British Tertiary Volcanic Province

C. H. Emeleus
Reader in Geology,
University of Durham

and

M. C. Gyopari
Senior Hydrogeologist,
Groundwater Consulting Services

(with contributions from G. P. Black and I. Williamson)

GCR editors: W. A. Wimbledon and P. H. Banham

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Chapter 4

Ardnamurchan

INTRODUCTION

The Ardnamurchan Peninsula is the site of a Tertiary igneous complex which was emplaced into Moine schists, Mesozoic sediments, and early Cenozoic volcanic rocks. It is much less rugged and mountainous than the other British Tertiary Volcanic Province central complexes, yet in many ways, it more strikingly – and often much more simply – demonstrates the salient geological features common to many of the centres.

The complex igneous geology of Ardnamurchan became recognized through the investigations of several geologists during the nineteenth century (for example, Judd, 1874, 1886; Geikie, 1888, 1897); however, it was not comprehensively mapped and examined until the official survey was undertaken by Richey and Thomas (1930). Despite appearing over half a century ago, the Ardnamurchan Memoir probably remains the most complete and widely used work on the area, although some of the interpretations and general conclusions reached in it have been questioned by subsequent investigators. The recent facsimile (1987) reprint of this Memoir is to be welcomed.

The Ardnamurchan Centre is renowned for its development of sets of cone-sheets and numerous arcuate, dominantly gabbroic intrusions which were, almost without exception, interpreted by the authors of the Memoir as ring-dykes. From the disposition of the ring-dykes and cone-sheets, Richey and Thomas (1930) recognized that these arcuate intrusions defined three separate centres of igneous activity (referred to henceforth as Centres 1, 2 and 3 respectively) and that the focus of the activity, as indicated by these centres, had shifted progressively with time (Table 4.1). Although there are many other features of interest in the igneous rocks of Ardnamurchan, it is these features in particular for which the area is renowned and upon which its claim to be of both national and international geological importance rests. The geology of the area has been the subject of several reviews and field guides (Richey, 1933; Richey, 1961; Stewart, 1965; Deer, 1969; Gribble *et al.*, 1976; Emeleus, 1982, 1983). It should, however, be mentioned that the status of the three independent but overlapping centres has been questioned (for example, Durrance, 1967; Green and Wright, 1969, 1974; Gribble *et al.*, 1976), as has the interpretation of many of the gabbroic and other intrusions as ring-dykes (for example, Wells, 1954a; Bradshaw, 1961; Skelhorn and Elwell, 1966). The Tertiary igneous geology of Ardnamurchan is represented by six SSSIs (Fig. 4.1).

Relicts of the earliest activity, which was dominantly volcanic and probably covered much of the peninsula, are now found in the Ben Hiant area (Table 4.1). Remnants of mildly alkaline plateau lavas, overlying a basal ashy mudstone, are cut by a series of vents and pitchstone lavas of intermediate composition which post-date the basalts. The relationships of these rocks, together with numerous later dolerite intrusions, including a set of cone-sheets, are all excellently displayed in the Ben Hiant site; coarse volcanic breccias, possibly representing vent infills, are particularly well developed at Maclean's Nose.

The painstaking field and laboratory investigations of Richey and Thomas (1930) demonstrated the presence of a complex series of suites of cone-sheets and ring-dykes. Representative sections across such intrusions, assigned in the Memoir to Centre 2, are present in the Beinn na Seilg–Beinn nan Ord and Ardnamurchan Point to Sanna sites, while the most complete major ring structures are exposed in Centre 3 representing the final focus of activity. Studies made on these intrusions since the appearance of the Memoir have revealed features which, in some instances, do not conform to the expected pattern of the classic ring-dyke. Variations in these patterns have been noted in the two outermost intrusions of Centre 2 (Richey, 1940; Wells, 1954a, 1954b; Skelhorn and Elwell, 1966, 1971; Wells and McRae, 1969; Butchins, 1973). In addition to field studies, the mineralogy and geochemistry of the two principal centres (Centres 2 and 3) have received considerable attention (Bradshaw, 1961; Smith, 1957; Walsh, 1971, 1975; Gribble, 1974; Walsh and Henderson, 1977). Other features such as the dolerites, xenolithic inclusions and associated granophyric bodies with their distinctive net-veined relationships in dolerites have been described by Gribble (1974), MacGregor (1931), Wells (1951), Brown (1954), Paithankar (1968) and Vogel (1982).

The mutual relationships between all three centres of activity, and the successive truncation of the margins of intrusions and internal megascopic structures by later intrusions, are demonstrated in the Glas Bheinn–Glebe Hill site, where remnants of the former volcanic cover of the peninsula are also present as a screen between two ring-dykes. Intense thermal metamorphism of country rocks adjoining the major intrusions has

Table 4.1 The geological succession in the Ardnamurchan Central Complex (based on Richey and Thomas, 1930, Chapter 7)

(youngest)

- Late NNW-trending dolerite dykes

Centre 3

- Quartz monzonite
- Tonalite
- Fluxion biotite gabbro of Glendrain
- Fluxion biotite gabbro of Sithean Mor
- Quartz–biotite gabbro
- Quartz dolerite, granophyre-veined
- Inner Eucrite
- Biotite eucrite
- Quartz gabbro, southern side of Meall an Tarmachain
- Quartz gabbro of Meall an Tarmachain summit
- Outer Eucrite
- Great Eucrite
- Cone-sheets of Centre 3 (sparse)
- Porphyritic gabbro of Meall nan Con screen
- Gabbro, south-east of Rudha Groulin
- Gabbro of Plochaig
- Fluxion gabbro of Faskadale
- Quartz gabbro of Faskadale

(Migration of focus of activity to Achnaha area)

Centre 2

- Felsite, south of Aodann
- Fluxion gabbro of Portuairk
- Younger quartz gabbro of Beinn Bhuidhe
- Quartz gabbro of Beinn na Seilg
- Quartz gabbro of Loch Caorach
- Eucrite of Beinn nan Ord
- Inner cone-sheets of Centre 2
- Quartz dolerite of Sgurr nam Meann
- Quartz gabbro of Aodann
- Older quartz gabbro of Beinn Bhuidhe
- Granophyre of Grigadale
- Quartz gabbro of Garbh-dhail
- Old Gabbro of Lochan an Aodainn
- Hypersthene gabbro of Ardnamurchan Point
- Glas Eilean vent
- Outer cone-sheets of Centre 2

(Migration of focus of activity to Aodann area [NM 453 664])

Centre 1 and the Ben Hiant vent*

- Cone-sheets of Centre 1 (penecontemporaneous with the quartz dolerite intrusion of Ben Hiant)
- Ben Hiant quartz dolerite
- Composite intrusion of Beinn an Leathaid
- Augite diorite of Camphouse
- Quartz dolerite of Camphouse

Table 4.1 *contd*

Porphyritic dolerite of Ben Hiant
Granophyre west of Faskadale
Quartz gabbro west of Faskadale
Old Gabbro of Meall nan Con
Porphyritic dolerite of Glas Bheinn
Agglomerates of Northern Vents
Tuffs, agglomerates and lavas of Ben Hiant vents
Trachyte plug
(Igneous activity localized at Ben Hiant and also centred on a focus *c.* 1.3 km west of Meall nan Con)
Palaeocene basalt lavas and thin sediments
Jurassic and Triassic sandstones, shales, limestones, conglomerates
Moine metasediments
(oldest)

*The relative ages of many of the units assigned to Centre 1 and Ben Hiant are uncertain. (From Emeleus, in Sutherland, 1982, table 29.5).

been noted at several localities. A classic example of hornfelsed, aluminous, iron-rich, sediments (bole?) occurs in the site at Glebe Hill (Richey and Thomas, 1930), while a complex suite of calc-silicate hornfelses containing the mineral kilchoanite, first identified on Ardnamurchan (Agrell, 1965), crops out a short distance to the east.

Many of the Tertiary central complexes in the British Isles contain examples of cone-sheets, but those belonging to the Ardnamurchan complex are perhaps the most obvious, well exposed, easily accessible and widely studied (Harker, 1917; Richey and Thomas, 1930; Anderson, 1936; Kuenen, 1937; Durrance, 1967; Le Bas, 1971; Holland and Brown, 1972; Phillips, 1974). The most extensive suites are those developed about Centre 2, and the Glas Eilean–Mingary Pier site has been selected as a standard reference section where the form, petrology, contact-metamorphic effects and, to some extent, the emplacement mechanism of these intrusions can be studied. In Richey and Thomas's classification, the cone-sheets in this site comprise part of the outer set of Centre 2; members of the inner set may be seen in the Beinn na Seilg–Beinn nan Ord site and the rather poorly developed suite attributed to Centre 3 may be studied on the south-east of the Centre 3 site (Table 4.1). The Glas Bheinn-Glebe Hill site contains cone-sheets attributed to Centre 1, but it has been suggested that all the cone-sheets belong to a single spiral suite (Durrance, 1967), and Holland and Brown (1972) were unable to discriminate geochemically between sheets assigned to Centres 1 and 2.

Ardnamurchan is the site of a positive Bouguer gravity anomaly (Bott and Tuson, 1973) but the anomaly is markedly less intense than those found on Mull, Skye or Rum which indicates a rather shallower body of mafic rock underlying the Ardnamurchan complex. Radiometric age determinations on rocks of the complex indicate that the activity took place in the Palaeocene (*c.* 60 Ma; Miller and Brown, 1965; Mitchell and Reen, 1973) but the data do not allow the different intrusions or centres of activity to be separated, since the duration of igneous activity at Ardnamurchan was probably of the order of one million years, comparable with the margin of error of the Ardnamurchan age determinations (cf. Table 1.1; Mussett *et al.*, 1988).

BEN HIANT

Highlights

The steep slopes of Ben Hiant provide an excellent cross-section of volcanic vents filled with agglomerate, ash and pitchstone lavas. The vent rocks are cut by large basic intrusions of complex origins.

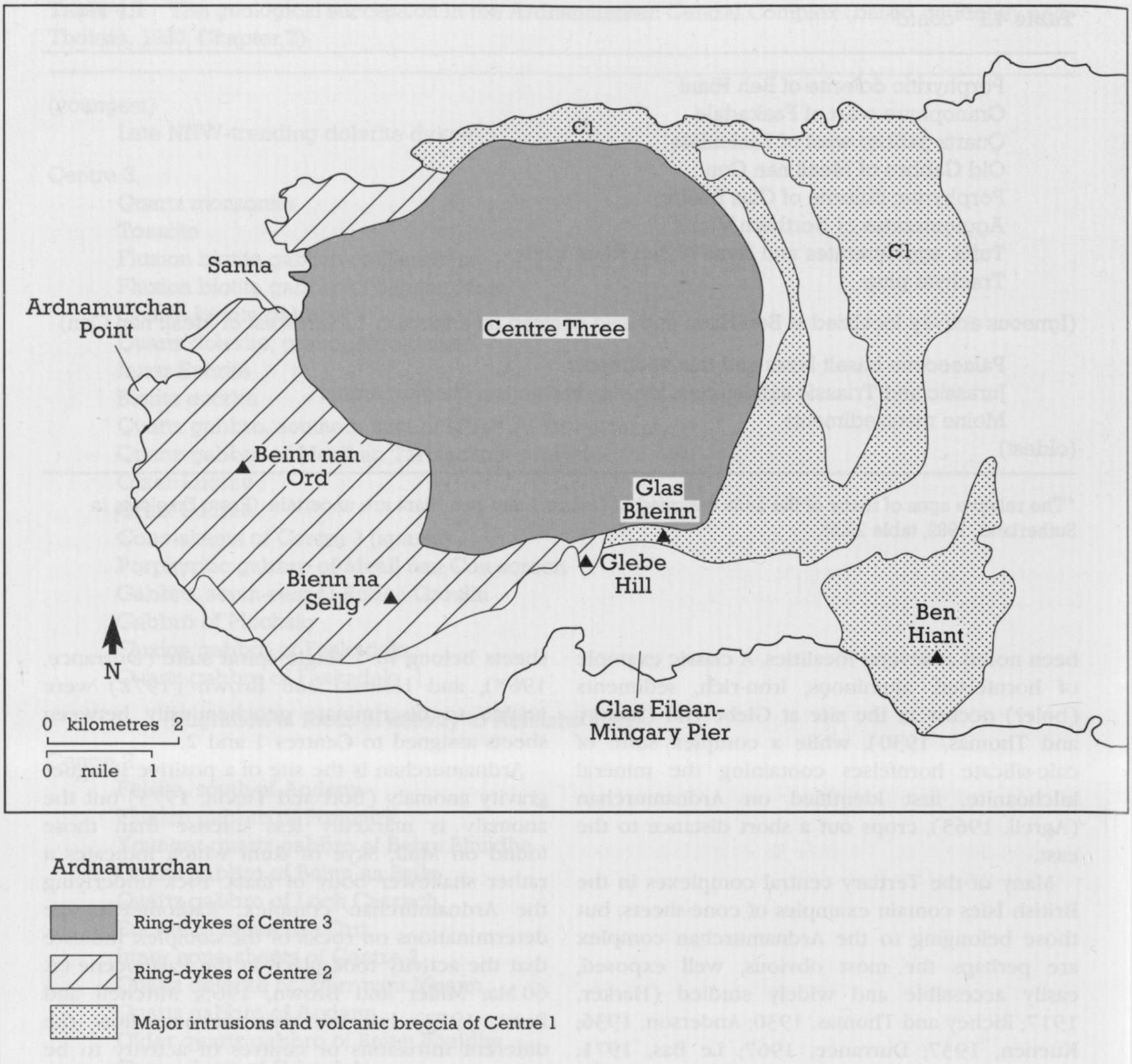


Figure 4.1 Map of the Ardnamurchan Peninsula showing localities mentioned in the text.

Introduction

The geological interest of Ben Hiant and the neighbouring hills of Beinn na h-Urchrach and Stallachan Dubha lies in the well developed assemblage of volcanic vents, associated lavas and major basic intrusions which are part of the early Centre 1 of the Ardnamurchan complex. The Ben Hiant quartz dolerite mass and vent agglomerates dominate the geology of the site and thin remnants of the earlier lava plateau of this region are also well represented (Figs 4.2 and 4.3).

Early research in Ardnamurchan centred largely around the Ben Hiant area (Judd, 1874, 1886, 1890 and Geikie, 1888, 1897), but the significance and complexity of the area was not revealed until the work of Richey and Thomas (1930) and Richey (1938). Subsequently, little research specifically related to the area has been published, although samples from Ben Hiant have been used in a petrological study of doleritic intrusions within the Ardnamurchan complex by Gribble (1974) and in an investigation of the radiometric ages of the rocks in the complex by

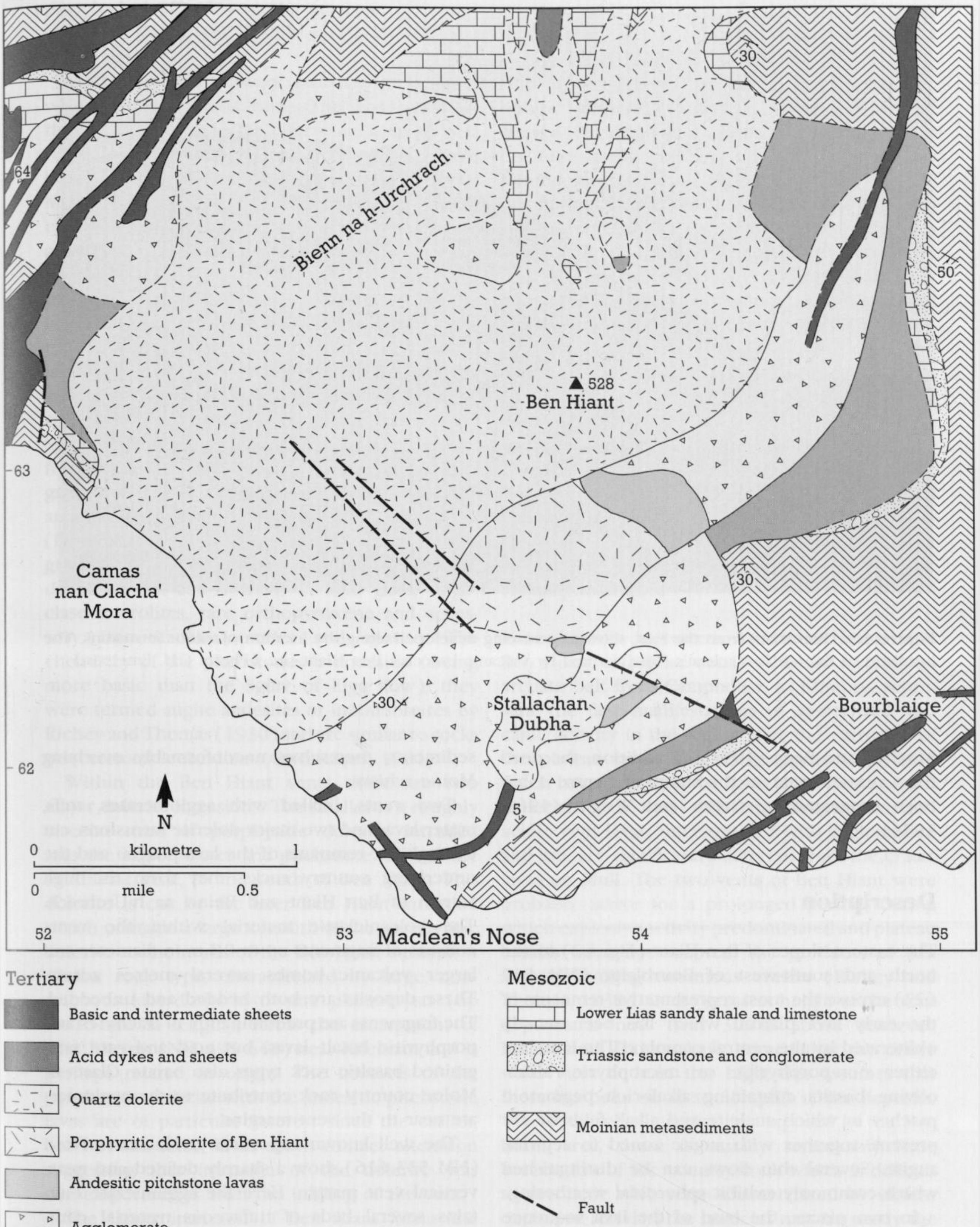


Figure 4.2 Geological map of the Ben Hiant site (after Gribble, 1976).

Figure 4.3 Ben Hiant from the east, showing terracing developed along the location of minor intrusions. The headland to the left is Maclean's Nose, formed by volcanic breccias. Ben Hiant site. (Photo: C.H. Emeleus.)

Mitchell and Reen (1973). In addition, the need for a reassessment of the status of Centre 1 has been suggested by Green and Wright (1969, 1974).

Description

The eastern slopes of Ben Hiant (Fig. 4.2) to the north and south-west of Bourblaige (NM 547 623) expose the most representative remnants of the early lava plateau which has been mostly obliterated by the central complex. The lavas are either non-porphyritic or microphyric, alkali-olivine basalts containing alkali-rich pegmatoid patches in which analcite and alkali feldspar are present, together with augite zoned to aegirine augite. Several thin flows can be distinguished which commonly exhibit spheroidal weathering.

In two places, the base of the lava sequence rests upon a basal mudstone of a similar nature to sediments beneath the Mull lavas (Bailey *et al.*, 1924). This deposit is underlain by Triassic sediments, themselves unconformably overlying Moine schists.

Two vents, infilled with agglomerates, tuffs, crater lavas and two major dolerite intrusions, cut through the remnants of the lava plateau and the underlying country rocks; they form the high terrain of Ben Hiant and Beinn na h-Urchrach. The volcaniclastic material within the vents consists of fragments up to 0.3 m in diameter and larger volcanic bombs several metres across. These deposits are both bedded and unbedded. The fragments are predominantly of trachytes and porphyritic basalt lavas, but acid and rare fine-grained basaltic rock types also occur. Clasts of Moine country rock contribute to the agglomerate near to the vent margins.

The well known exposures at Maclean's Nose (NM 533 616) show a sharply defined and near-vertical vent margin. Here the agglomerate contains several beds of tuffaceous material composed of comminuted basic rock, plus crystals of quartz and mica likely to have been derived from Moine schists. Large basaltic blocks have close petrological affinities to the adjacent lavas and appear to have fallen into the vent from the walls of the crater.

In the south-eastern vent, lavas are intercalated with the volcaniclastic rocks. The most noteworthy is a suite of andesitic pitchstone lavas seen at three localities, which are considered to have been erupted within a caldera. At least three flows interbedded with thin tuffs are recognized, each showing a triple-tiered structure comprising a slaggy amygdaloidal lava top overlying a layer of lava with small, subhorizontal columns and passing downwards into a layer characterized by larger vertical columns; such a flow structure is typical of lavas which have cooled slowly. There is some evidence in the pitchstone lavas to suggest at least limited auto-intrusion not dissimilar to that found in the pitchstone of the Sgùrr of Eigg (see above). The rocks are relatively fresh, dark-brown to black in colour with a fine-grained or glassy texture. Microphenocrysts of augite–ferroaugite, pigeonite–ferrous pigeonite (Emeleus *et al.*, 1971) and labradorite occur in a groundmass which shows different degrees of devitrification and consists of acid glass, oligoclase microlites, rare orthopyroxene and accessory iron–titanium oxides and apatite. The chemistry of the pitchstones is andesitic (being more basic than the Sgùrr of Eigg flow); they were termed augite andesites or inninmoreites by Richey and Thomas (1930) and are similar to rocks now termed icelandites (Carmichael, 1964).

Within the Ben Hiant vents there are two major dolerite intrusions. The smaller is a roughly circular mass of porphyritic dolerite intruded into the agglomerates and pitchstone lavas of the south-east vent, to the south of Ben Hiant. This dolerite is cut by the later Ben Hiant intrusion which contains a large xenolith of the porphyritic dolerite to the north of the Ben Hiant summit. A similar rock type, characterized by large, conspicuous labradorite/bytownite phenocrysts (up to 15 mm in length), forms the escarpment of Glas Bheinn (NM 495 648) near Kilchoan and is perhaps related in origin. The contacts of the porphyritic dolerite with the andesitic pitchstone lavas are of particular interest since the earlier, but not the later, lavas show contact alteration suggesting that intrusion of the dolerite was contemporaneous with the infilling of the vent.

The larger intrusion of Ben Hiant forms the hills of Ben Hiant, Beinn na h-Urchrach and Stallachan Dubha and reaches the coast at Camas nan Clacha' Mora (NM 524 626). The mass consists of a number of varieties of quartz dolerite and of less common olivine dolerite, all having strong tholeiitic characteristics. The intrusion is best described as a non-porphyritic, ophitic dolerite; however, larger crystals of altered olivine, augite, ilmenite and labradorite do occasionally occur. A mass of columnar-jointed variolitic rock, probably formed by chilling at the upper contact, overlies and grades into normal dolerite to the south-west of the Ben Hiant summit. Labradorite microphenocrysts lie in a typically feathery-textured, variolitic groundmass of acicular augite, magnetite and oligoclase/andesine feldspar. Rare glomeroporphyritic aggregates of augite and labradorite also occur. The margins of the Ben Hiant intrusion contain xenoliths of basic volcanic rocks and of schist; where the latter have suffered partial melting, hybrid rocks are in evidence.

Minor intrusions are scattered throughout the site and include basic and composite dykes and intermediate cone-sheets.

Interpretation

Vent deposits in eastern Ardnamurchan around Ben Hiant, and those outside the site forming an arcuate belt from Camphouse to Kilmory, represent the first manifestations of centralized volcanic activity in the region after the extrusion of the plateau lavas. The vents appear to be of a much later date than the lavas since they contain material of a very different composition and acidic vent lavas, interstratified with agglomerate and ash, are significantly different from the crater lavas on Mull. The two vents of Ben Hiant were probably active for a prolonged period, during which explosive activity predominated and plateau basalts were not erupted; the products of this activity infilling enormous craters (Richey and Thomas, 1930). As the greatest height of the vent deposits is now over 300 m above sea-level, Richey and Thomas have argued that the crater walls were at least this high; this assumes that there has been no tectonic uplift of the deposits. Where the vent margins are exposed in the Ben Hiant area, there is usually remarkably little brecciation of the country rock which is difficult to reconcile with vents characterized by violent explosive activity; the breccias may be partly the products of debris avalanches off the walls.

The form of the Ben Hiant intrusion is of particular interest and uniqueness. Judd (1890) erroneously interpreted the terrace- or scarp-like topographic features of the south-eastern parts of the outcrop as a succession of lava flows but Geikie (1888) correctly concluded that the dolerite was intrusive (Fig. 4.3). He speculated that the intrusion has the form of a suite of coalescing sills, an interpretation also favoured by Gribble (1974). Richey and Thomas (1930) interpreted the north-western part of the intrusion, which overlies agglomerate, as a lateral off shoot extending from a lower mass with vertical contacts, while the south-eastern margin was considered to be formed by a suite of sheets which coalesced to form a single intrusion. The sheets dip at angles slightly less than those shown by the Centre 1 cone-sheets with which they share a similar composition. The intrusion is therefore suggested to be a mushroom-shaped body in part and also an assemblage of coalesced sheets. The rocks which form the successive terraces vary slightly in chemistry (Gribble, 1974; Gribble *et al.*, 1976) and modal mineralogy (Gribble *et al.*, 1976, confirming Judd, 1890). Gribble (1974) has argued that the intrusion is not a single homogeneous body and it is possible that several pulses of magma were responsible for the intrusion, the problems that it poses not yet having been resolved.

In comparison with the other major late dolerites of Ardnamurchan (Richey and Thomas, 1930; Skelhorn and Elwell, 1966; Holland and Brown, 1972; Gribble, 1974), those of Ben Hiant are distinctly tholeiitic, showing only slight iron-enrichment trends. Gribble (1974) suggested that the magma which formed the Ben Hiant Intrusion was the parental magma for all the rocks of Centre 1 and the source from which the rocks of Centre 2 and 3 were ultimately derived having a composition similar to the non-porphyritic Central Magma Type of Bailey *et al.* (1924).

Conclusions

Early explosive volcanic activity and limited lava effusion produced the vents of Ben Hiant and eastern Ardnamurchan which represent the first manifestations of the central complex. A significant repose period had intervened between this activity and the earlier eruption of plateau basalts. The vents were active for a prolonged period and were later intruded by doleritic and quartz gabbro masses and the largest of these, the Ben Hiant intrusion, is probably largely a mass of coalesced cone-sheets. The magma which formed this intrusion may have been parental to all the rocks in Centre 1 and compositionally similar to the parent magmas for the intrusions in Centres 2 and 3.

GLAS EILEAN–MINGARY PIER

Highlights

One of the best sections through a cone-sheet swarm to be found in the British Tertiary Volcanic Province is exposed on the shore west of Mingary Pier. Numerous basic, rare acid and composite sheets enclose thin screens of country rock, some of which have developed distinctive thermal metamorphic minerals. A well exposed linear volcanic vent on Glas Eilean cuts the cone-sheets and is itself cut by a tuffisite dyke.

Introduction

The numerous cone-sheets of the Ardnamurchan complex are exceptional in their development and are of international importance. The 1.5 km stretch of coast between Glas Eilean on Kilchoan Bay and Mingary Pier provides a representative section through a large number of basic and less-abundant felsite sheets associated with Centre 2. Other features of interest within the site include remnants of the early lava plateau and deposits in a linear vent (Fig. 4.4).

The cone-sheets of Ardnamurchan were originally mapped by the Survey (Richey and Thomas, 1930) which led to the recognition of several distinct sets related to each of the intrusive centres. The origin of the intrusions has been subject to continuing debate since the interpretations of Bailey *et al.* (1924) and Richey and Thomas (1930) for the cone-sheets of Mull and Ardnamurchan, respectively. These workers, and Anderson (1936), attributed the sheets to the updoming of the country rock by rising magma which resulted in conical fractures along which the cone-sheets were emplaced. Durrance (1967), Phillips (1974) and Walker (1975) have subsequently presented modified interpretations on the mechanisms of cone-sheet emplacement. The geochemical characteristics of these intrusions have been studied by Richey and Thomas (1930) and, more recently, by Holland and Brown

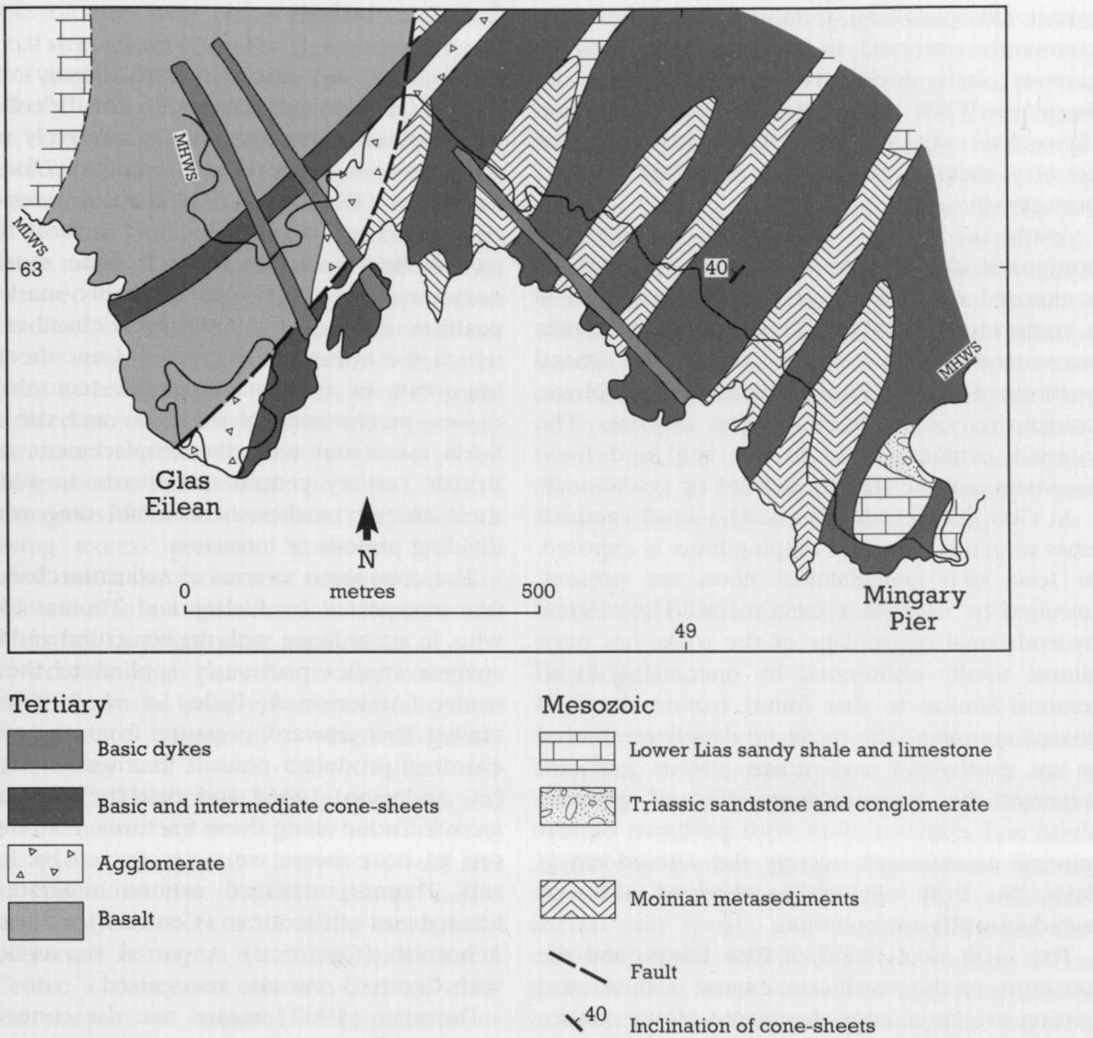


Figure 4.4 Geological map of the Glas Eilean–Mingary Pier site (after Gribble *et al.*, 1976).

(1972). Reynolds (1954) described and discussed features of the Glas Eilean linear vent.

Description

The predominantly intertidal exposures in the site (Fig. 4.4) demonstrate a profusion of cone-sheet intrusions which are so frequent that the proportion of igneous rocks often exceeds that of the country rocks they intrude. They belong to the outer set of cone-sheets associated with Centre 2 and include some of the most silicic compositions in the complex (Richey and Thomas, 1930; Holland and Brown, 1972), although being mostly of non-porphyritic quartz-dolerite, porphyritic dolerite or basalt. Individual cone-sheets vary greatly in inclination (20° to 75°) and range in thickness, from 0.5 to 15 metres; however, most are inclined at 35° to 45° towards the Aodainn–Achosnich area and are between 0.5 and 2 metres thick. In general, they cannot be traced for any substantial distance along strike and in many places the sheets interdigitate and form anastomosing masses several metres thick. Country rocks are biotite-grade Moine psammites and phyllites, Triassic breccias and conglomerates, Lias limestone–shale rhythmic sequences and Tertiary lavas, against all of which the cone-sheets are conspicuously chilled. Contact-metamorphic effects involving the formation of idocrase, sphene, garnet, clinopyroxene, tremolite and prehnite are commonly observed in the adjoining Lias calcareous shale rocks. The sheets are cut by numerous WNW- to NW-trending basic dykes and themselves cut earlier dykes and sills. The country rocks occur as thin septa, or screens, between the cone-sheets.

South of Mingary Pier (NM 494 627), a composite sill of quartz dolerite and granophyre is exposed and, a few metres to the west, there is a composite cone-sheet. Such composite sheets have margins of basic quartz dolerite and central portions of felsite (often xenolithic), granophyre, craignurite or acidified quartz dolerite. The internal contacts between the acid and basic members may be sharply defined or gradational.

At Glas Eilean (NM 484 628) a small remnant mass of gently westerly dipping lavas is exposed. At least two amygdaloidal flows are present, intruded by numerous cone-sheets. The original hydrothermal assemblage of the rocks has been almost totally obliterated by pneumatolytic alteration similar to that found around the Mull central complex. The rocks are deeply weathered to an earthy-red and green colour and are traversed by anastomosing veins of chlorite, albite and epidote, often with prehnite. Similar mineral assemblages occupy the altered amygdales. No fresh olivine has survived, although pseudomorphs are common.

The small tidal island of Glas Eilean, and the foreshore to the north-east, expose a linear vent cutting the lavas, cone-sheets and Moine schists. It is broken into two outcrops by a fault which, in places, throws the lavas against the schists. Fragments of quartz dolerite and tholeiitic basalt derived from the cone-sheets occur within the vent agglomerate, which also contains fragments of Moine schist, basalt lava, Jurassic sandstone, limestone and shale. The clasts lie in a devitrified, chloritic matrix containing spherulites of quartz and alkali feldspar. The agglomerate is locally intricately veined by an acid tuff composed of devitrified acid glass enclosing bodies of basic devitrified glass (Paithankar, 1968). A tuffisite dyke with flow-textured margins cuts the agglomerate. The dyke matrix, which closely resembles the agglomerate matrix, contains a variety of clasts, of which basalt is the dominant type. The clasts increase in size from the margins of the dyke towards its centre, where the concentration of coarse fragments may make it difficult to distinguish the rock from the normal vent agglomerate.

Interpretation

Cone-sheets are associated with many of the central intrusive complexes in the British Tertiary Volcanic Province but are relatively scarce elsewhere, implying unusual conditions for their formation (Walker, 1975). Their outcrops are concentric and they are inclined inwards having an inverted cone shape, each cone sharing a common apex. The apex probably marks the position of the roof to the magma chamber from which the intrusions originated. Cone-sheets are important in understanding the tectonic processes, mechanisms of intrusion and the stress fields associated with the emplacement of the British Tertiary central complexes. In addition, their ubiquity makes them useful time markers dividing periods of intrusion.

The cone-sheet swarms of Ardnamurchan were first interpreted by Richey and Thomas (1930) who, in accordance with the structural and stress analysis studies previously applied to the Mull centre (Anderson *in* Bailey *et al.*, 1924), concluded that upward pressure from the magma chamber produced conical fractures in its roof (cf. Anderson, 1936) and that the cone-sheets were intruded along these fractures. Two distinct sets of cone-sheets were recognized by Richey and Thomas, arranged around separate foci located east of Glendrain (Centre 1) and south of Achosnish (Centre 2). A partial set associated with Centre 3 was also recognized.

Durrance (1967) argued that the cone-sheets could not be divided into two independent suites but occupy one large conjugate spiral (as opposed to concentric) shear fracture system centred on Sanna. This focus is located at the periphery of the complex and corresponds closely with the gravity maximum of the Ardnamurchan complex (Bott and Tuson, 1973). This model postulated that a release of magma pressure and associated compressional stresses, coupled with a degree of torsion, resulted in the spiral fracture system along which the cone-sheets were subsequently injected when the magma pressure increased. Gribble *et al.* (1976) strengthened this model by noting that the cone-sheets originally attributed by Richey and Thomas (1930) to Centre 1, and to the outer set of Centre 2, occupy predominantly sinistral shear fractures. However, the inner set belonging to Centre 2 and the few Centre 3 cone-sheets, tend to have been intruded into dextral fractures. According to Durrance's model, the shear sense of these fractures would have been controlled by torsional stresses set up by the high-level emplacement of magma bodies.

Walker (1975), in presenting a new concept for the evolution of the Tertiary intrusive centres, suggested a radically different mechanism for cone-sheet formation. The cone-sheets in the British Tertiary Volcanic Province generally coincide with areas of updoming, presumed to have been caused by early uprising acid diapirs (but see Le Bas, 1971). Walker suggested that the sheets are emplaced passively along fractures produced by rising magma which tended to move in the direction of maximum hydrostatic pressure (the amount by which the fluid pressure of the magma exceeds the lithostatic pressure). Where basic magmas followed preferred pathways of increasing excess pressure, governed by the perturbations in the surfaces of equal excess fluid pressure near to a high-level acid diapir, cone-sheets instead of dykes were produced.

The Ardnamurchan cone-sheets vary considerably in lithology and texture, but chemically all of them appear to belong to a single tholeiitic lineage (Richey and Thomas, 1930; Holland and Brown, 1972). They range from plagioclase- and clinopyroxene-bearing quartz dolerites to felsites; composite examples are also known. Holland and Brown concluded that on the basis of 'mean' chemical analyses, there is no easily distinguishable difference in magma type between Centre 1 and Centre 2 cone-sheet swarms, and no evidence to support or oppose the hypothesis of Durrance (1967). On total alkali–silica plots, the cone-sheets cluster around the Hawaiian alkali-basalt–tholeiite field boundary (MacDonald and Katsura, 1964) and appear to be quite different from the regional Hebridean alkaline trends (Bailey *et al.*, 1924; Tilley and Muir, 1962; Thompson *et al.*, 1972).

The variation in clast size within the tuffisite dyke intruding the Glas Eilean vent must reflect a marked increase in gas velocity towards the centre of the dyke, where the entrained fragments are as much as 100 mm across compared with the 2–4 mm sizes of the marginal fragments.

Conclusions

Magma intruding a series of fractures centred beneath Sanna gave rise to the dense outer cone-sheet swarm associated with Centre 2, and possibly also to the cone-sheets associated with Centre 1. Diapirs of acid magma may have caused uprising basaltic magma to be diverted in the direction of maximum excess hydrostatic pressure to form the cone-sheets. The cone-sheets intruded cold country rocks against which individual intrusions were chilled; thermal metamorphic effects were limited and distinctive mineral assemblages were confined to the compositionally-favourable Jurassic calcareous shales. The Ardnamurchan cone-sheets have tholeiitic affinities and contrast with the regional alkaline basaltic lavas. The Glas Eilean linear vent, which cuts the cone-sheets, is the youngest major body of pyroclastic rocks in Ardnamurchan, the intrusive tuff, or tuffisite, cutting it demonstrates the ability of flowing gases to entrain and transport fragments of considerable size.

GLAS BHEINN–GLEBE HILL

Highlights

Several massive, arcuate, cross-cutting intrusions belonging to Ardnamurchan Centres 1, 2 and 3 intruded and metamorphosed pre-Tertiary country rocks and Tertiary plateau basalts. Centre 2 gabbros contain distinctive sapphire-bearing xenoliths derived by alteration of contemporaneous soil (bole) and weathered basalt; calcareous Jurassic sediments at the margins of the gabbros have been altered to high-temperature calc-silicate hornfelses which contain the rare mineral kilchoanite (type locality). The age relationships between Centre 2 cone-sheets and the major intrusions are well-illustrated here.

Introduction

The original survey of Ardnamurchan by Richey and Thomas (1930) identified three independent but overlapping centres of igneous activity and showed them to consist of volcanic vents, various types of arcuate intrusion and cone-sheet swarms. Within the relatively small area of the Glas Bheinn–Glebe Hill site (*c.* 3 km^2), various intrusions belonging to all three centres are represented, with a clear demonstration of their relative ages. The site also contains exposures of the contact between the intrusions and the country rocks which include Moine schists, Lower Lias sediments, Tertiary lavas and minor intrusions other than cone-sheets, a small remnant mass of

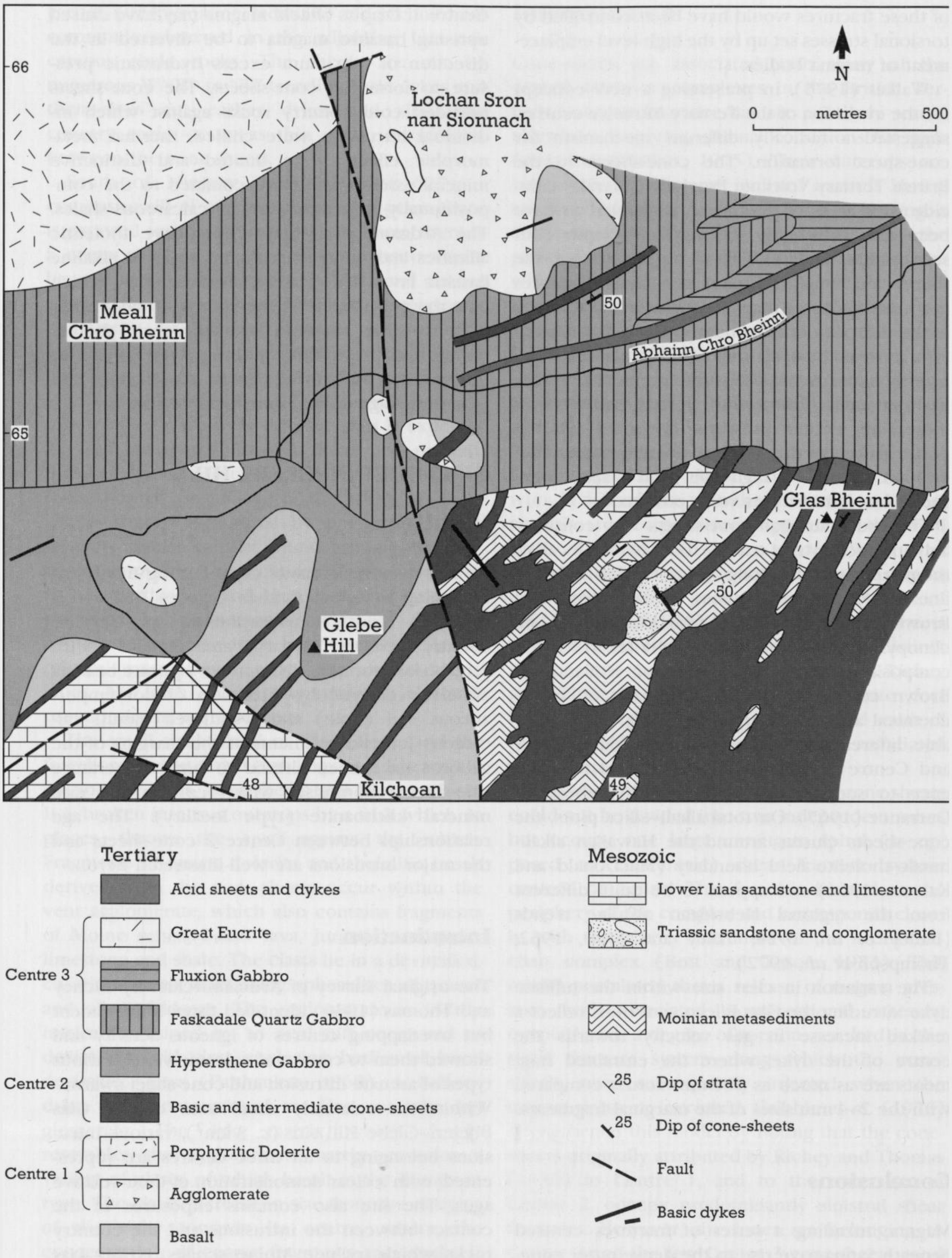


Figure 4.5 Geological map of the Glas Bheinn–Glebe Hill site (after Gribble *et al.*, 1976).

agglomerate and highly metamorphosed xenoliths in the outer gabbros of Centre 2 (Fig. 4.5). Agrell (1965) studied the thermally metamorphosed calcareous Lias sediments and identified a wide range of minerals, including kilchoanite ($Ca_3Si_2O_7$) west of Glas Bheinn.

Description

On Glas Bheinn (NM 493 648), a large, E–W-trending, dyke-like intrusion of plagiophyric dolerite (attributed to Centre 1) is poorly exposed. The intrusion appears to have near-vertical and often chilled, aphyric contacts with Moine psammites and Lias shaly sandstones. It is dissected by a swarm of non-porphyritic and (later) feldspar-phyric cone-sheets belonging to the outer set of Centre 2 and a later porphyritic sheet which is inclined towards the Centre 3 focus (Richey and Thomas, 1930). The main intrusion is a quartz dolerite or gabbro, bearing zoned labradorite phenocrysts in a matrix of acicular labradorite, augite and brown basaltic glass. Schistose xenoliths are commonplace and gabbroic xenoliths, of probable cognate origin, occur about 300 m west of the Glas Bheinn summit (NM 497 647). Near to the summit, the dolerite is intruded by a small mass of felsite or granophyre which, together with the cone-sheets and country rock, is almost entirely recrystallized owing to the thermal effects of the nearby Faskadale Quartz Gabbro of Centre 3.

The Faskadale Quartz Gabbro is poorly exposed within the site on the southern side of the Abhainn Chro Bheinn, and the form and intrusive relationships have been largely inferred rather than observed here. Cone-sheets do not cut this intrusion. Although typically a medium-grained quartz gabbro, the Faskadale intrusion varies from olivine eucrite to a basic granophyre especially towards the roof (Richey and Thomas, 1930; Gribble *et al.*, 1976). The occurrence of internal contacts between coarse- and fine-grained members implies that the mass probably has a composite form.

Glebe Hill (NM 480 647) is formed from baked and partially granulitized amygdaloidal basaltic lavas which are cut by thin, basic cone-sheets, a few minor felsites and the Hypersthene Gabbro. Most of the basalts are aphyric, containing olivine pseudomorphs and the amygdale assemblages have been altered to chlorite and plagioclase. The lavas are probably related to the relatively unaltered mildly alkaline, olivine-basalt lavas around Ben Hiant. At Glebe Hill, the lavas form a roof to the Hypersthene Gabbro intrusion, the contact varying between being virtually horizontal and steeply inclined. The Hypersthene Gabbro is generally a fine-grained, pyroxene-rich rock but, around Glebe Hill, coarse pegmatitic quartz gabbro and allivalitic–troctolitic varieties are prevalent. Xenoliths, which are frequently observed in the gabbro, contain equigranular plagioclase and dark-green hercynitic spinel accompanied by interstitial, colourless and blue corundum (including sapphire) and magnetite with exsolved ilmenite lamellae. These were derived from aluminous sediments, possibly bole horizons in the lavas.

The contact between the Hypersthene Gabbro and the Faskadale Quartz Gabbro trends east–west to the north of Glebe Hill. Partial exposure of this contact occurs in the bed of the Abhainn Chro Bheinn a few metres north of where the stream turns westwards before passing under the Kilchoan–Sanna road. The Hypersthene Gabbro is shattered, deeply weathered and veined by granophyre. The Quartz Gabbro is chilled towards the contact and locally a thin screen of amygdaloidal basalt intervenes. Elsewhere, the position of the contact can be accurately inferred although it is rarely exposed. On following the contact eastwards towards Glas Bheinn, the Hypershene Gabbro, Faskadale Quartz Gabbro and the Glas Bheinn Porphyritic Dolerite, with its numerous cone-sheets, can all be seen in close proximity to one another.

Around Lochan Sron nan Sionnach (NM 484 656), the slopes of Meall an Tarmachain expose a mass of basalt lava and agglomerate roofing the Faskadale Quartz Gabbro and the Great Eucrite. These are cut by sparse cone-sheets inclined towards the focus of Centre 3 and consist mostly of basaltic, felsitic and country rock fragments in a tuffaceous matrix. The lavas and agglomerates are highly thermally metamorphosed and closely resemble a similar rock assemblage which forms part of the Meall nan Con screen (see below). The Centre 3 cone-sheets, which find geomorphological expression as a series of low, often inconspicuous, terrace features in the Quartz Gabbro and the volcanic rocks, dip at about 50° towards the focus of this centre near Glendrain. They are largely plagiophyric basalts and dolerites with rarer non-porphyritic examples. West of Lochan Sron nan Sionnach, the weathering contrast between the Quartz Gabbro and the Great

Eucrite is demonstrated; the actual contact appears to be complex, with narrow intervening zones of fine-grained gabbro occurring at intervals. There is also evidence for the alteration and crushing of the Quartz Gabbro by the emplacement of the Great Eucrite.

Interpretation

The exposures at Glas Bheinn–Glebe Hill provide an excellent opportunity to demonstrate how the evolution of the Ardnamurchan complex has been elucidated using the intricate field relationships of the various intrusions. Within this relatively small site (*c.* 3 km), representative ring-dyke intrusions belonging to all three centres are in close association, enabling the major phases of development of the complex to be studied. The contacts of the porphyritic dolerite on Glas Bheinn with the surrounding intrusions and cross-cutting cone-sheets shows that, relatively, it must be the earliest. This intrusion is assigned to the first centre of plutonic igneous activity on Ardnamurchan and cuts older Centre 1 agglomerates which appear to belong to the extensive Northern Vents (Richey and Thomas, 1930). The dolerite is similar to the porphyritic dolerite of Ben Hiant and an olivine-bearing variety also occurs to the north of Camphouse.

The Faskadale Quartz Gabbro mass extends in a broad arc from Faskadale (NM 501 708) southwards and westwards to Beinn na Seilg and may well continue further west under a roof of Centre 2 rocks to re-emerge south of Sanna Bay as the Ben Bhuidhe intrusion (Gribble *et al.*, 1976). This mass is the outermost ring intrusion of Centre 3; cone-sheets belonging to Centre 2 are absent and it cuts the earlier Hypersthene Gabbro and Glas Bheinn porphyritic dolerite. Likewise, the Great Eucrite is a younger intrusion of Centre 3, as demonstrated by field relationships described above. The Hypersthene Gabbro, discussed in detail for Beinn na Seilg–Beinn nan Ord (see below), is the earliest ring intrusion of Centre 2 cutting the Porphyritic Dolerite of Glas Bheinn and truncating the Faskadale intrusion. High emplacement temperatures for the ring-dyke intrusions are clearly demonstrated by the sanidinite-facies mineral assemblages developed in adjoining country rocks.

Conclusions

The contact relationships between major ring intrusions and the associated cone-sheet swarms within the site, belonging to each of the three centres of Tertiary plutonic activity on Ardnamurchan, can be used to study the evolution of the complex. The early Glas Bheinn Porphyritic Dolerite of Centre 1 is cut by the Hypersthene Gabbro of Centre 2, which is in turn truncated by the Centre 3 Faskadale Quartz Gabbro and Great Eucrite masses. The high-temperature intrusions have given rise to distinctive thermal metamorphic mineral assemblages in altered, weathered basalt lavas and sandy limestones.

BEINN NA SEILG–BEINN NAN ORD

Highlights

The site contains major arcuate gabbroic and doleritic intrusions of Centre 2, including the Hypersthene Gabbro, part of a layered intrusion, which has severely metamorphosed adjoining country rocks. The later, granophyric Quartz Dolerite of Sgurr nam Meann contains superbly exposed evidence for the former coexistence of basic and acid magmas.

Introduction

This extensive site provides a valuable traverse through the arcuate intrusions of Centre 2 of the Ardnamurchan complex. It is of special importance in demonstrating the contact relationships between the complex and the country rocks surrounding it. The arcuate masses include the outer Hypersthene Gabbro which dominates the geology of the site, the granophyric Quartz Dolerite and quartz gabbros and eucrites. The inner set of cone-sheets associated with Centre 2 is also well represented.

The Beinn na Seilg–Beinn nan Ord area was first investigated in detail by Richey and Thomas (1930), following field surveys between 1920 and 1923. There has been no comprehensive account of the area since, but investigations describing the form, field relations and petrology of the Granophyric Quartz Gabbro have been published by Wells (1954a), and the field characteristics of this intrusion have been excellently described by Skelhorn and Elwell (1966). In addition, the structure and petrology of the

Hypersthene Gabbro has been studied by Wells (1954b) who also investigated its xenoliths (Wells, 1951). A recent study by Day (1989) details much new information about the Hypersthene Gabbro and its contact effects.

Description

At Dubh Chreag (NM 452 633), 2 km west of Ormsaigbeg (Fig. 4.6), the outer contact of the Hypersthene Gabbro is exposed against Lower Lias shales and limestones. This is the outermost major intrusion of Centre 2, the contacts of which dips southwards at angles of 45°–60°. Further to the east, around Lochan Ghleann Locha, the Hypersthene Gabbro intrudes Palaeocene basalt lavas overlying Middle Jurassic (Bajocian) sandstones and limestones; these rocks form a narrow strip parallel to the contact (1.5 km long and with a maximum width of 150 m) and are bounded to the south by a fault which downthrows them against Lower Lias. The sediments are intruded by numerous thin cone-sheets belonging to the outer set of Centre 2 inclined to the north at angles of between 35° and 40°. These are beautifully exposed, standing out in stark contrast against the cream-coloured sandstones and pale limestones of the Lias; they were first noted in the coastal cliffs by MacCulloch (1819) and later by Geikie (1897).

The thermal effects of the Hypersthene Gabbro are widespread, but intense thermal metamorphism occurs only within a few hundred metres of the contact. At Dubh Chreag, the Lias shales have been altered to hard, fissile hypersthene–biotite–magnetite–feldspar hornfels with possible cordierite. The impure limestones are now clinopyroxene–sphene–garnet–anorthite–hornblende hornfels, while the purer, Middle Jurassic limestones are now calc-silicate assemblages of recrystallized calcite, garnet, diopside and tremolite. Within the thermal aureole, the lavas and early cone-sheets also show considerable alteration and have become flinty and more massive. Closer to the contact, they are granular clinopyroxene–olivine–plagioclase–magnetite hornfelses often with orthopyroxene. Thoroughly hornfelsed country-rock xenoliths of igneous origin occur at various points along the contact of the gabbro. Day (1989) has demonstrated that extreme thermal metamorphism produced distinctive rheomorphic melts from the varied country-rock lithologies.

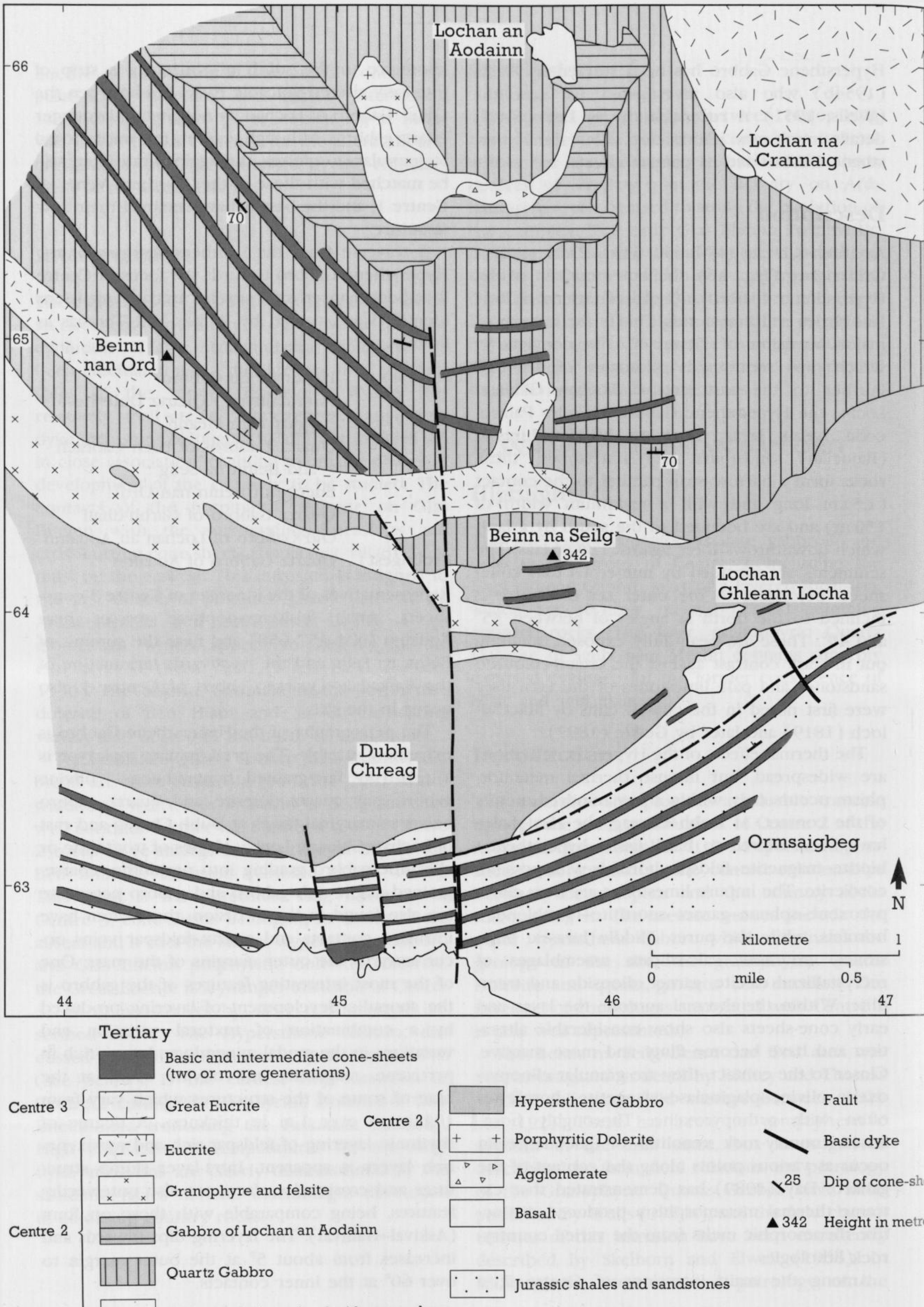
Among the main intrusions of Centre 2, a kilometre to the south of Sonachan, a strip of intensely altered volcanic rocks lies between the Older Gabbro of Lochan an Aodainn and younger quartz gabbros. Although severely metamorphosed to granular hornfelses, the agglomerates can still be matched with those of the 'Northern Vents' of Centre 1, and the basalts have retained their flow structure.

A traverse from the southern margins of the Hypersthene Gabbro towards the focus of Centre 2 at Sonachan crosses several arcuate intrusions identified and named by Richey and Thomas as follows:

(oldest)	Hypersthene Gabbro
	(Granophyric) Quartz Dolerite of Sgurr nam Meann
	Quartz Gabbros of Loch Caorach and Beinn na Seilg
	Eucrite of Beinn nan Ord
	Quartz Gabbro of Garbh-dhail
	Old Gabbro of Lochan an Aodainn
(youngest)	Quartz Gabbro of Aodainn

Representatives of the inner set of Centre 3 cone-sheets, small felsite/granophyre masses near Aodainn (NM 457 658) and near the summit of Beinn na Seilg and the westwards termination of the Faskadale Quartz Gabbro of Centre 3 also occur in the site.

The petrography of the Hypersthene Gabbro is extremely variable. The predominant rock type is a relatively fine-grained hypersthene – olivine gabbro but quartz dolerite and quartz gabbro occur as marginal facies at Dubh Chreag and east of Lochan Ghleann Locha. Masses of troctolitic or allivalitic gabbro grading into peridotite, coarse-grained augite-rich gabbro and gabbro pegmatite are also found in the intrusion; these often have intrusive contacts and quartz–feldspar veins occur towards the outer margins of the mass. One of the most interesting features of the gabbro is the sporadic development of layering produced by a combination of textural variation and variations in the modal mineralogy. Layers rich in pyroxene, magnetite and olivine occur at the base of some of the structures which vary from 10 mm to over 1 m in thickness. A degree of rhythmic layering of feldspar-rich and pyroxene-rich layers is apparent. Intra-layer slump structures and erosional surfaces are also noteworthy features, being comparable with those on Rum (Askival–Hallival). The layering dips inwards and increases from about 5° at the outer margin to over 60° at the inner contacts.



Lochan an Aodainn
Lochan na Crannaig
66
65
64
63
70
Beinn nan Ord
70
Beinn na Seilg
342
Lochan Ghleann Locha
Dubh Chreag
Ormsaigbeg
N
0 kilometre 1
0 mile 0.5
44
45
46
47
Tertiary
Basic and intermediate cone-sheets (two or more generations)
Centre 3
Great Eucrite
Eucrite
Granophyre and felsite
Centre 2
Gabbro of Lochan an Aodainn
Quartz Gabbro
Quartz Dolerite veined with granophyre
Centre 2
Hypersthene Gabbro
Porphyritic Dolerite
Agglomerate
Basalt
Jurassic shales and sandstones
Fault
Basic dyke
25 Dip of cone-sheets
342 Height in metres

The granophyric Quartz Dolerite of Sgurr nan Meann truncates the Hypersthene Gabbro on the north and east. Along most of its inner contact, it adjoins the Quartz Gabbro of Loch Caorach but its southern extremity lies entirely within the Hypersthene Gabbro, and along a short length in the north, its inner contact lies against the Beinn nan Ord Eucrite. The mass is younger than the Hypersthene Gabbro and the contact between the two is complex, with sill-like apophyses penetrating the older rock for distances of up to a kilometre. In contrast, the inner contact is simple and near vertical. The lithology of the Quartz Gabbro intrusion is its most outstanding feature. It comprises an association of feldspar-phyric and aphyric dolerite and gabbro xenoliths, often of great size, which are locally penetrated by an anastomosing plexus of acid net-veining associated with dykes and sheets of felsite/granophyre. A full petrological account of this intrusion has been published by Skelhorn and Elwell (1966); the detailed petrography is therefore not described here. The thicker sheets and dyke-like bodies of granophyre with aphyric dolerite inclusions penetrate the porphyritic dolerite and, in some exposures, the margins of the porphyritic dolerite appear to be chilled and phenocryst free; in others, the phenocrysts are abruptly truncated by the sheets or dykes and the grain size of the dolerite does not decrease towards the contact. Thus, there is conflicting evidence for the relative ages of the two dolerites. However, evidence that the porphyritic dolerite is the earlier is drawn from its inclusion as xenolithic blocks within the aphyric dolerite, with granophyre generally intervening between the two.

The Quartz Gabbros of Loch Coarach (NM 433 656) and Beinn na Seilg were considered by Richey and Thomas (1930) to be parts of a single ring-dyke, although they differ petrologically. The most basic type is an olivine gabbro consisting of olivine, augite, labradorite and accessory ore. On this original assemblage changes have been superimposed, changes caused by 'acid material of late consolidation' (Richey and Thomas, 1930) such as schillerization of feldspars, de-schillerization of pyroxene, development of hypersthene and locally abundant acid mesostasis which has crystallized as alkali feldspar and quartz. To the west and south-west, the Quartz Gabbros are bounded by the Quartz Dolerite (and the Hypersthene Gabbro in the case of the Beinn na Seilg mass). The contact is poorly exposed and is difficult to interpret. These gabbros are not cut by the inner cone-sheets of Centre 2, but they do inject some of the components of the Granophyric Quartz Dolerite which is therefore probably the older intrusion. Along their inner contacts, where the quartz gabbros adjoin the Eucrite of Beinn nan Ord, both rocks are brecciated at exposed junctions. At a few localities sharp contacts show the Quartz Gabbro cutting and chilled against the Eucrite.

Figure 4.6 Geological map of the Beinn na Seilg-Beinn nan Ord site (after Gribble *et al.*, 1976).

The Eucrite of Beinn nan Ord lies to the north and east of the Quartz Gabbros and can be traced from Beinn na Seilg northwards and westwards across Beinn nan Ord to Sanna Bay. It is a moderately coarse-grained rock with abundant olivine, ophitic augite associated with large magnetite crystals and plagioclase (labradorite–bytownite). The olivine is usually associated with biotite and hypersthene where it is unaltered. Variants rich in olivine, pyroxene or plagioclase also occur and acidification and granulitization are widespread. The form of the Eucrite is unusual in possessing two arms projecting inwards to the focus of Centre 2 cutting across the earlier Quartz Gabbro of Garbh-dhail. The rock is resistant to weathering and generally well exposed in conspicuous glaciated crags. Over much of its extent, the rock has been microbrecciated possibly due to explosive shattering by an acid magma (Richey and Thomas, 1930). The outer contact against the Quartz Gabbros of Beinn na Seilg and Loch Caorach has been described above. The inner contact is against an earlier gabbro, the Quartz Gabbro of Garbh-dhail, which is cut by cone-sheets and linear crush lines, both of which are absent in the Eucrite. Both contacts of the Eucrite appear to be steep.

The Quartz Gabbro of Garbh-dhail forms much of the north-eastern part of the Beinn nan Ord and Beinn na Seilg area and, like the other quartz gabbros of Ardnamurchan, displays great variation in composition and texture. More basic and finer-grained varieties prevail in the exterior part of the mass, while the interior is more silicic and internal intrusive contacts suggest a composite nature, an initial injection of basaltic magma being followed by a relatively silicic magma. Flow-banding, dipping at high angles towards the focus of Centre 2, is locally present. The gabbro is chilled against the Hypersthene Gabbro on Beinn na Seilg and against the Old Gabbro of Lochan an Aodainn. Cone-sheets from the inner set of Centre 2 cut this Quartz Gabbro and both are baked against the Eucrite of Beinn nan Ord.

The Old Gabbro of Lochan an Aodainn outcrops in an arc between Lochan an Aodainn and Achosnish and is considered to be a very early intrusive member of Centre 2. It is now very altered but it was originally a variable fine- to coarse-grained olivine-bearing dolerite with olivine-free, olivine-rich, allivalitic and fine-grained augite-rich varieties. The gabbro has a distinctive dull, matt, dark-grey appearance caused by numerous opaque inclusions in the feldspar and alteration of the mafic minerals. Crushing and shattering are widespread, with segregation and migration of acid material locally producing a rock resembling an augite granophyre. The Old Gabbro is in contact with a small mass of basalt lavas and agglomerates along its north-eastern margin, but elsewhere its margins are entirely determined by later intrusions.

North of the Old Gabbro, the Quartz Gabbro of Aodainn crops out and is heterogeneous both in texture and in the proportion of acid mesotasis. It is generally a moderately fine-grained rock bearing both orthopyroxene and clinopyroxene and a little interstitial alkali feldspar and quartz. Coarser areas appear to be xenolithic towards the porphyritic finer-grained rocks. Internal contacts are both sharp and gradational, and other textural variations indicate the possibility of a composite origin for the intrusion. The Aodainn mass clearly veins and intrudes the Old Gabbro, with chilling and some hybridization occurring along this contact. North-east of Lochan an Aodainn, a strip of dark-grey rock containing phenocrysts of plagioclase, augite and olivine intervenes between these masses; this has been interpreted as a remnant of a still older intrusion. The Quartz Gabbro is truncated to the north by the Great Eucrite of Centre 3 which caused the thermal metamorphism noted in the earlier intrusions.

The Quartz Gabbro of Faskadale, the outermost intrusion of Centre 3, enters the eastern margin of the Beinn nan Ord–Beinn na Seilg area and appears to underlie many of the Centre 2 arcuate intrusions indicating a subsurface, south-westerly extension to Centre 3 (see Glas Bheinn above for a description of the Faskadale intrusion).

Small, roughly circular masses of granophyre or felsite, unrelated to the major intrusions, occur in at least two localities with the site. A small mass of dark-grey, non-porphyritic felsite forms a rocky hill south of Aodainn and, on Beinn na Seilg, a shattered outcrop of pink granophyre is found between the Beinn nan Ord and Garbh-dhail quartz gabbros. Dykes do not commonly cut the Centre 2 intrusions but several basic and a few acid examples are known. A thick (1.0–1.5 m) dyke of greenish, flow-banded spherulitic pitchstone outcrops on the shore at Ormsaigbeg and can be traced northwards for about 2 km, cutting the Hypersthene Gabbro, but terminating short of the quartz gabbros.

Interpretation

The sequence of arcuate intrusions and their intricate contact relationships in this area provide a valuable record of the development of Ardnamurchan, Centre 2. The results obtained by Richey and Thomas (1930), from their survey of the area, attracted international attention and rapidly became of outstanding importance as a demonstration of a 'typical' ring-dyke complex. Parts of the area have been reinvestigated by later workers in the light of newly developed concepts in igneous petrology and, while solving some problems, have encountered more. For most of the area, however, no published later work has superseded that of Richey and Thomas and the majority of the problems that they recognized, but perforce had to leave unsolved, have not received the attention that they deserve. The research potential of the area must rank among the highest in Britain and this greatly augments the international value of the area as a 'type locality' for a ring-dyke complex.

Two of the dominant intrusions in the site, the Hypersthene Gabbro and granophyric Quartz Dolerite of Sgurr nam Meann, have been reinvestigated more recently; the conclusions from some of these studies are discussed below.

The Hypersthene Gabbro is the earliest intrusion of Centre 2 and was initially considered to be a ring-dyke by Richey and Thomas (1930). Subsequent work by Wells (1954a) and Skelhorn and Elwell (1971) has shown that, although the contact between the gabbro and the country rocks is mostly outwardly dipping at moderate angles, in places it is demonstrably steep or flat-lying, or complicated by large xenoliths and stoped blocks of the host rock. Wells (1954a) considered the original overall shape to be an upwardly flaring cone with a domed roof, while Skelhorn and Elwell (1971) suggested a more boss-like form. Wells (1954a) concluded that the form of the intrusion, particularly its considerable width, bears little resemblance to a ring-dyke and was probably forcefully intruded. The layered structures in the Hypersthene Gabbro dip inwards and have a conical shape and, according to Wells, gravity accumulation of crystals in the lower part of the intrusion, which had a conical form, played a significant role. The steepening of the layering at the inner contacts of the intrusion was suggested by Skelhorn and Elwell (1971) to have resulted from the deformation of the roughly circular mass by ring faulting or gradual subsidence of a central block. Palaeomagnetic evidence supplied by Wells and McRae (1969) suggests that if this hypothesis is accepted, then the deformation must have occurred before the rocks had cooled below their Curie temperature. Wells (1954a) also suggested that a quartz gabbro marginal facies to this intrusion crystallized from pre-Hypersthene Gabbro magma which was driven towards the upper surface during the forceful intrusion of the Hypersthene Gabbro. The recent study of this intrusion by Day (1989) contains much new factual information and interpretations.

The Quartz Dolerite was recognized by Richey and Thomas (1930) as a ring-dyke, although they were aware of the extensive apophyses projecting from the main mass. Wells (1954b) described the mass as a 'ring-dyke/sill intrusion'. Skelhorn and Elwell (1966) regarded Wells's hypothesis as one possibility but also presented three others: a sill connected to a ring-dyke or plug which is now replaced by a later intrusion; a ring-dyke with stepped contacts, the present erosion surface coinciding with a shallow step; or a marginal remnant of a ring-dyke cap formed above the block which subsided to allow the intrusion of the ring-dyke. Walker (1975) suggested that the mass may have been formed by successive laterally directed injections of magma into a 'curved flange' fracture caused by the differential subsidence of the rocks adjoining the magma chamber. The form of the mass clearly requires further investigation as was pointed out by Black (in discussion, Skelhorn and Elwell, 1971) who noted in addition that the maps produced by the Survey, Wells (1954b) and Skelhorn and Elwell (1966) differ significantly owing to the use of differing criteria to identify the Quartz Dolerite. Earlier, Black (pers. comm.) demonstrated his view that the so-called 'Quartz Dolerite' was in fact an igneous *mélange* of blocks of gabbro (shown on the maps of other workers), intrusions of various types of dolerite, and felsite emplaced along a partial ring-fracture which also served as a channel for gas fluxing.

The granophyric Quartz Dolerite of Sgurr nam Meann demonstrates clearly the association of acid and basic magmas in the intrusions of Centre 2 and in the Ardnamurchan complex as a whole (Blake *et al.*, 1965). Vogel (1982) has published a detailed petrological study of the acid–basic net-veined intrusion. It was observed that the basic aphyric and porphyritic components occur as pillow-like xenoliths, with cuspate and crenulate margins within the silicic rock and with chilling at many contacts indicative of 'liquid–liquid' relationships. Whole-rock chemistry indicates that magma mixing between basaltic and silicic liquids was a dominant process along with limited crystal fractionation. Vogel (1982) suggested that this net-veined complex presents a rare example of the interaction at a high level between mafic and silicic melts in the Ardnamurchan magma chamber before the silicic magma was lost to surface volcanism. It is a clear example showing that basic and acid magmas coexisted in a single intrusive body.

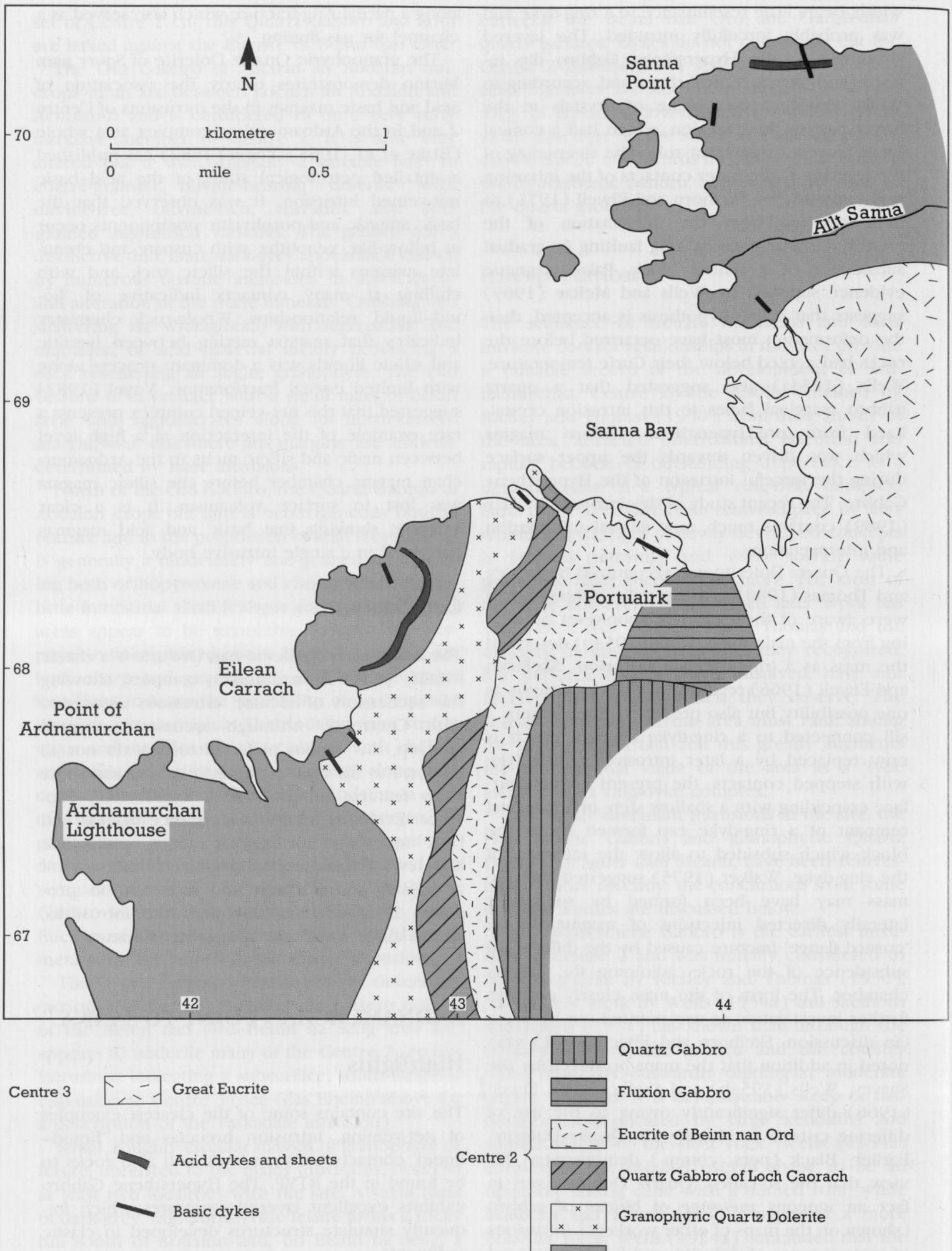
Conclusions

The Beinn na Seilg–Beinn nan Ord site is a classic locality in the Ardnamurchan complex, showing the succession of arcuate intrusions associated with Centre 2. Although arcuate in overall outcrop, the various major intrusions do not all conform to the classic ring-dyke model and some show features unique within the Tertiary Province. Evidence for the coexistence of acid and basic melts and for magma mixing within the high-level Ardnamurchan magma chamber as well as crystal accumulation and fractionation processes is afforded by many of the intrusions, almost all of which are composite in nature.

ARDNAMURCHAN POINT TO SANNA

Highlights

The site contains some of the clearest examples of net-veining, intrusion breccias and 'liquid–liquid' contacts between basic and acid rocks to be found in the BTVP. The Hypersthene Gabbro exhibits excellent layered structures which frequently simulate structures developed in clastic sediments.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Sanna Point
Allt Sanna
Sanna Bay
Portuairk
Eilean Carrach
Point of Ardnamurchan
Ardnamurchan Lighthouse
Centre 3
Great Eucrite
Acid dykes and sheets
Basic dykes
Centre 2
Quartz Gabbro
Fluxion Gabbro
Eucrite of Beinn nan Ord
Quartz Gabbro of Loch Caorach
Granophyric Quartz Dolerite
Hypersthene Gabbro

Introduction

The coastal strip from the Point of Ardnamurchan to Sanna Point, including Sgurr nam Meann, provides an excellent traverse across several of the intrusions of Centre 2 and demonstrates their truncation by the Great Eucrite of Centre 3. Many features of petrological interest are easily accessible; these include net-veining, igneous brecciation, igneous layering and the occurrence of pyroxene granulites.

The area has been thoroughly investigated and described by Richey and Thomas (1930); the granophyric Quartz Dolerite of Sgurr nam Meann in particular has received considerable mention by these authors and by Wells (1954b), and was selected for special study in this area by Skelhorn and Elwell (1966).

Description

A traverse from Ardnamurchan Point to Sanna crosses the following intrusions (Fig. 4.7):

1. Hypersthene Gabbro of Ardnamurchan Point
2. Granophyric Quartz Dolerite of Sgùrr nam Meann
3. Quartz Gabbro of Loch Carrach
4. Eucrite of Beinn nan Ord
5. Fluxion Gabbro of Portuairk
6. Great Eucrite of Centre 3

The full sequence is seen between Ardnamurchan Point and the southernmost shores of Sanna Bay where the Great Eucrite is reached. Beyond the outcrop of the latter intrusion, from Sanna to Sanna Point, the Hypersthene Gabbro and granophyric Quartz Dolerite of Sgurr nam Meann (Butchins, 1973) are again exposed, but the Quartz Gabbro of Loch Carrach and Eucrite of Beinn nan Ord are absent, having been truncated by the Great Eucrite. The salient petrographic features and contact relations of all these intrusions, except for the Fluxion Gabbro, are given in the descriptions for Beinn na Seilg–Beinn nan Ord or the Centre 3 areas and are not repeated in this account, where attention is drawn to features not found elsewhere or better displayed in this area.

Figure 4.7 Geological map of the Ardnamurchan Point–Sanna site (after Gribble *et al.*, 1976).

The Hypersthene Gabbro to the west of the lighthouse has a quartz doleritic outer marginal facies and passes eastwards into a coarser, rather silicic quartz gabbro facies. The intrusion is cut by cone-sheets belonging to the outer set of Centre 2 (Richey and Thomas, 1930). On Eilean Carrach, the layering in the gabbro dips to the east at 30° and extensive tabular masses of pyroxene granulite occur parallel to the layers.

The area between the lighthouse pier (NM 423 675) and Eilean Carrach contains superb exposures of the granophyric Quartz Dolerite of Sgùrr nam Meann. In this area, porphyritic dolerite roofs a complex intrusion of aphyric dolerite and granophyre. From place to place, the granophyre varies from being volumetrically dominant to subordinate; small-scale anastomosing veins which cut both dolerites can be traced to sheet-like acid masses which contain a varied assemblage of basic rock types as inclusions (Fig. 4.8). The inclusions frequently exhibit fine-grained, crenulated, chilled edges against the enclosing granophyre. Further to the north, the Quartz Dolerite contains several large, raft-like masses of Hypersthene Gabbro and steeply dipping contacts between the Dolerite and Hypersthene Gabbro are exposed south of Eilean Carrach. Eastwards, the granophyric Quartz Dolerite of Sgurr nam Meann is bordered by a narrow outcrop of the Quartz Gabbro of Loch Caorach, which in turn adjoins an augite-rich variety of the Eucrite of Beinn nan Ord containing felsic veins bearing fine-grained basic xenoliths. The contact relationships of these intrusions have not been convincingly demonstrated.

To the east of the Eucrite of Beinn nan Ord there occurs a mass of laminated gabbro known as the Fluxion Gabbro of Portuairk (Richey and Thomas, 1930). The intrusion is not homogeneous and its variable features were attributed by Richey and Thomas to the modification of basic magma by silicic melt prior to intrusion, probably when the basic rock was in a solid or semi-solid state. It is characterized by feldspar lamination or fluxion texture, which serves to distinguish it from the Beinn nan Ord Eucrite; no clear contacts between these two have been reported. The Fluxion Gabbro is cut by the later Great Eucrite of Centre 3, but again the contact is not readily interpretable because of the lack of contact alteration and the presence of a flow-banding structure in the outer zones of the Great Eucrite.

The Great Eucrite forms the shores of Sanna

Figure 4.8 Granitic net-veining and an intrusion breccia of gabbro and dolerite fragments. Centre 2 ring-dykes, near the lighthouse, western tip of Ardnamurchan. (Photo: C.H. Emeleus.)

Bay, from Portuairk to the north of the Sanna River, and is seen in intrusive contact against the Hypersthene Gabbro to the north. At Sanna Point perfect mineralogical layering dipping to the south at angles of between 10° and 20° towards the Aodainn centre is present in the Hypersthene Gabbro. Occasional anorthosite, peridotite and iron-oxide-rich bands are found and igneous lamination, especially of plagioclase, is locally marked. Rhythmic banding and density stratification are also present in places. From the north of the Sanna River around Sanna Point and for 2.5 km to the east, sill-like bodies of granophyre containing inclusions of aphyric and porphyritic dolerite cut the Hypersthene Gabbro. Butchins (1973) considered those near Sanna Point to be apophyses from the granophyric Quartz Dolerite of Sgurr nam Meann.

Interpretation

Although the features seen in the section from Ardnamurchan Point to Sanna duplicate to some extent those seen in parts of Beinn na Seilg–Beinn nan Ord, many are much better displayed. Exposures of the granophyric Quartz Dolerite of Sgurr nam Meann (Centre 2) provide clear evidence as to its form and contact relationships with the Great Eucrite (Centre 3) and the excellent shore exposures south-east of Eilean Carrach clearly demonstrate the 'mixed magma' character of the granophyric Quartz Dolerite (Skelhorn and Elwell, 1966; Vogel, 1982). This is arguably the best exposure of net-veining, intrusion breccias and chilling of basic magma against acid magma to be found in the BTVP. On Eilean Carrach and elsewhere in the Hypersthene Gabbro, mafic pyroxene-granulite xenoliths are comparable with inclusions found in the mafic plutonic rocks of Skye, Rum and at other localities. Previously considered to be of sedimentary origin (Wells, 1951), an igneous origin for the xenoliths was suggested by Brown (1954) in accordance with the interpretations of similar rocks elsewhere (for example, Rum, Askival–Hallival). As a consequence of the very varied, well exposed geology, this section is of great significance within the Ardnamurchan complex and is used extensively for educational purposes (for example, see Gribble *et al.*, 1976), despite the fact that some of the contact relationships remain poorly understood.

The excellent examples of layering found east of Sanna Bay contain many structures which simulate those developed in clastic sediments. Although extensive reappraisal of the origins of igneous layering have taken place recently (for example, Parsons, 1987), the layering in the Hypersthene Gabbro provides evidence which supports the contention that the structure results from gravity-controlled accumulation of crystals, probably aided by convection currents (Skelhorn and Elwell, 1966; in agreement with Wells, 1954a) and that the gabbro may form part of a large layered intrusion.

Conclusions

The outstanding feature of the Ardnamurchan Point to Sanna section is the exceptionally fine exposure of net-veining and intrusion breccia near Eilean Carrach (Fig. 4.8); this shows clearly that basic and acid magmas coexisted, that basic magma was chilled against acid magma and that both magmas mixed to give a variety of intermediate (hybrid) rocks. This type of relationship is common throughout the BTVP, but the examples exposed here are certainly the most accessible and arguably the best exposed in the Province. The igneous layering in the Hypersthene Gabbro is closely comparable with layering found in gabbros and ultrabasic rocks in Skye and Rum, and lends support to the suggestion that this gabbro is part of a layered intrusion. The manner in which the Hypersthene Gabbro structures are truncated by the Great Eucrite provides evidence for the relatively late emplacement of Centre 3.

CENTRE 3, ARDNAMURCHAN

Highlights

The Great Eucrite in this site forms one of the most perfect annular intrusions in the British Tertiary Volcanic Province; it gives rise to a nearly complete ring of hills which dominates the Ardnamurchan Peninsula. The intrusive sequence in Centre 3 changed with time, from early eucrites and gabbros to late intrusions of intermediate and acid compositions.

Introduction

This site encompasses Centre 3 which represents the final stage in the intrusive evolution of the Ardnamurchan complex. Centre 3 consists debatably of seventeen concentric intrusions of highly variable petrography, ranging from coarse gabbros and dolerites to minor, late, intermediate tonalites and quartz monzonites. The Centre has been conventionally regarded as an almost perfect set of nested ring-dykes and is of international repute as such. The form of the masses is excellently reflected by the topography of the area. However, their contact relationships where exposed are often obscure. The contacts of the Centre 3 intrusions with the earlier rocks of the complex are also demonstrated.

Centre 3 was first recognized and described by Richey and Thomas (1930), who interpreted its intrusions as ring-dykes. More recent work by Smith (1957), Bradshaw (1961), Wills (1970) and Walsh (1971, 1975 and in Gribble *et al.*, 1976) has challenged this interpretation, and new models of the form of the centre and its constituent intrusions have been proposed. The geochemistry and petrogenesis of the intrusions and their relationships has been investigated by Walsh (1975) and Walsh and Henderson (1977).

Description

The rocks assigned to Centre 3 (Fig. 4.9) of the Ardnamurchan complex crop out in a natural amphitheatre spanning 7 km from east to west and 6 km from north to south, the topography accurately reflecting the concentric outcrops of the various intrusions. Richey and Thomas (1930) recognized seventeen intrusions as ring-dykes which generally become progressively younger towards the middle of Centre 3. The following sequence of intrusions was proposed:

(oldest)

A	Quartz Gabbro of Faskadale
B	Fluxion Gabbro of Faskadale
C	Gabbro of Plocaig (outside site)
C1	Gabbro, south-east of Rudha Groulin (outside site)
D	Porphyritic Gabbro of the Meall nan Con screen
E	Great Eucrite
E1	Outer Eucrite

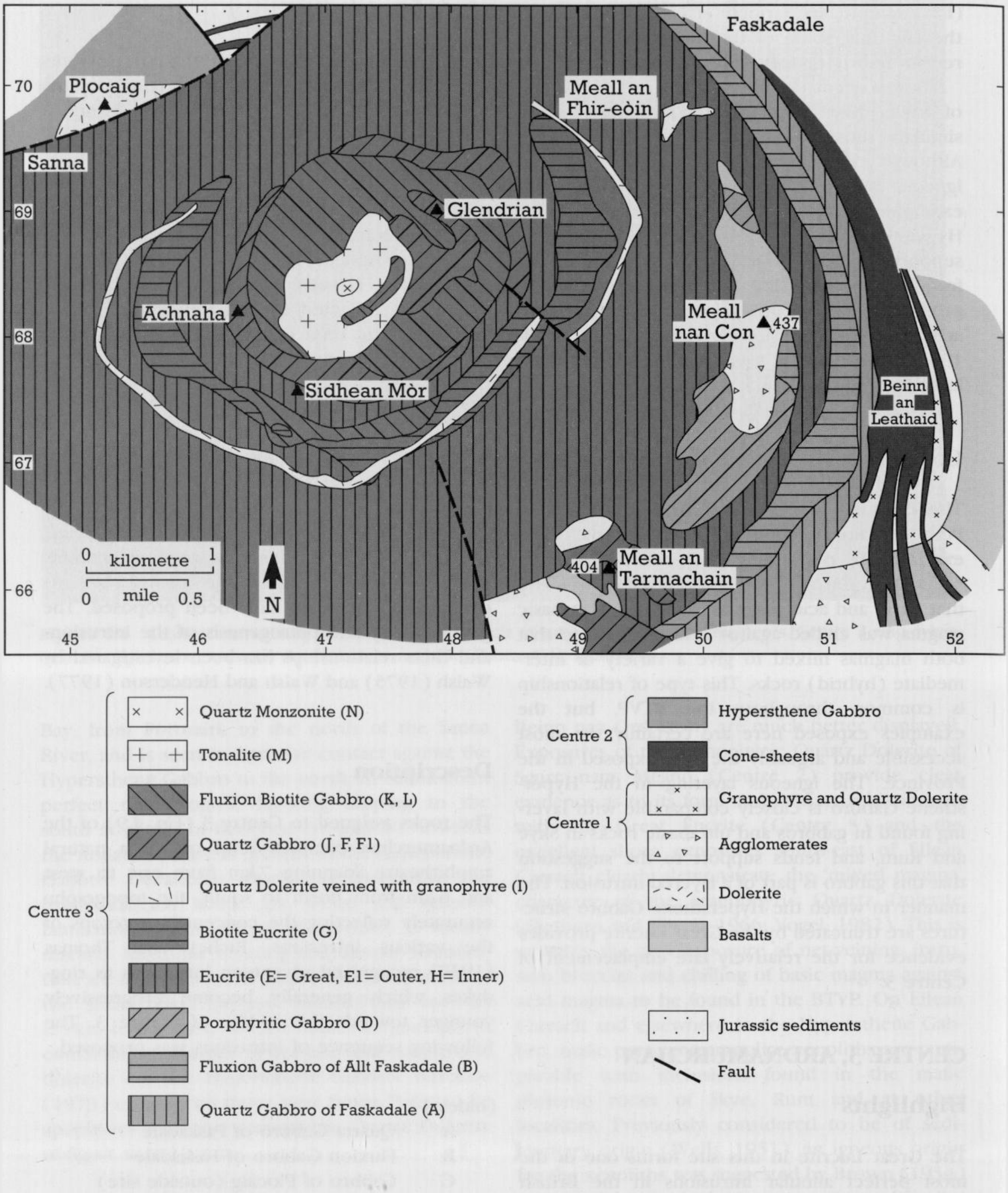

Figure 4.9 Geological map of Centre 3, Ardnamurchan (after Gribble *et al.*, 1976).

Figure 4.10 The natural amphitheatre of Centre 3, Ardnamurchan. The imposing arcuate ridges in the distance are formed by the Great Eucrite. (Photo: A.P. McKirdy.)

F Quartz Gabbro of Meall an Tarmachain summit
F1 Quartz Gabbro, south side of Meall an Tarmachain
G Biotite Eucrite
H Inner Eucrite
I Quartz Dolerite veined with granophyre
J Quartz Biotite Gabbro
K Fluxion Biotite Gabbro of Sithean Mor
L Fluxion Biotite Gabbro of Glendrian
M Tonalite
N Quartz Monzonite
(youngest)

The majority of the rocks are coarse-grained gabbros and dolerites and intermediate rocks comprise only a small fraction of the centre. Few contacts between the individual intrusions are visible and their recognition is based upon minor differences in mineralogy or the presence or absence of structural features rather than clear intrusive relationships.

The intrusions of Centre 3, demonstrated by this site, are described below from the outermost inwards; this order corresponds approximately with the age sequence proposed by Richey and Thomas (1930).

The Quartz Gabbro of Faskadale (A) is the outermost and oldest ring intrusion of Centre 3 and has been described in detail above in Beinn na Seilg–Beinn nan Ord. This mass extends in an unbroken arc from Faskadale Bay, between Beinn an Leathaid and southwards through Meall nan Con and Glas Bheinn to pass beneath the intrusions of Centre 2 on the northern and eastern slopes of Beinn na Seilg. The petrography of the intrusion is very variable and ranges from olivine eucrite to basic granophyre.

On Glas Bheinn (NM 493 648), the truncation of the outer cone-sheets of Centre 2 and Centre 1 country rock by the Faskadale intrusion is very marked, although the actual contact is not visible. Along its contact with the Hypersthene Gabbro of Centre 2 exposures are discontinuous and the relationships of the two rocks are obscured by intervening screens of amygdaloidal basalt and possibly by shattering (Richey and Thomas, 1930). To the south-west of Meall an Tarmachain (NM 493 663), highly metamorphosed remnants of an original volcanic cover form a roof to the Quartz Gabbro, the contact dipping gently to the south-west. On its inner margin, the Quartz Gabbro of Faskadale is in contact with at least three later intrusions of Centre 3 – the Fluxion Gabbro of Faskadale, the Quartz Gabbro of Meall an Tarmachain and the Great Eucrite.

The arcuate Fluxion Gabbro of Faskadale (B) extends from Faskadale along the Allt Faskadale to the south-eastern slopes of Meall an Tarmachain. Its outer margin abuts the Quartz Gabbro of Faskadale and petrographically there is little other than the texture to distinguish the two rocks; at the single exposure of their contact described in the Memoir, the supposedly older Quartz Gabbro shows no thermal metamorphism. The petrological features of the Fluxion Gabbro have been described above.

At Plocaig (NM 453 698), beyond the north-eastern limit of the site near Sanna Bay, a small and apparently lenticular mass of moderately coarse-grained, occasionally feldspar-phyric olivine gabbro (C) lies between the north-western margin of the Great Eucrite and the Hypersthene Gabbro (Centre 2). This intrusion contains xenoliths of granular, hypersthene-bearing hornfels and of the Hypersthene Gabbro. The contacts are obscure but this gabbro is believed to be intermediate in age between these two major intrusions.

The Meall nan Con ridge and summit are formed of highly metamorphosed agglomerates intruded by a small mass of gabbro (D). The gabbro extends in two short, arm-like projections on either flank of the agglomerate. Thermal alteration of the gabbro 'arms' led Richey and Thomas (1930) to conclude that the gabbro is older than the adjoining eucrites; Bradshaw (1961), however, argues that the gabbro might well be part of the Great Eucrite, a view reinforced by the work of Walsh (1971).

The Great Eucrite (E), which here includes the Outer Eucrite (E1), Biotite Eucrite (G) and Inner Eucrite (H) of Richey and Thomas (1930), is the most spectacular unit of the Ardnamurchan complex. It forms an almost continuous, bold, glacially sculptured annular ridge in marked topographic contrast with the subdued landforms developed from the intrusions it encircles. The eucrite is thus the only example in Ardnamurchan of a complete ring-intrusion and, at the present level of erosion, makes up over half of the outcrop of Centre 3. The rock is typically coarse and feldspathic, but like many of the Ardnamurchan intrusions, varies greatly in detail; the proportions of feldspar, augite and olivine vary, often abruptly. Flow-banding is restricted to the inner parts of the intrusion and the outermost zones are rich in tangential, near-vertical, augite-rich pegmatite veins. The Great Eucrite is presumed to be younger than the Faskadale Quartz Gabbro, and Fluxion Gabbro, although the evidence for this is inconclusive because of the poor exposure in the critical areas. According to Richey and Thomas, the Biotite Eucrite lies between the Great and Inner Eucrites, distinguished by the widespread, but by no means ubiquitous, occurrence of biotite. However, Bradshaw (1961) has shown that biotite occurs in all the Ardnamurchan eucrites and there appears to be little convincing evidence to show that the three eucrites are separate intrusions.

The Quartz Gabbro forming the summit at Meall of an Tarmachain (F) is a small intrusion which contains localized olivine-rich and eucritic segregations. The clinopyroxenes in this gabbro are markedly different from all other gabbros, within the complex, being enriched in iron and deficient in calcium (Walsh, 1975), thus supporting its status as an independent intrusion. It is disputably younger than the adjoining eucrite and the Quartz and Fluxion Gabbros of Faskadale. A second mass of quartz gabbro outcrops to the south of the summit (F1); both intrude agglomerates and basalts.

A narrow arcuate intrusion of dolerite veined by granophyre (I) crops out intermittently in small isolated knolls in the low-lying area within the Great Eucrite outcrop. It extends in an extremely narrow, discontinuous horseshoe from Meall an Fhir-eoin (NM 486 698) south, west and northwards to terminate close to the Allt Sanna. It was the first intrusion to be mapped as a ring-dyke on Ardnamurchan by the Survey. The attitude of the contacts with the older Great Eucrite can be closely estimated to dip outwards at about 70°. The dolerite is remarkably homogeneous compared with the coarser gabbros and eucrites, and it contains a relatively higher proportion of biotite and more sodic plagioclase. Localized hornblende and biotite indicate that the mass may be partly a hybrid in origin.

Three masses of quartz-biotite gabbro (J) around Glendrian (NM 479 690), Achnaha (NM 463 682) and Druim Liath (NM 475 683) were presumed by Richey and Thomas (1930) to be parts of a single intrusion which once occupied the central parts of the complex, but was disrupted by later intrusions. Exposure is generally poor here and the contact relationships with the adjoining eucrite are difficult to establish. The gabbros are petrographically heterogeneous and show considerable variations in grain size, from dolerites to pegmatites and in modal mineralogy.

Two intrusions of fluxion gabbro have been mapped within Centre 3; these are known as the Glendrian (L) and Sithean Mor (K) Gabbros respectively. The Glendrian intrusion is a titaniferous, magnetite-rich, basic rock, and it has an almost complete ring-shaped outcrop about Centre 3 and forms a resistant, prominent ridge above the inner, younger intrusions. It is closely associated with a quartz–biotite gabbro which it almost certainly post-dates, xenoliths of the quartz–biotite gabbro being reported, but chilling being absent at the exposed contact. The fluxion texture is produced by the lamination of labradorite crystals dipping inwards towards Centre 3 at 30°-40°. Hybridization by an acid magma before emplacement has been suggested (Richey and Thomas, 1930), this resulting in the local concentration of apatite and abundant interstitial feldspar growths of quartz and alkali feldspar. The Fluxion Gabbro of Sithean Mor (K) crops out as a small, crescent-shaped body which forms a prominent steep-sided ridge surrounded by eucrites. Although termed a fluxion gabbro (Richey and Thomas, 1930), only the northern parts show any alignment of feldspars and the rock grades southwards into a uniform quartz gabbro. The rock appears to be younger than the adjoining Inner Eucrite against which it is chilled and it also bears a few xenoliths of the eucrite.

The Tonalite (M) occupies low-lying, poorly exposed ground in the middle of Centre 3 and its outcrop forms one of the most extensive areas of intrusive intermediate rocks within the BTVP. The mass is roughly ovoid, being elongated north-east to south-west, and has a distinctive appearance with large platy biotites in a leucocratic feldspathic groundmass. The margins of the intrusion against the Fluxion and Quartz gabbros are finer grained, more acidic and leucocratic and have been interpreted as the products of chilling, thus establishing that the Tonalite is the younger. Exposures of the contacts are rare and their form confusing; some dip steeply outwards and others dip steeply inwards. A substantial mass of quartz- and biotite-bearing gabbro lies within the eastern part of the Tonalite.

The later Quartz Monzonite (N) forms a small, poorly exposed oval mass within the Tonalite outcrop and can be distinguished in the field by the presence of more abundant, larger, deep-brown biotite crystals in a finer-grained, feldspathic groundmass. At its contacts with the enveloping Tonalite, the Quartz Monzonite is finer-grained and the contacts appear to dip inwards at 65°. Both rocks contain the disequilibrium assemblage of plagioclase, alkali feldspar, quartz, augite, hornblende, biotite, magnetite, ilmenite, apatite and chlorite and have generally been interpreted as hybrids or the results of crustal contamination and assimilation.

The Centre 3 complex is dissected by many crush lines and minor faults generally trending NS or NNW–SSE, as is clearly shown on aerial photographs (for example, see Stewart, 1965 and cover photograph of Gribble *et al.*, 1976). A set of radial joints and crush lines marked by erosion hollows is also prominent. From Meall nan Con to Beinn an Leathaid the intrusions of Centre 3 truncate those assigned to Centre 1. The earlier intrusions (mainly quartz dolerites and granophyres) cut earlier volcanic rocks and are themselves intruded by dense swarms of cone-sheets. The composite sheet-like body of Beinn an Leathaid belongs to Centre 1. In this intrusion, dolerite at the base is succeeded by a granophyre carrying xenoliths of Moine schist and gneiss; a thin transition zone between the dolerite and granophyre occurs east of the summit. Farther to the east, agglomerates of the Northern Vents are exposed. A few NNW-trending dolerite dykes cut the Centre 3 ring-dykes, for example to the east of Achnaha.

Interpretation

Centre 3, Ardnamurchan was first recognized by Richey and Thomas (1930) who, despite an almost total absence of evidence relating to the contacts between intrusions, interpreted it as a series of nested ring-dykes. In more recent years, Richey's axiom that the contacts dip steeply outwards has been challenged and it has been postulated that the contacts dip gently inwards to produce a saucer- or funnel-shaped intrusion (Smith, 1957; Bradshaw, 1961; Wills, 1970; Walsh, 1971, 1975). Therefore, Centre 3 is important both because of its long acceptance as an almost perfect example of a nested ring-dyke complex and because of the doubts raised by subsequent research as to whether it is a ring-dyke complex at all. The problem at present has not been resolved although geophysical investigations (Bott and Tuson, 1973; Binns *et al.*, 1974) have revealed that the maximum positive gravity anomaly for the Ardnamurchan complex is less than half of that found over the Skye, Rum and Mull complexes, indicating that the Ardnamurchan complex occupies a much smaller volume than the others. Moreover, the gravity maximum is located over Centre 2 and not Centre 3. Although these facts are admittedly inconclusive, they can hardly be said to support the hypothesis that Centre 3 consists of a nested complex of ring-dykes some 3 km in radius, each ring-dyke having been formed by the subsidence of a central block of pre-existing, relatively dense igneous rock.

More recent workers on Ardnamurchan have tended to reduce the number of components in the complex by combining two or more of Richey and Thomas's intrusions into single entities. Thus, Smith (1957) and Bradshaw (1961) suggested that the Great Eucrite (E), the Biotite Eucrite (G) and the Inner Eucrite (H) form a single intrusion and Walsh (*in* Gribble *et al.*, 1976) suggested that the fluxion gabbros B and L are not independent intrusions but parts of the adjacent quartz gabbros (A and J). Stewart (1965) listed the ring-dykes but omitted the gabbro south-east of Rudha Groulin (C1) which was described as a sheet, and combined F and F1 into a single intrusion. The Outer Eucrite (E1) is petrographically identical to the Great Eucrite (E) and, although described as a separate mass on the basis of unsatisfactory evidence (Richey and Thomas, 1930), was not shown as an independent entity on the map which accompanied the Memoir. It is listed by Stewart (1965), but has been tacitly combined with the Great Eucrite in the most recent literature and maps of Walsh (1975) and Gribble *et al.* (1976). If this body of work is accepted *in toto*, the number of discrete intrusions (apart from cone-sheets and dykes) forming Centre 3 is reduced from seventeen to ten.

Richey and Thomas (1930) regarded all the Centre 3 intrusions as having derived from a single magmatic parent. More recently, however, Walsh (1975) has shown that this may be true only of the eucrites, gabbros and dolerites. The pyroxenes in the Tonalite (M) and Quartz Monzonite (N) fail to show the significant iron-enrichment to be expected if they had formed from the same magma as the basic intrusions. On these grounds, Walsh (1975) considered the intermediate rocks to be hybrids of basic magma contaminated by assimilation and partial anatexis of country rock and previously emplaced intrusions, a view also supported by Walsh and Henderson (1977) on the basis of rare-earth-element geochemistry.

It is clear that although Centre 3 has long been regarded as containing some of the most perfect examples of ring-dykes in the BTVP, the status of these intrusions is now far from clear and the centre really demands a concerted and co-ordinated field and laboratory investigation to resolve the outstanding problems of the form of its constituents and their spatial and chemical relationships to one another.

Conclusions

Centre 3 has long been accepted as being a classic example of a ring-dyke complex. New evidence, however, contradicts this interpretation and the Centre is probably a saucer- or funnel-shaped intrusion. The controversy surrounding this Centre gives the site special significance. Many of the originally mapped intrusions have been argued to be part of the same intrusion and it is now suggested that the intrusions number no more than ten. The basic intrusions are probably genetically related to the same parent magma, but the intermediate rocks appear to be the result of contamination of a basic magma with crustal rocks.