The structure and petrology of the volcanic rocks of Eigg, muck and Canna, N. W. Scotland

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THE STRUCTURE AND PETROLOGY OF THE VOLCANIC ROCKS OF EIGG, MUCK AND CANNA, N. W. SCOTLAND

(2 Volumes)

by

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ABSTRACT

The early research and the more recent contributions are reviewed. The stratigraphical succession of lavas on each of the three islands is established and conclusions drawn concerning the relative ages of the lava piles. More than one source is indicated for the lavas of Eigg and Canna, and various localised eruptions occurred on Muck and Eigg.

Basic minor intrusions occur on all three islands. Dykes are remarkably abundant on Muck, forming about 10% of the island, and are extremely rare on Canna, only sixteen being documented. Eigg contains sheets and sills in addition to dykes. The petrography of the lavas and the basic minor intrusions is described and comparisons are made between them.

Six bodies of acidic rock outcrop on Eigg, including the famous Sgurr pitchstone, the origin of which was hotly debated at the beginning of this century. From extensive field studies, it was concluded that the Sgurr pitchstone is of an extrusive origin, with some auto-injection during cooling. The base of the pitchstone was mapped in detail and a plan of the pre-pitchstone topography constructed. Comparisons are made between the Sgurr and Oigh Sgeir (Hyskeir) pitchstones.

The red beds of Eigg and Muck, and the various sedimentary deposits of Canna are described. The red beds are thought to be of a tuffaceous origin. The conglomerates of Canna are fluvial, while some of the finer grained, bedded deposits are probably of lacustrine origin. The Canna conglomerates include igneous pebbles, which imply deposition after the Central Intrusive Complex of Rhum was at least partially unroofed.

An account of the mineralogy of the basic and acid rocks is included, and their geochemistry is described. A comparative study of the lavas and basic minor intrusions of Eigg, Muck and Canna with other Hebridean suites (the lavas and dykes of Skye, the lavas of Rhum and Mull, and the cone sheets of Ardnamurchan) is included. Hypotheses on the petrogenesis of the acid rocks of Eigg are proposed.

The Tertiary volcanic activity on Eigg, Muck and Canna is summarised and the petrogenesis of basic rocks assessed. The magmas are the result of a partial melting event at a depth in excess of 30 km (the estimated depth to the Moho in the area). This depth is reflected in the transitional nature of the basic rocks and the association of the basalts with the thermal divide in the plagioclase-olivine - clinopyroxene - nepheline/quartz system.

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CHAPTER 1

INTRODUCTION

1.1 The Scope of the Research

The initial aim of this research was to study the Tertiary igneous rocks of Eigg, Muck and Canna in north-west Scotland. The study was to include stratigraphical, petrographical, geochemical and mineralogical studies of the rocks found during field work. However, in addition to the basaltic lavas, basic minor intrusions occur in abundance on Muck, acidic rocks outcrop on Eigg and various fragmental deposits are found intercalated with the lavas on all three islands. In the time available, it was not possible, in the field or laboratory, to make a full study of all the facets of the Tertiary igneous geology of Eigg, Muck and Canna. Rather than specialise in any one aspect or island, the author decided to cover as much of each topic as was feasible. The stratigraphy and geochemistry of the lavas is described in detail, but many of the other topics (e.g. the pitchstone of the Sgurr of Eigg, the conglomeratic deposits of Eigg and Canna, the red interbasaltic horizons found on Eigg and Muck and the dykes of Muck) deserve much more detailed study than is afforded them herein.

1.2 Topography of Eigg, Muck and Canna

Eigg is the largest of the three islands, covering about 12 square miles It also contains the highest ground, with over half the island being over 152 metres (500 feet) above sea level It may be divided into two parts by the lowland stretch between Laig Bay (47008818) and Kildonnan (48938505) (see Figure 1.1). The western part is dominated by the Sgurr and its associated pitchstone ridges. These reach a maximum height of 393 metres (1,295 feet) at the east end of An Sgurr (46348770), and the terrain of the pitchstone is characterised by many small lochs. The basaltic lavas reach a maximum height of 344 metres (1,136 feet) just east of Loch nam Ban Mora (c. 45568535). The north-western coast is guarded by cliffs reaching 76 metres (250 feet) in height. Cliffs also occur along the western and southern coasts of this part of Eigg. The northern part of Eigg forms a long band of high ground reaching a maximum height of 334 metres (1,101 feet) at the northern end of Beinn Bhuidhe (48908890). The high ground slopes gradually to the south, but on the other three sides it is bounded by cliffs, with scree slopes below.

Exposure is excellent, if inaccessible, along the cliffs near the coasts of Eigg and on the high ground to the north. In the central parts of Eigg there is a considerable cover of heather and bracken, and locally peat (e.g. Blar Dubh - 47358711 and Blar Mor - 47538606). The high ground forming the An Sgurr (46008475) to Beannan Breaca (44608658) ridge (the pitchstone lava) in the south-west of Eigg, is almost completely free of vegetation.

During the field and subsequent laboratory studies of the succession of lavas on Eigg, it proved convenient to consider the two parts of Eigg separately - Western and Northern Eigg of Chapter 2, for example. Indeed from the geochemistry (see Chapter 10), it would appear that the two parts are formed of lavas of distinctive compositions, and thus perhaps of different sources. The presence of the lowland stretch used in the topographical division of Eigg may be due to this difference in the lavas. Several faults also occur in this lowland area, which will also affect the topography.

The island of Muck is little more than 1 square mile in area. The highest ground is concentrated in the west - Beinn Aireinn (40317915), the highest point, is 137 metres (451 feet) above sea level (see Figure 1.2). If topographical subdivision of such a small area is necessary, the two major bays along the south coast (Camas Mor and Port Mor) serve to divide it into three parts. Both of these bays were found to coincide with fault lines Topographical subdivision was not used in the stratigraphical studies of Muck, but obviously the uppermost flows are concentrated in the Beinn Aireinn area.

Muck's vegetation is predominantly short grass, suitable for sheep grazing. Peat occurs in a small area in the east (north-west of Carndearg - 42457950). Boulder clay and small patches of raised beach deposits are found in the vicinity of Gallanach (40728012), and between Port Mor (42357935) and Toalinn (41758034).

The island of Canna can be divided into two almost equal parts by the low ground running from Tarbert Bay (24000545) to Camas Thairbearnais (23600648) (see Figure 1.3). The western half reaches a maximum height of 129 metres (424 feet) at Sron Rugail (20840452) at the west end of the island. The highest ground in the western half is concentrated along the cliff tops along the south coast. Cliffs also occur along the west and north coasts of this part of Canna. The eastern half of Canna contains the highest point on the island - the summit of Carn a'Ghaill (210 metres/693 feet at 26380645). Southwards from the highest ground, the terrain exhibits the stepped topography typical of basaltic lavas. This type of topography enabled the author to trace many flows for considerable distances.

The island of Sanday lies to the south of Canna, and is connected to it by a footbridge. Compared with Canna, it is extremely flat lying, reaching a maximum height of only 59 metres (196 feet) at Tallabric (26470410), at the south-west end of Sanday. It is here (on Sanday), and in Canna Harbour, that abundant conglomeratic deposits are to be found. These fairly easily eroded materials may account for the lack of relief in this area.

Exposure of solid geology on Canna and Sanday is good. The main vegetation cover is rough grass. Boulder clay occurs around Tarbert (26810543) and south of Camas Thairbearnais (c. 23750600). Raised beach deposits occur north of Tarbert Bay (24000545) and near An Coroghan (27700561).

Stratigraphical correlations have been made between eastern Canna and Sanday (see Chapter 2). Also, the conglomerates and lavas of the islands of Canna Harbour have been correlated with both Sanday and eastern Canna. However, only a few lavas of the eastern Canna succession have been traced to the western half of Canna Thus, like Eigg, the two parts of the main island of Canna may have been formed of lavas originating from different sources.

1.3 History of Previous Research

The major geological research on the Tertiary igneous rocks of Eigg, Muck and Canna dates from the second half of the 18th and early 19th centuries, when the field was dominated by Alfred Harker and Archibald Geikie. Before these authors began their research, however, the major features of the Tertiary geology of the three islands were known.

The earliest known geological reference to the area dates from 1695, when Martin (reprinted in 1884) first published 'A Description of the Western Islands of Scotland'. He says of Canna that "there is a high hill in the north end, which disorders the compass", clearly a reference to what is now known as Compass Hill on account of the effect described. He also noticed that on Eigg "the coast guarding the north west is a soft quarry of white stone" - the Jurassic sandstones of the Laig Bay area. During the 18th century, Mendez da Costa (1762) knew of the "polygon pillars" above Canna Harbour, and MacLean (1794) describes the "plumb-pudding-rock" of eastern Canna (around Coroghan Mor and Alman), in which he found the remains of trees with fibres like those of oak. The 'plumb-pudding-rock' refers to the extensive conglomeratic deposits of that part of Canna

The stratigraphical succession of the cliffs of eastern Eigg was first described by Jameson (1800). However, he mistakenly identifies the intrusive sills in the Jurassic sediments as being basaltic layers interbedded with the sediments. This helped to instigate the idea that the basalts were of Jurassic (or Oolitic) age. He also observed basaltic dykes intruding the sequence described, and he knew of the pitchstone dykes of Rudh' and Tancaird on Eigg. The Sgurr of Eigg was also known to be formed of pitchstone and to contain radiating columns. The Jurassic age of the basalts was supposedly confirmed by W. Nicol (1833), who studied longitudinal and transverse thin slices of fossilised coniferous material found among "the debris of the prismatic columns of porphyritic pitchstone constituting the Scuir of the island of Eigg".

The first author to make any interpretative study of the Sgurr pitchstone was Hay Cunningham in 1839. From the manner in which the pitchstone cross-cuts the basalts at the east end of the Sgurr ridge, he concludes that the pitchstone forms "a great vein which has been erupted through the older Plutonic rocks". He is the first also to record conglomeratic deposits below the pitchstone. In the conglomerates he found "angular shaped masses of pitchstone-porphyry, the same as that of the Scuir, with fragments of trap". ('Scuir' is an old spelling of Sgurr.) In addition, he reports on the occurrence of another pitchstone, similar to those of Arran, along the road between Kildonnan and Cleadale. This is presumably a glassy facies of the Sron Laimrhige felsite described in this thesis. Hay Cunningham makes an interesting observation on the origin of the basalts and the pitchstones of Eigg:-

> "None of the basaltic greenstone or pitchstone ranges can ever be viewed as examples of consolidated mineral streams which have issued from a crater."

Clearly he followed the Neptunist school of thought on rock formation!

The only other notable contribution to the knowledge of the Tertiary geology of Eigg, Muck and Canna prior to the advent of Geikie was made by J. Nicol (1844). He gives a summary of the known geology of the three islands, but of the Canna conglomerates he says that "the superior trap (basalts) seem to have flowed over the bottom of the sea, where these (the boulders in the conglomerates) were deposited, enveloping the loose boulders, which thus form the conglomerate".

In the period 1865 to 1897, Geikie published at least ten works on Scottish geology, and volcanic rocks in particular. His work culminated with the publication of his book 'The Ancient Volcanoes of Great Britain' in 1897. His first contribution of relevance to the research area is that of 1867 (published in 1869), where he suggests a Tertiary age for all the basalts of the Brito-Icelandic province. This he bases largely on the Miocene age attributed to the plant remains from the Ardtun deposits of Mull (*see* Argyll 1850). This age was later confirmed for Canna by the discovery of similar plant remains in a highly laminated brown clay in a cave in the north west of that island (*see* Heddle 1882). To confirm the Tertiary rather than Jurassic age of the basalts of Eigg, Geikie recognised that the basalts interbedded with the Jurassic sediments were intrusive sills (*see* Geikie 1871). Geikie also knew of all three felsite intrusions on Eigg - that at the north end of the island (the Sgorr Sgaileach felsite), that of the Laig area (the Sron Laimrhige felsite) and that outcropping below the south face of the Sgurr (the Grulin felsite).

Geikie's major work, however, was on the Sgurr of Eigg. The Sgurr pitchstone he believed to be the result of several outpourings of acidic magma, forming the alternating bands of pitchstone and felsite. He noted the brecciated base and the underlying conglomerates (Geikie 1871). What impressed him most, however, was the amount of erosion involved in the formation of the Sgurr in its present form. He had observed the water-worn pebbles (of red and white sandstone and basalt) and wood fragments in the conglomerates below the pitchstone. He therefore concluded that:-

> "an old Tertiary river flowed southwards through a forest-clad region, of which the red Cambrian mountains of Ross-shire and the white sandstone cliffs of Raasay and Skye are but fragments, that it passed over a wide and long tract of the volcanic plateau which has been so worn away that it now remains in mere islets left standing out of the deep Atlantic,

> that since then mountain and valley have alike disappeared and that in Eigg a fragment of a river valley has been preserved solely because it has been sealed up under streams of vitreous lava which could better withstand the progress of waste." (Geikie 1871)

Later he postulates a continuation of this river of Eigg to Oigh Sgeir, on the evidence given by Heddle (1892) that Oigh Sgeir is formed totally of pitchstone identical with that of Eigg (see Geikie 1896). There is, however, no conglomerate exposed on Oigh Sgeir, so his hypothesis remains unproven, although the petrographical and chemical similarities of the rock with the pitchstone of Eigg are most striking (see Chapters 7 and 11).

This hypothesis of the origin of the Sgurr pitchstone stood unchallenged until 1906, when Harker revived the idea of an intrusive origin. With great thoroughness he refuted Geikie's hypothesis, preferring to regard the pitchstone as an intrusion fed by the Grulin felsite and further intruded by a number of sheets of felsite. He missed one vital point, however, which contradicts his hypothesis. The Sgurr pitchstone clearly postdates the intrusion of the basic dykes of Eigg, while the Grulin felsite is cut by dykes (see Chapter 6). Thus the Grulin felsite cannot possibly be a feeder to the Sgurr pitchstone. The two rival hypotheses were discussed by Bailey (1914), who agreed with Geikie that the main mass of the Sgurr was formed by extrusion of acidic magma along a river valley. He agrees with Harker, however, that:-

> "the apparent stratification of the mass is due to injection and not, as Geikie thought, to the piling of lava-flow upon lava-flow". (Bailey 1914)

Geikie's other major contribution to the Tertiary geology of the research area was a study of the Canna conglomerates (see Geikie 1896 and 1897). The majority of these he attributes to the action of a river system similar to those seen in the volcanic wastes of Iceland today. He envisages a river flowing "perhaps in many separate channels across the basalt fields of the Inner Hebrides and was liable to have its course shifted from time to time by fresh volcanic eruptions". The sea stack of Dun Beag on Sanday is the only example of a true channel deposit, but even that channel was eventually flooded by lava, as evidenced by the fact that the conglomerate is overlain by basalt. He reports pebbles of basalt, Torridonian sandstone, gneiss, grey granite, grits and schists in the conglomerates. The coarse fragmentary deposits below Compass Hill are interpreted by Geikie as an agglomerate - "a vast sheet of lava fragments swept away from one or more volcanic cones of slag and cinder, or from the rugged surface of a lava stream".

Few studies of the conglomerates have been made during the 20th century, but that of Emeleus (1973) is significant in that he found pebbles similar to the western granophyre of Rhum in the conglomerate. This implies that the conglomerates (and hence the overlying lavas) must postdate the unroofing of the western granophyre of Rhum and are thus a relatively late event in the Tertiary igneous activity of the area (like the lavas of Rhum). This hypothesis is confirmed by the author's studies of the conglomerates (see Chapter 8).

The only major publication to cover the complete geology of the islands of Eigg, Muck and Canna in recent years is the Geological Survey Memoir of the Small Isles of Inverness-shire (Harker 1908). Harker, however, interprets the basalt pile as being predominantly of intrusive dolerite sills, with only the amygdaloidal, softer layers being the lavas. The geochemical nature of the basic and acidic rocks of the three islands (and Rhum) was studied by Ridley (1971 and 1973). He describes the basic rocks as being intermediate between alkali and tholeiitic basalts, a feature confirmed by this thesis. He finds that the acidic rocks are most probably the derivatives of partial melting of tholeiitic material or of sialic crust, rather than of fractional crystallization of basaltic material (see Chapter 11 for further discussion). A more recent publication (Carter et al 1978) on the Neodymium and Strontium isotopic contents of lavas from Skye, Mull, Muck and Eigg concludes that there has been substantial contamination of these lavas by Precambrian Lewisian basement.

The remaining publications concerning the research area are on more specialised subjects. Tilley (1947 and 1952) discusses the Camas Mhor gabbro and its effects on the surrounding rocks (basalts and Jurassic limestones). Carmichael, in a series of papers between 1960 and 1967, describes various features concerning the crystallization history of some Tertiary acid glasses, including the Sgurr pitchstone of Eigg. His work is discussed in Chapter 11.

CHAPTER 2

STRATIGRAPHY OF THE BASALTIC LAVAS

2.1 Introduction

The stratigraphy of the lavas of the islands of Eigg, Muck and Canna is considered in three sections, one for each island. By their insular nature, it is obviously impossible to make stratigraphical correlations between the islands. Some suggestions concerning possible age relationships of the lavas of the three islands, and nearby Tertiary lavas (e.g. Skye and Rhum) are given in Section 2.5.

It should be noted that all grid references quoted in this, and all subsequent, chapters are given as eight figure references. In 1975, the Ordnance Survey published their first contoured maps of Eigg, Muck and Canna, to the scale of 1:10,000. In the case of all three islands, these new maps are composed of parts of the older six-inch series. In the case of Muck, there is now one 1.10,000 scale sheet and this represents parts of four old sheets:- NM 37 NE, NM 38 SE, NM 47 NW and NM 48 SW. For Canna, there are two sheets at the 1:10,000 scale. In terms of the old six-inch grid, they represent:-

(i) NG 20 NW & SW;
(ii) NG 20 NE & SE.

For Eigg, there are now three sheets, which in terms of the older grid, are:-

(i) NM 48 NW & SW;
(ii) NM 48 NE & SE,
(iii) NM 48 NE & NM 49 SE.

The sample numbering system adopted in this thesis differs slightly from the author's original field and thin section numbering. The difference is the result of an attempt to produce a reasonably standardised system of numbering for the three islands without having to drastically renumber all the thin sections and hand specimens. This, the author feels, could have too easily led to errors. A key to the sample numbering used in this thesis as compared to that on the hand specimens and thin sections is included (*see* Appendix 1).

2.2 Muck Stratigraphy

2.2.1 Introduction

Over 75% of the exposed lavas on Muck are olivine-phyric basalts. Although at least 7 different olivine-phyric flows were proved in the cliffs of An Stac (40307888) and on the slopes of Beinn Aireinn (40307915), it was difficult to distinguish these from each other in either hand specimen or thin section. Lateral variation within flows was also proven by examining thin sections from different localities within what appeared to be the same flow from examination of the cliffs. Perhaps they were merely contemporaneous flows, which appear to be continuous in the particular section exposed. The result is that much of Muck cannot be subdivided into different flow groups; nor could individual flows be mapped on the ground, because of the similarity of each specimen.

As a result of the shallow dip (a few degrees to the northwest), it is generally only within half a kilometre of the south coast, of the island, that the lower flows (below the olivine-phyric group) are exposed. In all, nine sequences through the Muck succession were established in this area, details of which are given in Figure 2.2.1. The localities, from which they were collected, are shown in Figure 2.2.2.

The lava pile of southern Muck can be divided into three groups, listed from top to base:-

1) Beinn Aireinn - An Stac Group;
2) Port an t-Seilich Group;
3) Basal Group.

The geographical extent of these groups is shown on Figure 2.2.2. There are obvious difficulties with this map, because of the lack of exposure, in northern Muck, of flows obviously belonging to the two lower Groups. Where the flows in the north resemble the Beinn Aireinn-An Stac Group, they are assigned to this Group.

2.2.2 Beinn Aireinn - An Stac Group

This Group forms the top two-thirds of the Muck succession. The type locality is taken as the gully (40307888) between Sron na Teiste and Sgorr nan Laogh, and its upward continuation to the summit of Beinn Aireinn (40407915). Only part of the sequence above the Main Red Bed (40307888) belongs to this Group. Here, the group reaches a maximum thickness of 102 metres.

The upper part of the sequence consists of four flows. Three of these are of olivine-phyric basalt, indistinguishable from each other in hand specimen. The uppermost forms the columnar crags at the top of Beinn Aireinn (40307915), and is 26 metres thick. The flow below is a poorly-exposed, olivine-and plagioclase-phyric basalt, about 10 metres thick, and overlain by 0.02 metres of red mudstone. It is underlain by the second of the olivine-phyric flows, which is 14 metres thick and forms isolated massive crags above the top of the gully (40207898). The top of the cliffs, at the head of the gully (40267890), are formed by the third olivine-phyric flow. The basal 1.05 metres of this 10 metres thick flow are highly vesicular and altered.

The lower three flows of the Group are exposed down the gully (40287887). They are olivine-phyric, medium to coarse grained, amygdaloidal basalts, all overlain by thin red beds. They weather more easily and are more altered than the upper flows. The top two flows consist of ellipsoidal pods of fairly competent basalt (1 metre thick and several metres long) in a matrix of highly altered, amygdaloidal basalt. This must mean that these two flows in this area are composed of several small flow units. The lowest flow is more massive than the other two. At the top, it is banded, the banding consisting of units 0.3 metres thick, on average, of varying competence.

The thin red beds (0.2 metres thick at maximum) seen above the flows are formed of a mudstone-like deposit. Below these the flows are purple-red in colour, due to post-extrusion alteration, to a depth of about 1 metre. The red mudstone infills cracks in the tops of the flows. The uppermost red bed occasionally expands to 0.4 metres, infilling depressions in the top of the underlying flow. It is then a more sandy deposit, and encloses pieces of purple-red, highly vesicular basalt, similar to the altered basalt below.

Thin sections and chemical data for the olivine-phyric flows collected from the other sequences were examined, in an attempt to correlate them with those of the type locality. Various definite correlations could be made, on the grounds of petrography and/or chemistry. However, considerable differences were found to exist between samples taken from what could definitely be said to be the same flow at the type locality. Therefore it is considered that the olivine-phyric basalts of the other sequences are, at least, time equivalents of the Beinn Aireinn - An Stac Group, with some true lateral equivalents.

2.2.3 Port an t-Seilich Group

This Group of plagioclase-phyric lavas is separated from the overlying Beinn Aireinn - An Stac Group by the Main Red Bed. This is well exposed at the type locality for the preceding Group (40307888). Here there is 0.4 metres of a bright red-orange coloured, unstratified and highly jointed mudstone. It contains no fragments of altered basalt, and is essentially separate from the underlying flow.

Equivalents of the Main Red Bed are seen at various other localities and these are tabulated in Table 2.2.1. In each case, it is a red mudstone, which can be proved to separate plagioclase-phyric from overlying olivine-phyric flows. At several localities, rounded fragments of altered red-purple basalt occur in the mudstone, in varying amounts.

The type locality of this Group (up to four plagioclase-phyric flows below the Main Red Bed) is a gully on the west side of Port an t-Seilich (41837845), sequence 7 in Figure 2.2.1, where it reaches a maximum thickness of 26 metres. The Main Red Bed is not exposed here, but its position can be inferred between the uppermost plagioclase-phyric basalt (41757847) and the overlying olivine-phyric crags (41737846). From here the lowest olivine-phyric basalt can be traced westward and shown to be equivalent to the flow above the Main Red Bed in the Sloc an Dubhaich cliffs (41607855).

At the type locality the top flow, 7 metres thick, is exposed as a series of crags of fine grained basalt, with rare plagioclase phenocrysts, and quite prominent horizontal jointing. It is underlain by two flows of massive, fairly fine-grained basalt, with relatively abundant plagioclase phenocrysts. The upper flow is 6 metres thick. The lower one, 8.2 metres thick, has a rather broken up base which passes down into the top of a brecciated flow. This breccia, 4.5 metres thick, is composed of fragmented amygdaloidal, plagioclase-phyric basalt. It can only be traced to the west, and is assumed to die out to the east. The fine-grained, aphyric flow below the brecciated one belongs to the Basal Group (see Section 2.2.4).

Thin sections, in addition to field evidence, were used to correlate the other sequences of plagioclase-phyric basalt with those of the type sequence. In contrast with the olivine-phyric basalts, samples from the same flow closely resembled each other. Thus, correlations between sequences, carried out by petrography, are considered to be accurate. Details of these correlations are given in Figure 2.2.1.

The area east of Port Mor (42357945), south of Carndearg (42457949) and west of Eilean Dubh (42957950) was mapped in detail, see Figure 2.2.3 and Figure 2.2.4 (the latter details the sequences). Flows belonging to the Port an t-Seilich Group decrease from three, south of the hamlet of Port Mor (42357912), to two, separated by the brecciated equivalent of the middle one, around the Cairn (42597912). Further reduction, to a single flow (the lowest one) occurs south-west of Torr Creagach (42787938), where the Main Red Bed is underlain by the brecciated equivalent of the uppermost flow. Here, the lowest flow attains its maximum thickness of 11.3 metres.

The brecciated equivalents of flows, as they die out, are similar to the bottom flow at the type locality of the Group, that is, highly vesicular, plagioclase-phyric basalt fragments, with no matrix. The fragments are altered, purplish in colour, and locally the breccia shows reddening at the top. Presumably these brecciated flows represent 'palaeo-flowfronts'.

2.2.4 Basal Group

This consists of a variable series of lavas and sediments which occur in several places below the Port an t-Seilich Group. Details of the sequences, of this Group, are shown in Figure 2.2.1, which indicates that only the top of the Group has any uniformity. Consequently, the Group is divided into two subgroups:-

1) Upper Basal Subgroup;

2) Lower Basal Subgroup.

2.2.4.1 Upper Basal Subgroup

The type locality of this subgroup is the lower part of the gully at the western side of Port an t-Seilich (41837845). It is 8.35 metres thick and consists of two fine-grained, aphyric flows, both overlain by a red bed. The upper one is, on both chemical and petrographic basis, a basalt, and has a rather broken top. The red bed above is very thin - a few millimetres. The lower flow chemically resembles a mugearite and is separated from the upper one by 0.35 metres red-orange, sandy mudstone.

The sequence at Torr nam Firheach (40807973) is identical with that at the type locality. In the An Stac cliffs (40407910), the Port an t-Seilich Group is underlain by 7 metres of mugearite with a brecciated top. The upper flow must therefore die out eastwards, since it is not found here. Further west, on the foreshore east of Sgorr nan Laogh (40407890), there is no mugearite; it presumably dies out westward.

Along the south coast, east of Port Mor (42357945), the mugearite at sea level is overlain by 1.7 metres of brecciated basalt, which is composed of red-purple, angular fragments of basalt, showing pahoehoe structures. This may be the broken-up equivalent of the upper flow of the Group, which, for some reason, is not represented at Torr nam Firheach (see above), or it may be a separate flow, roughly contemporaneous with the upper flow as seen further west.

2.2.4.2 Lower Basal Subgroup

No type locality is established for this subgroup because there is a lack of uniformity between the exposures. They are described separately below.

At the type locality for the Upper Basal Subgroup, the mugearite is underlain by a highly vesicular basalt, with abundant plagioclase phenocrysts. This flow is not seen elsewhere. To the east, the mugearite forms the wave cut platform, and no lower flows are seen.

At Torr nam Firheach (40807937), 0.4 metres of tuffaceous sandstone, containing reddened fragments of basalt, occurs below the mugearite. These fragments are generally small, a few centimetres at maximum, but one measures 0.35 metre across. Below there is a fine-grained, finely layered, carbonaceous sediment, which is seen to be faulted against Jurassic sediments.

At the eastern end of An Stac (40407910), this subgroup is represented by a complex sequence of sediments; but exposure is incomplete. The sequence consists of 1 metre of crudely bedded deposit, brown-grey in colour, with numerous basaltic fragments. Below this there is no exposure for 0.6 metre, after which there is a 0.8 metre thick brown-red mudstone, containing small, angular fragments of basalt and red ellipsoidal fragments. The mudstone becomes broken towards its base, beneath which occurs 1 metre of red-purple, tuffaceous sandstone. Within a few metres a thin basalt flow, underlain by a fine-grained, grey sediment is seen. Beneath the grey sediment there is 10 metres of unexposed ground before the Jurassic sediments of Camas Mor Bay are exposed.

The foreshore below Sgorr an Laogh (40407890) exposes a series of red-orange sediments interbedded with thin lava flows. There are four fine-grained, aphyric basalts, each about 0.5 metre thick. The sedimentary units are each approximately 1 metre thick and consist of red-purple mudstone. The mudstones are interbedded, in varying proportions, with a coarser grained, orange-red sandy mudstone. This sequence terminates against a dyke (46457900), which must correlate with a fault plane, since there are Jurassic limestones to the eastern side of the dyke.

2.2.5 Conclusions

The volcanic activity on Muck, as represented by the exposed lavas, went though four phases. Everything began rather hesitantly, resulting in the series of lavas and sediments which form the Lower Basal Subgroup. This was followed by a period of extrusion of mugearitic lavas. Then came the major basaltic outpourings, first the plagioclase-phyric flows of the Port an t-Seilich Group and then the thicker sequence of olivine-phyric basalts of the Beinn Aireinn-An Stac Group.

2.3 Eigg Stratigraphy

2.3.1 Introduction

A total of eleven stratigraphical sequences were established on Eigg (see Figure 2.3.1). Lateral variation between these sequences is considerable; no flow was found to be continuous across the island. In addition, there are difficulties in correlating the successions found in the two topographically distinct parts of Eigg (see Chapter 1). Only one of the basal marker horizons of the definable Groups is present in both areas, and few other flows are definitely continuous between the two areas. Consequently, it was considered expedient to describe the two halves of Eigg separately for stratigraphical purposes, defining different Groups for each area, and, ultimately, discussing the possible relationships between the two successions (see Figure 2.3.2 for the geographical extent of the Groups defined).

2.3.2 Western Eigg

Geographically, this area forms the southwestern part of Eigg, as defined in Chapter 1. The general dip of the lavas is a few degrees (5^{o} - 10^{o}) to the south; it was not possible to establish an accurate value due to the lack of continuity of distinctive flows. Faulting occurs throughout the area, but the direction and amount of throw is not always detectable due to lateral variation of the flows. The majority of the faults have a northwesterly strike and downthrow to the northeast, with an average vertical displacement of approximately 10 metres. This fault pattern leads to repetition of flows on the eastern slopes, for example, around 47008600, where the basal marker horizon of the Brutach Dearg Group is repeated three times (see Figure 2.3.2).

Eight of the eleven sequences collected on Eigg are from this western area (Nos. 3 - 11, Figure 2.3.1). The succession established from these sequences was divided into six Groups, using distinctive flows as basal marker horizons. All but one of these marker horizons were defined on field criteria (and subsequently confirmed by petrographical examination); the other, that of the Cnoc Creagagh Group, was defined by petrographical evidence alone (see Table 2.3.1 for details of the Groups and their respective marker horizons). The names of the Groups should not be thought of as strict type localities for them. The individual nomenclature was developed from prominent features within the areas in which the Groups form the immediate bedrock.

2.3.2.1 Cora-bheinn Group

This, the uppermost series of flows, is only preserved in the high ground of south west Eigg (for example, on the slopes of Cora-bheinn - 45908555), being present only in sequences 4, 6, 9, 10 and 11 (see Figures 2.3.1 and 2.3.2). In the field, its basal member was defined as the first plagioclase-phyric flow encountered above the series of predominately olivine-phyric flows, which make up a large proportion of the Eigg succession. Where sampled (at sequences 4, 9, 10 and 11), this flow proved to contain plagioclase, olivine and clinopyroxene phenocrysts, and to be easily recognisable in thin section. It is thickest in the south, 50 metres near An Sgurr (45878456) in sequence 11, and thins northwards to 10 metres near Cora-bheinn (c. 45608570) in sequence 1. This suggests that this flow either originates in the south, or has infilled a pre-existing hollow in this area.

The remainder of this Group is variable across the area. Around Cora-bheinn (sequences 4 and 6), there are correlatable plagioclase and olivine-clinopyroxene phyric flows, with an extra olivine-phyric flow in sequence 4 (see Figure 2.3.1 for details). None of these flows can be correlated with the more southerly sequences (9, 10 and 11). Furthermore, these three sequences have little in common with each other, apart from the basal marker horizon (see Figure 2.3.1). The Group reaches a maximum thickness of 65 metres near Gualainn na Sgurra (4608477) - sequence 14 - and thins northwestwards (40 metres thick on the north side of Cora-bheinn (45708570).

The difficulties encountered in trying to correlate the flows of this Group across the area probably imply more than one source for these lavas. As has been noted, the basal marker probably originated to the southeast, but the author feels that the gross dissimilarities seen between the sequences can only be explained by very localised centres of eruption. There is no field evidence for any such centres however, or for feeder dykes.

The youngest flows on Eigg must be the aphyric flows at the top of sequence 9 (outcropping below the pitchstone of Cora-bheinn (45688545). The flow below this one correlates with the top flow of sequence 10 (the sequence showing the maximum thickness for this Group); thus the original thickness of the Group must have been in excess of 65 metres.

2.3.2.2 Cnoc Creagach Group

As with the preceding Group, this is confined to the high ground of southwestern Eigg (see Figure 2.3.2). In the field no suitable marker horizon can be found in the predominately olivine-phyric flows of the upper middle parts of the Eigg succession. On petrographical examination, however, a distinctive fine-grained basalt with small olivine phenocrysts was found in several of the sequences (Nos. 6, 10 and 11, see Figure 2.3.1). As with the basal marker of the Cora-bheinn Group, the basal marker of this Group shows its maximum thickness, 45 metres, in sequence 11 (just east of Allt na Criche (45258450)). To the northwest it is only 10 metres thick (see Figure 2.3.1), suggesting a southeasterly source for this flow, as for the Cora-bheinn marker horizon. The Group itself attains its maximum thickness in the south, 85 metres, around Gualainn na Sgurra (46708477) - sequence 10, as does the Cora-bheinn Group. Correlating the individual flows of each of the sequences proved virtually impossible, as none bore any petrographical similarities to the others. This problem was increased by the Grulin felsite intruding sequence 11 (south of An Sgurr 45888450). North of An Sgurr (46498505), sequence 9 has no representative of the basal marker of this Group, and only one aphyric flow could be assigned to this Group. There is a fault in this vicinity (see Figure 2.3.2, 45508502), and it is presumed that the Cnoc Creagach Group is missing because of this. In the north, around Sliabh Beinn Tighe (45208725), again the basal marker horizon is absent (see Figure 2.3.1, sequence 3.1). The basal marker of the Brutach Dearg does not exist in this sequence either, and the two olivine-phyric flows, which complete this sequence, most resemble the two upper olivine-phyric flows of the Cnoc Creagach Group in sequence 6. They are thus assigned to this Group, but this correlation is by no means certain.

The only other sampled representative of this Group is a mugearitic flow found below the flows of the Cora-bheinn Group north of Cora-bheinn (c. 45608576 - sequence 4, Figure 2.3.1). The flow above the basal marker horizon in sequence 11 (south of An Sgurr) is also mugearitic, but, because of the overlying pitchstone unconformity, it is impossible to say whether these are part of the same flow. From its position in sequence 4, this could well be the uppermost flow of this Group.

Lateral variation within the Group is extreme. As with the preceding Group, this is suggestive of several small centres of eruption. It is interesting to note that the basal marker thins northwestwards - as does the basal marker of the Cora-bheinn Group. This may mean that both came from the same source, perhaps a more permanent fissure or vent than produced the other flows of the two Groups.

2.3.2.3 Brutach Dearg Group

This Group outcrops predominantly in the centre of the area, between approximately 150 metres and 250 metres O.D. (see Figure 2.3.2). North of Gleann Charadail (sequence 3), its extent is much reduced, and it is confined to ground above c. 200 metres O.D. The Group reaches a maximum thickness of 85 metres in the south (sequence 9, west of Brutach Dearg 47388480), but it must be noted that the top of the Group is hard to define here, due to the lack of representation of the basal marker horizon of the overlying Group in the sequence. As a whole, the Group thins markedly to the northwest, being represented by only 5 metres of the basal marker horizon.

The basal marker horizon is a readily recognisable, a very fine-grained, olivine-phyric basalt. It was traced, in the field, from the south side of Gleann Charadail (46608640), as far as Brutach Dearg (47408420), southwest of which it could not be found. Thus it is not represented in sequences 10 and 11, and these sequences were not surveyed in detail below this stratigraphical level. North of Gleann Charadail (sequence 3), the basal marker horizon was defined by petrographical examination. It appears to be the only representative of this Group here, the overlying flows having been assigned to the Cnoc Creagach Group (see Section 2.3.1.2).

Correlation between flows in this Group is much easier than for either of the preceding Groups. Fairly definite continuity of the four basal flows was proven both in the field and the laboratory (sequences 6, 8 and 9 - see Figure 2.3.1), some of the flows dying out southwards. Olivine-phyric flows make their appearance in the southeast (sequence 9) and these can be continued to the south (sequence 10) and west (sequence 11) - see Figure 2.3.1.

This leaves a rather complex picture. There must be a source for the olivine-phyric flows of sequences 9, 10 and 11 to the southeast, as they die out northwestwards. There must be a second source for the lower flows, which can be correlated across sequences 6, 8 and 9, as these die out southeastwards. As has already been noted, all flows in the Group, except the basal marker, die out northwestwards (see sequence 3, Figure 2.3.1). These lower flows cannot therefore originate from the northwest. None of the Cleadale flows (see Section 2.3.4), to the northeast can be correlated with the lower flows of this Group, so perhaps the source is to the southwest. As noted for the preceding Groups, however, there is no evidence of fissures or vents. The flows of this Group are, in general however, more persistent, suggesting that eruption at this time was not quite so localised as at the time of the later groups.

2.3.2.4 Glac an Dorchadais Group

This Group was only defined north of a line passing through Sandavore (47758461), and is thus not recorded in sequences 10 and 11 (see Figure 2.3.2). In contrast to the Brutach Dearg Group, this Group increases in thickness from southeast to northwest, reaching a maximum thickness of 85 metres, north of Gleann Charadail (46008700) - sequence 3 (see Figure 2.3.1).

The basal marker horizon is a basalt containing extremely abundant olivine phenocrysts; it is readily identifiable in the field and in thin section. It is of relatively constant thickness throughout its outcrop (10 - 15 metres), and is absent only in sequence 8. The base of this Group in sequence 8 is taken at the level of a red tuffaceous mudstone horizon. This was done because one of the overlying olivine- and clinopyroxene-phyric flows above this tuffaceous horizon is petrographically similar to the flow which overlies the basal marker horizon of sequence 9 (see Figure 2.3.1). Thus, in the south (see Figure 2.3.2 - sequences 8 and 9), in the vicinity of Brutach Dearg (47388480), the Group is dominated by olivine-and clinopyroxene-phyric flows, with an aphyric flow at the top in sequence 8 (see Figure 2.3.1).

Around Glac an Dorchadais (47658680), sequence 6, only the top flow of the Group can be related to the sequences examined to the south (see Figure 2.3.1). The rest of the flows in sequence 6 are olivine-phyric, as are the majority of the flows in this Group north of Gleann Charadail (sequence 3). Despite the increase in the number of flows (four in sequence 6, eight in sequence 3), correlations proved possible on petrographical grounds (see Figure 2.3.1 for details).

As with the overlying groups, there are differences in the flows present in the sequences of the northern and southern parts of the area (see Figure 2.3.1). This again suggests at least two sources for the lavas. The greater thickness of the sequence north of Gleann Charadail, when compared with the other sequences, suggests that this area was perhaps nearer one of these source areas.

2.3.2.5 Gleann Charadail Group

This Group forms the central lowland area from near Poll Duchaill (45408811) to Bealach Clith (49108520), including the excellently exposed basal marker horizon of the Grey rock (as seen, for example, in the crags near Laig Farm - 47008735). This Grey rock (a mugearite chemically) was considered to be a sill by Harker (1908), who maintained that it was transgressive towards the basaltic lavas. The author found no such evidence; in fact, at two localities (46698739 and 47708788) a reddened, broken up, upper surface is exposed. Such a surface implies an extrusive origin.

The Group reaches a maximum thickness of 70 metres north of Gleann Charadail (sequences 3 and 5, see Figure 2.3.1). Four flows overlie the Grey rock in sequence 3; three in sequence 5. They are all basaltic, except for a hawaiitic flow above the Grey rock in sequence 5, and have a variety of phenocrysts. Only one flow is definitely common to both sequences - the uppermost flow in each case (see Figure 2.3.1). A similar flow occurs in the area between Cnoc a'Breacnaich (48308534) and the school (48038633) - sequence 7. Here it is also the uppermost member of the Group. A plagioclase-phyric flow can also be correlated with the sequences to the north (see Figure 2.3.1), but the thickness of the Group is reduced to 55 metres in this area.

Flows stratigraphically below the Glac an Dorchadais Group, and hence part of this Group, occur around Glac an Dorchadais (47758620) and Cnoc Parlain (47958471) - sequences 6 and 8 respectively (see Figure 2.3.2). Only the upper part of this Group is represented, and none of the flows seen can be correlated petrographically, or in the field, with any of those seen elsewhere. Sequence 8 has already been referred to (see Section 2.3.2.4), on account of the lack of basal marker horizon for the Glac an Dorchadais Group. The fact that the flows below the mudstone horizon selected as the base of that Group do not resemble those of this Group make this a problematical area. Perhaps, around here, there was a localised eruptive centre, whose effusions prevented the more extensive flows from covering this area.

2.3.2.6 Laig Group

The only complete example of this Group in western Eigg is seen in the gorge 600 metres east of Laig Farm (47308745) - see sequence 5, Figure 2.3.1. The Group is 20 metres thick, and overlies Cretaceous sediments (Hudson 1960). The basal flow is notable for its prominent columnar jointing. It, and the succeeding flow, are capped by thin red mudstone horizons, suggestive of slight explosive volcanicity at this time.

A columnar flow is known to form the bedrock in the area around Crois Bheag (48838528), and this must underlie the Grey rock of sequence 7 (see Figure 2.3.2). This is thought to be the same flow as that seen in the gorge east of Laig Farm (sequence 5).

At the west end of the crags of the Grey rock near Laig Farm (46618755), an olivine-and clinopyroxene-phyric flow outcrops below the Grey rock. This must belong to the Laig Group, and is petrographically similar to the top member of the Laig Group, as seen in the gorge 600 metres east of Laig Farm (sequence 5 - see Figure 2.3.1).

2.3.3 Northern Eigg

As defined in Chapter 1, this is the area north of the central lowland, the succession being excellently displayed in the cliffs behind Cleadale (48508925), the cliffs below Dunan Thalasgair (48059075), and along the inaccessible cliffs of the east coast of Eigg. Only two sequences (Nos. 1 and 2 - Figure 2.3.1) were established in this area. As has already been noted (see Section 2.3.1), the succession here is markedly different from that established in western Eigg. This necessitated the formation of different groups for this area. The basal marker horizon for the Gleann Charadail Group (the mugearitic Grey rock) outcrops in northern Eigg and is used as a marker horizon here also. This allowed some correlation of the two areas (see Section 2.3.4). No other distinctive flows were found during fieldwork, the succession being predominantly made up of olivine-phyric flows. Using petrographical criteria, however, subdivision of the succession was possible (see Table 2.3.2 for details). On account of the petrographical subdivision, extrapolation of the Groups from the known sequences to other areas (e.g. the east coast cliffs) proved very difficult. Geographical extent of the Groups (as shown on Figure 2.3.2) was achieved by reference to aerial photographs, photographs of the Cleadale and east coast cliffs (see Figures 2.3.3, 2.3.4 and 2.3.5). The total thickness of the lava succession in this area is just under 300 metres.

2.3.3.1 Upper Cleadale Group

The clifftops east of Cleadale (48508925) and the high ground (above c. 270 metres O.D.) of Beinn Bhuidhe (48908890) and An Cruchan (48608795) are the only areas where this Group outcrops (see Figure 2.3.2). The majority of the flows sampled in sequence 2 (see Figure 2.3.1) appeared to be olivine-phyric in the field, and it was only after petrographical examination that the two olivine-and clinopyroxene-phyric flows at the base of this Group were discovered. These, and the overlying olivine-phyric flows of the Group, are all basalts, judging from their petrography. Most of them were too altered to make chemical analysis of them worthwhile. The Group has a total thickness of 70 metres.

2.3.3.2 Middle Cleadale Group

Below the basalts of the Upper Cleadale Group, in the Cleadale cliffs (sequence 2 - Figure 2.3.1), there is a thick series (c. 130 metres) of predominantly olivine-phyric flows. At the base of these flows (the Middle Cleadale Group), there are two highly amygdaloidal flows, the upper aphyric of the two being the only non-olivine-phyric flow in the Group. Below the two amygdaloidal flows, there is a petrographically distinctive olivine and plagioclase-phyric flow. The Middle Cleadale Group is best defined as the flows lying above this distinctive flow.

This Group also outcrops in the cliffs below Dunan Thalasgair (48059075). The steepness of the cliffs, however, made access for sampling impossible. As a result of the petrographical nature of the base of this Group, this and the Lower Cleadale Group are mapped as one unit on Figure 2.3.2.

2.3.3.3 Lower Cleadale Group

This Group consists of a variety of flows, which outcrop below the olivine-phyric flows of the Middle Cleadale Group. The base of the Group is taken as the base of the easily mapped Grey rock. It was possible to sample the cliffs below Dunan Thalasgair at this stratigraphical level in addition to the cliffs east of Cleadale (sequences 1 and 2 - Figure 2.3.1).

Combining the succession of flows (sequence 2 - Figure 2.3.1) seen in the stream near A'Chuagach (47858811) and the ground to the southwest, as far as the small quarry at Bealach Clithe (47618777), this Group attains a maximum thickness of 50 metres. The Grey rock itself is 30 metres thick, its maximum anywhere on Eigg. Of the two flows above the Grey rock (a hawaiitic flow and an olivine- and plagioclase-phyric flow), only the upper olivine-and plagioclase-phyric one can be correlated with the members of this Group collected from the cliff below Dunan Thalasgair (see Figure 2.3.1 for details). The Group as a whole thins to 40 metres, with a dramatic thinning of the Grey rock (from 30 metres to 10 metres), from the Cleadale cliffs (sequence 2) northwards to the Dunan Thalasgair cliffs (sequence 1).

2.3.3.4 Basal Group

This Group is the direct equivalent of the Laig Group of western Eigg, consisting of the flows between the Tertiary/ Mesozoic unconformity and the base of the Grey rock. Below the cliffs of Dunan Thalasgair (48059075), the complete Group is just over 40 metres thick (see sequence 1 - Figure 2.3.1). Here a thin layer of dark, altered material is just accessible between the Jurassic sediments and the base of the Tertiary lavas. This material was palynologically analysed at Sheffield University; no spores were recovered, but it was proven to be more probably of a sedimentary than an igneous origin (R. Porter 1976 pers. comm.). The author believes that it is most probably a tuff, as there is no evidence for a water body (e.g. pillow lavas) in the earliest Tertiary lavas.

The flows comprising this Group, as seen below Dunan Thalasgair, are all basalts, but each contains different phenocryst assemblages (see sequence 1 - Figure 2.3.1 for details). The olivine-phyric flow is capped by 0.40 metres of red tuffaceous mudstone. This and the possible tuff at the base imply some slight explosive volcanicity at the time when these lavas were being extruded. Immediately below the Grey rock, at the top of the Basal Group, there is a brecciated flow. This is presumably a flow front, and is the only example of such seen on Eigg.

The flows below the Grey rock (and often the Grey rock itself) along the cliffs east of Cleadale are largely obscured by scree and slipped material (see Figure 2.3.2). In a small roadside quarry near Bealach Clithe (47618777), however, an olivine-phyric flow outcrops below the Grey rock (sequence 2). Petrographically, this can be correlated with the olivine-phyric flow of this Group found in the cliffs below Dunan Thalasgair (sequence 1) - see Figure 2.3.1 for details.

Along the east coast, this Group can be seen to be represented by two flows (see Figure 2.3.5), the lower of which shows prominent columnar jointing. This is most easily correlated with the flow seen at the base of the Laig Group of western Eigg (see Section 2.3.4 for further discussion).

2.3.4 Correlations between western and northern Eigg

On account of the extensive lateral variation noted in the Groups of both northern and western Eigg, the only possible means of correlating lies in the more persistent basal marker horizons. As had already been noted (Section 2.3.1), only the lowest basal marker (the Grey rock) is common to both areas. It follows therefore that the flows between this and the Mesozoic rocks (the Basal Group of northern Eigg and the Laig Group of western Eigg) are likely to be direct time equivalents. The only direct correlation between these two areas within these Groups is the columnar flow found at the base of the succession in the east coast cliffs, northern Eigg and the similar flow encountered above the Cretaceous sediments in the gorge 600 metres east of Laig Farm, and in the area around Crois Bheag (sequences 5 and 7 respectively), western Eigg. This flow must die out northwards as it is not seen in the series of flows seen below Dunan Thalasgair (sequence 1), and also westwards, as it is not seen in the Cleadale cliffs (sequence 2) - see Figure 2.3.1 for details.

In the Groups immediately above the Grey rock (Lower Cleadale Group of northern Eigg; Gleann Charadail Group of western Eigg), only one flow can be definitely said to occur in both areas. This is the petrographically distinctive olivine- and plagioclase-phyric flow, which forms the uppermost member of the Lower Cleadale Group. This flow is not found south of Gleann Charadail (see Figure 2.3.1 for details), and must therefore originate to the north.

Above this stratigraphical level, correlations become even more difficult, largely due to the very uniform series of olivine-phyric flows, which lack distinctive marker horizons, found at this stratigraphical horizon (e.g. the Middle Cleadale Group of sequence 2).

Three of the olivine-phyric flows of the Middle Cleadale Group of northern Eigg can be correlated petrographically with three flows of the Glac an Dorchadais Group, as that Group is seen north of Gleann Charadail, western Eigg (sequence 3) - see Figure 2.3.1 for details. As the olivine-phyric flows of the Glac an Dorchadais Group die out southeastwards, it would thus appear that they do indeed originate from the north or northwest, as suggested in Section 2.3.2.4.

The upper part of the Middle Cleadale Group and the Upper Cleadale Group of northern Eigg cannot be correlated with any of the flows of western Eigg, despite the fact that both successions contain outwardly similar olivine-phyric flows. No definite petrographical correlations could be made, and field correlations are impossible due to discontinuity of outcrop (see Figure 2.3.2). In all probability, the upper parts of the Middle Cleadale Group and the Upper Cleadale Group are time equivalents of the Brutach Dearg, Cnoc Creagach and possibly even the Cora-bheinn Groups. The difference in the maximum thicknesses of the lava piles in each area (430 metres for western Eigg; c. 300 metres for northern Eigg) implies that either the uppermost flows of western Eigg are indeed younger than those of northern Eigg, or that the thickness for one or other area is in error. The author is fairly confident of the accuracy of the thickness quoted for northern Eigg. That for western Eigg, however, is merely a maximum value achieved by adding together the maximum thicknesses achieved by the different Groups. As noted throughout, there is considerable lateral variation within the Groups, so that the quoted value is most probably an overestimate. Three hundred and forty metres (340 metres) (calculated from the thicknesses of the Groups in sequences 5, 6 and 10) is probably more realistic.

Thus, if the effusion rates for the two areas were roughly similar, then the two successions are approximately contemporaneous, possibly with the Cora-bheinn Group (the uppermost Group of western Eigg) being a little younger than anything seen in northern Eigg.

2.4 Canna Stratigraphy

2.4.1 Introduction

As was previously noted (Chapter 1), Canna can be divided into four areas on the basis of topography. They are treated as separate units for stratigraphical purposes. For each unit, the succession of lavas was determined by comparing samples and field observations from the various hillside or cliff sequences. Correlations were then made between the different area units using both field and laboratory observations. Throughout Canna the lavas are predominantly basaltic in nature. Rarely, they reach levels of 50% SiO_2 or over (e.g. the 'platey' basalt and the Eilean a' Bhaird valley-infill flow).

2.4.2 Eastern Canna

The lavas are virtually horizontal here, a dip of 1 degree being measured on the base of the 'platey' basalt of Beul Lama Sgorr (26800625). Faults, never throwing more than 10 m, follow most of the streams, but it proved relatively easy to correlate the sequences across them. Details of the sequences examined are given in Figure 2.4.1 and their locations are shown in Figure 2.4.2.

As a result of considerable lateral variation in the lava pile, each hillside sequence differs somewhat from those on either side of it. However, several flows are continuous across the whole area:- a 'platey' basalt near the top; a prominent plagioclase-phyric basalt; a columnar, aphyric basalt; and a flow with macroscopic glomerophyric plagioclase phenocrysts near the base of the succession. These were used to divide the succession into five groups, listed from top to base.-

(1) Beul Lama Sgorr Group;

(2) Upper Main Group,

(3) Middle Main Group,

(4) Lower Main Group;

(5) Basal Group.

Only the uppermost group is sufficiently uniform to allow designation of a type locality.

Each group is described below. The lateral extent of each group is shown on Figure 2.4.2.

2.4.2.1 Beul Lama Sgorr Group

This Group forms the top part of the lava pile and is defined as those flows lying above the base of the 'platey' basalt. This 'platey' basalt, which is 10 m to 15 m thick, is readily distinguishable in the field by a very prominent subhorizontal jointing and by a light coloured weathering. Locally it shows subhorizontal colour banding, which is parallelled by the long axes of flattened vesicles. In hand specimen, it is a light coloured, fine grained, aphyric basaltic rock. Chemically it is slightly differentiated (Chapter 10).

At the type locality, Beul Lama Sgorr (26800625), the 'platey' basalt is overlain by three plagioclase-phyric flows, 30 m in aggregate thickness. They are distinguishable from each other by grain size and abundance of plagioclase phenocrysts. The middle flow is distinctive by being fine grained with small (c.4 mm long) relatively rare phenocrysts. The other two are both coarser grained and have abundant phenocrysts.

In uppermost flow, the phenocrysts appear to exceed the matrix; the phenocrysts in the lowest flow present a distinctly less crowded appearance.

Considering the rest of Eastern Canna, this Group is seen in four other areas:-

1. On Carn a' Ghaill (26390646), the 'platey' basalt is overlain by three plagioclase-phyric basalts, which can be directly correlated with those of the type sequence.

2. Around Cnoc Mhor (25850577), exposures of 'platey' basalt occur below a flow with very abundant plagioclase phenocrysts - the equivalent of the lowest of the three plagioclase-phyric flows of the group.

3. On Blar Beinn Tighe (25570618), the 'platey' basalt forms the flat ground on the hill top.

4. In the vicinity of Beinn Tighe (25300622), isilated crags above the 'platey' basalt suggest two flows of fairly fine grained basalt, both very rich in plagioclase phenocrysts, above the 'platey' basalt in this area.

2.4.2.2 Upper Main Group

This Group is defined as the flows between the base of the 'platey' basalt and the base of the prominent plagioclase-phyric basalt. This latter flow forms rounded, massive crags, and is a fine grained basalt with abundant plagioclase phenocrysts. It is easily recognisable in the field and is distinctive in thin section. On average, the Group is 43 m thick having a maximum thickness of 50 m in the hillside below Carn a'Ghaill (26390646).

In the east, below Beul Lama Sgorr (26600580), the Group consists of the prominent plagioclase-phyric basalt, here with the plagioclase phenocrysts subhorizontally aligned. This is overlain by a series of four thin flows, each about 5 m thick. All four flows have rare plagioclase phenocrysts and, with the exception of the very fine grained lowest flow, they are fairly coarse grained. They directly underlie the 'platey' basalt. Two conglomeratic deposits are thought to occur in this sequence: one above the prominent plagioclase-phyric flow; the other between the upper two and lower two plagioclase-phyric flows. They are inferred from the presence of abundant small pebbles of basalt and red sandstone in rabbit holes in unexposed parts of the sequence.

West of Beul Lama Sgorr (26800625), on the hillside below Carn a' Ghaill (26100575), the series of thin plagioclase-phyric flows below the platey basalt is replaced by two flows (each 10 m thick) with similar petrographical characteristics to the thin flows of Beul Lama Sgorr. Continuing westwards, this is reduced to one such flow below Blar Beinn Tighe (25450595) and on the south side of Beinn Tighe (25330597). On the western slopes of Beinn Tighe (24900610), however, the platey basalt is underlain by two flows, both very rich in plagioclase phenocrysts. It is assumed that these two flows die out eastwards as the flow with rare plagioclase phenocrysts, found in a similar stratigraphical position on the south side of Beinn Tighe (25330697), dies out towards the west.

In all the hillside sequences, apart from Beul Lama Sgorr, the prominent plagioclase-phyric basalt is separated from the overlying plagioclase-phyric flows by aphyric flows. On the western slopes of

Beinn Tighe (24650641), there is one 10 m thick flow, with prominent subhorizontal jointing. In thin section, it gives the appearance of being slightly differentiated (the plagioclase composition is around An_{20}-oligoclase). To the east on the southern slopes of Beinn Tighe (25310592) and below Blar Beinn Tighe (25500590), this horizon thickens to approximately 20 m of thin, rather altered flows, which are petrographically similar to the flow seen at the same stratigraphical horizon to the west. On the hillsides below Cnoc Mhor (25850565) and Carn a' Ghaill (26270572), this part of the sequence is not exposed, but it seems reasonable that it should be similar to that seen further west. On Carn a' Ghaill (26270572), there are pebbles of basalt and red sandstone in rabbit holes at this stratigraphical horizon. As on the slopes of Beul Lama Sgorr, this is taken to imply conglomeratic deposits (presumably interdigitating with thin flows) at this stratigraphical horizon.

2.4.2.3 Middle Main Group

This Group, which directly underlies the Upper Main Group, has, as its base, a fairly coarse grained, aphyric flow, with prominent columnar jointing. The Group reaches a maximum thickness of 70 m on the western slopes of Beinn Tighe (25500550) (excluding the exposures on Cnoc Bhrostan (27350590) and Compass Hill (28000610), where the top part of the Group is missing).

The lowest flow of the Group - the columnar, aphyric basalt - can be traced across the whole of Eastern Canna. It increases in thickness from 30 m at Earnagream (24050632) to a maximum of 39 m below Cnoc Mhor (25800533), where the base is seen to undulate quite markedly, reflecting an erosional surface, onto which the flow was extruded. Eastwards it thins progressively to a minimum of 10 m in the cliffs east of Compass Hill (28070598).

In the west, in the cliffs of Earnagream (24050632), the columnar flow at the base is overlain by 28 m of aphyric basalt. It is impossible to say how many flows this represents, due to the isolated nature of the crags in which it outcrops. Eastwards, on the southern slopes of Beinn Tighe (24700560), a similar sequence is seen, but with 6 m of basalt, with abundant plagioclase phenocrysts, outcropping between the columnar flow and the isolated crags of aphyric basalt. On the slopes below Beinn Tighe (25640560), 9 m of coarse, aphyric basalt occurs between the plagioclase-phyric basalt and the basal flow. This presumably thins westwards as it is not found south of Beinn Tighe (24700560). Above the plagioclase-phyric basalt in the Blar Beinn Tighe sequence, there is 12 m of unexposed ground to the base of the Upper Main Group. This is presumably a continuation of the coarse, aphyric basalt seen further west. South of Cnoc Mhor (25770558), only 8 m of plagioclase-phyric basalt, similar to that seen to the west, are exposed between the columnar, aphyric basalt and the Upper Main Group.

On the hillside below Beul Lama Sgorr (26600560), the basal flow is overlain by three flows with rare plagioclase phenocrysts. These have an aggregate thickness of 36 m. The two upper flows are thought to be separated by a thin band of conglomerate, inferred from the occurrence of numerous pebbles of red sandstone and basalt below crags of the uppermost flow (26960598). None of these flows can be correlated with the plagioclase-phyric flows seen in the sequence further west; the latter have flows with abundant plagioclase phenocrysts, rather than those with rare phenocrysts seen below Beul Lama Sgorr (26900598).

It is presumed that the sequence of predominantly aphyric basalts seen to the west interdigitates with this sequence.

The outcrops below Carn a'Ghaill (26400550) are rather confused and do not readily correlate. The fault, which follows the Allt Lag a'Ghriumadeal may be the cause of this confusion, but it may also reflect the interdigitation of the different sequences seen east and west of Carn a'Ghaill. Here, there is no equivalent of the columnar, aphyric basalt taken as the base of this group. This sequence is described with those of the Lower Main Group (Section 2.4.2.4).

Both Cnoc Bhrostan (27350590) and Compass Hill (28000610) are capped by a flow with rare plagioclase phenocrysts, which can be correlated with the lowest such flow of the Beul Lama Sgorr sequence (26690572). In both cases, however, the flow is thicker (25 m on Cnoc Bhrostan and 30 m on Compass Hill) than on Beul Lama Sgorr (17 m). In the cliffs east of Compass Hill (28030618), the plagioclase-phyric flow is underlain by 10 m of stratified, fairly fine grained conglomerate. Being inaccessible in the cliffs, a continuation of it was found and sampled in the bed of the Allt Thaligaridh (27690610). Pebbles found include abundant basalts of various kinds, green and red sandstone (probably Torridian), gabbro, porphyritic felsite, granophyre and quartz porphyry. These are further discussed in Chapter 8. The conglomerate is underlain by 10 m of columnar, aphyric basalt, assumed to be the eastward continuation of the basal flow of this Group. A similar flow is found 10 m below the plagioclase-phyric flow on Cnoc Bhrostan (27300572) and the unexposed 10 m is presumed to be the westward continuation of the conglomerate seen in the cliffs below Compass Hill (28040618).

2.4.2.4 Lower Main Group

This Group forms the lowest parts of the hillside sequence, usually up to a height of about 50 m above sea level. It includes the flows below the Middle Main Group and above the base of the glomerophyric basalt. This basal flow is a fairly fine grained basalt with stellate aggregates of plagioclase phenocrysts. Each aggregate is about 4 cm in diameter and there is usually one glomerophyric group every square metre. They can be easily seen on weathered surfaces.

The full sequence is only seen on the hillside below Cnoc Bhrostan (around Tighard - 27230564). Here it is 43 m in thickness. Elsewhere all, or most, of the glomerophyric basalt is missing. Despite this, the maximum thickness of 50 m is recorded on the hillside below Beul Lama Sgorr (26600540) and on the southern slopes of Beinn Tighe (24700550).

Below Cnoc Bhrostan (27230564), the glomerophyric basalt is overlain by 10 m of aphyric basalt, above which there are 10 m of unexposed ground to the base of the Middle Main Group. In the cliffs below Compass Hill (28080597), a similar flow, 7 m thick, is overlain by 25 m of thin flows and conglomeratic sediments. These are presumed to continue westwards and to occur in the unexposed part of the Cnoc Bhrostan sequence.

The lower part of this Group at Compass Hill (28080597) consists of 57 m of very coarse grained conglomerates and breccias, containing fragments of various types of basalt, with less abundant red sandstone and minor amounts of metamorphic rocks and a porphyritic felsite. The conglomerates are described fully and the provenance of the fragments found in them established in Chapter 8. No glomerophyric basalt is found here and it is presumed that the deposition of the conglomerates and breccias was contemporaneous with the extrusion of the glomerophyric basalt.

Westwards, on Rubha Dubh (26500509), at the base of the Beul Lama Sgorr sequence, the glomerophyric basalt is exposed. Its base is not seen and, between it and the base of the Middle Main Group, three flows, with abundant plagioclase phenocrysts and a total thickness of 39 m, are exposed. The only possible correlation with the exposures to the east is with some of the inaccessible flows intercalated with the conglomeratic sediments seen below the columnar flow of the Compass Hill cliffs (28080597). The uppermost flow of this Group in the Beul Lama Sgorr sequence shows reddening at the top, which implies a time interval before the extrusion of the overlying columnar flow (the basal flow of the Middle Main Group). A similar cessation of extrusive activity at this time is implied by the conglomeratic deposits of Compass Hill (28080597) and by the undulating topography below the base of the columnar flow in the Cnoc Mhor sequence (25800533) - see Section 2.4.2.3.

To the west, the sequences below Cnoc Mhor (25850525), Blar Beinn Tighe (25400535), and south of Beinn Tighe (24700550) are all similar. The base of the sequence consists of the glomerophyric basalt (5 m thick below Cnoc Mhor), overlain by a breccia (over 8 m thick south of Beinn Tighe). It is thought that the breccia is part of the glomerophyric basalt and that south of Beinn Tighe it probably represents all that remains of that flow (a flow front, in fact). It is overlain by a flow with rare plagioclase phenocrysts and a maximum thickness of 15 m below Blar Beinn Tighe. This is overlain by a series of thin aphyric flows, 37 m thick, south of Beinn Tighe and 40 m thick below Blar

Beinn Tighe. South of Cnoc Mhor, this part of the sequence (25 m thick) is unexposed, but it is thought that it is a thinner equivalent of the series of thin flows.

To the north, the sequence seen on the foreshore of Camas Thairbearnais (23700620) and in the cliffs of Earnagream (23930628) differs from that described above only by having an 11 m thick, columnar, aphyric basalt above the series of thin flows and by having a second flow with rare plagioclase phenocrysts (over 5 m thick) at the base of the exposed sequence. The series of thin aphyric flows is much thinner here (9 m as opposed to 37 m south of Beinn Tighe). No glomerophyric basalt is seen.

On the western side of Rubha Langanes (23900680), the sequence is essentially the same as that of Camas Thairbearnais/Earnagream, except that a plagioclase-phyric basalt, below the thinner columnar flow of Earnagream is seen to die out southwards towards Earnagream. Also the thin flows, below the thinner columnar flow, are replaced by a series of bedded tuffaceous sediments, with lenses of coal and a conglomeratic base. The top of the underlying plagioclase-phyric basalt is seen below high-water-mark at the base of the headland.

In summary then, Eastern Canna shows two distinct series of flows in this Group in the west (Cnoc Mhor, Blar Beinn Tighe, West Beinn Tighe and Rubha Langanes sequences), there are either one or two flows with rare plagioclase phenocrysts above the glomerophyric flow, succeeded by a series of thin aphyric flows; in the east (Beul Lama Sgorr, Cnoc Bhrostan and Compass Hill sequences), the glomerophyric basalt is overlain by up to three plagioclase-phyric flows, with or without intercalated conglomeratic sediments. In the field, it was not possible to correlate any of these flows (except the glomerophyric flow). Petrographically also they are dissimilar.

The rather confused exposures at this stratigraphical level below Carn a' Ghaill (26260545) may well hold the key to this problem. There is no equivalent of the columnar flow taken as the base of the Middle Main Group. The three lowest flows seen are columnar with abundant plagioclase phenocrysts. They closely resemble the three flows overlying the glomerophyric flow, as seen to the east. Above this there is a series of thin plagioclase-phyric flows, which may be thin equivalents of the plagioclase-phyric flows of the Middle Main Group, as seen to the east. Alternatively, one of them could be the lateral equivalent of the plagioclase-phyric flow overlying the breccia seen below Cnoc Mhor. The 20 m thick plagioclase-phyric flow seen above the series of thin flows of the Carn a' Ghaill sequence has been correlated with the plagioclase-phyric flow of the Middle Main Group of Cnoc Mhor (25770558). This is overlain by the prominent plagioclase-phyric flow, which forms the base of the Upper Main Group.

2.4.2.5 Basal Group

This Group includes all the flows below the glomerophyric basalt. It is only exposed on the hillside and foreshore below Cnoc Bhrostan (27200530), where it is 43 m thick, and on the islands of Canna harbour, where the lowest part of the Group is seen. The exposures in Canna harbour are considered separately (Section 2.4.4).

Below the glomerophyric basalt of the Cnoc Bhrostan sequence (27580567), there are isolated exposures of vesicular basalt. In the gully of the Allt Thaligaridh (27720585), vesicular basalt is seen to be underlain by a conglomerate, with predominately basalt and some red sandstone pebbles. This presumably continues westwards represented by the unexposed ground north of the Square (27030528), where it is underlain by a columnar, very fine grained, aphyric basalt. Below this, the sequence is seen a few metres east of the Square (27130522) - a fine grained, aphyric basalt with a spheroidally weathered base, overlying a series of conglomerates and tuffs. This sequence is shown diagrammatically in Figure 2.4.3. It can be correlated with the exposures in Canna harbour and hence with Sanday island (Section 2.4.4).

2.4.3 Sanday

Sanday can be divided into four fault blocks - as shown in Figure 2.4.2. The sequences collected were assigned to one of these fault blocks. Lateral variations between sequences, even within the same fault blocks, are marked. Several flows are seen to die out in the field (e.g. a plagioclase-phyric basalt dies out north westwards along the coast from Camas Stianabhaig - 28350437), or to thin to virtually nothing (e.g. the clinopyroxene-rich flow of Creag Ard (26300455), which thins from 10 m at Creag Ard to 1.5 m further south). It was, therefore, assumed that the other flows behaved in a similar manner, thus complicating correlations, particularly across faults. In many cases, especially in the main part of Sanday, where all the flows are plagioclase-phyric, flows could not be individually identified in the field. Thus petrographical evidence was combined with field observations to provide the correlations given below.

Each fault block is now considered separately, and its correlations with the other blocks determined.

2.4.3.1 Tallabric Block

This is the area south west of the Traigh Bhan fault. The limits of the area and the sequences examined therein are shown in Figure 2.4.4.

In the cliffs of south Tallabric (26450450), the sequence reaches a maximum thickness of almost 60 m. The upper two flows of this sequence are both massive, sensibly aphyric in the field and separated by two flows of amygdaloidal basalt, 3 m in total thickness, and distinguished by the lower one having a thin (0.05 m) red horizon at the top.

In thin section, the upper flow is seen to carry microphenocrysts of olivine, the lower one to be aphyric. Below, there is 10 m of amygdaloidal basalt, with 2 m thick pods of massive, apparently aphyric basalt. They are seen to carry olivine, and plagioclase microphenocrysts in thin section. A markedly columnar flow separates this from another 10 m of amygdaloidal basalt, this time without massive pods. The columnar flow is aphyric in hand specimen, but reveals microphenocrysts of olivine and clinopyroxene set in a matrix, which shows grain size layering, when it is examined microscopically. When traced eastwards, it terminates abruptly, with radiating columns, in amygdaloidal basalt. The basal 15 m, below the lower amygdaloidal basalt, consists of 3 m of tuffs and sediments, underlain by scoriaceous lavas, lava breccias, and patches of conglomerate. The lava breccias are thought to be the broken up top of a flow, complicated by the conglomerates, which are probably the result of fluvial action (Chapter 8). The conglomerate contains pebbles of basalt, red laterite, and red sandstone, all about 10 cm across.

The sequence seen to the north (26460430) is similar - essentially aphyric flows interbedded with amygdaloidal basalts, conglomerates and sediments. The correlations are shown in Figure 2.4.4. The main point of note is the lack of petrographical similarity between the lower of the two uppermost flows of each sequence. That seen here has both plagioclase and olivine phenocrysts and grain size layering (when seen in thin section), while the flow from south Tallabric is aphyric and unlayered.

When the columnar flow with microphenocrysts of olivine and clinopyroxene is traced northwards, it is found to increase from 2 m to 10 m in thickness around Creag Ard (26300455). The clinopyroxene phenocrysts here have subophitic margins - these are discussed in Chapter 3. Flow banding is prominent, being mainly horizontal, but with some contortions in the upper part of the flow. The banding is due to variation in grain size and clinopyroxene content. Coarse grained, clinopyroxene-rich layers become more fine grained upwards, whereupon they are sharply overlain by the next coarse layer. The layers vary from 3 cm to 10 cm in thickness. The origin of such banding is discussed in Chapter 3.

On the south coast of Traigh Bhan (26580473), a fine grained aphyric basalt, of unknown thickness, is exposed. Petrographically, it shows similar grain size banding as the clinopyroxene phyric basalt of Creag Ard, but with smaller clinopyroxenes. It is thought to be a northward continuation of this flow.

East of the fault at the east end of the Tallabric cliffs (26800410), two aphyric flows (each 3 m in thickness) are underlain by 2 - 5 m of columnar plagioclase-phyric basalt. This lies on an irregular surface of sediments, conglomerates, ash, thin coals and scoriaceous lava (see sketch in Figure 2.4.5). Further east (26850410), this flow thickens to a maximum thickness of 15 m and a second plagioclase-phyric flow appears below it, on the wave-cut platform. Petrographically, the two flows are similar, having abundant plagioclase and fairly abundant olivine phenocrysts. Between the two flows, there are a series of ash bands, carbonaceous shales, and lenses, overlain by a conglomerate containing basalt and red sandstone pebbles up to 40 cm in diameter. A thin red tuffaceous horizon occurs at the top of the conglomerate. A similar conglomerate overlies the upper flow and is seen to die out to the east. The top of the sequence here is amygdaloidal basalt.

The aphyric flows of the Tallabric sequence are not seen anywhere else on Sanday. They appear to thin to virtually nothing northwards (Section 2.4.4), and are thus probably not represented in Eastern Canna either.

2.4.3.2 Eastern Block

This is the area east of the Camas Stianabhaig fault (see Figure 2.4.2), which downthrows about 30 m to the east. Thus this area has the uppermost flows of the Sanday sequence excluding the Tallabric sequence, which is known to overlie plagioclase-phyric basalts (Section 2.4.3.1). A small fault south of Rubha Camas Stianabhaig (28800470) causes the sequence of the headland to be upthrown by approximately 4 m relative to the rest of the block. The sequence examined and the correlations made are shown in Figure 2.4.6. The succession may be summarised as shown in Table 2.4.1.

The three uppermost flows (flows 4 - 6) are all very similar in the field, being rich in plagioclase and having rare large plagioclase phenocrysts. Mostly they are crudely columnar. Petrographically, they are very similar and it is possible that they form one 30 m thick flow rather than three flows. No flow tops are seen but the presence of terracing suggests the subdivision into three flows. Flow 3, the aphyric basalt with inclusions, is very different from the rest of the sequence, and is only seen in this area (28770390). Flow 2 of this sequence is petrographically distinct; it has abundant plagioclase phenocrysts. The plagioclases are clearly visible and abundant, when the rock is examined in the field. It serves as a correlation with the fault block to the west (Section 2.4.3.3).

The conglomerates of the foreshore of the Uamh Ruadh area (29220419) are inaccessible. From the cliff top, large pebbles (estimated at 40 cm across) of red sandstone and basalt are seen. Towards Rubha Camas Stianabhaig (28930429), finer grained sediments are seen to replace the conglomerates. It may be that the conglomerates seen further south are overlain by such sediments and that a northerly component of dip has taken the conglomerates below sea level. On Rubha Camas Stianabhaig (28770437), fine grained sediments with coal lenses are seen at the same stratigraphical horizon as the conglomerates. The flow below the conglomerates (flow 1) is similar to flows 4 - 6, except that it is somewhat coarser grained.

2.4.3.3 East Central Block

This is the area bounded by the Camas Stianabhaig fault to the east and the Rubha nam Feannag fault to the west (see Figure 2.4.2). As a result of the easterly downthrow of the Camas Stianabhaig fault, the sequence here correlates with the lower part of the Eastern Block sequence (Section 2.4.3.2) and continues it downwards. An east-west trending fault on the west side of Camas Stianabhaig (26450425) throws the sequence down by about 2.5 m to the north. The sequences established are shown in Figure 2.4.7 and the succession is summarised in Table 2.4.2.

The upper part of the sequence, flows 4 - 6, is directly comparable with the lower part of the Eastern Block sequence, but flow 3 (the aphyric flow) of the Eastern Block is missing, presumably having died out westwards. Flow 5 of this block is petrographically identical with flow 2 of the Eastern Block - both have extremely abundant plagioclase and olivine phenocrysts. Flow 4 closely resembles flow 1 of the Eastern Block. It is characterised by having lath-shaped plagioclase phenocrysts, which show a gradation in size from 2 mm in length down to the size of the matrix plagioclases (0.1 mm).

The lower part of the succession (flow 3 and below) is below sea level in the Eastern Block. This part consists of two flows separated by 3 m of conglomerate. The upper of the two flows is inaccessible, the lower is seemingly aphyric in the field, but shows olivine and plagioclase phenocrysts in thin section. It is underlain by another conglomerate, with basalt and red sandstone pebbles, as seen at the base of Dun Mor (28730375). At the east end of Creag nam Faoileann (28780385), there is a similar deposit, but here it is overlain by carbonaceous shales. The lowest flow is unsampled, only the altered top of it being exposed at low tide below Dun Mor and Dun Beag. The conglomerates of this area are discussed separately in Chapter 8.

2.4.3.4 West Central Block

This block separates the Tallabric Block from the East Central Block. It is bounded in the west by the Traigh Bhan fault and the Rubha nam Feannag fault in the east (see Figure 2.4.2). The Rubha nam Feannag fault downthrows by approximately 20 m to the west and thus the sequence seen here correlates with the top part of the East Central Block sequence. A fault, within the block, running north-west- southwest across Sanday at the west end of Creag Liath (27390456) downthrows about 10 m to the west. The sequences established are shown in Figure 2.4.8.

The highest ground is the crags of Creag Liath (27400460). It is formed of basalt with abundant small plagioclase phenocrysts and fairly abundant olivine phenocrysts. Petrographically, it can be correlated with flow 6 of the East Central Block (Section 2.4.3.3). Continuing northwards from Creag Liath, this flow is underlain by 5 m of unexposed ground and this is underlain by a seemingly aphyric basalt. In thin section, this is seen to contain abundant plagioclase and less abundant olivine phenocrysts. This flow has insufficient phenocrysts to correlate with flow 5 of the Eastern Block, but it could be a finer grained variant of flow 4 of that Block. Below, on the foreshore, a conglomerate is exposed. It contains pebbles of red sandstone and basalt.

The flow seen at Creag Liath (27400460) is petrographically identical to that forming the south-facing crag seen 400 m north of Cnoc Ghreannabric (26990423). This is underlain by 0.50 m of fine grained, brownish sediment, with a basal conglomerate containing pebbles of basalt, red feldspathic sandstone, a porphyritic felsite and a granophyre (see Chapter 8). The underlying aphyric flow, seen along the north coast, is missing here. Presumably it dies out southwards.

Below the conglomerate, on the foreshore, southwards to Cnoc Gheannabric (27500405), at least four thin, plagioclase-phyric flows, with irregular, rubbly tops and bases, are exposed. Conglomeratic patches, infilling channels in the irregular tops of the flows, occur locally (e.g. south-west of Cnoc Ghreannabric, 26300390). Below Cnoc Ghreannabric (27470390), 10 m of plagioclase-phyric basalt, with crude columnar jointing throughout the basaltic xenoliths at the base, is overlain by another channel-fill conglomerate (sketched in Figure 2.4.9). It is not known which flow this correlates with. The four, thin overlying flows could represent flows thinning from the west (unexposed from below Tallabric), or flows 1 - 4 of the East Central Block thinning from the east.

When the sequence is traced westwards, along the north coast, little change is seen. The conglomerates on the headland north-west of Cnoc Tionail (26980465) contains some tuffaceous bands. On the headland of Am Mialagan (26760487), however, the conglomerates are replaced by fine grained, brownish sediments and amygdaloidal basalts, with some conglomerate lenses. A sample from the amygdaloidal basalts shows similar, if altered, petrographical features as the clino-pyroxene-phyric basalt of the Tallabric Block (Section 2.4.3.1). It is assumed that this represents an interdigitation of the clino-pyroxene-phyric basalt from Tallabric with the sediments of the main Sanday sequence. Thus the Tallabric sequence must be a time equivalent of part of the plagioclase-phyric sequence of the rest of Sanday.

The crags of Am Mialagan (26760487) consist of glomerophyric basalt, identical to that seen at the base of the Lower Main Group of Eastern Canna (Section 2.4.2.4). The glomerophyric basalt must die out eastwards and southwards, as it is not seen anywhere else on Sanday. This implies that the Sanday sequences correlate with the Basal Group of Eastern Canna and probably also with the lower part of the Lower Main Group of Eastern Canna. This is further discussed in the section dealing with Canna harbour (Section 2.4.4.5).

2.4.3.5 Sanday Succession - Conclusions

The Sanday sequences are summarised in Figure 2.4.10, which shows the known correlations. Each sequence is generalised to some extent and in some instances two or more sequences are combined together to show the full sequence.

The upper of the two plagioclase-phyric flows at the base of the sequence of east Tallabric is petrographically similar to flow 2 of the West Central Block sequence. The lower flow cannot be so easily correlated. If the hypothesis that the four thin plagioclase-phyric flows of the West Central Block are the equivalent of the flows 2 - 5 of the East Central Block is correct, then these flows may well die out before east Tallabric is reached. Thus the lower plagioclase-phyric flow of east Tallabric may be one of the oldest flows on Sanday. This implies a time gap between the upper and lower plagioclase-phyric flows of east Tallabric and this is compatible with the irregular topography, over which the upper flow was extruded (*see* Figure 2.4.5).

Evidence from the north coast suggests that at least two flows die out. One (flow 3 of the East Central Block) is seen to die out along the coast north-west from Camas Stianabhaig (28400435). Flow 1 of the East Central Block most closely resembles flow 4 of the West Central Block, implying that flow 5 of the West Central Block has died out westwards.

In conclusion, therefore, it appears that the plagioclase-phyric basalts die out westwards, presumably having a source to the east. The flows of Tallabric, however, seem mainly to die out eastwards, suggesting an origin to the west. This suggests two sources for the lavas on Canna, one to the east the other to the west of Sanday. There is probably some degree of time equivalence between the two sets of flows, but direct equivalents cannot always be determined.

2.4.4 Canna Harbour

The exposures discussed in this section include those seen on Iolann an Eilean (26920496), Eilean a'Bhaird (27000500), Eilean Ghille Mhartein (26800508), and along the southern foreshore of Canna as far west as Rubha Dubh (26500509). A large scale map of the area is included (Figure 2.4.11) and the sequences established are shown in Figure 2.4.12.

2.4.4.1 Iolann an Eilean

Two fine grained, apparently aphyric flows are exposed here (26900497), separated by 0.30 m of ashy tuff, containing small, rounded, polished, basaltic pebbles. In thin section, the upper flow is seen to carry rare olivine phenocrysts (usually pseudomorphed). The prominent flow-banding, visible in the field, is due to alterations of fine and coarse grained layers. The clinopyroxenes occur as large plates with sub-ophitic margins, and this, coupled with the grain size layering, suggests a correlation with the flow seen below the glomerophyric basalt of Am Mialagan, Sanday (26760487), and hence with the layered clinopyroxene-phyric basalt of the Tallabric block, Sanday (Section 2.4.3.1). The base of the flow is spheroidally weathered and shows elongate lenses (0.5 to 1 cm in thickness) of massive, vesicular basalt in a highly altered basaltic matrix. The very fine grained lower flow is not flow-banded and, in thin section, is seen to be aphyric. No stratigraphical equivalent is known on Canna or Sanday.

2.4.4.2 Eilean a'Bhaird

On the south-west side of this island (27000497), two fine grained, aphyric flows, each underlain by thin conglomerates, are exposed. The conglomerates are similar to those seen on Iolann an Eilean (26900497), containing rounded, basalt pebbles. The lower flow is markedly flow-banded, and is correlated with the upper flow of Iolann an Eilean. The upper flow is also flow-banded and shows rare, rounded olivine phenocrysts in thin section. It is presumed to overlie the flows seen on Iolann and Eilean.

The rest of Eilean a' Bhaird is formed of a single sensibly aphyric flow, which has a maximum thickness of 10 m at the east end of the island (27090502). In thin section, it is seen to have plagioclase phenocrysts, with rare opaque-oxide and clinopyroxene microphenocrysts. The lower two-thirds of the flow are columnar, while the top part is characterised by horizontal jointing. The relationship of this flow to the flows of south-west Eilean a' Bhaird is seen at the east end of the island (27090502), as sketched in Figure 2.4.13. The flow steeply cuts off the other two flows, as if infilling a hollow At the base of the hollow there is a conglomerate of predominantly basaltic pebbles. Vesicular and amygdaloidal basalts predominate. Some can be likened to bombs, having very vesicular cores and fine grained margins. Others resemble the broken-up crust of a lava flow. Some small, well-worn pebbles of red sandstone occur also, in the matrix of fine grained, basaltic material. The presence of the conglomerate suggests water action, perhaps the hollow is the cross-section of an old river valley. This is consistent with the glassy base of the overlying flow (which implies rapid cooling) and with the pipe amygdales. In addition to the pipe amygdales, there are vesicles, which are elongated and parallel to each other and to the base of the flow. Some of these vesicles are infilled, mainly with agate. Within about 1 m of the base of the flow, several basaltic xenoliths are enclosed by the flow. They average about 0.20 m across. Angular, rounded and plastic shaped ones are found. They could have originated in the underlying conglomerate. The plastically shaped ones could possibly represent bombs which landed in the conglomerate during its formation.

On the north side of Eilean a' Bhaird, the flow, which infills the hollow, can be seen to thin westwards (see Figure 2.4.14). The columnar part of the flow thins to about 1 m east of the little bay (27030508). Several small faults occur along the coast but their combined effect is very slight. West of the bay (27030508), the flow shows only horizontal jointing and is about 2 m thick.

2.4.4.3 Eilean Ghille Mhairtein

Conglomerate, with boulders of red sandstone and basalt (averaging about 0.30 m across) covers most of the island. It is thought to be a westward continuation of the conglomerate which is seen in the bottom of the hollow on Eilean a' Bhaird (27090502). In the north-east corner of the island (26820509), however, there is a small outcrop of brecciated, very fine grained basalt. It can be easily distinguished from the conglomerate by the angular nature of the fragments and the lack of red sandstone pebbles. Petrographically, the fragments resemble the flow infilling the hollow on Eilean a' Bhaird. It is assumed to be the brecciated equivalent of this flow, perhaps part of the flow front. Thus the Eilean a' Bhaird flow must continue to thin westwards, as first seen along the north coast of Eilean a' Bhaird (Section 2.4.4.2), and to die out near Eilean Ghille Mhairtein. This implies that the flow has a source to the east.

2.4.4.4 Southern Foreshore of Canna

One hundred and fifty metres west of Rubha na Cor (26850518), a fine grained aphyric flow is exposed on the foreshore. Locally, it is vesicular and shows 'swirling' flow-banding features. In thin section, it can be seen to be extremely fine grained with some layering due to different (but still very fine) grain sizes. It carries plagioclase, clinopyroxene and rounded opaque oxide phenocrysts. Five different types of rounded xenoliths were seen:-

1. Very coarse grained basalt, with altered olivines and granular clinopyroxene.

2. Plagioclase-rich, aphyric basalt.
3. Fine grained, plagioclase-rich basalt, with ophitic clinopyroxene.
4. As (3) but coarser grained.
5. Very fine grained, plagioclase-phyric basalt.

Petrographically, the flow as a whole is very similar to the Eilean a' Bhaird infill flow. Here, however, its relationship with the surrounding conglomerates are not exposed.

Rubha na Cor (27000515) consists of an essentially aphyric flow. In thin section, it shows layering due to different grain size, and rare, green pseudomorphed, olivine phenocrysts. Most of the clinopyroxenes are ophitic, but one small area, in which they occur in large plates with subophitic margins was seen. This identifies it with the upper flow on Iolann an Eilean (26900497) and the lower flow of south-west Eilean a' Bhaird (27000497).

Further east, by the disused chapel (27130522), the basal part of the Cnoc Bhrostan sequence of Eastern Canna (Section 2.4.2.5) is seen. The fine grained, aphyric flow, which occurs above the series of conglomerates and tuffs, is petrographically similar to the flow seen on the foreshore at Rubha na Cor (27000515). The significance of this is discussed below (Section 2.4.4.5).

To the east, conglomerates outcrop along the southern foreshore of Canna as far as the pier (27800506). Essentially they are the same as those already described, the only variation being in the size of the pebbles. Locally, and usually near the top, the conglomerates are seen to be interbedded with finer grained sediments. On the foreshore below Canna House (27420540), conglomerates can be seen to overlie bedded sediments with plant remains. Here, however, both are cut off by an aphyric basalt, as shown in Figure 2.4.15. A few metres to the west (2738033) another lava flow (this one, plagioclase-phyric) is seen to underlie conglomerate. These exposures imply contemporaneous volcanic and fluvial activity.

2.4.4.5 Correlations between Canna, Canna Harbour and Sanday

From the field evidence, the only definite means of correlation is the glomerophyric basalt, which occurs on Am Mialagan, north-west Sanday (26760487), and which forms the base of the Lower Main Group of Eastern Canna, with outcrops on Rubha Dubh (26500509) and in the crags below Tighard (27220559). The conglomeratic deposits on the north coast of Sanday, and below the glomerophyric basalt of Am Mialagan (26760487) are thought to be equivalent to those on the south coast of Canna.

Petrographical comparisons of samples has allowed correlation of the middle flow of the Canna Harbour sequence (the upper flow of Iolann and Eilean (26900492), the lower flow of Eilean a' Bhaird (27000497) and the flow exposed on Rubha Dubh (27000515), on the southern foreshore of Eastern Canna, with the flow above the conglomerates in the Cnoc Bhrostan Basal Group (Section 2.4.2.5) - hence correlating Canna Harbour with Eastern Canna. It can also be correlated with the flow seen below the glomerophyric basalt of Am Mialagan (26760487), north-west Sanday, and this flow has already been correlated with the clinopyroxene-phyric basalt of Tallabric (Section 2.4.3.4). Thus the clinopyroxene-phyric basalt forms a marker, traceable from the southern cliffs of Tallabric (26450450), through its maximum development at

Creag Ard (26300455) to Am Mialagan (26760487) and the islands of Canna Harbour, to the lower part of the Basal Group of the Cnoc Bhrostan sequence, Eastern Canna (27130522).

The fact that the glomerophyric basalt of Am Mialagan (26760487) overlies a continuation of the clinopyroxene-phyric basalt of the Tallabric sequences and that the glomerophyric basalt itself is not represented in the Tallabric sequence, presupposes that the upper part of the Tallabric sequence (above the clinopyroxene-phyric basalt) thins northwards and the glomerophyric basalt dies out southwards along the west coast of Sanday. The situation is probably similar with regard to the relationship between the glomerophyric flow and the plagioclase-phyric flows of the eastern and central parts of Sanday, with the conglomerates on the northern foreshore as a linking horizon.

The flows of Canna Harbour (perhaps excluding the valley-infill flow of Eilean a' Bhaird - <u>see</u> Section 2.4.4.6) therefore, are contemporaneous with some of the plagioclase phyric flows of eastern and central parts of Sanday, and with some of the Tallabric sequence. One flow (the middle flow of the Canna Harbour sequence) can be correlated with a flow of the Basal Group of Cnoc Bhrostan, Eastern Canna. This implies that the Canna Harbour sequence forms part of the Basal Group of Eastern Canna.

2.4.4.6 Note on the Age of the Eilean a' Bhaird Valley-Infill Flow

From the evidence of the exposures at the east end of Eilean a' Bhaird (27090502), the valley infill flow must postdate the clinopyroxene-phyric basalt and one flow above it. No other exposures reveal contacts with any known stratigraphical horizon. The flow is seen to die out westwards (on Eilean Ghille Mhairtein (26820509) - Section 2.4.4.3), so that its relationship with the glomerophyric basalt, exposed on the east side of Rubha Dubh (26650520), is not seen.

There are two possible interpretations:- that the Eilean a' Bhaird flow predates the glomerophyric flow (as shown in Figure 2.4.12), occurring between it and the clinopyroxene-phyric basalt, and hence being part of the Basal Group of Eastern Canna; or that it represents a much later episode in the volcanic history of Canna, postdating most of the lavas of Canna.

For the first hypothesis to be true, all that is required is penecontemporaneous erosion of the Canna landscape during the time when the Basal Group lavas were being extruded. That such erosion occurred at this time is amply shown by the intercalated lavas and conglomerates seen in many parts of Sanday and also in the exposures below Compass Hill (28080597). The conglomerate, which fills the bottom of the valley now occupied by the Eilean a' Bhaird valley infill flow, is very similar to the other conglomerates of this area (containing pebbles of basalt and red sandstone). This hypothesis requires only a relatively small amount of vertical erosion (about 10 m).

The alternative hypothesis - that the valley-infill flow is a very late event in the volcanic evolution of the area - is based largely on the similarity of the flow with the latest flows on Rhum (Emeleus 1978, pers. comm.). However, as the base of the lavas is not seen anywhere on Canna, the lavas of Rhum (where the Torridonian/Tertiary unconformity is seen) may well be contemporaneous with the early lavas of Canna - those, at present, below sea level. If this is so, then the similarity of the valley-infill flow to the latest flows on Rhum is reasonable, but it does not imply that it must represent a late event on Canna. The majority of the exposed Canna lavas, according to this suggestion, therefore, are younger than those of Rhum. It may be noted also that for this flow to be a late event (i.e. post-dating all the other lavas on Canna), there must have been 200 m of erosion, assuming that the full series of flows seen, for example, on the slopes of Beul Lama Sgorr (268000625) continued southwards to cover the area now occupied by Canna Harbour. (There is no evidence to suggest that these flows die out southwards.) This may seem a rather excessive amount of erosion, but it must be remembered that Canna did not then sit on the edge of a wide Atlantic Ocean in temperate latitudes. The climate was most probably subtropical, and the north Atlantic had barely started to open. Erosion may well have been more rapid than at the present day.

Comparable valley filling flows are seen in Eigg and on neighbouring Rhum. On Eigg, the maximum valley depth seen in the Sgurr pitchstone valley infill is around 150 m (see Chapter 6). This is the same order of magnitude as the Eilean a' Bhaird situation by the second hypothesis. However, the Sgurr pitchstone is definitely a younger phenomenon than the basaltic lavas of Eigg, postdating the dykes and possibly the faulting also. The Eilean a' Bhaird flow is not intruded by dykes, but as this is true of most of the flows on Canna, this does not definitely prove it to be a younger flow. However, it is affected by faults (see Figure 2.4.14), which suggests that it is not as young as the Sgurr, which appears to be unaffected by faulting (see Chapter 6). Thus the time gap between the extrusion of the valley-wall and valley-infill flows must be less for the Canna situation than in the Eigg one.

This tends to point to the first, rather than the second, hypothesis for the age of the Eilean a' Bhaird flow - that it was caused by penecontemporaneous erosion at the time of extrusion of the Basal Group of flows.

The Tertiary lavas of Rhum largely infill valleys. On Bloodstone Hill, a valley of about 50 m depth existed in Tertiary times, between the eruption of Group 4 and Group 5 lavas (Emeleus pers. comm. 1979). On Orval, the valley depth is around 100 m in depth and about 0.5 km wide. These are of the same order of magnitude as the valley required by the second hypothesis for the Eilean a' Bhaird flow. There is no evidence concerning the width of the Eilean a' Bhaird valley, except that, at the east end of the island, it is at least 70 m wide. This suggests that the lavas of Rhum have similar origins, but does not shed any light on the age of the Eilean a' Bhaird flow.

The island of Reunion supplies more modern examples of similar phenomena (Upton and Wadsworth 1965). On the windward eastern flanks of the volcanoes of Reunion, there are many examples of flows, structurally similar to the Eilean a' Bhaird flow, infilling contemporaneously eroded ravines. Thus it is possible to have such a situation, as envisaged by the first hypothesis in a volcano environment, given the right climate. Erosion in such a situation would be rapid. The coarseness of the conglomerates associated with the Eilean a' Bhaird valley infill flow is consistent with a rapid erosion environment.

The author favours the first hypothesis - that there was contemporaneous erosion of the lavas in the vicinity of Eilean a' Bhaird immediately prior to the extrusion of the infill flow. Until there is an accurate way of dating the flows involved, either of the two hypotheses could be correct.

2.4.5 Western Canna

In this area, west of Camas Thairbearnais, the lavas are again virtually horizontal. A dip of 2 degrees was calculated on the base of the prominent flow, which can be traced from Gualann Sgorr an Duine (23530511) to the cliffs west of Camas Thairbearnais (23500603). As with Eastern Canna, faults follow most of the streams. Details of the sequences examined are given in Figure 2.4.16. Their locations are shown in Figure 2.4.2.

It was decided to concentrate on the south coast of this area. The cliffs here are higher than along the north coast and are accessible only at some of the gullies. Samples were collected where possible, including a full sequence from a gully near Bre Sgorr (21350415). Sketches were made of the inaccessible cliff sections in each of the fault blocks. Correlations were achieved by tracing flows by eye along the cliffs. Such correlations were checked by comparing samples, where available, chemically and petrographically. Correlation with Eastern Canna was achieved by field mapping of the hillside west and north of Fang na Fola (23200520), and then by tracing flows across the foreshore of Camas Thairbearnais (23600610).

As seen in Eastern Canna, there is considerable lateral variation within the area. However, it proved possible to correlate each of the sequences with neighbouring ones, and to establish a correlation with Eastern Canna (Section 2.4.5.4). The succession was divided into three groups, listed from top to base -

1. Sliabh Meadhonach Group
2. Bre Sgorr Group
3. Basal Group

2.4.5.1 Sliabh Meadhonach Group

This Group forms the cliff and hill tops of Western Canna. It is defined as the flows above the base of a fine grained plagioclase-phyric basalt. The Group reaches a maximum thickness of 30 m, on the slopes of Leob an Fionnaidh (21400480), and again below Sliabh Meadhonach (22000494). The latter locality, where the Group is best exposed, is taken as the type locality for the Group.

At the type sequence (above Iola Sgorr - 22000423 to the top of Sliabh Meadhonach - 22000494), the basal flow forms a prominent crag above the cliff tops. It is overlain by two fairly fine grained flows with abundant plagioclase phenocrysts. A third flow may well form the top of Sliabh Meadhonach (22000494), but it is not exposed.

West of Allt Bhre Sgorr, the basal plagioclase-phyric flow forms the cliff tops. It is seen to be overlain by a flow with abundant plagioclase phenocrysts, just west of Allt Bhre Sgorr (21510431). A second flow is thought to form the top of Leob an Fionnaidh (2140480), but none is exposed.

To the east of the type sequence, around Cnoc Loisgte (227000479), the basal flow occurs as a prominent crag at about 120 m above sea level. Here it is overlain by a coarse aphyric basalt, which has no equivalent to the west. The hill top is formed of a poorly exposed, plagioclase-phyric basalt, thought to be the equivalent of the lowest of the three flows seen above the basal flow of the Group as seen at the type sequence.

2.4.5.2 Bre Sgorr Group

This Group is best developed in the cliffs near Bre Sgorr (21300420), where it is 55 m thick. It is defined as the flows which lie between the base of a columnar aphyric basalt and the base of the overlying Sliabh Meadhonach Group. At the type locality, Bre Sgorr (21300420), the basal flow is overlain by four flows, all rich in plagioclase phenocrysts and forming crudely columnar crags. There is little intervening amygdaloidal basalt, in contrast with the sequence seen above the basal flow on the east side of Allt Bhre Sgorr (21340416). Here the group consists of 35 m of predominantly plagioclase-phyric lenses set in a matrix of amygdaloidal basalt, above the basal flow, which is almost 20 m thick here.

The basal flow can be traced right across Western Canna, till it is found forming the hill top east of Fang na Fola (23300460) and Gualann Sgorr an Duine (23550517). It reaches a maximum thickness of 40 m in the sequence east of Glac Bhre Sgorr (21850415). Throughout it appears as a columnar flow, usually with large columns at the base and less regular, thinner columns in the upper third of the flow. Below Am Beannan (22650430) and Iola Sgorr (22000423), however, the flow takes on a three-tiered columnar structure, with a second series of thicker columns at the top of the flow.

The Group itself reaches a maximum thickness of 65 m in the cliffs west of Glac Bhre Sgorr (21650415). The basal flow is overlain by horizontally bedded, amygdaloidal basalt, which continues upwards into isolated crags of predominantly plagioclase-phyric basalt above the cliff top. East of Glac Bhre Sgorr (217504290), the Group thins to about 20 m forming the cliff tops and crags immediately above. At one locality near Iola Sgorr (21800415), the inter-relationships of several lenses of basalt can be seen, as sketched in Figure 2.4.17.

The cliff tops of Am Beannan (22650430) consist of a columnar flow of coarse aphyric basalt, which overlies the columnar flow defined as the base of the Group. This is overlain by isolated exposures of aphyric basalt, which are seen in thin section to have rare plagioclase and olivine phenocrysts. These two flows are thought to be time equivalents of the Bre Sgorr group, above the basal flow, as seen further west. It seems unlikely that they are direct equivalents of any of the lenses in amygdaloidal basalt seen at this horizon elsewhere. They are overlain by the basal flow of the succeeding group, which forms a prominent crag east of Cnoc Loisgte (23000475). Further east, around Gualann Sgorr an Duine (23550415), only the basal columnar flow remains due to erosion.

2.4.5.3 Basal Group

This Group forms the cliffs around Fang na Fola (23200486) and the lower parts of the cliffs of Glac na Criche Deise (22400470). It reaches a maximum thickness of 80 m between Fang na Fola (23200486) and Glac na Criche Deise (22400470). The sequence was sampled in the west (below Bre Sgorr - 21300419), where it consists of a fine grained aphyric basalt (seen to contain plagioclase phenocrysts in thin section), underlain by two plagioclase-phyric basalts, and a lowermost aphyric flow. The lower of the two plagioclase-phyric flows is seen to die out south-eastwards, as sketched in Figure 2.4.18 (21257400). As one follows the flow to the south-east, it passes into a breccia of broken-up fragments of basalt. This gives way to outcrops of plastically deformed lumps of basalt (up to 0.5 m across) enclosed in a brownish matrix. The lumps of basalt each have a very fine grained margin, and resemble pillows. The whole is interpreted as a palagonite pillow breccia, and presumably the lava flowed into a small water body at this locality.

Between the palagonite breccia and the underlying flow, there is a lens (about 1 m thick) of sediments. These consist of carbonaceous shales, with thin sandy lenses. This is overlain by a conglomerate, with red sandstone and basalt pebbles about 1 cm in diameter, and this is succeeded by shale with thin sandy lenses. This points to a water body at this locality prior to extrusion of the overlying flow, and is consistent with the nature of the overlying flow at this locality (a palagonite pillow breccia).

Elsewhere the Group is only known by its characteristics visible from the cliff tops. The cliffs themselves are inaccessible. At most localities, there are a series of poorly exposed, crudely columnar flows. These reach a maximum thickness of 50 m below Am Beannan (22650434). There are thought to be three or perhaps four flows represented here. From Glac Bhre Sgorr (21750428) to Am Beannan (22650434), a thick columnar flow appears at sea level, below the series of crudely columnar flows. It is thought to correlate with the lowest flow of the sequence seen just east of Allt Bhre Sgorr (21340416), in which case it is a fine grained aphyric basalt (seen to contain microphenocrysts of olivine and plagioclase in thin section).

2.4.5.4 Correlation with Eastern Canna

The correlation of the east and west halves of Canna was achieved by tracing the columnar, aphyric basalt of Gualann Sgorr an Duine (23550517), the basal flow of the Bre Sgorr Group of Western Canna, northwards, and locating it stratigraphically in the sequence seen in the cliffs on the west side of Camas Thairbearnais (23400610). The sequence found here and the correlations made between Eastern and Western Canna are given in Figure 2.4.19. Two flows, with rare plagioclase phenocrysts, were traced across the foreshore of Camas Thairbearnais (23600610) to Earnagream (24050631), with no evidence for a fault which one might expect to follow the low ground in this area.

The Sliabh Meadhonach Group of Western Canna closely resembles the Upper Main Group of Eastern Canna - a fine grained flow with abundant plagioclase phenocrysts overlain by an aphyric flow and further plagioclase-phyric flows. The aphyric members of the two groups are petrographically dissimilar, but are presumably time equivalents.

The basal flow of the Bre Sgorr Group of Western Canna was traced in the field from Gualann Sgorr an Duine (23550517) to the cliffs west of Camas Thairbearnais (23400610). This latter flow is known to be equivalent to the thinner columnar flow at the base of Earnagream (24050631). The flow thickens from 11 m at Earnagream (24050631) to 35 m in the Am Beannan cliffs (22650434).

As has already been noted (Section 2.4.5.2), the flows seen above the basal flow of the Bre Sgorr Group at Am Beannan (22650434) cannot be directly correlated with those seen further west. Those seen at Am Beannan (22650434) are aphyric and are thought to be at least time equivalents of the thicker columnar, aphyric flow of Earnagream (24050631) and the overlying aphyric flow, seen in isolated outcrops above. Thus the Bre Sgorr Group of Western Canna is the time equivalent of the Middle Main Group of Eastern Canna.

The Basal Group of Western Canna is thought to be a time equivalent of the Lower Main Group of Eastern Canna. No direct correlation could be made because of the lack of sampling of the Basal Group of Western Canna. Part of the Basal Group of Eastern Canna may also be represented, the glomerophyric basalt, which is taken as the base of the Lower Main Group of Eastern Canna ceases to outcrop above sea level before Tarbert (23800560) is reached.

2.5 Conclusions

In an I.G.S. report on the Sea of the Hebrides (Binns et al 1974), there is a map of the geology of the sea-floor of the area around Eigg, Muck and Canna (part of this is reproduced in Figure 2.5.1). The sea-floor between Eigg and Muck is shown to be composed of Tertiary lavas and minor intrusions, and this ridge extends southwards to Mull. Thus one could reasonably expect similarities between the lavas of Eigg and Muck, and perhaps between those two islands and Mull. The uppermost Group of flows on Muck (the Beinn Aireinn – An Stac Group) bear petrographical similarities with the lavas of Eigg (they are predominantly olivine-phyric). Geochemical similarities also exist between the lavas of Eigg and Muck (see Chapter 10, where comparisons with Mull are also made). Thus the lavas of Eigg and Much could possibly be co-magmatic and probably roughly contemporaneous. Radiometric dating of the lavas of Eigg, Muck and Canna (currently in progress at Liverpool University Geophysics Department) may prove helpful in this respect.

There is an obvious problem in correlating the lavas of Eigg and Muck with those of Canna – the presence of Rhum and the Camasunary-Skerryvore fault (see Figure 2.5.1). There is, however, a ridge of Tertiary basalts joining Skye with Canna, suggesting possible grounds for similarities between the lavas of those two islands. Geochemical comparisons between the lavas of Canna and Skye are discussed in Chapter 10.

It has been suggested that the lavas of Canna are related to those of Rhum (Emeleus 1973). The Rhum lavas have been established as a relatively late stage episode on the Tertiary igneous activity on Rhum, by the presence of pebbles of the rocks of the Central igneous complex in the conglomerates associated with the lavas (Emeleus and Forster 1979).

The age of the Canna lavas is not definitely known, but they are cut by remarkably few dykes (see Chapter 4), suggesting that the lavas postdate the major phase of Tertiary minor intrusions. In the conglomerates, which outcrop at, and near, the base of the exposed lava pile, gabbroic pebbles were found (see Chapter 8). The presence of such pebbles (as in the conglomerates of the Rhum conglomerates) implies that, at the time of formation of the conglomerates, some of the Central Igneous Complexes of the area were unroofed. Thus the Canna lavas could well be contemporaneous with those of Rhum. It is interesting to note that the conglomerates below the Sgurr pitchstone of Eigg (see Chapter 6) contain no such pebbles, suggesting that the conglomerates of Eigg (and hence the underlying lavas) are older than those of Rhum and Canna. It could equally well be, however, that there were no suitably sited Central Igneous Complexes for the river, which deposited the Eigg conglomerates, to erode.

CHAPTER 3

THE PETROGRAPHY OF THE EXTRUSIVE BASIC ROCKS

3.1 Field Observations

The majority of the samples collected from Eigg, Muck and Canna could only be classified as basalts, with or without phenocrysts of olivine and/or plagioclase in the field. Only one flow, from the west coast of Sanday (Canna), could be said to contain clinopyroxene phenocrysts.

Typically, the basalts are dark grey or black in colour, weathering to a rusty brown. Only samples with phenocrysts larger than 9.5 cm could be said to be definitely porphyritic. For this reason, many samples, originally classed as aphyric, were found to contain either rare phenocrysts or microphenocrysts, when examined in thin section.

Some flows exhibit flow banding, normally of a fairly regular, planar nature. In some cases, however, the banding is more contorted, suggesting turbulence during extrusion (see Figures 3.1a and 3.1b). Microscopical examination reveals that the flow banding is caused by variations in grain size across the banding, and is often accompanied by strong parallel orientation of the included feldspars. Occasionally, elongate vesicles and amygdales also define a flow structure (e.g. in the Grey rock of Eigg). The amygdales, where present, were found to contain zeolites, calcite and often chloritic material.

Columnar jointing occurs in certain flows (see Figure 3.2a). It is rare in Muck, occasionally present in Eigg (e.g. the basal flow seen on Eigg, as seen along the east coast, and in the gorge 600 m east of Laig Farm - 46618755) and it is very common in Canna. Most of the flows on the south facing terraced slopes of eastern Canna are columnar. Often, as with the relatively continuous flow seen along the roadside west of Rubha Dubh (26550512), the top part develops smaller and less regular columns than the basal parts. This is a result of more rapid cooling at the air/lava interface as compared with the land/lava junction. More rarely a sub-horizontal jointing develops (e.g. in the 'platey' basalt of the Beul Lama Sgorr Group of Canna). This is usually associated with a trachytic texture, and often leads to fissility of the rock.

Very rarely, xenoliths were observed in the field, as seen, for example, in one of the flows along the south coast of Sanday, Canna (see Figure 3.2b). Here they are basaltic and rounded, being on average 0.15 m across. Xenoliths also occur in the Eilean a' Bhaird valley infill flow (27090502) in Canna Harbour. Again they are all basaltic and average about 0.20 m across. They vary in shape, however, from rounded to angular. Some show signs of plastic deformation, suggesting that this magma picked up not only already consolidated fragments, but also some that were in a plastic state. These latter could possibly be autoliths - fragments picked up from the marginal, semi-consolidated parts of the same flow.

Only seven flows in the three islands could be definitely designated as differentiated (hawaiites and mugearites) on purely field characteristics. Five criteria were used to identify these flows:-

1) light grey colour when fresh;

2) very fine grain size;

3) apparent lack of phenocrysts;

4) platey jointing;

5) elongate vesicles or amygdales.

No one lava shows all five criteria, the Grey rock of Eigg being the closest, showing all but the platey jointing. Chemically and petrographically, it is a mugearite. Near the top of the Eigg succession, the uppermost flow of the Cnoc Creagach Group (E7471) is a relatively dark coloured rock, when compared to the Grey rock, but its extremely fine grain size suggests a differentiated chemistry. This was confirmed by petrographical examination and chemical analysis.

Three flows on Canna appear differentiated in the field. The 'platey' basalt (SR252 and C7538) shows a light colouration, fine grain size and platey jointing. Chemically and petrographically, it is either a mugearite (SR252) or a hawaiite (C7539). The valley infill flow of Eilean a' Bhaird (SR254) is extremely fine grained (glassy in parts) with platey jointing near the top and amygdales near the base. Petrographically, it is classed as a mugearite, while chemical analysis proved it to be a hawaiite. The middle flow of the three which outcrop on the islands of Canna Harbour show platey jointing, fine grain size and light colouration, implying a differentiated nature. Petrographically, it would appear to be a hawaiite. It was not analysed.

On Muck, two flows of the Upper Basal Group near Port an t-Seilich (41817841) were classed as differentiated in the field on account of their extremely fine grain size, aphyric nature and fairly light colouration. The lower flow (M7655) proved to contain olivine- and plagioclase-phenocrysts when examined petrographically, but was too altered to be analysed. The other (M7655) is chemically and petrographically a mugearite.

3.2 Microscopical Examination

Of the order of 500 samples of the basic extrusives were collected from the three islands and most of these were examined in thin section, often to try to settle stratigraphical correlations. About 200 of the freshest samples were selected for chemical analysis, and it is mainly on the thin section study of these samples that the following discussion on petrography is based.

During thin section examination, samples were initially grouped by phenocryst content. Then the samples classed as differentiates in the field were re-examined and split into two groups, those having oligoclase as the feldspar and those with andesine. Using these samples as a basis for classification, others having similar characteristics were then re-grouped.

The chemically analysed samples were classified according to the scheme developed by Thompson et al (1972) and a comparison made between the chemically defined mugearites and hawaiites, and the petrographical differentiates. With a few exceptions, a good correspondence was noted. Some chemically defined mugearites were classed with those bearing andesine (mugearites should have oligoclase) and likewise chemical hawaiites were found to contain oligoclase in thin section. Some highly plagioclase-rich samples grouped chemically with the hawaiites, while petrographically they are basalts. This is to be expected from the nature of the chemical classification. The other main source of error in the petrographical groupings could be attributed to the fine grain size of the samples involved (e.g. M7543 and C7503, which are chemically basalts, but the fine grain size and trachytic texture suggested a more differentiated classification). One interesting exception is M75144, which has oligoclase in the matrix, suggesting a mugearitic composition, but which also contains xenocrystic plagioclase, which must be sufficiently calcic and abundant to cause the chemical classification as a basalt.

However, in general, the match between the petrographical and chemical classifications is sufficiently accurate to allow the name 'mugearite' to be applied to the petrographical group containing oligoclase, and 'hawaiite' to that containing andesine (compare Tables 3.2 and 3.3).

Before dealing in more detail with the petrographical groups, it is interesting to note the relative abundance of the different groups in the three islands. This is summarised in Table 3.1. In all three islands, basalts are by far the most abundant (c.80% of all types). A striking difference between Eigg and Muck on the one hand, and Canna on the other is noted when the major type of basalt in each island is calculated. Eigg and Muck have predominantly olivine phyric basalts (c.30% of the total extrusives), while over half of the flows on Canna contain both plagioclase- and olivine-phenocrysts, olivine phyric basalts comprising a mere 4% of the total. This adds weight to the hypothesis that Canna is part of a province of igneous activity, distinct from Eigg and Muck, perhaps being more akin to Rhum (pers comm. C. H. Emeleus).

3.3 The Basalts

These rocks can be defined as those lavas having plagioclase at least as calcic as labradorite. In practice, however, the author defines everything that does not fit the description of a differentiate (hawaiite or mugearite) as a basalt. They have been subdivided on the basis of their phenocryst content into ten sub-groups, although not all ten are present in any one island. Eigg is the most varied with nine sub-groups, Canna has six, and Muck has only four. Of the four sub-groups on Muck, two of them account for 90% of the basalts seen on the island (see Table 3.1). Analysed samples included in the various groups are shown on Table 3.2, with their chemical classification shown, for comparison, in Table 3.2.

3.3.1 Aphyric Basalts

These are predominantly coarse grained rocks; the olivines, for example, in these rocks range from 0.1 to 0.5 mm across. In most cases the plagioclase composition could be measured, and in all samples yielded anorthite contents between 50 and 66% (i.e. labradorite). One plagioclase, from E7481, was analysed by electron microprobe and found to contain 70% anorthite, 29.5% albite and 0.5% orthoclase - a calcic labradorite. In two samples from Muck (M7643 and M7576), a trachytic texture was noted. Elsewhere the plagioclase show no preferred orientation.

The olivines in the aphyric basalts are often altered but have anhedral outlines. In one sample (C7545), they show alteration only around the edges. Two other samples from Canna (C7511 and C7514) are interesting in that they have two generations of olivines. The earlier, larger ones (0.5 mm across) are often altered, zoned and have spinel inclusions. The smaller anhedral ones (0.2 mm across) are fresh and predate the rest of the mineral assemblage.

Electron microprobe analysis of olivines from E7481 confirmed the zoning in thin section. The core of the analysed crystal contained 80% fosterite, while the margin only measured 66% (see Chapter 9).

The clinopyroxenes seen in these basalts are most commonly a dark purple brown colour, with pleochroism to an orange brown. Some show similar pleochroism but of a much lighter shade. A few samples from Eigg (e.g. E7467 and E7481) show brownish-pink pyroxene, which is non-pleochroic.

Three of the Eigg samples (E7462, E7606 and E7668) show interesting zoning in the pyroxenes - colourless to pink-brown in the centre and dark purple to orange-brown at the margins. Unfortunately, analyses of these pyroxenes are not available, but the slight zoning in pyroxenes from E7481 shows up in the electron microprobe analysis as a decrease in magnesium content toward the margins and a corresponding increase in titanium and iron.

Predominantly, the aphyric basalts exhibit ophitic textures. More rarely, a more subophitic relationship between the pyroxenes and plagioclases is seen. Very occasionally, it is granular (e.g. in M7639 and C7514). One of the Eigg samples (E7462) shows large laths of clinopyroxene (up to 4 mm across), which are only ophitic at the margins. They perhaps began to crystallise before the plagioclases and may even have been phenocrysts in the early stages of crystallisation.

Two other variants are worthy of note. One sample from Canna (C7504) and one from Muck (M7639) show a similar development of a glassy mesostasis. It is most pronounced in C7504, where olivine (0.2 mm across) and plagioclase (0.5 mm long) crystals occur in a brown glassy material. Close examination of the glass reveals that it contains brown clinopyroxene charged with abundant tiny opaque oxides It has been suggested that this lava was quenched after some olivine and plagioclase had crystallised, the clinopyroxenes and opaque oxides crystallising later from the glass (pers. comm. J. Preston 1976).

3.3.2 Olivine Phyric Basalts

This group of basalts is characterised by having olivine phenocrysts. They constitute about 40% of all the lavas of Muck and Eigg, but are relatively rare in Canna (only 4% of all the lavas). Variety in size, shape and abundance of the phenocrysts is extreme and unrelated to other features of the flows The largest phenocryst seen was 4 mm across (in E7482). Zoning is occasionally strong and thus detectable in thin section. Five olivine phenocrysts from the olivine phyric basalts of Eigg were analysed by electron microprobe. The analyses reveal quite strong zoning, the maximum being from 86% fosterite to 68% fosterite in a phenocryst from E7487. Many of the phenocrysts contain spinel inclusions, some of which are dark brown in colour, rather than opaque.

Plagioclase compositions, as expected, are labradorite (An_{50} to An_{64} being measured in thin section). They occur predominantly in laths, and occasionally show a tendency towards a trachytic texture. Sometimes slight alteration of the feldspars to zeolite was noted. In addition, the matrix contains small anhedral olivines, clinopyroxenes and anhedral opaque oxide grains. Occasional elongate opaque oxides occur and are probably ilmenite.

Four different groups of clinopyroxene were distinguished on the basis of colour and intensity of pleochroism. The most common of these is where the pyroxenes show only faint pleochroism from pinkish-brown to colourless. Very common also in Eigg is a non-pleochroic variety, where pink-brown or colourless pyroxenes show no variation in colour with rotation of the specimen. Rather more rare are the light and dark purple-brown to orange-brown pleochroic varieties.

Texturally, the pyroxenes show all graduations between granular and ophitic relationships with the plagioclases. Granular textures are most common in the non-pleochroic and faintly pleochroic varieties, while ophitic textures predominate in the more strongly pleochroic types. Texture may also be affected by grain size the banded example from Canna (C7586) shows ophitic pyroxenes in the coarse bands and granular textures in the finer grained bands.

3.3.3 Plagioclase phyric basalts

Basalts with plagioclase as the single phenocryst phase are relatively rare, forming 6% of all lavas over all three islands, and much less in Muck (2%). As with the olivine phenocrysts, all ranges of size and abundance of phenocrysts per sample exist. The largest phenocryst measured was 8 mm in length and, like all the plagioclase phenocrysts, it is lath shaped. Mostly they show albite twinning, enabling estimates of the anorthite content to be made. Carlsbad twinning is often present along with the albite variety. Compositions measured in thin section vary from An_{88} to An_{56}, the more calcic varieties possibly being xenocrystic.

Zoning from calcic cores to more sodic margins is frequently seen in the phenocrysts. Oscillatory zoning was noted in one of the samples from Canna (C7540). Unzoned cores overgrown by zoned margins are seen in a sample from Eigg (E7473). Another sample from Eigg (E7644) showed glomerophytic groups of plagioclases. The groups measured 1 mm across, with the individual laths being, on average, 0.5 mm long.

As with the olivine phyric basalts, this group can be subdivided on the basis of the colour and intensity of pleochroism of the included pyroxenes. All the plagioclase phyric basalts contain pyroxenes with some degree of pleochroism. Faintly pleochroic pink-brown to colourless, light purple-brown to orange-brown and dark purple-brown to orange-brown pleochroism is seen. In addition to pyroxenes, the matrix includes labradorite laths, small anhedral olivines and opaque oxides. The opaques are predominantly anhedral and equant, but rare elongate ones also occur.

Texturally, most of the samples show ophitic relationships between the pyroxenes and plagioclases. One sample from Canna (C7540), however, has predominantly granular pyroxenes with occasional ophitic areas. Rarely the matrix plagioclases show a trachytic texture. This appears to be confined to samples from Canna. One such sample (C7541) also shows granular pyroxenes elongated parallel to the plagioclases.

3.3.4 Plagioclase and olivine phyric basalts

Taking the three islands together, this is the single most abundant group, with 30% of all lavas belonging to it. Taking each island separately, however, the proportion of lavas with both plagioclase and olivine phenocrysts is very different. Over half of the lavas on Canna belong to this group; only one quarter of those of Muck; and a mere tenth of those of Eigg. In terms of relative proportions of the two phenocrysts, 85% of the lavas belonging to this group on Muck and 90% on Canna have plagioclase in excess of olivine. Eigg, on the other hand, shows a predominance of olivine over plagioclase.

As is to be expected, a range of sizes and quantities of phenocrysts, and variation in the matrix grain size is found in this group. The olivine phenocrysts occur in all shapes from euhedral to anhedral. They are often rounded and the euhedral crystals normally show corrosion around the edges. Some exhibit zoning and some have spinel inclusions. In most cases, it can be proven that they pre-date the plagioclase phenocrysts, the former often occurring partially enclosed by the latter.

The plagioclase phenocrysts, which are frequently found in glomerophytic groups with the olivine phenocrysts, are normally lath-shaped and have albite and/or Carlsbad twinning. They reach a maximum length, in the samples examined, of 10 mm in their lath-shaped habit. They often show corrosion around the margins, especially the fairly rare equant crystals. Most of them also show some zoning, sometimes confined to the margins when inclusions parallel to the edges of the phenocrysts are also usually present. Others (e.g. T526) show oscillatory zoning. Where measurement of the plagioclase phenocrysts composition was possible, it was found to be labradorite.

Occasionally, in samples from Canna, two generations of plagioclase phenocrysts occur. The earlier ones are equant (over 1 mm across) and show corrosion at the margins. They are probably xenocrystic. The second generation are lath-shaped and are very abundant. They grade in size from fairly large crystals (0.5 mm long) down to the size of the matrix plagioclases.

The groundmass of the samples from this group is, in general, similar to that of the other groups already discussed - clinopyroxene of varying colour and pleochroic intensity, small olivine anhedra and opaque oxides. The pyroxenes occur both as granular grains and in ophitic intergrowths with the plagioclase. Again the group may be subdivided on the basis of the clinopyroxene colour and pleochroism.

Colourless, non-pleochroic varieties and slightly pleochroic pinkish-brown to orange-brown pleochroic pyroxenes are found. The different subgroups appear in approximately equal proportions. Occasionally (as in C7560 and C7539), the pyroxenes occur in brown patches heavily charged with opaque oxides. This is reminiscent of the aphyric basalts where a glassy mesostasis had developed, and from which pyroxene and opaque oxides had crystallised at a relatively late stage. As previously suggested, this may be indicative of quenching. Only rarely were the pyroxenes seen to be zoned.

The predominant texture seen in these lavas is an ophitic one, over one third of the group showing it. Occasionally, pyroxenes, which have only developed an ophitic relationship with the feldspars at the margins, are seen. This suggests that, in these cases, the pyroxenes must have started to crystallise before the plagioclases. About one quarter of the group shows trachytic textures in the plagioclases. This is best seen near phenocrysts and is often associated with grain size banding in the groundmass itself. As with the phenocrysts, the matrix plagioclases are labradorite in composition.

3.3.5 Other types of basalt

In Eigg, and to a lesser extent in Canna, there are some basalts which do not fit in any of the groups already described. On Canna this is a mere 8% of the total extrusives, but on Eigg, 23% of all lavas cannot be classified in any of the preceding groups.

These 'other types' are those basalts in which plagioclase and/or olivine phenocrysts are joined by phenocrysts or microphenocrysts of clinopyroxene and/or spinel. The majority of these have olivine as the major phenocryst phase, or have olivine and plagioclase phenocrysts in roughly equal proportions. On the basis of which mineral is the major phenocryst phase, these 'other types' have been further subdivided.

3.3.5.1 Basalts with olivine as the major phenocryst phase

These are confined almost entirely to Eigg. There are two types: those in which olivine is joined by spinel microphenocrysts, and those in which the second phenocryst phase is clinopyroxene. With regard to the olivine phenocrysts and the matrix, samples belonging to this group are similar to the olivine phyric basalts. Ophitic and granular textures are found and the pyroxenes are mainly non-pleochroic or slightly pleocroic from colourless to pinkish-brown. The plagioclases are labradorite and often show trachytic textures.

The spinel microphenocrysts are generally rare and small in comparison to the olivine phenocrysts, but are large compared with the opaque oxides in the matrix. Occasionally, they are seen within the olivine phenocrysts. Their composition is unknown, but many appear brownish rather than black in thin section.

The clinopyroxene phenocrysts are occasionally true phenocrysts (e.g. E7434 where they are rare and occur as euhedral grains 0.25 mm across). These true phenocrysts can be compared with the other pyroxenes in the samples and, in many cases, it can be seen that the non-ophitic cores were once phenocrysts, which have since been overgrown to give ophitic margins. In E7475 some such pyroxene exist and are seen to have been euhedral phenocrysts with later overgrowth. In other samples, granular pyroxenes are of sufficient size to be classed as micro-phenocrysts (e.g. E7413 and E7652).

In some rare samples from Canna (e.g. C7512), plagioclase joins olivine and spinel as a minor phenocryst phase. The plagioclase normally occurs as laths of labradorite. Often they are corroded and show inclusions parallel with the margins.

3.3.5.2 Basalts with plagioclase as the major phenocryst phase

These types are confined to Eigg. Clinopyroxene and/or olivine and spinel join the plagioclase as phenocryst phases. In all samples, the plagioclase occurs in two generations large, irregular-shaped crystals (up to 3 mm across), which are full of inclusions and are very corroded; and smaller, lath-shaped crystals (1 - 3 mm long), which show much less corrosion and which have albite twinning. Clinopyroxene phenocrysts are rather rare, occurring usually in small crystals (up to 1.5 mm across). They are normally brownish in colour and, like many of the clinopyroxene phenocrysts already discussed, show ophitic overgrowths. They pre-date the lath-shaped plagioclases, but postdate the larger corroded plagioclases.

The olivines, where present, are small and anhedral in shape. The spinels are similar to those present in the olivine and spinel phyric basalts (see Section 3.3.5.1).

3.3.5.3 Basalts with plagioclase and olivine phenocrysts in equal amounts

Clinopyroxene is the only additional phenocryst in these basalts. They occur in both Eigg and Canna. The phenocryst phases are similar to those already described, although the order of crystallisation of the phenocrysts varies from sample to sample.

Texturally, granular relationships between the pyroxenes and the plagioclase in the matrix are present in all but two of the samples of this group (both of these are from Canna C7535 and C7533). In one of these (C7533), the texture is ophitic, while in the other (C7535) it is variable.

3.4 The Differentiates

Differentiated rocks are distinguished from the basalts primarily by their plagioclase composition, (which is more sodic than An_{50}). They are usually more fine grained and lighter in colour than the basalts, commonly also exhibiting platey jointing and elongate vesicles. They are subdivided into two groups, based again on their plagioclase composition.

3.4.1 Hawaiites

Few chemically classified hawaiites were so designated petrographically. In the case of Canna, many of the chemical hawaiites are simply basalts with extremely abundant plagioclase, which would tend to raise their Thorton-Tuttle differentiation index, on which the chemical classification is based. In the case of the olivine phyric and aphyric samples, which were chemically classified as hawaiites, the author could find no way of distinguishing them from petrographically similar basalts. Areas of alkali feldspar have been found in the Rhum hawaiites during electron microprobe analysis (Emeleus, pers. comm. 1979). They also contain more opaques than the basalts and possibly contain biotite.

With the petrographically defined hawaiites, which were also chemical hawaiites, the main distinguishing feature is their plagioclase composition. Where determination is possible (as for example, the phenocrysts in C7531 and M7612), their composition is andesine. The tiny laths in the matrix normally show extinction at small angles, implying compositions slightly more calcic than oligoclase.

Plagioclase is the only phenocryst seen in the hawaiites. Matrix minerals include olivine (except in the sample from Canna - C7531), slightly pleochroic, brownish clinopyroxene of variable textural habits and, as with the mugearites, an abundance of small opaque oxide grains. Commonly, also like the mugearites, they show trachytic textures.

3.4.2 Mugearites

These are the differentiates with oligoclase as the plagioclase. In many cases, accurate determination of the tiny laths proved impossible, but straight extinction of the laths was taken as being indicative of the presence of oligoclase. Most of the samples are fine to extremely fine in grain size, and many reveal a trachytic texture, which is seen to deflect around phenocrysts. Banding due to grain size variation was also noted in some of the Muck samples.

On account of the fine grain size, it is often difficult to identify all the mineral phases present. Tiny laths of oligoclase and small anhedral grains of opaque oxides are ubiquitous and very abundant. Colourless, or sometimes faintly pinkish brown, clinopyroxene can usually be identified. Occasionally, it is present charged with abundant, extremely small opaque oxides. It most often occurs with a granular habit, but shows a tendency towards a subophitic habit in E7471, and in M7607 it occurs in both granular and ophitic patches. Olivine is extremely rare and almost always altered when present. Biotite occurs in a few of the mugearites, notably the Grey rock of Eigg (E7412).

In the field, the mugearite all appeared to be aphyric and most proved to be so in thin section. Relatively common, however, are plagioclase phenocrysts. Occasionally, microphenocrysts of opaque oxides occur. In the Grey rock of Eigg they are 0.4 mm across and, despite their corrosion, they reveal euhedral outlines.

One of the Eigg mugearites (EA29), in the Cnoc Creagach Group, is rather distinctive. It contains plagioclase and opaque oxide phenocrysts and, in addition, rare microphenocrysts of apatite. The rock also contains a pinkish brown mica in the groundmass. Chemically, it is quartz normative and thus not strictly a mugearite.

CHAPTER 4

BASIC MINOR INTRUSIONS

4.1 Introduction

The basic minor intrusions of Eigg, Muck and Canna include all the small bodies of basaltic material which intrude either the Tertiary lavas or the underlying Mesozoic sediments. In all, 159 basic minor intrusions were examined in the field. Another 19 from Canna were received. The two received from Dr. C. H. Emeleus were analysed, but the other 17 received from Drs. A. Mussett and P. Dagley of the Department of Geophysics of Liverpool University were donated to the City of London Polytechnic (Dr. A. Baxter) for chemical analysis. Thus only petrographical descriptions of these Canna samples are included in this thesis.

On Muck and Canna, only dykes were found. On Eigg, the Jurassic sediments of the northern coastal regions of the island are intruded by many sills and sheets of dolerite. It may well be that similar sills, as yet unexposed, intrude the Jurassic sediments which underlie the lavas of Muck. As the sub-lava terrain of Canna is not known accurately as yet, it is not possible to predict a similar abundance of sills on Canna.

The relative abundances of dykes on the three islands is striking. On Muck, according to Harker (1908), there is a dyke every 20 or 30 yards, and the author found that dykes form about 10% of the surface of Muck. On Eigg, they are much less frequent; for example, the section just north of Laig Bay (46958915) comprises only 1.5% dykes. Just as on Muck dykes are striking by their abundance, equally on Canna, they are striking by their absence. Seventeen were sampled by the party from Liverpool University, this from an area of about 13 sq km. The abundance of dykes on Muck suggests that the island lay over a site of fairly intense igneous activity during the Tertiary. It is perhaps significant that Eigg and Muck, where the base of the lava pile is exposed, have more dykes than Canna where only the upper part of the lava pile is seen.

A table of all the basic minor intrusions examined, with grid reference, trend, thickness and brief notes on the outcrops, is presented (Appendix 2).

4.2 Field Observations

This section may conveniently be subdivided into five subsections:-

Internal dyke features;
Dyke/country-rock relationships;
Dyke relationships with other intrusions;
Sills and inclined sheets.

4.2.1 Internal dyke features

Where the edges of the dyke may be seen (e.g. in many of the dykes seen on the rocky foreshore north of Laig Bay - 46958915), often they can be seen to be much finer grained at the margins when compared to the central parts. A dyke intruding the basalts of the Cleadale cliffs, north of Bealach Nigh 'n Eaghain (47968629) shows fine grained margins (E7418) either side of a coarser grained central part (E7417). The finer grained margins are 0.5 and 0.8 m thick on either side of the dyke, which is 3 m in total thickness.

Throughout it is plagioclase phyric, the phenocrysts being approximately the same size in the core and marginal parts of the dyke, but being set in a much finer grained matrix at the margins. It is also notable for the prominent alignment of the plagioclase phenocrysts, their long axes being parallel with the margins of the dyke. Two of the dykes have extremely fine grained margins (tachylitic) - MD35 and E7449.

On Muck the marginal parts of some of the dykes show a greater abundance of vesicles than the central parts. In two of them (MD17 and MD18), these vesicles are arranged in lines parallel with the edges of the dykes. Sketches of these two dykes are included - Figures 4.1 and 4.2. A thinner dyke found a few metres to the east of MD17 (42437919) has pipe amygdales arranged perpendicular to the margins of the dyke. The central part of this dyke shows lines of spherical vesicles arranged in lines paralleling the edges of the dyke. In addition, it has developed jointing parallel to the margins of the dyke. Other dykes show jointing in various attitudes. Vertical and horizontal jointing, or some combination of the two, is seen. Often, especially in inland areas, this jointing helps to distinguish the intrusions from the lavas. Three sets of jointing, one horizontal and the other two intersecting at an acute angle, are seen in two dykes (EA39 and EA40) which intrude the Grulin felsite (45518461). Columnar jointing, with the columns orientated perpendicular to the margins of the dyke, was noted in a few dykes, notably E7449 on the south east coast of Eigg (48818444).

Three multiple dykes were noted in the field, one in the Laig Bay section on Eigg (c.46958915) and two on Muck. They are all characterised by having internal chilled margins, implying more than one phase of intrusion along the same line of weakness. Only one of these complex dykes was studied in detail, that found near Rubh' Leam na Laraich, north-west Muck (39227970). The area in question is intruded by three dykes (MD55, MD56 and MD57 - see Figure 4.3), but only two of these are actually in contact with each other (MD55 and MD57). MD55 is a very coarse grained intrusion, very rich in pyroxene. MD57 is a finer grained dolerite, which contains, at its margins, some xenoliths of coarse grained material very similar to that forming MD55. This suggests that MD55 predates MD57. The third dyke (MD56) shows another feature noted in many other dykes - bifurcation. More usually the dykes show a single forking (e.g. two of the dykes examined in Gallanach Bay, northern Muck (MD22 and MD24 - 40658020)).

It was noted that one of the dykes in the complex near Rubh' Leam na Laraich (MD57) contained xenoliths of a second dyke in the area. Rarely this was observed elsewhere, notably in the dykes intruding the Jurassic sediments. One of those examined, in Laig Bay, Eigg (47808883) contains xenoliths of the Jurassic sandstone into which the dyke is intruded. A similar situation is found in a dyke intruding Jurassic limestone in Camas Mhor, Muck (40737935). The unusual intrusion above Garbh Asgarnish, Canna (28080585) also shows xenoliths. This is a rather irregular body of columnar rock intrusive towards the conglomerates of the cliffs above Garbh Asgarnish. The xenoliths include fine grained gabbros, and what appear to be baked sediments, presumably derived from the conglomerates.

4.2.2 Dyke/country-rock relationships

One of the most common features which falls into this category is side-stepping. On following a dyke along its trend, often it then side-steps (usually by about 1 m) and then continues on approximately the same trend. Such a situation is seen on the south-east coast of Muck (42877928) - see sketch in Figure 4.4. A little to the west (42827932), two dykes are seen in the cliff. The more westerly of the two shows the unusual feature of dying out downwards (see Figure 4.5). This is the only example of this that was noted on any of the islands, emphasising the uniformity of trend seen on Muck.

Again along the south-east coast of Muck (42877930), the influence of the country-rock is strikingly demonstrated. In the cliffs of lava the dyke (MD39) is 0.6 m thick. However, on entering the breccia, exposed on the foreshore, it initially thickens to over 2 m in width and then disappears. Presumably in the less competent breccia the intrusive magma was able to follow many different lines of weakness, compared with the lavas, where it would be confined to a single line of weakness (e.g. a prominent joint).

Two of the more classical features of intrusive rocks, updoming and thermal metamorphism of the country-rocks, are only rarely seen in the basic minor intrusions. This is because they predominantly intrude basaltic lavas, which do not readily deform, and which, because of their similar chemistry, do not readily suffer thermal metamorphism as they are intruded by basic magma. A study of the zeolites in the lavas might reveal some evidence of such metamorphism in the lavas. The dykes which intrude the Jurassic sediments, however, are in a highly suitable environment to develop such features, and two of those examined do so. A dyke (MD122) intruding the Jurassic sediments of Camas Mhor, Muck (40737935) show both updoming and thermal metamorphism of the shales and limestones it intrudes. The thermal metamorphism is best seen in a 1.4 m wide block of shales and shelly limestones outcropping between MD122 and a neighbouring dyke (MD121). The heat caused by the intrusion has baked the shales and partially recrystallised the limestones. The outcrop is sketched in Figure 4.6.

Several of the dykes outcropping on the foreshore north of Laig Bay, Eigg (e.g. at 46928925) also show thermal metamorphism of the Jurassic country-rocks. Here the dykes intrude sandstones, which have undergone some recrystallisation as a result of proximity of the dykes. One of the dykes shows quartz veins; this may be a result of local anatexis of the surrounding sandstones.

4.2.3 Dyke relationships with other intrusions

Throughout all three islands only one example of a dyke cutting another was found. This occurs in Gallanach Bay on the north coast of Muck (40848020), where a small dyke (0.3 m wide) cuts a larger one (2.80 m wide) at an angle of 82°. The larger of the two (MD32) follows the usual trend of the Muck dykes (approximately SSE to NNW), while the smaller one (MD31) trends roughly SW to NE. Such a lack of cross cutting relationships in the dykes emphasises the parallelism of the swarm.

On Eigg, east of the north pier, dykes are seen to intersect with inclined sheets known as Kildonnan sheets (Harker 1908). Two fairly large dykes (E7448 and E7449 at 48778440 and 48818444 respectively) are seen to be cut by a Kildonnan sheet, while a smaller dyke (E7447 at 48738437) cuts the sheet.

More unusual dyke/sill relationships are seen in some of the dykes of the foreshore north of Laig Bay, Eigg. One of these (at 47058882) is merely thin sill-like extensions of the dyke, the sill-like extensions occurring along bedding planes in the Jurassic sediments. A second one (E7404 at 46928925) has a much thicker sill associated with it (see Figure 4.7). It intrudes sandstones and appears to have a large xenolith of limestone included in it between its glassy base and the coarser grained core.

4.2.4 Sills and inclined sheets

These are confined to the Isle of Eigg. Most of them are concentrated in the Jurassic sediments of the northern coastal area. All of those examined are less than 10 m in thickness. Occasionally they are seen to split up into smaller sills, especially where they intrude shales (e.g. E7433 - 48029087). Where the upper and lower contacts are revealed, the sills can usually seen to be approximately concordant with the bedding in the Jurassic sediments. A sill seen on the foreshore north of Laig Bay (E7401 at 47248851) is 7 to 10 m thick and intrudes Jurassic limestone, which shows evidence of re-crystallisation within 0.17 m of the upper and lower edges of the sill (see Figure 4.8). The margins of the sill are finer grained than the central part, and at the contact with the sediments they are glassy.

Several inclined sheets also occur on Eigg. These are bodies of rock which intrude the country-rock at small angles to the horizontal, thus resembling sills more closely than dykes. One such sheet (E7424) is seen intruding the Sgorr Sgaileach felsite on the north coast of Eigg (48449130). A series of inclined sheets (known as Kildonnan sheets, Harker 1908) outcrop on the south-east coast of Eigg near the north pier (e.g. at 48738447). They all dip towards the east. They postdate most of the dykes (see Section 4.2.3) and are rather light coloured, suggesting a differentiated nature. Chemically they are interesting in that they are strongly hypersthene normative hawaiites.

4.3 Chronological Relationships of the Basic Minor Intrusions

On all three islands the dykes clearly postdate at least some of the lavas. This is all that can be said of the time scale of events on Canna; no cross cutting dykes are seen and the dykes only cut the lavas or their associated conglomerates. On Muck, however, the dykes can be said to be the result of more than one phase of intrusion. The cross cutting relationship of MD31 and MD32 (see Section 4.2.3) and the dyke complexes noted (see Section 4.2.1) are evidence of this. Not only do the dykes postdate the lavas (or at least some of them), they also postdate the Camas Mhor gabbro. This intrusion was not studied in detail, but dykes were seen to intrude it.

On Eigg the most intricate intrusive sequence of all the three islands can be deduced. An early phase of intrusive activity is indicated by the fact that one of the dykes (E7476) is seen to intrude the lavas below the Grey rock but not the Grey rock itself (47188742). It is just possible that this early intrusive phase also produced the sills and dykes that intrude the Jurassic sediments. A later phase of dyke intrusion postdates the Grey rock as implied by dykes such as E7414, which cuts the Grey rock to the west of Laig Farm (46478765). The Kildonnan sheets must postdate at least one of these phases of dyke intrusion. It is not known if the second phase of dyke intrusion already described is the same as that which cuts the Kildonnan sheets (see Section 4.2.4). Similarly, the felsites of Grulin, Sgorr Sgaileach and Sron Laimrhige, all of which are cut by dykes or sheets of basic material, must postdate one of these intrusive phases. The whole series of intrusive events is postdated by the erosion, which predated the extrusion of the Sgurr pitchstone.

4.4 Statistical Analysis of the Muck Dykes

For each of the 123 dykes examined on Muck, trend of the dyke and its width were measured. Location and trend of each of the dykes are shown on Figure 4.9. The majority of the dykes examined fall into five areas, or strips, of coastline; Gallanach Bay in the north; the south coast from the western extremity of Muck to Camas Mhor beach; the south coast from Camas Mhor beach to the outcrop of the Camas Mhor gabbro; the south coast from the Camas Mhor gabbro to Port Mor; and the south-eastern coastal strip east of Port Mor (see Figure 4.9). Statistical analysis was done on these five coastal strips, to check for any geographical variation in direction of trend or abundance of dykes within Muck. As a result of incomplete surveying of the area between Port Mor and Rubh a' Chroisein (c.42657911), the south-eastern coastal strip was reduced to the area between the Cairn north or Rubh a' Chroisein (42657911) and the eastern extremity of Muck for the purposes of statistical analysis.

A summary of the collected and calculated data for the Muck dykes is given in Table 4.1. Similar data was collected and calculated for the few samples that were collected from Eigg and these are presented for comparison in Table 4.2. The method of calculation of each of the statistical values listed in these two tables is now discussed along with any deducations made by the author concerning them.

4.4.1 Average trend and strike

The average trends of the Muck dykes were calculated for the five strips of coastline examined. An overall average for the whole of the island was then calculated.

Two values are presented for the average trend of the Gallanach dykes, one including MD31, which has a trend at approximately 80° to the rest of the dykes in the area. As noted above (see Section 4.2.3), this dyke cross cuts, and is therefore younger than, a dyke with the more general trend.

Rose diagrams showing the trends of the dykes in the four strips along the south coast of Muck are presented (Figure 4.10). They show that the predominant dyke trend on Muck is approximately SSE to NNW (an average of N 156° E). The cluster of dykes around this SSE to NNW trend is maintained if the north coast dykes are included (see Figure 4.11).

The paucity of dykes examined on Eigg (32) obviously makes any average trend unrealistic. However, there is remarkably little difference between the average trend for Eigg (N 145° E) and the N 156° E calculated for Muck. This suggests that the two islands were under the same stress system when their respective dykes were intruded. It should be noted that this direction is not parallel to the line of the mid-Atlantic ridge which would have been an active spreading ridge located not too far to the west of the Hebrides in the Tertiary.

The average strike is taken as an imaginary line perpendicular to the average trend for the area under consideration. It indicates the direction along which the geotension was applied to open the fissures up which the magma arose to form the dykes. Thus rather than being under the influence of a north west-south east tension as a result of the opening of the north Atlantic, as might have been expected, the dykes of Muck and Eigg were emplaced up fissures formed by tension in WSW to ENE direction, as were many of the other dyke swarms of the

Scottish and Irish Tertiary.

4.4.2 Average width

This is simply the average of all the dyke widths in the given area. For this calculation, however, the seven dykes examined from north-west Muck were excluded as the data on the widths of these dykes was not considered to be of sufficient accuracy. The average width for the whole of Muck is just over 2 m per dyke. In terms of maximum and minimum widths, the Muck dykes range from 0.25 to 16.7 m, the latter being a rather complex dyke in Port an t-Seilich (MD 111, 42067861). For Eigg, the average width is 1.68 m, based on 22 measurements. The fact that the average for Eigg is less than that for Muck correlates with the lower abundances of dykes on Eigg as compared with Muck.

4.4.3 Percentage dykes

From the total thickness of the dykes and the length of the strip (along the average strike direction), the percentage of the rock in each strip that is made up of dyke material can be calculated. For Muck this shows some geographical variation, from a minimum of 6.24% dykes in the south-eastern coastal strip to 11.33% dykes in the area between Port Mor and the outcrop of the Camas Mhor gabbro. Perhaps this suggests that the latter area was closer to the main magma source on Muck. This would fit with the intrusion of the Camas Mhor gabbro in this area also. The average figure for the whole of Muck is a little under 10%.

For Eigg, the percentage of dykes could only be calculated for a strip on the north side of Laig Bay (see Table 4.2). A value of 6.56% dykes was calculated for this strip. This is similar to the lowest value for Muck. Relatively few other dykes were found during fieldwork on Eigg. This suggests that dykes are generally much less abundant here than on Muck.

4.4.4 Percentage extension of the earth's surface due to dyke intrusion

This is the extension of this earth's surface on Muck as a result of dyke intrusion, expressed as a percentage of the total width of the swarm. The width in the cases of the five strips was taken as the distance from the most easterly to the most westerly dyke in each strip measured along the average strike direction. It was calculated according to the following formula:-

$$E = \frac{t \times 100}{d - t} \quad \text{........... Formula 1}$$

where E is the percentage extension;

t is the total dyke thickness in the swarm;

d is the length of the dyke swarm, measured along the average strike direction.

The percentage extension was thus calculated for the five strips and then an average figure for the whole island was taken from these five figures (see Table 4.1). As expected, the greatest extension was found to occur in the stretch of coastline between the Camas Mhor gabbro and Port Mor, where the percentage dykes was also at a maximum. Similarly, the minimum extension was found in the area east of Port Mor where the percentage dykes was also a minimum. The average percentage extension for the whole of Muck is 10.43%.

The direction along which the width of the dyke swarm was measured in each calculation of percentage extension was the average strike for that particular strip. However, not all the dykes are perpendicular to this direction and therefore the width of the dykes, as measured along this average strike, will not be the same as the width measured in the field (see Figure 4.12). Thus, before calculating the percentage extension, a correction ought to be made for the angle by which each dyke deviates from being perpendicular to the average strike. The width of a dyke along any selected direction can be made according to the formula:-

$$x = \frac{t}{\sin \theta} \quad \text{............. Formula 2}$$

where x is the width of the dyke along the chosen direction;

t is the measured width of the dyke perpendicular to its trend;

θ is the angle between the trend of the dyke and the chosen direction

(see also Figure 4.12.). Correcting each dyke for its angle of incidence on the average strike direction, a revised total dyke thickness for each swarm was calculated. This was then inserted in Formula 1 in place of the total measured thickness of the dykes. Thus a percentage extension, corrected for the angle of trend of each dyke, was calculated for each of the five strips. As most of the dykes intersect the average strike direction at angles other than 90°, the width of each dyke along the average strike will be greater than the measured width. Thus the extension corrected for angle is greater than the uncorrected figure. The values arrived at for each strip by the two methods are given in Table 4.1. The average figure for the whole of Muck is 10.43% (uncorrected) and 10.6% (corrected). The crustal extension calculated for the Laig Bay area of Eigg is 5.09% (uncorrected) - see Table 4.2.

4.5 Conclusions

The most striking features concerning the basic minor intrusions is their abundance in Muck and their scarcity in Canna.

From a study of the basal conglomerates on Canna, it would appear that they and the lavas of Canna postdate the unroofing of gabbros and granophyres probably on Rhum (*see* Chapter 8). The volcanic activity on Canna (like the Rhum lavas) is thus a late-stage event in the Tertiary igneous activity of the region. The few dykes seen on Canna have a northerly trend rather than the more typical north-westerly trend of Hebridean dyke swarms. As suggested by Speight (1972), a north-westerly trending dyke swarm may well be present on Canna, but at depth - a buried dyke swarm. The northerly trending dykes are thus considerably younger than the typical north-westerly dykes of elsewhere, as they must postdate the lavas.

The high intensity of dykes on Muck was known to Harker (1908), whose data (recalculated) implies a maximum crustal extension due to dyke intrusion of 6.3%. Speight (1972) calculates a maximum crustal dilation due to dyke intrusion of 8% for Muck, while the values quoted in this thesis range from 9.72% to 12.91%, with an average for Muck of 10.60%. These values are high compared with the data quoted by Richey (1961) for the south-east coast of Mull (3.79%) and Arran (6.94%). Speight concludes that this high intensity of dykes on Muck 'suggests that a body of Central Intrusive type is located at some depth below the present level of erosion, off the south coast of the island. Indeed, the presence of the Camas Mor Gabbro in south-central Muck is in part a corroboration of this hypothesis'.

Speight (1972) found a north-westerly trending axis of maximum crustal dilation running from south east Rhum to Laig Bay, Eigg. His value for crustal dilation for Laig Bay is a little over 3%. As with his data for Muck, this is rather lower than the value quoted in this thesis (5.09%). The crustal dilation due to dyke intrusion for the rest of Eigg (as given by Speight) is between 0 and 3%, the lowest values being from the north coast of Eigg and the largest from the south-west coastal area.

CHAPTER 5

THE PETROGRAPHY OF THE BASIC MINOR INTRUSIONS

5.1 Introduction

A total of 164 samples were collected and examined in thin section from the basic minor intrusions of the islands of Eigg, Muck and Canna. Just under 100 of these were analysed to determine the chemical nature of the minor intrusions.

Microscopical examination of the intrusive samples followed the same procedure as for the extrusives (see Chapter 3) Similar petrographical groups were defined - mugearite, hawaiite and basalts. In the basalts, two additional sub-groups were added to those already found for the extrusive samples. These are plagioclase and spinel phyric basalts and dolerites.

As with the extrusive samples, a comparison was made with the chemical groupings, based on the classification of Thompson et al (1972). Again a fairly good correlation was noted (compare Tables 5.1 and 5.2). Only one of the four analysed samples from Canna was incorrectly classified (SR247); it is chemically a basalt but petrographically it was classified as a hawaiite, containing andesine. The reverse is true of one of the Eigg samples; chemically it is a hawaiite but petrographically it has labradorite plagioclase, which is more characteristic of a basalt. Two samples, one from Eigg (E7646) and one from Muck (M7609), class chemically as basalts, but appear much more differentiated, largely on account of the abundant opaque oxides, in thin section (mugearites in fact). However, both show a greater degree of silica saturation than most of the other samples, which may have caused the unusual petrographical appearance (E7646 has 0.06% normative quartz and M7609 has 17.16% normative hypersthene).

The main area in which errors in classification were made was in the Muck hawaiites. Petrographically only one was identified, but chemically there are 12. One sample is both chemically and petrographically a hawaiite (MD8). The other chemical hawaiites are more closely related to basalts petrographically. Similar difficulties arose with the extrusive hawaiites, emphasising the problems involved in the petrographical classification of fine grained rocks.

The relative abundance of each petrographical type within the three islands was examined (summarised in Table 5.3). The relative abundances of the extrusive rock petrographical types are given for comparison (Table 5.3). Over all three islands, aphyric basalts are the most abundant group (26.2%), closely followed by the plagioclase and olivine phyric basalts (22.6%). As with the extrusive rocks, the plagioclase and olivine phyric basalts are by far the most abundant group in Canna (37.5% of all intrusives). In terms of the three chemically defined groups, again the basalts dominate - well over 80% of all intrusive rocks in Eigg and Canna and over 90% of all intrusives on Muck. Canna shows the greatest abundance of differentiated types (petrographically defined only) - 13.7% for Canna as compared with the three island average of 10.4%.

It is interesting to note that the plagioclase and olivine phyric basalts were also a prominent rock type in the extrusive rocks (29.9% of all extrusives). However, olivine phyric basalts, which were second in abundance to the plagioclase and olivine phyric basalts in the extrusives, are reduced to third place in the intrusives in favour of the aphyric basalts. This greater abundance of aphyric basalts in the intrusives is reasonable if the cooling took place more slowly in the environment of intrusive rocks as compared with their extrusive equivalents. This would allow the grains to achieve approximately equal dimensions irrespective of mineral type and when the mineral started to crystallise.

Each of the different petrographical types is now described in detail. In all cases, where equivalent groups occur in the extrusive rocks, the definition of the group (whether by phenocryst content or by plagioclase composition) is compared.

5.2 The Basalts

These are defined in exactly the same way as for the extrusives and similarly divided into subgroups on the basis of their phenocryst content (see Chapter 3). In the case of the intrusives however, two additional subgroups have been added to those already defined for the extrusives. These are plagioclase and spinel phyric basalts and dolerites, the latter being coarse grained equivalents of the aphyric basalts. As with the extrusives, no one island possesses all the basalt subgroups. With the intrusives it is Muck which shows the most variety in basalt types (11 out of the 12 subgroups are represented). This can only be expected from the great abundance of dykes on Muck; Eigg, where the lava pile is thickest, showed the most variety in extrusive basalt types. Canna, on the other hand, has fewest dykes of all three islands, and similarly has least variety in the basalt types present in the samples examined (5 out of the 12 subgroups).

5.2.1 Aphyric Basalts

These are the samples with no phenocrysts and an average grain size less than 1 mm. The average grain size for the subgroup is about 0.4 mm, although the plagioclases sometimes reach 0.8 mm in length (e.g. MD94). Aphyric basalts with an average grain size greater than 1 mm are classified as dolerites (see Section 5.2.2). Mineralogically, the aphyric basalts are composed of olivine, plagioclase (of labradorite composition), clinopyroxene and opaque oxides.

Four different types of clinopyroxene were identified. Most common is the dark brownish pleochroic variety. The samples from Eigg are a dark pink colour and are only slightly pleochroic. Those from Muck and Canna are the more usual dark brown-purple to orange-brown pleochroic variety seen in the extrusive rocks.

A second type of pyroxene found in the aphyric basalts of Eigg and Muck is a lighter colour. A similar distinction is seen between the two islands; those from Muck show much stronger pleochroism. A third type is seen in the Eigg and Muck samples - a colourless, grey or pinkish brown, non-pleochroic variety. A fourth type, seen in Muck and Canna, are grey or colourless to faintly brown, and are pleochroic. The two darker pleochroic varieties are the most common type seen.

The extrusive aphyric basalts predominantly showed ophitic relationships between the pyroxenes and the plagioclases. The intrusives are more usually granular, often with evidence that the pyroxenes started to crystallise before the plagioclases.

Several examples of zoned pyroxenes were noted (e.g. MD62, MD15, MD94 and T504). In all cases, as with the zoned pyroxenes in the extrusives, the darker colour is at the margins of the zoned crystals. Also, as with the extrusives, the intrusive aphyric basalts occasionally show a glassy mesostasis (e.g. MD64 and T506). This is usually brownish in colour and charged with abundant opaque oxides.

5.2.2 Dolerites

The dolerites are aphyric basalts with an average grain size greater than 1 mm. In some of the samples, the average grain size is as great as 3 mm (e.g. MD55B). In most respects they are similar to the aphyric basalts, with the exception of the coarser grain size. Zoning in olivines and plagioclases was noted in two samples (E7435 and MD11A respectively). In one sample (MD11B), spinel inclusions were found in the olivines.

Only two of the pyroxene types noted in the aphyric basalts were found in the dolerites. These are the faintly pleochroic colourless to pink-brown variety and the light purple-brown to orange-brown pleochroic type. Of these two types, the faintly pleochroic pyroxenes are the more common.

The predominant texture in the dolerites is sub-ophitic. Only one dyke (MD55A) shows granular pyroxenes. One of the samples from Eigg (E7435) has huge poikolitic clinopyroxenes, which frequently totally enclose plagioclase laths. They also show zoning from colourless cores to pink-brown, faintly pleochroic margins.

Many of the dolerites (e.g. C7581, T501 and E7414) have skeletal opaque oxides in the matrix. In E7414 these are set in a glassy groundmass, which forms a small proportion of the whole rock.

The presence of glassy mesostasis and skeletal opaque oxides suggests a late stage quenching of an already largely crystalline magma. This implies that at least some of the doleritic minor intrusions were intruded as a mush of crystals set in a small amount of interstitial liquid which now forms the glassy mesostasis.

5.2.3 Olivine phyric basalts

This type of basalt is much less common in the intrusives than in the extrusives. Even in Muck, where they are the second most abundant type of basalt (22% of all intrusions), they are less common than in the intrusives (44% of all extrusives). They are very rare in Eigg and Canna, only one sample from each island falling in this group. In overall mineralogy they are very similar to their extrusive equivalents (see Section 3.3.2).

The phenocrysts range in size from a few tenths of millimetres up to 2 mm across. All stages of alteration also exist. Zoning of the phenocrysts is occasionally detectable in the fresh samples, and in three of them (MD28, MD47 and MD61) the olivine phenocrysts include small spinels.

Only one sample (MD14) shows more than one generation of phenocrysts. The earlier larger grains are rather badly altered and corroded by the matrix. The smaller ones are fresh, enclose spinels and are normally zoned. The enclosed spinels are brown in colour.

Three different types of pyroxene may be identified on the basis of colour and intensity of pleochroism. The most abundant variety are dark brown to orange-brown ones. The samples from Eigg and Canna have this type of pyroxene. Light purple-brown to orange-brown pleochroic variants are also fairly abundant. Faintly pleochroic grey or colourless to pink-brown pyroxenes are least abundant type.

Texturally, ophitic relationships between the pyroxenes and the plagioclases predominate. Granular relationships are seen in a few samples only, for example, MD104 and MD107, where the pyroxenes can be seen to predate the plagioclases. Zoning in the pyroxenes was noted in a few samples (e.g. MD5, MD13, MD28 and MD60).

Trachytic textures are very rare in these samples. Two of the Muck samples do show faint alignment of the plagioclases (MD40(1) and MD70). This is best seen where the plagioclase laths are deflected around phenocrysts.

Glassy patches in the matrix are rare, being seen in only one sample (MD40(1)). The glass is colourless and heavily charged with opaques. Another of the Muck samples placed in this subgroup (MD105) has olivine phenocrysts set in an almost completely glassy matrix. As is usual in such samples, the glass contains light brown embryonic pyroxenes charged with opaque oxides.

One rather unusual sample was noted (MD12). It contains rounded patches of finer grained material. These are not like the other xenoliths seen - they have no definite margins, appearing to merge with the matrix of the host rock. They may represent xenoliths which have been partially digested by the magma

5.2.4 Plagioclase phyric basalts

As with the extrusives, plagioclase phyric basalts are rare in the intrusives (6% of the total intrusives). No plagioclase phyric basalts were found among the intrusives from Canna.

The plagioclase phenocrysts range in size from 0.7 mm (MD95) to 5 mm (MD91) in length. Most of them show predominantly Carlsbad twinning with polysynthetic twinning (e.g. MD53 and E7409) or solely Carlsbad twinning (e.g. MD82). They often show considerable corrosion by the matrix. The composition was measured for one sample (MD37(2) - 59% anorthite). Matrix plagioclases, where measurement was possible, also proved to be labradorite

Zoning was occasionally detected in thin section examination of the phenocrysts. In one sample (MD37(2)) strong oscillatory zoning was seen. Another (MD67) showed phenocrysts with unzoned cores surrounded by lines of inclusions parallel to the margins. The marginal parts of these phenocrysts, outside the lines of inclusions, show strong zoning.

Three different types of pyroxene were found in the plagioclase phyric basalts: dark purple-brown to orange-brown pleochroic types; light purple-brown to orange-brown pleochroic variants, and non-pleochroic, usually brownish pyroxenes. All three types occur in approximately equal abundance. In two samples (MD57B and MD95), embryonic type of pyroxene was found. This appears, on initial examination, to be a brown glass crowded with tiny opaques. Texturally, the pyroxenes, irrespective of colour or intensity of pleochroism, show all ranges between granular and ophitic relationships with the plagioclase laths.

One sample (MD82) shows pyroxenes of two different habits. One is granular, similar to the other samples with this type of pyroxene. The other pyroxene in MD82 is fibrous and charged with abundant tiny opaques. The granular pyroxenes appear to predate the plagioclase laths and the fibrous ones are thought to be a late stage mineral, perhaps of a quench origin like the embryonic pyroxenes discussed above.

5.2.5 Plagioclase and olivine phyric basalts

This subgroup is second in abundance to the aphyric basalts in the intrusives (22% of all intrusive rocks of the three islands). As with the extrusives, the basalts with plagioclase and olivine phenocrysts are very abundant in Canna (37.5% of all the Canna intrusives), and least abundant in Eigg (12% of all Eigg intrusives). In terms of general mineralogy, this subgroup is similar to the equivalent subgroup of the extrusive rocks (Section 3.3.4).

A considerable range in sizes of the phenocrysts is seen. The plagioclases vary from 0.2 mm to 5.5 mm in length, the olivines from 0.3 mm to 3 mm across. Occasionally the two phenocryst phases are found in glomerophyitic groups (e.g. MD39 and T512). The olivines can usually be seen to predate the plagioclases.

In terms of relative abundances of the two phenocryst phases, all possible variations are seen. In Canna, plagioclase phenocrysts predominate over olivines. In Eigg and Muck, all three possible combinations exist in roughly equal proportions.

The plagioclase phenocrysts are usually of labradorite composition, the actual measured range being from An_{49} to An_{71}. Rarely, very large plagioclases (up to 5.5 mm in length) occur, sometimes accompanied by smaller, more abundant phenocrysts. The large ones are usually very corroded and may well be xenocrysts. Two generations of plagioclase phenocrysts are seen in MD85. The large phenocrysts (up to 5.5 mm) have unzoned cores with strongly zoned marginal parts outside lines of inclusions, which parallel the margins. The second generation show similar zoning. The large crystals are probably xenocrysts, which have been overgrown at the time of crystallisation of the second generation of phenocrysts. Other samples also show zoning, usually confined to the margins of the crystals (e.g. T511 and T512). Rarely the plagioclase phenocrysts show parallel alignment (e.g. C7506), a feature also seen occasionally in the groundmass plagioclases (e.g. MD96(1)).

The olivine phenocrysts usually predate the plagioclases and often show spinel inclusions (e.g. MD92, MD63 and E7447). Zoning was noted in some of the olivines (e.g. MD48) and some of them show corrosion (e.g. MD17). Only one sample (MD77) shows two generations of olivine phenocrysts. The earlier ones are larger and more corroded than the later smaller ones. The former also have spinel inclusions.

The clinopyroxenes show all four variations of colour and pleochroic intensity that have already been noted in other subgroups. Embryonic pyroxenes, crowded with tiny opaques, occur in a few samples (e.g. MD57A and MD85). Zoning of the pyroxenes was also noted occasionally (e.g. E7449 and T512), in all cases having the darkest colour at the margins of the crystals. All variations from granular to ophitic textures are found in equal proportions.

5.3 Other Types of Basalt

Just under 13% of all the intrusives of the three islands do not fall into any of the groups defined above. On Canna, only 8% of all the intrusives cannot be classified in any of the above groups. On Eigg, however, as with the extrusives, quite a high proportion of the intrusives (18% of them all) cannot be placed in the groups already defined.

Three further basaltic subgroups can be defined -

Basalts with olivine as the major phenocryst phase;

Basalts with plagioclase as the major phenocryst phase;

Basalts with olivine and plagioclase phenocrysts in equal proportions.

Of these three subgroups, those with both olivine and plagioclase phenocrysts are the most common, closely followed by those with plagioclase as the major phenocryst phase.

5.3.1 Basalts with olivine as the major phenocryst phase

This type of basalt is confined to Eigg and Muck. Spinel or clinopyroxene join the olivine as phenocryst phases. Olivine and clinopyroxene phyric basalts are confined to a single sample from Eigg (E7666).

The general characteristics of these basalts are similar to the olivine phyric basalts (see Section 3.3.3). The clinopyroxene phenocrysts are usually less than 1 mm across, and often show considerable corrosion. They are predominantly brownish in colour and predate the olivines, being often seen included within the olivine phenocrysts as well as occurring as microphenocrysts.

All four variations in colour and pleochroic intensity of the matrix pyroxenes is seen. The type can be correlated with the phenocryst content of the basalt. Colourless, non-pleochroic varieties are confined to some of the olivine and spinel phyric basalts from Eigg. Other olivine and spinel phyric basalts from Eigg have dark purple to orange-brown pleochroic pyroxenes, while those of Muck mainly have the lighter purple to orange-brown pleochroic variants. Faintly pleochroic pink-brown to colourless pyroxenes are confined to the olivine and clinopyroxene phyric basalt from Eigg and to a few of the olivine and spinel phyric basalts of Muck.

5.3.2 Basalts with plagioclase as the major phenocryst phase

Basalts of this type are confined to Muck (MD56C and MD73). Clinopyroxene or spinel join the plagioclase as a phenocryst phase. Both samples show flow alignment of the plagioclase phenocrysts, which are of labradorite composition.

The spinel phenocrysts (in MD56C) are small (0.3 mm across) and are fairly rare. They often occur in groups. The matrix of this sample is very fine grained with embryonic clinopyroxene, abundant plagioclase laths, tiny olivine anhedra and abundant small opaque oxides.

The clinopyroxene phenocrysts (in MD73) are rare and fairly small (max. 0.8 mm). They are brown in colour and the larger ones usually have many inclusions. The matrix of this sample has pseudomorphs after olivine anhedra, abundant plagioclase laths and opaque anhedral grains in addition to granular pyroxene. The pyroxene in the matrix is faintly brown, non-pleochroic and appears to predate the plagioclases.

5.3.3 Basalts with olivine and plagioclase phenocrysts in equal proportions

This is the most abundant subgroup of the 'other types of basalt'. Clinopyroxenes or spinels join the plagioclases and olivines as phenocrysts. Of these two types, the olivine, plagioclase and clinopyroxene phyric basalts are the most abundant (4.3% of all intrusives).

The major phenocrysts are similar to those of the plagioclase and olivine phyric basalts (see Section 5.2.5). The spinel phenocrysts are dark brown in colour and are fairly small (on average 0.5 mm across). They predate the olivine phenocrysts and often occur within them. Usually their relationships with the plagioclases cannot be determined directly. However, the olivines normally predate the plagioclases. Thus the overall order of crystallisation of the phenocrysts was spinel followed by olivine and finally plagioclase.

The clinopyroxenes vary in colour from colourless to pink-brown, and range in size from 1 to 2 mm. Usually they are not pleochroic, but the pyroxenes in C7523 show faint pleochroism from colourless to light pink-brown. Those in E7403 are zoned with the darker colours at the margins. Another of the Eigg samples (E7613) has clinopyroxene phenocrysts with late stage ophitic overgrowths. Those in C7523 show euhedral outlines, but the rest all have anhedral pyroxenes.

One of the Eigg samples (E7403) has four different types of plagioclase phenocrysts in addition to olivine and clinopyroxene phenocrysts. It was possible to deduce the order of crystallisation of these various phenocryst types. First to crystallise were the olivines followed by the earliest of the plagioclases (twinned and unzoned laths). These were followed by the second plagioclases - these showing strong oscillatory zoning often with abundant inclusions. The pyroxenes then crystallised along with the cores of the third phase of plagioclases. This third phase of plagioclase phenocryst growth is characterised by oscillatory zoning in the cores overgrown by margins with normal zoning. The fourth type of plagioclase, the final phenocryst phase to crystallise, has normal zoning like the margins of the third phase. The margins of the third phase are probably coeval with the fourth phase.

5.4 The Differentiates

These are distinguished from the basalts in the same way as for the extrusive rocks (see Chapter 3) - by the sodic nature of the plagioclase (less than An_{50}). They exhibit similar fine grain size and vesicular nature as their extrusive equivalents. However, vesicles and jointing are common features of many of the intrusives irrespective of composition.

5.4.1 Hawaiites

As with the extrusive hawaiites, the intrusive ones are distinguished by having plagioclase of andesine composition. More accurate determinations of the plagioclase compositions were possible than with the extrusives and the compositions found are mostly calcic andesines. The rule of small extinction angles indicating andesine was applied to the intrusives as with the extrusives.

Many of the intrusive hawaiites are glassy (all except SR247). Those from Eigg (E7446 and E7615) have skeletal opaque oxides in the groundmass. Under high magnification these skeletal oxides prove to be lines of tiny opaque euhedra.

Apart from the ubiquitous plagioclase and opaque minerals, other minerals found in the hawaiites include olivine (usually pseudomorphed) and clinopyroxene. Two types of pyroxene were noted - colourless to faintly pink, non-pleochroic varieties (e.g. E7446) and darker, orange-brown pleochroic types (e.g. SR247).

Phenocrysts seen in the hawaiites include olivine (pseudomorphed), plagioclase and spinels. The spinel 'phenocrysts' of MD8 resemble late stage pyrite veins and patches under reflected light. Unfortunately it was not possible to optically determine the plagioclase phenocryst compositions.

The seven chemical hawaiites not originally so classed petrographically were re-examined more closely. Determination of some of the plagioclase compositions (in MD56A, MD72 and MD110) revealed calcic andesine in the matrix, although in MD56A this was accompanied by labradorite phenocrysts (An_{54}). The remaining four chemical hawaiites more closely resemble basalts petrographically, many of them having labradorite in the groundmass.

5.4.2 Mugearites

All the mugearites are fine grained or glassy rocks with identifiable plagioclase laths and opaque crystals. As with the extrusives, the plagioclases were often too small to allow accurate determination of the composition, but straight extinction of the laths was presumed to indicate an oligoclase composition.

Many of the mugearites are aphyric or have small plagioclase and opaque crystals set in a glassy matrix (e.g. T503). Phenocrysts observed include plagioclase, small spinels and clinopyroxene. Olivines, or pseudomorphs after olivine, were observed in two of the samples (M7609 and MD36M). In M7609 they are accompanied by plagioclase of labradorite composition. Both the plagioclase and olivine phenocrysts may be of xenocrystic origin.

The groundmass mineralogy, when this may be accurately determined, is usually dominated by abundant opaque oxide crystals and oligoclase laths. The oligoclase showed a trachytic texture in a few samples (e.g. MD1 and MD108). Clinopyroxene is not always identified, but when present, it is either in colourless, or brownish grains of granular habit, or it is of an embryonic nature. This latter type of pyroxene is found in the glassy and extremely fine grained mugearites (e.g. MD36M and M7609). It appears as a brownish glass densely crowded with opaque oxides. Biotite is occasionally seen (e.g. M7606) and in one sample, apatite was found (MD1).

Three of the mugearites show inclusions of foreign material. MD36M contains rounded dark brown glassy areas heavily charged with opaque oxides. These are probably blobs of more quickly cooled magma which became incorporated in the dyke during intrusion. It is interesting to note that this sample is from the margin of a dyke. Perhaps the inclusions represent the chilled margin of an earlier intrusion along the same line of weakness. MD108 shows coarse grained inclusions. They are circular in outline and the matrix is seen to deviate around them. Thus they must have been in a solid state when they were incorporated into the magma forming this dyke. The inclusions consist of plagioclase and an amphibole, which shows dark brown to green pleochroism and has a small extinction angle. This dyke is near to the Camas Mor Gabbro (see Figure 4.9); the inclusions may be, in some way, connected with the gabbro, or with some hydrothermal alteration it may have caused.

The third minor intrusion to show inclusions is M7606. The inclusions in this dyke are of quartz, calcite and opaque minerals. The calcite and opaque oxides are marginal while the quartz (sometimes radially arranged) occurs in the central parts. This arrangement suggests that they are cavity infills rather than inclusions (in the strict sense of that word). They are very numerous, so much so, that the outcrop was designated acidic in the field. It outcrops near the Jurassic sediments of Camas Mor. Perhaps the cavities are infilled with material derived from these sediments.

CHAPTER 6

THE ACID ROCKS OF EIGG - FIELD RELATIONSHIPS

6.1 Introduction

Eigg is the only one of the three islands to exhibit any acidic igneous rocks *in situ*. Canna has acidic pebbles contained in the conglomerates, which occur at, or near, the base of the exposed sequence of lavas. These are probably not of local origin, and are thus considered along with the other fragmental rocks (*see* Chapter 8).

The acidic rocks of Eigg occur as two distinct groups - the Sgurr of Eigg, an extrusive pitchstone; and several relatively small intrusions of felsite and pitchstone. The terms 'pitchstone' and 'felsite' are used here to describe porphyritic glass and finely crystalline, light coloured rock, respectively, in accordance with earlier work on the islands (e.g. Harker 1908). Petrographical classification of the two rock-types is given in Chapter 7, geochemical nomenclature of the various samples is given in Chapter 11.

6.2 Extrusive Acid Rocks

The only extrusive acid rock on Eigg is the pitchstone which forms the high ground in the south-west of the island. The term 'Sgurr of Eigg' or 'Sgurr pitchstone' will be used here to refer to the whole of the pitchstone ridge from An Sgurr (46008475) to just north of Bidein Boidheach (44158665), along with the two subsidiary ridges of pitchstone that join the main ridge from Beinn Tighe (44808690) and Cora-bheinn (45908560). The main ridge is almost

3 km long, with a maximum width of 460 m, and a minimum of 100 m. It runs in a sinuous course, approximately north-west to south-east, while the two subsidiary ridges run east to west, in the case of Corabheinn, and north-east to south-west for Beinn Tighe.

The origin of the Sgurr pitchstone was the subject of considerable controversy at the beginning of this century. Harker (1906) concluded that it was of intrusive origin, in complete contrast to the well accepted idea of Geikie (see Chapter 1 for details of references), who considered it to be a lava flow, infilling an old river valley. These hypotheses are discussed in the light of the author's own observations.

6.2.1 Field observations

The main field work on the Sgurr pitchstone, and its associated rocks, was done in August and September 1976. The base of the pitchstone was mapped throughout, and some of the non-columnar, felsitic bands were examined and sampled. The location, nature and fragmental content of the sub-pitchstone breccias and conglomerates were also noted, some of the fragments being sampled. A map of the pitchstone, with details of sample localities and field observations, is included (Figure 6.1).

All the evidence discussed below points to an extrusive, rather than intrusive, origin for the pitchstone. Nowhere is it seen interleaved with lavas. The basal breccia, the flow banding, which parallels the base, and the columns orientated perpendicular to the base all tend to support the extrusive hypothesis (Geikie's hypothesis rather than Harker's).

6.2.1.1 The base of the pitchstone and the age of the extrusion

The base of the pitchstone follows an undulating course. It can be seen to cross-cut the basalts near the Nose (46368470) - see Figure 6.2, and where the pitchstone projects to cut out a plagioclase-phyric basalt flow, approximately 300 m south-east of the south end of Loch Beinn Tighe (45208616). The pitchstone must therefore postdate, not only the extrusion of the basalts, but also a considerable period of erosion, during which an undulating topography developed. Further evidence for such a period of erosion lies in the exposures of conglomerate found at certain localities below the pitchstone (see Section 6.2.2 for details). The conglomerates are thought to be of fluvial origin, which implies development of a landscape with rivers on Eigg, prior to the extrusion of the pitchstone. All the evidence points to a considerable time-gap between the extrusion of the lavas and the pitchstone.

Near Bidein Boidheach (44098670) and The Nose (46368465), basic dykes are seen to be truncated by the pitchstone itself, in the case of Bidein Boidheach, and by its brecciated base, in the case of The Nose. These localities are reproduced in Figure 6.4a and 6.4b. The pitchstone therefore postdates the intrusion of the basic dykes on Eigg.

6.2.1.2 Column orientations

With the exception of the felsite sheets (see below - Section 6.2.1.4), the pitchstone is columnar. In general, the columns are perpendicular to the base of the pitchstone (with the exception of some of the columns away from the base). This is well illustrated just north of Lochan Nighean Dughaill (45128573), where the pitchstone 'flows' over a small hillock in the pre-pitchstone topography, and the columns fan accordingly, to maintain perpendicularity to the base.

The column orientations were not studied in detail. Where observations could be made concerning their relationships to the base of the pitchstone, they could be shown to be approximately perpendicular to the base. Only in the upper parts of the flow, where bizarre fans and contorted smaller columns are to be found, was this rule seen to fail.

Columns will form perpendicular to the cooling surface, or more correctly, perpendicular to the isothermal planes set up in the rock as it cools. The isothermal planes must parallel the base and top of the flow, as these are the points of greatest heat loss. This allows the formation of two sets of columns long, thin, irregular columns, which originate at the upper cooling surface (the top of the flow), and short, thicker and more perfectly formed columns from the base of the flow, (discussion after James 1920). This is exactly the type of columns seen in the Sgurr pitchstone. Thus it is very reasonable that, in the lower parts of the pitchstone, the columns should faithfully follow the base. At the top of the flow no such arrangement could be expected, as the cooling surface influencing column development would have been the top of the flow. The upper surface need not parallel the base, and it is very likely to be highly irregular in a viscous magma, such as the Sgurr pitchstone must have been. An irregular upper surface would help to explain the bizarre fans and contorted nature of the smaller columns found in the upper parts of the pitchstone.

6.2.1.3 Flow banding

Throughout most of its outcrop, the pitchstone shows flow banding, within a few metres of the base. This is well seen along the base of the pitchstone, from Loch Beinn Tighe (45008650) to Lochan Nighean Dughaill (45158560), around Beinn Tighe (44808684) and Cora-bheinn (45678554) and along parts of the north side of the An Sgurr ridge (e.g. 44908565). In the field, the banding is seen to be due to variation in the colour of the pitchstone - an alternation of light and dark bands, each a few centimetres thick (see Figure 6.5). In thin section, the dark bands are seen to be areas of glass, while the lighter coloured streaks are devitrified to a mat of tiny microlites of feldspar.

Where the dip of the base of the pitchstone can be seen, the flow banding is usually of the form of a regular planar surface, parallel to the base of the pitchstone (e.g. along the north side of An Sgurr, where the flow banding dips to the south, and the base of the pitchstone can be inferred, from the exposures at the east end of An Sgurr (46488463), to dip to the south also). Minor irregularities occur locally, where, for example, hillocks existed in the pre-pitchstone topography (e.g. just north of Lochan Nighean Dughaill (45128573), where the flow banding curves parallel to the base, as the pitchstone covers the hillock). More prominent irregularities are suggested at three other localities:-

1. Along the east side of Lochan Nighean Dughaill (45158570), where the flow banding is contorted;
2. 400 m west of Lochean Nighean Dughaill (44738551), where it is also contorted;

3. Along the north side of the An Sgurr ridge (45738488), where it is vertical for a short distance.

In general, where the pitchstone is flow banded, it does not show brecciation at the base. The only exceptions to this occur where the flow banding is markedly contorted, for example, 400 m west of Lochan Nighean Dughaill, and on the east side of that lochan, where, within a few metres of each exposure showing contorted flow banding, there are exposures of brecciated basal pitchstone. It is perhaps significant that fragments of brecciated, flow banded pitchstone predominate in the basal pitchstone breccia, implying that the pitchstone was originally flow banded. Thus three different situations can be defined.–

1. Flow banded pitchstone, with no brecciation at the base (e.g. along the south-west side of Loch Beinn Tighe – 48808650),

2. Contorted flow banding, with a brecciated base (e.g. 400 m west of Lochan Nighean Dughaill – 44738551);

3. No flow banding, but brecciation at the base, with fragments of flow banded pitchstone in the breccia (e.g. at the east end of An Sgurr – 46368465).

This is suggestive of three degrees of irregularity of the pre-pitchstone topography. Where there are few irregularities, the pitchstone is not brecciated and may develop flow banding; contorted flow banding and a brecciated base suggest a greater degree of irregularity; a lack of flow banding, with abundant fragments of flow banded fragments in a basal breccia, suggests an even more irregular topography. This is further discussed when the nature of the pre-pitchstone topography has been described (see Section 6.2.5).

Dip and strike of the flow banding in the pitchstone was measured, where possible; this is recorded on Figure 6.7. With a few exceptions, the dip directions of the flow banding points inwards along all margins of the pitchstone. Assuming that the flow banding follows the base of the pitchstone, this suggests that the pitchstone flowed out over a valley in the underlying topography along most of the length of its outcrop.

Strike directions of the flow banding, as derived from a number of pairs of apparent dip readings, virtually always parallel the local strike direction of the base of the pitchstone. The amount of dip varies from a minimum of 11° (recorded at three localities near Cora-bheinn - 45778555, 45688556, 45198565) to a maximum of 85° (300 m south-south-east of Loch Beinn Tighe - 45188614). The relationships of the dips to the slope of the pre-pitchstone topography will be discussed in Section 6.2.5.

6.2.1.4 Felsite sheets in the pitchstone

Along the south and west faces of the main pitchstone ridge, from near The Nose (46368465) to the south end of Beannan Breaca (44808590), the columnar pitchstone is cut by at least four separate sheets of more easily weathered, yellowish, non-columnar rock, referred to as felsite in this Section (*see* Figure 6.3). Most of these are sheet-like in form, but some (e.g. that are seen about 20 m above the base of the pitchstone, 400 m south of Loch nam Ban Mora - 45718469) are more lensoid in shape.

The relationships of these felsites to the pitchstone, as seen at outcrop, are variable. In some places (e.g. 500 m south-west of Loch nam Ban Mora - 45028490), the sheets are seen to interdigitate with the pitchstone, and thus can be said to have an intrusive relationship towards the pitchstone. At several other localities, they die out rapidly (e.g. 700 m north-west of Grulin Uachdrach - 45408570), also suggestive of an intrusive origin. In at least two places (400 m south-west of Loch nam Ban Mora - 45108401, and on the south side of An Sgurr - 45908468), the sheets appear to merge into the pitchstone, suggesting that at least some of the felsite sheets are closely related to the pitchstone. A further indication of this close relationship can be seen 250 m west of Botterill's Crack (46888469), where flow banding appears in the upper 0.20 m of the felsite sheet, and this flow banding passes upwards, without a break, into the overlying pitchstone.

Other occurrences of felsite, within the pitchstone, include a sheet, which cuts the flow banding at the base of the pitchstone, and is therefore definitely intrusive. This occurs 300 m north-west of Lochan Nighean Dughaill (44818573). Two sheets, about 20 m above the base of the pitchstone, outcrop at the south-west end of Beannan Breaca (from 44798591 to 44838596). They die out rapidly and are probably intrusive. Two sheets are seen at the base of the pitchstone, at the north end of Beannan Breaca (44448693) and along the east side of Beannan Breaca (44758650). The relationships of these sheets to the pitchstone are unknown.

Only one example of a dyke-like body of felsite, intruding the felsite, was found. This is located in a gully, approximately 500 m north-north-west of Lochan Nighean Dughaill (c. 44938619).

The weight of evidence points to an intrusive origin for the felsites. This is contrary to the ideas of Geikie (1892), who thought that the banding in the main pitchstone ridge represented successive flows of pitchstone and felsite. It is in accord with Harker (1906) and particularly with Bailey (1914), who decided that the felsites were intrusive into the pitchstone. However, the fact that in some places the felsite bands merge with the pitchstone, suggests that the two rock types are closely inter-related. The felsites seem to be mainly confined to the areas where the pitchstone is thickest (e.g. along the south side of An Sgurr - 46008470). The sheets were probably formed by some process akin to auto-injection. If there was sufficient insulation (and this would tend to occur where the pitchstone was thickest), small volumes of pitchstone could remain mobile, while the rest of it consolidated. Should these then become mobilised, partially intrusive felsite bodies would be expected to form. If this mechanism is correct then one could expect the felsites to be chemically more evolved than the surrounding pitchstone (see Chapter 11 for discussion).

6.2.2 Pre-pitchstone/post-basalt fragmental rocks

The conglomeratic deposits, which outcrop between the pitchstone and the basic lavas of Eigg, can be divided into two groups:- a discontinuous sub-pitchstone breccia, which is essentially the basal flow breccia of the pitchstone; and isolated outcrops of polymict conglomerate, which probably represent fluvial deposits in a valley system. Where the two deposits are found together, the conglomerate always underlies the breccia. At some localities, however, the two seem to be intermixed.

6.2.2.1 The conglomerates

At three localities, conglomeratic deposits are found below the pitchstone.

1. At the north-west end of the pitchstone ridge, near Bidein Boidheach (44098670), there is a lens-shaped outcrop of conglomerate at the cliff edge (see Figure 6.4a). Its shape is highly suggestive of a fluviatile origin, and this fits with the way that the flow banding in the pitchstone at this locality suggests a valley in the pre-pitchstone topography On the north side of the pitchstone at this locality, there is no conglomerate, the pitchstone rests directly on basalts. The basalts are out by a dyke, which itself truncated by the pitchstone. South of the outcrops of pitchstone, the conglomerate is just accessible at the cliff edge. It was observed to contain rounded pebbles of dark red sandstone and basalt, all of a relatively small size (probably around 0.20 m in diameter). Sampling proved impossible, due to a sheer drop of about 150 m here. The conglomerate is thought to attain a maximum thickness of 40 m. This agrees fairly well with Harker (1908), who estimates its maximum thickness at 100 ft (30.3 m).

2. Just below the base of Collie's Cleft (46308460), a conglomerate, composed predominantly of large (often over 1 m across) basaltic pebbles, outcrops. The different types of basalts represented include feldspar-phyric, light coloured feldspar-phyric, aphyric, and highly vesicular basalts. One shows vesicles arranged in rows parallel to each other, reminiscent of some of the dykes seen locally. The smaller pebbles are well rounded, suggesting water transport over a fairly lengthy period, the larger ones are less well rounded.

   In all, there are four outcrops of this basaltic conglomerate in this area, suggesting a total thickness of around 20 m.

The lower parts of the exposures contain a few small (0.05 m across) rounded pebbles, largely of metamorphic origin, in addition to the rather poorly rounded larger pebbles. The uppermost exposure reveal the contact of the basaltic conglomerate and the overlying pitchstone breccia. The junction is gradational - foreign pebbles decreasing upwards and being replaced by pitchstone fragments.

The conglomerate was sampled at all four localities. These are listed and the samples described in Section 6.2.3.

3. West of Botterill's Crack (46068462) for a distance of about 150 m, there is a recess below the pitchstone. Here in April 1976, a trench was excavated in the floor of the recess by the author and Dr. Hudson (of Leicester University). The following is an account of and the results of this excavation.

Figure 6.6 shows a plan of the area studied. The trench revealed a continuation of the pitchstone breccia, which can be seen outcropping below the pitchstone. It is the ease with which this breccia weathers that has caused the recess to form in the first place. The continuation of the breccia downwards is essentially the same as the exposed breccia, except for the presence of small (less than 0.02 m across) foreign pebbles (basalt and dark red sandstone) and also fragments of wood. The foreign pebbles and the wood fragments increase in abundance with depth. Pitchstone fragments disappear quite rapidly at a depth of about 0.20 m. The remaining 0.56 m to the base of the hole reveals a conglomerate, which consists predominantly of basalt fragments (0.01 to 0.02 m across), with some dark red sandstone pebbles and wood fragments, in a black carbonaceous matrix. There is an apparent passage from the pitchstone breccia down into this conglomerate. Various samples were collected at different levels within the trench, and these are described in Section 6.2.3.

Some very large boulders (c.1 m across) occur near the trench in the recess. These occur on a level with the top of the hole, and are therefore above the level where the pitchstone fragments die out in the trench (see Figure 6.6). However, the base of the pitchstone at this locality shows a dip of about 20° to the north. Thus the base of the pitchstone breccia could also rise to the south, assuming that it parallels the base. A dip of 20° to the north would easily take the breccia above the boulders.

One further occurrence of conglomerate is seen about 100 m west of Loch Caol na Cora-bheinn (45368547). However, it contains a significant proportion of pitchstone fragments, and it is described with the breccias (see Section 6.2.2.2).

6.2.2.2 The breccias

A breccia is seen at the base of the pitchstone at six localities. The predominance of pitchstone fragments in this deposit has led the author to assume that it represents the broken-up base of the pitchstone. That the pitchstone has such a breccia at its base, supports the hypothesis that it is a flow rather than an intrusion.

The breccia, as it is seen at each of the six localities, is described below.

1. Near The Nose (46368465), there is about 2.5 m of breccia

between the basalts and the pitchstone (see Figure 6.4b). The lower part of the breccia is of variable thickness (the average is about 0.50 m), as a result of the stepped topography of the underlying basalts. It is composed of angular fragments of basalt (including one which is identical to the dyke, which intrudes the basalts at this locality). There is very little matrix. This passes upwards, by the sudden incoming of pitchstone fragments and the less rapid disappearance of basalt fragments, into a breccia consisting primarily of fragments of flow banded pitchstone in a yellowish matrix. The matrix was sampled and is described in Section 6.2.3.

2. In the recess below the pitchstone, west of Botterill's Crack (46008460), 2 to 3 m of pitchstone breccia is seen below the base of the pitchstone. It is very similar to that seen at The Nose - angular fragments of flow banded pitchstone in a yellowish matrix. A few basaltic pebbles were also noted. In the excavation by Dr. Hudson and the author (see Section 6.2.2.1), the pitchstone breccia was seen to continue a further 0.20 m below the floor of the recess, where it contained basaltic and red sandstone fragments, and wood in addition to pitchstone. It is thought that the lower 0.20 m of the pitchstone breccia represent the absolute base of the pitchstone, where the brecciated base picked up pebbles (red sandstone, basalt and wood fragments) from the underlying conglomerate.

3. 400 m west of Lochan Nighean Dughaill (44738551), there is a small spur of pitchstone, on the north side of which there is about 1 m of pitchstone breccia at the base. Pebbles were sampled, and are described in Section 4.2.3. They are totally of flow banded pitchstone.

4. About 100 m west of Loch Caol na Cora-bheinn (45368547), the pitchstone is flow banded and brecciated at the base. This breccia contains not only the usual flow banded pitchstone fragments, but also basalt and red sandstone pebbles. The presence of the pebbles in such abundance is reminiscent of the situation found in the trench excavated at the recess west of Botterill's Crack (46008460). Such foreign, rounded pebbles imply water transport. This is thus a mixed deposit, probably caused by the brecciated base of the pitchstone flowing over a conglomerate. The conglomerate must have been unconsolidated for it to become so intimately associated with the pitchstone breccia.

5. 200 m south of Loch nam Ban Mora, there are two small exposures of pitchstone. One of these (45418495) has 0.50 m of pitchstone breccia at the base. The breccia contains elongate pieces of pitchstone in a yellowish matrix.

6.2.3 Petrography of the pre-pitchstone fragmental rocks

Petrographically, the pre-pitchstone/post-basaltic fragmental rocks are either conglomerates (with a predominance of rounded pebbles of varying sizes and types) or breccias (with a predominance of angular pitchstone fragments). The breccia fragments are very similar to the pitchstone itself, especially the samples from the lower parts of the pitchstone. As a result, they are described along with the pitchstone itself (Chapter 7). The petrography of the conglomerates and the matrix of the breccias are described below.

6.2.3.1 The conglomerates

Sampling proved possible at only two of the three conglomeratic exposures noted in Section 6.2.2.1. That near Bidein Boidheach (44098670) was inaccessible, but was seen to contain a mixture of red sandstone and basaltic pebbles, like the other outcrops.

Details of the petrography of the individual pebbles sampled are given in Table 6.1.

In the recess west of Botterill's Crack (46068462), three different types of pebbles were sampled. arkosic sandstones, basalts and acidic igneous fragments. The arkosic sandstones sampled are greenish with epidote and chlorite, although red sandstones were also observed in the field. One of the basalts is olivine-phyric (pseudomorphed olivine in an altered glassy matrix), while the other is plagioclase-phyric and also highly altered. Both could easily have been derived from the exposed lavas on Eigg, judging from field observations.

The acidic igneous fragments are a quartz-phyric glass and a porphyritic felsite. The glass is unlike any of the other acid rocks on Eigg, the only other quartz-bearing rocks being the felsitic intrusions of Sgorr Sgaileach and Sron Laimrhige. Both of these, however, have anorthoclase phenocrysts in addition to quartz. It is possible that it represents an unsampled margin of one of these intrusions, or alternatively that it is derived from some other intrusion or flow long since removed from Eigg, or its environs, by erosion.

The porphyritic felsite contains a similar phenocryst assemblage to the felsitic bands in the Sgurr pitchstone. However, the conglomerate is definitely at a lower stratigraphical horizon than the Sgurr pitchstone, and must therefore predate it. It suggests an earlier outflowing magma similar to the felsitic bands.

The extensive conglomeratic deposits below Collie's Cleft (46308460) were sampled at four separate localities, yielding fifteen pebbles in all. Of these, ten are basaltic, six of these being quite strongly differentiated mugearitic types. Chemical analyses reveal that they are, however, quartz normative (see Chapter 11). Three of the differentiated pebbles are aphyric, fine grained and show flow alignment of the tiny laths of oligoclase. Two of the others are oligoclase-phyric glasses, while the remaining one shows plagioclase, clinopyroxene and opaque oxide phenocrysts in a fine grained groundmass.

Of the remaining five basic pebbles, one is hawaiitic and contains rounded xenocrysts of plagioclase of unknown composition. Of other pebbles one is aphyric, and the other two are olivine-phyric.

The basaltic and hawaiitic pebbles could be derived from the lavas exposed on Eigg, although they may represent younger flows than seen today. The differentiated, quartz normative pebbles are more of a problem, however (see Section 6.2.3.3).

The three sandstone pebbles are all greenish or yellow-green, arkosic, fairly fine grained sandstones (average grain size of 0.2 mm), containing significant green pleochroic chlorite and yellow epidote. The remaining two pebbles that were sampled are rather more unusual one is a conglomerate in its own right; the other is an acidic igneous rock. The conglomeratic pebble contains fragments of basalt, arkosic sandstone and a basaltic glass, with angular quartz, plagioclase and pseudomorphed olivine crystals. The spaces between the fragments and crystals are infilled with fibrous radiating calcite and a light green glassy material. It implies a pre-existing conglomeratic deposit in the vicinity. It is conceivable that this represents some Tertiary sedimentary deposition on Eigg, prior to the formation of the Sgurr conglomerates.

The acidic rock is rhyolitic - plagioclase, anorthoclase, clinopyroxene, orthopyroxene and small opaque oxides set in a felted mat of fine crystals with low polarisation colours (probably feldspar and quartz). Opaque oxides are scattered through the matrix and tiny crystals with higher polarisation colours may be pyroxene. The phenocryst assemblage closely resembles that of the Sgurr pitchstone, while the felsitic matrix resembles the felsitic bands in the pitchstone. As with the similar pebble found in the recess west of Botterill's Crack, this suggests earlier outpourings of magma similar to that of the Sgurr pitchstone, or at least exposures of such rock at the time of formation of the conglomerates.

The provenance of the pebbles has been discussed with the petrography, except that of the sandstones. The only sandstone exposed on Eigg itself is Jurassic, and that is nothing like the red and green material found in the conglomerates. The lack of Jurassic pebbles in the conglomerates implies that, when these deposits were laid down, the Jurassic sediments were not exposed for erosion as they are today. Alternatively, they were too soft to survive transportation.

6.2.3.2 The matrices of the breccias and conglomerates

Three samples of the pitchstone breccia matrix were taken: two from the recess west of Botterill's Crack (46068462) and one from near The Nose (46368465). All three show crystals of anorthoclase, plagioclase and opaque oxides. These are in a similar state of corrosion as the phenocrysts in the pitchstone itself. In addition, there are small (0.2 mm) rounded basaltic fragments. The whole is set in a brown, non-polarising matrix crowded with tiny opaque oxides. One of the samples from the recess shows a sort of flow structure, best seen near crystal or basalt fragments, where the matrix is seen to curve round the fragments. In places the flow structure is simply an alternation of light and dark layers. Elsewhere it takes the form of lensoid, brown, non-polarising patches, which lack the abundant tiny opaques of the main parts of the matrix.

One sample of the conglomerate matrix was taken from the trench dug in the recess by the author and Dr. Hudson. It came from below the level of disappearance of the pitchstone fragments, and thus could be considered to be the matrix of the conglomerate. Rock fragments within the sample include schist, arkosic sandstones, red/brown sandstones showing graded bedding, plagioclase-rich and plagioclase-phyric basalts. The sandstone fragment showing graded bedding has an opaque-rich, coarse grained layer, reminiscent of some of the Torridonian sandstones from Rhum. In addition to the rock fragments, anorthoclase, plagioclase and small opaque oxide crystals occur. Black fragments may well be comminuted wood fragments; larger wood fragments were observed in the field at this level in the conglomerate.

The matrix is composed of a finely comminuted debris of various materials - crystals of feldspar and opaque oxide being the most common.

It contrasts strongly with the non-polarising matrix of the pitchstone breccia.

6.2.3.3 Conclusions

One of the main conclusions that can be drawn from the petrographical study is that the pitchstone breccia and the underlying conglomerate form two distinct deposits - the breccia has a very dark coloured, non-polarising matrix, while the conglomerate has finely comminuted debris as a matrix. The lensoid areas free of opaque oxides seen in one sample of the breccia matrix could conceivably be compressed glass shards. The conglomerate, on the other hand, is of true sedimentary origin, and the wood fragments imply a terrestrial and therefore fluvial origin.

The pebbles in the conglomeratic outcrops give some indication of the source of the river (or rivers) which deposited the conglomerates. The red and green sandstones are most probably of Torridonian origin. That seen in the matrix sample, which had graded bedding with opaque oxides concentrated in a coarse grained layer, is reminiscent of some of the Torridonian samples from Rhum. The schist fragment is probably from the east (Moinian). The basaltic fragments could easily have been derived from the lavas of Eigg. The quartz normative differentiated pebbles found below Collie's Cleft, however, do not resemble any flows at present exposed on Eigg. Chemically, they are more similar to some of the youngest flows on Rhum (pers. comm. C. H. Emeleus 1979), but as the present day Rhum lavas outcrop on the north side of Rhum, it seems unlikely that the pebbles originated from there. Most probably they represent some late lavas of Eigg, which have been removed by erosion, or lavas from southern or eastern Rhum, if such ever existed.

6.2.4 The nature of the pre-pitchstone topography

On the assumption that the pitchstone of Eigg is an extrusion rather than an intrusion, structure contours were constructed on the base of the pitchstone (or the pitchstone breccia, where present) to define the pre-pitchstone topography (see Figure 6.7). Several cross sections (see Figure 6.8) were constructed to elucidate the description of the landscape. The general picture one gets of Eigg immediately prior to the extrusion of the pitchstone is of a complex, relatively mature landscape with river valleys and spurs. Drainage was mainly to the west (e.g. the westerly running valley seen near Cora-bheinn - 45708555), and the land slopes away to the north, west and south, implying that there was higher ground to the east of the present outcrops of the pitchstone.

The main features of the landscape are the westerly running Cora-bheinn valley and its enclosing spurs, the plateau near Loch Beinn Tighe (44908662) and the associated westward running spur, and the steep southerly slope around An Sgurr (e.g. near The Nose - 46368465). From the cross sections (see Figure 6.8), the Cora-bheinn valley is seen to be relatively wide and V-shaped (Figure 6.8a) with a smooth longitudinal section (Figure 6.8b) decreasing in height from east to west. The Loch Beinn Tighe plateau and the spur to the west (Figure 6.8c) show stepped topography typical of eroded basalt lava terrain. The steep slope to the south as seen around The Nose (Figure 6.8d) is highly suggestive of one side of a ravine, the other side of which has been removed from present day outcrops. Further west (Figure 6.8e), that slope is rather more gentle.

In addition to the Cora-bheinn valley, there are three other minor valleys in the pre-pitchstone topography. Most significant of these is the westerly running one seen north of Bidein Boidheach (44158667), at the west end of the spur, which runs west from the Loch Beinn Tighe plateau. The valley first appears on the spur and its transverse section is steep sided (Figure 6.8f). The other two valleys - the westerly running one seen just north of the 86^{o}N grid line (44838603) and the northerly running one of Beinn Tighe (44718693) - are smaller scale features, nothing more than small tributary valleys to some main valley system.

Only one of the valleys can be definitely said to have ever had a river flowing through it - that seen north of Bidein Boidheach. The impressive conglomerate that outcrops below the pitchstone at this locality is almost certainly of fluviatile origin. There may be, as yet unexposed by erosion, similar conglomerates below the pitchstone in the other valleys.

It is significant that there are the extensive conglomeratic deposits below the pitchstone on the south side of An Sgurr (west of Botterill's Crack - 45988462 and south west of The Nose - 46308457). These are surely indicative of a valley here also, as suggested from the ravine-like slope. There is insufficient outcrop of the pitchstone to allow mapping of the base in this area, but if the evidence of the conglomerates is to be believed, then the landscape of south-west Eigg in pre-pitchstone times probably included a major valley running along just south of the present location of An Sgurr. This valley must have drained south-east to north-west, judging from the slope of the land. As suggested by Geikie (1894), it is just possible that this river continued a further 18 miles to the north-west to deposit as yet unexposed conglomerates below the Oigh Sgeir pitchstone, which is petrographically identical to the Sgurr pitchstone (see Chapter 7).

6.2.5 Relationships of the topography to the nature of the pitchstone

One of the most outstanding relationships between the pitchstone and the underlying topography is seen where the pitchstone is confined to the pre-pitchstone valleys (Figures 6.8a and 6.8b). By contrast, only a thin veneer of pitchstone (10 m at maximum) remains on the spur west of Loch nam Ban Mora (Figure 6.8g). This implies that the pitchstone was originally thickest in the valleys, as one would expect of an extrusion.

At its present erosion level, the pitchstone reaches thicknesses of 35 m in the valley north of Bidein Boidheach (Figure 6.8f) and 10 m in the Cora-bheinn valley (Figure 6.8a). The maximum thickness attained however is found at the east end of An Sgurr (Figure 6.8d), where it reaches almost 100 m.

The dip directions of the flow banding at the base of the pitchstone usually follow the dip of the slope of the pre-pitchstone topography. The striking exception to this rule is seen along the south, south-west and west sides of the main ridge. Here the flow banding dips to the north, north-east and east. Invariably this is totally in the opposite direction to the slope of the pre-pitchstone topography (e.g. at 44638460 where there is a dip of 38° to the north-east while the pre-pitchstone topography slopes to the south-west). It may be that there was some sort of caterpillar action at the pitchstone flow front, the flow over-riding itself producing a reversal in dip directions (A. Peckett pers. comm. 1978).

It was suggested in Section 6.2.1.3 that the presence or absence of flow banding and brecciation of the base and the nature of the flow banding may be indicative of varying degrees of irregularity in the pre-pitchstone topography. Although this is very difficult to detect, due largely to uncertainties in drawing the structure contours accurately between outcrops of the base, and also in constructing the cross-sections, the hypothesis seems to be reasonable. For example, south-west of Loch Beinn Tighe uncontorted flow banding with no brecciation was observed at the base of the pitchstone. From Figure 6.8c, it can be seen that the slope here is relatively smooth and free from irregularities. West of Lochan Nighean Dughaill more contorted flow banding with associated brecciation was noted, and from Figure 6.8b, it can be seen that, although smooth and relatively free from irregularities, as south-west of Loch Beinn Tighe, the slope here is steeper. No flow banding but a brecciated base is seen at the east end of An Sgurr. Here the slope is much steeper than at either of the other two localities. Perhaps the hypothesis should be:-

Uncontorted flow banding - no brecciation	Gentle slopes
Contorted flow banding - brecciation	Steeper slopes
No flow banding - brecciation	Very steep slopes

6.2.6 Conclusions

The above discussion indicates that the genesis of Sgurr pitchstone is more easily explained as an extrusion rather than an intrusive body.

It was suggested in Section 6.2.5 that the apparently reversed dip directions seen at the base of the pitchstone at various localities could be due to a caterpillar action at the flow front. This implies a source for the pitchstone magma to the north, north-east or east.

The only outcrops on Eigg which show any resemblance to the Sgurr are those of the pitchstone dyke found near the North Pier (48288418) - see Section 6.3.2.5. There are, however, petrographical differences, which may indicate that the two are unrelated.

The author concludes (Section 6.2.1.4) that the felsite bands in the pitchstone are, in general, intrusive towards the main pitchstone body. That the two were formed from closely related liquids is suggested by the evidence seen 250 m west of Botterill's Crack (46888469), where flow banding in the upper part of the felsite passes into the pitchstone without a break.

The pitchstone magma clearly buried a landscape in the process of development (Section 6.2.4). This implies a fairly substantial time gap between the extrusion of basic lavas on Eigg and the extrusion of the Sgurr. This is consistent with the observation that the pitchstone postdates the phase of dyke intrusion (Section 6.2.1.1). A more exact age cannot be obtained from field observation, but the lack of gabbroic or granite pebbles in the pre-pitchstone deposits suggests that it predates the unroofing of the major intrusions. This is in contrast with the conglomerates of Canna, which have yielded a gabbroic pebble and a granophyre similar to the western granophyre of Rhum. This would suggest that the lavas are younger than those of Eigg. Of course, there may have been no suitably sited major intrusions for the rivers, which formed the Eigg conglomerates, to erode.

From the form of the pre-pitchstone landscape (Section 6.2.4), it was concluded that the drainage was mainly to the west, with a major valley running along the south side of An Sgurr and to the west of Beannan Breaca. This valley must have drained to the west (see Figure 6.7) from Eigg to Rhum, in terms of the present geography. This is consistent with the pebble of schist (possibly Moinian), which could have originated from the present day Arisaig area. However, the sample of probable Torridonian sandstone is more of a problem. The above hypothesis implies that Rhum is in a downstream direction. The source of the pebble, and the many other probable Torridonian samples found in the conglomerates, is a problem, as there is no source for Torridonian to the east of Eigg, at the present erosion levels. If they did come from Rhum, and it is the nearest source, either the river flowed in the opposite direction to that indicated by the structure contours, or it flowed in a rather large meander from Rhum to Eigg and back again. This is the sort of situation envisaged, on Rhum (Emeleus pers. comm. 1979), where the drainage is tangential to the central complex, yet the pebbles in the Tertiary conglomerates are definitely from the Central complex.

6.3 The Acidic Intrusions

6.3.1 Introduction

There are five occurrences of acidic intrusions on Eigg:-

1. Sgorr Sgaileach felsite (48089122 to 49009071);
2. Sron Laimrhige felsite (around 47408770);
3. Grulin felsite (44658520 to 46208465);
4. Pitchstone dykes at Rubh' an Tancaird (48088320);
5. Pitchstone dyke near the North Pier (48288418).

Of these, the Sgorr Sgaileach and Sron Laimrhige intrusions are very similar and, like the Grulin felsite, are cryptocrystalline - hence the name 'felsite'. The Grulin felsite differs from the other two in phenocryst content (alkali feldspar, plagioclase, clinopyroxene and opaques instead of quartz and alkali feldspar). The pitchstone dyke at the North Pier is rather poorly exposed, but is outwardly similar to the Sgurr pitchstone. The Rubh' an Tancaird dykes are thin, predominantly glassy intrusions of an irregular, but mainly dyke-like, nature.

6.3.2 Field relationships and age

6.3.2.1 Sgorr Sgaileach felsite

This intrusion outcrops in a 120 m long strip (maximum width - 200 m) on the north coast of Eigg. It is elongate, with extension in a north-west/south-east direction, and covers approximately 28 sq m. It outcrops mainly in 40 m high coastal cliffs, which show excellently developed columnar jointing and flow banding dipping to the east.

The nature of the intrusion is difficult to determine due to a lack of exposed contacts with the country rocks. It must intrude Jurassic sediments, as it outcrops well below the level of the base of the Tertiary basalts, as seen in the cliffs to the south (e.g. at 48109065). The trace of the felsite's contact with the country rocks (mapped largely on a vegetation change and a break of slope) cuts directly across the contours, suggesting a plug-like nature. This disagrees with Harker (1908), who maintains that it is sheet-like in form.

The fact that it intrudes Jurassic sediments, implies that the felsite is of post-Jurassic age. At least one occurrence of a basic sheet intruding the felsite was observed by the author. If this sheet is of the same age as the Tertiary sills, which intrude the Jurassic sediments in the cliffs to the south (48109075), and which are assumed to be coeval with the Tertiarv dykes which postdate the basalts, then the felsite is older than the dykes.

6.3.2.2 Sron Laimrhige felsite

In the centre of Eigg, east of Laig Farm (around 47408770), a second felsite intrusion occurs. Petrographically, it is identical to that of Sgorr Sgaileach, although it does not show the same columnar structure in outcrop.

The Sron Laimrhige felsite outcrop is roughly circular, with a diameter of approximately 350 m (an area of 10 sq m). It has faulted contacts on the north and south sides, while the other contacts roughly follow the contours. This suggests a sheet-like nature, although the circular outline is more suggestive of a plug-like intrusion.

Whether or not it is part of the same intrusion as the Sgorr Sgaileach felsite, is very difficult to determine. There are no outcrops of felsite in the 3 km intervening between the two intrusions but petrographical evidence for a co-magmatic origin is strong (see Chapter 7).

This felsite intrudes both basalts and Jurassic/Cretaceous sediments. A specimen of sandstone was collected from near the contact with the felsite. It shows little sign of thermal alteration.

As with the Sgorr Sgaileach felsite, a basic sheet intrudes the felsite, providing evidence that the two felsites are of approximately the same age, i.e. post-Tertiary lavas, but pre-Tertiary minor intrusions.

6.3.2.3 Grulin felsite

South of the main Sgurr ridge, around the old settlements of Grulin (from 44658520 to 46208465), a third felsite outcrops in an elongate strip 1200 m long and 80 m wide at maximum. From the map (Figure 6.1), it can be seen to have the form of a transgressive, inclined sheet. A dip of 10° to 20° towards the north-east was measured on the top of the sheet (45138474). This contradicts the hypothesis of Harker (1908), who maintains that it is a dyke-like body, occupying the fissure up which the Sgurr magma rose. As has already been shown (Section 6.2.1.1), the Sgurr pitchstone postdates the basic minor intrusions. The Grulin felsite, which is cut by a dyke (*see* below), is older, and hence cannot occupy the fissure of the Sgurr pitchstone. Thus the author suggests that Harker's hypothesis is not in accord with current field observations.

At its eastern end, the felsite tapers and finally dies out before the east end of the pitchstone ridge is reached (46198453). At the west end, outcrops of felsite were not found north-west of the fault at 44658515. Presumably the felsite thins to nothing in this vicinity also, although it could possibly be affected in some way by the fault, so that it does not outcrop at the surface again.

The Grulin felsite intrudes basalts in the upper part of the Eigg sequence (Cnoc Creagach and Cora-bheinn Groups). It is however cut by basic dykes (as seen at 45518461). Thus it must postdate the lavas of Eigg, but predate the phase of minor intrusions. Thus all three felsites are approximately contemporaneous. In thin section, however, the Grulin felsite contains mafic phenocrysts (see Chapter 7) in addition to feldspar. It lacks the quartz phenocrysts of the other two felsites, and thus most probably did not originate from the same magma.

6.3.2.4 Rubh' an Tancaird dykes

At Rubh' an Tancaird, on the south coast of Eigg (47088320), two thin, highly irregular pitchstone dykes outcrop near the cliff edge. Approximately 8 m of basalt separates the two intrusions. They both intrude basalts, which can be referred to the lower part of the middle Eigg succession, but as they do not intersect any basic dykes or sills, their age cannot be fixed any more definitely than post-basaltic lavas.

The more westerly of the two dykes has a maximum thickness of 0.8 m, and is totally composed of a bluish-black pitchstone. It shows some development of colour flow banding, parallel to the walls of the dyke. In general, it is thinner and has less abundant phenocrysts than the eastern dyke.

The eastern dyke has, in its northern part, which is wider (0.9 m as opposed to 0.70 m), a central development of grey felsite. Progressively, from the core to the margins, the colour of the dyke material changes from grey, through bluish to a black. It carries phenocrysts of feldspar throughout. As with the western dyke, there is some colour banding parallel to the walls. Here, there are also lines of elongate vesicles, sometimes infilled with calcite, which parallel the flow banding.

Petrographically, the dykes are distinct from the felsites and from the other outcrops of pitchstone on Eigg. Hence, they are not directly connected with any of the other acidic rocks of Eigg.

6.3.2.5 North Pier pitchstone dyke

The last acidic intrusion known on Eigg is a plug-like one found near the North Pier in south-east Eigg (48288418). This was only found to outcrop at one locality by the author. Harker (1908) found it to be 4.5 m wide, and traceable northwards from the old pier for about 30 m. He reports that it is felsitic at its northern end. As regards age, the author did not find any definite evidence, except that it postdates the basalts. Harker (1908) says that it cuts a Kildonnan sheet and is unaffected by a fault, thus making it a fairly late event in the Tertiary igneous activity of Eigg. It cannot be said that the author has great confidence in all Harker's observations. For example, he (Harker (1908) - p. 175) states firmly that the Grulin felsite cuts a basic dyke. This is completely in contrast with the author's observations (*see* Section 6.3.2.3). Thus the North Pier pitchstone may or may not be cut by the Kildonnan sheet (one of a series of inclined sheets, roughly contemporaneous with the phase of minor basic intrusions).

CHAPTER 7

PETROGRAPHY OF THE ACID ROCKS OF EIGG

7.1 Introduction

On Eigg, there are six areas in which pitchstones and felsites outcrop (see Chapter 6). Only one of these six is composed of an extrusive mass - the pitchstone of the Sgurr ridge. The others intrude basaltic lavas, with the exception of the Sgorr Sgaileach felsite, which intrudes the Jurassic sediments below the lava pile. Irrespective of the degree of crystallisation of the matrix, all six outcrops are porphyritic, with varying assemblages of phenocrysts (see Table 7.1 for details).

On the basis of the phenocryst content, in particular the type of feldspar which occurs as a phenocryst, five petrographical groups can be defined:-

1. Those with abundant plagioclase and anorthoclase phenocrysts;
2. Those with rare plagioclase and anorthoclase phenocrysts;
3. Those with sanidine phenocrysts;
4. Those with plagioclase as the only feldspar phenocryst;
5. Those with anorthoclase as the only feldspar phenocryst.

As there are only six different outcrops of acidic rock on Eigg, this implies that all but two of them differ petrographically. The two which belong to the same petrographical group are the Sron Laimrhige and Sgorr Sgaileach felsites.

7.2 Acid rocks with abundant plagioclase and anorthoclase phenocrysts

Rocks of this type are confined to the Sgurr pitchstone and its associated felsites. In addition to the feldspars, clinopyroxene, orthopyroxene and opaque oxides also occur in varying quantities and combinations as phenocrysts.

7.2.1 Variation in phenocryst content with mode of occurrence

Before describing the mineralogy and textures seen in these samples, the variations in abundance of the five phenocryst phases found in the samples are considered (*see* Table 7.2 for modal analyses). Initially the samples were grouped according to their field relationships to the main body of extrusive pitchstone. There are four such groups:-

1. Samples of the extrusive pitchstone (E7406, E7443 and EA1);
2. Samples which show intrusive relationships towards the main body of pitchstone, but which also appear to be gradational with it (EA27, EA43 and EA44);
3. Samples which are definitely intrusive towards the main body of pitchstone (e.g. those showing cross-cutting relationships towards the flow banding in the pitchstone - E7442 and EA48);
4. Samples whose relationships with the main body of the pitchstone are unknown, but which are probably intrusive (EA9 and EA46).

Several interesting correlations between mode of occurrence and phenocryst content can be drawn from the modal analyses (*see* Table 7.3).

First, the proportion of phenocrysts in the sample decreases from the extrusives through the partial intrusives to the definite intrusives. The proportion of mafic phenocrysts (pyroxenes and opaques oxides) also decreases in a similar manner, especially when considering only the extrusives and partial extrusives. More important perhaps is the abundance of the individual mafic minerals (see Table 7.3b). In particular, orthopyroxene only occurs as a phenocryst in the extrusive samples, while clinopyroxene is markedly less abundant in the partial intrusives as compared with the extrusives, and is not present in the definite intrusive. Opaque oxides, on the other hand, show a variable distribution throughout the defined groups. It should be noted that samples from bodies whose relationships to the main body of pitchstone are unknown (EA9 and EA46 - group 4 above) and from the dyke (E7442) do not show such correlations. All these samples have phenocryst contents which are similar to those of the extrusive or partially intrusive pitchstones and felsites (see Tables 7.1 and 7.2).

Variation in the feldspar phenocryst content (the salic minerals of Table 7.3a) with the mode of occurrence is less well defined than for the mafics. Great variation is seen within the individual groups defined above (overall variation is between 15 and 22% modal feldspar). However, in the extrusive pitchstones, the plagioclase always predominates over the alkali feldspar. In the partially and totally intrusive samples, however, this is not always the case (see Table 7.2 for details). It is of interest that Carmichael (1960b) reports only a trace of plagioclase in his sample of the Sgurr pitchstone. The author identified as plagioclase any feldspar which had polysynthetic twinning (rather than the faint cross-hatch twinning seen in many of the alkali feldspars). Thus it would appear that Carmichael's sample is rather unusual at least compared with the samples described herein.

Unfortunately, the locality from which his sample was taken is unknown.

The field relationships of the various samples to the main body of the pitchstone allows comment on their relative ages in terms of extrusion and final crystallisation of the Sgurr pitchstone mass. Those which are extrusive must be the oldest. The samples from the felsite bodies which show both gradational and intrusive relationships towards the main body of the pitchstone must be somewhat younger, probably dating to the last stages of crystallisation. The definitely intrusive samples must be the youngest. It therefore follows that the variations seen in the phenocryst contents of these three groups must reflect changes in the pitchstone magma as it consolidated.

Some, if not all, of the phenocrysts may have been carried up with the pitchstone magma, as it was extruded. If crystal settling took place within the magma after extrusion, then variation in the phenocryst content with height in the pitchstone mass could be expected. Unfortunately, a vertical section through the pitchstone was not sampled. However, EA1 is from within a few centimetres of the base, while E7443 and E7406 are from points a few metres above the base. The total phenocryst content of EA1 (33.25%) is considerably greater than that of the other two samples (24.93% and 20.36%). The abundance of the individual phenocryst species (except clinopyroxene) is also greatest in the sample taken nearest the base - see Table 7.2.

One would also expect that the extrusive samples should contain more phenocrysts than the partially and totally intrusive samples, as the latter must have remained in a liquid state longer than the main pitchstone mass. The partially and totally intrusive samples (excluding the dyke E7442) do, in fact, contain less phenocrysts than the extrusive samples (less than 20% phenocrysts as compared with more than 20%). Also notable is the concentration of pyroxenes (the densest of the phenocrysts, excluding the opaque oxides) in the extrusive and, to a lesser extent, in the partially intrusive samples. The opaque oxides (titanomagnetite and ilmenite - see Chapter 9) show a fairly even distribution throughout the samples, despite their high density. They occur, however, in small crystals, compared with the other phenocrysts, and hence will not be so affected by any crystal settling.

To invoke crystal settling in an acidic magma, such as the Sgurr pitchstone would have been on extrusion, is perhaps a little unconventional, as such magmas are normally considered to be too viscous for such phenomena. This is further discussed when the geochemical variation of the Sgurr pitchstones and felsites has been described (see Chapter 11).

7.2.2 Petrography

The phenocryst minerals of the acidic rocks forming the Sgurr and associated ridges are similar irrespective of whether the matrix is glassy or felsitic. The matrix of the pitchstones is always glassy, usually brown in colour and with abundant microlites of feldspar and opaque oxides. EA1 was observed to be flow banded in hand specimen, This banding is seen, in thin section, to be caused by interleaving of glassy and more lightly coloured, more devitrified bands. E7406 has some perlitic cracks.

The felsites have a matrix formed of a felted mat of tiny microlites. Feldspar and opaque oxides can usually be identified. One sample (EA48) has rounded glassy patches associated with the phenocrysts.

Two others have fine-grained patches within them (EA27 and EA43) and another two (EA43 and EA44) show faint flow textures in the feldspar microlites, especially around the phenocrysts.

Plagioclase, normally the most abundant phenocryst, occurs in all but one of the Sgurr ridge samples (EA44). It forms lath-shaped crystals with polysynthetic twinning, and range in size from 0.5 to 2 millimetres. Corrosion is often seen around the edges of the phenocrysts (e.g. in EA1), and this corrosion can be more or less severe than that seen in the alkali feldspars. Rarely, they are rimmed by alkali feldspar (anorthoclase), implying that they predate the crystallisation of that mineral. Plagioclase is seen to enclose both clinopyroxene and orthopyroxene phenocrysts in many of the samples examined. Often it is also seen moulded onto the clinopyroxenes. This suggests that both pyroxenes crystallised before the plagioclases.

Anorthoclase, usually second in abundance to plagioclase, is present as a phenocryst phase in all the samples examined. It occurs in equant or rounded grains, which are often corroded and range in size from 1 to 5 millimetres. Normally, it shows the typical fine tartan twinning characteristic of anorthoclase, and may otherwise be distinguished from the plagioclase by its relatively small optic axial angle (c. 50^o). Sometimes the phenocrysts exhibit zoning, which can be very marked. In most samples, the anorthoclase can be seen to postdate the crystallisation of both types of pyroxene (if present).

When both types of pyroxene occur in the same sample, they can be distinguished by their colour, degree of pleochroism and extinction angle. The orthopyroxenes exhibit straight extinction and are pleochroic from pink to faint green. It is most probably hypersthene (see Chapter 9 for details of mineralogy), and usually occurs in elongate, lath-shaped crystals. The majority are about 1 millimetre in length, possibly with a second smaller generation 0.2 to 0.3 millimetres in length. The clinopyroxenes are normally colourless (e.g. in EA1) or greenish, but non-pleochroic (e.g. in E7443 and E7406). In EA1, it is seen to be rimmed with a similar pyroxene, which has grown in a different optical orientation to the original crystal. This suggests two periods of clinopyroxene growth, at least for this sample. As with the orthopyroxenes, there appear to be two generations of clinopyroxenes - larger crystals 0.5 to 1 millimetre across and smaller ones 0.1 to 0.2 millimetre across.

Opaque oxides occur as fairly abundant microphenocrysts in all the samples examined. Individually, they are c. 0.2 millimetre in diameter, but they occur also in aggregates of c. 0.5 millimetre across. There are both titanomagnetites and ilmenites present (see Chapter 9). They usually occur as anhedral, rounded grains, and as such, can be seen to predate all the other phenocryst phases. When they occur as independent phenocrysts, they commonly show interstitial, presumably late stage, overgrowths.

7.2.3 Note on the petrography of the Oigh Sgeir pitchstone

Geikie (1894) noted the similarity of the pitchstones of the Sgurr of Eigg and Oigh Sgeir, which is situated some 19 miles northwest of Eigg. Harker (1908) has reported petrographical similarities between the two pitchstones. The author was able to examine three samples of the Oigh Sgeir pitchstone (SR303A, B and C), which were kindly provided by Mr. D. H. McGaw, Principal Keeper of the lighthouse on Oigh Sgeir.

In terms of mineral species and their relative abundances as phenocrysts, the pitchstone of Oigh Sgeir is indistinguishable from that of the Sgurr of Eigg. One sample from Oigh Sgeir (SR303C) shows zoned anorthoclase phenocrysts, a feature also noted in some of the Sgurr samples. Another sample (SR303A) shows plagioclase phenocrysts coated with anorthoclase. Again such coating was noted in the Sgurr samples. The matrix of the Oigh Sgeir pitchstone is similar to the pitchstone samples from the Sgurr - a brown glass with feldspar and opaque oxide microlites.

7.3 Acid rocks with rare plagioclase and anorthoclase phenocrysts

Samples of this type are confined to the outcrops of a felsite which was intruded into the basaltic lavas just south of the main An Sgurr ridge (the Grulin Felsite of Chapter 6). The anorthoclase phenocrysts average 2 millimetres across and are rectangular in outline. They show typical fine tartan twinning and some also have inclusions. They show relatively little corrosion. The plagioclase phenocrysts occur as 4 millimetre long, elongate, thin crystals.

Rather surprisingly, a third feldspar phenocryst occurs - orthoclase. It is more abundant than either of the other feldspars and occurs as rounded, badly corroded crystals with abundant inclusions of groundmass material. They range up to 5 millimetres across.

The mafic phenocrysts consist of small clinopyroxenes (0.5 millimetre across) and opaque oxides (0.5 to 1 millimetre across). The pyroxenes are very pale green to colourless, and are euhedral in shape.

They can usually be seen to predate the orthoclase phenocrysts. The opaques show considerable corrosion.

The groundmass is that typical of a felsite - a fine-grained mat of feldspar and quartz, with opaque oxides. There are also some rare tiny ferro-magnesian minerals (presumably pyroxene).

The presence of three feldspar phenocryst phases is rather unusual. Orthoclase is more usually associated with larger, more slowly cooled bodies of acid rock. The extensive corrosion of the orthoclase phenocrysts suggests that they are not in equilibrium with the host liquid. They are perhaps of xenocrystic origin, derived from a more slowly cooled acidic body.

7.4 Acid rocks with sanidine phenocrysts

Sanidine phenocrysts are confined to the two acid dykes which intrude the basic lavas at Rudh' an Tancaird (47798380) on the south coast of Eigg. The sanidines occur as rhombohedral, euhedral crystals. Sometimes they are in clusters, especially in E7456. Samples from the more easterly dyke (E7454 and E7455) both have crystallites growing on the corners of the sanidine phenocrysts. Small opaque oxide phenocrysts also occur, but they are of infrequent occurrence. Ridley (1971) also reports rare fayalite phenocrysts, but this was not confirmed by the author.

A third phenocryst phase, now completely pseudomorphed by abundant small calcite crystals, also crystallised from the magma which formed these dykes. They are usually elongate and probably were originally plagioclase.

The groundmass is either glassy (E7454 and E7456) or felsitic (E7455). The glass is colourless or brown with feathery crystallites. Both samples show a flow texture of the crystallites around the phenocrysts. The direction of growth of the crystallites on the sanidine phenocrysts (see above) parallels this trachytic texture. The felsitic matrix is extremely fine grained and has spherulitic structures in it. This suggests that it is a devitrified glass.

7.5 Acid rocks with plagioclase as the only feldspar phenocryst

This type of acid rock is found in the pitchstone dyke which outcrops near the North pier (48278480). The plagioclase phenocrysts occur in lath-shaped crystals up to 1 millimetre in length. Some of them exhibit polysynthetic twinning, occasionally with untwinned margins full of inclusions. They are seen to enclose (and therefore postdate) the clinopyroxene phenocrysts.

In addition to plagioclase, small, normally euhedral opaque oxide phenocrysts occur. These often show slight corrosion and predate all other phenocryst minerals. Two types of pyroxene also are seen as phenocrysts. The larger ones (0.75 millimetre) are greenish in colour and show oblique extinction. They are thus clinopyroxenes and have euhedral or subhedral outlines. The smaller pyroxenes (0.25 millimetre) are lath-shaped and show straight extinction. The pink to light green pleochroism of these pyroxenes suggests hypersthene. Sometimes they occur in clusters.

The groundmass is a dark coloured glass with feathery crystallites.

7.6 Acid rocks with anorthoclase as the only feldspar phenocryst

Samples of this type were collected from the felsite intrusions of Sron Laimrhige (c. 47408770) and Sgorr Sgaileach (c. 48459125). In the field, the two intrusions appeared to be very similar. Petrographically they are indistinguishable from each other.

The alkali feldspar phenocrysts frequently are almost totally pseudomorphed by calcite (E7407 and E7415). However, those in E7408 and E7423 are only partially altered to calcite and are identifiable as anorthoclase, on account of the fine tartan twinning and moderate optic axial angle (c. 50^0).

Anorthoclase is accompanied by quartz as a second phenocryst phase. The latter occurs as rounded grains and, in the samples from the Sron Laimrhige intrusion (E7407, E7408 and E7415), it is corroded. In a sample from Sgorr Sgaileach (E7423), a quartz phenocryst is seen to be enclosed within an anorthoclase phenocryst, thus implying that the former predate the latter.

The matrix consists of a felted mat of quartz and feldspar microlites. Small opaque oxide grains also occur. Calcite occurs in the matrix of all samples. This, and the calcitic alteration of the anorthoclase phenocrysts, may be due to the close proximity of the Jurassic sediments. The Sgorr Sgaileach felsite actually intrudes the Jurassic rocks, while that of Sron Laimrhige intrudes near the base of the lava pile.

7.7 Conclusions

In terms of the feldspar phenocrysts, the bulk of the acidic rocks of Eigg have two different types of feldspar. The exceptions are the Grulin felsite with three feldspar phenocryst phases; the North pier pitchstone, the Sron Laimrhige felsite and the Sgorr Sgaileach, each of which has just one feldspar phenocryst. However, it has been suggested that the orthoclase phenocrysts in the Grulin felsite are of xenocrystic origin (*see* Section 7.3), thus making it also a two-feldspar felsite.

Carmichael (1963) has discussed the crystallisation of feldspars in volcanic acid liquids. He concludes (p. 126) that there are three types of acid liquids:-

1. Those with one-feldspar (plagioclase or anorthoclase);
2. Potassic, two-feldspar (plagioclase and sanidine) acidic volcanics;
3. Pantellerites with soda in excess of alumina.

Examples of the first two types are found on Eigg.

Two examples of the one-feldspar acid type are seen on Eigg. The North Pier pitchstone dyke has plagioclase phenocrysts and no free quartz, thus conforming to the more common silica-poor nature of such acidic rocks. The Sron Laimrhige and Sgorr Sgaileach felsites also belong to this one-feldspar group. They, by contrast, have quartz phenocrysts, implying that they represent more silica-rich liquids.

The two-feldspar acidic rocks of Eigg are the Sgurr pitchstones and felsites, the pitchstone dykes of Rudh' an Tancaird and the Grulin felsite. Carmichael (1963) reports sanidine and plagioclase as the two phenocryst phases and such as assemblage is seen in the pitchstone dykes of Rudh' an Tancaird. The Sgurr and Grulin samples, however, yield samples which contain anorthoclase and plagioclase phenocrysts. This implies that their initial liquids were more sodic than those which formed the dykes of Rudh' an Tancaird. Chemical analyses (see Chapter 11) show that there is little difference in Na_2O content. The Rudh' an Tancaird samples have, in fact, lower K_2O than the others.

Carmichael (1963) proposes that the one-feldspar acid volcanics are the products of fractional crystallisation of tholeiitic magma. The basaltic lavas and minor intrusions of Eigg are transitional to alkaline rather than tholeiitic (see Chapter 10). The two-feldspar acidic rocks are thought to be due to either sialic anatexis or the sialic contamination of the fractional crystallisation product of a tholeiitic magma (for further discussion, see Chapter 11).

CHAPTER 8

THE FRAGMENTAL ROCKS ASSOCIATED WITH THE BASALTIC LAVAS

8.1 Introduction

The fragmental rocks include all types of sediment found in intimate association with the Tertiary lavas. The conglomerates and breccias below the pitchstone of the Sgurr of Eigg have been described elsewhere (see Chapter 6). This chapter includes a description of the field relationships and petrography of the conglomerates of Canna and the finer grained sediments found intercalated with the lavas on all three islands.

8.2 Fine Grained Sediments

These include the red beds found between some of the lavas of Eigg and Muck. These are reminiscent of the red interbasaltic horizons found among the lavas of North Antrim and elsewhere, which are usually referred to as baked laterites. As will be seen, the author prefers to consider the red beds of Eigg and Muck as tuffs.

The fine grained sediments from Canna are not red beds. They are usually found intercalated with the conglomerates, and are thought to be of fluvial origin like the conglomerates themselves (see Section 8.3.2).

8.2.1 Red beds of Eigg and Muck

The red beds of Eigg and Muck, with the exception of those from the lower parts of the Muck succession (the Basal Group), consist of a bright red or orange-red mudstone-like material. Rarely, this has faint suggestions of bedding (e.g. M7635 - 42437918), but more usually it is very fine grained and friable. The friable nature is caused by the closely spaced vertical and horizontal jointing, such as is well seen in the Main red bed of Muck (M7535 - 40327887). This red bed also shows the typical sharp junction of the red mudstone with the overlying lava and a more intimate relationship with the underlying flow (see Figure 8.1). The red mudstone appears to invade cracks in the top of the underlying flow. This is clearly illustrated by the other red beds seen in the gully with the Main red bed (M7631 - 40287891 and M7623 - 40287890).

Occasionally the red beds include rounded fragments of altered vesicular basalt (see Figure 8.2). Commonly this is associated with reddening of the underlying flow, suggesting sub-aerial erosion prior to deposition of the red bed. The rounded basalt fragments are probably derived from the underlying flow. One rather different case of basalt fragments within a red bed was noted in a red bed on the foreshore of Camas Mhor (40877931). Here an oval-shaped fragment of basalt is seen to rest in a hollow in a fine grained sediment with thin carbonaceous layers. The overlying sandy deposit is thickest around the basalt fragment (see Figure 8.3). The manner in which this oval fragment appeared to have embedded itself in the underlying sediment suggests that it may be a bomb that landed in this red bed prior to deposition of the overlying sandy part of the deposit.

Where both reddening of the underlying flow and a red bed occur together, it can be clearly seen that the two are distinct. The infilling of cracks in the altered basalt by material identical with the overlying red bed implies that the red bed was deposited after alteration of the basalt. This, along with petrographical evidence and the presence of the bomb in one red bed, has led the author to believe that the red beds are very probably tuffaceous deposits rather than the result of laterization of the underlying basalts.

The red beds of Eigg are not so abundant as those of Muck (at the present erosion level at least). They seldom contain fragments of basalt, being simply red mudstone deposits (see Figure 8.4).

The red beds found in the Basal Group of Muck are distinctive by the fact that they are usually bedded. The best examples of this were collected from the foreshore (the inter-tidal zone mainly) just east of Sgorr nan Laogh (around 40407890). Here a thin lava flow (0.50 m thick) is underlain by about 1.5 m of interbedded red and orange mudstone. The red layers are sandy and rather similar to the red beds already described. The orange layers appears to be coarser grained and bedded. This bedding and the interleaving of the two types of deposit suggests that these deposits were lain down in water. However, the petrography of the samples collected from this locality (M7540, M7541 and M7542) suggests that they are tuffaceous, like the rest of the red beds.

8.2.2 Fine grained deposits of Canna

No red beds were found on Canna. This suggests that the rate of extrusion here was greater than on either Eigg or Muck, where there were sufficiently long breaks in extrusive activity to allow not only weathering of the flow tops but also deposition of the red beds.

The fine grained sediments are much less abundant than the conglomerates on Canna. A few fine grained deposits do however occur. Two of them are simply fine grained intercalations within the conglomerates. One of these (C7726) forms a white, fine grained layer in the conglomerates below the irregular intrusion just north of Garbh Asgarnish (28100590). The other (C7771) is a small pocket of tuff overlying conglomerates in the cliffs north of Dun Beag (28760384).

Two other fine grained deposits were observed but not sampled. At Rubha Langanes (23850675), about 5 m of tuffaceous shales with fragments of carbonaceous material are exposed below the lavas forming the cliff tops. The fine grained sediments are underlain by conglomerates, which are exposed at intervals on the foreshore below high water mark. Below Bre Sgorr (21250400), a small outcrop of fine grained conglomerate, with pebbles (all less than 10 mm in diameter) of basalt and reddish sandstone, underlies the palagonite pillow breccia (see Section 2.4.5). Thin sandy and carbonaceous shale layers occur within the fine grained conglomerate.

8.2.3 Petrography of the fine grained sediments

With one exception (M7610), the fine grained sediments can be subdivided into three groups, on the basis of the included fragments:

those with no identifiable fragments;
those with crystal fragments;
those with crystal and lithic fragments.

Of these three groups, the sediments with both crystal and lithic fragments are the most abundant. Table 8.1 lists the samples which fall into the three groups.

The samples with no identifiable fragments are all red beds from Muck. Most of them have some discernible fragment outlines, which are too altered to be identified. Three of them (M7535, M7539 and M7623) contain zeolitic material, presumably of secondary origin, as with the zeolites in the lavas and minor intrusions. All the samples are composed of a deep red amorphous, clay-like material.

The other fine grained fragmentary rocks are subdivided on whether or not they contain lithic fragments in thin section. It is interesting to note that, with one exception (M7661), the fragmental rocks petrographically classed as having only crystal fragments are not found to contain rounded basalt inclusions. M7661 contains only rare basalt fragments.

The mineralogy of the crystal fragments in both groups is given in Table 8.2. A total of nine minerals are represented in the crystal fragments. Most common of these is feldspar, which is present in some form in all but three of the samples examined. Quartz and opaque oxide grains are also fairly common. Muscovite and biotite occur in some of the samples, as do olivine and clinopyroxene.

The quartz grains are commonly strained. Both angular and rounded grains occur, and some show corrosion. Those in M7616 show secondary overgrowths of quartz on original rounded grains. This roundness suggests that the original quartz grains in this sample are of sedimentary origin. One of the samples from Eigg (E7648) shows some crystals which resemble quartz. However, some of them yield biaxial positive interference figures, while others are uniaxial with a negative sign, rather than the positive uniaxial interference figure of quartz. They do not appear strained, which might cause anomalous interference figures. One crystal is wedge-shaped, suggesting tridymite. Many of them may well be sanidine or unaltered orthoclase, but it is very difficult to be certain.

Various types of feldspar were recognised. Plagioclase, with polysynthetic twinning, is common, especially in samples with both crystal and lithic fragments. Unfortunately, determination of the composition of the plagioclase laths was not possible in any of the thin sections. Alkali feldspar is also common. In many cases it was not possible to determine the type of the alkali feldspar present, often as a result of zeolitization of the crystals. Orthoclase was identified from one of the Muck samples (M7616). Anorthoclase occurs in three of the Muck samples (M7540, M7563 and M7572). This is surprising as there are no acidic outcrops on Muck. Equally surprising is the presence of microcline (with typical cross-hatch twinning) in two other Muck samples (M7631 and M7652). The presence of these minerals, normally associated with acid igneous rocks in the red beds of Muck, suggests that acidic bodies of rock must have existed in the source region of the red beds. Alternatively, the microcline could have been derived from Torridonian sediments.

Olivine, usually pseudomorphed, occurs occasionally (see Table 8.2 for details), as does clinopyroxene. Possible orthopyroxene occurs in M7652. Small rounded opaque grains are fairly common.

One of the Canna samples (C7771) is rather different from the rest on account of the presence of epidote found in the sample. It is more of a proper sediment than a tuffaceous deposit, and is probably of a more similar origin to the conglomerates of Canna than the red beds of Eigg and Muck.

Lithic fragments are most commonly basaltic. Various types of basalt were found. For example, E7648 has three different types of basalt fragments within it:- an opaque-rich variety, one showing a trachytic texture and an aphyric basalt with ophitic clinopyroxene. The other common type of lithic fragment is deep red in colour and strongly resembles the matrix of the red beds. Thus they are probably fragments of pre-existing red beds incorporated in this later deposit. One sample (E7648) has glassy fragments in addition to the other types of lithic fragments which have already been described.

Again the sample from Canna (C7726) is distinct in having arkosic and sandstone fragments. Like the other sample from Canna (C7771 - see above), this is probably of a similar origin to the Canna conglomerates.

The matrix of all the samples is very similar to the samples with no identifiable crystal or lithic fragments. Slight colour variations exist, from deep red to brown-red or orange-red. The groundmass of the Canna samples are usually more brown than red.

8.2.4 Conclusions

The fine grained sediments from Canna are most probably of fluvial origin, like the conglomerates, with which they are normally associated. Those from Eigg and Muck (the red beds), however, are markedly different, having either crystal fragments or both crystal and lithic fragments, all of which are usually of igneous origin. The field evidence (see Section 8.2.2) suggests that the red beds are distinct deposits from the reddening of the tops of the underlying lavas. If the identification of tridymite and cristobalite in E7648 is correct, this suggests an explosive origin for the red beds, the tridymite and cristobalite being explosively ejected from great depth. It is the opinion of the author that the red beds of Muck and Eigg are more akin to tuffaceous deposits than baked laterites, the more conventional interpretation of red horizons in basaltic lavas. Some of the reddened basaltic fragments in these deposits imply erosion of basaltic lavas in the immediate vicinity.

8.3 Coarse Grained Fragmental Rocks

Apart from the conglomerates and breccias found below the pitchstone of the Sgurr of Eigg (see Chapter 6), the only other coarse grained fragmental rocks are found on Canna. They are largely confined to the eastern part of the island - east of Allt Thaligaridh (27680595), the islands in Canna Harbour and along the east and south coasts of Sanday. In the north, conglomerates are seen in the cliffs as far west as Am Basadain (27550640). They occur at various horizons in the cliffs from there around the east side of Compass Hill (28100605), as far south as Alman (28030545). They outcrop again along the north coast of Canna Harbour (e.g. just west of the church (27600538) and south of The Square (27080518)). The island of Eilean Ghille Mhairtein (26770508) is almost totally composed of conglomerate, and this also outcrops on Eilean a' Bhaird (27050507) and in a thin band on Iolann an Eilean (26900496). On the north coast of Sanday several outcrops of conglomerate occur (e.g. east of Am Mialagan - 26880485). In the cliffs, sea-stacks and on the foreshore from Rubha Camas Stianabhaig (28800435) around the east and south coasts of Sanday as far west as Creag nam Faoileann (28550379), various exposures of conglomerate were noted. The most westerly outcrop of conglomerate on Sanday occurs in a small bay on the south coast (27000420).

The majority of the conglomeratic exposures contain abundant dark red sandstone and basalt pebbles, both of which are usually well rounded. Rarely, small pebbles of acidic and basic intrusive rocks are found.

Two extensive outcrops of conglomerate were examined in detail. Those in the cliffs above Garbh Asgarnish (28170613) are shown diagrammatically in Figure 8.5. The lower part of the exposure outcrops in a crag about 300 m north of Garbh Asgarnish. The basal 10 m of this crag is composed of large angular blocks of basalt. Many of them are over 1 m in diameter. Some of the basalt fragments show reddening, which suggests that they were exposed to atmospheric weathering prior to incorporation into the deposit. The size and angularity of the fragments decrease upwards and the basalts are joined by non-basaltic pebbles, but acidic igneous pebbles were also found. The lower part, that with only basaltic fragments, shows no stratification, but the upper part of the crag exhibits faint bedding in the finer grained sediments.

Between 50 and 80 m above sea level, the cliffs are composed of alternating conglomerates and basaltic lavas. It proved impossible to sample these. One hundred metres above sea level, about 10 m of conglomerate are exposed in the cliffs. This upper conglomerate is again exposed in the bed of the Allt Thaligaridh (27660610), west of Compass Hill. A great variety of pebbles, with an average diameter of 0.1 m, were observed. These included various types of basalt, glassy igneous fragments, red sandstone and gabbroic pebbles. The red sandstone pebbles predominate. At one locality in the stream bed, the conglomerate contained elongate pebbles which had their long axes arranged sub-parallel to each other and sub-horizontal.

In the sea-stacks of Coroghan Mor (27980553) and Alman (28030545), rather confused outcrops of columnar basalt and conglomerate are exposed.

The columnar basalt may be a southern extension of the irregular columnar intrusion noted in the cliffs above Garbh Asgarnish (28070581) - see Chapter 4. In the northern face of Alman, the conglomerate is seen to infill a hollow in the columnar basalt.

The second extensive outcrop of conglomerate is seen in the sea-stacks of Dun Mor (28730375) and Dun Beag (28820378) on the south coast of Sanday, and in the cliffs north of the sea-stacks. The succession found in these three cliffs is shown diagrammatically in Figure 8.6. Unfortunately, it proved impossible to sample any of the rocks on Dun Beag. Thus precise correlation of the lavas of this stack with those of Dun Mor and the cliffs to the north was impossible. The correlations of Dun Mor with the cliffs to the north is shown in Figure 8.6. The tuff above the lower conglomerate of the cliffs to the north of Dun Mor must die out westwards as it does not outcrop in Dun Mor. Both bands of conglomerate contain rounded pebbles of red sandstone and basalt. Both conglomerates thin fairly rapidly westwards.

The conglomerate of Dun Beag is unusual because of its vertical contact with the basalt lavas which form the southern half of the sea-stack (see Figure 8.7). It is also unusual in the way it fills the overhang in the middle flow of the stack. The conglomerate must post-date at least the two lower flows of the sea-stack and that represented by the scoriaceous top which forms the wave-cut platform at the base of the stack. The massive flow which caps the sea-stack may well post-date the conglomerate.

The Dun Beag conglomerate resembles the lower conglomerate of the Compass Hill succession. It has large angular fragments, totally of basalt, at the base. The grain size and angularity of the fragments gradually decrease upwards in the conglomerate, and the basalt fragments are joined by red sandstone pebbles. Near the top of the deposit there is a coarse horizontally bedded pebbly sandstone layer.

8.3.1 Petrography of the pebbles from the Canna conglomerates

The conglomerates of Canna were sampled at six localities:

1. Lower 10 m of the crag, c.300 m north of Garbh Asgarnish, Canna (C7501) - 28170613;
2. Upper part of the crag sampled at 1, (C7502) - 28150612;
3. In the bed of the Allt Thaligaridh (C7510) - 27660610;
4. Foreshore south of The Square (C7510) - 27080518;
5. Foreshore east of the church, north-west of Rubha Corr-inis (C7522) - 27600538;
6. Small bay on the south coast of Sanday (C7591) - 27000420.

The pebbles collected from these six localities can be grouped into three rock types, as shown in Table 8.3. Sampling of each locality was not always representative of the rock types present, but the apparent predominance of basalt and sandstone pebbles is confirmed by field observations.

8.3.1.1 Basic pebbles

Basalts are the most abundant type of basic pebble. Four different varieties of basalt, based on the same petrographical classification as used for the extrusives, were identified. Of the basalt pebbles collected, plagioclase- and olivine-phyric basalts predominate, with aphyric basalts as the second most abundant type.

Little attempt was made to choose different petrographical types when the pebbles were collected, so the collected basalt pebbles are probably a fairly representative sample. It is interesting to note that plagioclase- and olivine-phyric basalts were the most abundant type found in the lavas (52% of all extrusives), followed by aphyric basalts (14% of all extrusives). This suggests that the basaltic pebbles could well have been derived from lavas similar to the currently exposed lava pile. Petrographically, they also resemble the Canna lava samples (see below).

In the plagioclase- and olivine-phyric basalts, the olivines predominate over the plagioclases, which are usually fairly rare and of microphenocryst size. One sample (C7501G) contains larger rounded plagioclase phenocrysts of bytownite composition (An_{80}). These could well be xenocrysts. The olivine phenocrysts range in size from 0.4 mm (C7501F) to 2 mm (C7501G) in diameter. They are usually pseudomorphed and often contain spinel inclusions. Olivines (usually altered), labradoritic plagioclase, colourless or brownish pyroxene and opaque oxides from the groundmass. Both granular (e.g. C7518A) and ophitic (e.g. C7501F) relationships between the pyroxenes and plagioclase laths were noted.

The aphyric basalts are, in general, similar to the groundmass of the plagioclase- and olivine-phyric basalts. The olivines are always pseudomorphed, and the plagioclases are of labradorite composition, sometimes showing zeolitization. All but one of the samples (C7502G) show colourless, granular pyroxene. C7502G has pink-brown pleochroic pyroxene, which shows zoning and ophitic relationships with the plagioclases.

The plagioclase phyric basalt sampled (C7501B) has groups of labradorite (An_{68}) phenocrysts. The individual laths are 2 mm in length and the groups average 5 mm across. The matrix shows pseudomorphed olivines, abundant small plagioclase laths, pyroxenes and opaque oxides. The pyroxene occurs in groups of tiny granules, which gives an initial ophitic appearance.

The olivine phyric pebble has bowlingite pseudomorphs after olivine phenocrysts (0.2 mm across). Some have spinel inclusions. Again the matrix olivines are altered. The small, very abundant plagioclase laths show a faint flow alignment. Small colourless granules of pyroxene and opaque oxide grains make up the matrix of this sample.

All the basalts show some degree of alteration, usually in the olivines. Zeolites are also commonly present in the matrix.

Two hawaiitic samples were collected (C7501E and C7510H). One of them (C7501E) has ladradorite phenocrysts (possibly of xenocrystic origin) in a very fine grained, or glassy, flow banded matrix. The groundmass has the typically abundant plagioclase laths and opaque oxides of a hawaiite. This sample was chemically analysed and found to be a hawaiite by the classification of Thompson et al (1972).

The other hawaiite (C7510H) contains phenocrysts of all four minerals normally found in basaltic rocks. Most common are the plagioclase phenocrysts, which average 0.7 mm in length and are of andesine composition. The olivines (up to 1.1 mm across) are pseudomorphed, but originally had subhedral outlines. Microphenocrysts of spinel (less than 0.1 mm) are subhedral and fairly rare. The pyroxenes (0.4 mm) are also subhedral, fairly rare and are brownish in colour. The matrix is composed of similar minerals. It is very fine grained, has granular pyroxenes and a trachytic texture in the plagioclases.

The third type of basic pebble is gabbroic. One of these (C7510E) is rather unusual. It has patches of very coarse grained material composed of zoned plagioclases (labradorite), brown, slightly pleochroic pyroxene, altered anhedral olivines and anhedral opaques. Usually these patches show evidence of having been broken. They are enclosed by a grey coloured, glassy material with included fragments of zoned plagioclases, clinopyroxene and opaque oxides. The coarse patches do not show chilling against the glassy matrix, or vice versa. This may be an explosively shattered gabbro. It was collected from the bedded conglomerate found near the top of the Compass Hill succession. This deposit is definitely not an agglomerate, as might be suggested by the presence of this pebble. The other gabbro pebble (C7510A) is also from this deposit. It shows normal gabbroic mineralogy. The olivines are however altered and the sample includes radiating, granophyric aggregates of quartz and alkali feldspar, suggesting that it is from a tholeiitic gabbro.

8.3.1.2 Sedimentary pebbles

Almost as abundant as the basalt pebbles are those of sandstone. On the basis of feldspar content, these samples were divided into three groups - sandstones, feldspathic sandstones and arkoses. In the sandstones (including the quartzitic sandstone C7591C), quartz is the single most abundant form of detritus. Feldspars and other minerals form only a small proportion of the rock. The feldspathic sandstones still have quartz as the most abundant form of detritus, but feldspars are fairly abundant. In the arkoses, the feldspars are more abundant than quartz. All but three of the sedimentary pebbles collected (C7518B, C7522A and C7591C) are either sandstones or feldspathic sandstones, and of these two groups, the feldspathic sandstones are slightly more abundant than the sandstones.

The sandstones have ubiquitous quartz grains with an average grain size between 0.05 mm and 0.2 mm. In some samples (e.g. C7502D and C7502E), the quartz is angular; in others (e.g. C7502B and C7510B), it is subrounded. Frequently it is strained, suggesting a metamorphic origin. Small quantities of feldspar occur in all the sandstone pebbles collected. Plagioclase and alkali feldspar could be identified in most samples, and microcline, with its usual tartan twinning, was found in C7591F only. Muscovite is also relatively common. In C7502J, the muscovite is aligned along the bedding planes. In C 7591F, it is clearly of metamorphic origin. A dark green to brown pleochroic biotite occurs in some of the pebbles from the upper part of the crag c.300 m north of Garbh Asgarnish (C7502B, C7502E and C7502J). Epidote also occurs in pebbles from this outcrop (C7502D and C7502E) and from one other exposure (C7510B) on the south coast of Sanday. An isotropic mineral with high relief was found in C7591F. It is presumably garnet. Opaque rich layers occur in two of the samples (C7510B and C7591F). The matrix of these samples is usually highly haematite rich, thus giving the sandstones their dark red colouration.

The feldspathic sandstones are also composed predominantly of quartz, often with strain shadows. In the feldspathic sandstones, the grain size varies from 0.1 mm to 0.5 mm. Solution boundaries within what is now a single crystal were found in C7591B. All shapes of quartz grains from angular to subrounded are seen, even within the same sample. Plagioclase and alkali feldspar are fairly abundant in these samples. Orthoclase and microcline are the most common types of alkali feldspar seen. Perthitic alkali feldspar occurs in a few samples. In C7502I, these are true perthites (potassium-rich blebs in a sodium-rich matrix), while those in C7502F are anti-perthites (sodium-rich blebs in a potassic matrix). Also, in C7502I, there are microcline crystals with perthitic alkali feldspar overgrowths. In C7591E, the feldspars show evidence of the haematite staining seen in the rock as a whole. Opaque oxide grains, muscovite, green/brown pleochroic biotite and epidote occur fairly rarely in some of the pebbles. Biotite and epidote are confined to pebbles from the upper part of the conglomerate in the crag c.300 m north of Garbh Asgarnish (C7502A, C7502F and C7502H). Fragments of earlier sediments are included within C7502I. Two of the samples show coating of the mineral grains with haematite (C7502H and C7591G). The matrix of these feldspathic sandstones is similar to that of the sandstones - a red clayey material.

Two arkoses, in which the feldspar grains exceed the quartz, were found (C7518B and C7522A). Quartz and plagioclase are present along with various types of alkali feldspar. Perthitic feldspar, microcline and sanidine occur in C7518B, while C7522A contains anorthoclase, orthoclase and microcline, all of which are badly altered. C7518B also contains small amounts of epidote and green biotite. In both samples, the mineral fragments are quite angular and in C7522A the cement is a yellow-brown colour (?limonite). The average grain size of C7518B is less than 0.5 mm, while that of C7522A is about 1 mm.

The other sandstone sample collected (C7591C) is very rich in quartz grains. The quartz occurs as angular grains of up to 0.2 mm in diameter. Some of them show strain shadows. Rare grains of muscovite, green/brown pleochroic biotite, opaque oxides and feldspar also occur. The bedding visible in hand specimen is found to be due to alignment of the micas. There is very little identifiable cement.

8.3.1.3 Acidic igneous pebbles

Two different types of acidic igneous pebbles were found in the Canna conglomerates:- porphyritic felsites and granophyres. The majority of them are from the upper conglomerate of the Compass Hill succession (C7510C, F, G and I) and from the exposure on the south coast of Sanday (C7591A and D). One (a porphyritic felsite) is from the upper part of the conglomerate in the crag c.300 m north of Garbh Asgarnish (C7502C).

The majority of the acidic pebbles are porphyritic felsites. One of them (C7591A) has sanidine phenocrysts set in a predominantly glassy matrix. Some coarser patches in the matrix are composed of a mat of tiny feldspar laths. The glassy parts contain feathery microlites, especially around the phenocrysts. Often the phenocrysts have a fringe of microlites.

The other three porphyritic felsites have a more varied phenocryst assemblage. C7510C has plagioclase phenocrysts (1.3 mm long), which show polysynthetic twinning and strong zoning. Many show considerable alteration and are often corroded. It also contains small, rounded quartz crystals and an altered green pleochroic mineral (probably amphibole), which occurs in groups with the plagioclases. Fairly abundant opaque oxides also occur. The matrix is a very finely crystalline mat of quartz, alkali feldspar and opaques. C7510G has a similar phenocryst assemblage and matrix. C7502C has two types of feldspar. Corroded anorthoclase crystals with very fine tartan twinning are fairly easily identified. The other feldspar is essentially untwinned and has a refractive index less than the mounting medium. It is either albite or orthoclase. Green clinopyroxenes, largely altered, and opaque oxides were also found. The matrix is a finely crystalline mat predominantly of feldspars.

The granophyres (C7510F and C7591D) are characterised by micrographic intergrowths of quartz and alkali feldspar. Both samples contain plagioclase (An_{28} was measured in C7591D) and alkali fledspar (identified as anorthoclase in C7510F). In addition, hornblende, with green to yellow pleochroism, and opaque oxides occur in both samples. C7591D has, in addition, small, rare crystals of brown, pleochroic biotite.

The remaining acidic pebble (C7510I) is rather different, having a predominantly felsitic matrix, but with patches of the micrographic intergrowths of quartz and alkali feldspar, which are characteristic of the granophyres. The micrographic intergrowths are associated with the alkali fedlspar phenocrysts. This sample shows banding caused by the interleaving of felsitic and glassy bands (with spherulitic textures) in the matrix. In addition to the abundant alkali feldspars, strongly zoned plagioclase laths, quartz, opaque oxides and colourless or greenish pyroxene occur in fairly small quantities. Also included in this pebble are dark patches, which usually show dendritic opaque oxide crystals at the margins. The edges of these inclusions also appear to be glassy, as if chilled against the acidic host magma. This implies that they must have been in a semi-molten state when they were incorporated in the acidic magma. The dark patches are composed of plagioclase and opaque oxides, with possible olivine and pyroxene, both of which are rather badly altered.

8.3.2 The provenance of the pebbles from the Canna conglomerates

As stated above (Section 8.3.1), the basaltic pebbles in the Canna conglomerates could well have been derived from lavas of similar petrographical characteristics as the exposed lavas on Canna today. This is also true of the hawaiites. The gabbroic, sedimentary and acidic pebbles, however, have no equivalent *in situ* on Canna today.

The sedimentary fragments are all sandstones, and the vast majority of them are red, feldspathic sandstones, very reminiscent of the Torridonian outcrops of north-west Scotland. Skye and Rhum are both possible sources for the Torridonian pebbles in the Canna conglomerates. The bands of opaque grains found in two of the pebbles (*see* Section 8.3.1.2) are very similar to some of the Torridonian of Rhum, so perhaps Rhum is the source region for the red sandstone pebbles from the Canna conglomerates. It is also possible that some of them could have been derived explosively from the Canna basement, but, as the sub-basaltic rocks of Canna are still a matter of some debate, this must remain purely speculative.

Some of the acidic pebbles resemble some of the Tertiary acid intrusions on Rhum. Emeleus (1973) has already noted the similarity of a granophyric pebble from the conglomerates on the south coast of Sanday with the Tertiary granophyre of north-west Rhum. C7510F is another such pebble. Two of the porphyritic felsites (C7510C and C7510I) may also have been derived from Tertiary acid intrusions from Rhum. The others have no known origin, and may represent some intrusion which has since been eroded away.

The shattered gabbro sample (C7510E) could possibly also be from Rhum. There are shattered gabbroic masses in the northern part of the Central Complex (Emeleus and Forster 1979). The other gabbro may also be from Rhum, or possibly Skye. Dr. C. H. Emeleus (pers. comm. 1979) feels that, on petrographical evidence, most of the fragmentary material comes from Rhum, with the exception of the basalts, which could have come from the environs of Canna itself.

Geikie (1896) claims to have found schist and gneiss pebbles in the upper conglomerate of the Compass Hill cliff section. He suggests the western highlands (to the east of Canna) as a source for these pebbles. The author found no metamorphic pebbles in any of the Canna conglomerates In his studies of the Canna conglomerates, Emeleus (pers. comm. 1979) failed to find metamorphic pebbles also. If Geikie's claim is justified, it implies a fluvial connection between Canna and the western highlands of Scotland, and suggests a westerly flowing river.

Many of the conglomerates (excepting the lower parts of the exposure c.300 m north of Garbh Asgarnish - 28170613, and the basal part of that on Dun Beag - 28820378) exhibit bedding. This, and the predominant roundness of the pebbles, points to deposition in a body of water. The deposits are clearly not marine, as shown by the carbonaceous inclusions found in the fine grained sediments associated with conglomerates at Rubha Langanes (23850675). The conglomerates are thought to be of fluvial origin, in agreement with Geikie (1896).

Harker (1908) and Geikie (1897) both refer to the lower parts of the Compass Hill deposits as agglomerate. Likewise, they should also classify the lower parts of the Dun Beag conglomerate. It is true that the deposits in question consist entirely of angular basaltic debris, but the reddening of many of the fragments (<u>see</u> Section 8.3) rather suggests atmospheric weathering prior to their incorporation in the deposits. This suggests to the author that these weathered samples must have been derived from pre-existing lava flows. The passage upwards into true conglomerate with some bedding at both localities rather suggests that the agglomerates of Harker and Geikie do not represent the site of an explosive vent. Certainly some of the angular basaltic fragments may have been derived from the slopes of a nearby vent, perhaps located between Rhum and Canna of which nothing remains today. The ill-sorted nature of the deposits and the predominance of large fragments in these deposits implies both a local source and a high energy environment.

An important deduction concerning the age of the Canna lavas can be made by considering the ages of the pebbles found in the conglomerates. The presence of acidic and particularly gabbroic pebbles imply that the host conglomerates (and hence the overlying lavas) must postdate not only the intrusion of some plutonic bodies, but also their unroofing. The lavas of Eigg and Muck clearly predate most of the dykes, and are thus much older than those of Canna. The lavas of Rhum and Canna may well be contemporary, and may possibly also originate from the same magma chamber.

The conglomerates below the pitchstone of the Sgurr of Eigg postdate the intrusion of the basic dykes. It is possible that they are of a similar age as those on Canna. They may even form part of the same river system, as envisaged by Geikie (1896).

CHAPTER 9

MINERALOGY

9.1 Introduction

A few olivine pyroxene and plagioclase analyses of the basic rocks of Eigg and Muck were made using the electron microprobe at Durham University. Alkali feldspars (from the acid rocks of Eigg) proved difficult to analyse and few reliable analyses were obtained (none are presented). The method of analysis was the wavelength dispersive system, using a flow counter. The raw data was processed by an online mini computer.

Analysing conditions and the standards used during analysis are summarised in Table 9.1. The peak angle used for each wavelength varied slightly from one analysis session to the next; the values quoted are averages. Whenever possible, background measurements for each element were made on standards of a similar atomic number to the element being analysed. For Mn, Fe, Ni and K, however, this proved impractical, and the background levels were calculated using the standard on which the peak angle for the element was measured. The background measurement was taken to be the average of two values taken 2° either side of the peak.

To supplement the author's data for the basic rocks, the mineralogical data of Ridley (1973) is included - olivines, pyroxenes, feldspars and spinels from Eigg and Muck. Ridley's data is quoted either as an average for each mineral from each sample analysed, or as two analyses reflecting the range of compositions seen in the major elements for each mineral type.

No analyses of minerals from the acid rocks of Eigg were made by the author. A note on these is included (see Section 9.3), using the data of Ridley (1973) and Carmichael (1960a, 1960b, 1963 and 1967).

9.2 The Basic Rocks

9.2.1 Olivines

In all 23 olivine analyses were made from rocks ranging from basalt to hawaiite (Thorton-Tuttle differentiation index from 20 to 33). An unsuccessful attempt was made to find olivine in a mugearite (E7471) during analyses of other minerals in this sample. The analyses, along with five olivine analyses by Ridley (1973), are presented in Table 9.2.

In terms of fosterite content, the olivines show a range from Fo_{64} to Fo_{90}; the fosterite content decreases with increasing Thorton-Tuttle differentiation index of the host rock (see Figure 9.1). Only two unzoned olivines were found among those analysed by the author. These are both from basaltic intrusions (E7403 and MD13). Normal zoning was found in all other crystals where analyses of both core and margin of the same grain were made. The greatest difference noted in a single olivine was from Fo_{86} at the centre to Fo_{68} at the margin of a phenocryst in the olivine-phyric basalt E7487.

Nickel and manganese are the two most important trace elements found in olivines. Magnesium-rich olivines are considered to be the principal host of nickel in the common volcanic minerals (Carmichael et al 1974). The abundance of each of these elements (as weight per cent oxide) has been plotted against the fosterite content of the host olivine (<u>see</u> Figures 9.2 and 9.3). The nickel content increases with increasing fosterite. Manganese shows a remarkably good negative correlation with fosterite content, especially if the intrusive samples of Muck are excluded.

9.2.2 <u>Pyroxenes</u>

The pyroxenes analysed (<u>see</u> Table 9.3 for analyses) were plotted in the pyroxene quadrilateral - diopside, hedenbergite, enstatite and ferrosilite (<u>see</u> Figure 9.4). In the nomenclature of Poldervaart and Hess (1951), most of the pyroxenes are augites. Those from a hyperstene-normative dyke (a basalt) from Eigg (E7403) are endiopsides, plotting close to the dividing lines between endiopside, diopside and augite. One of the olivine-phyric basalts from Eigg (E7486) contains pyroxenes which fall just within the salite field (over 45% wollastonite). The nepheline-normative hawaiite dyke (E7402) from Eigg has pyroxenes which plot near the ferrous end of the salite field.

Comparing the pyroxenes from Eigg and Muck with those from Skye (Skye data from Ridley 1973) show that, for the hawaiites and mugearites, the Skye lavas have more calcic pyroxenes than those from Eigg and Muck. The pyroxenes from the Skye mugearites are also more enriched in iron than those analysed by the author.

Predominantly, the pyroxenes from the basic rocks of Eigg and Muck fall between the trends established for the pyroxenes from the Garbh Eileann sill (Shiant Isles) and the British and Icelandic acid glasses. They are also more calcic than pyroxenes from the Skaergaard intrusion. This suggests that the host rocks of the Eigg and Muck pyroxenes are intermediate in composition between the alkalic Garbh Eileann sill and the tholeiitic Skaergaard intrusion. This is compatible with the way that the whole rock analyses cluster near the Hawaiian dividing line on a total alkalis versus silica diagram (see Chapter 10).

Three samples contain pyroxenes which do not conform to the trend described above. A basaltic dyke from Eigg (E7403) contains pyroxenes which plot on the magnesium-rich end of the Skaergaard trend (see Figure 9.4), perhaps suggesting that the host rock is tholeiitic. The whole rock analysis of E7403 yield 7.16% normative hypersthene, thus confirming the suspected tholeiitic nature of this sample. The nepheline-normative hawaiite E7402 has more calcic pyroxenes than any of the other samples from Eigg and Muck. They plot on a ferrous extension of the trend for the pyroxenes from the differentiated teschenite sill from New South Wales, Australia. This suggests a more alkalic host, and the total alkalis (4.18%) and the silica (48.20%) contents confirm this. The third sample to fall off the described trend is the brown pyroxene from the mugearite E7471. It has a low CaO content, but is very rich in Na_2O (3.60%) compared with the other pyroxenes.

During thin section studies (see Chapters 3 and 5), some of the pyroxenes were noted to be zoned, usually with colourless cores grading outwards to darker pleochroic margins. Core and margin analyses of the same grain of pyroxene were made for five of the samples, and this data is summarised in Table 9.3. Only two of the five pyroxenes show any appreciable zoning from core to margin (E7468 and E7481). Definite zoning was noted in thin section only in one of these two samples (E7468).

Brown, or purplish brown, colouration in clinopyroxenes is usually attributed to the presence of titanium. Table 9.4 lists the colour of the analysed pyroxenes (from the petrographical studies) and their respective TiO_2 contents. The two pyroxenes with the deepest colouration (E7402 and MO13) have the highest concentrations of TiO_2 (around 2%). It is known also that TiO_2 is more abundant in pyroxenes from undersaturated magmas than from tholeiitic magmas (Brown in Poldervaart and Hess 1951). Four of the eight samples, for which pyroxene analyses are available, were processed by the discriminant analysis method (see Chapter 10). It is significant that the most TiO_2-rich pyroxene analysed comes from the most alkaline of the samples (discriminant analysis score of -0.671).

9.2.3 Feldspars

The author analysed four plagioclase phenocrysts, all from the lavas of Eigg (see Table 9.6). Analyses by Ridley (1973) are limited to a series of traverses across feldspars from two dykes, one from Eigg, the other from Muck (see Table 9.6). All the author's analyses are labradorites Core and margin analyses of one of the phenocrysts from E7472 (a hawaiite) reveal little zoning. Both Ridley's samples, however, show strong normal zoning. The feldspar from Eigg ranges from bytownite (An_{72}) to andesine (An_{42}). The Muck sample shows even more extreme zonation. The cores of these feldspars are either andesine or labradorite, but in all cases, the margins are anorthoclase, with a maximum orthoclase content of Or_{34}.

9.2.4 Iron-titanium oxides

To complete the mineralogy of the basic rocks, the author includes two analyses of spinels (see Table 9.7). These are average analyses calculated from the data given by Ridley (1973). Ridley finds only one spinel phase in the samples analysed - a homogeneous titanomagnetite. This contrasts with the Icelandic basalts where both ilmenite and titanomagnetite commonly coexist.

9.3 The Acid Rocks

The author did not analyse any minerals from the acidic rocks of Eigg. What follows is a resumé of the published mineralogical data on the acid rocks of Eigg - that of Ridley (1973) and Carmichael (1960a, 1960b, 1963 and 1967).

9.3.1 Pyroxenes

The pyroxene analyses available from the literature are listed in Table 9.8. The analyses by Carmichael (1960a) are by semi-micro methods, while those of Ridley (1973) are by electron microprobe. There are three calcium-rich pyroxenes from the Sgurr of Eigg, one calcium- and iron- rich pyroxene from one of the pitchstone dykes of Rudh' an Tancaird and two calcium-poor pyroxenes from the Sgurr of Eigg. The proportions of wollastonite, enstatite and ferrosilite (Ca, Mg and Fe of Table 9.8) have been plotted in the pyroxene quadrilateral (see Figure 9.5). The calcium-poor pyroxenes from the Sgurr pitchstones are clearly magnesium-rich hypersthenes. They coexist with relatively magnesium-rich augites, which fall on the trend defined by the augites of the Skaergaard intrusion (Brown 1957). By contrast, the calcium-rich pyroxene from the western pitchstone dyke of Rudh' an Tancaird is very enriched in iron, and falls within the field of ferrohedenbergite, as defined by Poldervaart and Hess (1951). It is not associated with a calcium-poor pyroxene, and falls on the iron-rich end of the trend of the Skaergaard pyroxenes.

All the pyroxenes from the acidic rocks of Eigg show enrichment in MnO and depletion in TiO_2 and Al_2O_3 compared with the ferroaugites of the Skaergaard intrusion (see Table 9.9). The solubility of these three elements is controlled by temperature, and thus the relatively rapid cooling of the Eigg samples compared with the slowly cooled Skaergaard intrusion will have influenced the relative abundances of these elements in the pyroxenes (Ridley 1973). Ridley also points out the preferential partitioning of Al_2O_3 and TiO_2 into the monoclinic rather than the orthorhombic pyroxenes of the Sgurr samples.

Compared with other pyroxenes from Tertiary acid glasses (see Carmichael 1960a), those of the Sgurr are very rich in magnesium. They fall in the augite and hypersthene fields, while the other Tertiary acid glass pyroxenes quoted by Carmichael are ferroaugites and ferrohypersthenes, eulites or orthoferrosilites.

The pyroxenes in the Sgurr could be phenocrysts in equilibrium with each other and the enclosing liquid (as represented by the residual glass), or they could be xenoliths, or possibly metastable phases, such as are found during heating experiments of natural granites (to melting point). The parallelism of the tie-lines between the calcium-poor and calcium-rich pyroxenes of the Sgurr pitchstone and the pyroxenes of the Skaergaard rocks (see Carmichael 1960a, Figure 2) suggests that the pyroxenes of the Sgurr pitchstone are in equilibrium with each other.

That they are in equilibrium with the surrounding liquid is evidenced by the lack of zoning and dissolution of the phenocrysts (see Carmichael 1963).

The magnesium-rich pyroxenes of the Sgurr are in strong contrast with the ferrohedenbergite found in the Rudh' an Tancaird dyke. This suggests strong iron depletion and magnesium enrichment during formation of the Sgurr magma, but strong iron enrichment in the magma which formed the Rudh' an Tancaird dykes. Crystallisation of magnetite will strongly deplete the liquid in iron. Anhedral magnetite microphenocrysts are fairly abundant in the Sgurr pitchstone, and many of them must have crystallised early, as they are enclosed by other phenocrysts, including the pyroxenes. By contrast, magnetite microphenocrysts occur but rarely in the Rudh' an Tancaird pitchstones. This is in complete agreement with Carmichael (1963), who concludes that "early precipitation of magnetite ..... will markedly impoverish these acid liquids in iron, and the pyroxene components of the liquid will become increasingly magnesian as magnetite continues to crystallise".

Ridley (1973) also reports calcium-rich pyroxenes, of similar composition to those found in the Sgurr, in a pitchstone at Kildonnan (no analyses quoted however). He did not find hypersthene in this pitchstone. The author found coexisting calcium-poor and calcium-rich pyroxenes in the North Pier pitchstone, which outcrops near Kildonnan. However, as Ridley does not give the exact location for his Kildonnan pitchstone, one cannot be sure that it is the same pitchstone body as the North Pier pitchstone of this study. If it is, then on the evidence of the pyroxenes, the North Pier pitchstone is very similar to that of the Sgurr.

9.3.2 Feldspars

Analyses from the acidic rocks of Eigg are given in Table 9.10. These are of alkali feldspars from the Sgurr pitchstone, the Cleadale felsite (Sron Laimrhige felsite of this study) and the dykes of Rudh' an Tancaird, and plagioclases from the Rudh' an Tancaird dykes. As with the pyroxenes, the analyses from Carmichael (1960b) are by semi-micro methods, while those from Ridley (1973) are by electron microprobe.

Thin sections of the Sgurr pitchstone examined by the author revealed two types of feldspar phenocrysts:- plagioclase, with polysynthetic twinning, which are rarely rimmed by anorthoclase; and anorthoclase, with tartan twinning (see Chapter 7). Ridley (1973) finds no cases of plagioclase coexisting with discrete anorthoclase. Rather the plagioclase phenocrysts in his samples have rims of alkali feldspar ($An_{44}Ab_{53}Or_5$ to $An_{18}Ab_{62}Or_{19}$) and there are also sieve textured sodic plagioclases with thin alkali feldspar rims. Carmichael (1960b), on the other hand, finds only rare plagioclase phenocrysts, in addition to the very abundant alkali feldspars. Clearly the petrography of the Sgurr pitchstone is very variable, and warrants a detailed study.

Carmichael (1960b) has made optical determinations of an alkali feldspar from the Sgurr pitchstone. These are tabulated, along with the optical data for the high and low temperature alkali feldspars (from Deer et al 1966), in Table 9.11. On refractive indices alone, the Sgurr feldspar could belong to any of the four series, but the optic axial angle restricts it to three.-

orthoclase - low albite series;

sanidine - anorthoclase - high albite series;

high sanidine - high albite series.

The high sanidine - high albite series can be eliminated, because the only naturally occurring feldspars in the series have over 67% orthoclase; the analysed Sgurr sample has 42.4% orthoclase. High Fe_2O_3 content (up to 0.4%) is characteristic of the high temperature feldspars (Deer et al 1966). The Sgurr alkali feldspar contains 0.43% Fe_2O_3, thus suggesting that it belongs to the sanidine - anorthoclase - high albite series. The tartan twinning, noted during thin section examination of the Sgurr pitchstone, is normally associated with anorthoclase, further confirming the high temperature nature of the alkali feldspar.

The analysed feldspars are plotted in the Qz-Ab-An diagram (Figure 9.6 - after Ridley 1973), and the nomenclature of the plagioclase and high temperature alkali feldspar series (from Deer et al 1966) has been superimposed on the diagram. It can be seen that the Sgurr feldspars show a range of compositions through the anorthoclase, oligoclase and andesine fields. Compared with feldspars from the other acidic rocks of Eigg, they are enriched in anorthite.

When plotted in the An-Ab-Or system (see Figure 9.7 - after Ridley 1973), the Sgurr feldspars clearly do not follow the trend of the feldspars from the Icelandic pitchstones as defined by Carmichael (1963). Ridley (1973) suggests that this is due to the Icelandic feldspars equilibrating at lower temperatures and possibly higher water vapour pressures, and thus being less capable of ternary solid substitution. Carmichael (1960b) has determined that the feldspar phenocrysts are in equilibrium with the residual glass (by plotting their compositions on the synthetic plagioclase solidus together with the corresponding plagioclase components of the residual glass).

The alkali feldspars from the Rudh' an Tancaird pitchstone dykes straddle the anorthoclase/sanidine boundary (see Figure 9.6), and contain less than c.3% anorthite. Optically, they are sanidines with very small optic axial angles (see Chapter 7). The plagioclase phenocrysts from the Rudh' an Tancaird dykes are strongly zoned from andesine cores (An_{44}) to anorthoclase margins ($An_{18}Or_{17}$). Clearly there are two distinct feldspars in the Rudh' an Tancaird pitchstones, whereas in the Sgurr pitchstone there appears to be a continuous range from anorthoclase to andesine, which appear as two distinct phenocrysts phases in at least some of the thin sections.

9.3.3 Iron-titanium oxides

The analyses quoted in Table 9.12 are averages of the data presented by Carmichael (1967) and Ridley (1973). The earlier analyses of Carmichael (1963) are known to be in error (see Carmichael 1967, p. 37) and are therefore not included in this thesis. Both authors used the electron microprobe to analyse the iron-titanium oxides (all from the Sgurr pitchstone) and have used the method outlined by Carmichael (1967) to calculate the amount of Fe_2O_3 present.

Ridley (1973) reports that the titanomagnetites are homogeneous. Carmichael (1963) finds no exsolution lamellae at a magnification of 950 times and that the homogeneity is only disturbed by irregular wisps of secondary haematite. He also finds that, occasionally, ilmenite can be seen moulded onto the magnetite crystals.

The spinel phase is titanomagnetite, with 37.6 mol.% ulvospinel (Fe_2TiO_4), while the rhombohedral phase is an ilmenite containing

15.1 mol.% R_2O_3 (Al_2O_3 + V_2O_3 + Cr_2O_3 + Fe_2O_3). From this data Carmichael (1967) has calculated the temperature of equilibration of the iron-titanium oxides, using the method of Buddington and Lindsley (1964). This yields an equilibration temperature of 910°C. He has also established that the oxides are slow to equilibrate to changes in the environment, and claims that reaction between the iron-titanium oxide phases and the liquid will have ceased at the time of quenching of the Sgurr pitchstone magma. Thus the temperature of equilibration of these oxide phases gives an approximation to the liquidus temperature of the residual glass of the pitchstone. Carmichael (1967) has also calculated the oxygen fugacity for the coexisting iron-titanium oxide pair at $10^{-11.4}$ atm. Ridley (1973) discusses the temperature indicated by the quartz-albite-orthoclase components of the whole rock analysis of the Sgurr pitchstone. He concludes that the iron-titanium oxides began to crystallise when the pitchstone liquid was within 1.5 and 2.5 km of the surface.

CHAPTER 10

BASIC GEOCHEMISTRY

10.1 Analytical Method

Chemical analyses of the collected material were carried out using the X-ray fluorescence equipment available in the Department of Geological Sciences, Durham University between 1974 and 1977. The pressed powder method of sample preparation was employed. Details of sample preparation procedures and the operating conditions for the X-ray fluorescence equipment are given in Appendix A3.1.

The method of processing the raw X-ray fluorescence data for major elements in use at Durham at the time the samples were analysed was that described by Holland and Brindle (1966), and Reeves (1971). This method makes use of linear regression techniques for calibration of the samples, for which chemical analyses are already known, both before and after mass absorption correction of the data. It can be clearly seen from plots of count rate against concentration of any given element for specimens of known composition (e.g. the International Standards), that a curve is the best fit to the data (graphs are not reproduced). It is also known that curvi-linear regression methods provide the best approximation to the data after mass absorption correction (A. Peckett, pers. comm. 1978). The curves all show that count rates 'tail off' at high concentrations of any element, this being a direct result of the lack of 'dead time' correction in the X-ray fluorescence system. Holland and Brindle (1966) do, in fact, imply that a polynomial fit would be the best method of calibration for major elements. A second major criticism of the available method is its failure to allow the iterative procedure for mass absorption correction to converge. Rather, the analyses are re-summed to 100% after a fixed number of iterations.

The method finally adopted by the author involves the use of a computer program developed by Dr. A. Peckett at the Department of Geological Sciences, Durham University. This program fits a cubic spline polynomial to the data (thus eliminating the 'dead time' effect of the X-ray counters) and allows the iterative mass absorption correction procedure to converge, rather than re-summing to 100%. Several combinations of specimens of known compositions were used as standards before a final set of reproducible standards was accepted for calibration. These standards include some of the International Standards available at the Department of Geological Sciences, Durham University, supplemented by additional basaltic material obtained from various sources (see Appendix 3.2 for further details of the standards used and for details of reproducibility).

The range of totals of the unknown material processed by the cubic spline polynomial method was rather greater than anticipated (90 to 113 wt. %). For the samples included in the thesis, the range is only slightly less (90 to 111 wt. %). These initial analyses totals are plotted as a histogram (see Figure 10.1). The average for the population of totals lies between 99 and 100 wt. % and the data approaches that of a normal frequency distribution. Some of the low totals may be attributed to water content. The H_2O content of some of the samples was measured, and the maximum value obtained was 2.82 wt. %. This is too low to raise sufficiently the totals around 90 wt. % to an acceptable level (for details of water content - see Appendix 3.3). Obviously the totals in excess of 100 wt. % are rather harder to explain.

Possible errors, which might lead to totals differing greatly from the expected, could occur in the correction procedure, the counting techniques of the machine, the sample preparation and freshness, and in the machine settings. Errors in the correction procedure cannot be ruled out, despite good reproduction of the standards. The cubic spline polynomial fit is very sensitive to the choice of standards. Interpolation between standards, which differ by more than a few per cent, can be inaccurate (see Appendix 3.4 for possible inaccuracies thus caused). Extrapolation beyond the range of the standards is impossible with the routine used. Counting techniques of the machine have already been mentioned and it was hoped that the cubic spline polynomial fit would eliminate at least some of these effects (e.g. 'dead-time'). Sample preparation was identical for all samples (pressed powder pellets were used), and thus can be eliminated as a major source of error. Similarly, only the freshest samples are included in this thesis, so the effects of weathering should be approximately constant for all samples Machine settings were controlled by the staff in charge of the X-ray equipment. It should be noted that most laboratories prefer the borate fusion techniques of sample preparation for major element X-ray fluorescence analysis, as this method appears to be more accurate.

Thus there would appear to be no satisfactory explanation for the spread of analyses totals. Re-summing to 100% was found to improve some of the analyses of known composition (see Appendix 3.5 for details). This is largely because the element most in error, in the absolute sense, is SiO_2. Relative errors are greatest in MgO and Al_2O_3 (A. Peckett, pers. comm. 1978). It is, however, unreasonable to compare analyses, which total much over or under 100%, so the author decided to re-sum to 100%.

To eliminate the effects of post extrusion/intrusion oxidation, Fe_2O_3 was calculated according to the method outlined by Thompson et al (1972). This oxidation correction was applied to the initial analyses and then the final analyses (as quoted in Appendices 5 and 6) were obtained by resumming the corrected analyses to 100%.

For trace elements, the raw X-ray fluorescence data was processed using the computer program TRATIO (written by R. C. O. Gill at the Department of Geological Sciences, Durham University). The standards used were those prepared for the lunar investigations (for further details see Appendix 3.1).

10.2 Comparison of Analyses done at both Durham and Manchester Universities

In addition to the samples from Eigg, Muck and Canna, material from the lavas of Rhum (supplied by Dr. C. H. Emeleus) and Skye (supplied by Dr. J. Esson) were analysed as unknowns. The Skye and Rhum material was also analysed at Manchester by wet chemical and X-ray fluorescence techniques respectively. The Skye material is that described by Thompson et al (1972). The Rhum data is, as yet, unpublished (1979).

For comparative purposes, the FeO and Fe_2O_3 of the Manchester chemical analyses were recalculated as total iron (Fe_2O_3), and re-summed to 100% excluding H_2O. The Durham analyses are the initial analyses (iron as total Fe_2O_3) re-summed to 100% to make them approximately consistent with the final analyses quoted in this thesis. The two sets of analyses are shown in Figure 10.2 and are quoted in Appendix 4.

The analysis of SiO_2 (except at concentrations over 52%), total iron, K_2O, TiO_2 and MnO show a good correspondence between the results obtained at Manchester (by wet chemical and X-ray fluorescence methods) and Durham (the author's analyses). Analyses of the Skye lavas for Al_2O_3, MgO, CaO and Na_2O done by wet chemical means at Manchester are also very similar to the results achieved by the author. For Al_2O_3, the Manchester X-ray fluorescence analyses (the Rhum lavas) are 1 to 2% higher than the values obtained by the author, while the MgO content (as measured at Manchester) of the same group of samples is 2 to 3% lower than the author's data. For low concentrations of CaO, the author's analyses of the Rhum lavas show similar CaO contents to the Manchester values, but at higher CaO concentrations the author's data shows up to 2% less CaO than the Manchester X-ray fluorescence analyses. Na_2O contents of the Rhum lavas are similar for both sets of analyses, except at concentrations less than 2.5%, where the Durham analyses can contain up to 1% less Na_2O than those from Manchester. For P_2O_5, the Durham analyses reproduce the Manchester wet chemical ones (the Skye lavas) well at low concentrations, but at higher concentrations, and for all the Manchester X-ray fluorescence analyses (the Rhum lavas), the Durham analyses are consistently lower than those from Manchester (by up to 0.30%).

Thus for most elements, the analyses obtained at Durham are reasonably similar to those for the Skye lavas obtained at Manchester by wet chemical means. The author has reservations about the Rhum analyses however. To ensure that like is compared with like, the author has used the analyses of these samples as obtained at Durham. However, the K_2O content measured at Durham for SR230 and SR232, and the TiO_2 for SR230, appear to be in error. Other research students at Durham University have found similar anomalies and the analyses and sample numbers will have to be checked. To provide a more consistent chemical nature for the Rhum Group 5 lavas (the grouping is that of Emeleus, pers. comm. 1978), the Manchester concentrations for the elements thought to be in error in the Durham analyses have been used.

10.3 Alkaline or Tholeiitic Magma?

Basaltic rocks of the Hebrides are usually referred to as alkaline or tholeiitic. Many workers have found that certain of the Hebridean lavas are intermediate between the true tholeiites and alkali basalts. These authors include Ridley (1973), who studied some samples from the Small Isles of Inverness-shire (Eigg, Muck, Canna and Rhum). The analyses quoted in this thesis confirm this transitional nature, and when the lavas and minor intrusions of Eigg, Muck and Canna are plotted on a total alkalis versus silica diagram, they are seen to cluster around the Hawaiian alkali/tholeiite dividing line (see Figure 10.3). The extrusive samples plot predominantly just to the alkaline side of the Hawaiian dividing line, while the intrusives have a considerable number on the tholeiitic side. Similarly, the plot of the plagioclase projection into the system plagioclase - olivine - clinopyroxene - nepheline or quartz shows a clustering of the samples (only basalts are plotted) around the plane of critical undersaturation, which is represented on this diagram by the olivine-clinopyroxene join (see Figure 10.4). Samples fall fairly equally on either side of the plane, which separates the nepheline-normative alkali olivine basalt and olivine tholeiite fields. Only two samples (MD35T - the tachylitic margin of a Muck dyke - and C7518C - a pebble from the Canna conglomerates) fall in the quartz-normative tholeiite field. The only other quartz-normative samples in the suite are restricted to some of the more differentiated rocks from Eigg and Muck. Considering all the samples, hypersthene normative basic rocks predominate in Canna and in the intrusives of Eigg (see Table 10.1). A more equal distribution between hypersthene and nepheline normative samples is seen in the Eigg extrusives and the basic rocks of Muck.

Thus the majority of the samples from Eigg, Muck and Canna are transitional between true alkaline and tholeiitic basalts (and their derivatives). They may be compared with the hypersthene normative lavas found on Skye by Thompson et al (1972), and the Mull lavas described by Beckinsale et al (1978). Various other types of basalt have been described from the Hebrides, for example, the Preshal Mhor and Fairy Bridge magma types of the Skye dyke swarm described by Mattey et al (1977). Comparisons have been made with the work of these and other authors on Hebridean basalts (see below, and Section 10.7). The author also comments on the nature of the Rhum lavas, as compared with the intrusive and extrusive samples of Eigg, Muck and Canna. Major and trace element analyses, along with C.I.P.W. norms, of the material are tabulated in Appendices 5 and 6.

10.3.1 Discriminant function analysis

A further method of classifying basaltic rocks in terms of alkaline and tholeiitic basalts, using discriminant function analysis, was applied to the samples from Eigg, Muck and Canna. This involved the use of computer program developed in the Department of Geological Sciences (see Forster 1980 for details of the method). For calculation of the discriminant function, the program uses 248 samples, data to be input to the program must be restricted to the same limits (see Table 10.2). Thus 230 of the author's samples were processed by the discriminant analysis program.

The literature samples used to calculate the discriminant function fall into two distinct populations (see Figure 10.5a). It should be noted that negative discriminant function scores indicate alkaline affinities, while positive scores indicate tholeiitic. The extrusives of Canna and Muck plot predominantly in the alkaline field, with only two samples from each being tholeiitic (see Figures 10.5g and 3 respectively). With average discriminant function scores of between -0.4 and -0.5, however, they are markedly less alkaline than the literature alkali basalts. The extrusives of Eigg (see Figure 10.5f) contain both tholeiitic and alkali basalts, with an average discriminant function score of 0.14, indicating that the Eigg lavas are truly transitional. The intrusives of Canna (see Figure 10.5d), like the extrusives, are mildly alkaline, while those of Eigg (see Figure 10.5c) are predominantly tholeiitic. The intrusives of Muck (see Figure 10.5b) show an extreme range from strongly alkaline (discriminant function scores over -1.0) to thoroughly tholeiitic (discriminant function scores of +0.8). If the dykes are indeed feeders of the lavas, as suggested by many authors (e.g. Mattey et al 1977), the above discussion implies that a considerable quantity of tholeiitic extrusives are missing from Muck, and a similar quantity of alkaline lavas on Eigg have but few intrusive equivalents.

Forster (1980) has compared his data for the basic minor intrusions of Rhum with that from other Hebridean lavas by the discriminant analysis method. The actual discriminant function scores quoted herein may differ slightly in magnitude to those quoted by Forster (pers. comm.

1980), as Foster's data incorporates later modifications to the method. This does not, however, affect the overall distribution relative to the alkaline and tholeiitic samples from the literature.

10.4 Nomenclature

Ridley (1973), the only other author to discuss the geochemistry of the volcanic rocks of Eigg, Muck and Canna in recent years, follows Tilley and Muir (1964) when classifying the various differentiates found in the area (see Table 10.3). The scheme used by Ridley is based on the Thorton-Tuttle differentiation index. Recent workers in the Hebrides (e.g. Beckinsale et al (1978) working on the lavas of Mull) have followed the scheme laid down by Thompson et al (1972) for the lavas of Skye (see Table 10.3), rather than that of Ridley. Thompson's scheme is based on both the Thorton-Tuttle differentiation index and the percentage of anorthite in the normative plagioclase. The two schemes are similar, but differ in the differentiation index ranges for the different rock types (see Table 10.3).

The author plotted the Thorton-Tuttle differentiation index against the anorthite content of the normative plagioclase for the samples from Eigg, Muck and Canna to assess the suitability of Thompson's scheme for the volcanics of these islands (see Figure 10.6). The range of anorthite contents of the normative plagioclase increases with increasing differentiation index. This is caused largely by the relatively high anorthite contents of the normative plagioclases in the Canna hawaiites. The majority of the samples do, however, fall into the areas representing basalt, hawaiite and mugearite on Thompson's scheme.

There are three groups of samples from Eigg, Muck and Canna which do not easily classify by the Thompson scheme. One of these consists of three Eigg intrusive samples (E7613, E7633 and E7637). They have differentiation indices like the basalts (less than 30), but the anorthite content of their normative plagioclases is rather high (over 70%). They are referred to as basalts, but they do show some distinctive geochemical features (see Sections 10.5 and 10.6). A second group of samples have basalt-like differentiation indices (less than 30), but have anorthite contents like the hawaiites (30 to 50%). The author has erected a separate group for them - basaltic hawaiites. It could also be used for samples with hawaiite-like differentiation indices (30 to 45) and basalt-like anorthite contents (50 to 70%). The third group of samples, which cannot be readily classified by Thompson's scheme, are those with mugearite-like differentiation indices (45 to 65) and hawaiite-like anorthite contents (30 to 50%). These, with two exceptions, are quartz normative. The two exceptions are M7606 (a nepheline-normative Muck dyke) and C7559 (a nepheline-normative Canna lava). The Canna lava plots just outside the hawaiite field, with a differentiation index of 45.5, and is hence classed as a hawaiite. The Muck dyke has already been singled out, on account of the cavities infilled with quartz, calcite and opaque oxides, which occur in abundance throughout the sample (see Chapter 5). The quartz and calcite in the cavities would increase (respectively) the differentiation index and the apparent anorthite content on the normative plagioclase. The sample would be a mugearite if the calcite enhances the anorthite content of the normative plagioclase more than the quartz enhances the differentiation index, or a hawaiite if the reverse situation exists.

Thus the nomenclature used by Thompson et al (1972), with the additional field of basaltic hawaiite, is suitable for all but some of the quartz-normative differentiates. Other quartz-normative samples plot in the basalt, hawaiite and mugearite fields (see Figure 10.6). However, hawaiites and mugearites are normally considered to be associated with alkali basalts, and as such, they should never be quartz-normative. Thus a separate set of rock names should be used for the quartz-normative samples.

No-one has yet published a classification scheme for a tholeiitic differentiation series from the Hebrides. Holland and Brown (1972) define a Hebridean tholeiitic magma (the Ardnamurchan cone sheets), but they do not subdivide the differentiation series. Terms such as 'tholeiitic basaltic andesite' and 'tholeiitic andesite' have been used for the products of the volcano Thingmuli in Iceland (Carmichael 1964). Emeleus (pers. comm. 1979) refers to the youngest lavas of Rhum (some of the differentiates from Bloodstone Hill and south Fionchra) as icelandites. These Rhum lavas are very similar to the most differentiated, quartz-normative samples from Eigg and Muck (see Sections 10.5 and 10.6).

Following Johannesson (1975), the author classifies the quartz-normative samples from Eigg, Muck and Canna according to their silica content, as shown in Table 10.4. The analyses quoted by Johannesson are from Iceland and are fairly similar to the Eigg, Muck and Canna samples, except that they have rather higher total iron and CaO contents.

Two of the quartz-normative samples (E7471 and EA29) have not been classed with the rest of the quartz-normative rocks. Geochemically, they resemble the true mugearites of Eigg and Muck (e.g. E7412) much more than they do the other quartz-normative differentiates. This is well illustrated by their P_2O_5 content (see Section 10.5.1). They contain less than 2% normative quartz. A small change in the oxidation ratio would cause these two samples to be hypersthene-normative, like, for example, E7412 (13.4% normative hypersthene).

10.5 Major Element Variation

The variation in major element geochemistry (SiO_2, Al_2O_3, total iron (as FeO), MgO, CaO, Na_2O, K_2O, TiO_2, MnO and P_2O_5) was examined using Harker diagrams, where each element is plotted against silica. The extrusive and intrusive samples are considered separately, and the three islands are distinguished on the plots to allow inter-island comparisons to be made. Only diagrams which show features of interest are reproduced. All reference to concentrations are given as weight per cent oxide.

10.5.1 Extrusive samples

Harker diagrams for all the fresh extrusives of Eigg, Muck and Canna for total iron, MgO, CaO, TiO_2 and P_2O_5 are presented (see Figure 10.7). Lavas showing similarities with the Fairy Bridge magma type described by Mattey et al (1977) are distinguished (see Section 10.7.7). Of the other major elements, Na_2O and K_2O show the anticipated positive correlation with silica content. Na_2O concentrations range from 2 to 5%, while K_2O contents are from 3.5% to trace amounts. MnO contents of the extrusives appear to decrease slightly with increasing silica. All samples, except the most differentiated quartz-normative ones, have MnO contents between 0.1

and 0.4%. Al_2O_3 content shows little correlation with the amount of silica present in the sample. Concentrations of Al_2O_3 range from 13 to 21%.

Before discussing the notable features of the chemical variation on the Harker diagrams included, the compositional gap in the Eigg and Muck lavas should be noted. For both islands, this gap approximately coincides with the change from hawaiite to mugearite (between 51 and 53% SiO_2 for Eigg; 47 and 52% SiO_2 for Muck). No such gap is seen in the Canna lavas, whose silica contents range continuously from 45 to 52%. Such a compositional gap is known from other anorogenic volcanic suites (see Thompson 1972), but the discontinuity more normally occurs at about 50% normative anorthite than around 30% as seen in the Eigg and Muck lavas.

Easily identifiable on all the Harker diagrams are the three icelandites from Eigg (pebbles from the conglomerates below the Sgurr pitchstone). They are the only extrusives to exceed 56% SiO_2. The other quartz-normative samples are not so readily distinguished from the other lavas.

On the plot of total iron against SiO_2 (see Figure 10.7a), there is clearly a split in the samples from Eigg and Muck, with SiO_2 contents less than 50%, into two groups (either high or low concentrations of total iron). The Canna basalts, in general, plot with the high iron group, or are intermediate between the two groups. Such a subdivision is also seen in the mugearites. Four mugearites from Muck (M7597, M75127, M75146 and M7638) and one from Eigg (E7471) have over 11% FeO, while the remaining samples have less than 10%. It should also be noted that the basaltic icelandite from Muck has a higher concentration of FeO than the basaltic icelandites from

Eigg (over 10% as compared with 8 to 9%). This may be connected with the fact that the Muck sample is aphyric, and those from Eigg are all porphyritic.

A grouping of the Eigg samples with less than 50% SiO_2 (mainly basalts) into high and low MgO concentrations can be seen on Figure 10.7b. Unlike the FeO contents, however, the Muck samples do not show the same distribution, rather they group with the Canna lavas, being intermediate between the two groups seen for Eigg. The grouping seen in the FeO contents of the mugearites is not repeated by their MgO contents. The only other notable features on the MgO Harker diagram are the low MgO contents of the Eigg icelandites as compared with the other differentiates, and the relatively high MgO content of the quartz tholeiite pebble from Canna (C7518C).

The Harker diagram for CaO (Figure 10.7c) again shows a possible split in the samples from Eigg with low silica contents. Some of the Muck basalts plot with the low CaO group from Eigg, but the majority are intermediate between the two Eigg groups, like the samples from Canna. The other notable feature of this diagram is the low CaO of the hawaiites and mugearites of Muck, compared with samples of similar silica contents from Eigg and Canna.

TiO_2 contents of the Eigg and Muck samples with less than about 50% silica clearly show a grouping into either high or low concentrations of the element (see Figure 10.7d). The Canna samples are intermediate between the two groups of Eigg and Muck. Three hawaiites from Muck (M7552, M7553 and M7555) and one from Eigg (EA21C - a pebble from the conglomerates below the Sgurr pitchstone) have higher TiO_2 contents (over 3%) than the rest of the samples. As seen for FeO, the Muck basaltic icelandite has higher TiO_2 than its counterparts from Eigg.

The P_2O_5 Harker diagram (Figure 10.7e) shows a variety of trends. The samples from Eigg show two trends with increasing silica - one culminating in the icelandites at about 0.75% P_2O_5, the other in the mugearites at over 1.4% P_2O_5. The two samples with highest P_2O_5 are the mugearites with quartz in the norm (see Section 10.4). Their high P_2O_5 precludes their classification with the strongly quartz-normative icelandites, which have over 8% quartz in the norm, and much lower P_2O_5 concentrations.

There would appear to be low and high P_2O_5 basalts from Eigg. The group rich in P_2O_5 is associated with the low silica lavas from Muck. The trend followed by the Muck extrusives is rather unusual. P_2O_5 increases rapidly from the basalts to the hawaiites (c.0.15% to 0.60% in about 2% SiO_2), while the mugearites have about the same P_2O_5 contents as the hawaiites. The mugearites of Muck are thus much poorer in P_2O_5 than those of Eigg, while the hawaiites of Muck show P_2O_5 enrichment relative to Eigg. The basaltic icelandite of Muck also contains more P_2O_5 than similar samples from Eigg.

Subdivision of the Eigg lavas of low silica into two groups has been noted on all the Harker diagrams described above. To assess whether these apparent groupings are real or simply a function of the phenocryst content, the aphyric and sparsely porphyritic samples from each island were plotted on a second set of Harker diagrams. Six of these diagrams (see Figure 10.8) reveal definite grouping of the low silica samples from Eigg (basalts and hawaiites). The major element characteristics of these two groups are given in Table 10.5.

The stratigraphical and geographical locations of the members of the two groups of Eigg lavas are revealing. All of the Group 2 samples (groupings as given in Table 10.5) are either from Northern

Eigg or from the northern part of Western Eigg (near Laig Farm 46808770). Stratigraphically, they belong to the Basal and Lower Cleadale Groups of Northern Eigg (E7427, E7429, E7430 and E7479) and to the Gleann Charadail Group of Western Eigg (E7458). One of the Group 1 lavas (E7649) is from the Gleann Charadail Group, but it is located in the southern part of Eigg (47898525). All the other Group 1 lavas are confined to younger stratigraphical units. Thus there are chronological and geographical differences as well as geochemical ones between the two Groups of Eigg lavas. The Group 2 lavas are early effusions confined to the northern part of the island. The Group 1 lavas are younger and concentrated in the southern and central parts of Eigg.

The Muck basalts and hawaiites most clearly resemble the Group 2 lavas of Eigg, except for total iron, where they are depleted in FeO compared with the Group 2 lavas of Eigg. On the majority of the Harker diagrams, the Canna basalts and hawaiites are intermediate to the two groups of Eigg.

The discriminant function scores for the two groups of Eigg basalts and hawaiites are shown in Table 10.6. (EA21C was not processed as it included elements in excess of the required ranges.) Clearly the subdivision into tholeiitic and alkali basalts is artificial for Eigg. All the tholeiitic samples and the least alkaline of the alkali basalts form the Group 1 lavas of Eigg. The samples from Muck and Canna yield discriminant function scores between -0.240 and -1.003 for Muck and between -0.187 and -0.937 for Canna. This suggests association with the Group 2 lavas of Eigg. For Muck, this confirms the evidence of many of the major element Harker diagrams where the Muck samples are often associated with the Eigg Group 2 lavas.

The analyses made of some of the Rhum lavas are also plotted on the aphyric and sparsely porphyritic Harker diagrams (see Figure 10.8). The similarities between them and the lavas of Eigg, Muck and Canna are summarised in Table 10.7. The grouping used for the Rhum lavas is that established by Emeleus (pers. comm. 1978). Group 2 samples from Rhum are the most difficult to compare, as they have lower silica concentrations than any of the lavas from Eigg, Muck and Canna. The most important points of comparison are the similarities between the Orval hawaiites (Rhum Group 3 lavas) and the Canna lavas, and between the icelandites of Rhum (Group 5 lavas) and the icelandite pebbles from below the Sgurr pitchstone on Eigg. Group 4 lavas from Rhum vary with the element under consideration, but they most frequently resemble the Canna hawaiites. They are, however, quartz-normative, which the hawaiites of Canna are not. The resemblance is therefore somewhat superficial. It is interesting to note that some of the Canna pebbles resemble the Group 1 lavas of Rhum (found only as pebbles in conglomerates at the base of the Rhum succession). The remaining Canna pebbles are most like the Canna lavas. This suggests that some of the Canna and Rhum pebbles may have originated from the same source.

10.5.2 Intrusive samples

Harker diagrams for the fresh intrusive samples for total iron (as FeO), MgO, CaO, Na_2O, TiO_2 and P_2O_5 are included (see Figure 10.9). Distinguished on these plots are the samples which resemble the Preshal Mhor and Fairy Bridge magma types as described by Mattey et al (1977) - see Section 10.7.7 for details. Al_2O_3 concentrations vary from 11 to 19 wt. % and show little correlation with silica content. The range in Al_2O_3 contents is similar to that seen in the extrusives, but at lower concentrations (the extrusives range from 13 to 21 wt. %). Similarly MnO shows little correlation with silica content, and concentrations range from 0.15 to 0.30 wt. %. K_2O shows the expected positive correlation with silica. The intrusive basalts have, however, less K_2O than their extrusive equivalents. More differentiated samples show similar concentrations of K_2O as the extrusives.

The total iron content of the majority of the intrusives (those with less than 50% SiO_2) lies between 10 and 16% FeO (see Figure 10.9a). This corresponds to the overall range seen in the two groups of lavas from Eigg (i.e. the grouping of samples into high and low concentrations of FeO is not seen in the intrusives). Several samples from Eigg and Muck have higher FeO contents than this main group of intrusives, and these samples have no extrusive equivalents. The few samples which have 10% or less FeO likewise have few extrusive equivalents. The quartz-normative samples are, in general, more iron enriched than the other samples with similar silica contents. Compared with their extrusive equivalents, the intrusive basaltic icelandites and icelandites (Muck only) are slightly enriched in iron.

In terms of MgO content (see Figure 10.9b), the intrusives do not show the high and low MgO groups of the extrusives. The other notable feature seen on this diagram is the higher MgO content of the intrusive icelandites (from Muck) as compared with the icelandite pebbles from Eigg.

The intrusive basalts of Eigg have predominantly higher concentrations of CaO than samples of similar silica content from Muck (see Figure 10.9c). The intrusives of Canna (all basalts) plot with the Muck basalts. Compared with the groupings noted in the extrusives of Eigg (see Figure 10.7c), the Muck and Canna intrusives are similar to the Canna lavas (intermediate between the two Eigg extrusive groups) while those of Eigg usually have higher concentrations of CaO than even the high CaO group of the Eigg extrusives (Group 1 of the extrusives). The quartz-normative differentiates have similar CaO concentrations as their extrusive counterparts.

The Na_2O Harker diagram is included for the intrusives (Figure 10.9d) mainly to show the low Na_2O content of three of the Eigg intrusives (E7613, E7633 and E7636). These are the three samples already noted (see Section 10.4) for the high anorthite content of their normative plagioclases. They are also among the most CaO-rich samples from Eigg (11.50 to 12.00% CaO). Excluding these three samples, the intrusives show a similar range in Na_2O contents as the extrusives (c.2 to 5%).

The majority of the intrusive samples have TiO_2 concentrations between 1.0 and 2.5% (see Figure 10.9e). They all have lower TiO_2 contents than the high TiO_2 group of the extrusives, which thus have no intrusive equivalents in terms of TiO_2 content.

As seen in the extrusives (see Figure 10.7e), the intrusives show two distinct trends, when P_2O_5 is plotted against silica content (see Figure 10.9f). The hawaiites and mugearites follow a high P_2O_5 trend (to c.1.3%), while the quartz-normative samples form a trend to lower P_2O_5 concentrations (to c.0.9%). Only one possible equivalent of the high P_2O_5 extrusive hawaiites is seen in the intrusive basalt MD77 (0.46% P_2O_5).

There is no evidence that the basic minor intrusions show a similar grouping of the samples as that seen in the basic extrusives.

This is confirmed when the aphyric and sparsely porphyritic intrusives only are plotted on Harker diagrams. As these diagrams do not show any features which cannot be seen on the Harker diagrams described above (Figure 10.9), they are not included.

A summary of the similarities between the basic minor intrusions and the lavas of Rhum is included (Table 10.8). The Group 1 lavas of Rhum resemble the basic minor intrusions with relatively low total iron, TiO_2 and P_2O_5 and relatively high MgO and CaO. The Group 2 lavas of Rhum do not have any direct equivalents among the intrusives of Eigg, Muck and Canna because of their low SiO_2 content. In terms of concentration of many of the elements, they are, however, similar to the majority of the minor intrusions. In contrast with the Group 1 lavas, the Group 3 hawaiites of Orval resemble intrusives with low MgO and CaO. The Group 4 differentiates from Rhum are most similar to the quartz tholeiites from the Muck intrusives. The Rhum icelandites (the Group 5 lavas) are like the icelandite intrusives (all porphyritic) from Muck.

10.6 Trace Element Variation

As for the major elements, the variation in the trace elements (Ba, Nb, Zr, Y, Sr, Rb, Zn, Cu, Cr, and Ni) is described with the aid of Harker variation diagrams. The intrusive and extrusive samples are again considered separately, and each island is distinguished on the plots to allow inter-island comparisons to be made. Diagrams, which fail to show more than the normal trends for basaltic rocks, are not included.

10.6.1 Extrusive samples

Harker diagrams for all the trace elements analysed, except Zn and Cu, are included (see Figure 10.10). All the fresh extrusive samples are plotted on these diagrams. Zn shows a range of 0 to 230 ppm, but shows no relationship with silica content. Cu ranges from 0 to 240 ppm and appears to decrease with increasing silica.

One of the most notable features of the trace element Harker diagrams is the distinction of two groups in the mugearites of Muck. This can be seen on all but the Ni and Cr plots. The trace element characteristics of the two groups are outlined in Table 10.9. In all cases, the mugearites M7597 and M75127 (Group 1 on Table 10.9) have concentrations of each trace element, which are closer to those of basalts rather than differentiated rocks. The other mugearites from Muck have similar trace element concentrations to the mugearites of Eigg, except for Ba, where they are depleted in the element as compared with Eigg. They have similar concentrations of Ba to the basaltic icelandites and icelandites.

On several of the diagrams there appear to be two groups in the basalts and hawaiites of Eigg and sometimes of Muck. The Canna basalts usually plot intermediate between the Eigg and Muck groups, as is often the case with the major elements. To determine whether this apparent grouping bore any resemblance to that already described for the basalts and hawaiites of Eigg in terms of major element geochemistry, the trace element Harker diagrams were replotted for only the aphyric and sparsely porphyritic samples. Six of these (for the elements Zr, Y, Sr, Cu, Ni and Cr) show two distinct fields for the basalts of Eigg (see Figure 10.11). The basalts always split into the same two groups already defined by the major element geochemistry (see Section 10.5.1). The trace element characteristics of the two groups are given in Table 10.10. The Eigg hawaiite E7479 consistently plots with the Group 2 basalts, as it did on the major element Harker diagrams (see Figure 10.7). The other Eigg hawaiites are more closely associated with the Group 1 basalts.

The basalts and hawaiites of Muck generally plot with the Group 2 lavas of Eigg. On the Sr and Cu diagrams (see Figures 10.11c and d), a number of them are intermediate between the two groups of Eigg. One Muck basalt (M75148) also plots in an intermediate position on the Zr, Y and Cr diagrams (see Figures 10.11a, b and f). The Canna lavas are, in general, intermediate between the two Eigg groups. Most of the pebbles from the Canna conglomerates are similar to the lavas, but some of them have relatively high Sr, Cu, Ni and Cr compared with the lavas.

Trace element analyses for Cu, Ni and Cr only were made by the author on the Rhum lavas. Dr. C. H. Emeleus kindly supplied analyses for the other trace elements (analysed at Durham by Dr. J. G. Holland). These analyses are plotted on the aphyric and sparsely porphyritic Harker diagrams (see Figure 10.11). A table of comparisons of the Eigg, Muck and Canna lavas with those of Rhum for the trace elements is included (Table 10.11). Comparisons have already been made for the major element data (see Section 10.5.1), and the trace element data largely confirms the observations made for the major elements. To summarise the findings, however, the Group 3, and possibly the Group 2, lavas of Rhum are most like the Canna lavas. Some of the Canna pebbles resemble the pebbles found at the base of the Rhum succession (the Group 1 samples from Rhum). Group 4 lavas from Rhum have no equivalents among the Eigg, Muck and Canna extrusives. Only in Zr content, where the Eigg samples are more enriched in the element, do the Group 5 lavas of Rhum differ substantially from the icelandite pebbles of Eigg.

10.6.2 Intrusive samples

Trace element Harker diagrams for the intrusive samples from Eigg, Muck and Canna for the analysed elements (except Zn and Cu) are presented in Figure 10.12. The samples, which resemble the Preshal Mhor and Fairy Bridge magma types of Mattey et al (1977) are distinguished (see Section 10.7.7 for further details). Zn shows no relationship with silica content and values range from 0 to c.240 ppm. Cu content appears to decrease with increasing silica content, from a maximum of about 250 ppm in the basalts to trace amounts in the most differentiated samples. Both elements have similar ranges as seen in the extrusive samples.

Seven Muck intrusive basalts (MD12, MD13, MD14, MD15, MD44, MD56C and MD57A) appear to have rather unusual concentrations of the elements Ba, Nb, Zr, Rb, Sr and Zn (e.g. MD56C and MD57A are, in other respects, indistinguishable from the other basalts, but they have over 2000 ppm Sr and over 3000 ppm Ba). The author prefers to treat these analyses as suspect, and they are not plotted on the Harker diagrams for these elements. The analyses of Cu, Cr and Ni were done on a completely separate run of the X-ray fluorescence equipment, and, as a result, the measured concentrations of these elements are reliable for the samples quoted as suspect above. In addition, analyses for Ba, Nb, Y, Zr, Sr, Rb and Zn were not available for certain samples, in particular, some of the more differentiated rocks.

Various restrictions were made on the range of values plotted for certain elements. For Ba (see Figure 10.12a), only samples with under 2000 ppm were plotted, thus excluding a Muck hawaiite (MD110 - 3757 ppm Ba). Only samples with less than 700 ppm Zr are plotted (see Figure 10.12c), again excluding MD110 (2193 ppm Zr) and also a hawaiite from Muck (MD57B - 1186 ppm Zr). MD57B (219 ppm Rb) is again excluded from the Rb Harker diagram (see Figure 10.12f), where only samples with less than about 100 ppm Rb are included.

Several features of these Harker diagrams are worthy of mention. The plot of Ba against silica (Figure 10.12a) for the intrusives does not show the same positive correlation with silica that was noted for the extrusives. This is, in part at least, due to the lack of Ba analyses of the differentiated intrusives. On three of the diagrams (Nb - Figure 10.12b, Zr - Figure 10.12c, and Rb - Figure 10.12f), four Muck basalts (MD19B, MD53, MD60 and MD61) and one hawaiite (MD110) have higher concentrations of the element under consideration than the majority of the intrusives (over 12 ppm Nb, 200 ppm Zr and 20 ppm Rb). If these Nb, Zr and Rb enriched samples, and any others which fall outside the range plotted, are excluded, the range in trace element concentrations observed in the intrusives is fairly similar to that seen in the extrusives.

As with the major elements, the trace element concentrations of the basic minor intrusions do not show any tendency to divide into two groups, as seen for the extrusives. Again the Harker diagrams for the aphyric and sparsely porphyritic intrusives do not reveal any features which cannot be seen on the diagrams already described (Figure 10.12) and are thus not included.

The trace element concentrations of the basic minor intrusions have been compared with those of the Rhum lavas (see Table 10.12). The Group 1 lavas of Rhum show broad similarities with the minor intrusives, especially with those relatively depleted in Zr and Sr. There are no direct equivalents of the Group 2 lavas, although they do resemble some of the Muck basalts in Ba and Sr contents. The Orval hawaiites (Group 3) show similarities with the minor intrusives with low Zr, Ni and Cr and high Sr contents. In terms of major elements, the Group 4 lavas of Rhum are similar to the quartz tholeiites of Muck. To a lesser extent this is also true for their trace element concentrations. The icelandites of Muck were only analysed for Ni and Cr. For these two elements they are very similar to the icelandites of Rhum (Group 5), as was seen in their major element contents.

10.7 Comparative Study with other Hebridean Basaltic Suites

Recent work on Hebridean basaltic lavas and minor intrusions includes that of Thompson et al (1972) on the lavas of Skye, Holland and Brown (1972) on the cone sheets of Ardnamurchan, Beckinsale et al (1978) on the Mull lavas, and Mattey et al (1977) on the Skye dyke swarm. Thompson et al describe two distinct lava series on Skye. The SiO_2-poor series from basalt through hawaiite to mugearite and benmoreite is also characterised by relatively high total iron and low K_2O. The basalt to trachyte series, on the other hand, is relatively enriched in SiO_2 and K_2O, and depleted in total iron compared with the basalt to benmoreite series. Beckinsale et al define three groups in the Mull lavas. The Group 1 and 2 lavas resemble, respectively, the SiO_2-poor and SiO_2-rich series of Skye. This has been confirmed by Morrison (1978). Mattey et al (1977), working on the Skye dyke swarm, find that 70% of the dykes are essentially similar to the Skye Main lava series as described by Thompson et al. In addition, they identify dykes similar to the low alkali, high CaO tholeiite lavas described from the Preshal Mhor area of Skye by Thompson et al, and define a new magma type (the Fairy Bridge type). Holland and Brown (1972) were the first authors to describe the chemical variation of a truly tholeiitic Hebridean basaltic suite.

With the aid of some of the diagrams plotted by the authors mentioned above, the samples from Eigg, Muck and Canna are compared in some detail with those described in literature. The aphyric and sparsely porphyritic samples are considered, except in the cases of the Canna pebbles and intrusives, where only porphyritic samples occur. Comment is also made on the Rhum lavas.

10.7.1 The total alkalis versus silica diagram

The widely used plot of total alkalis against silica is used by all the authors mentioned above, except Mattey et al (1977). The extrusives of Eigg, Muck and Canna (see Figure 10.13a) fall predominantly on the alkaline side of the Hawaiian dividing line as defined by MacDonald and Katsura (1964). The majority of the Canna lavas fall on the trend of the SiO_2-rich lavas of Skye. The lavas of Muck appear to define a separate trend, which comprises basalts and hawaiites with relatively high alkali contents (almost as high as the SiO_2-poor trend of Skye), but with mugearites which converge with the SiO_2-rich trend of Skye. It is essentially intermediate between the two Skye trends. The lavas of Eigg are more complicated in their relationships. Some basalts and hawaiites (roughly equivalent to the Group 2 lavas of Eigg) follow the Muck trend. A second less alkaline group are like the Canna lavas and follow the SiO_2-rich trend of the Skye lavas, while a third group lie approximately on the basic end of the Ardnamurchan cone sheets trend. This tholeiitic trend culminates in the icelandite pebbles of Eigg. The Eigg samples involved in each trend are summarised in Table 10.13.

Considering the Mull lavas of Beckinsale et al (1978), it would appear that their Group 1 lavas, although similar to the SiO_2-poor trend of Skye, are slightly less alkaline than the Skye lavas, and thus rather more similar to the lavas of Muck and more alkaline lavas of Eigg. Many of the Group 2 lavas of Mull are less alkaline than the SiO_2-rich trend of Skye, thus resembling the Eigg lavas referred to the basic end of the Ardnamurchan cone sheets trend. Some of the Eigg, Muck and Canna lavas plot in the field of the Mull Group 3 lavas.

The Group 1, 4 and 5 lavas of Rhum follow the Ardnamurchan cone sheets trend. As with the major element geochemistry, the Group 4 Rhum lavas have no extrusive equivalent on Eigg, Muck and Canna. The Group 3 lavas of Rhum fall nearest to the SiO_2-rich trend of Skye, and are thus similar to the Canna lavas and the Group 1 samples from Eigg. The Group 2 lavas of Rhum are less siliceous than any of the trends described above. They plot where the two Skye trends could be expected to converge.

The majority of the intrusives fall on the basic end of either the SiO_2-rich trend of Skye or the Ardnamurchan cone sheets trend (see Figure 10.13b). Differentiated samples are rather rare in the intrusives, but there appear to be equivalents of the SiO_2-rich trend (Skye lavas) and of the Ardnamurchan cone sheets trend. The basaltic icelandites are, however, rather more alkaline than their Ardnamurchan equivalents. It should be noted that, in terms of total alkalis and silica, the Muck lavas and the most alkaline lavas of Eigg have no intrusive equivalents. As seen in the major and trace element geochemistry, the quartz tholeiite intrusives of Muck are very similar to the Group 4 lavas of Rhum.

10.7.2 AFM diagram

Plots of the Eigg, Muck and Canna samples on an AFM diagram (with F calculated as FeO + Fe_2O_3) are presented as Figure 10.14. The more basic extrusives (basalts and some hawaiites - see Figure 10.14a) cluster around the basic end of the SiO_2-poor trend of Skye. The Canna extrusives appear to follow the SiO_2-poor trend of Skye quite accurately. The mugearites and quartz normative differentiates of Eigg, however, fall on the SiO_2-rich Skye trend. This implies that, compared with the more basic lavas, the differentiates are depleted in iron. One of the mugearites of Eigg (E7412) and several from Muck (M7579 and M7608) show an even greater degree of iron depletion.

The icelandite extrusives are depleted in iron compared with the Ardnamurchan cone sheets on the AFM diagram. However, they followed this trend on the total alkalis versus silica diagram. Such depletion also characterises the icelandites of Rhum (the Group 5 lavas).

That the lavas of Canna follow the SiO_2-poor trend of Skye on the AFM diagram is rather unexpected, as they followed the Skye SiO_2-rich trend on the total alkalis versus silica diagram. This implies strong iron enrichment in the Canna lavas as compared with the SiO_2-rich lavas of Skye. Such iron enrichment is also seen in the Group 2 and 3 lavas of Rhum.

The intrusive basalts, the hawaiite MD36, and the quartz tholeiite MD35 all lie on the basic end of a trend which parallels the SiO_2-poor trend of Skye, but which is less alkaline (see Figure 10.14b). It also resembles the trend of the Ardnamurchan cone sheets, but achieves greater iron enrichment. The more differentiated intrusives show similar degree of iron depletion as some of the differentiated extrusives.

10.7.3 Selected major elements plotted against the F/F + M ratio

Thompson et al (1972) and Beckinsale et al (1978) use plots of selected major elements against the ratio $FeO + Fe_2O_3/$ $FeO + Fe_2O_3 + MgO$ (commonly abbreviated to F/F + M) to highlight the differences between their SiO_2-rich and SiO_2-poor series. Three such plots are reproduced for the samples of Eigg, Muck and Canna (see Figure 10.15). The $FeO + Fe_2O_3$ plot for the extrusives (Figure 10.15a) shows the Canna lavas following the SiO_2-poor trend of Skye, as they did on the AFM diagram. This confirms the iron enrichment of these lavas compared with those of the Skye SiO_2-rich trend. The Eigg Group 1 lavas, however, cluster around the basic end of the SiO_2-rich trend of Skye, as they do on the total alkalis versus silica diagram. Thus they are not iron enriched compared with the SiO_2-rich Skye lavas. This plot reveals iron enrichment, relative to the SiO_2-poor trend of Skye, in the Eigg Group 2 and Muck lavas. The mugearites and quartz normative differentiates are not included in this iron enrichment, however, as they fall on the SiO_2-rich trend of Skye.

The intrusive samples on the FeO + Fe_2O_3 plot (Figure 10.15d) show a trend, in which the total iron content increases as the F/F + M ratio increases, for the basalts and hawaiites. The mugearites and icelandites do not continue this trend. They have rather lower F/F + M ratios than might be expected, due to the iron depletion of these samples, which has already been noted on the AFM diagram (Figure 10.14b).

On the plot of K_2O against F/F + M ratio for the extrusive samples (Figure 10.15b), the basalts and hawaiites of Muck and the Eigg Group 2 lavas lie on the SiO_2-poor trend of Skye. The Group 1 lavas of Eigg are closer to the SiO_2-rich lavas of Skye. The icelandites of Eigg fall on the SiO_2-rich trend of Skye, but the other differentiates of Eigg and Muck appear to be strongly enriched in K_2O. This is a result of their relatively low iron content, causing them to have low F/F + M ratios compared with the Skye lavas. The Canna lavas parallel the SiO_2-poor trend of Skye, but show slight K_2O enrichment compared with this trend. In terms of total alkalis, however, the Canna lavas are known to be similar to the SiO_2-rich lavas of Skye. They may therefore be depleted in K_2O relative to the SiO_2-rich lavas of Skye, as well as being enriched in iron.

The intrusives predominantly follow the SiO_2-poor trend of Skye on the K_2O versus F/F + M diagram (<u>see</u> Figure 10.15e). This is in contrast with the evidence of the total alkalis versus silica diagram, where most of the intrusives followed the SiO_2-rich Skye trend. The basaltic icelandites and mugearites do not fall on either of the Skye trends as a result of their low F/F + M ratios.

The plots of SiO_2 against F/F + M (Figures 10.15c and f) show no new features. The Canna lavas and the majority of the intrusives are intermediate between the two Skye trends, on account of their iron enrichment. Eigg Group 1 lavas, the mugearites and the icelandites follow the SiO_2-rich trend of Skye, with the Muck mugearites characterised by low F/F + M ratios. The Muck basalts and hawaiites along with the Group 2 lavas of Eigg follow the SiO_2-poor trend of Skye.

On the SiO_2 and K_2O versus F/F + M diagram (Figures 10.15b, c, e and f), the three Mull lava groups are plotted for comparison. In terms of silica, thr Group 1 lavas of Mull follow the SiO_2-poor trend of Skye, while the Group 2 lavas follow the SiO_2-rich Skye lavas. In terms of K_2O, however, the Group 2 lavas of Mull are like the Canna lavas - with apparently much lower K_2O contents than the SiO_2 lavas of Skye.

10.7.4 Na_2O versus K_2O diagram

Thompson et al (1972) find that the two trends established for the Skye lavas can be distinguished by plotting Na_2O against K_2O. This plot is reproduced for the Eigg, Muck, Canna and Rhum samples (see Figure 10.16). The Canna extrusives (see Figure 10.16a) appear to follow the SiO_2-poor trend, rather than the SiO_2-rich trend they followed on the total alkalis versus SiO_2 diagram. This implies that they are either Na_2O enriched or K_2O depleted compared with the Skye SiO_2-rich lavas. K_2O depletion has already been suggested as a partial explanation of the position of the Canna lavas on the K_2O versus F/F + M plot. The Muck basalts and hawaiites, and the Group 2 lavas of Eigg are well within the field of the SiO_2-poor lavas of Skye, but the Group 1 basalts of Eigg do not clearly plot in either field. The mugearites of Muck plot in or near the field of the SiO_2-rich lavas of Skye, but the Eigg mugearites and particularly the icelandites show quite strong depletion in Na_2O relative to the SiO_2-rich lavas of Skye.

All of the intrusives, except the quartz normative samples, follow the SiO_2-poor trend of Skye on this diagram (see Figure 10.16b). On the total alkalis versus silica diagram, none of the intrusives are as alkaline as the Skye SiO_2-poor Skye lavas. As with the Canna lavas, this suggests Na_2O enrichment or K_2O depletion. K_2O depletion has already been postulated for the intrusives on the evidence of the K_2O versus F/F + M diagram.

The Group 1 and 2 lavas of Rhum plot in the indeterminate region on this diagram, where the two series of Skye lavas intersect. The Group 3 lavas, like those of Canna, follow the SiO_2-poor Skye trend, while the Group 4 and 5 lavas follow the SiO_2-rich trend of Skye.

10.7.5 Selected major and trace elements plotted against Zr

Plots of this type are used by Beckinsale et al (1978) to distinguish the three lava groups of Mull. Four such plots (Ba, Sr, Y and K_2O) are reproduced in Figure 10.17. None of the samples from Eigg, Muck, Canna or Rhum accurately follow the more alkaline Group 1 lavas of Mull. On the Ba and K_2O plots, the Canna lavas, the Group 1 basalts of Eigg and the Group 1, 2 and 3 lavas of Rhum approximately follow the Mull Group 2 trend (see Figures 10.15a and d). Such a correlation was also noted on some of the major element Harker diagrams (see Section 10.7.3). Some of the Canna pebbles and the mugearite from Canna deviate from the Mull Group 2 trend on the K_2O plot, being relatively depleted in K_2O compared with their Mull equivalents. The same group of samples define a trend unlike any of the Mull trends on the Sr plot (see Figure 10.17b). It shows a very rapid increase in Sr with increasing differentiation. Again some of the Canna pebbles and the mugearite deviate from the trend of the majority, having rather low Sr contents.

The only samples to plot with the Mull Group 3 lavas are some of the intrusives on the Sr, Y and K_2O plots (see Figures 10.17f, g and h). On the plots of Ba, Sr and K_2O, the Group 2 lavas of Eigg and the lavas of Muck form a separate trend, which lies intermediate between those of the Mull Group 1 and 2 lavas (see Figures 10.17a, b and d). In terms of Ba, the trend shows an exponential increase from the hawaiites to the Eigg mugearites.

The Y versus Zr plot for the extrusives (see Figure 10.17c) reveals the Eigg Group 1 basalts plotting in the field of the Group 3 lavas of Mull, along with some pebbles from Canna and some of the intrusives (see also Figure 10.17g). The remainder of the extrusives and a few of the intrusives fall on a trend unlike any of those defined for the Mull lavas. This trend shows much greater enrichment in Y with increasing Zr than the Mull trends. It should be noted, however, that the mugearites of Muck, one mugearite from Eigg and the Eigg icelandites have lower Y contents than the rest of the Eigg, Muck, Canna and Rhum samples.

On further point to be noted from these diagrams is the lower Zr content of the Eigg icelandite pebbles compared with the icelandites of Rhum (the Group 5 lavas). They are also depleted in Ba and slightly in Sr compared with the Rhum Group 5 lavas.

10.7.6 Selected Major elements plotted against P_2O_5

Beckinsale et al (1978) also use plots of various elements against P_2O_5 to distinguish the three groups of lavas found on Mull. For the samples from Eigg, Muck, Canna and Rhum, the TiO_2 and K_2O plots are the most revealing (see Figure 10.18). Of the extrusives (see Figures 10.18a and b), the only samples to plot consistently on a Mull trend are the Group 1 basalts of Eigg, and they fall either on the basic end of the Mull Group 2 trend or in the field occupied by the Mull Group 3 lavas. The Canna lavas and all of the Rhum lavas, except Group 5, define a trend intermediate to the Group 1 and 2 trends of Mull on both plots. The Eigg Group 2, the Muck lavas and the Group 5 lavas of Rhum fall on the Mull Group 1 trend on the TiO_2 plot (see Figure 10.18b). They are thus more TiO_2 enriched than the lavas of Canna. On the K_2O versus P_2O_5 diagram (see Figure 10.18a), however, they define yet another trend, intermediate between the Canna trend and the Group 1 trend of Mull. This suggests that the Muck lavas and the Eigg Group 2 lavas are more enriched in P_2O_5 than the Canna lavas, which are more P_2O_5 enriched than the Eigg Group 1 lavas and the Group 2 lavas of Mull. The mugearites of Eigg are very strongly P_2O_5 enriched, as noted previously (see Section 10.5.1).

10.7.7 Preshal Mhor and Fairy Bridge magma types

Mattey et al (1977) defined these magma types from the Tertiary dykes of the Skye swarm. In terms of major elements, the Fairy Bridge type is not readily distinguishable from the Skye Main Lava Series (as defined by Thompson et al 1972). The Preshal Mhor type was originally identified from rare extrusives from Skye (basalts with high CaO and low alkalis) by Thompson et al (1972) and subsequently by Mattey et al (1977) found considerable numbers of this type of magma type among the dykes of the Skye swarm.

The two magma types can readily be distinguished on plots of Y and Ti (recalculated in the case of the Eigg, Muck and Canna samples as ppm) against Zr. Both types are similar in having low Y/Zr ratios (less than 0.53), but the Fairy Bridge type may be distinguished by their higher Ti contents. Such plots are reproduced for the samples from Eigg, Muck and Canna (see Figure 10.19). The fields of the Preshal Mhor and Fairy Bridge magma types as defined by Mattey et al from the Skye dyke swarm are indicated. Samples must fall in the relevant field on both diagrams to be included in this magma type.

Clearly there are no extrusives of the Preshal Mhor type among the Eigg, Muck and Canna samples, but three basalts from the lavas of Eigg (E7438, E7457 and E7632) and one hawaiite pebble from Canna (C7501E) fall within the field of the Fairy Bridge magma type (see Figures 10.19a and b). The intrusives have samples belonging to both types (see Figures 10.19c and d). The Preshal Mhor type intrusives are all basalts, one from Canna (SR250), two from Eigg (E7409 and E7414) and four from Muck (MD41, MD111, MD116 and MD118). The intrusives falling in the Fairy Bridge magma type field consist of three basalts from Eigg (E7403, E7434 and EA39) and three from Muck (MD45, MD48 and MD119), along with one basaltic hawaiite (MD73) and two hawaiites (MD63 and MD72), also from Muck. The analyses of these Preshal Mhor and Fairy Bridge type samples are listed separately in Appendices 5 and 6

The major and trace element ranges of the samples classified as Preshal Mhor and Fairy Bridge types are listed with those so classified by Mattey et al (1977) from the Skye dyke swarm (see Tables 10.14 and 10.15). If the hawaiitic samples are excluded, the ranges quoted for the Eigg, Muck and Canna samples are fairly similar to the Skye samples. The range in MgO contents shows that Eigg, Muck and Canna include some more MgO rich samples of both magma types than are found among the Skye dykes. In terms of TiO_2 and Zr, the Preshal Mhor type dykes of the Skye swarm include samples with lower concentrations of both these elements than their equivalents from Eigg, Muck and Canna. The Fairy Bridge type samples from the Skye dyke swarm are usually enriched in K_2O and Sr compared with those from Eigg, Muck and Canna. In terms of the Ti/Zr ratio, the Eigg, Muck and Canna samples of both the Preshal Mhor and Fairy Bridge magma types show a greater range than those of the Skye dyke swarm.

On the Harker diagrams plotted for Sections 10.5 and 10.6, the samples referred to the Preshal Mhor and Fairy Bridge magma types are distinguished from the other samples. On only one diagram (the plot of all the intrusives for Zr against SiO_2 - Figure 10.12c) do the Preshal Mhor and Fairy Bridge samples fall into a distinct group, characterised by low Zr. The Preshal Mhor samples do not form a distinct group of high CaO basalts, as is seen in the samples of this type from Skye, but they are among the most CaO-rich samples.

Mattey et al (1977) noted a petrographical distinction between the Fairy Bridge and Preshal Mhor magma types. The groundmass pyroxenes of the Fairy Bridge type are distinctly lilac-brown or brown in colour and contain numerous titanomagnetite inclusions. The Preshal Mhor types have pale green ophitic pyroxenes in the matrix.

The majority of the samples from Eigg, Muck and Canna contain brown or pinkish-brown groundmass pyroxenes of varying shades (see Chapters 3 and 5). The majority of samples referred to the Preshal Mhor type have light pink-brown to orange-brown pyroxenes, most of which show faint pleochroism, and an ophitic texture. None of the contained pyroxenes could be described as pale green, as found by Mattey et al (1977). Those referred to the Fairy Bridge magma type have predominantly ophitic pyroxenes, but the pyroxenes show the complete range of colour described from the samples of Eigg, Muck and Canna - light coloured, pink-brown non-pleochroic to dark purple-brown pyroxenes, which show pleochroism to orange-brown.

The Preshal Mhor type dykes of the Skye swarm were found to concentrate strongly in the centre of the Sleat peninsula of Skye, where crustal dilation also reaches a maximum. Three out of the four Preshal Mhor type dykes of Muck occur in the strip between the Camas Mhor gabbro and the beach of Camas Mhor, where crustal dilation was estimated at 9.72% - a minimum value for Muck. The Preshal Mhor dykes collected from Eigg are from the environs of Laig Farm (46708770). As with the Skye dykes, dykes of the Fairy Bridge magma type show a wide distribution throughout both Eigg and Muck. The lavas of Eigg referred to this type show a range of distribution throughout the stratigraphical succession. One (E7438) is the uppermost flow below the pitchstone of the Sgurr of Eigg, while the others occur in the Brutach Dearg and Gleann Charadail groups (see Chapter 2 for details). The Fairy Bridge sample from Canna is a pebble from the conglomerates at the base of the lava pile. It is just possible that it originated from Skye.

10.8 Conclusions

The majority of the lavas and minor intrusions of Eigg, Muck and Canna are broadly similar to the Skye Main Lava Series of Thompson et al (1972) and to the Mull lavas of Beckinsale et al (1978). The Group 1 lavas of Eigg show strong similarities to the SiO_2-rich lavas of Skye in terms of major elements. Similarities between these lavas and the Mull Group 2 lavas (the equivalent of the SiO_2-rich series of Skye) are also seen in terms of trace elements. The Canna lavas and the majority of the intrusives also show broad similarities with the SiO_2-rich series of Skye (e.g. on the total alkalis versus silica diagram - Figure 10.13). However, both show enrichment in total iron and P_2O_5, and depletion in K_2O compared with the SiO_2-rich lavas of Skye. They also show enrichment in Y compared with the Group 2 lavas of Mull.

Quartz normative lavas and minor intrusions are relatively rare in Eigg, Muck and Canna. Their differentiated members resemble the Group 4 and 5 differentiates of Rhum. They and the Rhum lavas follow the trend defined for the Ardamurchan cone sheets (Holland and Brown 1972).

There are also a few samples from Eigg, Muck and Canna which can be likened to the Preshal Mhor and Fairy Bridge magma types, as described by Mattey et al (1977). The Preshal Mhor type samples from Eigg, Muck and Canna cannot be so readily distinguished by high CaO and low alkali contents as can their equivalents from the Skye dyke swarm. They are enriched in TiO_2 and Zr compared with the Skye dyke swarm samples. By contrast, the Fairy Bridge basalts of Eigg, Muck and Canna show depletion in K_2O and Sr compared with Skye. Both groups show a more restricted range in Al_2O_3 and higher MgO contents than the Skye samples.

CHAPTER 11

GEOCHEMISTRY OF THE ACID ROCKS OF EIGG

11.1 Introduction

There are six bodies of acidic igneous rock on Eigg (see Chapter 6). The geochemistry of the Sgurr pitchstone, the Cleadale felsite (Sron Laimrhige felsite of this study) and the Rudh' an Tancaird pitchstone dykes has been discussed by Carmichael and McDonald (1961) and Ridley (1971 and 1973). The author presents analyses for five of the six acidic rock bodies (Appendix 7), the North Pier pitchstone being unsuitable for analysis.

11.2 Nomenclature

The term 'pitchstone' has been used throughout this thesis to refer to the glassy facies of the Rudh' an Tancaird dykes and the Sgurr mass. Williams et. al. (1954) define pitchstones as glassy acidic rocks with up to 10% H_2O, as opposed to obsidians, which have up to about 1% H_2O. Ridley (1973) and Carmichael (1960a) quote H_2O contents of between 3.53% and 6.00% for the Rudh' an Tancaird dykes and between 1.51% and 3.04% for the Sgurr samples. Thus 'pitchstone' is a suitable name for these rocks. The crypto-crystalline varieties (e.g. the Sron Laimrhige intrusion) are more appropriately termed 'felsites'.

11.3 The Acid Rocks of Eigg in relation to the System Quartz - Albite - Orthoclase - H_2O

Petrographically the acid rocks of Eigg have been divided into five groups (see Chapter 7). Analyses of four of these five petrographical groups are available; the North Pier pitchstone - the example of the group with plagioclase as the only feldspar phenocryst phase - has not been analysed. On the quartz - albite - orthoclase diagram (Figure 11.1a), the analysed samples may be divided into three chemical groups:-

1. The Sron Laimrhige and Sgorr Sgaileach felsites (those with anorthoclase as the only feldspar phenocryst) fall close to the minimum at 500 bars. One of the samples from the Sgorr Sgaileach felsite falls just inside the quartz field, while the other and the sample from the Sron Laimrhige felsite fall just to the feldspar side of the minimum. They plot close to the field of analysed granites as given by Carmichael et. al. (1974).

2. The Sgurr pitchstones and felsites, and the Grulin felsite (both with anorthoclase and plagioclase phenocrysts) fall well within the feldspar field at any pressure. They cluster mainly to the orthoclase side of the low temperature trough, which runs from the alkali feldspar side of the diagram to the minimum at 500 bars. Most of the felsitic samples from the Sgurr are enriched in orthoclase relative to the pitchstone samples.

3. The Rudh' an Tancaird pitchstone dykes (with sanidine phenocrysts) fall within the feldspar field at pressures less than

1000 bars. They fall to the albite side of the low temperature trough for such pressure conditions.

The normative feldspars of the Rudh' an Tancaird dykes are very similar to those of the Sgorr Sgaileach and Sron Laimrhige felsites, except that the latter have a greater anorthite component (see Figure 9.6). The analysed feldspars show similar differences; those from the Sron Laimrhige felsite contain about 4% anorthite, while those from the Rudh' an Tancaird dykes contain less than 1% anorthite (see Chapter 9). Carmichael et. al. (1974) suggest that the greatest ternary solid solution in feldspars is seen in rocks which crystallised at high temperatures and low pressures. This suggests that the Rudh' an Tancaird dykes crystallised at lower temperatures and higher pressures than the Sgorr Sgaileach and Sron Laimrhige felsites.

Analyses of alkali feldspars are available for the Sgurr pitchstones, Rudh' an Tancaird dykes and Cleadale (Sron Laimrhige) felsite. These have been expressed in terms of albite and orthoclase only and plotted, with the whole rock analyses (an average in the case of the Sgurr pitchstones) on the quartz – albite – orthoclase diagram (Figure 11.1b). The tie lines show that both the Sgurr and Rudh' an Tancaird pitchstones have crystallised alkali feldspars, which are enriched in orthoclase relative to the whole rock analyses. The Sron Laimrhige felsite, on the other hand, has crystallised a feldspar, which is considerably more sodic than the whole rock composition. That the Rudh' an Tancaird dykes contain relatively orthoclase-rich feldspars is rather unexpected as the whole rock composition falls to the albite side of the low temperature region. Equally unexpected are the relatively sodium-rich feldspars in the Sron Laimrhige felsite.

11.4 Silicic or Sub-silicic Acid Magmas?

Ridley (1973) subdivides the acidic rocks of Eigg into silicic and sub-silicic types, quoting the Cleadale (Sron Laimrhige) felsite as the only example of the silicic type. To judge the relative degrees of silica enrichment of the analysed samples, the author plotted the SiO_2 content against the Thorton Tuttle differentiation index (see Figure 11.2). From this diagram it would appear that the Sron Laimrhige and Sgorr Sgaileach felsites, along with the samples from the Rudh' an Tancaird dykes, could be classified as silicic, with over 70% SiO_2. The samples from the Sgurr and from the Grulin felsite could therefore be classed as sub-silicic with 60% to 69% SiO_2. Samples from each group with similar differentiation indices (70 and over) show that the Grulin and Sgurr samples contain about 5% less SiO_2 than samples from the other group.

It has already been suggested that the samples from the Rudh' an Tancaird dykes crystallised at lower temperatures and higher pressures than those from the Sgorr Sgaileach and Sron Laimrhige felsites (see Section 11.3). The fact that they are silicic (from Figure 11.2) suggests that perhaps they should fall within the quartz field on the quartz- albite- orthoclase diagram (Figure 11.1a). For this to occur, they would have formed at pressures in excess of 1000 bars.

11.5 Major and Trace Element Variation

Average analyses for the different types of acid rock found on Eigg are given in Table 11.1. There are considerable variations in the concentrations of several of the elements. The Sron Laimrhige and Sgorr Sgaileach felsites are noticeably depleted in FeO and Na_2O, and enriched in SiO_2 relative to the rest of the acidic samples. The Rudh' an Tancaird dykes are also relatively enriched in SiO_2, but they do not show FeO and Na_2O depletion. Rather they are markedly depleted in CaO, K_2O and Ba, and enriched in Y and Zn. The Grulin felsite shows enrichment in MgO (over twice as much as any of the other samples), CaO, TiO_2, P_2O_5 and Sr relative to most of the other acidic samples. It contains rather low concentrations of SiO_2, Y, Rb and Zn. The samples from the Sgurr show similar characteristics as the Grulin felsite, but with lower MgO.

Variations occur in the Sgurr samples and these can be correlated with the mode of occurrence. The average analysis for the intrusive samples given in Table 11.1 (analysis 4b) is calculated assuming that EA46 is indeed intrusive, as suggested in Section 7.2. The SiO_2, K_2O and Zr contents of the intrusive samples are noticeably higher than for the extrusives. By contrast, FeO, MgO, CaO, Ba and Sr are relatively enriched in the extrusive samples.

11.6 Comparison with other Rhyolites

Carmichael et. al. (1974) quote analyses of several types of rhyolite, these are listed in Table 11.2, with iron recalculated to total iron as FeO to conform to the average analyses quoted in Table 11.1. The Sgorr Sgaileach and Sron Laimrhige felsites show strong geochemical similarities with rhyolites from Thingmuli, Iceland, especially in their trace element concentrations. The MgO and CaO contents of the Eigg felsites are rather higher than those for the Thingmuli rhyolites, while the Na_2O content is rather lower.

The Rudh' an Tancaird pitchstones are enriched in total iron, Y and Zn, and depleted in Ba compared with the Icelandic rhyolites. The enrichment in Y and Zn, and slight enrichment in Nb and Zr is reminiscent of the peralkaline comendites (see Table 11.2). Peralkaline rocks, however, are characterised by having $Na_2O + K_2O$ in excess of Al_2O_3 (expressed as molecular proportions or atomic proportions of Na, K and Al), and this is not seen in the Rudh' an Tancaird dykes.

The Grulin felsite, and the pitchstone and felsites of the Sgurr ridge differ in concentrations of all elements compared with all the rhyolites quoted by Carmichael et. al. (1974). They are noticeably enriched in Al_2O_3, MgO, Ba and Sr.

11.7 Origin of the Acidic Rocks of Eigg

There are several possible ways of generating acidic magma. These include.-

1) Fractional crystallisation of a basaltic magma;

2) Partial melting of basaltic rocks;

3) Partial melting of Torridonian arkose,

4) Partial melting of Lewisian gneiss.

Both Torridonian arkoses and Lewisian gneisses are known to outcrop on the sea floor in the vicinity of Eigg (see Figure 2.5.1). There is the additional possibility of contamination of the melt.

Ridley (1971 and 1973) has proposed Torridonian arkose as the parental material for the Cleadale (Sron Laimrhige) felsite, but

Emeleus (pers. comm. 1980) doubts whether the relatively high level Torridonian sediments can ever have been significantly mobilised (either wholly or partially) to give sizeable bodies of granitic composition. Ridley (1973) suggests a potassic gneiss as the source rock for the Sgurr pitchstone; he regards the magnesian pyroxenes, moth-eaten calcic plagioclases and potassic nature of the Sgurr pitchstones as evidence against an origin by fractional crystallisation or partial melting of a basaltic magma. Ridley (1973) regards the Rudh' an Tancaird pitchstones as possible basalt derivatives. They fulfil many of the mineralogical features of advanced fractionation of a basaltic magma (Ridley 1973).

The most likely basaltic parent magma for the acidic rocks of Eigg are the transitional to tholeiitic basalts, and in particular those which evolved, by fractional crystallisation, to give the icelandites. The Group 1 basalts of Eigg (see Chapter 10) are the most likely candidates. On a plot of total alkalis against silica (Figure 11.3) the Group 1 basalts of Eigg cluster around the basic end of the Ardnamurchan cone sheets trend, while the icelandites lie just to the alkaline side of the same trend. If a trend is drawn through the Group 1 basalts and the icelandites (a trend slightly enriched in alkalis compared with that of the Ardnamurchan cone sheets), then the Sgurr pitchstones and most of the felsites would lie on a projection of this trend. This suggests that a transitional tholeiite, such as the Group 1 lavas of Eigg, could have been the parental magma for the Sgurr samples. The Grulin felsite is enriched in total alkalis compared with the basaltic fractionation trend defined on Figure 11.3, while the Rudh' an Tancaird dykes and the felsites of Sgorr Sgaileach and Sron Laimrhige are depleted in total alkalis. They cannot therefore be directly derived from a basaltic parent.

Several major and trace element Harker diagrams for the Group 1 basalts, the icelandites and the acidic rocks were plotted to further assess the hypothesis of a basaltic parent for the Sgurr rocks. Selected of these diagrams are reproduced as Figure 11.4. The projection of the fractionation trend for the Group 1 basalts and the icelandites to higher concentrations of SiO_2 was drawn with reference to the date of Johannesson (1975) as a guide to the direction of the trend. On all the major element plots the Sgurr pitchstones lie near or on the projected trend. The lack of K_2O enrichment (see Figure 11.4c) is contrary to the findings of Ridley (1971), who states that the Sgurr pitchstones could not have been derived from a basaltic magma without the intervention of a K_2O-rich phase. It should be noted, however, that the more siliceous felsites of the Sgurr mass do not continue the trend on the total iron, CaO and K_2O plots. They show depletion in total iron and CaO, and enrichment in K_2O relative to the proposed trend. The Rudh' an Tancaird dykes are notably enriched in total iron and depleted in Na_2O and K_2O relative to the basaltic fractionation trend shown. The felsites of Sgorr Sgaileach and Sron Laimrhige are depleted in Na_2O and K_2O relative to the basaltic fractionation trend, while the Grulin felsite shows enrichment in K_2O.

In terms of trace elements again the Sgurr pitchstone samples fall close to the proposed extension of the basaltic fractionation trend. The intrusive felsites of the Sgurr mass are notably enriched in Zr compared with the other acidic rocks (see Figure 11.4f). The Rudh' an Tancaird dykes are depleted in Zr and Rb, and enriched in Y relative to the basaltic fractionation trend. The Sgorr Sgaileach and Sron Laimrhige felsites show Zr and Y depletion, while the Grulin felsite is depleted in Rb and Y relative to the basaltic fractionation trend.

The evidence discussed above points to a basaltic parent for the magma which formed the Sgurr pitchstones. The pyroxenes of the Sgurr samples are however unusually enriched in MgO for their environment, being more typical of the pyroxenes from basic or intermediate basaltic fractionates. Carmichael (1962) suggests that early crystallisation of titanomagnetite will deplete the magma sufficiently in iron to cause the pyroxenes that crystallise to be more MgO-rich than would otherwise be the case. That titanomagnetites crystallised early is amply shown by the way that they are found enclosed by the other phenocryst phases in the pitchstones and felsites of the Sgurr (see Chapter 7). Both the orthopyroxenes and clinopyroxenes of the Sgurr rocks, however, exhibit the high MnO characteristic of acidic pyroxenes. The augites of the Sgurr pitchstones contain between 0.69 and 1.27% MnO, whereas those from the basalts, hawaiites and mugearites of Eigg and Muck all contain less than 0.4% MnO. This also suggests that they are not xenocrysts derived from a basalt.

Tuttle and Bowen (1958) suggest that basalts could become partially liquid at between 35 and 40 km depth. The liquid so formed would be of andesitic composition and by fractional crystallisation such a liquid could evolve to give a granitic magma. Clearly melting of the Tertiary lavas is not a possible mechanism for generating the Sgurr magma. Taylor et. al. (1968) suggests that production of a large body of magma by fractional crystallisation will lead to enrichment of the incompatible elements, whereas by partial melting no such enrichment would be expected. The incompatible elements Ba, Sr, Zr and P_2O_5 show enrichment in the Sgurr and Grulin samples (see Table 11.1) relative to the other acidic rocks of Eigg. This suggests that the Sgurr samples and also the Grulin felsite (see below) were derived by fractional crystallisation rather than by partial melting.

The similarity in all aspects of petrography and geochemistry of the Oigh Sgeir and Sgurr of Eigg pitchstones suggests that both had a similar mode of origin. The analysis of the Oigh Sgeir pitchstone plots with those of the Sgurr pitchstone on all the diagrams. This confirms the suggestion that they originate from very similar sources, or indeed were truly co-magmatic, as Geikie (1894) believed.

Petrographically, the Grulin felsite is rather similar to the Sgurr felsites. The feldspars are not so corroded as those of the Sgurr and a third feldspar (orthoclase) occurs. Incorporation of orthoclase into a magma such as that which formed the Sgurr pitchstones would cause an increase in the K_2O content of the final product as compared with the Sgurr samples. The K_2O enrichment of the Grulin felsite relative to the basaltic fractionation trend (see Figure 11.4c) is the most characteristic feature of the Grulin felsite. The author therefore suggests that the Grulin felsite represents a batch of magma similar to that which formed the Sgurr mass, but which developed at an earlier time in the volcanic history of Eigg, and which was subjected to contamination by crustal material containing orthoclase. The contaminant could have been a granite, a potassic gneiss or Torridonian sandstone. The complete absence of xenocrystic quartz in the Grulin felsite samples make a potassic gneiss the most probable source of contamination.

The Sgorr Sgaileach and Sron Laimrhige felsites show depletion in Na_2O, K_2O, Ba, Nb, Zr and Y relative to the trend of basaltic fractionation. It is unlikely that they were derived by any mechanism from a basaltic source. Any contamination during fractionation of a basaltic magma would tend to enrich the final product in certain elements rather than deplete them as seen in the felsites. The proposal of Ridley (1971) of partial melting of Torridonian arkose has been criticised by Emeleus (see above). The only other possible source is partial of some source rock other than Torridonian arkose and basalt. Mesozoic sediments can be ruled out both on compositional grounds and because they occur at a high level in the earth's crust.

From their relative positions on the quartz - albite - orthoclase diagram (Figure 11.1a), Lewisian gneiss of the composition quoted by Ridley (1973) for Rhum cannot have acted as a source for the Sgorr Sgaileach and Sron Laimrhige felsites. They fall fairly close to the field of analysed granites (as given by Carmichael et. al. 1974 - see also Figure 11.1a). This suggests that partial melting of a granite could have given rise to the magma which subsequently formed the Sron Laimrhige and Sgorr Sgaileach felsites. This however assumes the presence of a fairly large mass of granitic material in the vicinity of Eigg during the Tertiary, and located at a suitable depth to be available for partial melting.

Ridley (1971) proposes an origin by partial melting of a basaltic magma for the Rudh' an Tancaird pitchstones. The silicic nature of these rocks (see Section 11.4) suggests that they must have a tholeiitic rather than alkaline basalt as a parent. However, they show depletion in Na_2O, K_2O, Ba and Zr, and enrichment in total iron and Y relative to the basaltic fractionation trend defined on Figure 11.4. It is thus unlikely that they were formed by fractionation or partial melting of a basalt. The enrichment in total iron implies that they had a different source from the Sgorr Sgaileach and Sron Laimrhige felsites. From their relative positions on the quartz- albite- orthoclase diagram (Figure 11.1a), it is possible that a Lewisian gneiss of the composition quoted by Ridley (1973) could have been the source material for the Rudh' an Tancaird dykes. The gneiss must have been capable of producing a melt enriched in total iron and Y compared with the other acid rocks of Eigg.

Ridley (1973) believes that the source of the acidic rocks of Eigg may have been situated nearer Rhum than actually on Eigg itself. He cites the lack of a separate gravity Bouguer anomaly over Eigg, and the presence of a large positive anomaly over Rhum, which extends towards Eigg. The size of the anomaly indicates that a dense source of hot material is unlikely to have underlain Eigg. He envisages partial melting between Eigg and Rhum followed by migration of the magmas towards Eigg. From this research, it is known that such melting and subsequent migration must have occurred at least twice, as the Grulin felsite and Sgurr pitchstones and felsites are demonstrably of different ages.

11.8 Origin of the Compositional Variation in the Sgurr Pitchstone/Felsite Mass

It was noted above that the intrusive felsites of the Sgurr have higher differentiation indices (see Figure 11.2), are enriched in SiO_2, K_2O and Zr, and depleted in FeO, MgO, CaO, Ba and Sr compared with the extrusive pitchstone samples. With the exception of the relative Ba contents, this is the type of variation which could be expected from fractional crystallisation of the Sgurr magma after, or during, extrusion.

Crystal settling in the Sgurr magma has been proposed as a possible mechanism to explain the variation in phenocryst content noted in the samples (see Chapter 7). This Section assesses the feasibility of crystal settling in such an acidic magma as the Sgurr pitchstone must have been.

Shaw (1965) has shown that silicate liquids behave as Newtonian fluids (i.e. they do not exhibit peculiar behaviour as a result of widely differing rates of shear) even when cooled significantly below their liquidus temperature. Such behaviour characterises the material until it has cooled below the annealing point, which is usually assumed to occur when the viscosity reaches 10^{13} poises. Assuming that the Sgurr magma contained 3% H_2O (as measured by Ridley 1973) and that it approximates to the system albite- orthoclase- SiO_2- H_2O, the viscosity will be about 10^7 poises (<u>see</u> Figure 1, Shaw 1965). Normative quartz + albite + orthoclase of the Sgurr samples represents 80% of the bulk composition, which is rather low for an acidic rock. This represents a departure from the 'pure' albite- orthoclase- SiO_2- H_2O system and will tend to reduce the viscosity. Thus the Sgurr magma would behave as a Newtonian fluid, and would be capable (theoretically) of having crystals settling through it.

To assess the amount of crystal settling that is possible in a magma, one needs to know how the following factors vary with time:-

1. Type and size of crystals;
2. Number of crystals of various changing sizes;
3. Effect of changing composition;
4. Effect of temperature;
5. Effect of volume concentration of crystals on the bulk viscosity of the magma.

Clearly it is impossible to know any of these factors accurately. Using the data of Shaw (1965), however, estimates of the settling rates of the observed phenocrysts (excluding opaque oxides) in the Sgurr rocks have been made (see Table 11.3).

The rate at which the crystals settle is affected by small crystals in suspension in the liquid, but the bulk viscosity (and hence the rate of settling) is not greatly influenced until the magma is more than half crystallised (Shaw 1965). In addition, it is affected by the quantity of crystals present and Shaw (1965) suggests that the settling velocity as calculated by Stoke's Law (the basis of Shaw's calculations) will be an order of magnitude too high when the crystal concentration in the magma is one third of the total volume. All the Sgurr samples examined (see Chapter 7) show phenocryst contents of c. 20%. Thus the settling rates (see Table 11.3) may be a little high, but are in error by less than an order of magnitude.

The present day maximum thickness of extrusive pitchstone on Eigg is at the east end of An Sgurr, where it is about 100 m in thickness. For crystals to settle this distance, the Sgurr magma must have remained above its annealing point for 1000 years.

Thus it is theoretically possible that the Sgurr magma underwent some crystal settling. Tuttle and Bowen (1958) suggest that zoned crystals are indicative of fractional crystallisation. Only the anorthoclase phenocrysts in the Sgurr samples show any zoning. If the felsites, and in particular the ones that were shown to be partially or totally intrusive to the main pitchstone mass, were derived from the magma of the extrusive pitchstone by fractional crystallisation, one would expect them to plot nearer to the low temperature region than the pitchstone samples. This does not however occur (see Figure 11.1a). Tuttle and Bowen (1958) show the trends followed by liquids during fractionation in the system quartz- albite - orthoclase; two of these are shown on Figure 11.1a. Clearly the Sgurr pitchstones and felsites do not follow these curves. Therefore, straightforward crystal settling alone cannot explain the compositional variation in the Sgurr pitchstones and felsites.

CHAPTER 12

HISTORY OF VOLCANIC ACTIVITY

On account of their insular nature, no definite correlations could be made between the lavas of Eigg, Muck and Canna. Therefore the volcanic history of each island is considered separately.

12.1 Muck

There were only two phases of volcanic activity on Muck - the extrusion of the basic lavas followed by the intrusion of the abundant basic dykes. Volcanic activity started very hesitantly on Muck, giving rise to thin flows (on average 0.5 m thick) interbedded with sediments. The sediments are varying shades of red, from brownish through purplish-red to orange-red, all of which imply terrestrial rather than marine conditions. Only rarely are they seen to be bedded (e.g. at the east end of the An Stac cliffs - 40407910), and such deposits probably accumulated in a lacustrine environment. Only one outcrop of carbonaceous sediment was found (at the base of the lava/sediment sequence of Torr nam Firheach - 40807937), suggesting a scanty vegetation cover on Muck at this time.

Extrusions of lava increased during the time represented by the Upper Basal subgroup and the Port an t-Seilich Groups, where the individual flows (excluding the brecciated units) range in thickness from 7 to 11.3 m. The flows forming the Port an t-Seilich Group are not separated by any red beds, suggesting short time intervals between the flows and hence a fairly rapid extrusion rate. A series of palaeo flow fronts may be traced in the Port an t-Seilich Group.

The uppermost flow is represented by a breccia at Port an t-Seilich (41837845), the flow above the basal one thins to a breccia around the cairn, south-east of Port Mor (42597912) and only the basal flow remains unbrecciated south-west of Torr Creagach (42787938). Clearly the lavas of the Port an t-Seilich Group had a source to the west of Port an t-Seilich.

Almost half a metre of unstratified red mudstone separates the Port an t-Seilich Group from the overlying Beinn Aireinn – An Stac Group at most localities. This suggests an appreciable time interval in extrusive activity. If the tuffaceous origin for the red beds is correct (see Chapter 8), fairly extensive explosive activity must have occurred in the vicinity of Muck at this time. Such activity continued, but with less vigour, while the first flows of the Beinn Aireinn – An Stac Group were extruded. At the type locality of the Group (see Section 2.2 for details), the first three flows show reddening of their upper surfaces, each being overlain by a few centimetres of red mudstone. Flows of the Beinn Aireinn – An Stac Group are, with one exception, olivine phyric basalts. This contrasts with the outpourings of plagioclase phyric basalt, which characterise the Port an t-Seilich Group lavas. This probably represents a change in conditions in the source magma.

Harker (1908) noted an apparent paucity of dykes in the upper parts of the lava pile on Eigg. This suggests that some of the dykes may be feeders to some of the later lavas, although the author saw no evidence of this in the field. The Camas Mhor gabbro described by Tilley (1951) was not studied by the author, but dykes were noted to cut it, suggesting that it predates at least some of the dykes.
The great abundance of dykes on Muck suggests that the area was still

characterised by considerable partial melting, although on a scale insufficient to form lava flows. It was also presumably under tension to cause the opening of the fractures into which the dykes were intruded. Speight (1972) has suggested, on account of the abundance of dykes, that a plutonic body underlies Muck, with the Camas Mor gabbro as its surface expression.

12.2 Eigg

Four main phases of volcanic activity can be defined on Eigg:

1. Extrusion of the basic lavas;
2. Intrusion of acidic bodies (Grulin, Sron Laimrhige and Sgorr Sgaileach felsites);
3. Intrusion of basic sheets, sills and dykes,
4. Extrusion of the Sgurr pitchstone.

From the study of the stratigraphy of the basic lavas (see Chapter 2), it would appear that there was more than one source for the basic lavas of Eigg. The majority of the lavas of northern Eigg do not have direct equivalents in the sequences of western Eigg. Only five flows were definitely found in both parts of Eigg. All five are from the lowest three stratigraphical Groups of Western Eigg.

In northern Eigg, volcanism started fairly hesitantly; several tuffaceous sediments are found intercalated with the lavas of the Basal Group. The Lower Cleadale Group shows a variety of rock types, including the Grey rock (a mugearite) and a hawaiite. The top of the Grey rock shows reddening locally, suggesting a cessation in volcanic activity after its extrusion, when the surface of the flow underwent oxidisation. By the time the flows of the Middle Cleadale Group were being extruded, however, the feeder of the lavas was tapping fairly uniform supplies of olivine phyric basalt, and judging by the lack of surface reddening and intercalated red beds, extrusion was fairly rapid. A slight variation in magmatic conditions occurred when the first flows of the Upper Cleadale Group were formed, giving rise to clinopyroxene and olivine phenocrysts in the basalts. The youngest flows of northern Eigg represent a return to similar magmas to those which formed the olivine phyric basalts of the Middle Cleadale Group.

In western Eigg there is additional evidence for explosive activity resulting in tuffaceous deposits at the start of the volcanic activity. There are red mudstone horizons overlying both flows of the Laig Group, the lowest stratigraphical group. Flows extruded during the time represented by the Laig and Gleann Charadail Groups are relatively persistent across the area. The flows of the Glac an Dorchadais Group, which were extruded after those of the Gleann Charadail Group, show differences between the northern and southern parts of western Eigg, suggesting two sources of magma at this time. The Group as a whole thins to the south-east, suggesting that the more prominent source lay to the north-west. The next series of flows (the Brutach Dearg Group) show interdigitation of lavas from two sources. Flows in the north die out south-eastwards (like those of the older Glac an Dorchadais Group), while those in the south die out to the north-west. The two youngest Groups of western Eigg (the Cnoc Creagach and Cora-bheinn Groups) both show overall thinning to the north-west, suggesting that the source lay to the south-east. These two Groups also show evidence of localised centres of eruption making correlation within the Groups very difficult. Only the two basal marker horizons are at all continuous, and were presumably fed by a more persistent source.

The second phase of igneous activity on Eigg was the intrusion of the felsites. All three felsites clearly predate at least part of the phase of intrusion of the basic minor intrusives and two of them (the Sgorr Sgaileach felsite excluded) demonstrably postdate the lavas. Only the Sron Laimrhige felsite intrudes near any known point of weakness - a fault (see Figure 2.3.2). The Sgorr Sgaileach and Sron Laimrhige felsites are thought to represent the fusion of a granite, while the Grulin felsite formed by contamination of a melt similar to that which, later in the volcanic history of Eigg, formed the Sgurr pitchstones and felsites (see Chapter 11). They clearly represent a small thermal event in the vicinity of Eigg at this time.

The exact timing of the intrusion of the basic sheets, sills and dykes of Eigg is uncertain. There is evidence for at least two phases of dyke intrusion, and it is known that the Kildonnan sheets postdate some dykes and are themselves intruded by others. In all probability, the intrusion of dykes, sills and sheets proceeded along with the extrusion of lavas, and may well have continued thereafter.

A considerable period of erosion followed these first three phases, sufficient for the development of a river system on Eigg and the establishment of trees, as evidenced by the presence of wood fragments in conglomerates below the Sgurr pitchstone (see Chapter 6). Finally, the Sgurr pitchstone was extruded, sealing up the valleys formed by the river system. The pitchstone lava may have extended as far as Oigh Sgeir, 19 miles to the north-west of Eigg.

12.3 Canna

Extrusion of basaltic lavas is the predominant form of igneous activity represented on Canna. There is also ample evidence of contemporaneous erosion by fluvial action and for some explosive volcanic activity. Intrusion of basic dykes represents a small later event.

The earliest volcanic activity on Canna was accompanied by considerable fluvial action, as evidenced by the extensive conglomeratic deposits interbedded with the lavas of Sanday, Canna Harbour and eastern Canna. Lavas extruded at this time vary with location: those of eastern and central Sanday are plagioclase phyric; those of Tallabric (western Sanday) are aphyric; those of eastern Canna are also aphyric. The agglomerates near Garbh Asgarnish (28170613) also date to approximately the time of the Basal Group (to which the lavas of Canna Harbour and Sanday have been assigned - see Chapter 2). They suggest an active vent situated somewhere between Canna and Rhum at this time.

Only the oldest flow of the Lower Main Group (the glomerophyric basalt) is represented on Sanday. In the eastern part of eastern Canna, this time was characterised by outpourings of aphyric lava with interbedded conglomerates. Further west the conglomerates die out, and the aphyric flows are replaced by plagioclase phyric ones. At Rubha Langanes (23900680) bedded tuffaceous sediments with lenses of coal, which overlie conglomerate, are of this age. They suggest a lacustrine environment at this locality and some explosive activity in the vicinity at the time of the Lower Main Group. In western Canna, aphyric and plagioclase phyric flows were extruded at this time. A second area of lacustrine deposits occurs on the foreshore near

Bre Sgorr (21257400). Here carbonaceous shales with sandy lenses are overlain by fine grained conglomerates. Further evidence of a water body in this area at this time is given by the palagonite pillow breccia overlying the sediments (see Section 2.4.5.3).

The reddening of the uppermost flows of the Lower Main Group in eastern Canna and the undulating surface onto which the columnar flow, the basal marker of the overlying Middle Main Group, was extruded, point to a period of erosion. Again there is evidence of continuing fluvial activity in the east of eastern Canna, where plagioclase phyric flows are intercalated with conglomerates. Further west, different plagioclase phyric flows (with abundant rather than rare plagioclase phenocrysts) and aphyric flows were extruded. This suggests more than one source for the lavas of eastern Canna at this time. In western Canna, flows with abundant plagioclase phenocrysts (from the Bre Sgorr Group) outcrop in the west of the area, but are replaced by aphyric flows and a columnar aphyric basalt in the east. This suggests more than one source for the lavas of western Canna at this time. Thus there may have been as many as four sources of magmatic activity on Canna at the time of the Middle Main Group.

The succeeding Group of flows (Upper Main Group of eastern Canna) shows a similar lack of correlation between the sequences of the eastern and western parts of eastern Canna. Again the flows in the east are intercalated with conglomerates, implying a continuation of the fluvial activity. The flows of the western part of eastern Canna are similar to those forming the contemporaneous Sliabh Meadhonach Group of western Canna. Thus it is only necessary to postulate two sources for the lavas of Canna at the time of the Upper Main Group.

The youngest lavas in Canna (the Beul Lama Sgorr Group) only occur in the eastern part of the island. All flows of the Group, except the basal marker - the 'platey' basalt - are strongly plagioclase phyric. There are no intercalated conglomerates, so by this time, all the river channels must have been blocked by lava flows.

A minor phase of dyke intrusion followed the extrusion of the lavas, sixteen dykes in all being found on Canna (see Speight 1972). The scarcity of dykes on Canna, as with the Rhum lavas, led Speight (1972) to the conclusion that the Canna lavas are a late stage event in the Tertiary igneous activity of the area, postdating the main phase of basic minor intrusions, as seen for example on Rhum. It is most likely that they are contemporaneous with the Rhum lavas (see Chapter 8).

12.4 Concluding Statement

It would appear, therefore, that the lavas of Canna are younger than the main phase of dyke intrusion on Rhum (as are the Rhum lavas). Assuming that the dykes of Eigg and Muck are of a similar age to those on Rhum (Speight (1972) assigns them all to a Small Isles swarm), then it follows that the lavas of Eigg and Muck are probably of a similar age, and are older than those of Canna (and Rhum).

It is perhaps of some significance that the lavas of Canna and Rhum show ample evidence of contemporaneous erosion, while those of Eigg and Muck do not, once the eruptions were well established. This suggests rather different topographical conditions and rates of extrusion of the basaltic lavas for Eigg and Muck as compared with Canna and Rhum. This is, no doubt, connected with the apparent age difference in the two sets of lavas.

The presence of fluvial deposits on both Canna and Eigg (the conglomerate below the Sgurr pitchstone) led Geikie (1896) to the conclusion that they represented parts of the same great river system. The conglomerates below the Sgurr pitchstone on Eigg demonstrably postdate the phase of dyke intrusion. Therefore, if the dykes of Canna do indeed represent a later event than the main phase of dyke intrusion (as suggested by Speight 1972), the two series of conglomerates may well be at least broadly contemporaneous.

The pitchstones of the Sgurr of Eigg and Oigh Sgeir are most probably the youngest volcanic event in the area of the Small Isles (Eigg, Muck, Canna and Rhum).

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