Introduction to the geology of the Ardnamurchan Peninsula

The Ardnamurchan peninsula mainly consists of Tertiary igneous rocks intruded into Moine Schists and thin overlying Mesozoic sediments.

The igneous rocks here constitute a centre of Tertiary igneous activity, one of several such centres found on the western coast of Scotland, the others occurring in Skye, Rhum, Mull and Arran. These Tertiary igneous rocks (including Rockall, the Small Isles, Morvern, St Kilda and Ailsa Craig) form part of the North Atlantic or Thulean province which extends to N. Ireland, the Faroes, Iceland and Greenland. Recently, another such centre has been described in the Blackstones Bank off west Scotland (McQuillin et al. 1975), termed the Blackstones complex (Figure 1).

Four main events are recognised in the development of most of the igneous complexes in the British Tertiary province. These are:

1. Eruption of basic lavas which are mainly alkali-olivine basalts. The thickness of these varies throughout the Scottish Tertiary Province, from 1500 m in Mull to 600 m in Skye, and approximately 100 m in Ardnamurchan, where some of the flows may have been removed by erosion.
2. Establishment of central vents giving rise to vent agglomerates and tuffs, with associated small flows of rhyolites, pitchstones and porphyritic basalt.
3. Emplacement of plutonic and hypabyssal rocks occurred at central complexes. The intrusive rocks are arcuate or annular in form and arranged concentrically round one or several centres (within a single igneous complex). Richey and others delineated three main centres of igneous activity in Ardnamurchan in their classic Memoir of 1930. The concentric intrusions consist of thick ring dykes, up to 2 km thick. In Ardnamurchan most of these are composed of gabbro or dolerite, but range from eucrite types to monzonite and granophyre, with occasional composite (acid/basic) rock types. Most ring complexes are not circular in plan but more often oval in shape such as Centre 3 of Ardnamurchan which is roughly oval with a north-east to south-west long axis. The ring dykes are accompanied by cone-sheets, which are also arranged concentrically round the same centres of igneous activity. The cone-sheets are thin (less than 3 m thick) usually basic but can be composite with later acid granophyric or felsitic material intruded into the earlier basic magma. Cone-sheets are inclined inwards and downwards towards a common focus, at variable angles depending on their distance from this focus. In Ardnamurchan, Centre 2 possesses two sets of cone-sheets; an inner, steeply dipping set and an outer set, which dips at much shallower angles. If both sets are projected downwards with their observed angles of inclination, a depth for the focus of about 5 km is deduced; and other Hebridean suites of cone-sheets give similar results. These data fit quite well with modern estimates of subsurface geology (see section 4 below).
4. Intrusions of swarms of dykes (accompanied by sills) are taken as forming the final phase. This is an over-simplification for, although many dykes were intruded late in the sequences of events, the evidence from Mull and Skye suggests that igneous activity also began with dyke intrusion feeding the early plateau basalt lava flows and that dyke emplacement occurred at a number of stages throughout the development of these complexes.

Unlike the dykes associated with Skye, Mull and Arran, those of Ardnamurchan show no radial component in their distribution. This may imply that the Ardnamurchan centres are the surface expressions of a much smaller plutonic body than, for instance, Mull, which acted as a focus for dyke intrusion throughout its active history. The relative smallness of the body underlying the Ardnamurchan centres is confirmed by interpretation of the gravity anomalies over the Hebridean igneous complexes (Bott and Tuson 1973). These studies imply that Ardnamurchan is underlain by a vertical cylindrical body of gabbroic composition with a diameter of 12 km, extending to a depth of 4.5 km, compared with the Skye centre which has a diameter of 20 km and a depth extent of 16 km.

In Ardnamurchan, the igneous complexes consist of volcanic vents, ring intrusions and cone-sheets, which are concentrically arranged around three separate centres of intrusion.

Igneous activity began with the extrusion of basalt lavas and continued with the formation of small explosion vents which pierce both the basalts and the earlier country rocks (Moine schists and Mesozoic sediments). The vents are frequently infilled with agglomerates containing fragments of rocks which include some acid extrusive types, the original outcrops of which are no longer in existence. Associated with these early vents are small areas of extrusive and intrusive igneous activity, represented by pitchstone lavas and various porphyritic basic rocks. From the arrangement of these rocks and the large numbers of associated cone-sheets, an early centre of intrusion (or centre of igneous activity) called Centre 1 is recognised, which is situated in the eastern peninsula area (Figure 2).

Another centre of intrusion (Centre 2) is similarly recognised, on the outcrop pattern of several ring dykes and two sets of cone-sheets, in the western peninsula area (Figure 2).

Like Centre 1, most of Centre 2 has been replaced by igneous rock masses related to the youngest centre (Centre 3), located almost midway between the two earlier centres.

Centre 3 consists almost entirely of ring dykes with very rare cone-sheets. It contains neither volcanic vents nor extrusive rocks.

According to Richey et al. (1961), the time sequence of events is as follows, beginning with the earliest events:

Centre 1 Volcanic vents mainly filled with agglomerates and traversed by cone-sheets and major intrusions often ambiguous in form.

Centre 2 Abundant outer cone-sheets surrounding later ring dykes essentially basic in composition. These ring dykes are divided into two age groups, respectively earlier and later than an inner set of cone-sheets. A volcanic vent associated with this centre (Glas Eilean) is later than the outer cone-sheets.

Centre 3 A suite of basic and ultrabasic ring dykes surrounds innermost acid igneous types (tonalite and quartz-monzonite). The outermost (and earliest) ring dyke is cut by some cone-sheets.

The cone-sheets are usually composed of dolerite, but occasionally may be composite with granophyric centres. The basic ring dykes consist of gabbroic rocks, sometimes displaying fluxion structures, and the ultrabasic rocks are invariably eucrite in type.

Evidence afforded by these plutonic intrusions for the presence of three distinct centres of intrusion is very limited. For instance, the attitude of the layering in the hypersthene-gabbro of Ardnamurchan Point (Centre 2) is ambiguous (Skelhorn and Elwell 1972), and the arcuate outcrops of the older gabbro of Lochan an Aodainn of Centre 2 may be controlled by younger intrusions. Even Richey et al. (1930) suggest that the Centre 2 gabbros of Beinn Bhuidhe and Portuairk may be related to Centre 3. Thus it is possible that the plutonic intrusions of Centres 2 and 3 may be continuous.

(Table 1) Radiometric ages of Tertiary igneous rocks (based on Mussett et al. 1988)

Green and Wright (1969), assuming negligible differential movements, cannot envisage how an older land surface, such as the surface-deposited volcanics of Centre 1 on Ben Hiant, can be preserved at a lower topographical level than younger plutonic rocks, such as those of Beinn na Seilg (Centre 2) and Meall Meadhoin (Centre 1), which must have solidified beneath at least 1000 m of domed overburden. They suggest that the Ben Hiant event could be a flank eruption younger than both the Centre 2 and Centre 3 activity, implying that the cone-sheets of Centre 1 were also emplaced at a late stage in the evolution of the complex. Le Bas (1971) points out that differential movement must have taken place when the cone-sheets were emplaced, resulting in uplift of the central areas of the complex by an amount determined by the thickness and dip of the cone-sheets (Kuenen 1937), but Green and Wright (1974) note that the cone-sheets must also have produced a considerable increase in the topographic level of Ben Hiant. Isotopic age determinations on various Ardnamurchan rocks (Mitchell and Reen 1973) also appear to confirm the interpretation that the Ben Hiant event occurred at a late stage. A quartz-dolerite from the Ben Hiant intrusion gives an age of 55.9 ± 0.9 m.y. This is younger than the ages of both the Centre 1 cone-sheets (57.8 ± 0.9 m.y. to 61.4 ± 1.1 m.y.), and the Centre 2 cone-sheets (56.3

± 1.2 m.y. to 60.7 ± 2.0 m.y.), but comparable with the age of the youngest plutonic intrusion of Centre 3 (56.4 ± 0.9 m.y. to 57.5 ± 0.8 m.y.).

Thus, if the relative age of the cone-sheets and related structures in the complex cannot be clearly determined, the separate identities of the three centres also becomes open to question. Nevertheless, as no clear reinterpretation of the position of the plutonic intrusions and cone-sheets of Ardnamurchan has yet emerged, the classification established by Richey et al. (1930) must still be regarded as the most reasonable, and is the one which has been used throughout this account.

The Moine country rocks

The oldest rocks of the region are found to the east of the main Tertiary complex, and also along the southern part of the Ardnamurchan peninsula between Kilchoan Bay and Ben Hiant. These metamorphic rocks belong to the Precambrian Moine series. Radiometric dating on similar rocks to the east of this has confirmed this.

The rocks are psammitic in type comprising white or pale coloured, fairly pure sandstones, with occasional pelitic bands. In section the rocks consist of quartz and subordinate alkali-feldspar, with occasional iron ores and micas (both biotite and muscovite).

To the east of Ben Hiant, the Moine schists are isoclinally folded in tight vertical folds with north-west/south-east axes, but on the eastern flanks of Ben Hiant, and along the Kilchoan shore, the dips are shallow, usually less than 30° and to the west.

Mesozoic sedimentary rocks

In Ardnamurchan, Mesozoic rocks outcrop in several areas, being best exposed along the southern shore, from Kilchoan Pier westwards for a distance of about 5 km. Smaller isolated exposures occur elsewhere, particularly between Sanna Point and Faskadale Bay, and also on the shore north of Swordle at Garbh Rudha. Richey et al. (1930) examined the sediments in detail, and reported that the rocks are Jurassic sediments with an occasional thin band of Trias sediments separating the Jurassic rocks from the underlying Moines. The succession and thicknesses of the modern stages and zones of the Jurassic found in Ardnamurchan are given in (Table 2) with descriptions of each stratigraphic unit including some of the fossils obtained from each (Richey et al. 1930, ch. iv). The succession, which is given from youngest to oldest rocks, is not complete, only those zones actually found at Ardnamurchan being described.

(Table 2) Mesozoic rocks of Ardnamurchan.

Tertiary igneous rocks

Basalt lava flows (alkali-olivine basalts)

These basalt lavas represent the earliest Tertiary igneous rocks, and occur in a broad north-south trending belt just east of Beinn an Leathaid, about 2 to 3 km wide at Faskadale in the north narrowing to about 1 km width at Camphouse in the south. Small outcrops of basalt are seen north and west of Glas Eilean on the Kilchoan foreshore, and to the west of Ben Hiant approximately 2 km east of Mingary, while other isolated basalt outcrops occur south of Aodann, on the southern side of Meall an Tarmachain and north of Meall nan Con. In all these places, the lavas occur in association with volcanic vent material. To the east of Ben Hiant, two outliers of basalt occur; one on the eastern flanks of Ben Hiant, and the other, larger one further to the east, separated from the first by a large north-north-west to south-south-east trending fault with a 75 m downthrow to the east. Loch Mudle is situated on this fault line and is probably fault controlled; the fault being called the Loch Mudle fault.

In the Ardnamurchan peninsula the total thickness of the lava flows is about 100 m. Individual flows frequently show signs of alteration and, as a result of subsequent vent explosions, are often brecciated. The greatest thickness of lava flows is seen in the wide belt trending southwards from Faskadale (in the Braehouse area), but since trap featuring is not present, details of the basalt structure and the total thickness of the lava pile are difficult to ascertain.

The lavas generally comprise plateau basalt (microporphyritic) types, but examples of macroporphyritic basalt and mugearite are seen in the Kilmory area, about 3 km east of Faskadale. The basalts are often vesicular with occasional amyealoidal patches, and everywhere show extensive alteration. The small basalt outcrops in the west of the peninsula are often baked and thermally altered by later intrusions, and the later explosive vents have also disrupted the flows.

The freshest basalts are found in the eastern Ben Hiant area. Here they are black, microporphyritic (or non-porphyritic) with fine-grained ophitic texture. Phenocrysts of olivine with subordinate labradorite occur in a matrix of plagioclase feldspar, titaniferous augite, olivine and magnetite. Alkali-rich patches are found in which analcite and alkali-feldspar are present, together with augite often surrounded by a rim of aegirine. Patches of glass can also be recognised.

Some of the alteration may be caused by weathering, but much is caused by pneumatolytic action of later igneous intrusions.

The basalts commonly rest directly on the Moine schists, but in some areas thin beds of Jurassic sediments usually comprising mudstones, shales, sandstones and limestones intervene between the lavas and the basement Moines. On the eastern flanks of Ben Hiant the lavas rest on top of a basal Tertiary mudstone overlying Lower Lias limestones, which in turn rest on top of Triassic sandstones and grits.

Centre 1

The outcrop of the rocks which comprise Centre 1 is shown on (Figure 2). They form a broad arcuate belt on the eastern part of Ardnamurchan from Faskadale Bay to Mingary Pier (approximately 3 km wide). Centre 1 mainly includes vent agglomerates, lavas and varied basic intrusive igneous rock types, and acid igneous rocks are rare.

Vent rocks (and associated extrusive rocks)

Richey et al. (1930) described these under two headings: the Ben Hiant vents and the Northern vents (Figure 2). These vents constitute the first signs of igneous activity after the extrusion of plateau lava, and are fairly widespread in east Ardnamurchan, being found circling Ben Hiant (the Ben Hiant vents, (Figure 3)) and also north of the Camphouse area, in an arcuate belt from Camphouse to Kilmory in the north at Faskadale Bay (the Northern vents). A few more isolated vents occur, particularly on the north-west shore at Rudha Carrach, inland at Meall nan Con and Meall an Tarmachain, and at Glas Eilean on the west side of Kilchoan Bay. Other vent rocks were ascribed to Centre 2 by Richey et al. (1930) and are described under the account of Centre 2 in this guide. However, their compositions are remarkably similar throughout Ardnamurchan.

The agglomerates consist of angular rock fragments of varying sizes as well as volcanic bombs, often of a very large size, held in a tuffaceous matrix. These fragments include rhyolite and dacite types, which are particularly well displayed in the Faskadale agglomerate. Trachytes and other intermediate volcanic types often showing vesicular textures also occur, but it is difficult to determine whether these rock fragments are bombs or disrupted blocks of lava. Fragments of some basaltic rocks have been observed in the agglomerates, particularly two huge masses of large-feldspar, porphyritic basalt near Maclean's Nose. In the Northern vents, large blocks of Mesozoic rocks have been observed, particularly near Achateny and Kilmory, and on the foreshore north of these settlements. Similar fragments have been observed within the other vents in the region.

The tuffaceous matrix is fine-grained with small grains of quartz and mica, probably derived from the early Moine country rocks, but the bulk of material constituting the tuffs is derived from igneous rocks, probably the earlier basalts.

The contact between the agglomerates and other rock types can be observed in several places, particularly in two vents which comprise the agglomerates on the east side of Ben Hiant. In a stream on the east flank of Ben Hiant the agglomerate/basalt boundary of the northern vent is well displayed (dipping south-west at about 20°). This is much more gently inclined than that observed by Richey et al. (1930, p. 123) who consider 35° to 50° as the dip of the contact.

However, observations in parallel stream valleys suggest that the dip of this contact is very variable.

Towards Maclean's Nose the junction between agglomerate and basalt, and agglomerate and Moine country rocks, of the southern Ben Hiant vent can be seen in several places on the scarp slope to the west of the abandoned village of Bourblaige. In this area, basalt blocks are found in the agglomerate more than one hundred metres below the present level of the in situ basalts, suggesting that the basalts must have fallen into the open vent at the time of its eruption. Very rarely is the contact between agglomerates and wall rocks (basalts or Moine country rocks) seen, but where observed, the contacts are steeply dipping and brecciation of the vent wall rock is often absent. This is in marked contrast to the Glas Eilean vent of Centre 2 on the shore east of Kilchoan Bay, where shattering of the wall rock is so marked that the boundary of this vent cannot be placed with any accuracy. In the broad belt of agglomerates trending north from Camphouse, comprising the Northern vents, the nature of the contact with country rocks is unknown, but north-west of Loch Mudle the agglomerate/Moine contact is very steep as seen in the valley of the Achateny Water.

In general, the agglomerates and tuffs found infilling the vents in Ardnamurchan represent the earliest eruptive phase, post-dating the extrusion of the plateau lavas. Evidence of prevent intrusions and igneous activity is provided by the fragments of acid igneous rocks (rhyolites and dacites etc.) found as fragments in the agglomerates, and also by a dyke cut by the agglomerate on the east side of Ben Hiant. In some cases evidence of violent formation is displayed by the highly brecciated margins (Glas Eilean), whereas in others (Maclean's Nose area) the wall rocks are smooth and show little brecciation.

Pitchstone lavas

Within the vents extrusive rocks occur, and the most important of these are the pitchstone lavas. These occur only on the south-east flank of Ben Hiant about 350 m above sea level, forming a knoll of rock rising above the lower escarpment (see Gribble 1970, pl. 1). The pitchstones are considered to be lava flows within the crater itself (i.e. the south Ben Hiant vent), and several flows are interbedded with tuffaceous material. Occasional columnar jointing is seen and the vesicular top of each flow is often infilled with minerals such as calcite and agate quartz. From the field evidence two or three flows are present.

The pitchstones are very fresh, extremely fine-grained, glassy rocks with small phenocrysts. Crystals of plagioclase feldspar and augite occur in a pale brown, glassy matrix containing some iron ores and apatite. The feldspars are labradorite with microliths of oligoclase set in the ground mass, and the augites are of a green aluminous variety, with rare crystals of orthopyroxene also present. The overall composition of the pitchstone lavas is similar to that of andesite.

The pitchstone lavas are thought to be contemporaneous with the initial phase of igenous activity, but to post-date the main plateau lavas.

Trachyte lavas

A small outcrop of trachyte material (possibly a plug) occurs to the east of Ben Hiant, within an area of Moine country rocks. The trachyte resembles blocks found within the vent agglomerates and may thus pre-date or be almost contemporaneous with the agglomerates and pitchstone lavas. This trachyte plug gives rise to a small crag near the Kilchoan–Salen road, north of where the road crosses the Allt Tòrr na Moine stream. The rock is a biotite-trachyte containing laths of alkali-feldspar in a felted arrangement, with plates of brown biotite, subordinate iron ores and augite.

Intrusive rocks (plutonic and hypabyssal types)

The remaining Centre 1 rocks are all intrusive igneous plutonic or hypabyssal types, usually basic, but with one acid intrusion of granophyre at Faskadale Bay. It is difficult to ascertain their order of age. Undoubtedly the. agglomerates and lavas are the earliest but the sequence of the remaining intrusions is not known with certainty as most are rather isolated and quite small in size, apart from the dolerites of Ben Hiant and Beinn an Leathaid. These are described roughly in the order employed by Richey et al. (1930).

Gabbro of Meall nan Con

This small intrusion, which is now considered of doubtful age and is mentioned with Centre 3 rocks (p. 57) is intruded into plateau lavas and early agglomerates against which it shows a chilled margin, but is completely surrounded by the large ring dykes of Centre 3 which have thermally altered the rock.

The rock is a typical dark, olivine-bearing gabbro with basic plagioclase and augite found in an ophitic relationship, and with additional olivine and iron ores.

Quartz-gabbro of Faskadale

This is a dyke-like intrusion extending from west Faskadale Bay westwards for about 2 km. Although it appears to be continuous with an outer quartz-gabbro of Centre 3 (see p. 55), Richey et al. (1930, p. 145) assign it to Centre 1 because of the number of cone-sheets cutting it, which are older than Centre 3 rocks. It has suffered thermal alteration from the Centre 3 intrusions and the rock is highly sheared in places. Richey et al. (1930) consider that these factors make interpretation of this intrusion difficult and that probably more than one phase of emplacement exists.

Petrographically the intrusion is variable with typical quartz-gabbro and olivine-gabbro types present, the minerals being augite and plagioclase feldspars (labradorite in the olivine-bearing types, and more soda-rich feldspar in the quartz-bearing gabbros). Occasional veining of acidic granophyric material appears — a common occurrence in ring intrusions of Centres 2 and 3. Thermal alteration from Centre 3 intrusions has led to the development of green hornblende from olivine or olivine pseudomorphs. At Faskadale Bay the rock is more doleritic although frequent shear zones tend to obscure the mineralogy. The feldspars here are often highly altered, which may be due to the influence of the Faskadale granophyre which bounds it to the north, as well as the effects of shearing.

Granophyre of Faskadale

The granophyre post-dates the quartz-gabbro which forms a boundary to the south, as the granophyre is chilled against it. Some later basic cone-sheets cut the granophyre, which is acidic in composition and frequently contains xenoliths of schist. About 1 km west of Faskadale Bay, the granophyre is cut by a thin basic sheet of gabbroic texture. Westwards from this point the granophyre is more basic in composition.

The acidic granophyre has a micrographic texture in which minute alkali feldspar crystals are surrounded by a micrographic growth becoming coarser outwards.

The more basic granophyre has a similar texture, but contains acicular amphibole in addition to the quartz and feldspar of the acid variety. Some biotite and secondary chlorite patches also occur.

Some mineralogical changes are seen where the granophyre is in contact with the gabbroic sheet mentioned above (the granophyre becoming more basic with large amphibole crystals developing in the rock).

The dolerites

Three main dolerite intrusions are present (excluding the cone-sheets; see p. 48), of which the dolerites of Ben Hiant and Beinn an Leathaid are the largest and the most important.

However, a number of smaller intrusions also belong to Centre 1 and, although age relationships are difficult to ascertain, the earliest of these is the porphyritic dolerite.

Porphyritic dolerite

This comprises two masses, a small circular one south of Ben Hiant, and another more elongate east–west one approximately 4 km long, running from west of Glas Beinn to north of Camphouse.

The porphyritic dolerite of Ben Hiant appears as a dark, fine-grained dolerite with plentiful phenocrysts of plagioclase feldspar about 10 mm long. The intrusive nature of the dolerite is seen in a gully crossing its eastern margin, where the dolerite/agglomerate boundary dips north-west at 80°, the dolerite showing a chilled contact against the agglomerate.

The dolerite/pitchstone contacts suggest that the porphyritic dolerite was intruded during the infilling of the Ben Hiant vent.

In thin section the porphyritic dolerite exhibits labradorite phenocrysts in a fine-grained matrix of augite, acicular labradorite feldspar crystals and patches of brown glass containing microliths and iron ores. The phenocrysts show slight zoning and antiperthitic textures are common, with a soda-rich feldspar phase exsolving. Various textures are formed within this intrusion; many of the most striking occurring along boundaries with other rock types (particularly the main Ben Hiant dolerite).

The other porphyritic dolerite running west and north from Camphouse exhibits similar mineralogy and textures, but is extremely badly exposed.

Quartz-dolerite of Camphouse

This intrusion mentioned by Richey et al. (1930, pp. 152–153) is now only exposed in an extremely weathered bank of rock on the stream behind the site of the old Camphouse farm. It is later than the porphyritic dolerites as it intrudes these.

Augite-diorite of Camphouse

This intrusion appears as a series of small knolls of rock about 1 km east-south-east of Camphouse farm, and the shape of the outcrop suggests a possible small circular intrusion with indeterminate age-relations with the other igneous rocks of Centre 1.

It is not indicated on the coloured map, but precise details of its location are given in the excursion description (6A). The hand specimen shows a very fresh, porphyritic, coarse-grained rock with large black augites more than 20 mm in length, contained in a white matrix of feldspar.

In thin section the augites exhibit zoning and are contained in a matrix of feldspar with accessory sphene and apatite. Two types of feldspar may be present — a labradorite and a perthitic potash feldspar both of which show extensive alteration.

The main dolerite intrusions of Beinn an Leathaid and Ben Hiant.

(a) The Beinn an Leathaid dolerite is a composite intrusion, which Richey et al. (1930) consider may represent a sheet-like body gently dipping to the west (Richey et al., p. 156; cf. Gribble 1974, p. 76), comprising a doleritic base with a granophyric upper half, the total thickness being greater than 100 m.

On the ridge top, numerous xenoliths of schist and gneiss can be recognised within the granophyric upper part. The change from acid material to underlying dolerite occurs across a very narrow transition zone, well displayed on the cliffs east of the Beinn an Leathaid summit.

Petrographical investigation shows the dolerite to consist of labradorite feldspar (zoned with K-feldspar rims), augite and secondary amphibole set in a granophyric matrix comprising about 20% of the rock's volume. Magnetite also is present in reasonable amounts. The narrow transitional zone shows a decrease in the ferromagnesian minerals of the dolerite accompanied by a corresponding increase in the granophyric material, and the uppermost sheet of granophyre is rich in rock glass with occasional oligoclase and quartz.

(b) The Ben Hiant dolerite has recently been examined in detail by Gribble (1974). It forms the main summit of Ben Hiant having a thickness there of more than 200 m. Fresh dolerite is rare on the Ben Hiant crags which usually display excellent onion-skin weathering. The dolerites of Hiant were compared with the ring dyke dolerites of Centres 2 and 3 (Gribble 1974, p. 73), and the mineralogy given for both olivine-bearing and quartz-bearing dolerites as follows:

Olivine-dolerites	Quartz-dolerites
Plagioclase An$_{63}$ (core) zoned to An$_{30}$ (rim)	Plagioclase An$_{45}$ (core) zoned to An$_{28}$ (rim)
Olivine F$_{32}$ to Fa$_{43}$	

Augite $Ca_{40}Mg_{34}Fe_{26}$ to $Ca_{33}Mg_{42}Fe_{15}$ (2V 38° to 52°)

All the dolerites of Centre 1 contain large amounts of glass, and although the main minerals of each rock type appear to have been in equilibrium with each other, the norms of all the dolerites except the most basic contain free quartz (Gribble 1974, table 3). These Ben Hiant dolerites are not found in the field in association with the variolite of Ben Hiant (Richey *et al*. 1930, p. 166), which probably represents early formed crystals and magmatic liquid which was quickly chilled during emplacement. It is unlikely that the dolerites of Ben Hiant represent a single large homogeneous intrusion. In large homogeneous intrusions regular changes in mineralogy and chemical composition occur within a differentiated sheet, numerous examples of which have been described. In a systematic sampling from top to bottom of Ben Hiant, there is not a simple progression from acidic material near the top to basic dolerite at the bottom; instead a series of steps occur of varying thicknesses and of different chemical compositions, which do not show regular changes. It is possible that the Ben Hiant dolerites represent several cone-sheets which have coalesced within the earlier volcanic vent (Gribble 1974); thus agreeing with the ideas of Geikie (1897). The variolite or glassy dolerites which occur in patches to the west-south-west of the Ben Hiant summit probably represent quickly chilled magma in which the normal doleritic minerals appear in a very fine-grained spherulitic texture. Analyses of dolerites of Ardnamurchan are plentiful (Richey et al. 1930; Skelhorn and Elwell 1966; Holland and Brown 1972; Gribble 1974), but no analyses 'of variolite exist, although the mineralogy of these rocks suggests that they will be similar to normal dolerites. Gribble (1974) also analysed the rock glass contained in the normal dolerites, which proved to be very siliceous and (Table 3) shows this, as well as including analyses of the main rock types from the Centre 1 dolerite.

Table 3 Compositions of Centre 1 rocks and magmas

	1	**2**	**3**	**4**	**5**	**6**
SiO_2	72.57	54.38	46.87	49.8	52.5	50.0
TiO_2	0.32	2.29	2.33	1.0	1.0	2.5
$A1_2O_3$	10.54	13.51	13.45	13.9	13.5	13.0
Fe_2O_3	n.d.	4.72	4.83	9.7	—	—
FeO	5.90	7.96	10.71			
MnO	0.10	0.21	0.23	—	—	—
MgO	0.51	2.85	6.38	9.2	8.5	5.0
CaO	0.47	6.37	8.62	12.9	12.0	10.0
Na_2O	3.22	3.13	2.38	1.8	2.0	2.8
K_2O	6.64	2.13	1.33	.2	1.0	1.2
P_2O_3	—	0.60	.38	—	—	—
H_2O	—	2.17	2.19	1.0	—	—
Total	100.27	100.32	99.70	99.5	100.00	97.5

Analyses from Gribble (1974, tables 1 and 5), except for no. 6.

1. **Rock glass from dolerite on Ben Hiant.**
2. **Quartz-dolerite, Ben Hiant.**
3. **Olivine-dolerite, Ben Hiant.**
4. **Estimate of average primary cumulate of Centre 1.**
5. **Estimate of average primary magma of Centre 1.**
6. Non-porphyritic central magma type (Bailey *et al.* 1924).

The dolerites of Ben Hiant are therefore tholeiitic in composition, and show a light Fe-enrichment trend when plotted into an AFM diagram. Gribble (1974, p. 88) considers that the Centre 1 dolerites of Ben Hiant crystallised from a magma of approximately the composition of analysis no. 5 in the table above (roughly equivalent in composition to the non-porphyritic central magma type of Bailey et al. 1924, p. 14). The same magmatic source gave rise to the later dolerites of Centres 2 and 3 with slight elemental changes (richer in Al_2O_3 and Na_2O in 2 and 3, but poorer in SiO_2, Ba and Cu). Further studies by Gribble have suggested that the real differences may, in fact, lie between cone-sheets and ring dykes, with the cone-sheets of Centres 1 and 2 being from the same magmatic source (including the dolerites of Ben Hiant and Beinn an Leathaid). These cone-sheets perhaps post-date the basic ring dyke dolerites of Centres 2 and 3; which would explain why the magma giving rise to the cone-sheets is richer in SiO_2 and Ba (and probably Rb —though this is not easily detectable), and poorer in Al_2O, and Na_2O than the earlier basic magmas forming the ring dykes.

Since the cone-sheets of Centres 1 and 2 are essentially similar in composition and mineralogy, these are dealt with together at the end of the section on Centre 2.

Centre 2

Vent rocks

A small linear vent at Glas Eilean, south of Kilchoan, is generally considered to be related to Centre 2 (Richey et al. 1930; Paithankar 1967). It contains agglomerates with fragments of quartz-dolerite probably derived from the outer cone-sheets of Centre 2. However, these fragments are indistinguishable from the cone-sheets of Centre 1 and 'cannot provide evidence of the relative age of the vent. The vent is not cut by any of the Centre 2 cone-sheets.

Along the shore of Glas Eilean the vent is bounded by basalt lava to the north-west and Moine schists to the south and east (Figure 4). The north-western margin is largely fault controlled. In addition to the quartz-dolerite, fragments of Moine schist, porphyritic basalt, Jurassic limestone, sandstone, and shale occur within a matrix which consists largely of devitrified glass. Details of the matrix show the presence of chloritic shards, suggesting a basic origin, and lenticular bodies consisting of chlorite spherulites together with quartz and alkali-feldspar spherulites. This indicates a unique association of acid and basic glass. Within the matrix are fragments up to 1 m long, usually angular, and thoroughly mixed, with some vertical displacement from their original positions.

Occupying an intricate veining system within the agglomerates is an acid tuff of devitrified acid glass enclosing bodies of basic devitrified glass. Occasionally acid nuclei occur within these basic bodies. A small acid dyke is also present cutting the agglomerate and showing fluxion structure parallel to its margins, which are also roughly parallel to the trend of the vent. Paithankar (1967) notes that the opposite walls of this dyke cannot be matched and, as it contains a large number of agglomerate fragments, suggests a non-dilatational mechanism of emplacement. The dyke rock is essentially rhyolitic in composition with quartz and feldspar phenocrysts, but texturally is similar to the matrix of the agglomerate and the vein material. Reynolds (1954) calls this rock an 'intrusive ignimbrite', but Paithankar (1967) prefers the term tuffisite.

Paithankar (1967) considers that the vent was initiated by a shattering of the country rocks by gases, followed by gas-streaming which brought about the emplacement of the tuffisite. The intimate association of acid and basic glass provides evidence for liquid immiscibility in conditions of high water vapour pressure and super-heating.

Intrusive plutonic rocks

The sequence of intrusion of the plutonic rocks of Centre 2, described by Richey *et al.* (1930) is (from oldest to youngest):

Earlier than the inner cone-sheets	Hypersthene-gabbro of Ardnamurchan Point
	Older gabbro of Lochan an Aodainn Quartz-gabbro of Garbh-dhail Granophyre of Grigadale
	Older quartz-gabbro of Beinn Bhuidhe Quartz-gabbro of Aodann
	Granophyric quartz-dolerite of Sgùrr nam Meann
Later than the inner cone-sheets	Eucrite of Beinn nan Ord
	Quartz-gabbros of Loch Caorach and Beinn na Seilg
	Younger quartz-gabbro of Beinn Bhuidhe
	Fluxion gabbro of Portuairk
	Aodann felsite

Paithankar (1968) has cast doubt upon some of the relationships of the Grigadale granophyre and associated gabbros, while Richey (1933) reiterates an earlier suggestion that the younger quartz-gabbro of Beinn Bhuidhe is a westward continuation of the Centre 3 quartz-gabbro of Faskadale. The mechanism of ring dyke emplacement, involving the formation of a ring fault and subsidence above a magma chamber as a consequence of a wholesale reduction in magmatic pressure, as originally proposed by Bailey and Maufe (1916) and elaborated by Anderson (1936), is still largely accepted.

Hypersthene-gabbro of Ardnamurchan Point

This is the earliest of the ring-shaped intrusions of Centre 2, and is considered by Richey et al. (1930) to be a ring dyke, although its inner margin is everywhere in contact with younger intrusions. Wells (1954a) however, suggests that the intrusion probably extended as a continuous roughly circular mass before the inner part was displaced by later intrusions. The outer margin of the hypersthene-gabbro is bounded by Mesozoic sediments, Tertiary basalts, plutonic intrusions of Centre 1. and the outer cone-sheets of Centre 2. The Mesozoic rocks are folded into a dome which partly surrounds the hypersthene-gabbro, and this pre-dates the emplacement of the outer cone-sheets. Nevertheless, the formation of this dome, the emplacement of the cone-sheets and the intrusion of the hypersthene-gabbro, are events all probably closely related in time, especially as some cone-sheets post-date the hypersthene-gabbro. Moreover, the intrusion of the hypersthene-gabbro does not appear to have altered the inclination of the earlier cone-sheets.

Wells (1954a) recognises several different types of contact between the hypersthene-gabbro and the host rock. These are either simple contacts which may be flat-lying or dip outwards at various angles, or complex contacts where the form of the intrusion has been controlled by the structure of the adjacent host rock and stoping of blocks occurs; but these seem restricted to those few areas where the dip of the host rock is toward the intrusion. Numerous basic xenoliths occur within the hypersthene-gabbro, sometimes attaining the form of substantial inclined sheets which dip toward the centre of the mass. These inclusions cannot have been moved far from their place of origin, and their presence probably marks the vicinity of the roof or wall of the intrusion. From this evidence it can be argued that the hypersthene-gabbro now exposed is the upper part of a boss-like or cone-shaped intrusion immediately below an eroded roof. Wells (1954a) believes it to be probably cone-shaped, but Skelhorn and Elwell (1971) consider that the attitude of the contact at the present level of erosion is not consistent with this interpretation, and suggest a boss-like form with the hypersthene-gabbro occupying the space above a more or less cylindrical block which dropped as a result of cauldron subsidence.

Richey et al. (1930) recognise that the hypersthene-gabbro has a marginal facies of quartz-dolerite and quartz-gabbro, and Wells (1954a) notes that although the hypersthene-gabbro forms a distinct unit, it contains several different rock types which are often sharply bounded against their neighbours. A relatively fine-grained hypersthene-gabbro forms the predominant rock type, with a plagioclase grain size of 1–2 mm and ophitic pyroxene up to 20 mm across. The average modal composition is plagioclase 60%, pyroxene 30% (generally more than 20% augite and less than 10% hypersthene), olivine 8%, and iron ore about 2%. The hypersthene characteristically forms a discontinuous rim around olivine which continues outwards into sub-ophitic growths with plagioclase. In the absence of hypersthene, augite may partially enclose olivine, but when both pyroxenes are present, the augite forms independent ophitic growths.

Troctolitic gabbro, usually allivalitic in character, also occurs, but is a very subordinate rock type, giving rise to narrow bands which grade into peridotite. Coarser-grained, augite-rich xenolithic gabbros are found scattered throughout the intrusion. These tend to be more felds-pathic than the hypersthene-gabbro, and also richer in iron ore. Gabbro pegmatites are rare in the hypersthene-gabbro, but are sometimes found near its outer margin. These pegmatites often possess cores of quartz-feldspar rock with granophyric texture, and may be produced by melting of inclusions, but they could be the result of liquid segregation.

As noted above, quartz-gabbro and quartz-dolerite occur as a marginal development. The width of the zone is usually less than 100 m, but these rocks grade into the hypersthene-gabbro and the position of the boundary is indeterminable. Skelhorn and Elwell (1971) believe this margin represents a chilled phase of the magma which produced the more central lithologies, but Richey et al. (1930), Wells (1954a), and Richey and Harry (1963) consider that the intrusion as a whole involved two magmatic pulses, the early phase forming the marginal facies. Quartz-feldspar veins are a conspicuous feature of the marginal facies, being very abundant near the contact. The larger veins are highly feldspathic, but the smaller may be composed entirely of quartz.

One of the most interesting features of the hypersthene-gabbro is the presence of mineralogical layering. Richey et al. (1930) consider this to be a fluxion structure confined to a zone near the inner margin of the intrusion, but Wells (1954a) shows that the layering is more widespread. However, the layering is best and most extensively developed in the inner part of the outcrop, and even here it is confined to certain zones, which do not persist far either vertically or laterally (Figure 5) and (Figure 6). Wells (1954a) lists the following essential features of the layering:

1. The layers consist of variable proportions of olivine, augite, hypersthene, magnetite and plagioclase. Occasional bands of peridotite, anorthosite and thin seams of iron ore occur.
2. Modal differences are accompanied by slight textural variations.
3. The sequence of layers appears to be haphazard in most areas, although some degree of order is provided by occasional rhythmic banding between more feldspathic and more pyroxene-rich layers.
4. Evidence of gravity stratification is provided by concentrations of pyroxene and iron ore toward the base of the layers, and eroded olivines.
5. Thicknesses vary, even in adjacent layers, from about 10 mm to 1 m. Between layers, large thicknesses may show no banding.
6. Layer surfaces dip inwards, steepening from about 10° where present near the outer margin, to about 60° near the inner margin.
7. Contacts between layers are generally sharp, but unchilled and with interlocking crystals.
8. A crystallographic preferred orientation occurs parallel to the layering.

The under-surfaces of certain layers have protuberances similar in appearance to load-casts in sedimentary rocks. In a few places slumps occur, and occasionally erosion surfaces within the layers are observed. Skelhorn and Elwell (1971) consider that there is convincing evidence that the layering was produced by bottom, accumulation on successive floors of a magma chamber, which were more or less horizontal. However, as the dip of the layering steepens inwards, they suggest that a phase of later deformation must have occurred, letting down as much as 75% of the intrusion along a central ring-fault, and downwarping the layering in the adjacent rock. The formation of this ring-fault permitted the emplacement of the granophyric quartz-dolerite of Sgùrr nam Meann which, in turn, obliterated direct evidence for the presence of the fault. Palaeomagnetic studies by Wells and McRae (1969) show that this process must have occurred before the layered rocks had cooled below their Curie temperature of about 570°C.

Sedimentary xenoliths have been recognised in the gabbro (Wells 1951), and in addition Wells (1954a) recognises inclusions of igneous origin which may have been formed by three main processes. Firstly, he believes that the presence of primary basalt and dolerite can be recognised by a relict porphyritic structure, while the presence of recrystallised amygdales allows the separate recognition of basalt. Secondly, autometatnorphism of an early chilled facies of the gabbro itself may ,result in inclusions. Richey et al. (1930) regard this as a widespread phenomenon, but Wells (1954a) considers this difficult to prove. Finally, the hypersthene-gabbro may have incorporated narrow dyke-like bodies, producing a marginal interlamination between the dykes and the gabbro. These interlamination structures suggest that shearing took place on opposite sides of the dyke during its injection and consolidation. The dykes also show a fluxion structure, and as no chilling effects are exhibited, the hypersthene-gabbro was probably still hot when the dyke material was crystallising. The dykes may have - been derived either from pockets of magma lying within the crystallising hypersthene-gabbro, or from the partial fusion and mobilisation of xenolithic material.

Some of the most interesting xenolithic masses are the sapphire-bearing rocks which occur on the northern slope of Glebe Hill, north of Kilchoan village near the Amhainn Chro Bheinn stream, where the hypersthene-gabbro is in contact with basaltic lava. The intrusion here may be an early consolidation phase which contains xenoliths of aluminous country rock, such as an aluminous bole produced by the weathering of the adjacent Tertiary lava, in which thermal alteration allowed the growth of sapphire. Alternatively, the sapphire may have formed in xenoliths which were only moderately aluminous, additional alumina having been added from the magma. Previous to Wells' (1951) work, these provided the only examples of xenoliths for which a sedimentary origin had been proposed, a remarkable fact since sedimentary rocks form the principal host for the intrusion. Even the sedimentary inclusions recognised by Wells (1951)-are of very minor quantitative importance. Some rounded blocks of sandstone, now in the form of aegirine-granophyre cores surrounded by pyroxenite, occur near Rubha Carrach, and finely laminated blocks are found near Sanna Point. These latter inclusions consist of basic andesine surrounded by hypersthene, and with an outer zone of norite, in which layers of hypersthene and magnetite suggest relict bedding. The magnetite may represent ironstone bands.

Wells (1951) considers that the "basic granular hornfels" xenoliths are probably of sedimentary origin but Brown (1954) considers that to derive these from sedimentary rocks would require much metasomatic replacement, as well as complete recrystallisation. Instead he suggests that these are thermally metamorphosed layered ultrabasic or basic igneous rocks, derived from some level beneath the layered hypersthene-gabbro.

Older gabbro of Lochan an Aodainn

This is the only intrusion of Centre 2 which possesses a volcanic host on parts of its inner margin. Where these agglomerates and basaltic lavas, which are similar to those associated with Centre 1 activity, are present, the gabbro becomes fine-grained and resembles a quartz-dolerite. The remainder of its contacts are formed by younger intrusions, so that no original marginal modifications are apparent. Richey et al. (1930) consider that sufficient of the original inner wall is preserved to demonstrate a curvature about the focus of Centre 2 at Aodann (the old settlement centred round the Sonachan Hotel), and that the gabbro is in the form of a ring dyke and does not merely form a capping to the later quartz-gabbros with which it is in contact. However, if the volcanics are viewed as the remains of a once, more extensive screen, the use of their contact with the gabbro as an indicator of the focus of Centre 2 becomes very uncertain.

Although definite age relationships cannot easily' be determined, the gabbro is certainly early. Even though it is traversed by only a single cone-sheet, it is definitely older than both the quartz-gabbro of Garbh-dhail and the Grigadale granophyre, both of which are extensively intruded by the inner cone-sheet suite of Centre 2.

The rock was originally an olivine-bearing dolerite but is now highly altered. Alteration effects are principally a marked cloudiness to the feldspars, and physical crushing and shattering, accompanied by a segregation and migration of acid material which locally assumes the character of an augite-granophyre. Occasionally masses of fine-grained basic rock occur within the gabbro.

Quartz-gabbro of Garbh-dhail

The arc formed by the outcrop of this intrusion is very restricted, being limited to the north by the Grigadale granophyre, and to the east by the quartz-gabbro of Faskadale (Centre 3). Great variations in both composition and texture occur throughout the mass, with the quartz-gabbro in several places grading into a quartz-dolerite with porphyritic feldspar. The modal composition of this rock, as xenoliths within the Grigadale granophyre, is: quartz 9.4%, plagioclase (zoned) 61.2%, pyroxene 20.1%, iron ore 5% and apatite 4.3%. A sharp, intrusive contact between different varieties of quartz-gabbro has been observed, indicating perhaps a composite intrusion. Indeed, Paithankar (1968) considers that whereas some parts of the intrusion are clearly older than the adjacent Grigadale granophyre, others are younger.

Xenoliths are locally abundant, and sometimes occur as bands of fine-grained basic rock similar to the xenoliths in the hypersthene-gabbro of Ardnamurchan Point (p. 29). Acid veins generally traverse the quartz-gabbro and the xenolithic bands. Both the quartz-gabbro and the acid veins are cut by the inner cone-sheet suite of Centre 2. The quartz-gabbro is clearly younger than the hypersthene-gabbro with which it makes contact at Beinn na Seilg, but older than the eucrite of Beinn nan Ord. Its inner margin shows chilling against the gabbro of Lochan an Aodainn, with the development of a fine-grained quartz-dolerite marginal facies.

Granophyre of Grigadale

As the largest mass of granitic rock in Ardnamurchan this intrusion deserves special attention. It is in contact with the gabbro of Lochan an Aodainn, the quartz-gabbro of Garbh-dhail, and both the younger and older quartz-gabbros of Beinn Bhuidhe. Richey et al. (1930) consider the granophyre to be younger than the Garbh-dhail and Lochan an Aodainn gabbros, but older than both the Beinn Bhuidhe gabbros. Paithankar (1968), however, produces evidence that it includes xenoliths of the older gabbro of Beinn Bhuidhe. He also observes that whereas in some places the quartz-gabbro of Garbh-dhail is chilled against the granophyre, in others the reverse is the case. The granophyre is typically fine-grained, medium grey in colour with dark spots of altered augite and magnetite. Its modal composition is: quartz 4.5%, plagioclase (zoned, and edged with orthoclase) 60.8%, acid mesostasis (micrographic matrix of quartz and alkali-feldspar) 26.3%, augite 2.7% and iron ore 5.7%. Richey et al. (1930) consider the whole granophyre to be contaminated with gabbroic material. Paithankar (1968) believes that emplacement of the granophyre was accomplished by a fluidised system, initiated by a ring-fault, in which a gas-liquid-solid emulsion produced shattering of the solid gabbros and their incorporation into the granophyre.

Older quartz-gabbro of Beinn Bhuidhe

This small intrusion lies to the south of the younger quartz-gabbro of Beinn Bhuidhe and to the north of the Grigadale granophyre. Richey et al. (1930) believe it to be clearly younger than the granophyre, with the development of a chilled margin, but Paithankar (1968) reverses this sequence, and suggests a correlation with the older phase of the quartz-gabbro of Garbh-dhail. However, its invasion by the inner cone-sheet suite of Centre 2 shows it to be earlier than the younger quartz-gabbro of Beinn Bhuidhe, which is unaffected by these cone-sheets. It is a medium-grained rock with veins and patches throughout of acid material. A typical modal composition is: plagioclase 47%, acid mesostasis 23.3%, quartz 2.4%, pyroxene 19.1% and iron ore 8.2%.

Quartz-gabbro of Aodann

This intrusion forms the central zone of the Centre 2 complex, and is cut by the inner suite of cone-sheets. Its outer margin occupies an irregular arc of about 180° with the older gabbro of Lochan an Aodainn, against which it grades rapidly into a quartz-dolerite with porphyritic feldspar. Apart from this marginal modification, the quartz-gabbro also shows considerable variation both in texture and the development of an acid mesostasis. This variation leads to the recognition of two main types, a fine-grained gabbro with porphyritic feldspar, and a coarser grained non-porphyritic gabbro. Both sharp and gradational contacts between these two types are present, and where sharp contacts occur the fine-grained rock usually shows thermal alteration. Furthermore, the two varieties differ in their marginal behaviour against the Lochan an Aodainn gabbro, the finer rock having sharply defined chilled contacts, while the coarser rock becomes hybridized near the contact. Richey et al. (1930) consider that this evidence indicates two phases of injection, the finer grained rock forming first as a capping to the succeeding intrusion of coarser gabbro.

Near the junction with the Great Eucrite of Centre 3, the gabbro is finer grained and more basic in composition than elsewhere, while near the contact with the felsite south of Aodann, a porphyritic texture is developed. No contact is visible with the younger gabbro of Beinn Bhuidhe, which lies north-west of Aodann. Paithankar (1968) suggests a correlation with the older phase of the quartz-gabbro of Garbh-dhail.

Granophyric quartz-dolerite of Sgùrr nam Meann

Three rock types present within this intrusion include porphyritic dolerite (with feldspar phenocrysts), aphyric dolerite and granophyre (Figure 7). The granophyre is developed as net-veins in the dolerites and locally in the adjacent hypersthene-gabbro of Ardnamurchan Point. The inner margin is determined by the later intrusion of the-quartz-gabbro of Loch Caorach, which has in some places fused the acid component of the granophyric quartz-dolerite, and this fused material has back-veined the quartz-gabbro, causing the development of a gradational contact. The outer contact is formed by the hypersthene-gabbro. On Beinn na Seilg the contact is flat-lying, the hypersthene-gabbro clearly forming a capping to the granophyric quartz-dolerite. Immediately to the south of Beinn na Seilg, however, the contact dips south at about 30°. Still further south, northerly dipping contacts are present. Skelhorn and Elwell (1966) suggest that detailed variation in the form of the contact is controlled by the attitude of the layering in the hypersthene-gabbro, marginal sills having formed parallel to the layering. The general dip of the contact is, nevertheless, outwards at between 25° and 30°, although a few areas do occur where steeper dips are found. The intrusion as a whole does not, therefore, have the form of a ring dyke at the present level of erosion. Indeed, the development of sheeted relationships suggests that magmatic emplacement was not vertical for parts of the intrusion. Skelhorn and Elwell (1966) list four possible forms of the intrusion; namely a ring dyke in which contacts are stepped, the present erosion level coinciding with a shallow step; a sill which connected centrally with a ring dyke or plug now replaced by later intrusions; a marginal remnant of ring dyke cap; or lastly, a ring dyke with a number of sills given off outwards (as proposed by Wells 1954b). This last possibility is probably the most reasonable, as Butchins (1973) records the presence of several sheets of granophyric dolerite cutting the hypersthene-gabbro between Sanna Bay and Sanna Point. Similarly, in the area of Plocaig, the sheet of granophyre (considered to be an acid cone-sheet by Richey et al. 1930) which cuts the hypersthene-gabbro is probably an extension of the granophyric quartz-dolerite.

The association of the granophyre with the aphyric dolerite is most interesting. The granophyre may contain inclusions of dolerite up to 10 m or more across, many of the large inclusions being rounded. In some places the dolerite inclusions have a fine-grained margin against the granophyre, ranging from a few centimetres to a metre wide. In other places nearby, or even on a different section of the same contact where the dolerite may have an angular contact with the granophyre, the dolerite can possess uniform texture throughout. Inclusions with a fine-grained margin often contain a faint banding parallel to their contact with the granophyre, and in some there occurs a development of minute feldspathic veins also parallel to the contact.

Net-veins of granophyre are given off sporadically into the wall rocks or dolerite bodies. The material of these net-veins appears to fill fractures in the dolerite, as dolerite blocks are often of such shape that they would approximately fit together were the veining material removed. Toward the large scale veins from which they arise, the net-veins may widen and include disorientated fragments of dolerite which cannot be so reconstructed. Skelhorn and Elwell (1966) believe that the small, entirely fine-grained bodies, and those larger bodies with fine-grained margins, formed by being enclosed in a granophyric magma when still unconsolidated. The angular bodies which do not show a fine-grained margin, and those with net-veining, must have formed after the dolerite had solidified.

The granophyric veining in the porphyritic dolerite is in the form of irregular sill-like and dyke-like bodies. Although the porphyritic dolerite only forms angular masses, both fine-grained margins coarsening inwards and coarse textures throughout are found. These are thought to have been formed in the same manner as the features seen in the aphyric dolerite. Detailed relationships between porphyritic dolerite, aphyric dolerite and granophyre, show that the emplacement of the porphyritic dolerite preceded that of the aphyric dolerite, a sequence confirmed by the presence of fragments of porphyritic dolerite within the aphyric dolerite. The intrusion is cut by members of the inner cone-sheet suite of Centre 2. Gribble (1974), in a geochemical study, compares the composition of the aphyric dolerite with dolerites associated with Centre 1 cone-sheets (the main Ben Hiant dolerite intrusion) and Centre 3 ring dykes, and finds little chemical difference with the rocks from Centre 3, but significant difference with those from Centre 1. This may indicate that whereas the petrogenesis of the cone-sheet dolerites is distinct from that of the ring dyke dolerites, there is no such distinction between ring dykes from Centres 2 and 3.

Eucrite of Beinn nan Ord

Resistance to weathering results in this intrusion generally forming higher ground than the quartz-gabbros on either flank. Its dyke-like form is better displayed than any other ring dyke in Ardnamurchan, with steeply dipping contacts apparent on Beinn na Seilg and Beinn nan Ord. This ring dyke is also characterised by the presence of two inwardly projecting arms, which cut through the earlier quartz-gabbro of Garbh-dhail. Further evidence for the relative age of this intrusion is provided by the absence of cone-sheets in the eucrite, whereas cone-sheets can be seen in the quartz-gabbro of Garbh-dhail to within a short distance of its margin with the eucrite. Brecciation makes the exact position of the contact difficult to discover, but nearby the eucrite generally becomes finer grained, and shows fluxion structure, while the quartz-gabbro becomes thermally altered.

The eucrite is a moderately coarse-grained rock composed of fairly abundant olivine, ophitic greenish-brown augite with associated iron ores, and a basic plagioclase of the labradorite-bytownite type which frequently shows extensive albitization. In some parts the intrusion is allivalitic, while in others the rock is rich in clinopyroxene. Intermixture of these two types can also be seen. Small rounded masses of coarsely ophitic, augite-rich eucrite, which occur in the more allivalitic parts, are suggested by Richey et al. (1930) to be cognate xenoliths. In many places the rock shows the effects both of brecciation and the later emplacement of granophyric material, which also forms patches of quartz and orthoclase. Richey et al. (1930) believe that after emplacement the eucrite was subjected to explosive shattering by an acid magma.

Quartz-gabbros of Loch Caorach and Beinn na Seilg

Although forming separate intrusions, these two masses are considered by Richey et al. (1930) to be portions of a single ring dyke. but they differ in rock type, the quartz-gabbro of Beinn na Seilg being distinguished by the presence of a secondary acid mesostasis, and so the correlation is not immediately obvious. The outer contact of both intrusions is generally against the granophyric quartz-dolerite, and inclusions, sometimes very large, of this rock are found in the marginal parts of the quartz-gabbros. Marginal areas also usually show the development of thin acid veins. On Beinn na Seilg, part of the outer contact of the quartz-gabbro is with the hypersthene-gabbro of Ardnamurchan Point. Members of the inner cone-sheet suite of Centre 2, which cut the granophyric quartz-dolerite and hypersthene-gabbro, do not penetrate the quartz-gabbro, but show evidence of thermal alteration in its vicinity. The inner contact of both gabbros is with the eucrite of Beinn nan Ord. In detail this is obscured by brecciation that affects not only the eucrite but the adjoining portion of the quartz-gabbros. North of Loch Caorach a sharp contact is seen, with the quartz-gabbro becoming finer toward the eucrite, but on the southern shore of Sanna Bay the contact is very vague. Richey et al. (1930) suggest these features indicate that there is little difference in age between the eucrite and quartz-gabbros, and one injection followed closely upon the other.

These gabbros, like many other gabbros in Ardnamurchan, show considerable variation in the amount of late crystallising acid material and the effects of this on the earlier formed constituents. In its least modified from. the magma has crystallised as an olivine-gabbro of eucritic affinities, but the olivine is usually decomposed. On Beinn na Seilg the intrusion has been affected by the migration of an acid magma, causing either hybridization or the develop-ment of an acid mesostasis. The effects of this later acid migration had been much less intense on the intrusion of Loch Caorach resulting only in a general albitization of the feldspars in the rock.

Younger quartz-gabbro of Beinn Bhuidhe

Unlike the older quartz-gabbro of Beinn Bhuidhe, this intrusion is not cut by the inner cone-sheets of Centre 2. Both the older quartz-gabbro and the cone-sheets show thermal alteration near their contact with this later intrusion, while the older quartz-gabbro is also intruded by quartz-dolerite which connects with the younger quartz-gabbro of Beinn Bhuidhe. The intrusion of the younger quartz-gabbro is also clearly a later event than the emplace-ment of the Beinn nan Ord eucrite, a screen of thermally altered eucrite occurring with a steeply dipping contact within the quartz-gabbro near the northern summit of Beinn Bhuidhe. There also, a coarse-grained, light weathering quartz-gabbro in contact with the fluxioned margin of a dark weathering quartz-gabbro suggests that the mass may include more than one intrusion. Elsewhere the rock is highly variable, with the development of an acid mesostasis. Near the contact with the Great Eucrite of Centre 3, the rock becomes fine-grained, and has been largely recrystallised. No contacts are visible with the fluxion gabbro of Portuairk or the quartz-gabbro of Aodann. Richey et al. (1930), and Richey (1933), have suggested that this intrusion is probably a west-ward continuation of the quartz-gabbro of Faskadale, which will be considered in the section on the plutonic rocks of Centre 3.

Fluxion gabbro of Portuairk

Although mapped as a distinct unit by Richey et al. (1930), because of the widespread development of a characteristic fluxion structure, this mass is clearly of a mixed nature, and has been produced by the modification of gabbroic or eucritic material by an acid magma. This interaction may have taken place with the basic rock in a solid or partially solid condition, but before the intrusion of the mass into its present position. The migration of an even later phase of acid magma has locally exaggerated the effects of this alteration.

The contacts of the mass with the three adjacent intrusions are generally obscure. Although an apparent contact with the Great Eucrite of Centre 3 is seen on the coast, in which the fluxion gabbro would appear the earlier intrusion, there is no marked contact alteration, and the exact significance of this contact is complicated by the fact that the outer part of the Great Eucrite is itself a fluxion rock.

Richey et al. (1930) suggest that the mass is later than the younger quartz-gabbro of Beinn Bhuidhe. If their correlation of that intrusion with the quartz-gabbro of Faskadale is accepted, it follows that the formation of the fluxion gabbro of Portuairk is more properly considered a Centre 3 event. They suggest its likely correlation with the fluxion gabbro of Faskadale. A detailed account of fluxion structures in gabbros is given on p. 63.

Aodann felsite

Small masses of dark grey, microporphyritic felsite are found cutting various members of the plutonic suite and the inner cone-sheets of Centre 2. The largest intrusion occurs to the south of Aodann and consists of a feldspathic matrix containing small crystals of albite-perthite and xenoliths of basalt. It is cut by a quartz-dolerite sheet and by thin basic dykes, but its general affinities are unknown.

The acid and basic magmas of Ardnamurchan

The spatial and temporal association of acid and basic magmas is a characteristic feature of most of the plutonic intrusions of Centre 2. In several bodies it is also evident that the emplacement of the two magma types was roughly contemporaneous. A similar association of acid and basic magmas occurs in intrusions of Centre 3 (p. 59) and even Centre 1 (p. 22).

Wells (1954b) suggests that the acid material of the granophyric quartz-dolerite owes its origin to having separated from a crystallising basic parent under the influence of a sudden reduction of external pressure. In contrast Skelhorn and Elwell (1966) believe it more likely that the acid material was derived as a result of the fusion of Lewisian country rock. They also suggest that the high-alumina basalt (porphyritic dolerite) facies of the granophyric quartz-dolerite was formed from a tholeiitic magma under high water pressure, and that the variation in composition of the aphyric dolerite facies was produced by mixing of a tholeiitic magma with an acid magma. Similar arguments may apply to other members of the intrusive complex. In terms of magmatic evolution, Skelhorn and Elwell (1966) disagree with Richey et al. (1930), who consider that the tholeiitic magma was produced by removal of olivine from an alkali basalt magma, which in turn produced the acid series by fractionation. Kennedy (1933) also considers that the tholeiitic magma was the parent for the alkali basalt, acid and eucrite-allivalite magmas. Skelhorn and Elwell (1966), however, believe that the alkali basalt magma was the parent for the high alumina basalts (which formed by accumulation of a basic plagioclase), and (by further accumulation of olivine) the eucrite-allivalite series. Holland and Brown (1972) note that a gap occurs in the composition range of the cone-sheets of Ardnamurchan, closely comparable to that discussed by Thompson (1972). They suggest that this gap may be formed by plagioclase separation together with some olivine, a mechanism which would favour crystal/liquid fractionation rather than the mixing of basalt and locally derived granitic liquids. However, they also consider that in addition to a fractionation mechanism, contamination by Lewisian country rock may have occurred during the production of the cone-sheet magma.

It is apparent, therefore, that evidence exists which supports both fractionation of basaltic magma and the assimilation or fusion of country rock, as factors acting in the petrogenesis of the intrusive complex. There is also evidence which both supports and argues against the direct association of the various magma types. However, work by Gribble and O'Hara (1967) suggests that incorporation of country rock material in basic magmas can only be on a small scale, since experimental evidence from the system $CaO–MgO–Al_2O_{3–}SiO_2$ reveals the presence of several thermal divides which would tend to restrict any such assimilation process from operating on a large scale.

The cone-sheets of Centres 1, 2 and 3

Intrusion of the cone-sheets was preceded by a period of updoming. This produced an elongate structure in Mesozoic sediments and Tertiary volcanics which trends north-east to south-west across the centre of the complex. The majority of the cone-sheets are quite thin but they occur in vast numbers and may collectively form extensive outcrops, although individually they are usually of very limited arcuate extent. The cone-sheets are chiefly composed of non-porphyritic quartz-dolerite, porphyritic dolerite or porphyritic basalt, but composite cone-sheets occur in which the margins are typically quartz-dolerite, with more acid centres of craignurite, granophyre or felsite. In the chilled edges and fine-grained marginal zones of the porphyritic cone-sheets, phenocrysts are not usually developed. Individual cone-sheets appear to have been intruded successively, for they bear well-chilled margins whether in contact with country rock or with an earlier cone-sheet. Even within a small area of sheets of similar trend a long history of activity may be indicated by dykes both cutting and cut by the cone-sheets. Cone-sheet fractures appear to have been formed before the emplacement of the cone-sheet magma, as fracture planes lying parallel to the cone-sheets, yet not occupied by intrusive material, may be observed. Where injection has occurred displacement of the wall rock takes place in a vertical sense.

Richey et al. (1930) divide the cone-sheets of Centre 2 into an outer suite and an inner suite. The outer suite, which has affinities with the Centre 1 cone-sheets, is principally composed of non-porphyritic quartz-dolerite sheets inclined at angles of the order of 30°, and which pre-date the emplacement of the hypersthene-gabbro of Ardnamurchan Point. In contrast, the inner suite, which has affinities with Centre 3 cone-sheets, is mainly composed of porphyritic dolerite and porphyritic basalt sheets inclined at about 70°, which post-date the emplacement of the hypersthene-gabbro. The inner cone-sheets of Centre 2 pre-date the emplacement of the Beinn nan Ord eucrite, whereas the Centre 3 cone-sheets pre-date the Great Eucrite of Centre 3.

This simple pattern of an outer and inner series is further confused by the presence of members of the outer cone-sheet suite cutting the hypersthene-gabbro near An Acairseid, to the south-east of Beinn na Seilg, and near Sanna Point, and the occurrence of non-porphyritic quartz-dolerite in the inner suite and porphyritic dolerite and porphyritic basalt in the outer suite.

Since many of the inner cone-sheets occur as isolated exposures, and have measured dips of 90° (observed by one of the authors, C.D.G., in the inner sheets about 1 km south-west of Achosnich), it is possible that some of the inner cone-sheets could be Tertiary basic dykes vertically intruded into the earlier igneous complexes.

The non-porphyritic quartz-dolerite cone-sheets are fine-grained rocks rich in iron ore and composed of a moderately basic plagioclase, augite, titanomagnetite, alkali feldspar of an albitic character, and quartz. They generally show a separation of the coarser grained and more basic components from an acid residuum, which was capable of migration and segregation into well-defined but unevenly distributed areas. The porphyritic cone-sheets are ordinary basalts and quartz-dolerites, containing phenocrysts of plagioclase.

Within the composite cone-sheets, the contact between basic and acid portions may be either sharp or gradational, or the two zones may be separated by a zone of intermediate composition which usually contains much altered and partly resolved basic xenoliths. Some of the felsitic centres may approach pitchstone in character, with the suggestion of an original glassy texture.

Holland and Brown (1972) state that chemically the cone-sheets cannot be subdivided into separate suites either in terms of their relative age of emplacement, or according to their disposition in relation to the three possible centres of magmatic activity. However, they have been able to provide evidence for the definition of a Hebridean tholeiitic series, but whether this series implies crystal fractionation of tholeiitic basalt magma, or mixing of this magma and a granitic melt derived by partial melting of crustal rocks, is uncertain. They do suggest, though, that tholeiitic basalt magma was available in large quantities during the Tertiary volcanism in north-west Scotland, shown by the formation of large, layered basic intrusions with tholeiitic affinities (Wager and Brown 1968); and that the cone-sheets may have originated by tapping of a basalt reservoir emplaced at fairly high levels within the crust, generally slightly later than the formation of the alkali basalt plateaux. Thus two Hebridean basalt magma series exist.

Since it is unlikely that the Ardnamurchan rocks differ from those of closely related complexes on Skye and Mull, then the strontium isotope data of Moorbath and Bell (1965) favours generation of the acid magmas chiefly from partial melting of the Precambrian crustal basement. Conversely, the lead isotope data of Moorbath and Welke (1969) shows extensive variation in the mixing proportions of younger upper mantle lead with ancient crustal lead in both acid and basic rocks, indicating that there is not only contamination of the basalts (alkali and tholeiitic), but the acid rocks appear to be a mixture of basalt differentiates and crustal remelts. In this context, Green and Wright (1969) note that, from the data given by Holland and Brown (1972), it appears that the cone-sheets of Centre 1 and those of Centre 2 near Mingary are the most silicic suggesting that this may be an area of late magmatic activity. It is also interesting to note that the progression from more basic to more acid is observed in small volcanic centres such as Glas Eilean (Paithankar 1967) and within most of the ring dykes of Centre 2 (Richey et al. 1930; Skelhorn and Elwell 1966).

Walker (1975) considers that the evolution of the Ardnamurchan igneous complex along with other Tertiary centres, is heralded by the rise of an acid diapir, which caused updoming of the overlying Mesozoic sediments and Tertiary basaltic volcanics, and preceded the rise of its parent basaltic magma. The emplacement of the cone-sheets is governed by a tendency of the rising magma to move in the direction of maximum excess hydrostatic pressure (see also Bradley 1965).

No remains of this acid diapir are preserved on Ardnamurchan, so that the acid magma, if present, must have either been entirely ejected to form acid volcanics, or removed by erosion if it ever formed a high-level pluton.

In contrast to this hypothesis of almost passive emplace-ment of the cone-sheets, Phillips' (1974) concept involves the dynamic loading of the cover to a magma chamber by magmatic pressure. Sudden expansion of magma may give rise to the initiation of shear fractures at several levels on the shoulder of the magma chamber, which by upward extension would allow the central region of country rock, overlying the magma chamber, to rise. This would be accompanied by the opening of the shear fractures and the inflow of magma to form the cone-sheets, but Walker (1975, in discussion) points out that basalt magmas seem to be the least likely to exert localised pressures, and that no structures interpreted as the surface or near surface manifestation of cone-sheets have been described from modern basaltic volcanoes. Phillips' (1974) hypothesis does, however, explain the absence of cone-sheets from the zone of country rock near the apparent focus of any suite. This is one of the major objections to the mechanism of emplacement of the cone-sheets along tensile fractures originating from localised magmatic pressure, as proposed by Anderson (1936). Nevertheless, Phillips' (1974) hypothesis may also be criticised in terms of the periodic history of activity required to account for the cone-sheet development on Ardnamurchan, and the requirement that three independent yet intersecting fracture systems in close spatial and temporal proximity must have formed if the cone-sheets are considered to occur along fractures which are circular in plan.

Durrance (1967) suggests that the outcrop pattern of all the cone-sheets of the complex may be explained in terms of a single conjugate shear fracture system which originated from a centripetal stress field caused by a reduction in magmatic pressure, the fractures opening to admit the cone-sheets when magmatic pressure increased. Durrance (1967) also suggests that torsional stresses may accompany the emplacement of the cone-sheets along the fractures, determining whether sinistral or dextral shears open. In this context, it is interesting to note that the cone-sheets attributed to Centre 1 and the outer suite of Centre 2 largely occupy sinistral shears, and are generally composed of non-porphyritic quartz-dolerite, while the inner suite of Centre 2 cone-sheets and the cone-sheets of Centre 3 largely occupy dextral shears and are generally composed of porphyritic dolerite or porphyritic basalt. These divisions perhaps represent a broad grouping of the cone-sheets in order of intrusion.

Centre 3

Centre 3 is the youngest plutonic ring complex of Ardamurchan (Figure 2) and forms the largest and most complete set of ring intrusions in the British Isles. Richey et al. (1930) regarded the rocks of this Centre as outward dipping ring dykes, becoming progressively younger towards the centre and formed by a process of cauldron subsidence. However, this model is not universally accepted and more recent studies have suggested inward dipping, funnel or saucer shapes for at least some of the intrusions of Centre 3. This account attempts to describe the geology of Centre 3 in the light of these recent studies, including work by Smith (1957), Bradshaw (1961), Wills (1970) and Walsh (1971). The rocks are mainly coarse-grained gabbros with the development of a relatively small volume of intermediate rocks in the centre of the complex. Since the structure of the complex is not known for certain, the descriptive term "ring intrusion" is used here in preference to the genetic term "ring dyke".

Intrusive plutonic rocks

The subdivisions of the rocks ascribed to Centre 3 are shown in (Figure 8). It should be borne in mind that in many cases the sequence of intrusion is uncertain and. as is shown in the account, the divisions themselves are in some respects inadequate.

Quartz-gabbro of Fuskadale

This is the outermost ring intrusion of Centre 3 and extends from Faskadale Bay south and then west around almost half the circumference of the complex (Figure 8). It may also continue westwards under a roof of rocks of the Centre 2 ring complex to re-emerge south of Sanna Bay as the younger quartz-gabbro of Ben Bhuidhe (see p. 45).

The gabbro is typically composed of augite, zoned labradorite and substantial amounts of magnetite with small amounts of interstitial quartz and alkali feldspar. (Table 4) gives approximate modal compositions for the Centre 3 rocks. An indication of the petrography of the representative samples of the quartz-gabbro of Faskadale is given in (Table 4). However, the quartz-gabbro is a very variable rock in detail, and locally may range from an olivine-eucrite to a basic granophyre where an acid mesostasis has developed.

The outer contacts of the intrusion cut the outer cone-sheet complex and the Centre 2 ring intrusions in the south. However, the junction with the surrounding rocks cannot be located with sufficient accuracy to establish the shape of the intrusion.

Fluxion gabbro of Faskadale

The quartz-gabbro of Faskadale (Figure 8) surrounds the fluxion gabbro of Faskadale, which occupies a narrow strip of country mainly to the west of the Allt Faskadale.

(Table 4). Modal proportions of the Centre 3 rocks.

	Eucrites	**Quartz gabbros**	**Fluxion gabbros**	**Dolerite**	**Tonalite**	Quartz-monzonite
Plagioclase	64	52	51	57	39	36
(An65-75)	(An 50-60)	(An 50-60)	(An 50-60)	(An 30)	(An-20-30)	(An-20-30)
Quartz +Alk. Feldspar		2	2	3	*10/20	*90/28
Pyroxene	17	30	30	27	7	5
Olivine	16					
Biotite		2	2	4	8	9
Hornblende					4	4
Opaques	3	8	9	6	6	5
Accessories + Alteration		6	6	3	6	3

*Quartz/Alkali feldspar

The values given are *very* approximate, especially for abundances below 10%. Some of the intrusions have insufficient data to give even approximate values.

Fluxion gabbro is common in Ardnamurchan and Richey et al. (1930) point out that this rock, like the other fluxion gabbros, has small amounts of biotite as a normal constituent. However, biotite can also be found in the quartz-gabbros, and there is very little difference in petrography between quartz-gabbros and fluxion gabbros. This is shown in (Table 4), where the fluxion gabbro modal analysis would approximate to the mode of typical samples of the fluxion gabbro of Faskadale. The fluxion structure is regarded as evidence for injection of the mass in a semi-fluid condition. The fluxion planes dip at an angle of 20 to 40 degrees towards the focus of Centre 3. However, there is no direct evidence for the shape of the intrusion. Contacts between the fluxion gabbro and the outer quartz-gabbro are difficult to locate but the limited evidence available suggests the fluxion gabbro is the later (Richey et al. 1930).

Gabbro of Plocaig

This is a small mass on the margin of the Great Eucrite, which appears separate from, and older than, the Great Eucrite (Richey et al. 1930, p. 291).

Porphyritic gabbro of Meal! nan Con screen

This is a small area of altered gabbro which is entirely surrounded by, and may be part of, the Great Eucrite (Bradshaw 1961). This conclusion is supported by analyses of this "gabbro" (Walsh 1971), which show differences in chemistry between the eucrites and the gabbros of Centre 3. The analyses from the porphyritic gabbro of Meall nan Con show greater similarities to the analyses from the eucrites.

Great Eucrite

The most prominent topographical feature of the area occupied by Centre 3 is the massive ring of the Great Eucrite (Figure 8). This rock is highly resistant to weathering and occupies a ridge of high ground, producing a natural amphitheatre around the lower-lying area of the inner part of the complex. There is much evidence of glaciation with abundant roches moutonnées and glacial erratics. The Great Eucrite is by far the largest of the intrusions of Centre 3, representing over one half the total area of the exposed rocks.

Petrographically the Great Eucrite is typically a coarse feldspathic gabbroic rock containing both augite and olivine, the proportions of which can vary substantially, a representative modal composition being given in (Table 4). The term eucrite has no unequivocal definition, generally being used for a gabbroic rock with a zoned calcic plagioclase near to bytownite in composition, and containing olivine and pyroxene, with subordinate iron ore and orthopyroxene. In a few localities orthopyroxene may be more abundant than clinopyroxene, but clinopyroxene usually predominates. (Table 4) shows the major petro-graphic differences between the Great Eucrite and the quartz- and fluxion gabbros. In the field the higher concentration of plagioclase and the less abundant ore minerals give the eucrites a lighter colour. The presence of rusty coloured oxidation of the olivine is also frequently diagnostic of the eucrites. However, although typical eucrites and gabbros can readily be distinguished in the field, both rocks are very variable and in many places it is difficult to distinguish one from the other. The rocks surrounding the eucrite have in some places suffered contact alteration by the intrusion of the presumably later eucrite, but the eucrite itself shows no evidence of a chilled margin. Although contacts between the eucrite and the quartz- and fluxion gabbros of Faskadale are hard to find, the Great Eucrite is presumed to be the later intrusion but the evidence is not conclusive.

Biotite-eucrite and inner eucrite

These two "intrusions" may be conveniently considered together; and with the Great Eucrite. Richey et al. (1930) separates the Great Eucrite, the biotite-eucrite, and the inner eucrite and suggests further separate zones (Harry and Richey 1963; Richey personal communication). However, Bradshaw (1961) and Smith (1957) from a detailed study conclude that the three eucrites are all part of a single intrusion, emplaced more or less at the same time. Bradshaw shows that biotite occurs sporadically throughout the eucrites but is not restricted to, nor always present in, the biotite-eucrite. He also suggests that the intrusion is funnel-shaped. rather than an outward dipping ring dyke.

Quartz-gabbro of Meall an Tarmaehain summit

This small mass is considered by Richey et al. (1930) to be later than the surrounding eucrite. However, its relations with the surrounding rocks are hard to establish in the field.

A recent study of the clinopyroxene compositions from the rocks of Centre 3 (Walsh 1975) has shown that the pyroxenes of the Meall an Tarmachain gabbro are different from the pyroxenes of all the other Centre 3 gabbros. There is a substantial increase in the iron content of the clinopyroxenes from this intrusion.

Quartz-dolerite veined with granophyre

There is within the Great Eucrite a narrow ring intrusion of quartz-dolerite veined by granophyre. This intrusion runs intermittently around half of the centre but, as with several other intrusions, dies out to the north-west. The granophyre occurs as small masses and as "net-veining" in the dolerite and a discussion of this feature is given in the Centre 2 account (p. 47).(Table 4) shows that petrographically the dolerite can be distinguished from the gabbros and eucrites by the greater amount of biotite, and the more sodic composition of plagioclase feldspars. Unlike the gabbros and eucrites it is a very homogeneous rock, and is also finer grained. In the granophyre true granophyric texture is not common, and "microgranite" might be a better term. The intrusion of quartz-dolerite veined with granophyre was regarded by Richey et al. (1930) as the best example of a ring dyke in Centre 3. dipping outwards from the centre at about 70°. The dolerite portion was probably emplaced along a ring fracture, consolidated and then brecciated, before the emplacement of the "granophyre" along cracks and fissures. Despite its close association with so much basic material (granophyre forms less than 5% of the intrusion) the granophyre is a very acid rock with a silica content in excess of 72% even at the very contact with the dolerite (Walsh 1971). Gribble (1974) concludes, from a geochemical examination of this quartz-dolerite, that it is similar to the quartz-dolerite (also veined by granophyre) of Centre 2. but quite different from the quartz-dolerites of Centre 1.

Quartz-gabbros

The three quartz-gabbro masses of Centre 3 are presumed by Richey et al. (1930) to have originally been part of one intrusion which occupied the whole area of the inner part of the complex, which was subsequently intruded by later rocks. The outermost of the three masses forms an almost complete ring intrusion enclosed by the eucrites (Figure 8). It occupies a low-lying area of country and is poorly exposed, by comparison with other members of Centre 3.

The quartz-gabbros are heterogeneous rocks showing considerable variations in the proportions of the different minerals present ((Table 4) gives an average modal composition). The quartz-gabbros are frequently pegmatitic and in addition to the main mineral phases (plagioclase, augite and ore minerals) biotite is present, being here slightly more abundant than in the outer gabbros. The other minerals include alteration products which Wills (1970) identifies as a "greenschist facies assemblage superimposed during a long period of cooling and auto-metasomatism".

Detailed mapping of the gabbro by Wills (1970) fails to establish unequivocally whether the outer margin (of the outermost intrusion) dips inwards or outwards, or whether the gabbro is younger than the surrounding eucrite. There is no evidence of a chilled margin to the gabbro and while it is assumed that it is post-eucrite it was presumably emplaced whilst the eucrite was still warm.

Fluxion gabbro of Glendrian

This intrusion is closely associated with the quartz-gabbros described above (Figure 8). It forms a prominent topographical feature, is better exposed than the quartz-gabbros and has weathered out to form an "inner" ring within the major ring formed by the Great Eucrite.

(Table 4) shows the mineralogy of typical fluxion gabbro to be very similar to that of the quartz-gabbro. although some increase in the amount of oxide minerals is often found.

The Glendrian fluxion gabbro almost certainly post-dates the surrounding quartz-gabbro, as it contains xenoliths of quartz-gabbro. The fluxioning structure has been mapped in detail by Wills (1970) and generally dips inward towards the centre at 30° to 45°. Contacts between the fluxion gabbro and quartz-gabbro cannot be located accurately, partly through lack of exposure. and partly because the fluxion structure is not always well developed.

Fluxion gabbro of Sìthean Mór

Richey el al. (1930) suggests that the fluxion gabbro of Sìthean Mór post-dates the three quartz-gabbros and pre-dates the fluxion gabbro of Glendrian. However, there is no evidence at all to show the age of the Sìthean Mór intrusion, relative to the two innermost gabbros, and it is best considered separately from those.

The Sìthean Mór gabbro is a crescent-shaped mass which is entirely surrounded by the eucrites (Figure 8). Only the northern section of the intrusion is fluxioned. The southern portion is non-fluxioned and is a typical quartz-gabbro. The central part of the mass consists of inter banded layers of fluxion gabbro and quartz-gabbro.

The modal analyses given in(Table 4), of quartz- and fluxion gabbros indicate the approximate compositions of the gabbros. The Sìthean Mór intrusion has a marginal apophysis to the south which contains xenoliths of the eucrite and establishes the post-eucrite age of the intrusion. In the middle of the intrusion the bands of fluxion gabbro and quartz-gabbro dip towards the centre at approximately 60°. In addition the fluxioning dips towards the centre at a steep angle (about 70°). If the fluxioning structure lies parallel to the margins of the Sìthean Mór intrusion, there is little doubt that this mass dips inwards, and not outwards as suggested by Richey et al. (1930).

Tonalite and quartz-monzonite

The last stage in the development of the rocks of Centre 3 was the formation of the distinctive tonalite and related quartz-monzonite, which occupy the centre of the area. Although not large the oval-shaped intrusions form one of the most extensive areas of intermediate plutonic rocks in the Scottish Tertiary Igneous Province.

In hand specimen the rocks are quite distinctive with biotite set in a feldspathic groundmass. In thin section the rocks contain plagioclase, alkali feldspar, quartz, augite, hornblende, biotite, magnetite, ilmenite, apatite and chlorite, indicating a disequilibrium assemblage. In the tonalite the grain size variations are significant and the outer, fine-grained and more acid portion is regarded as a chilled margin. Acid veins also extend into the surrounding gabbroic rocks in places. However, there are no signs of alteration to the surrounding gabbros at the margin of the tonalite. Definite contacts between tonalite and the gabbro are very hard to find. Wills (1970) suggests, on the basis of two contacts, that the outer contact of the tonalite dips steeply outwards. On the other hand two contacts, found at the margin of the quartz-monzonite with the tonalite, dip inwards at 65°. It is unlikely, though not impossible, that these two intrusions have substantially different shapes.

The small mass of quartz-monzonite is distinguished from the tonalite by its greater biotite content, which is present as large brown platy crystals. (Table 4) gives the modal compositions of the tonalite and quartz-monzonite rocks.

The structure of Centre 3 and the importance of fluxion structures in the gabbros

One of the problems of Centre 3 which is still unresolved is whether the intrusions comprising the complex dip inwards or outwards. None of the recent studies has disproved the original concept that the intrusions are a series of outward dipping ring dykes (Richey et al. 1930) and the evidence from the quartz-dolerite veined with granophyre would certainly support this view. However, this is a relatively small intrusion, probably emplaced along a ring-fracture within the Great Eucrite, and it is quite possible that it has a different shape to the main ring intrusions.

On the other hand the fluxion structure of the three gabbro intrusions of Faskadale, Sìthean Mór and Glendrian suggests a funnel or saucer shape, assuming that the fluxioning structure is a flow phenomenon and lies parallel to the walls of the intrusion. However, this inference may be quite invalid, since examination of modern lava flows show that the fluxion banding and the boundary of the flows are not invariably parallel. The limited evidence from the contacts of the intrusions suggests that the Centre is funnel-shaped rather than the conventional "ring-dyke" structure.

The term fluxion gabbro is used by Richey et al. (1930) to describe gabbros in Ardnamurchan where there is alignment of the plagioclase feldspar crystals in one particular direction. The fluxion structure was considered to have been produced by flow within the magma that subsequently crystallised to form the various fluxion gabbros. Thus the term has both descriptive and genetic implications. The problem that remains unresolved is whether the fluxioning is parallel to the sides of the intrusions (in which case there is little doubt that the intrusions of Centre 3 dip inwards).

It is considered significant that in Centre 3 fluxion gabbro invariably follows and is closely associated with non-fluxion gabbro. The fluxion gabbro of Faskadale follows the quartz-gabbro of Faskadale, and indeed in places the two cannot be separated in the field. Richey et al. (1930, p. 289) regard them as separate intrusions but found only one apparent contact between the two intrusions. The Sìthean Mór intrusion is part quartz-gabbro and part fluxion gabbro with the central portion a mixture of fluxion and non-fluxion gabbro. Typical hand specimens of the fluxion biotite-gabbro of Glendrian can be distinguished from the surrounding quartz-gabbro, but Richey et al. (1930, p. 334) note that "in the field their line of separation is sometimes difficult to determine".

There is no substantial difference in modal petrography between Centre 3 fluxion and non-fluxion gabbros (Table 4), and there is also no discernible difference in their major or trace element chemistry (Walsh 1971). Nor can any difference in mineral chemistry be detected. Walsh (1975) showed very similar clinopyroxene compositions for all the main gabbro intrusions (Figure 9).

It is therefore tentatively suggested that the fluxion gabbros represent the later stages in the emplacement of the gabbro intrusions. The fluxioning structure was formed by movement of the magma in a semi-solid condition. as a crystal mush.

If this hypothesis is correct, then the fluxion structure indicates the direction of movement of the magma, and hence it would be reasonable to conclude that the intrusions dip inwards.

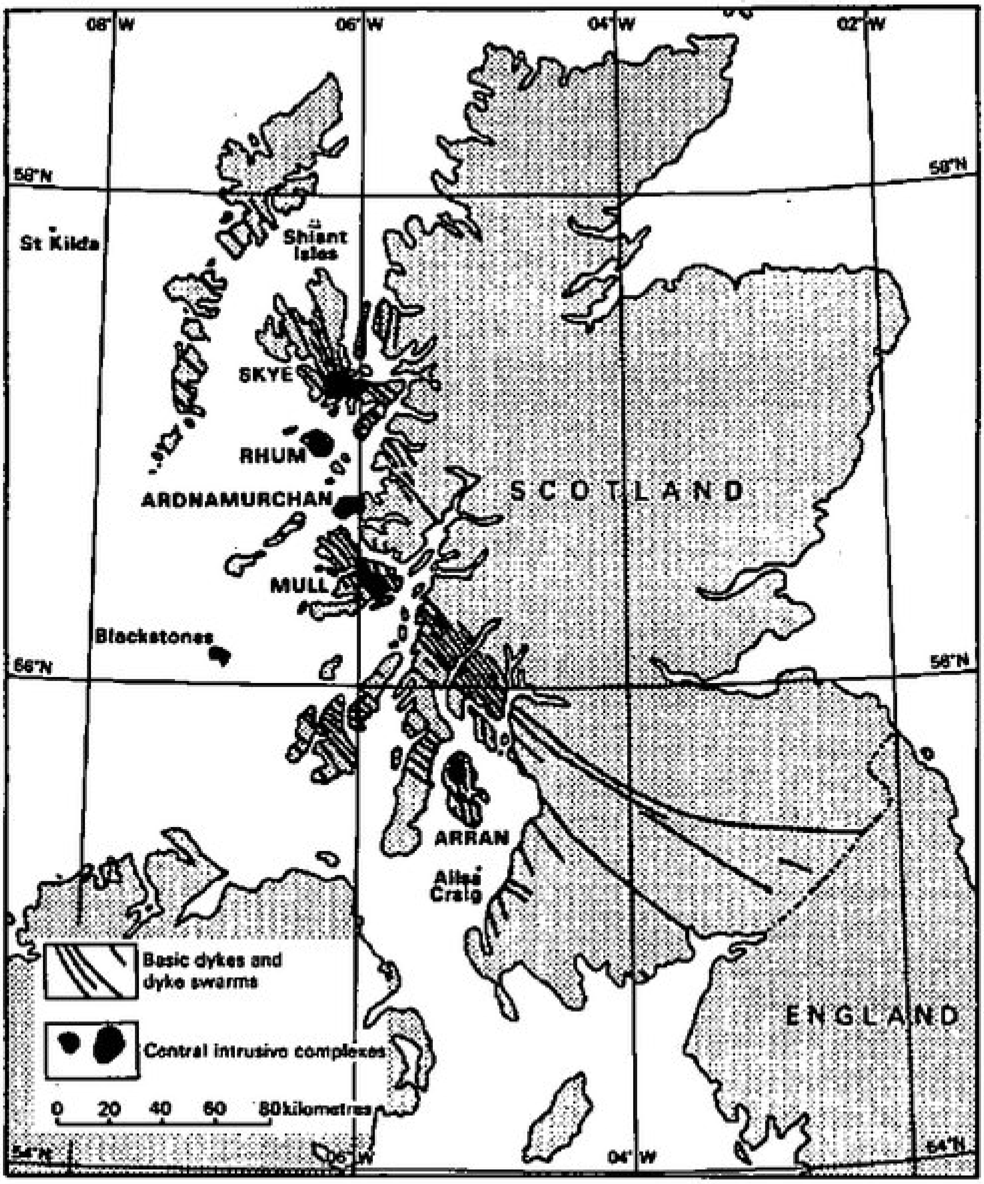
The petrogenesis of the rocks of Centre 3

It has now been demonstrated that all the basic rocks of Centre 3, the eucrites, the gabbros, and the dolerite, arc closely related and form three separate and distinct groups of rocks which are part of a fractionation sequence (Walsh 1975). Analyses of clinopyroxenes from the three eucrites show only a very small range of compositions, as do clinopyroxenes from the Centre 3 gabbro intrusions. No discernible differences could be found between the "outer" gabbros of Faskadale and the "inner" gabbros of Sìthean Mór and Glendrian. No differences are seen in clinopyroxene compositions from fluxion and non-fluxion gabbros (Figure 9). However, when the compositions of the gabbroic clinopyroxenes are compared with the eucritic clinopyroxenes there is a significant increase in Fe/Mg ratio. This systematic increase in Fe/Mg ratio continues for the dolerite of Centre 3, which shows a substantial iron enrichment relative to the gabbros. This trend in pyroxene compositions is comparable to other fractionated tholeiitic intrusions such as the Skaergaard intrusion of E. Greenland (Muir 1951; Brown 1957; Brown and Vincent 1963), and the Bushveld intrusion of South Africa (Atkins 1969). The Ardnamurchan clinopyroxenes also show changes in the concentrations of other elements such as a fall in the Cr and Ni contents. In addition the composition of biotites from Centre 3 gabbros and dolerite show the Fe/Mg ratio increasing from the gabbro to the dolerite.

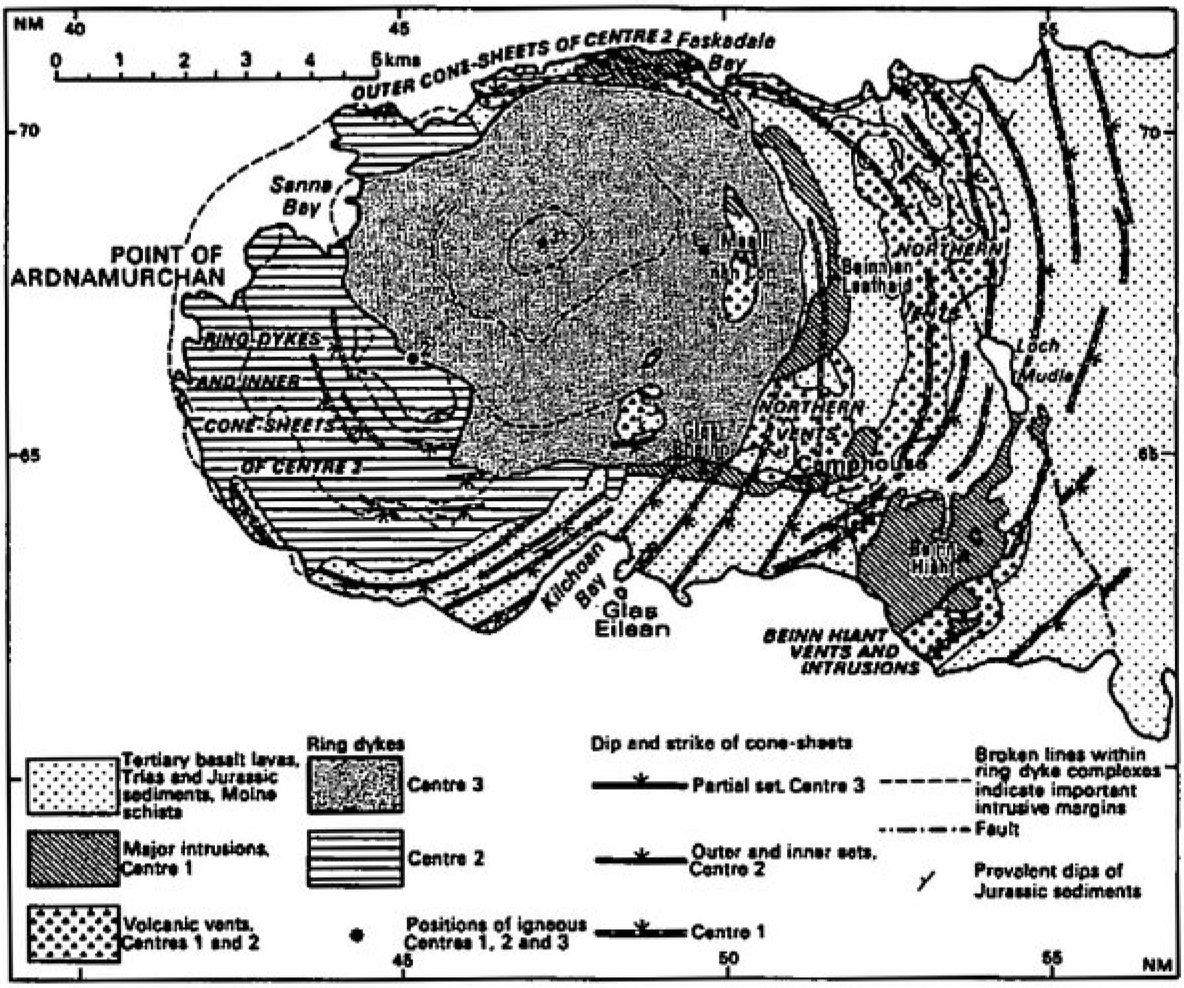
Nevertheless, these changes, which are characteristic of a tholeiitic fractionation sequence, are not found in the intermediate rocks, namely the tonalite and the quartz-monzonite. The Fe/Mg ratio of the clinopyroxenes from these intermediate rocks decreases instead of increasing and is substantially less than in clinopyroxenes of the dolerite (Figure 9). Furthermore the biotites from the tonalite and quartz-monzonite have lower Fe contents than biotites from either the dolerite or even the gabbros.

These results demonstrate that in Centre 3 all the basic rocks are closely related and represent three stages in the fractionation of basic magma. The tonalite and quartz-monzonite in the very centre of the complex cannot have formed by continued fractionation of the magma and instead are interpreted as hybrids formed by the partial remelting and assimilation of country rocks into basic magma.

References



(Figure 1) The Tertiary igneous centres of Scotland and their associated dyke swarms (based on Richey et al. 1930).



(Figure 2) The Tertiary intrusive complexes of Ardnamurchan—Centres 1. 2 and 3 (based on Richey et al. 1930).

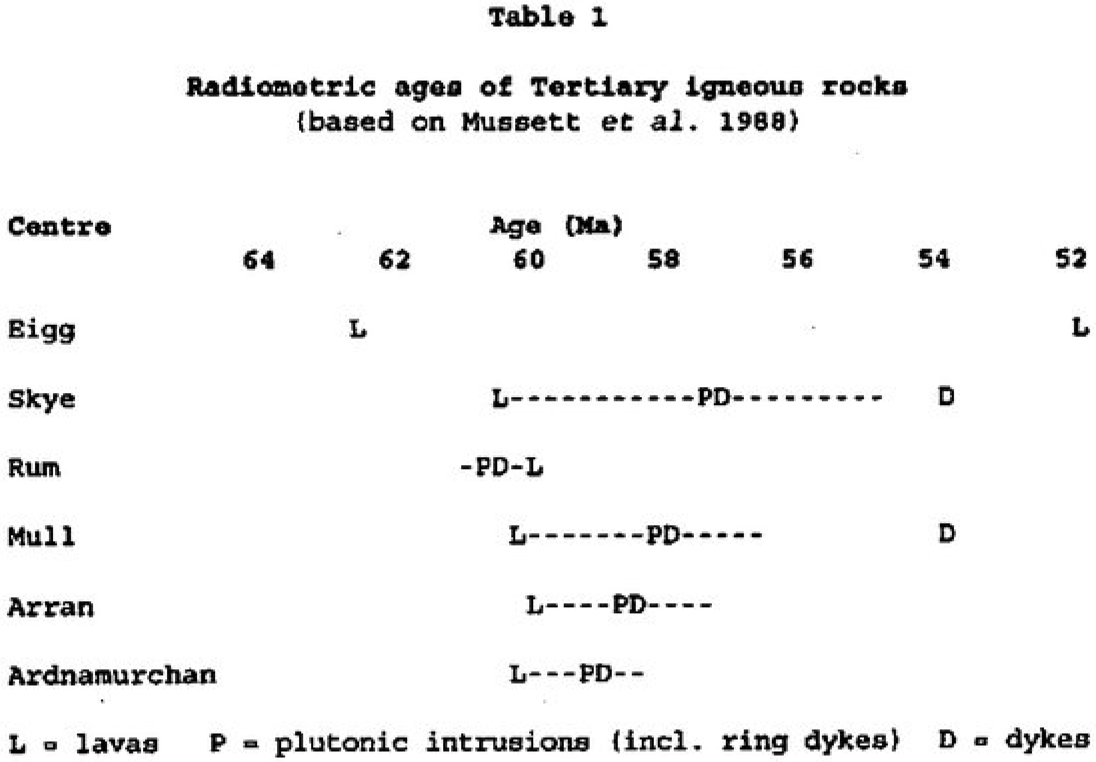


Table 1

Radiometric ages of Tertiary igneous rocks (based on Mussett et al. 1988)

Centre	Age (Ma) 64	62	60	58	56	54	52
Eigg		L					L
Skye			L------	------PD--	--------	D	
Rum			-PD-L				
Mull			L----	---PD--	---	D	
Arran			L----	PD----			
Ardnamurchan			L---	PD--			

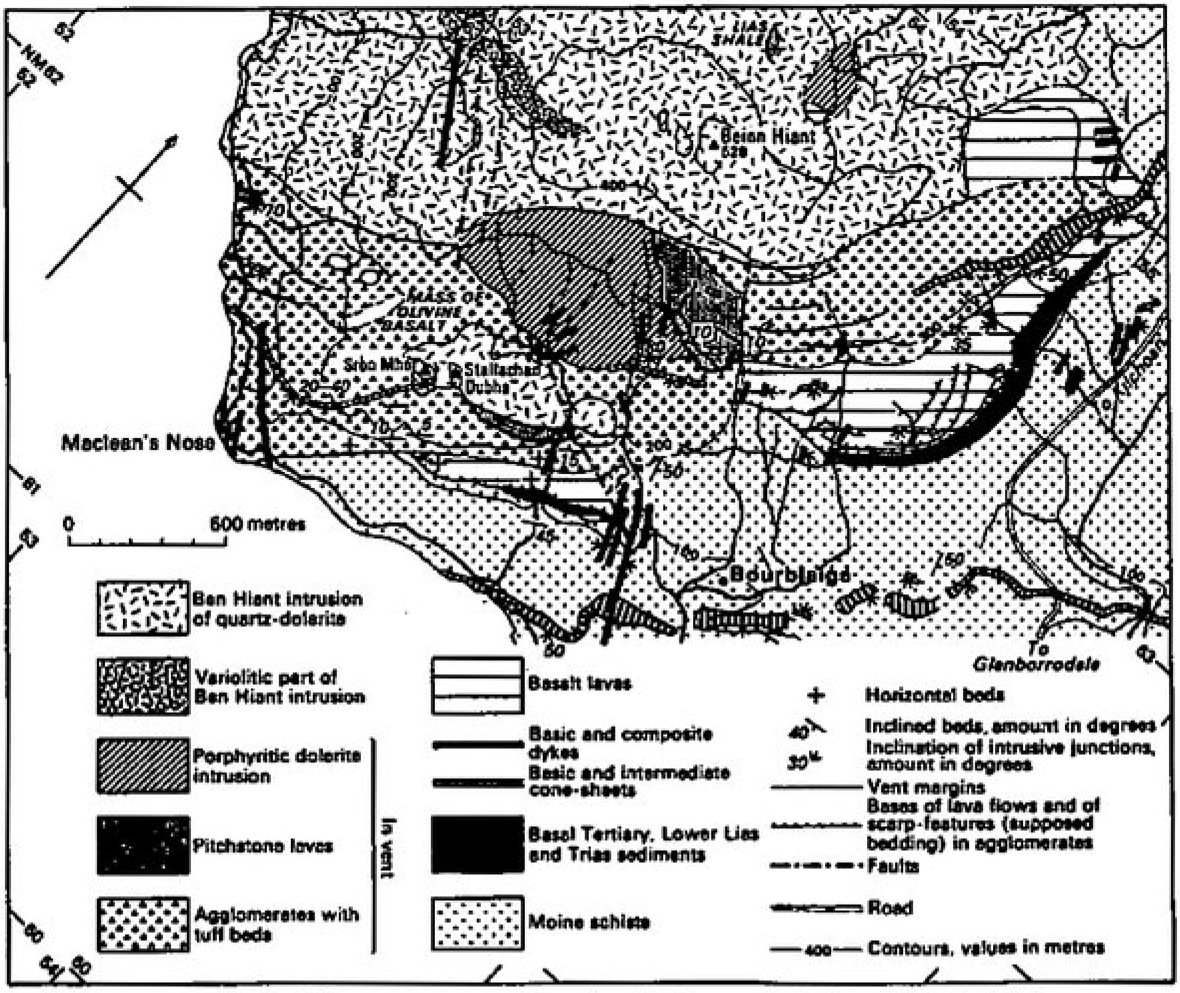
L = lavas P = plutonic intrusions (incl. ring dykes) D = dykes

(Table 1) Radiometric ages of Tertiary igneous rocks (based on Mussett et al. 1988)

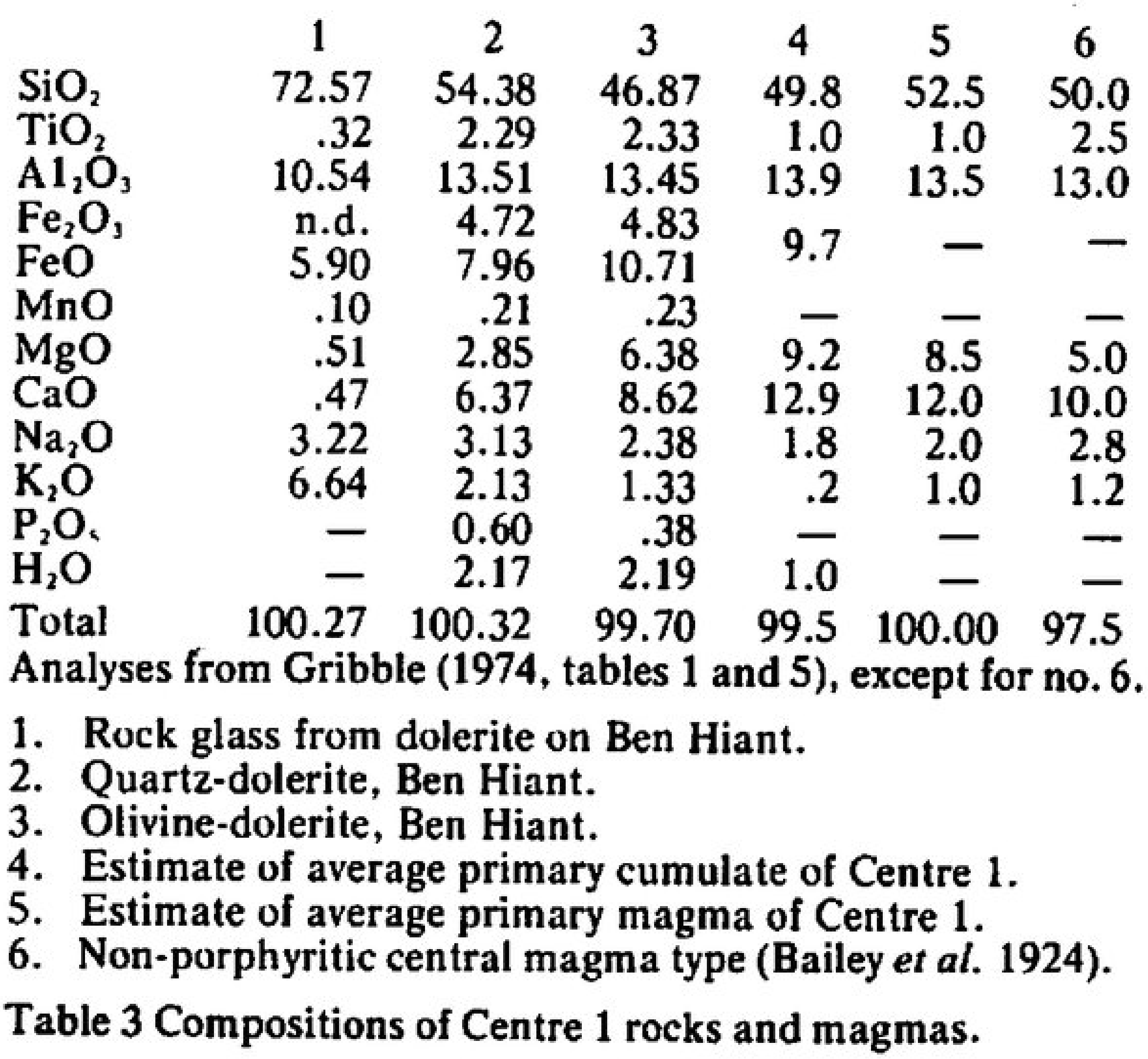
JURASSIC (176m +)

Series (location and thickness)	*Stages*	*Zones* (recognised or equivalent strata)	*Rock types and fossils*
Great Estuarine Series 3m (at Sron Bheag)	BATHONIAN and topmost BAJOCIAN		black fissile shales with *Estheria murchisoniae*
	LOWER BAJOCIAN	*Hyperlioceras discites* subzone	blue shales or flags with *Docidoceras* and calcareous beds with *Reynesella*: also limestone with *Platygraphoceras*
Inferior Oolite (g^4) 35m *in situ* only at Maol Buidhe, 2km S.W. of Kilchoan	AALENIAN	*Graphoceras concavum* zone	hard white limestone with *Ludwigella cornu*
		Ludwigia murchisonae zone	limestone with varied fauna including *Ludwigella flexilis*, blue sandy limestones and hard limestones with *Ludwigia* cf. *murchisonae* limestone with doubtful *Ancolioceras* (*Hudlestonia sinon* subzone?)
		Tmetoceras scissum zone	sandy beds underlying limestones containing many species of *Leioceras*
Upper Lias (g^3) 6m west shore of Kilchoan Bay 1.5km S.W. of Pier	TOARCIAN	*Pleydellia aalensis* subzone	dark flags and shales with *Pleydellia aalensis*.
		Dumortieria moorei subzone	flags and shales with cementstones containing *Dumortieria brancoi* fine-grained purplish shales with limey ironstone (= Raasay Ironstone). Rocks frequently baked by Tertiary igneous intrusions, but have yielded various species of *Dactylioceras*
Middle Lias (g^2) 12m north shore 3km east of Rudha Groulin	DOMERIAN	Scalpa Sandstone	sandstone without fossils, often baked
			sandy, well-bedded shales with poor fossiliferous horizons
On west side of Kilchoan Bay	LOWER PLIENSBACHIAN	Pabba Beds	including *Gryphaea obliquata* and other species of *Gryphaea*, belemnites and bivalves
Lower Lias (g^1) 120m + on foreshore, south of Mingary Pier	SINEMURIAN HETTANGIAN	Broadford Beds	hardened shales and thin limestones with *Ostrea* sp.
TRIASSIC (<5m in thickness) Found on foreshore at Kilchoan where Mingary pier is actually built on Trias. Also forms a thin band of sediments on eastern flank of Ben Hiant, separating the Tertiary rocks (basalts) from the underlying Moines			Various rock types comprise the Trias sediments, but generally these include red sandstones, conglomerates, schist-breccia and cornstones (fine-grained limestones). It should be noted that the basal Trias beds (conglomerates and red sandstones) are indistinguishable in the field from the Moines. No fossils have been discovered.

(Table 2) Mesozoic rocks of Ardnamurchan.



(Figure 3) The Ben Hiant vent-complex (based on Richey et. al. 1930 and Gribble 1974).



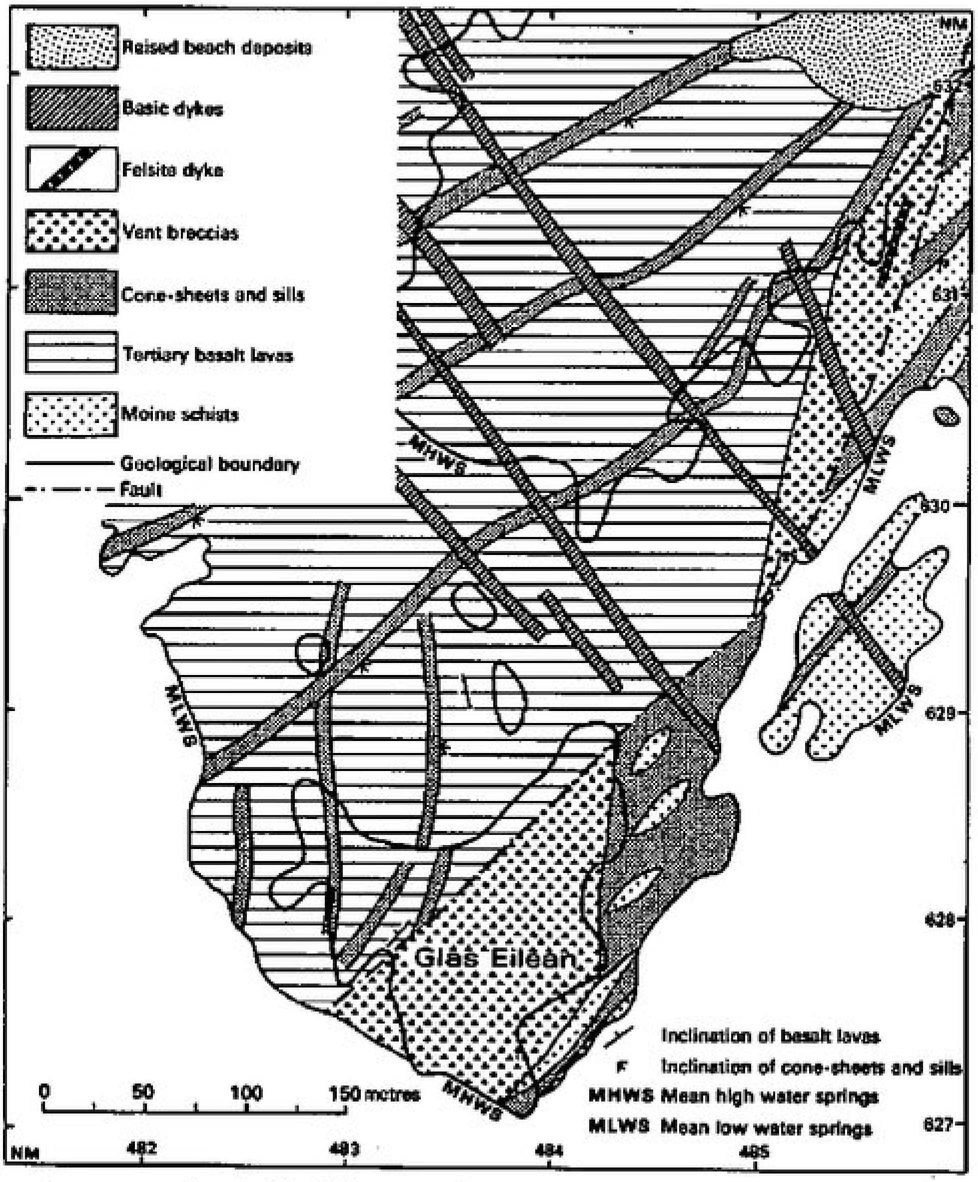
	1	2	3	4	5	6
SiO_2	72.57	54.38	46.87	49.8	52.5	50.0
TiO_2	.32	2.29	2.33	1.0	1.0	2.5
Al_2O_3	10.54	13.51	13.45	13.9	13.5	13.0
Fe_2O_3	n.d.	4.72	4.83	9.7	—	—
FeO	5.90	7.96	10.71			
MnO	.10	.21	.23	—	—	—
MgO	.51	2.85	6.38	9.2	8.5	5.0
CaO	.47	6.37	8.62	12.9	12.0	10.0
Na_2O	3.22	3.13	2.38	1.8	2.0	2.8
K_2O	6.64	2.13	1.33	.2	1.0	1.2
P_2O_5	—	0.60	.38	—	—	—
H_2O	—	2.17	2.19	1.0	—	—
Total	100.27	100.32	99.70	99.5	100.00	97.5

Analyses from Gribble (1974, tables 1 and 5), except for no. 6.

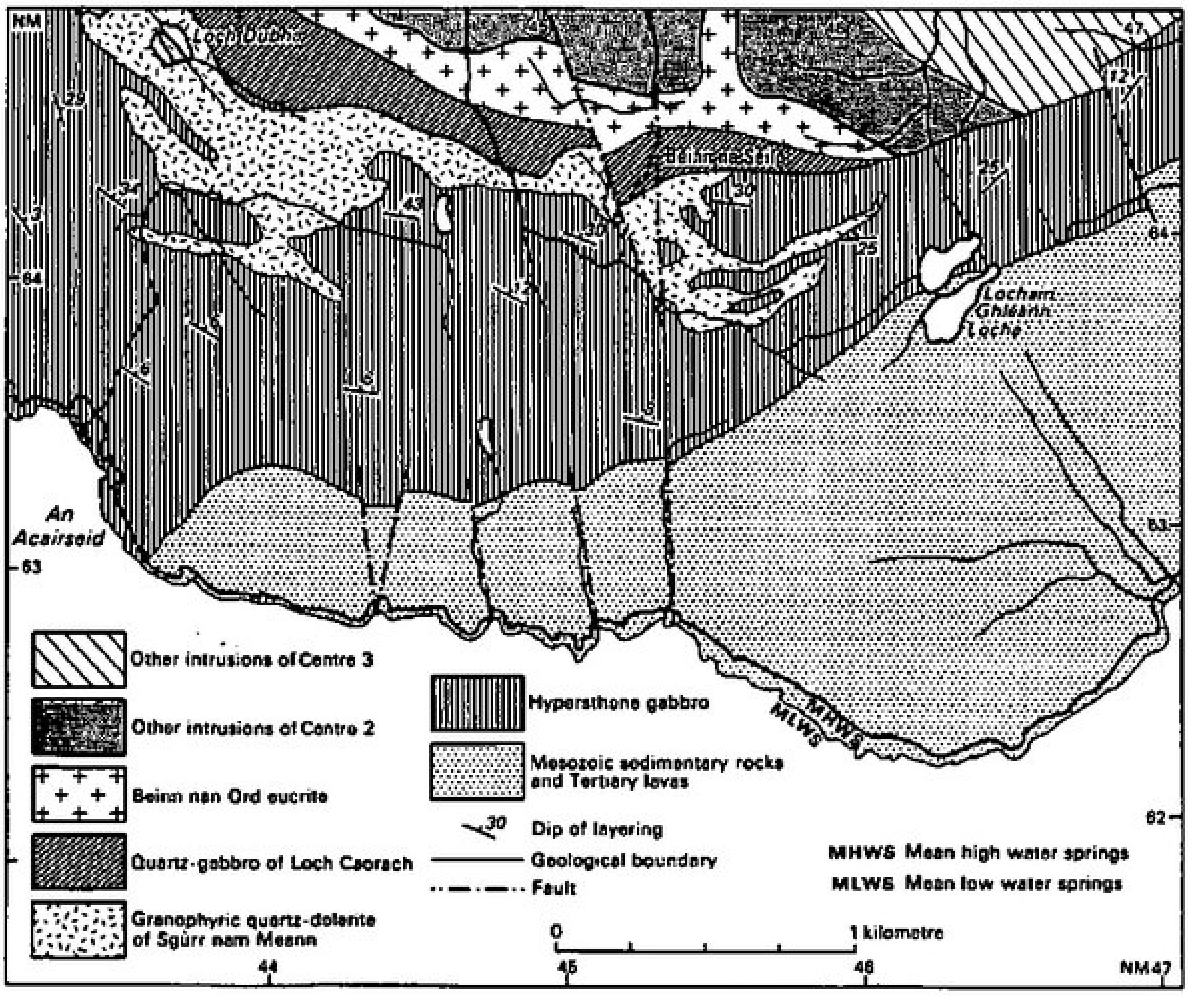
1. Rock glass from dolerite on Ben Hiant.
2. Quartz-dolerite, Ben Hiant.
3. Olivine-dolerite, Ben Hiant.
4. Estimate of average primary cumulate of Centre 1.
5. Estimate of average primary magma of Centre 1.
6. Non-porphyritic central magma type (Bailey *et al.* 1924).

Table 3 Compositions of Centre 1 rocks and magmas.

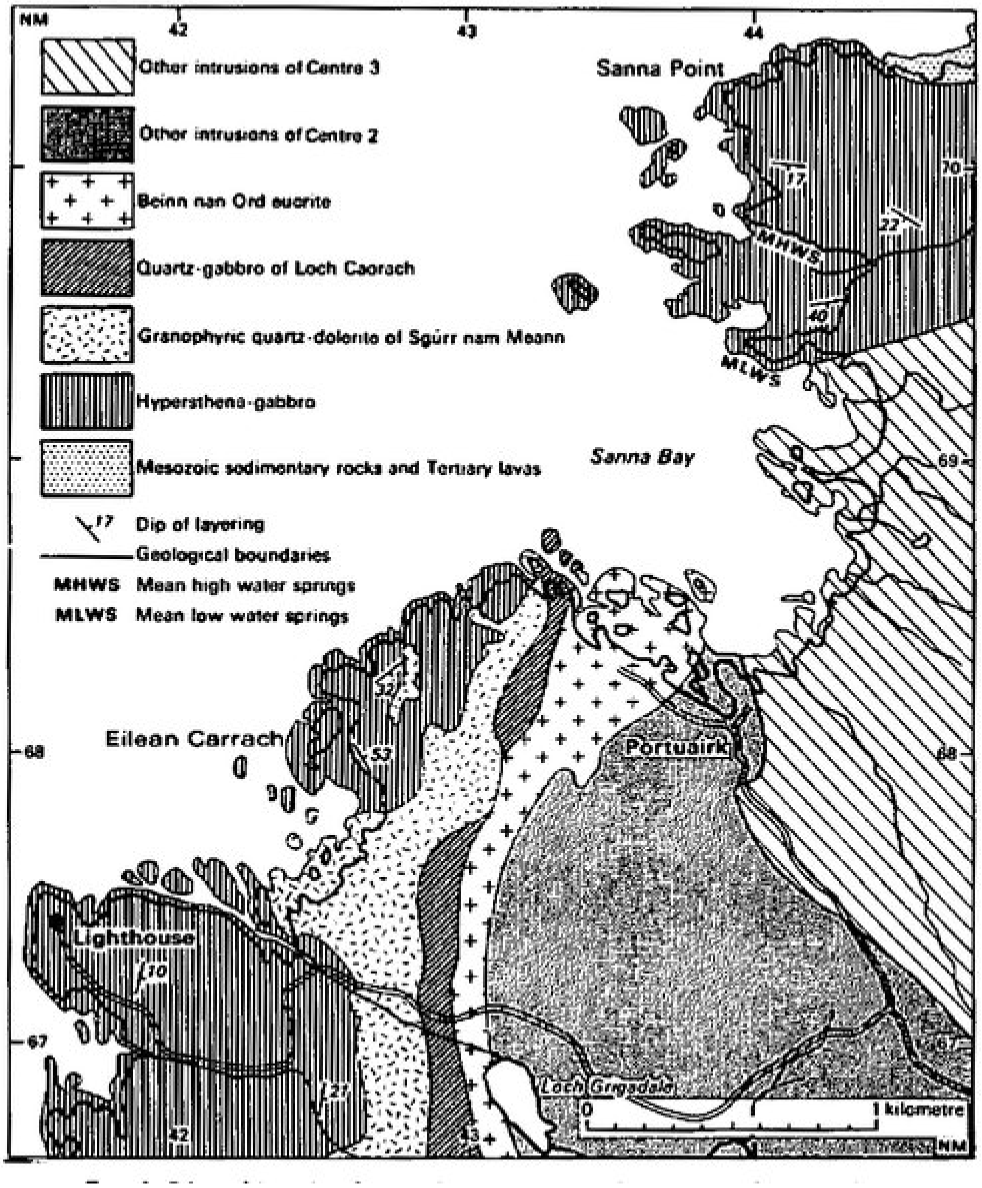
(Table 3) Compositions of Centre 1 rocks and magmas.



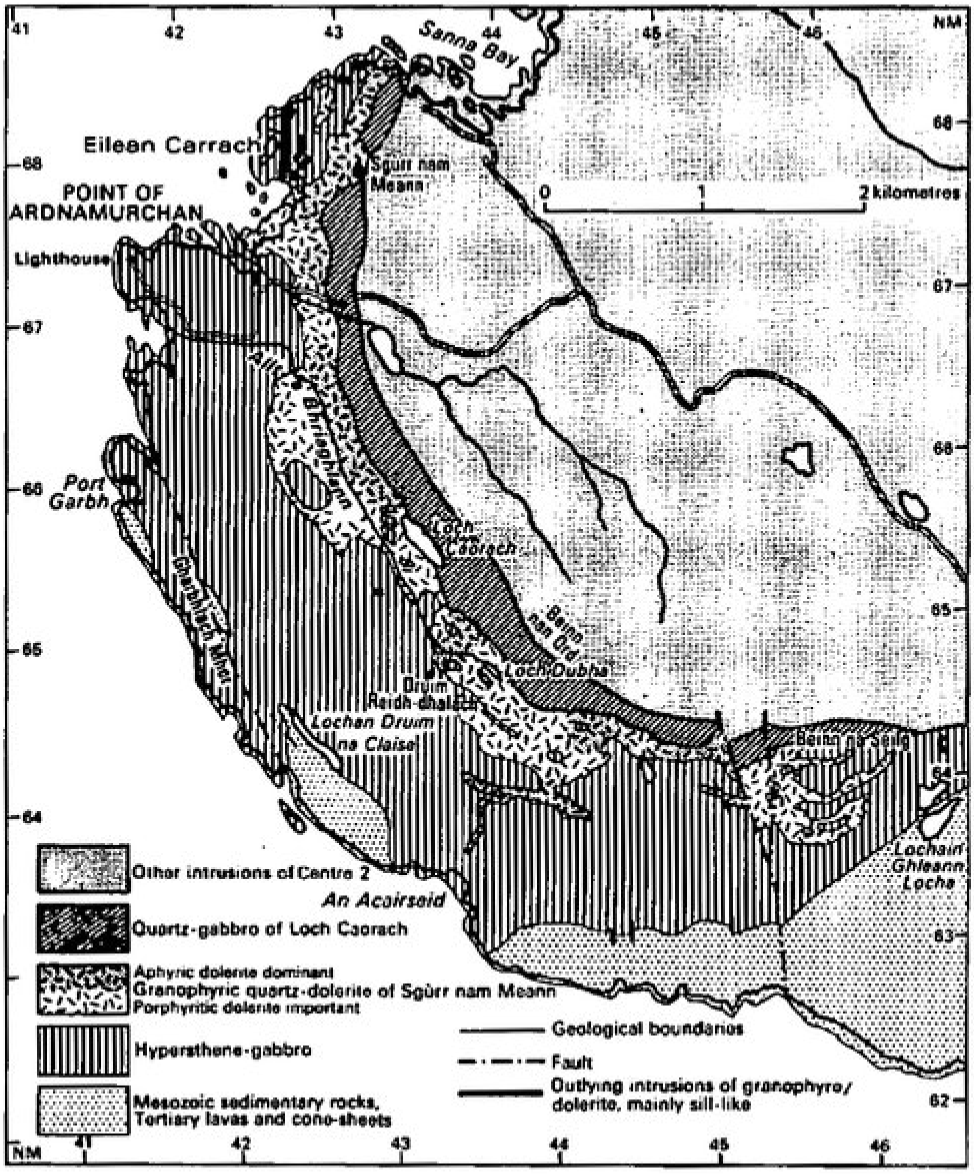
(Figure 4) Glas Eilean vent (based on Richey et al. 1930),



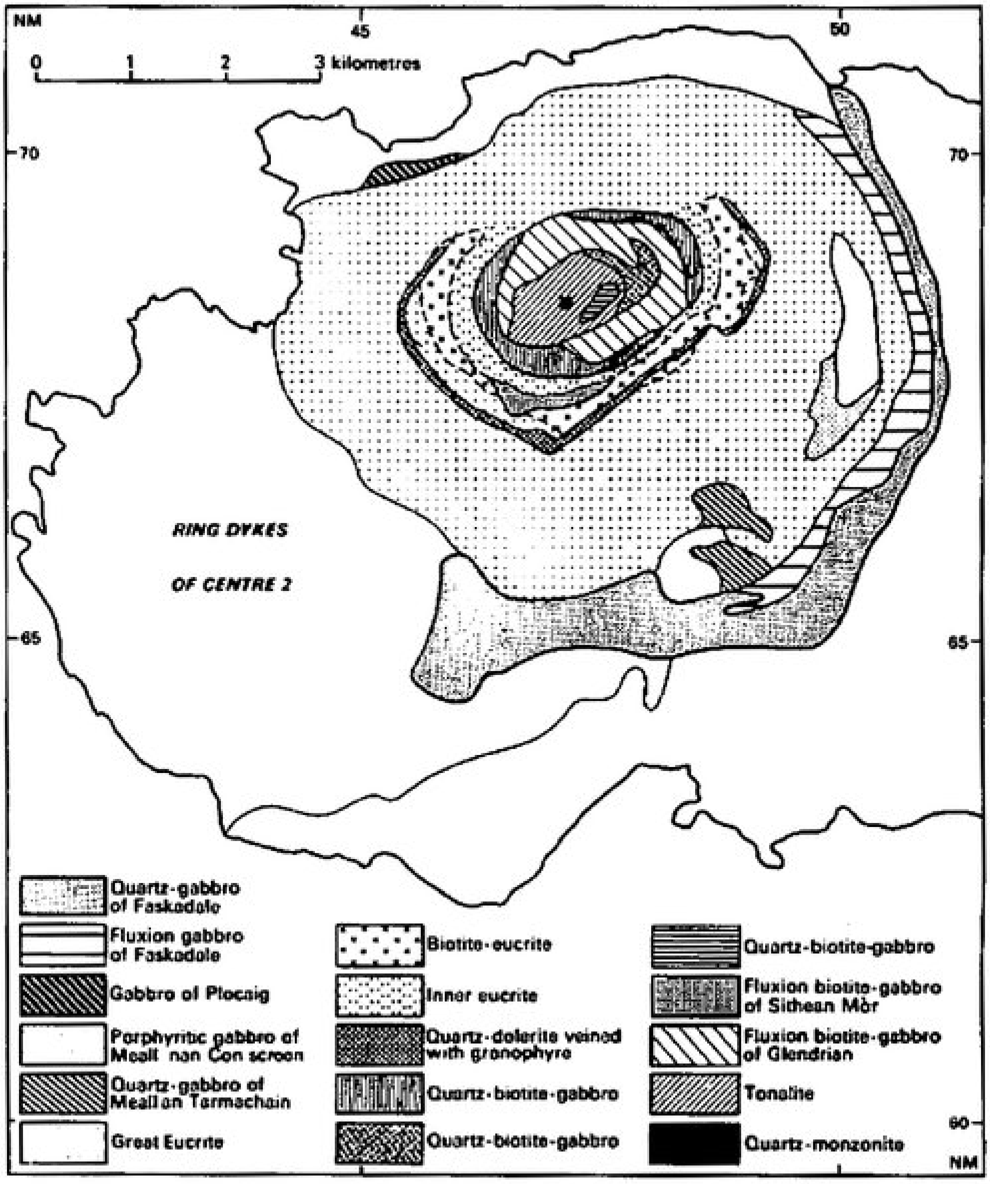
(Figure 5) Dips of layering for southern part of the hypersthene-gabbro (based on Skelhorn and Elwell 1971).



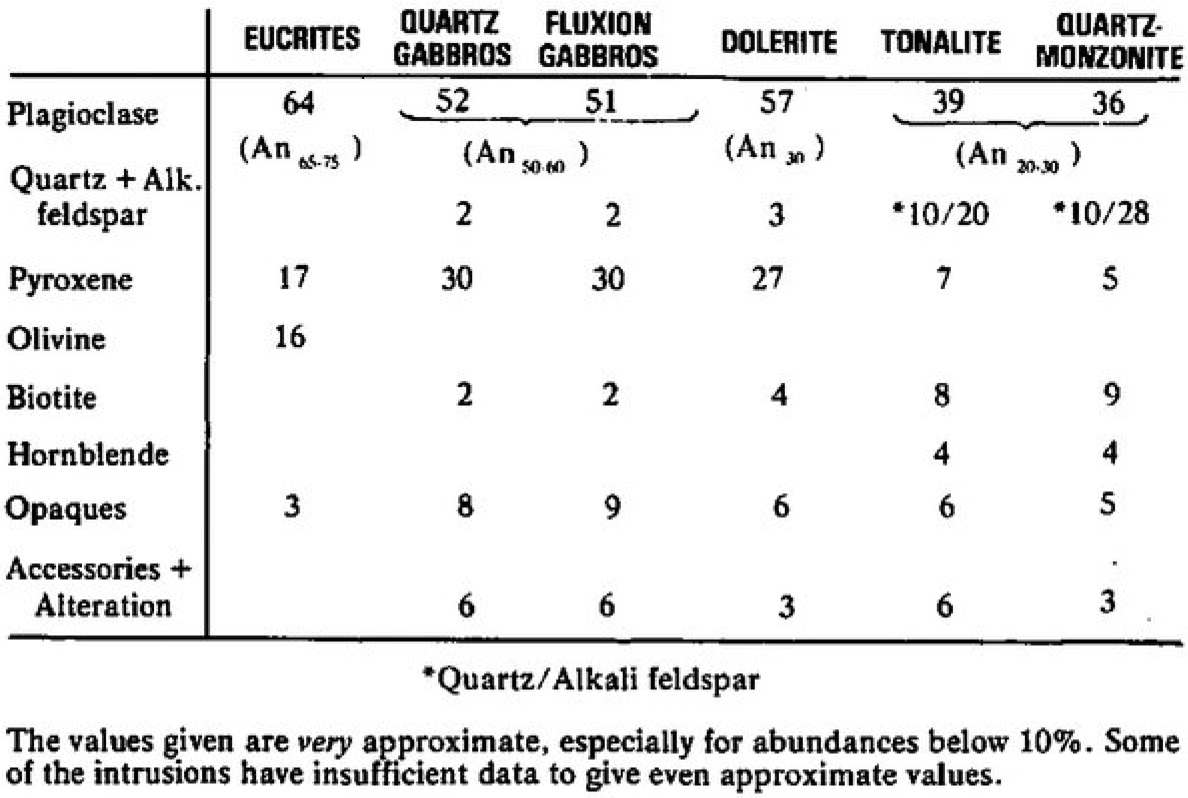
(Figure 6) Dips of layering for north-western part of the hypersthene-gabbro (based on Skelhorn and Elwell 1971).



(Figure 7) The granophyric quartz-dolerite and associated intrusions of Centre 2 (based on Skelhorn and Elwell 1971).



(Figure 8) The ring intrusions of Centre 3 (following Richey et al. 1930).

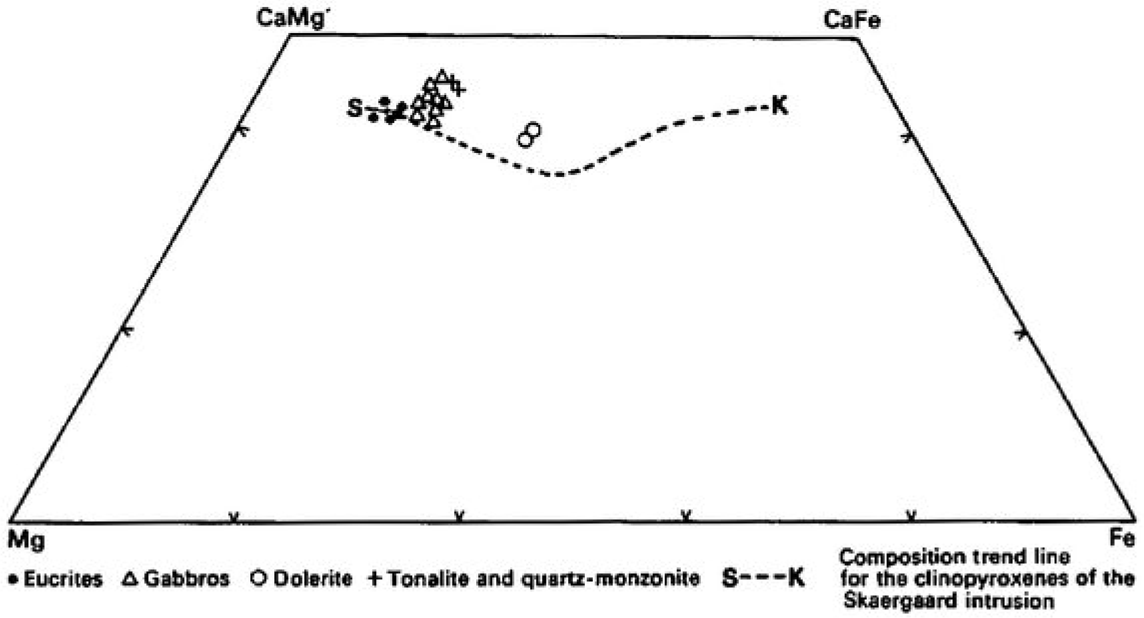


	EUCRITES	QUARTZ GABBROS	FLUXION GABBROS	DOLERITE	TONALITE	QUARTZ-MONZONITE
Plagioclase	64	52	51	57	39	36
	(An$_{65-75}$)	(An$_{50-60}$)		(An$_{30}$)	(An$_{20-30}$)	
Quartz + Alk. feldspar		2	2	3	*10/20	*10/28
Pyroxene	17	30	30	27	7	5
Olivine	16					
Biotite		2	2	4	8	9
Hornblende					4	4
Opaques	3	8	9	6	6	5
Accessories + Alteration		6	6	3	6	3

*Quartz/Alkali feldspar

The values given are *very* approximate, especially for abundances below 10%. Some of the intrusions have insufficient data to give even approximate values.

(Table 4) Modal proportions of the Centre 3 rocks.



(Figure 9) Compositions of clinopyroxenes from rocks of Centre 3. Clinopyroxenes from the eucrites are less iron-rich than clinopyroxenes from the gabbros. and clinopyroxenes from the dolerite show substantial iron enrichment. The trend is similar to the Skaergaard trend although with less calcium depletion. The samples from the tonalite and quartz-monzonite do not continue this iron enrichment trend, and are interpreted as hybrid rocks formed from the partial melting of pre-existing rocks by the basic magma. Samples from the small gabbro intrusion of Meall an Tarmachain have been omitted as their results are ambiguous.