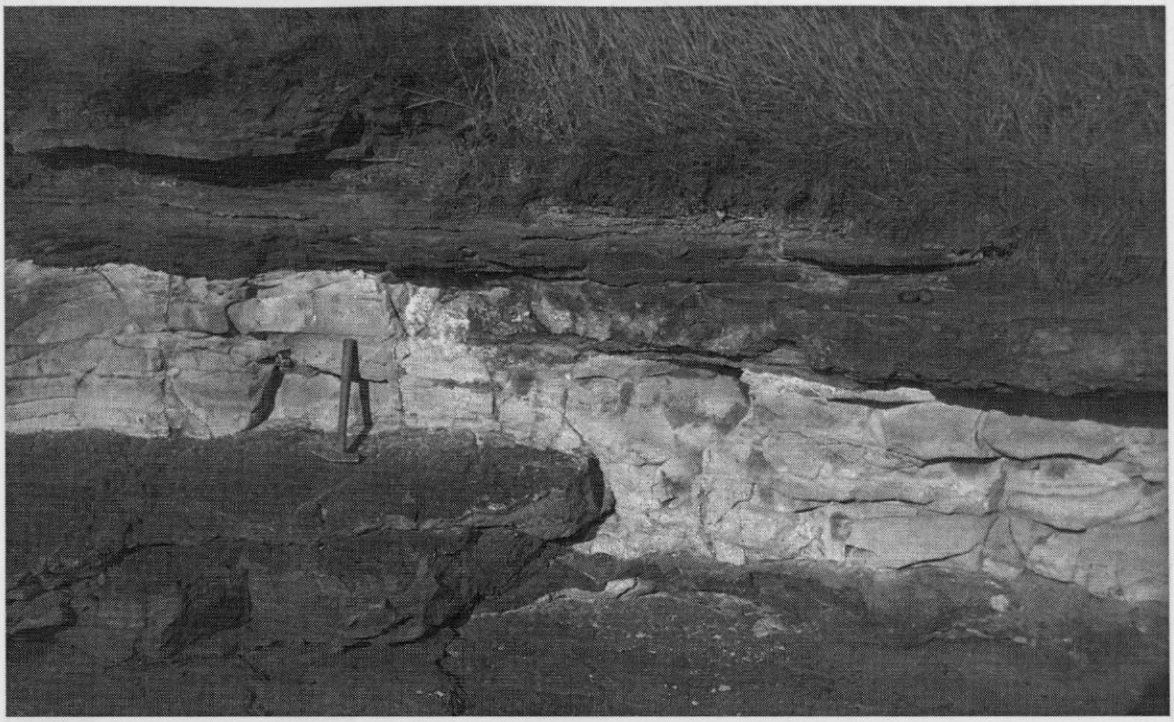

Figure 5.8 Basic sill intruding and transgressing sedimentary rocks of the West Lothian Oil-shale Formation and altered to 'white trap', South Queensferry shore. The hammer shaft is about 35 cm long. (Photo: A.D. McAdam.)

textures are preserved in places, but commonly only 'ghosts' of the original feldspar crystals remain, having been altered to aggregates of kaolin, isotropic silica, calcite, chalybite and some dolomite. Skeletal ilmenite and magnetite remain as accessories, particularly in the chilled margins (Stecher, 1888; Flett in Peach *et al.*, 1910; Day, 1930a).

Interpretation

The quartz-dolerite sill at Hound Point is a member of the Midland Valley Sill-complex, which is discussed at length in Chapter 6. Several other component sills of the complex are described as GCR sites and interpretations of their magmatic origin, evolution, structural setting and mode of emplacement apply equally to Hound Point. Consequently they are not repeated here. These tholeiitic sills do not have any known extrusive equivalents and were emplaced along E–W-trending fractures during a brief change in the stress regime that occurred in Late Carboniferous times (Francis, 1978b, 1982).

Walker (1923) described the petrographical variation within Mons Hill Sill in some detail, including the 'finer-grained marginal modifications' between the main rock-types. Despite the finer grain-size he did not observe glassy chilled margins towards the internal contacts and considered this as evidence for differentiation *in situ* rather than for separate injections of magma. Other alkaline basic sills of the Midland Valley are similarly composite, with a lithological range in some cases greater than that at Mons Hill. It is likely that some of the mechanisms that have been proposed for these sills also hold true for the Mons Hill Sill (see **Lugar**, **Ardrossan to Saltcoats Coast** and **Benbeoch** GCR site reports).

Numerous examples of the alteration of dolerite to 'white trap' have been recorded in the Edinburgh district. In most cases the original affinity of the dolerite cannot be determined, but the process is known to affect both alkaline and tholeiitic dolerites. Day (1930a) studied examples of 'white trap' within carbonaceous mudstones, oil-shales and coals from Dalmeny (this site), Granton, Weak Law and North Berwick and observed considerable variations in the chemical composition. He recognized a series of gradations between two end-members; one is clay-rich and retains some original igneous texture and the other is a more carbonated rock in which virtually nothing remains of the original rock. Flett (in Peach *et al.*, 1910) recognized that the presence of remnant igneous textures implies that the rock was fully crystallized prior to alteration. He proposed that heat from the intrusion distilled gases and solutions from the carbonaceous mudstones. Organic gases cannot affect rock-forming silicates at high temperatures and therefore modification occurred after the dolerite had solidified and the temperature had dropped. Day (1930a) proposed that the metasomatic process took place in two stages; first, kaolin and isotropic silica appeared as a result of the decomposition of feldspars and ferromagnesian minerals. This was followed by the gradual replacement of the whole rock by carbonates.

Conclusions

The South Queensferry to Hound Point GCR site contains both a tholeiitic, quartz-dolerite sill and a distinctive alkaline basic ('teschenitic') sill. Each represents a major intrusive suite in the Midland Valley of Scotland and was the subject of early studies. The alkaline Mons Hill Sill was emplaced during latest Visean times, possibly concurrent with volcanic rocks of this age that are preserved in the Bathgate Hills and west Fife. In contrast, the quartz-dolerite sill at Hound Point was emplaced as part of the Midland Valley Sill-complex during a very brief period in early Stephanian time when there was no known surface volcanism in the area (see Chapter 6).

Internal variations in mineralogy and texture are well developed in the Mons Hill Sill and details of internal contact relationships between distinctive lithologies are also clear. The Hound Point Sill exhibits the regular gradational zonation that is typical of Midland Valley quartz-dolerite sills. These factors, coupled with geochemical data, provide many clues as to the processes of magma generation and evolution responsible for both suites. The different geochemical characteristics of the two sills probably reflect magma generation at different depths below the Earth's crust and/or at different pressures and temperatures.

There is abundant evidence of the effect of heat upon the sedimentary host rocks adjacent to the major sills, and smaller sills show excellent examples of the alteration of dolerite to 'white trap', due to fluids and gases distilled out of carbonaceous mudstones and oil-shales by the heat of the intrusions.

ARDROSSAN TO SALTCOATS COAST, NORTH AYRSHIRE (NS 246 409–NS 224 417)

J.G. MacDonald

Introduction

South Bay, between Ardrossan and Saltcoats on the north Ayrshire coast (Figure 5.9), is flanked by promontories formed by resistant igneous rocks, products of Late Palaeozoic basic extrusive and intrusive activity. At Saltcoats, Coal Measures strata, resting on the Namurian Ayrshire Bauxitic Clay Member and lavas of the Troon Volcanic Member, have been intruded by the Inner Nebbock Sill of analcime-dolerite ('teschenite') and most notably by the Saltcoats Main Sill, a composite intrusion of analcime-dolerite and picrite. The latter has much in common with the better known and more studied Lugar Sill (see **Lugar** GCR site report) some 39 km to the SSE. Also of note, in the intertidal platform between the two sills, are fossil tree stumps of sigillarian type (Yuill, 1963). The headland of Castle Craigs, Ardrossan is also formed from a composite sill of dolerite and picrite which may be an extension of the Main Sill, displaced by a WNW-trending fault. On the north (inland) side of this fault, a separate sill of analcime basanite extends north-eastwards to form Castle Hill; it is intruded into Visean lavas, tuffs and sedimentary rocks. The area is cut by NW-trending basaltic and andesitic dykes of Palaeogene age.

Some of the sills were described by Geikie (1897) and Falconer (1907), and they were all described in relation to other intrusions in the north Ayrshire area in Geological Survey memoirs (Richey *et al.*, 1930; Monro, 1999). A detailed account of the petrography and geochemistry of the Saltcoats Main Sill was given by Patterson (1945, 1946). The area is frequently visited by field parties and features in excursion guides (Bassett in Bluck, 1973; Weedon in Lawson and Weedon, 1992). A K-Ar determination on the Castle Craigs Sill yielded an Early Permian age of 272 ± 7 Ma (*c.* 278 Ma using new constants) (De Souza, 1979), but a re-determination of the same sample by Ar-Ar gave a more precise, significantly older, Stephanian age of 298.3 ± 1.3 Ma (A.A. Monaghan and M.S. Pringle, pers. comm., 2002).

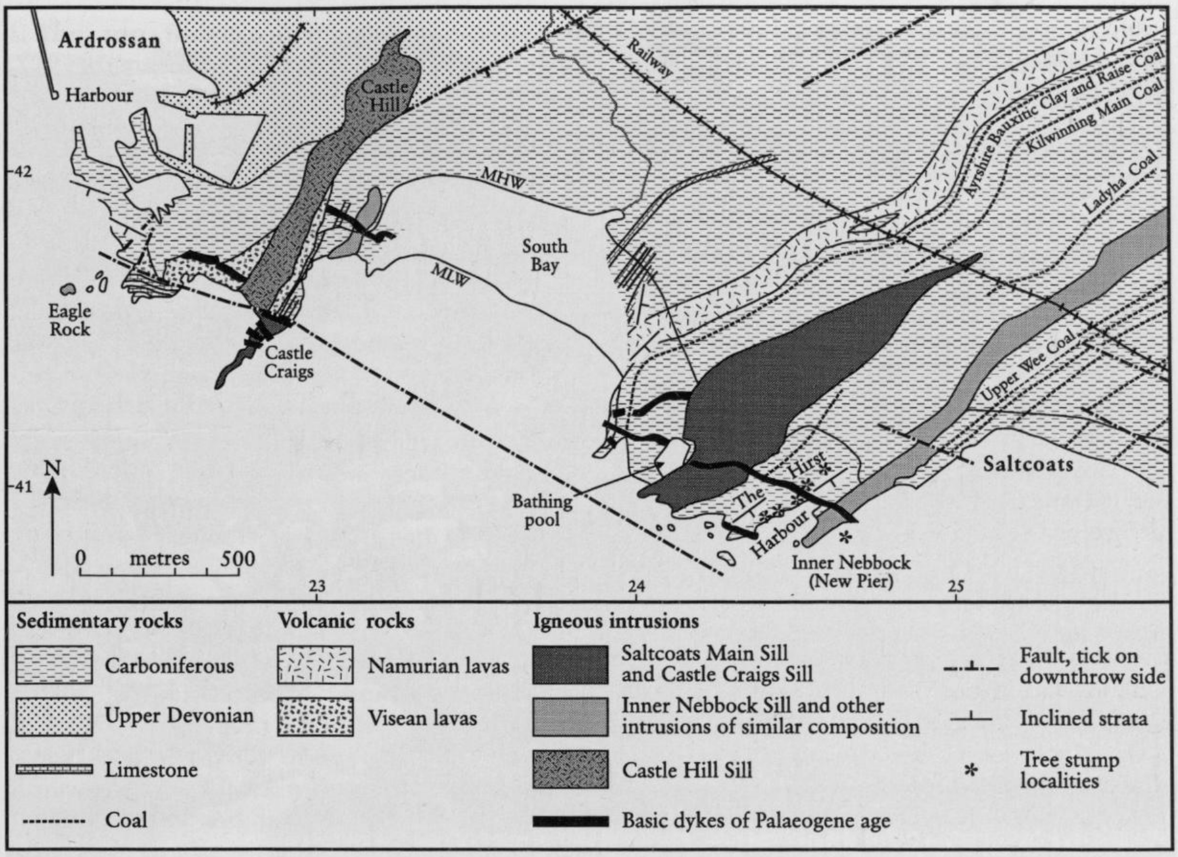

Figure 5.9 Map of the area around the Ardrossan to Saltcoats Coast GCR site. After Bassett (in Bluck, 1973).

Description

Namurian volcanic rocks

Near low-water mark, west of the Saltcoats Bathing Pool (NS 241 411), there are poor exposures of the Ayrshire Bauxitic Clay and the underlying Troon Volcanic Member, which together form the main part of the Passage Formation at the top of the Namurian Series in north Ayrshire (Monro, 1999).

The Troon Volcanic Member is over 50 m thick in the Saltcoats area but only the highly decomposed topmost few metres are exposed within the GCR site. Less altered samples from neighbouring localities have been identified as being composed dominantly of olivine basalt similar in character to the 'Dalmeny'-type basalt of the Visean Clyde Plateau Volcanic Formation.

The Ayrshire Bauxitic Clay Member varies in thickness up to about 20 m. On the Saltcoats shore it consists of approximately 1.2–1.5 m of massive light-grey to buff-coloured kaolinitic clayrock with ooliths and pisoliths that grades downwards into altered basalt. The highly oolitic upper portion passes downwards into a pale-brown to reddish clayrock containing specks of sphaerosiderite. Fragmentary plant remains are common. This is one of the few natural sections of this member available for study.

Saltcoats Main Sill

The Saltcoats Main Sill crops out on the foreshore south of the bathing pool, where it is about 18 m in thickness. It dips to the south-east in conformity with the Coal Measures strata. The base is in contact with the Kilwinning Main Coal that has been baked to a columnar coke (Figure 5.10). The outcrop can be subdivided into four distinct units (Figure 5.11) that occur in downwards succession from south-east to north-west as follows (Patterson, 1945, 1946):

Figure 5.10 The contact between the base of the Saltcoats Main Sill (pale weathering) and baked coal-bearing sedimentary rocks (dark). The sill has been altered to form 'white trap' adjacent to the coal. The hammer is 28 cm long. (Photo: C. MacFadyen.)

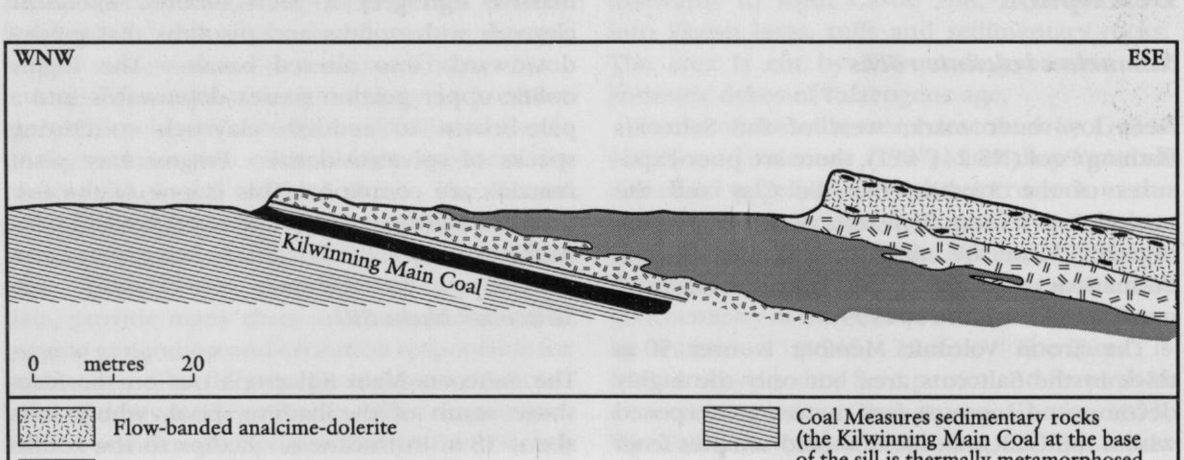

Figure 5.11 Diagrammatic cross-section of the Saltcoats Main Sill below the bathing pool. After Patterson (1946).

1. **The top flow-banded analcime-dolerite** ('teschenite'), which varies in thickness from about 1.8 m to 2.7 m, is generally fine grained with microphenocrysts of titanaugite and serpentinized olivine. The groundmass consists largely of microlites and laths of plagioclase, brown amphibole and abundant interstitial analcime. The rock has a characteristic brown colour on exposed surfaces and has well-developed flow-banding roughly parallel to the upper contact. The overlying fissile mudrocks have been baked and hardened. Xenoliths of hornfelsed mudrock occur towards the top of the unit indicating that they were broken off during intrusion. Some xenoliths of mudrock and coal occur near the bottom of the unit where it is in contact with the underlying biotite analcime-dolerite. There appears to be some marginal chilling of the base of the flow-banded analcime-dolerite close to the lower contact.
2. **The upper biotite analcime-dolerite** ('biotite-teschenite') is a little less than 3 m in thickness. It crops out as smooth rounded masses of black rock with cross-cutting segregation veins and patches rich in pale-pink analcime. The rock consists essentially of labradoritic plagioclase laths up to 2 mm in length, and titanaugite with lesser amounts of red-brown amphibole, and analcime. Biotite occurs as numerous small flakes moulded on feldspar and titanaugite. Olivine is variable in abundance but usually in small amounts and is invariably altered to 'serpentine'. There are a few small euhedral crystals of nepheline.

   The segregation veins contain elongate crystals of alkali amphibole, euhedral titanaugite and sparse flakes of biotite; plagioclase, zoned from oligoclase to albite, has largely been replaced by secondary analcime and chlorite. Within the veins there are also patches of analcime, vestiges of K-feldspar and a little nepheline. Similar veins occur in the Lugar Sill, where they have been termed 'lugarite' (see **Lugar** GCR site report), but at Saltcoats the rock is richer in potassium.

   It would appear that the underlying picrite has penetrated the base of the dolerite, prising off slabs, from which it has been concluded that the picrite was intruded after the dolerite (Patterson, 1946). However 'lugaritic' segregation veins originating in the alkali dolerite penetrate the picrite in a few instances – an indication that the picrite was intruded prior to the complete solidification of the dolerite.
3. **The central picrite**, about 9 m in thickness, is composed essentially of abundant serpentinized olivine with somewhat lesser amounts of alkali amphibole (red-brown barkevikite), augite and much-altered plagioclase. Patches of analcime may be primary in origin or may in part be derived from the breakdown of plagioclase. Biotite and opaque oxides occur as accessory minerals along with rare prisms of apatite.

   Both the upper and lower contacts with biotite analcime-dolerite are abrupt although neither the picrite, nor the units above and below, show signs of chilling. At both contacts there is a marginal gradation of the picrite into picrodolerite, marked by a decrease in the abundance of olivine and an increase in the proportion of feldspathic minerals. An 8 cm-thick 'lugaritic' vein, 60 cm below the upper contact, differs from those cutting the upper biotite analcime-dolerite in the presence of olivine and lack of biotite. Primary plagioclase has been replaced to a major extent by analcime, thomsonite and prehnite.
4. **The lower biotite analcime-dolerite** ('biotite-teschenite'), about 3.5 m in thickness, is intensely altered to yellowish 'white trap' for about 1.5 m above the lower contact as the result of carbonation by fluids produced by the thermal metamorphism of the underlying coal (Figure 5.10). Dark slabs of coal, prised off during intrusion, occur within the 'white trap'. Above this the unit is composed of much fresher rock, similar to the upper biotite analcime-dolerite, with analcime-rich patches and 'lugaritic' segregation veins.

The Inner Nebbock Sill

A substantial sill of 'teschenitic' alkali dolerite forms the south-west side of Saltcoats Harbour at the Inner Nebbock (NS 245 409); similar rock occurs offshore as the Outer Nebbock islet. Sedimentary rocks above the sill are noticeably hornfelsed. Although the sill is largely concealed by the harbour wall (New Pier) it is exposed in a railway cutting about 1 km to the north-east where it is seen to consist of three layers, each 3–4 m thick; a central picrite is flanked above and below by analcime-dolerite. At a quarry nearby, in the same intrusion, the coarse-grained picritic layer was at one time worked for 'osmond stone', a term used to denote rock suitable for the soles of bakers' ovens (Richey *et al.*, 1930). The sill can be traced inland to Stevenston as a topographical feature and still farther east in boreholes.

The Castle Craigs Sill

The low rocky promontory of Castle Craigs (NS 228 415) at Ardrossan is formed by a composite layered intrusion (Falconer, 1907). A lower, marginal layer of 'olivine-feldspar rock' is overlain by coarse-grained amphibole-bearing picrite. The upper part comprises a thin layer of amphibole-bearing dolerite overlain by finer-grained banded biotite analcime-dolerite. The latter becomes less olivine-rich upwards and develops alkali amphibole as it passes up into a metre-thick margin of analcime-basalt.

Another small alkali dolerite sill occurs on the beach about 400 m to the north-east of Castle Craigs.

Interpretation

Namurian volcanic rocks

The outcrop of the Troon Volcanic Member at Saltcoats is the north-western limit of a 40 km-wide Namurian volcanic field in north Ayrshire. Borehole evidence indicates a maximum thickness of about 160 m north of Troon. The resulting volcanic land surface that emerged from the surrounding deltaic environment, is much decomposed, consistent with the near-equatorial tropical latitude that has been inferred for this part of the Scottish crust at this time.

The Ayshire Bauxitic Clay Member, which rests directly on top of the weathered surface of the Troon Volcanic Member, is considered to have resulted from a prolonged period of post-volcanic subaerial lateritic weathering under wet tropical conditions. Although in some areas a complete gradation of the claystone downwards into underlying lava is indicative of residual weathering *in situ*, the claystone is commonly interbedded with other sedimentary rocks including coal and laminated mudrock. It is thus considered that much of the deposit has resulted from transport of the products of weathering and their deposition in shallow pools on the uneven surface of the underlying lavas (Monro *et al.*, 1983; Monro, 1999).

Sills

A reconstruction of the order of intrusion of the various units of the Saltcoats Main Sill by Patterson (1946) suggested that the top flow-banded analcime-dolerite (unit 1) was intruded first. A viscous, volatile-poor magma was intruded along a horizon at or just above the top of the Kilwinning Main Coal, with xenoliths of sedimentary rocks being incorporated into the basal and upper parts of the intrusion; the flow-banding is consistent with this. There was insufficient heat to cause major alteration of the underlying coal. This may be explained, at least in part, if the intrusion took place mainly in the fissile mudrock immediately above the coal. This first unit had probably completely solidified when further alkali basalt magma was intruded below it, but still above the partly disturbed coal, forming a sill over 6 m in thickness (units 2 and 4). The greater thickness of the second intrusion provided a more long-lasting heat source which led to the destructive distillation of the coal at its base to produce carbonate-rich volatiles that altered the base of the intrusion to 'white trap'. As the magma solidified, a volatile- and alkali-rich fraction became segregated to form the 'lugaritic' veins.

While it was still hot, and before there had been time for complete solidification, the biotite analcime-dolerite of units 2 and 4 was intruded by a third and final pulse of magma. Picritic magma (unit 3) split the dolerite a little more than halfway up, along the plane of weakness that would have existed where it was not yet entirely solidified. Some xenoliths detached from the dolerite contained still unconsolidated patches of alkali-rich differentiates, some of which penetrated the picrite. The high temperature of the enclosing rock delayed the cooling of the picrite, hence the lack of internal chilled margins between the units. The picritic magma was already partly solidified at the time of emplacement and was thus intruded as a mush of crystals. The crystallization of the groundmass led to a concentration of alkalis in the volatile-enriched residual liquid. This led to a further set of 'lugaritic' segregation veins. As the intrusion cooled, hydrothermal fluids expelled from the residual liquid attacked the olivine, converting most of it to 'serpentine'.

The clear evidence that the picrite was intruded soon after the alkali dolerite and the similarity of their respective residual liquids suggest a close genetic relationship. It is thus likely that they were each derived from the same parent magma by gravitational separation of olivine prior to intrusion of the resulting differentiated fractions (Patterson, 1946). However, the relationship of the flow-banded analcime-dolerite to the rest of the intrusive complex is unclear.

Evidence for successive intrusion of pulses of genetically related magmas to form composite sills is also found in the Inner Nebbock and Castle Craigs sills. The similarity of the main lithologies in the latter to those in the Saltcoats Main Sill, in particular the biotite analcime-dolerite and the amphibole-bearing picrite, led Richey *et al.* (1930) to suggest that the two outcrops are part of the same sill displaced by the WNW-trending Ardrossan Harbour Fault. However, the arrangement of the units is not directly comparable and Falconer (1907) considered that the doleritic facies was emplaced later than the picrite at Castle Craigs, which is the opposite to the order deduced for the Main Sill. A re-investigation of the field relationships and petrogenesis of the intrusions is clearly needed to resolve this and several other outstanding problems.

Conclusions

The Saltcoats Main Sill is representative of the analcime-dolerite ('teschenitic') varieties of Late Carboniferous to Early Permian basic alkaline sills in the west of the Midland Valley of Scotland and is an excellent example of a composite mafic to ultramafic intrusion. It provides evidence of successive pulses of magma that are likely to have had a common origin. Other basic sills within the area of the Ardrossan to Saltcoats Coast GCR site are also composite, but they all differ in detail from other sills of the same age and petrographical affinity (e.g. see **Lugar** GCR site report). In addition to a variety of mafic and ultramafic rock-types, the exposures show excellent examples of internal contacts between separate intrusive phases and external contacts with country rocks. Mudstones are baked, coal seams are reduced to coke, and volatiles expelled from the coals have altered the margins of some sills to a pale rock termed 'white trap'.

The site is also representative of the Troon Volcanic Member, the most extensive product of Namurian volcanism in the western Midland Valley (see 'Introduction' to Chapter 4). Exposures of these rocks are poor, but the basalt lavas exhibit evidence of deep weathering under wet tropical conditions soon after they were erupted. They grade upwards into the Ayrshire Bauxitic Clay Member, a pale aluminium-rich clayrock derived partly *in situ* and partly by accumulation of the products of weathering in hollows on the lava surface. This is one of few places where these deposits can be studied in natural sections.

LUGAR, EAST AYRSHIRE (NS 599 216–NS 601 213)

I.T. Williamson

Introduction

It is widely held that many of the alkaline basic sills and sill-complexes in the west of Scotland are probably comagmatic with the Early Permian Mauchline Volcanic Formation (see **Howford Bridge** GCR site report). Almost all the sills are olivine-bearing doleritic rock-types. Some are thick, differentiated, composite bodies showing a layering attributed to a variety of magmatic processes such as gravitational settling and upward volatile enrichment, elutriation (flow differentiation) and multiple intrusion.

A classic, textbook example of just such an intrusion is the Lugar Sill in the south-west of the Midland Valley. It is exposed in the valley of the Lugar and Glenmuir waters (Figure 5.12) and takes its name from the nearby village of Lugar, 3 km north-east of Cumnock. Historically this sill has played a very important role in developing the concept and mechanisms of magmatic differentiation and is regularly visited for the purposes of education and research. A field excursion was described by Weedon and Mykura (in Lawson and Weedon, 1992).

Although much of our knowledge of this sill is due to the early work of G.W. Tyrrell, his descriptions and interpretations were not the first published accounts. In a paper dealing with the classification of post-Carboniferous intrusions in the west of Scotland (Tyrrell, 1909a), he presented an outline of the Lugar Sill, but fully acknowledged the '...valuable and comprehensive paper on the Lugar intrusions...' by Boyle (1908). The petrography and field relationships of the sill, based upon the Glenmuir Water section, were described by Tyrrell (1917b), and his later papers (1948, 1952) concentrated upon nearby boreholes at

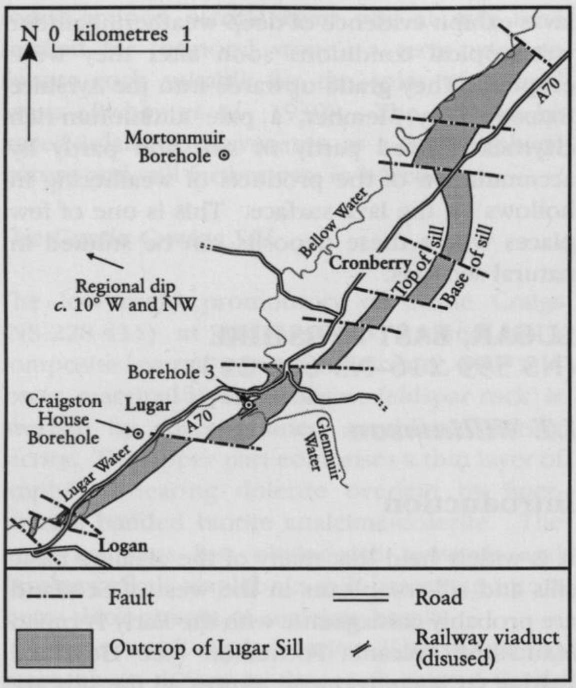

Figure 5.12 Map showing the outcrop of the Lugar Sill and the locations of boreholes through the sill. After Henderson and Gibb (1987).

Mortonmuir and Craigston House respectively. Tyrrell's work was augmented by the Geological Survey memoir (Eyles *et al.*, 1949), and later mineralogical and geochemical studies by Phillips (1968) and Henderson and Gibb (1987) have resulted in more refined models for the petrogenesis of the sill. Radiometric dates obtained by De Souza (1979) and Henderson *et al.* (1987) suggest an earliest Permian age.

Description

The Lugar Sill comprises two principal lithological units. Marginal analcime-dolerites (formerly termed 'teschenites') are separated by a central thick composite unit of nepheline-dolerite, kaersutite nepheline-dolerite and picrite (formerly termed 'theralites'). In detail, the analcime-dolerites are made up of a number of separate intrusions or magmatic pulses. Henderson and Gibb (1987) recognized four such pulses in each of the upper and lower units that form 'mirror images' on either side of the central unit, which was emplaced later as a single pulse. Hence the full composite section comprises nine units, which represent at least five separate intrusive pulses. Later differentiates cut all of these units.

The stream section

The best natural section is afforded by steep cliffs in the Glenmuir Water (Figure 5.13), which cuts through the sill between NS 6006 2134 and the confluence with the Bellow Water at NS 5988 2152. After this confluence, the stream is known as the 'Lugar Water'. Most units of the sill are exposed here and, although access is difficult in places, boulders in the stream bed provide excellent examples of most lithologies. The sill is here about 43 m thick and intrudes arenaceous strata of the Namurian Passage Formation, which dip regionally to the west or NNW at about 10°. The details of the Glenmuir Water section given by Tyrrell (1917b) remain the most comprehensive. They are not repeated here and should be consulted for specific locations. The following short descriptions are mainly taken from Weedon and Mykura (in Lawson and Weedon, 1992).

The basal contact of the sill, which is chilled against pale baked sandstone, is seen in the bed of the stream at NS 6006 2134. The basal facies of the sill is some 3 m thick and comprises basalt and analcime-dolerite with numerous layers of differing texture and colour, but there appears to be an upward gradation into more granular analcime-dolerite.

Downstream, to the north-west, this is followed up the sequence by peridotite and picrite, which form extensive, but deeply weathered cliff exposures, mostly on the outer bends of the stream (Figure 5.13) down to the disused railway viaduct (NS 5991 2142). No contact between the dolerite and the ultramafic facies is visible. North-west of the viaduct, the picrite is in contact with a dark-grey nepheline-dolerite. Neither the top nor the base of the nepheline-dolerite is well exposed. The lower part contains abundant amphibole (kaersutite) and is slightly coarser grained. The upper part is veined by a paler analcime-bearing variety. The contact with the overlying analcime-dolerite is not visible here, though elsewhere it is known to be sharp and chilled.

The upper marginal facies of the sill is, like the base, an analcime-dolerite or gabbro. Both medium- and coarse-grained varieties are exposed downstream from the viaduct and the upper contact with white thermally altered sandstones is exposed on the south bank of the stream, where it is joined by the Bellow Water to become the Lugar Water (NS 5986 2151).

Figure 5.13 Cliff exposures of the picritic central part of the Lugar Sill in the Glenmuir Water, upstream from the railway viaduct, Lugar GCR site. (Photo: K.M. Goodenough.)

This section is also the type locality for an unusual rock-type. This is a kaersutite- and/or augite-rich nepheline-gabbro or nephelinolite that has been termed 'lugarite'. In hand specimen it can be very striking as it is essentially a coarse-grained pegmatitic rock (Figure 5.14). It is exposed in the west bank of the Glenmuir Water 15 m north of the viaduct, close to the picrite–nepheline-dolerite contact, where it occurs as segregation patches up to 1.2 m thick. It also occurs as irregular, anastomosing veins, 2–12 cm wide, which cut the picrite.

Boreholes

Most of the detailed descriptions and interpretations of the Lugar Sill are based on the examination of borehole core. To date, three holes have specifically intersected the sill (Figure 5.12). These are at Mortonmuir (NS 5984 2337) (Tyrrell, 1948), Craigston House (NS 5908 2130) (Tyrrell, 1952) and Lugar Water (NS 5990 2150) (Henderson and Gibb, 1987). There is overall internal consistency between the boreholes in both the relative positions and the thickness of the majority of lithologies (Figure 5.15). However, they show that the sill has a much more complex internal structure than is revealed by the natural exposures alone. In detail, there are clear differences within the nepheline-dolerite facies and in the presence and position of lugarites (kaersutite-augite-rich nepheline-gabbro).

The Lugar Water Borehole, detailed by Henderson and Gibb (1987), was located at the junction of the Glenmuir and Bellow waters and hence the section closely resembles and significantly augments the natural section. Important additional details seen in the borehole core concern the complexity and nature of the internal contact relationships. The thicknesses of the upper and lower marginal analcime-dolerites are 4.45 m and 8.90 m respectively. Each comprises several distinct units of layered analcime-dolerite, which show chilled internal contacts with one another. Superimposed upon an overall inward-coarsening profile through the analcime-dolerites, these smaller units also coarsen individually into the sill. The 35.5 m-thick central part of the sill comprises a complex unit of nepheline-dolerite and picrite. The

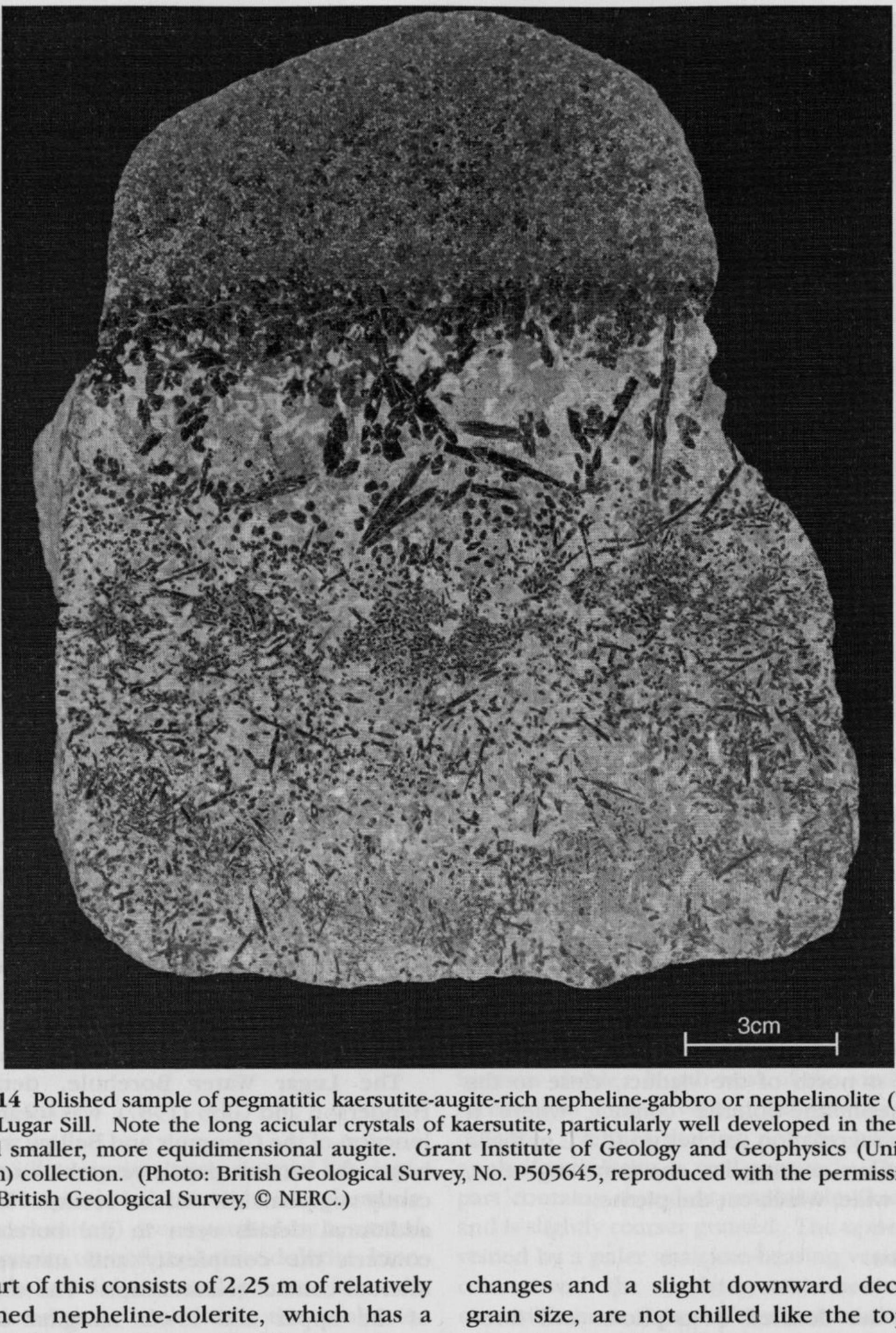

Figure 5.14 Polished sample of pegmatitic kaersutite-augite-rich nepheline-gabbro or nephelinolite ('lugarite') from the Lugar Sill. Note the long acicular crystals of kaersutite, particularly well developed in the marginal zone, and smaller, more equidimensional augite. Grant Institute of Geology and Geophysics (University of Edinburgh) collection. (Photo: British Geological Survey, No. P505645, reproduced with the permission of the Director, British Geological Survey, © NERC.)

upper part of this consists of 2.25 m of relatively fine-grained nepheline-dolerite, which has a sharp, chilled contact with the overlying analcime-dolerite. Below, but gradational into the nepheline-dolerite, is a substantial unit of kaersutite nepheline-dolerite that extends downwards for a further 13 m or so. With a downward increase in olivine and a concomitant decrease in kaersutite, this passes into picrite. The picrite unit is about 20 m thick. The lower few metres, though showing mineralogical changes and a slight downward decrease in grain size, are not chilled like the top of the central unit. Lugarite is present as four thin units interbedded within the upper part of the kaersutite nepheline-dolerite unit. These comprise both kaersutite- and kaersutite-augite-rich variants and each has a sharp contact with adjacent rock. They occur in the same position within the sill as in the exposed stream sections. Pink aplitic veins (probably microsyenitic) cut all the analcime-dolerite units.

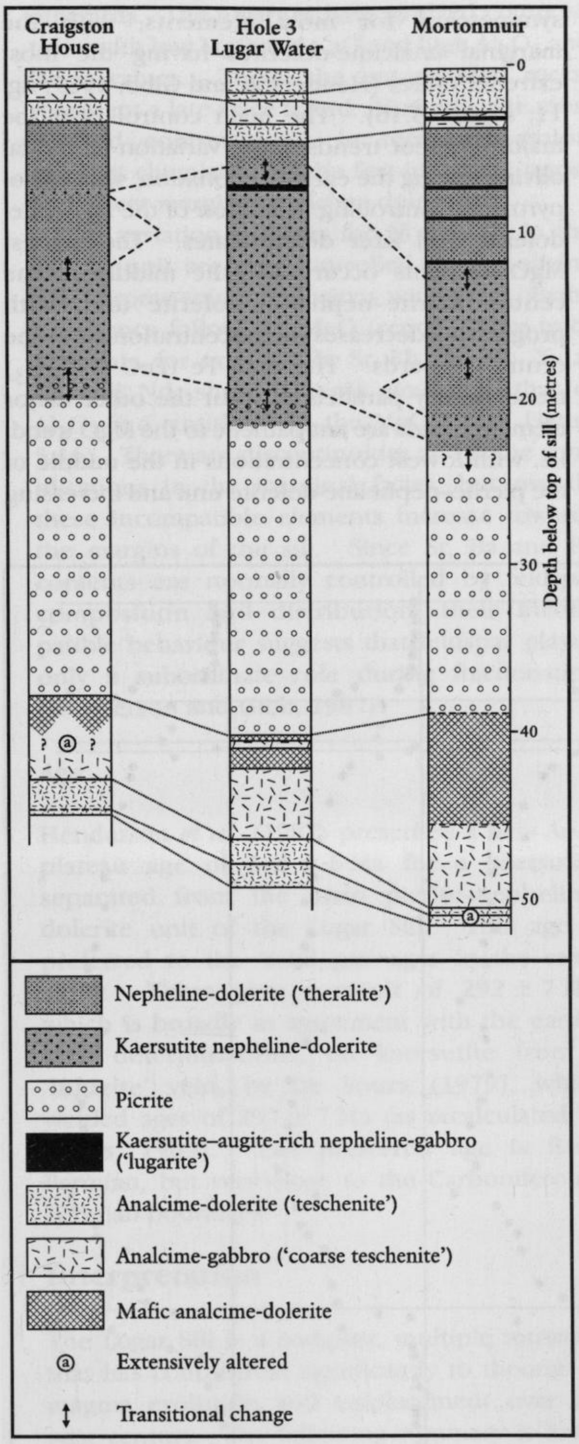

Figure 5.15 Correlation of borehole sections through the Lugar Sill. After Henderson and Gibb (1987). See Figure 5.12 for locations.

The profiles of the other boreholes illustrate an apparent slight increase in overall thickness eastwards, from Craigston House (44.7 m), through Lugar (50.2 m; cf. Tyrrell's field estimate of 42.7 m) to Mortonmuir (51.4 m). These are considered real, but in part they could also be attributed to the effects of varying dip. There are thickness changes in some of the units, for example the lower analcime-dolerites also thicken eastwards. The principal contrasts in lithology between the Lugar Water and Mortonmuir boreholes are seen in the relationship between the nepheline-dolerite and its kaersutite-bearing variant. In both boreholes these dolerites have similar thicknesses, but in the Mortonmuir Borehole, there are two kaersutite-bearing units and their total thickness is considerably less than at Lugar Water. Also, there are no lugarites in the Craigston House section as opposed to the complex multiple unit at Lugar and the three at Mortonmuir; at the latter, the upper two units are augite-rich varieties and the lower unit is a 'normal' kaersutite-augite-rich variety.

Internal variations in mineralogy and geochemistry

The gross petrographical variation from top to base through the Lugar Sill is, not surprisingly, mirrored by variations in both mineralogy and whole-rock geochemistry. These systematic variations have been documented comprehensively by Henderson and Gibb (1987). The following summarizes some of the essential points of their study.

The mineral compositions reflect an overall evolutionary trend from picrite, through kaersutite nepheline-dolerite and nepheline-dolerite to the kaersutite-augite-rich nephelinolite (lugarite) in the thick, central part of the sill. The earlier, marginal analcime-dolerites are even more evolved. The mafic phases (olivine, clinopyroxene, kaersutite and biotite) are compositionally zoned and, generally, all show maximum magnesium content within the picrite and kaersutite nepheline-dolerite of the central unit. Biotite and amphibole compositions show markedly symmetrical distribution patterns throughout the sill, becoming less magnesian towards both upper and lower margins (Henderson and Gibb, 1987, fig. 4). The main feldspar in the sill is a zoned plagioclase. The range of zoning, from anorthite-rich (*c.* An_{70-80}) to orthoclase-rich (*c.* Or_{42}) compositions, is considerable, but similar, in the marginal layered analcime-dolerites, the kaersutite nepheline-dolerite and the lower parts of the picritic unit. There is a much more restricted range in the rest of the picritic unit. Alkali feldspar occurs in the more marginal units (Henderson and Gibb, 1987, fig. 8) and it is likely that primary nepheline was originally present in all lithologies.

Alteration of both mafic and felsic minerals is common. Olivines are typically pseudomorphed by serpentine minerals, especially in the analcime-dolerites, and the feldspars, nepheline and interstitial areas are converted to analcime, zeolite and chlorite associations. Pyroxenes are generally unaffected, except in the lower analcime-dolerites.

The general pattern of variation in whole-rock chemistry with position in the sill is fairly symmetrical for most elements, with the marginal analcime-dolerites having the most extreme values (Henderson and Gibb, 1987, fig. 11; Figure 5.16). The main control over the major element trends is the variation in modal olivine during the early fractionation, with clinopyroxene controlling formation of the analcime-dolerite and later differentiates. The highest MgO contents occur near the middle of the central picrite–nepheline-dolerite unit, with progressive decreases in concentration from the centre outwards. The total Fe (FeO + Fe_2O_3) trend closely parallels this but the other major element trends are antipathetic to the MgO trend, i.e. with lowest concentrations in the middle of the picrite–nepheline-dolerite unit and increasing

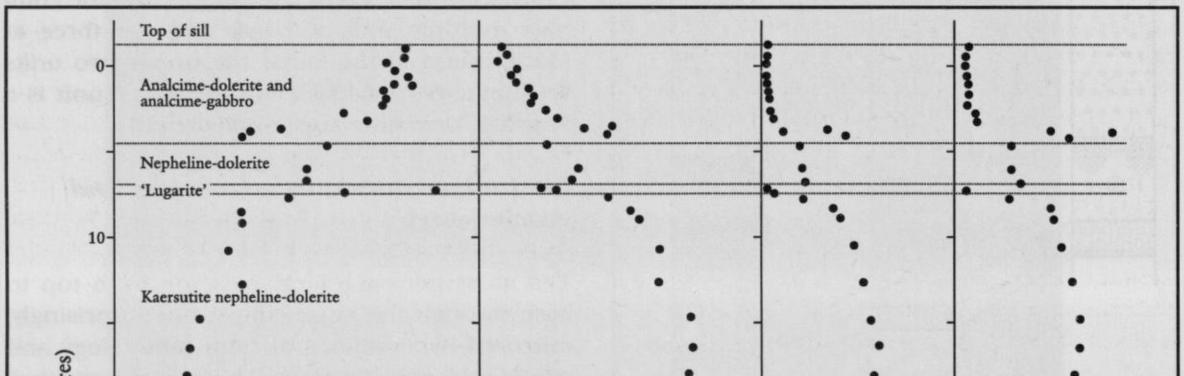

Figure 5.16 Variations of key major and trace elements in a vertical section through the Lugar Sill (Borehole 3). After Henderson and Gibb (1987). See text for details.

outwards. The lugarites have evolved compositions with low MgO and CaO and high Al_2O_3 and Na_2O values. These, the last-intruded rocks, represent a late-stage liquid. However, the most evolved compositions, in terms of major-element chemistry, are the first-intruded, upper and lower marginal analcime-dolerites.

The variation patterns for Ni and Cr in the central unit are also controlled by the olivine and chrome-spinel inclusions within the olivine and hence follow the MgO trend. Other trace elements, for example Zr, Sr, Rb, Ba, Nb, Y, La, Ce and Nd, show patterns similar to that of Al_2O_3 (i.e. antithetic to the MgO trend; Figure 5.16). There are discontinuities and some complications in the marginal facies, but overall, these incompatible elements increase towards the margins of the sill. Since Sr, Ba and Rb contents are normally controlled by feldspar composition and distribution, their incompatible behaviour suggests that feldspar played only a subordinate role during fractionation (Henderson and Gibb, 1987).

Age

Henderson *et al.* (1987) presented a new Ar-Ar plateau age of 288 ± 6 Ma for a kaersutite separated from the main picrite–nepheline-dolerite unit of the Lugar Sill. This age is preferred to the 'total gas' ages in the same study. These gave a result of 292 ± 7 Ma, which is broadly in agreement with the earlier K-Ar determinations, on kaersutite from a 'lugarite' vein, by De Souza (1979), which yielded ages of 297 ± 7 Ma (as recalculated by Wallis, 1989). The preferred age is Early Permian, but very close to the Carboniferous–Permian boundary.

Interpretation

The Lugar Sill is a complex, multiple intrusion that has contributed significantly to theories of magma evolution and emplacement over the past century. The following summary is based largely upon the most recent petrogenetic model of Henderson and Gibb (1987), who also include a comprehensive review of earlier models.

It has long been supposed that the lithologies that make up the Lugar Sill were all derived from a common parent. This is reasoned to have been a primary, relatively alkali-rich, picritic magma, likely to have originated in the upper mantle. It rose through the crust before fractionating in a low-level magma chamber. Here, gravitational settling of olivine, accompanied by ascent of the lower density residual melt, produced a vertically stratified column, with the denser, more mafic and therefore less-fractionated magmas, towards the bottom.

The earliest intrusion was formed when the more-fractionated magmas, towards the top of the chamber, were evacuated in a series of pulses. These had an analcime-dolerite composition. A final larger pulse emplaced the less-fractionated olivine-rich magma from deeper in the chamber to form the picrite–nepheline-dolerite unit. This has regionally transgressive margins in contact with the analcime-dolerites, the top margin being notably chilled, but has gradational internal contacts. The proportion of suspended olivine crystals increased during emplacement, as the magma chamber was purged of progressively more olivine-rich magma, so that the central part of the unit, the last to be emplaced, is the most olivine-rich. Thus, in simple terms, the profile of the sill was formed in sequence from more evolved analcime-dolerite, through nepheline-dolerite, to less evolved picrite.

Differentiation then continued *in situ* with gravitational settling and equilibration of the olivine crystals that were suspended in a liquid phase of nepheline-dolerite composition. This later settling explains the zonation of the unit from nepheline-dolerite to picrite and the fact that the greatest concentration of magnesium-rich olivines in the sill occurs just below the middle part of the central unit.

The segregations and veins of lugarite (kaersutite-augite-rich nepheline-gabbro or nephelinolite) were interpreted by Henderson and Gibb (1987) as auto-intruded, late-stage fractionation products of the central unit, involving in-situ differentiation and upward enrichment in residual liquid and volatiles. The aplitic veins cutting the analcime-dolerites were similarly interpreted as late-stage, in-situ differentiation products from the earlier analcime-dolerite magma.

Post-magmatic alteration is common across the entire sill. However, this phenomenon is most prominent and pervasive within the lower-most units. Henderson and Gibb (1987) suggested that circulating, super-heated ground-water below the sill may have accounted for this.

Conclusions

The Lugar Sill has a long-standing, international reputation as an example of a composite, differentiated, basic alkaline intrusion and is frequently visited for both teaching and research purposes.

It was probably emplaced in very early Permian time as a series of pulses of magma from a compositionally stratified magma chamber situated deep in the Earth's crust, below the final level of the sill. The more evolved, less dense magmas residing at the top of the magma chamber were the first to be evacuated, followed by successive pulses from sequentially deeper levels and hence more mafic magmas. The first phase of sill formation involved the intrusion of progressively less evolved analcime-dolerite magmas. This phase was then followed by the intrusion, into this early sill, of a large-volume pulse of olivine-rich nepheline-dolerite magma. Continued crystallization and settling of crystals *in situ* and an upward enrichment in residual liquids and gases subsequently gave rise to an unusual rock-type, a spectacular nepheline-gabbro with large crystals of pyroxene and amphibole. This has been given the local name of 'lugarite', from this, the type locality.

BENBEOCH, EAST AYRSHIRE (NS 484 085–NS 498 081)

J.G. MacDonald

Introduction

A suite of basic alkaline intrusions was intruded into the sedimentary basins that now comprise much of the Midland Valley of Scotland (Cameron and Stephenson, 1985). In the west of the Midland Valley, where the intrusions are mostly of Late Carboniferous to Early Permian age, they include the Saltcoats and Lugar sills (see **Ardrossan to Saltcoats Coast** and **Lugar** GCR site reports) and many others in the area between Patna and Dalmellington. These sills are typically olivine bearing and contain a variety of rock-types, with varying proportions of olivine or augite enrichment in the main parts of the intrusion.

The sill of dolerite and picrodolerite that forms Chalmerston Hill, 3 km north-east of Dalmellington (Figure 5.17), provides a good example of a type in which the petrography is dominated by olivine enrichment. The columnar-jointed crags of very fresh dolerite at Benbeoch, which form a distinctive feature at the eastern extremity of the hill, provide a continuous section, about 65 m in vertical

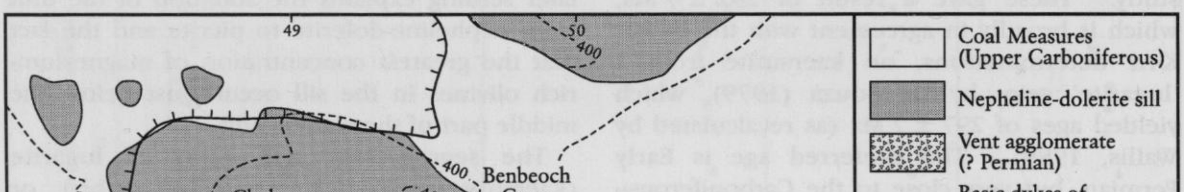

Figure 5.17 Map of the area around the Benbeoch GCR site. Based on Geological Survey 1:10 560 Ayrshire sheets 67NW; and 66NE (both 1910); and 1:63 360 Sheet 14, Ayr (1933).

thickness, through the greater part of the intrusion (Figure 5.18). Most of the western part of Chalmerston Hill has been excavated as part of a vast opencast coal development and the original land surface no longer exists. However, the opencast working has exposed the base of the sill, which was previously unseen, and a section through the lowest 30 m of sill is to be preserved and landscaped.

The rocks of the Benbeoch Sill are typically 'theralitic', in that they contain significant nepheline, with lesser amounts of analcime, and hence should be classed as nepheline-dolerites. They are also rich in fresh olivine and the sill was selected by Tyrrell (1912) as the type example of a rock-type he termed 'kylite', which is well developed in this part of south Ayrshire. The term was adopted as part of the classification used by the Geological Survey (Eyles *et al.*, 1929, 1949) and hence is of historical significance, but it is no longer used. The most detailed study of the sill was that of Drever and MacDonald (1967), who documented the extent of internal modal, mineralogical and chemical variation.

Description

The Benbeoch Sill is intruded into strata of the Upper Coal Measures at the local base of the Barren Red Measures. It forms the main mass of Chalmerston Hill, the highest part of which, Benbeoch (463 m), is bound to the south-east by Benbeoch Crags (NS 496 082) where columnar-jointed picrodolerite occurs in a 40 m-high cliff (Figure 5.18). Here, the top part of the sill has been removed by glacial erosion. The base at Benbeoch Crags is concealed by scree and boulders but some detached slabs, one notably 3 m long, contain a decreasing amount of olivine along their length, passing into what was most likely a chilled margin and hence the base of the intrusion. One such boulder occurs only 12 m below the foot of the cliff, and hence provides a maximum for the amount of the sill that is unexposed at this locality.

Opencast coal workings on the western flank of Chalmerston Hill have exposed a good section of the basal part of the sill around NS 485 084. Other sills have been encountered below the main sill and many of

Figure 5.18 Benbeoch Crags from the south-east. Note the strongly developed columnar jointing in the nepheline-dolerite of the Benbeoch Sill. The top of the sill has been removed by erosion and up to 12 m at the base is covered by scree and boulders, but a 40 m-thick section is exposed. (Photo: Scottish Natural Heritage.)

the coals close to these sills have reduced amounts of volatiles, enhancing their value. As the bottom contact and the contact zone in the underlying sedimentary rocks is not seen anywhere else, a representative part of the section has been preserved to allow future study. The sedimentary rocks consist of pale-green mudstone resting on laminated sandstones of shallow-water fluvial origin. Obvious baking fades away from the contact within a few metres and there is localized brecciation of the country rocks. The chilled margin of the sill contains sparse small vesicles. Over a distance of less than 1 m above the contact, the rock increases in grain size to a very fresh bluish dolerite in which faint layering can be discerned on weathered surfaces, possibly reflecting very slight modal variations. The coarser-grained gabbro above this is intersected in places by white veins (up to 50 mm in width), containing dark needle-shaped crystals of amphibole. The veins emanate from coalescing patchy areas, have gradational margins and hence are most likely derived from late-stage concentrations of alkali- and volatile-rich residual liquids from the magma. Similar veins, containing large acicular crystals of the titanium-rich amphibole kaersutite, occur as late differentiates of the Lugar Sill (see **Lugar** GCR site report). Although some good columnar jointing occurs, the outcrop is dominated by a set of closely spaced, planar, vertical joints trending around 110°. These joints are invariably filled by apparently later zoned veins, dominated by clay minerals and chlorite and containing prehnite, but exhibiting pseudomorphs after plagioclase, clinopyroxene and rare olivine. They have sharp but irregular margins but seem to be due to hydrothermal replacement.

Near the top of Chalmerston Hill, at NS 490 083, a variety of picrite, exceptionally rich in olivine occurs in a small knoll. It was named 'kylite-picrite' by Tyrrell (1912).

The chilled margin exposed in the large slab below Benbeoch Crags contains equant micro-phenocrysts of carbonated and serpentinized olivine set in a dark turbid groundmass with a few small fresh feldspar laths. About 0.5 m above the margin the rock, although still fine grained, is little altered and contains abundant olivine with peripheral zoning, along with small euhedral zoned pink augites in a sub-ophitic relationship with zoned plagioclase laths. Magnetite and analcime are also present. Both olivine and augite increase in grain size away from the chilled margin but while the augite decreases in abundance there is a corresponding increase in modal olivine (Figure 5.19).

The proportion of olivine in the main part of the Benbeoch Crags section varies only slightly from an average value of 35.5%, except at the top of the section where a decrease in olivine content and a corresponding increase in augite suggest a position only a few metres below the top contact prior to erosion. The olivine (Fo_{75}) is unzoned and occurs as rounded or subhedral crystals, in a few cases enclosed by augite. The strongly zoned, faintly pleochroic augite commonly displays hour-glass twinning. It is rich in titanium and appears to have

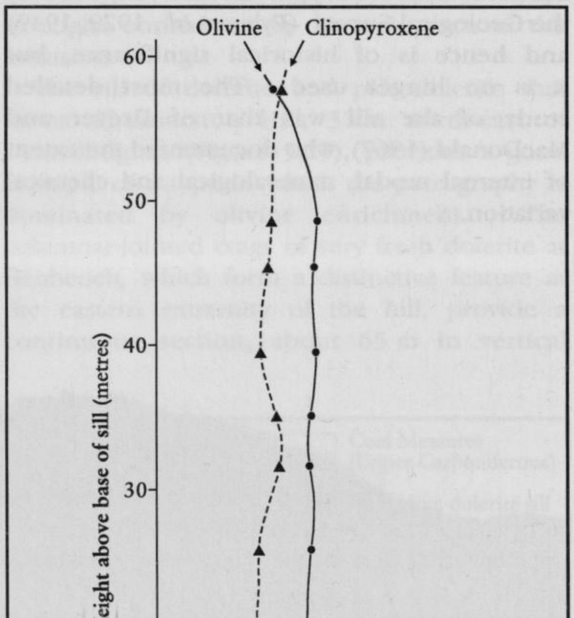

Figure 5.19 Variation in modal olivine and augite through the Benbeoch Sill.

commenced its crystallization prior to that of plagioclase in view of their sub-ophitic or intersertal relationship. The strongly zoned feldspar has cores of calcium-rich bytownite but grades to andesine at the margins. There is a small amount of fresh nepheline, and analcime and biotite occur as minor components. Tiny needles of apatite occur in the groundmass and as inclusions in the augite. The Chalmerston Hill picrite, estimated to be positioned about 15 m below the top of the sill, contains almost 55% olivine but both the olivine and the plagioclase have the same composition as in the rest of the sill although the augite is not so strongly zoned.

Whole-rock analyses of the Benbeoch and Chalmerston Hill picrodolerites and picrites, together with other 'kylitic' intrusions of Ayrshire, indicate a trend of high alkalinity and only moderate iron enrichment, relative to analcime-bearing olivine-dolerites such as those that are common in Palaeogene sill-complexes of Scotland (Drever and MacDonald, 1967). This could help to distinguish them from sills of Palaeogene age that crop out in adjacent areas of south Ayrshire (e.g. see **Howford Bridge** GCR site report).

Interpretation

In the Benbeoch Crags section, there is only minor inhomogeneity in the modal proportions of olivine and augite (Figure 5.19). This is matched by small variations in chemical composition. The apparent lack of internal chilled margins, or indeed any sudden discontinuities, suggests that the magma was emplaced in a single pulse. The observed variations in mode near the top and bottom of the sill make it clear, however, that the first intruded magma, as represented by the chilled margins, was significantly less enriched in olivine crystals than that which formed the main part of the sill. There is no evidence here of any measurable concentration of olivine by post-intrusive crystal settling, so such variation in olivine content as has been observed most likely arose in the magma prior to intrusion. The much greater abundance of olivine in the picrite at Chalmerston Hill at a level 'at or a little below the centre of the sill' (Tyrrell, 1912) could be evidence of a separate but contemporary pulse of magma, or an extreme of gradation, in either case representing the last part of the magma to be intruded. The former explanation would resemble the relationships observed in the Lugar and Saltcoats sills, where the most olivine-enriched portions are emplaced last, without chilling.

The lack of zoning of the olivine crystals suggests slow growth under conditions approaching stable chemical equilibrium. The similarity in composition of the olivine in both the picrite and the picrodolerite suggests that both rocks originated from the same batch of differentiated magma. If there had been any significant differentiation *in situ* it would have been reflected by a higher magnesium content in the olivine of the picrite. This points to olivine enrichment by some process prior to intrusion or associated with the movement of the magma in the conduit during emplacement. However, lack of exposure renders the precise relationship of the picrite to the rest of the intrusion uncertain.

Conclusions

The Benbeoch Sill comprises distinctive olivine-rich varieties of nepheline-dolerite and nepheline-gabbro ('theralites') within the Late Carboniferous to Early Permian alkaline basic sill suite of the western Midland Valley. The chilled base of the sill has recently been exposed in opencast coal workings and good continuous sections through parts of the sill are exhibited here and in natural crags. In addition to vertical variations in mineral proportions, late-stage alkali-rich patches and veins and various types of jointing are well exhibited. The exceptionally fresh condition of the rocks affords the opportunity to expand knowledge of their whole-rock and mineral geochemistry, and hence gain a valuable insight into the origin of the magma and its subsequent evolution prior to, during and following emplacement and crystallization. When linked with detailed studies of similar but subtly different sills, such as that at Lugar, such studies could significantly increase our understanding of Carboniferous–Permian magmatism in northern Britain and also contribute to a wider understanding of the petrogenesis of alkali-rich basic rocks. A continuous drill core through the sill on this site would be particularly useful.

CRAIGHEAD QUARRY, SOUTH LANARKSHIRE (NS 919 238)

J.G. MacDonald

Introduction

A disused quarry on the west side of Craighead Hill, 2.5 miles east of Crawfordjohn, exposes steeply dipping Ordovician greywackes into which a dyke-like intrusion of a distinctive rock, known as the Crawfordjohn 'essexite' has been emplaced (Figure 5.20). This porphyritic alkali gabbro contains large well-shaped black crystals of augite that give it a distinctive coarsely spotted appearance, especially on surfaces on which the groundmass of the rock has weathered to a pale-creamy-grey colour. It was worked for curling stones which were manufactured nearby in the village of Crawfordjohn in the 19th and early part of the 20th centuries (Figure 5.21a). The only other locality in Scotland where nearly identical 'essexite' occurs is at Lennoxtown, north of Glasgow, on the southern margin of the Campsie Fells, but Craighead Quarry is the only place where it has been quarried.

The rock was first described by Teall (1888) but the most detailed description is that of Scott (1915) who carried out petrographical studies and whole-rock chemical analyses. He concluded that the intrusion is probably 'an elongated plug or small boss' and confirmed the interpretation of Tyrrell (1912) that it is allied to the Late Palaeozoic alkali dolerites, rather than to the Palaeogene dykes of the area which, although they have a similar north-west–south-east trend, have tholeiitic affinities. Greig (1971)

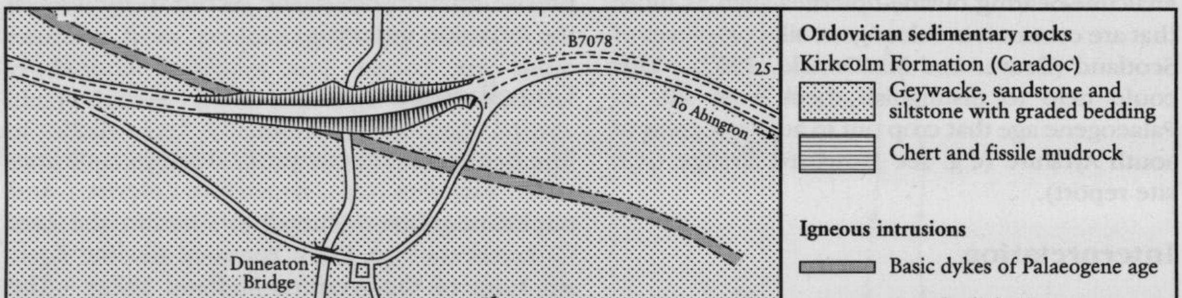

Figure 5.20 Map of the area around the Craighead Quarry GCR site. Based on Geological Survey 1:63 360 Sheet 15, Sanquhar (1937); and original mapping and proton magnetometer survey by J.J. Doody and J.G. MacDonald (2000).

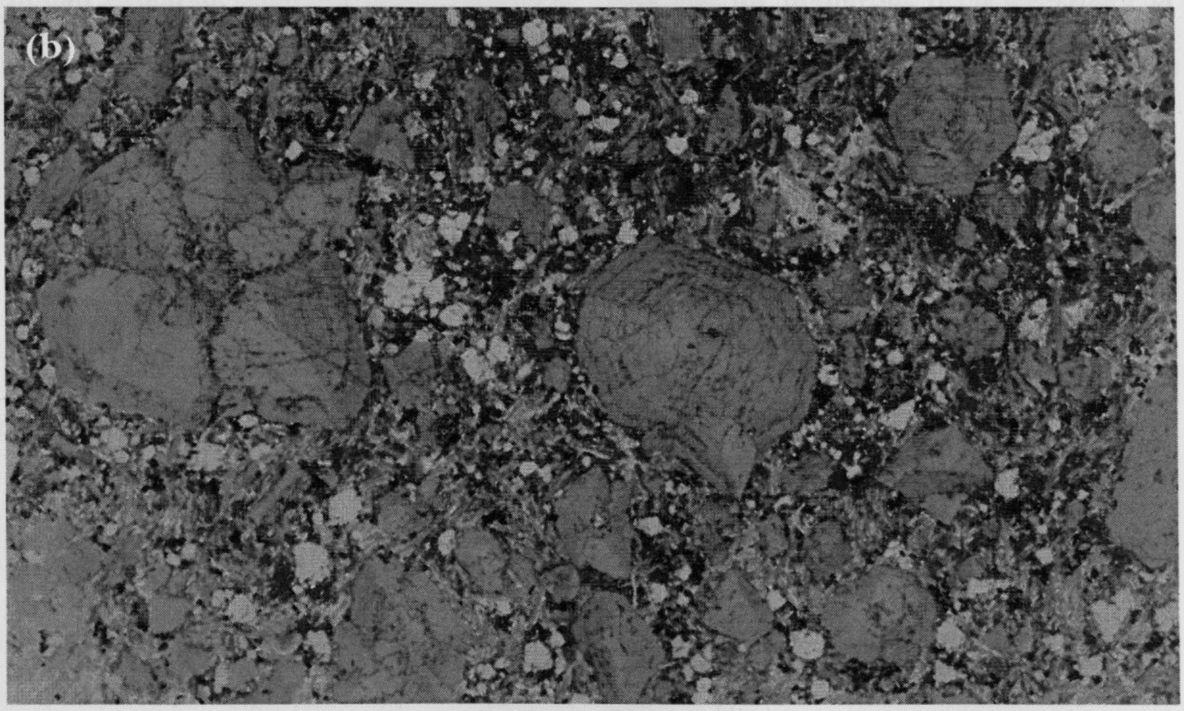

Figure 5.21 (a) Curling Stone made of nepheline-gabbro ('essexite') from Craighead Quarry. Compare the texture with that seen in the photomicrograph (b). (b) Photomicrograph of nepheline-gabbro ('essexite') from Craighead Quarry. Ordinary light. The largest single phenocryst is 5 mm in diameter. (Photos: J.G. MacDonald.)

referred to the intrusion as a NW-trending dyke of 'theralitic essexite' and more recent geophysical work has confirmed the dyke-like form. The most appropriate modern term for the rock-type is nepheline-gabbro.

Description

Craighead Quarry is the main exposure of the Crawfordjohn 'essexite', but smaller quarries and exposures occur between 120 m and 200 m to the south-east. The 1870 and 1937 editions of the Geological Survey map (Sheet 15) show the intrusion as a dyke extending for about 1.2 km to the north-west, beyond Duneaton Water. It is not exposed in the river, but boulders of 'essexite' occur on the west bank approximately on the projected line of the quarry outcrops and a trial pit some 130 m farther to the north-west has produced similar rock. A preliminary proton magnetometer survey has indicated that a magnetic anomaly extends south-eastwards for about 450 m beyond the last exposures, where drift cover is shallow (less than 6 m). To the north-west the anomaly can be traced for at least 1.3 km and it is concluded that the intrusion is in the overall form of a NW-trending dyke, 15 m to 25 m wide and at least 2 km long. The character of its dominant magnetization is consistent with a Permian field direction (D.W. Powell, pers. comm., 1971).

The main part of the quarry is entered along the line of the intrusion and a continuous cross-section is exposed in the main face at the south-east end (Figure 5.22). The intrusion margins are steeply inclined or near vertical and the width is somewhat variable, but at the quarry face it is about 24 m. At both contacts the intrusion is chilled against indurated sedimentary country rocks, which are tightly folded, near-vertical sandstone, siltstone and mudstone of the Ordovician (Caradoc) Kirkcolm Formation. Scott (1915) described the contact metamorphism in some detail. These greywacke facies rocks have been quarried extensively to the north of the main face where there is a major embayment on the north-eastern side of the quarry entrance.

In the main quarry face, there is a clear distinction between the chilled margins and most of the central porphyritic part. The margins are fine grained, with variable numbers

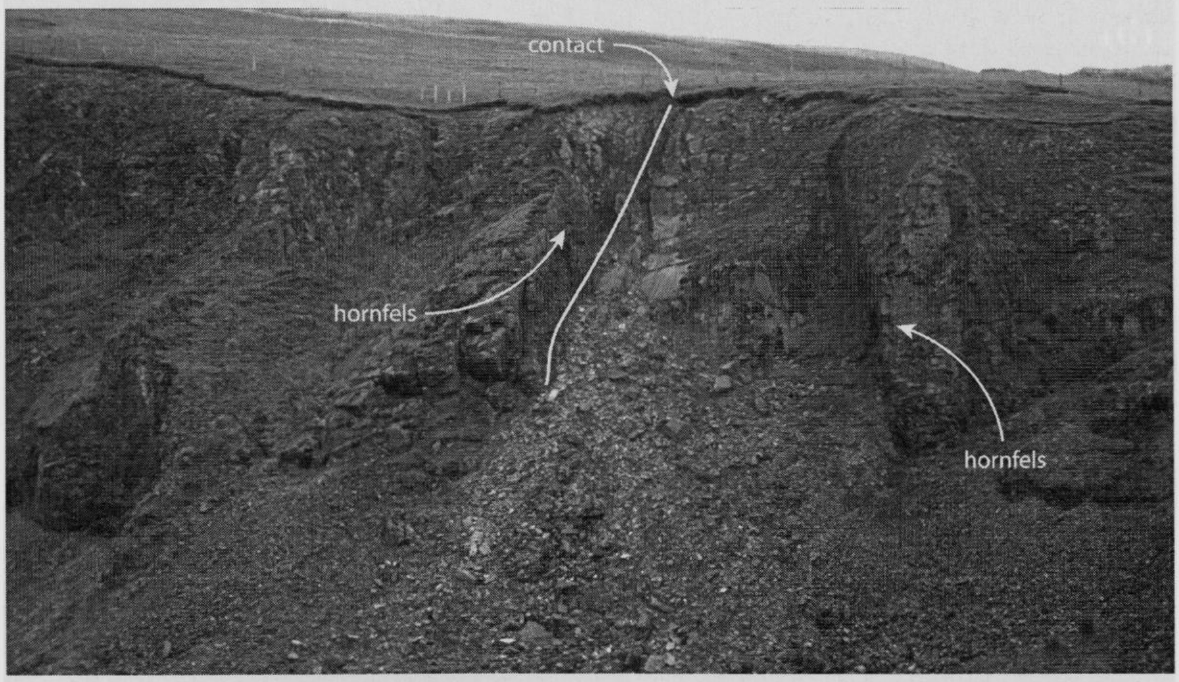

Figure 5.22 The south-east face of Craighead Quarry. The nepheline-gabbro ('essexite') dyke, here about 24 m wide, is exposed in the centre of the photo and the margins of thermally metamorphosed greywacke stand out on either side of the dyke. (Photo: J.G. MacDonald.)

of microphenocrysts of olivine, augite and rare plagioclase, set in an analcime-rich groundmass. This marginal rock was described as 'monchiquite' by Scott (1915) in view of its dominant feldspathoid. The central part of the intrusion, with its abundant large phenocrysts of augite, is separated from the marginal rock by a zone, a few centimetres in width, with few augite macrophenocysts. This zone, which was described by Scott (1915) as 'essexite-monchiquite', commonly has a spotted appearance due to abundant microphenocrysts of olivine and augite. These mafic minerals are set in a framework of plagioclase laths that tend to be flow-orientated parallel to the contacts. Olivine has been replaced by 'fibrous serpentine' and the augite displays varying degrees of alteration. Although the spotted zone has a well-defined non-gradational contact with the central part of the dyke, there is no sign of chill.

The bulk of the intrusion is strongly porphyritic (Figure 5.21a,b). The rock commonly comprises over 25% phenocrysts of titanaugite and more than 40% in places. The phenocrysts are equidimensional or slightly elongated, with well-developed crystal faces. They commonly exceed 5 mm and can exceed 10 mm in length. In thin section they have the purple coloration characteristic of titanium-rich augite and display both sector twinning and oscillatory zoning. Inclusions of groundmass minerals, including olivine, labradorite and apatite, are common and in many instances are aligned parallel to the crystal outlines. The groundmass consists dominantly of laths of labradorite, commonly exceeding 2 mm in length, and abundant rounded crystals of fresh olivine, generally less than 1 mm in diameter. Nepheline and analcime are fairly abundant, the latter as interstitial patches, and small grains of iron-titanium oxide make up about 5% of the rock. Small amounts of orthoclase, biotite and apatite also occur. (There is probably insufficient orthoclase to justify classification as nepheline-monzogabbro, the modern equivalent term for an essexite.)

Chemical analyses of the main part of the intrusion confirm the close affinity of the Crawfordjohn 'essexite' with that of Lennoxtown. The analyses are nepheline-normative and rich in alkalis, and Scott (1915) suggested that the rock has affinities with the 'theralitic' and 'kylitic' rocks of the western Midland Valley (see **Benbeoch** GCR site report).

Interpretation

There is little doubt that the Crawfordjohn 'essexite' was intruded as a NW-trending dyke. The only other major occurrence of a similar rock-type in Scotland is at Lennoxtown, where it occurs as a plug-like intrusion and an inclined sheet, and intrusions of any composition of this age are unusual in the Southern Uplands. The form of the intrusion may be related to its location within competent and well-lithified Lower Palaeozoic country rocks. These are deformed into tight folds with steeply inclined axial planes and are likely to have behaved differently, tectonically and structurally, from the water-saturated and perhaps not fully lithified Carboniferous sedimentary rocks of the Midland Valley into which the alkali dolerite sills of the same age were generally emplaced.

The lack of sharp internal boundaries indicates that the intrusion was emplaced as the result of the injection of a single pulse of magma. However, there must have been some fractionation during the ascent of the magma, which is reflected not just in the variable abundance of phenocrysts, but more notably in the compositional contrasts between the monchiquitic marginal rock and the porphyritic nepheline-gabbro of the main body. The presence of flow-textured feldspar laths in the transitional zone between the chilled margin and the main mass of the dyke provides clear evidence that much of the groundmass had already crystallized prior to intrusion. Hence the dyke must have been emplaced as a crystal mush in which as much as 50% of the material was already in solid crystalline form.

The abundance of large phenocrysts of titanaugite invites comparison with the highly mafic 'ankaramitic' lavas that commonly occur as members of alkaline to transitional volcanic sequences such as the Clyde Plateau and Arthur's Seat volcanic rocks (see Chapter 2). However, the highly developed oscillatory zoning of the phenocrysts in the nepheline-gabbro and their lack of resorption textures appear to indicate that they were in a closer state of chemical equilibrium with the groundmass than is common in many ankaramitic rocks. Inclusions of groundmass minerals within the augite crystals indicate that crystallization of the groundmass had begun prior to, or was taking place during, the growth of the phenocrysts, and small plagioclase laths have been trapped in the boundaries between individual crystals of augite in glomeroporphyritic clusters (Figure 5.21b).

The close resemblance of the main part of the intrusion to the porphyritic facies of the Lennoxtown 'essexite' indicates that the petrography is the result of processes, that, although unusual, were not unique in the petrogenesis of the Late Carboniferous to Early Permian alkali dolerites of Scotland.

Conclusions

The Crawfordjohn 'essexite' at Craighead Quarry constitutes an occurrence of an unusual and visually striking rock-type (a porphyritic nepheline-gabbro) that is known from only one other locality in Scotland. It is also a rare occurrence of an intrusion of Late Carboniferous to Early Permian age within the Southern Uplands. The quarry face provides easy access to fresh, little-weathered rock across the full width of the dyke, which exhibits significant variations in rock-type. Little of significance has been published on Scottish 'essexites' since the early part of the 20th century, and hence this site affords very significant potential for modern mineralogical and geochemical research which could throw light on the origin of augite-rich basic rocks of alkaline affinity. The site is also of historical significance in view of its use in the past as a source of rock for the manufacture of curling stones.

DUBH LOCH, ISLE OF COLONSAY, ARGYLL AND BUTE (NR 369 947)

B.G.J. Upton

Introduction

The Kilchatten Dyke is one of a pair of NW-trending Late Palaeozoic dykes on the Isle of Colonsay in the Inner Hebrides that are remarkable for their unusual compositions and their content of xenoliths and xenocrysts. Although both the Kilchatten and the nearby Riasg Buidhe dykes contain large biotite and amphibole crystals, the Kilchatten Dyke is the more spectacular of the two. The first detailed description of the dyke was provided by Flett (in Cunningham Craig *et al.*, 1911). The dykes also have considerable historical importance in that they were the subject of one of the earliest attempts at dating by radiometric methods (Urry and Holmes, 1941); detailed descriptions and analyses were also included in the same paper. Brief descriptions of the xenolith and xenocryst inclusions were given within a general overview of inclusions of mantle and lower-crustal rocks brought up by alkaline basic dykes in the north of Britain (Upton *et al.*, 1983) and they provided material for a detailed trace-element and isotopic study of Scottish mantle material by Menzies and Halliday (1988).

Description

The Kilchatten Dyke cuts rocks of the Colonsay Group, an enigmatic Late Proterozoic metasedimentary sequence that has been variously assigned to the Torridonian and lower Dalradian (Bentley, 1988). It has a width of approximately 1 m and can be followed on a north-west trend for several hundred metres across the hills to the east of the Lower Kilchatten cottages (NR 367 949) (Figure 5.23). The most striking feature of the dyke is its content of large lustrous biotite crystals up to 4 cm in diameter (Figure 5.24). The biotites, although somewhat resorbed, tend to retain a subhedral morphology. The big mica crystals, together with other 'megacryst' species and included rock fragments, are concentrated in the more central parts of the dyke, with the marginal facies being essentially devoid of them. Associated megacrysts include kaersutitic amphibole and augite, which also occur as partly resorbed crystals up to several centimetres across. Apatite prisms over 1 cm long and fragments of magnetite megacrysts are also present. A range of ultramafic rocks is represented among the xenoliths, including spinel lherzolite (generally carbonated), olivine-pyroxenite, wehrlite, biotite- and kaersutite-pyroxenite and 'glimmerite' (biotite-rich ultramafic rock). Other xenoliths of granulite-facies, pyroxene-bearing meta-igneous rocks with gabbroic and dioritic compositions also occur, together with some metasedimentary xenoliths. The xenoliths rarely exceed a few centimetres in diameter.

The matrix of the dyke is composed of twinned augite prisms (exhibiting an hour-glass structure), magnetite and strongly pleochroic red-brown biotite in a mesostasis of analcime, calcite, apatite, zeolites (natrolite?) and chloritic interstitial material probably secondary after residual glass. Ocelli, up to 2 mm across, occur abundantly. These contain analcime and calcite, with subordinate alkali feldspar, biotite and augite.

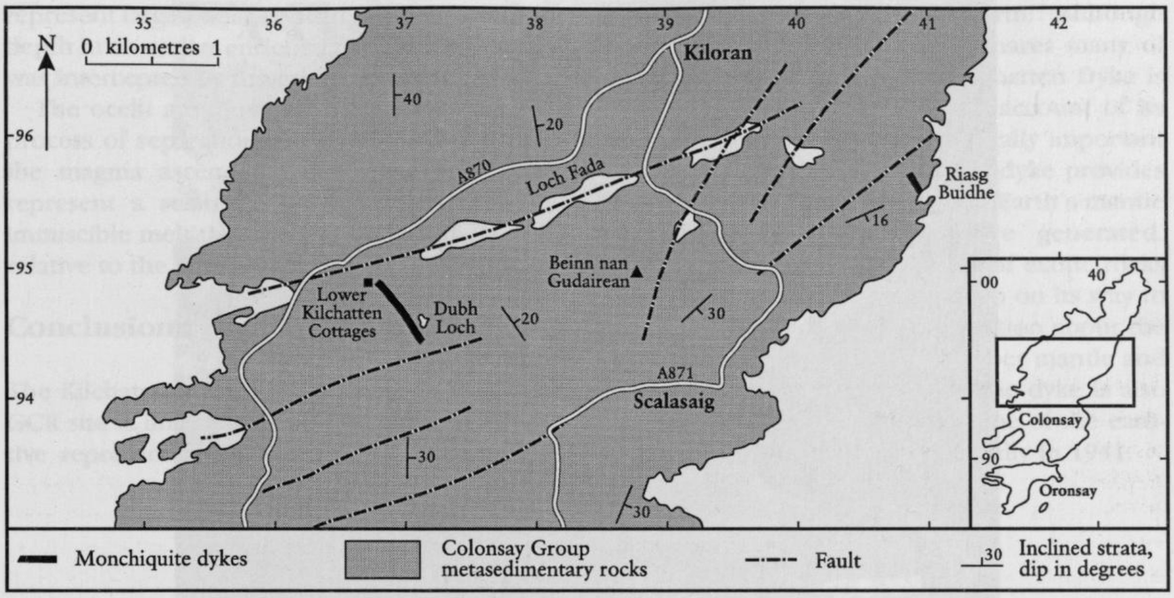

Figure 5.23 Map of the area around the Dubh Loch GCR site, Isle of Colonsay. Based on British Geological Survey 1:50 000 Provisional Series Sheet 35, Colonsay (1996). The inset shows the location of the main map.

Analysis of the dyke rock shows it to be strongly silica-undersaturated (less than 40% SiO_2) and distinctly potassic with $K_2O > Na_2O$. The rock could be described as a monchiquite, i.e. a feldspar-free lamprophyre containing silica-poor glass, commonly with analcime. However, typical monchiquites contain olivine (or pseudomorphs after olivine) whereas the Kilchatten Dyke, unlike the neighbouring Riasg Buidhe Dyke, is olivine-free. The term 'ouachitite', as used by Flett (in Cunningham Craig *et al.*, 1911), is similarly inappropriate and is now obsolete, so the rock is best referred to as an analcime monchiquite despite the qualifications.

Interpretation

The Kilchatten Dyke has long been regarded as one of a family of alkaline lamprophyric (mainly monchiquitic to camptonitic) dykes that traverse the western Highlands and Hebrides. The distinctive petrographical and geochemical features serve to distinguish these dykes from the more numerous dykes of Palaeogene age, which in many areas, including Colonsay, have an identical trend. Correlation of the lamprophyric dykes with the volcanic rocks of the Mauchline, Sanquhar and Thornill basins in south and central Scotland (see Chapter 4) suggested to Geological Survey workers that they are of Late Carboniferous to Permian age. However, this could not be proved from field relationships and the Kilchatten and Riasg Buidhe dykes were selected as representatives of this problematic set of rocks by Urry and Holmes (1941) for radiometric age determination by the Helium Method (see also **Clee Hill Quarries** GCR site report). These workers obtained ages of 130 Ma and 125 Ma respectively for the two dykes which, given the crude timescale of the day, was thought to be in accord with that tentatively assigned on geological grounds. It at least established them as post-Carboniferous and pre-Tertiary. More recent K-Ar determinations on amphibole and biotite from the Kilchatten Dyke have yielded 266 ± 7 Ma and 283 ± 8 Ma respectively (De Souza, 1979). These give a mean of 281 ± 8 Ma using new constants (Baxter and Mitchell, 1984), and an Ar-Ar determination on an amphibole megacryst has yielded a weighted mean age of 280 ± 2.6 Ma (M. Timmerman, pers. comm., 2002), confirming the Early Permian age.

The dyke is typical of the very silica-deficient rocks with high contents of incompatible elements and volatiles (water and CO_2) that characterize this west of Scotland Late Palaeozoic swarm. They were probably generated by the melting of a geochemically enriched source in the lithospheric mantle as a result of pressure

Figure 5.24 Close-up view of the analcime monchiquite dyke at the Dubh Loch GCR site, showing xenoliths of pyroxenite (dull black) and biotite-rich ultramafic rock 'glimmerite' (glossy black) in addition to large megacrysts of biotite (black). The lens cap is about 50 mm in diameter. (Photo: M. Anderson.)

release related to extensional tectonics (Upton *et al.*, 1998). These volatile-rich magmas are inferred to have ascended at high velocities from depths of 70 km or more, breaking off fragments of both upper-mantle and lower-crustal side-walls as they arose and sweeping these up to shallow levels. The upper mantle (at depths of *c.* 60–30 km) is inferred to be of spinel lherzolite associated with younger veins and layers of wehrlite, olivine-pyroxenite, biotite- and/or amphibole-pyroxenite and 'glimmerite'. The xenoliths in the monchiquitic magmas are regarded as 'accidental' samples acquired from these sub-Moho depths, whereas the granulite-facies meta-igneous xenoliths are samples from the lower crust. The megacrysts were probably derived partly from the mechanical and thermal disaggregation of very coarse-grained (pegmatitic) facies in the upper mantle although some (especially the subhedral biotites) may represent large phenocrysts that were forming at depth in an earlier enriched magma fraction that was intercepted by the monchiquite magma.

The ocelli are likely to owe their origin to a process of separation of two liquid fractions as the magma ascended. They are inferred to represent a relatively water-rich alkali silicate immiscible melt that was deficient in Mg and Fe relative to the host monchiquite melt.

Conclusions

The Kilchatten Dyke exposed at the Dubh Loch GCR site is important in that it is a very distinctive representative of the Late Palaeozoic west Highland lamprophyric dyke-swarm. Although the nearby Riasg Buidhe Dyke shares many of the same characteristics, the Kilchatten Dyke is by far the most eye-catching on account of its large mica crystals. It is scientifically important because the geochemistry of the dyke provides information on the nature of the Earth's mantle from which the magmas were generated. Detailed study of the fragments of exotic rocks and minerals that it has picked up on its way to the surface also provides information about the rock-types present within the upper mantle and deep crust beneath Colonsay. The dyke is also significant historically in being one of the earliest rocks to be dated radiometrically in 1941.