British Tertiary Volcanic Province

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

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Chapter 2

The Isle of Skye

INTRODUCTION

Skye is one of the classic areas of Great Britain for the study of igneous geology. The sea cliffs and hills in the north of the island magnificently expose a thick succession of mainly basaltic lavas which overlie Mesozoic sediments intruded by a suite of dolerite sills. Basaltic dykes of the north-west-trending swarm cut all these rocks. The Cuillins and Red Hills of central Skye have been eroded from the roots of a major volcano; they form a central igneous complex consisting of numerous intrusions of granite, gabbro and peridotite (Fig. 2.1). Suites of dolerite cone-sheets intrude the gabbros and peridotites and all members of the central igneous complex are also cut by at least some members of the dyke swarm. The island contains a long and complicated record of igneous extrusion and intrusion (Table 2.1) and is a particularly suitable area for the study of the field geology of extrusive and intrusive igneous rocks. Investigations throughout the nineteenth century elucidated and highlighted the diversity and abundance of igneous rocks present and firmly assigned the activity to the Tertiary (Geikie, 1888, 1894, 1897; Judd, 1874, 1878).

The geological importance of the island was acknowledged when, at the turn of the century, the Geological Survey of Great Britain commissioned Dr Alfred Harker to make a thorough examination of all aspects of the Tertiary igneous rocks. Harker's contributions on Skye include a set of extremely detailed (published) Six-Inch to One-Mile geological maps of the Cuillin and Red Hills centres together with surrounding rocks. These outstanding maps form the basis to the Survey's One-Inch scale geological maps (Minginish, Sheet 70 and Glenelg, Sheet 71) while Harker's detailed observations and deductions were published as the classic Memoir on *The Tertiary Igneous Rocks of Skye* (Harker, 1904).

The extensive literature on the Tertiary igneous geology of Skye has been summarized in several publications over the past decade or so (J.D. Bell, 1976; Emeleus, 1982, 1983; Bell and Harris, 1986). A considerable amount of this work has concentrated on the mineralogy, petrology and geochemistry of the igneous rocks, and it has included important contributions to the theory of the petrogenesis of both basaltic and granitic rocks (summarized by Thompson, 1982). Fourteen SSSIs have been selected to cover the Tertiary igneous geology of Skye (Fig. 2.2).

Tertiary volcanic activity commenced in the Palaeocene, when extensive NW-trending fissures acted as feeders for several phases of extrusion of basaltic and related magmas which built up the plateau lavas of the northern and south-western parts of the island (Table 2.2). The lavas were predominantly extruded subaerially, with periods of deep erosion and laterite formation between successive flows. Although the majority of the lava flows are mildly alkaline to transitional olivine basalts, more olivine-rich picritic flows occur and fractionated flows of hawaiite, mugearite, benmoreite and trachyte are present, particularly in the higher parts of the succession. The north Skye lavas were extensively subdivided by the Geological Survey (Anderson and Dunham, 1966; Table 2.2); they are now collectively grouped as the Skye Main Lava Series (SMLS), Thompson *et al.*, 1972). A few distinctly different tholeiitic flows fill valleys eroded in the SMLS of south-west Skye; these are the Preshal More type basalts (Thompson *et al.*, 1972; see Table 2.2).

Thompson *et al.* (1972) noted a tendency for progressive compositional changes from hypersthene-normative basalts, upwards to nepheline-normative basalts, alkali hawaiites and mugearites in the Beinn Edra, Ramascaig and Totaig groups (Table 2.2). However, both nepheline-normative and hypersthene-normative basalts and associated lavas occur locally throughout the SMLS. To explain the absence of any obvious strong evolutionary trend, the authors envisaged a complex plumbing system beneath Skye during the eruption of the Palaeocene lavas: there was probably no major magma chamber, but rather a whole series of small reservoirs fed from the mantle where the primary magmas were generated by partial melting of upper-mantle garnet lherzolite. Magma was generated at this source throughout the accumulation of the SMLS, some batches travelled quickly to the surface, others resided in reservoirs within the crust for varying times. Thus, the magmas which formed the lava flows followed a variety of paths to the surface, allowing for different amounts of fractionation, and of contamination by reaction with reservoir walls. In this way the somewhat random distribution of basalt and other effusive rock could be accounted for. Studies on the distribution of strontium, lead and neodymium isotopes in the lavas strongly indicate contamination by crustal rocks (Moorbath and Thompson, 1980; Thirlwall and Jones, 1983), supporting the model described above; furthermore, Thirlwall and Jones

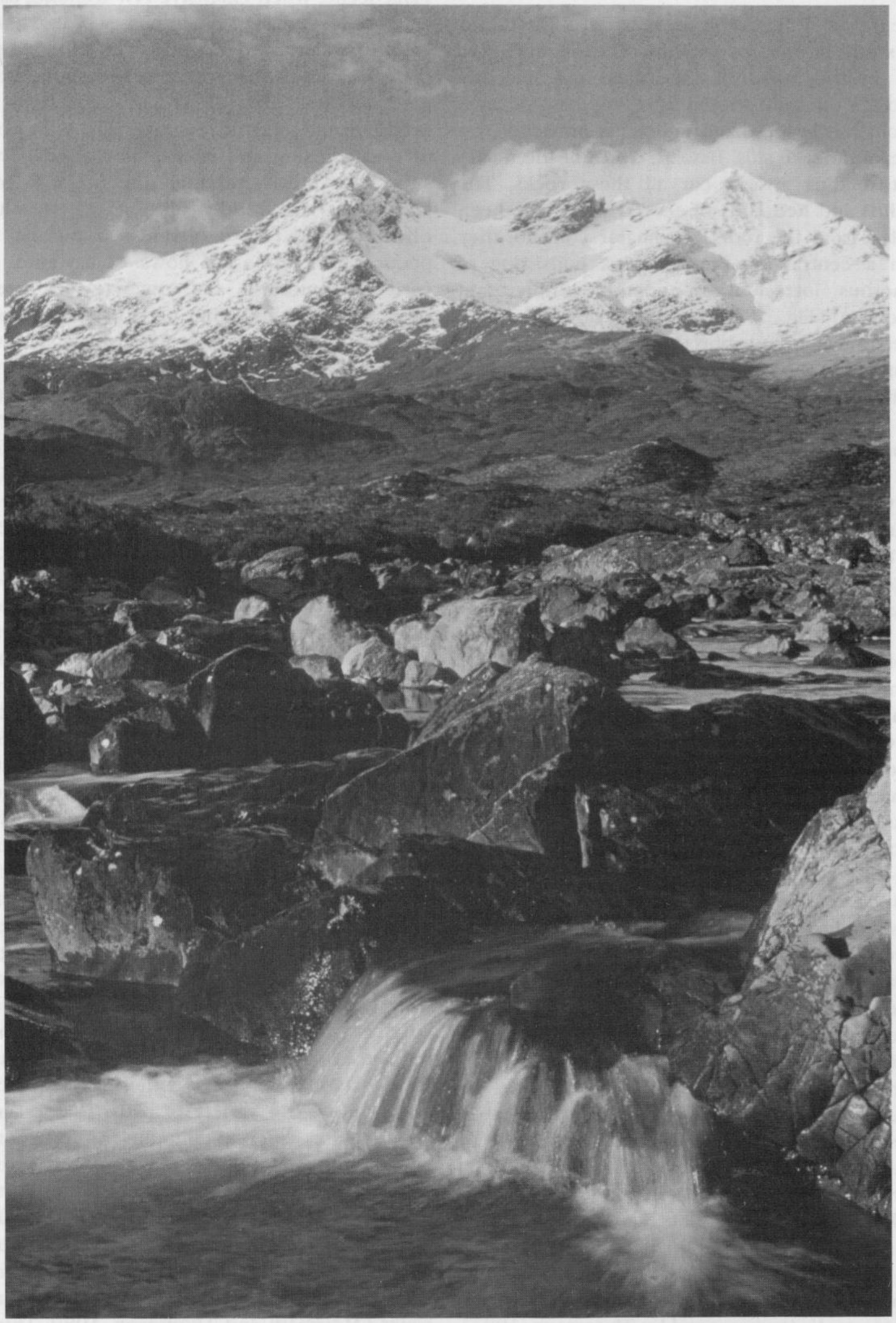


Figure 2.1 Sgurr nan Gillean and the Cuillin Mountains viewed from Sligachan, Isle of Skye. (Photo: David Noton Photography.)

Table 2.1 Summary of the Palaeocene igneous geology of the Isle of Skye (based on Bell, J.D., 1976, table 1; Bell, B.R. and Harris, 1986)

Late dykes (dolerite, felsite and peridotite)

Eastern Red Hills Centre
- Composite acid/basic sheets
- Five granite intrusions
- Kilchrist hybrids (possibly post-date some of the granites)
- Broadford and Beinn nan Cro gabbros
- Acid lavas, ignimbrites, tuffs and agglomerates of Kilchrist vent (may pre-date this Centre by a considerable amount)

Dykes (dolerite, pitchstone)

Western Red Hills Centre
- Marsco and Meall Buidhe granites
- Marscoite suite of hybrids, etc.
- Nine granite and major felsite intrusions
- Marsco Summit Gabbro
- Belig vent

Dykes (dolerite)

Strath na Crèitheach Centre
- Three granite intrusions
- Loch na Crèitheach vent

Dykes (dolerite)

Cuillin Centre
- Cone-sheets (dolerite)
- Coire Uaigneich Granophyre (but see text)
- Intrusive tholeiites
- Druim na Ramh Eucrite
- Explosive vents (of several ages)
- Inner Layered Series: allivalite, eucrite, gabbro
- Outer Layered Series: allivalite, eucrite, gabbro
- Layered Peridotite Series
- Border Group: gabbro, allivalite
- Cone-sheets and dykes (overlap with many of the above)

Palaeocene lavas
- Preshal More tholeiitic flows
- Skye Main Lava Series (SMLS) flows (with sparse clastic sedimentary horizons, and basal sediments and tuffs)

N.B. Additional details through text.

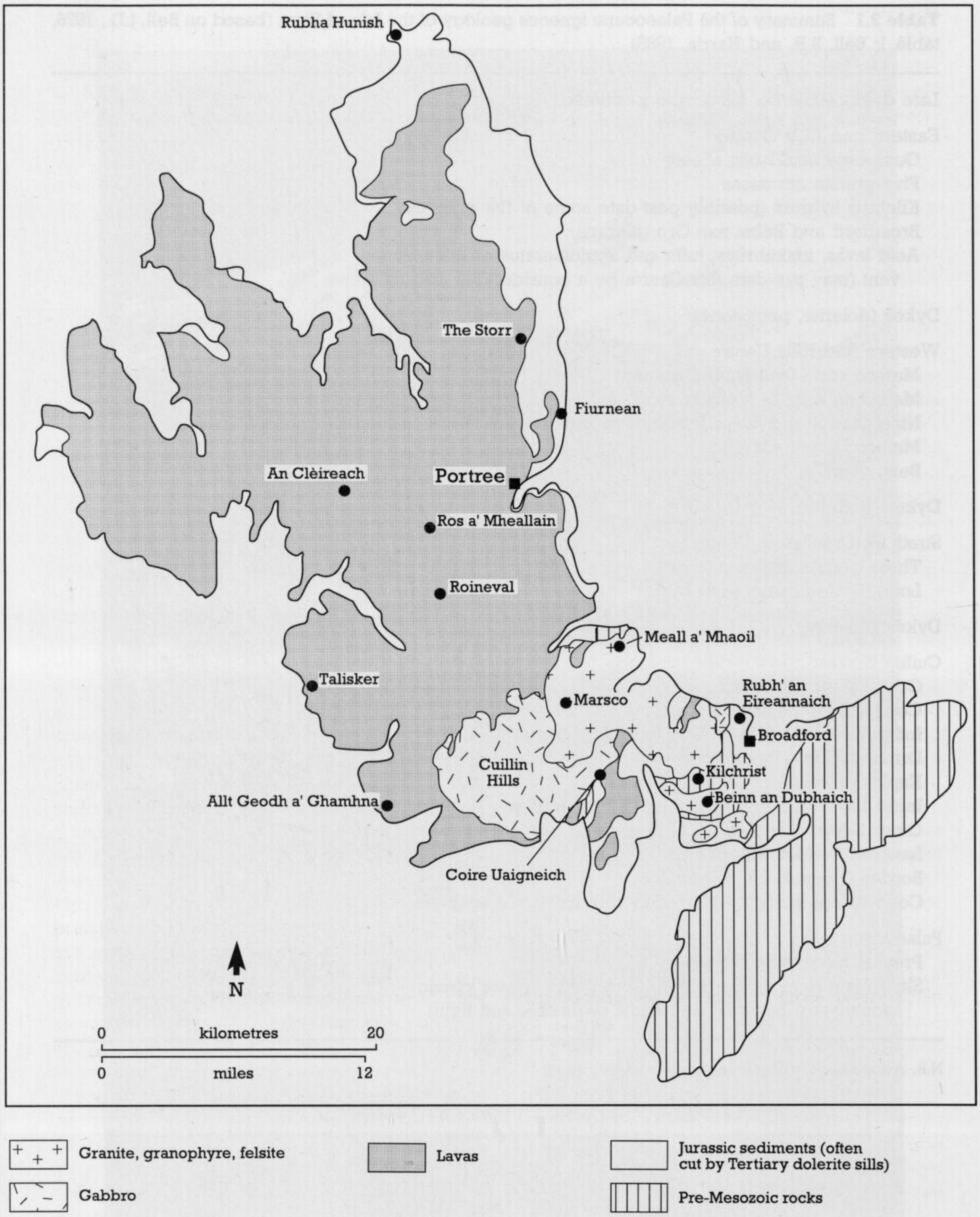


Figure 2.2 Map of the Isle of Skye, showing localities mentioned in the text.

Table 2.2 Correlation of the divisions of the Palaeocene lavas of the Isle of Skye (mainly after Williamson, 1979, table 1).

NORTHERN SKYE (1) Anderson and Dunham (1966)	WEST-CENTRAL SKYE (2) Williamson (1979)	Based mainly on NORTHERN SKYE (3) Thompson *et al.* (1972)
	7. Talisker Group	Preshal Mhor tholeiitic basalts
5. Osdale Group	6. Loch Dubh Group 5. Arnaval Group	Skye Main Lava Series Transitional and alkali-olivine basalts, hawaiites, mugearites, benmoreites and trachytes. More fractionated types are more common in the higher groups.
4. Bracadale Group	4. Tusdale Group	
3. Beinn Totaig Group	3. Cruachan Group*	
2. Ramascaig Group	2. Bualintur Group	
1. Beinn Edra Group	1. Meacnaish Group	

Individual groups are probably geographically restricted (see, for example, Anderson and Dunham, 1966, figure 13).

* The thick fluviatile conglomerates of the Allt Geodh a' Ghamhna site are at the base of this group.

found that contamination was most pronounced in the most primitive (hot) compositions, and least pronounced in the most evolved (cool) ones. Further investigations of lavas in Mull have shown similar distributions and the problem of magma plumbing has been examined using data from both islands (Figure 5.3; Morrison *et al.*, 1985). The Skye, Mull and other BTVP magmas appear to have been derived from mantle sources already depleted by partial melting and magma extraction during the Permo-Carboniferous (for example, Thompson and Morrison, 1988).

After extrusion of the SMLS flows, activity became focused in the area of the present-day Cuillin Hills where mafic magmas intruded to high crustal levels to form coarse-grained gabbros, eucrites, allivalites and peridotites, suites of cone-sheets and some of the dense swarms of dolerite dykes. At, or towards the end of this mafic magmatism, there was widespread explosive volcanicity in the Strath na Crèitheach area. Up to this stage, very little acid magma had been generated, except for the arcuate Coire Uaigneich granophyre.

Thereafter, the central igneous complex experienced changes in both the focus of activity and in magma composition. Three separate centres were established in succession:

1. the Strath na Crèitheach centre;
2. the Western Red Hills centre;
3. the Eastern Red Hills centre.

With time, activity moved progressively eastwards and granite became dominant at the present level of erosion, providing a particularly clear record of evolutionary changes taking place in the underlying magma chamber. However, despite the apparent dominance of granite in the later centres, basaltic magma was still clearly available and on occasions this mixed with acid magma to give distinctive hybrid bodies such as the marscoite suite, forming a ring-dyke in the Western Red Hills centre, and the Kilchrist Hybrids of the Eastern Red Hills centre. Further evidence of mixed magmas (acid–basic) comes from composite minor intrusions, such as the sills in the Broadford area. The final episode of igneous activity on Skye is represented by sparse NW-trending dolerite dykes.

Skye has been the site of notable geophysical experiments aimed at elucidating the deep structure of central intrusive complexes. Gravity surveys show that both the Cuillin Hills and the Red Hills are the site of a sharply defined, strong, positive Bouguer gravity anomaly. This is attributed to the presence of a large, steep-sided cylindrical or inverted cone-shaped mass of dense mafic rock extending to at least 15 km beneath all the central complexes (Bott and Tuson, 1973). An immediate implication of this is that the Red Hill granites are, despite their great areal extent, relatively superficial bodies probably not more than 2 km thick. Palaeomagnetic measurements made on the Cuillin gabbros and peridotites show that these rocks are reversely magnetized, as are the earlier SMLS lavas. However, some of the granites have normal polarities and magnetic investigations by Brown and Mussett (1976) indicate normal polarities over much of the area known, from the gravity studies, to be underlain by mafic rocks. Thus there must have been two periods when large quantities of mafic magmas were involved in the Skye centre; those producing the Cuillin centre were intruded when the Earth's magnetism was reversed, and those giving rise to the dense rocks under the granites were emplaced later when the polarity was normal. Radiometric studies indicate that the bulk of the igneous activity took place between about 60 Ma and 57 Ma ago, but that some intrusions were emplaced as recently as 53.5 Ma ago (Table 1.1).

Investigations of the oxygen isotope geochemistry of the rocks of the Skye central igneous complex and the surrounding lavas and sediments, show that there has been massive circulation of heated meteoric waters through and around the complex (Taylor and Forester, 1971; Forester and Taylor, 1977). This pervasive circulation, which was driven by heat from within the central complex, caused considerable metasomatic and hydrothermal alteration of both the igneous intrusions and adjoining basalts, frequently overprinting original igneous features in the intrusive rocks and the high-grade metamorphic effects in their surroundings. Thus doubts were cast on the igneous origins of some of the rock textures (for example, granophyric quartz–feldspar intergrowths in some of the granites) and on the validity of petrogenetic conclusions drawn from earlier geochemical and isotopic studies. Among the last were the isotopic investigations by Moorbath and Bell (1965) and Moorbath and Welke (1969) which had indicated that the granitic rocks of the Red Hills were largely derived from partial melting of Lewisian gneisses. As recounted in Chapter 1, these doubts and uncertainties were resolved by work on the Mull granites; subsequently isotopic data from Skye were refined and augmented by Dickin (1981) who demonstrated that both crustal and mantle sources have significantly contributed to the granite magmas of Skye.

FIURNEAN TO RUBHA NA H-AIRDE GLAISE

Highlights

The site provides excellent sections through the sediments and volcaniclastic rocks which form the base of the Skye Main Lava Series (SMLS, see Table 2.2). The presence of pillow lavas, glassy lava fragments and water-lain, plant-bearing volcanogenic sediments shows that the initial lava eruptions were into shallow water.

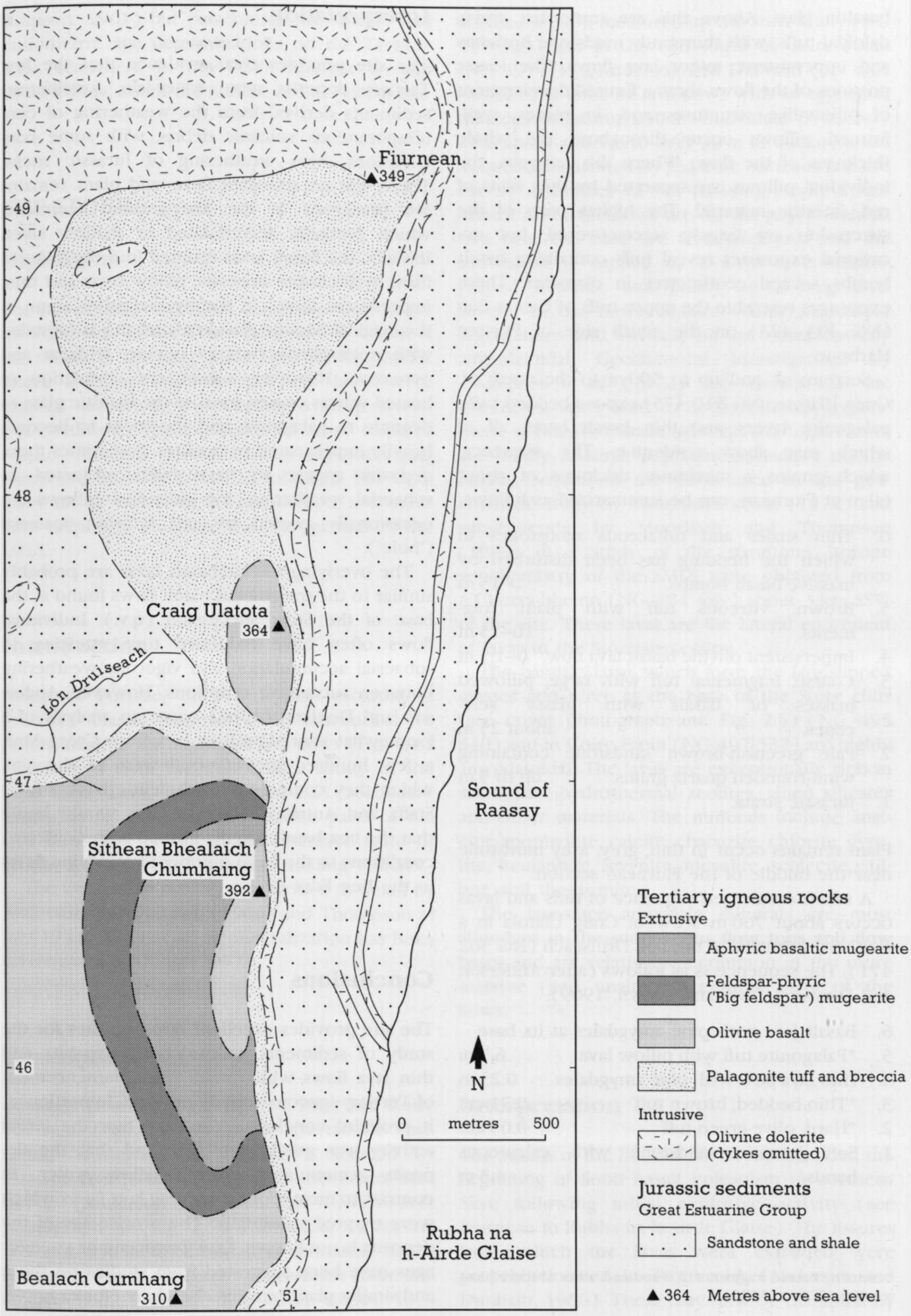
Introduction

The cliff exposures between Fiurnean and Rubha na h-Airde Glaise (Fig. 2.3), to the north of Portree Harbour, provide extensive sections through volcaniclastic rocks and associated lavas and sediments which mark the onset of Tertiary volcanism on Skye. Accordingly, the site represents the type locality for these rocks. Tuffs, including hyaloclastites produced by the eruption of magma into water, are associated with thin basaltic lavas and fossiliferous sediments; these lie between Jurassic sediments and the lavas of the Beinn Edra Group of northern Skye (Table 2.2; Anderson and Dunham, 1966).

Description

Good exposures of tuff crop out in the cliffs and scree between Rubha na h-Airde Glaise and Sithean Bhealaich Chumhaing (NG 509 467). The lower part of the succession is crystal-rich and contains well-formed and broken crystals of olivine, labradorite and augite in partly devitrified

Figure 2.3 Geological map of the Fiurnean to Rubha na h-Airde Glaise site (adapted from the British Geological Survey 'One-Inch' map, Northern Skye Sheet 80 and parts of 81, 90 and 91).



Fiurnean
349
49
48
47
46
Craig Ulatota
364
Lon Druiseach
Sound of Raasay
Sithean Bhealaich Chumhaing
392
N
0 metres 500
Rubha na h-Airde Glaise
Bealach Cumhang
310
51
Tertiary igneous rocks
Extrusive
Aphyric basaltic mugearite
Feldspar-phyric ('Big feldspar') mugearite
Olivine basalt
Palagonite tuff and breccia
Intrusive
Olivine dolerite (dykes omitted)
Jurassic sediments
Great Estuarine Group
Sandstone and shale
▲ 364 Metres above sea level

basaltic glass. Above this are somewhat amygdaloidal tuffs, with thin sandy mudstone horizons and impersistent, minor lava flows. The lower portions of the flows show a limited development of pillow-like structures and, in places, well-formed pillows occur throughout the whole thickness of the flow. Where this happens, the individual pillows are separated by thin skins of red, lateritic material. The higher parts of the succession are largely scree-covered, but occasional exposures reveal tuffs containing basalt bombs several centimetres in diameter. These exposures resemble the upper tuffs of Camas Bàn (NG 493 423) on the south side of Portree Harbour.

Sections at, and up to 500 m to the north of, Craig Ulatota (NG 510 475) expose bedded tuffs, palagonite layers and thin basalt lavas, all of which may show reddening. The sequence, which attains a maximum thickness of about 60 m at Fiurnean, can be summarized as follows:

6. Thin shales and tuffaceous sandstones in which the bedding has been disturbed by massive basalt bombs. > 15 m
5. Brown, vitreous tuff with plant fragments. 10–15 m
4. Impersistent olivine basalt lava flow. 0–1.5 m
3. Coarse, fragmental tuff with large, pillowed masses of basalt with glassy selvedges. about 25 m
2. Pale greenish-brown sandstone containing wind-rounded quartz grains. up to 5 m
1. Jurassic strata.

Plant remains occur in thin, grey, ashy mudstone near the middle of the Fiurnean section.

A much condensed sequence of tuffs and lavas occurs about 700 m WSW of Craig Ulatola in a southern tributary of the Lon Druiseach (NG 502 471). The sequence is as follows (after Anderson and Dunham, 1966 and Brown, 1969):

6. Basalt lava with pipe amygdales at its base
5. *Palagonite tuff with pillow lava 6.7 m
4. Thin lava flow with pipe amygdales 0.23 m
3. *Thin-bedded, brown tuff 0.71 cm
2. *Hard, olive-green tuff 0.05 cm
1. Soft Jurassic sandstone with calcareous bands 4.3 m

* contain charred fragments of wood and other obscure plant remains (Wilson, 1937).

Interpretation

The site provides clear evidence that the first Tertiary deposits were water-lain, fossiliferous sediments derived from the weathering of contemporaneous volcanic debris, with some contributions from weathering of Jurassic rocks. There was an abundant flora, and plant remains are preserved in the finer-grained sediments which probably accumulated in shallow lakes. Initially, the basalt lavas erupted into the lakes to form hyaloclastite deposits, pillow lavas and thin, impersistent flows. In the hyaloclastites some of the original basaltic glass remains; this is crowded with microphenocrysts of olivine, feldspar and pyroxene. However, subsequent circulation of heated waters caused most of the basaltic glass to degrade to palagonite and the rocks to become heavily impregnated by zeolites. Sometimes these deposits appear to have been subjected to subaerial weathering, for individual pillows are occasionally coated by red lateritic material ('bole').

The overlying olivine-basalt lavas are probably similar to the transitional basalt flows found at the base of the Storr succession (q.v.). Individual flows often have reddened tops attesting to subaerial accumulation and vigorous weathering between successive eruptions. However, Anderson and Dunham (1966) quote an analysis of a (somewhat altered) pillow lava from Creag Mor, a few hundred metres south-west of the site, which they compare with tholeiitic basalts from Staffa and Antrim. If correct, this would imply that the first basalt magma formed under different conditions to the large number of overlying flows in the Ben Edra Group.

Conclusions

The site provides excellent opportunities for the study of sediments, volcaniclastic deposits and thin lava flows which mark the commencement of Tertiary igneous activity on Skye. In particular, it provides conclusive evidence that the initial activity was mildly explosive and that the deposits accumulated under shallow water, in contrast to most of the overlying lava flows which were erupted subaerially. The precise age of the deposits is not known. Late Oligocene or younger ages have been suggested from studies on these and similar plant remains elsewhere (for example, Simpson, 1961) but palaeomagnetic studies and radiometric age determinations on the Tertiary lavas elsewhere in the BTVP indicate an age about 60 Ma, about the middle of the Palaeocene.

THE STORR

Highlights

The site contains excellent continuous exposures through lavas of the Beinn Edra Group, which is the oldest in the Skye Main Lava Series (SMLS). There is clear evidence that the lavas were erupted subaerially and weathered under warm, wet conditions. The abundant and varied suites of zeolite minerals formed under hydrothermal conditions after the lavas had solidified. The lavas show subtle variations in composition, and these have helped to elucidate the petrogenesis of the SMLS.

Introduction

North of Portree, the Trotternish escarpment provides classic exposures of transitional to mildly alkaline olivine basalt lava flows (Fig. 2.4). These lavas form the Beinn Edra Group of the Skye Main Lava Series (Table 2.2). Secondary hydrothermal mineralization within parts of the lava flows has produced an extensive suite of zeolite and associated minerals infilling vesicles.

The succession has been described in detail by Anderson and Dunham (1966) and Thompson *et al.* (1972); the late-stage mineralization has been investigated by King (1977).

Description

Between Beinn Dearg (NG 477 504) and Coire Scamadal (NG 495 547), the spectacular east-facing Trotternish escarpment is formed by massive lava flows belonging to the Beinn Edra Group (Anderson and Dunham, 1966; cover photograph and Fig. 2.5). The visible succession is about 250 m thick and it is estimated that a further 120 m is concealed beneath the scree and landslip which mantle the lower slopes. In a detailed section measured up the Storr Gully (NG 495 539) and in the cliff south of Coire Faoin (NG 497 535), Anderson and Dunham (op. cit.) identified at least 24 lava flows with an aggregate thickness of about 250 m. Individual flows vary from about a metre to over 30 m in thickness, are frequently separated by red bole horizons and are cut by a number of NW-trending basalt dykes. Almost all of the flows are olivine-phyric basalts; two near the base are feldspar-phyric and the succession is capped by a flow of columnar-jointed hawaiite and finally by a mugearite. Several of the flows contain coarse pegmatoid segregations and virtually all are conspicuously amygdaloidal. Geochemical investigations by Thompson *et al.* (1972) have shown that the lowermost flows tend to be transitional, hypersthene-normative basalts, whereas the higher ones are mildly alkaline, nepheline-normative olivine basalts. Several of the flows used in the geochemical study by Thompson *et al.* (1972) and subsequently by Moorbath and Thompson (1980) in a study of the strontium isotope geochemistry of the SMLS were obtained from A'Chorra-bheinn (NG 484 489) about 3 km SSW of the site. These lavas are the lateral equivalent of lavas in the Storr succession.

The basaltic lavas which form the landslipped masses and scree at the base of the Storr cliffs (see cover photograph and Fig. 2.5) (NG 495 540) and in Coire Faoin (NG 497 537) are highly amygdaloidal. The lavas are exceptionally rich in secondary, hydrothermal zeolites, allied silicates and other materials. The minerals include analcite, apophyllite, calcite, chabazite, chlorite, gyrolite, heulandite, levynite, mesolite, scolecite, stilbite and thomsonite.

The late-stage amygdale minerals are most abundant in the scoriaceous flow tops and flow bases and are relatively uncommon in the more massive (and unaltered) central parts of the flows.

Interpretation

The basalts of the Beinn Edra Group heralded the beginning of flood basalt volcanism in northern Skye following initial explosive activity (see Fiurnean to Rubha na h-Airde Glaise). The fissures from which the lavas were extruded were probably located in Trotternish (Anderson and Dunham, 1966). These may now be occupied by

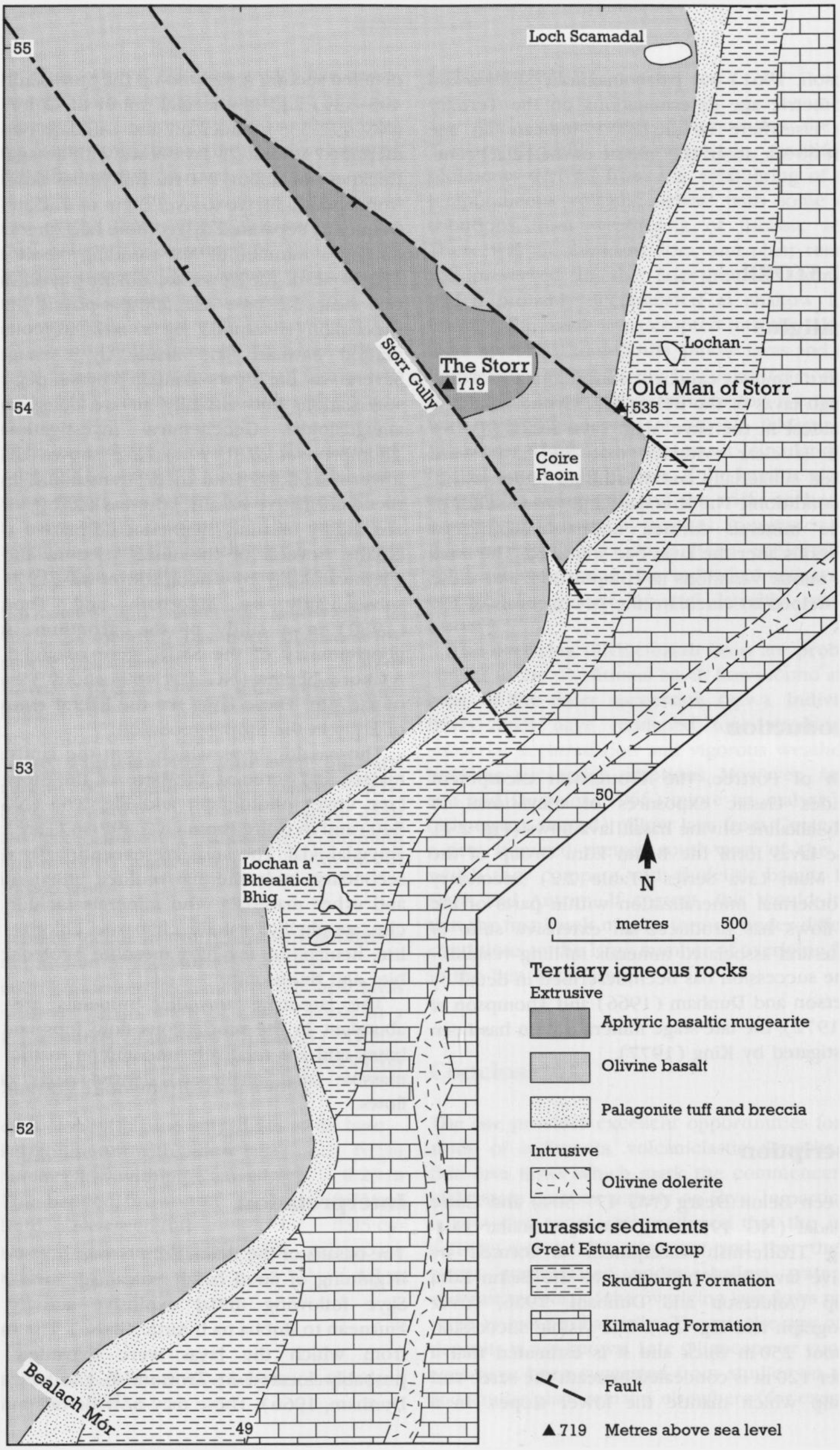

Loch Scamadal
55
Storr Gully
The Storr
▲719
Lochan
Old Man of Storr
▲535
54
Coire Faoin
53
50
N
Lochan a' Bhealaich Bhig
0 metres 500
Tertiary igneous rocks
Extrusive
Aphyric basaltic mugearite
Olivine basalt
Palagonite tuff and breccia
Intrusive
Olivine dolerite
Jurassic sediments
Great Estuarine Group
Skudiburgh Formation
Kilmaluag Formation
52
Fault
▲719 Metres above sea level
Bealach Mór
49

Figure 2.5 Basalt lavas of the Skye Main Lava Series. Slipped masses of lava, including the Old Man of Storr pinnacle, occur in the foreground and to the right. Storr site, Skye. (Photo: C.H. Emeleus.)

NNW-trending picrite dykes such as those at Beinn Tuath (NG 435 530) and Glen-uachdarach (NG 430 585) to the west of the site. The lavas were erupted subaerially and subjected to intense weathering. This caused leaching and oxidation and formed the bright red bole horizons which now separate many of the flows. Similar present-day weathering occurs where there is a combination of a warm climate and abundant rainfall; thus the presence of bole horizons in the Palaeocene lavas of Skye and other areas in the BTVP implies tropical or subtropical conditions.

The geochemical data obtained by Thompson *et al.* (1972) and Moorbath and Thompson (1980) from flows in the Beinn Edra Group provided some of the evidence for variability in both bulk chemistry and isotopes which lead to the novel hypothesis of magma plumbing beneath northern Skye (see Introduction, above; also cf. Fig. 5.3).

Figure 2.4 Geological map of the Storr site (adapted from the British Geological Survey 'One-Inch' map, Northern Skye Sheet 80 and parts of 81, 90 and 91).

The distribution of the zeolites and associated minerals in lava piles is known to be controlled by a combination of temperature, pressure, circulation of heated aqueous fluids and the bulk composition of the rock (Walker, 1960). A study of the lavas of the Beinn Edra Group by King (1977) has shown that much of the group contains zeolite assemblages similar to the analcime–natrolite zone defined by Walker (1960). In the alkali olivine basalts of the upper part of the sequence at the Storr, analcite is lacking and instead, first mesolite and then thomsonite–chabazite assemblages are present. However, the reappearance of analcite in the hawaiite which caps the cliff adds support to the suggestion by Walker that the chemistry of the host rock plays an important role in determining the types of zeolites and associated minerals formed by the circulating fluids.

Conclusions

The importance of this site lies in the continuous excellent exposure through the Beinn Edra

Group which forms the base of the Skye Main Lava Series (Table 2.2). At least 24 flows are exposed (Anderson and Dunham, 1966, pp. 83–4); the interrelationships show that they accumulated subaerially and were subjected to deep weathering under wet, warm tropical or subtropical conditions. The site is particularly noted for the abundance and variety of zeolite minerals within the lavas which provide conclusive evidence of hydrothermal activity after solidification.

The site is a vital link in the chain of geochemical evidence obtained from the Skye lavas which suggests that they were derived from the upper mantle and rose towards the surface in small batches, each batch having its own history of crystal fractionation and contamination by crustal rocks as it passed through the Palaeocene crust.

ROINEVAL

Highlights

The site contains an excellent example of a composite mugearite flow with an aphyric lower member and a strongly feldspar-phyric upper part.

Introduction

A type example of a composite mugearite lava flow forms the summit area of Roineval. Composite lavas on Skye were first described by Harker (1904) who interpreted them as sills, but they were later shown (by Kennedy, 1931b) to be lava flows. More recent investigations include those of Muir and Tilley (1961) and Boyd (1974).

Description

The Roineval flow lies within the Beinn Totaig Group of lavas in northern Skye (Table 2.2; Anderson and Dunham, 1966) and rests upon the weathered vesicular top of a non-porphyritic mugearite. The composite flow consists of an upper member with phenocrysts of plagioclase, olivine and titaniferous magnetite overlying an essentially aphyric mugearite. The boundary between the units is gradational over several centimetres, in contrast to other composite flows such as those at Druim na Criche (NG 435 375), in which the two components are separated by a sharp, non-erosional boundary. The upper porphyritic unit at Roineval contains abundant plagioclase phenocrysts together with lesser amounts of altered olivine and magnetite. Boyd (1974) reports homogeneous (An_{55}) cores to the phenocrysts, which are euhedral but often broken, and thin, more calcic rims (*c.* An_{60}), and jackets zoned from An_{51} to An_{40}. A small amount (15 vol.%) of similar plagioclase phenocrysts (An_{52-50}) occurs in parts of the otherwise essentially non-porphyritic lower unit. The bulk composition of the upper unit is hawaiitic, that of the lower unit is mugearitic. The porphyritic mugearites show a marked degree of iron enrichment, especially when recalculated to a phenocryst-free base (cf. Anderson and Dunham, 1966, tables 8 and 9; Muir and Tilley, 1961, table 4).

Interpretation

Composite lava flows are a feature of special petrological interest within the Skye plateau lava succession; the Roineval flow is one of several particularly clear examples. The strongly feldspar-phyric top member of the composite flow, overlying rock with a similar matrix composition but lacking numerous phenocrysts, suggests that the source was a differentiated body of magma in which large, labradorite crystals had sunk, together with olivine and opaque oxides, leaving an upper, crystal-free layer of magma. An initial eruption evacuated the aphyric portion, forming the basal mugearite which was rapidly followed by the remaining, phenocryst-rich magma of the upper unit. Boyd (1974) suggests that the slight compositional differences between the upper and lower units may be attributed to the concentration of phenocrysts in the upper part. The lack of chilling between the units, and the manner in which they merge over 10–20 cm, provides proof that there was very little time between the eruption of each unit; the porphyritic unit may well have followed virtually instantaneously. The well-defined break between the porphyritic and aphyric members of the composite flow suggests that there were tranquil conditions in the magma chamber for some time prior to eruption; strong convective or other movement would have mixed the two parts.

The relationships seen in the Skye composite flows strongly suggest that plagioclase feldspar might sink and accumulate in an evolved magma of hawaiitic or, as in this instance, mugearitic composition. This has important petrological implications since it has been claimed, in connection with the formation of layered gabbro complexes, that plagioclase flotation would be more likely (cf. McBirney and Noyes, 1979), in contrast with the earlier view that settling of feldspar occurred in these bodies (for example, Wager and Brown, 1968).

Conclusions

The composite lava flow of Roineval provides evidence that labradorite feldspar phenocrysts might have sunk in the iron-enriched magmas represented by the Skye mugearites. The relationships found at this site therefore have an important bearing on the crystallization processes in magma chambers and on the origin of layered structures frequently present in gabbroic plutons. They support the original models for the origin of igneous layering proposed by Wager and Deer (1939) and elaborated by Wager and Brown (1968), rather than alternative explanations offered by McBirney and Noyes (1979) and others.

TALISKER

Highlights

The spectacular coastal cliffs here provide some of the best sections through the highest part of the Skye Main Lava Series (SMLS) which is notable for the variety of lava types within it. The exposures on Preshal More and Preshal Beg demonstrate a thick, ponded flow of low-alkali, high-calcium olivine tholeiite which was erupted after a long erosional interval, following the last flows of the SMLS. The site is the type locality for this distinctive tholeiite which is matched by only one other flow in Skye, although many of the north-west dykes are of similar composition.

Introduction

A coastal cliff section and three well-exposed inland areas have been selected to demonstrate the diversity and complexity of the plateau lava sequence of west-central Skye (Fig. 2.6). Collectively, they provide evidence of a thick lava succession (>400 m) comprising flows of picrite, olivine basalt, hawaiite, mugearite and olivine tholeiite compositions belonging to the Arnaval and Talisker groups (Williamson, 1979). The area was subject to major reassessment by Williamson (1979) following earlier studies by Harker (1904), Anderson and Dunham (1966) and Esson *et al.* (1975).

Description

The Talisker Bay (NG 300 315–317 284), Stockval (NG 351 296) and Ard an t-Sabhail (NG 318 333) localities (Fig. 2.6) incorporate lavas belonging primarily to the Arnaval Group of Williamson (1979) which is probably equivalent to the youngest Osdale Group (Table 2.2; Anderson and Dunham, 1966) of northern Skye. The overall thickness of the Arnaval Group is probably in excess of 400 m, but nowhere is the whole sequence exposed and, in general terms, the following divisions are recognized (Williamson, 1979):

C Rare, thin, massive olivine basalts and mugearites. Hawaiites and mugearites become progressively more common towards the top. 175–200 m

B Porphyritic and non-porphyritic basalts with rare hawaiites and picritic basalts. 100 m

A Highly amygdaloidal olivine basalts and picritic basalts with mugearite. 150 m

The cliff sections around Talisker Bay afford excellent exposures of picritic basalts, well-developed brown/grey/red boles, and abundant amygdales filled with zeolites. A thick mugearite flow near to the base of the succession at MacFarlane's Rocks (NG 301 314) to the south of Talisker Bay, displays characteristic flow-jointing which has been intricately overfolded and also forms antiforms and synforms in the upper part of the flow. Major dislocations to the east have faulted the succession, rendering correlation with other areas difficult. Inland, at the Stockval ridge locality south of Gleann Oraid (NG 320 305), the

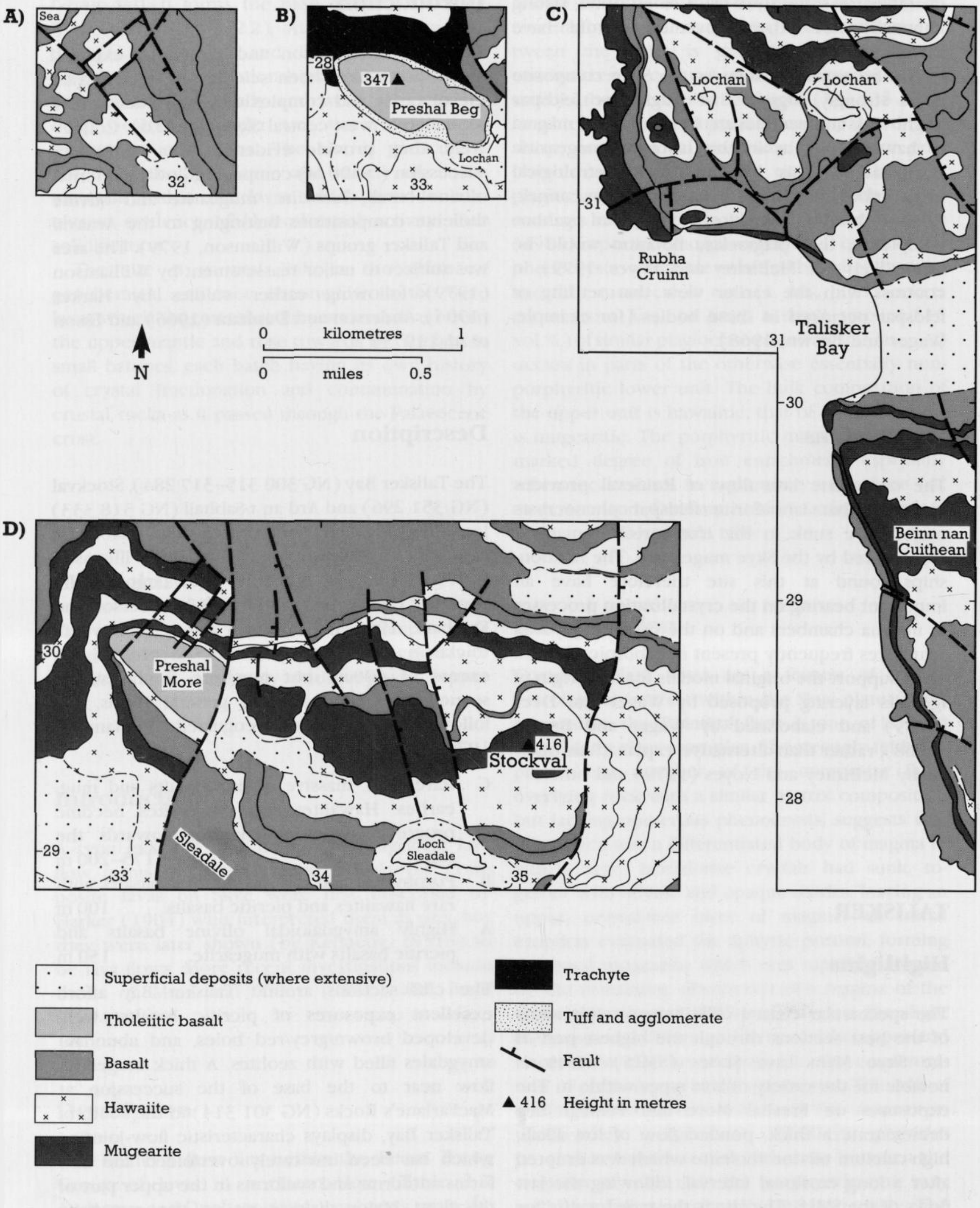


Figure 2.6 Geological map of the Talisker site (after Williamson, 1979). A) Area south-west of Fiskavaig; B) Preshal Beg area; C) coast north and south of Talisker Bay; D) area between Preshal More and Stockval.

upper part of the succession is exposed comprising mainly hawaiite and mugearite flows.

At Dun Ard an t-Sabhail, a composite lava flow overlies a sequence of alkali-olivine basalts. The lava is more basic than those at Roineval and at Druim na Criche (Harker, 1904; Kennedy, 1931b) but is similar in that the flow consists of a porphyritic member overlying a non-porphyritic member of a broadly similar rock type. The upper member carries between 14% and 27% volume plagioclase phenocrysts which are more numerous at the base and which appear to belong to two separate generations (Boyd, 1974). Labradorite predominates but rounded, resorbed andesine is also found. Williamson (1979) also recorded the presence of orthopyroxene phenocrysts (or xenocrysts) in the upper unit, thereby distinguishing this flow from the other composite flows of Roineval and Druim na Criche. Hercynite spinel microphenocrysts mantled by titaniferous magnetite are also present, these and the orthopyroxene may be relicts of a phase of high-pressure crystallization prior to eruption.

The twin hills of Preshal More (Fig. 2.7) and Preshal Beg consist mainly of a 100 m thick flow of olivine tholeiite belonging to the Talisker Group (Williamson, 1979). The two outliers exhibit spectacular columnar jointing. At Preshal More, a series of fine-grained, water-lain tuffs underlie the tholeiite flow along the north-eastern margins of its outcrop. In contrast, to the west the tuffs are absent and the flow rests directly upon a series of hawaiites, mugearites and basalts of the Arnaval Group. On Preshal Beg the tholeiite rests upon a coarse agglomerate associated with minor tuff horizons. The agglomerate overlies leucocratic, clinopyroxene-phyric trachytes or trachyandesites in the north, but at the southern margins of its outcrop it lies directly upon fine-grained hawaiite. The tholeiite has an unusual chemistry within the Skye lava succession and is only matched by a flow high in the Osdale Group (Table 2.2) near Edinbane (Esson *et al.*, 1975). It is an olivine tholeiite which is unusually depleted in alkalis and rich in calcium with a distinctive trace-element chem-

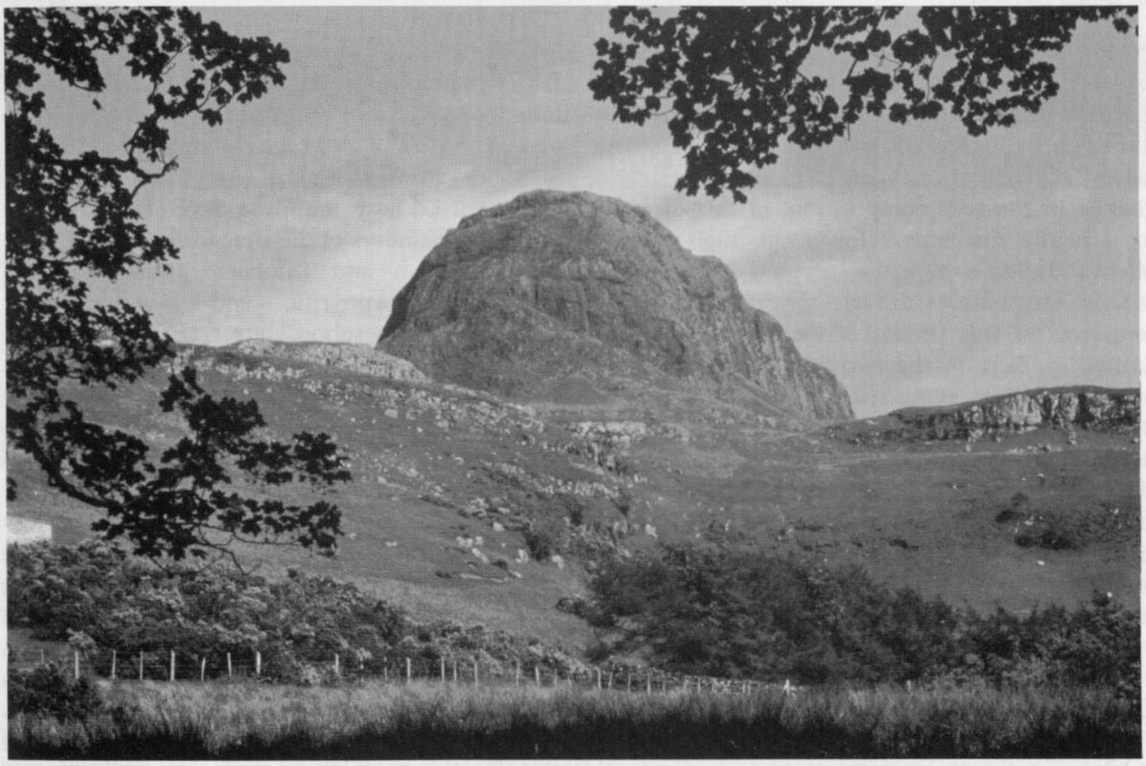


Figure 2.7 Late tholeiite lava forming Preshal More and infilling a former valley eroded in flows of the Skye Main Lava Series that form pale-coloured scarps below and to the right. Talisker site, Skye. (Photo: A.P. McKirdy.)

istry (Fig. 1.2; Esson *et al.*, 1975; Williamson, 1979). The thick flow is interpreted as a ponded lava lying on top of the Arnaval lavas (Esson *et al.*, 1975); ponding occurred either owing to a downstream obstruction, or when a thick flow outwith the area flooded back into the valley (cf. Fionchra, on Rum).

Interpretation

The site is largely occupied by the varied lavas of the Arnaval (Osdale) Group at the top of the SMLS. As with the lavas of the Storr (see above), these are transitional in geochemical character, but have a more varied composition (picrites, olivine basalts, hawaiites, mugearites and trachytes). Striking evidence for a major compositional change in the basaltic magma comes from the thick lava flow which forms Preshal More and Preshal Beg. This flow occupies a valley eroded in the upper flows of the transitional lavas of the Arnaval Group. The valley appears to have been partly floored by agglomerates and bedded water-lain tuffs, and it is most probable that the abnormally thick flow which overlies these deposits was ponded within the steep-sided valley. Thus, it is clear that the Preshal More–Preshal Beg flow was erupted after a significant erosional interval, a situation comparable with that of some basaltic andesites and icelandites on Rum (see Fionchra below). The analogy may be taken further since, as on Rum, there is major change in the lava composition; in this instance to a highly distinctive, low-alkali, high-calcium olivine tholeiite generally depleted in incompatible elements. Although the effusive representatives of this Preshal More magma type are limited on Skye to the two hills of this site, and one earlier flow, basic rocks of similar composition occur widely as intrusions and are particularly abundant in the Skye dyke swarm (Mattey *et al.*, 1977); the magma type is important in the British Tertiary Volcanic Province in general (Thompson, 1982) and has many similarities to mid-ocean ridge basalts (cf. Bell and Harris, 1986).

Conclusions

This is an important site for demonstrating both the structural and compositional complexity of the subaerially erupted lavas of the upper part of the SMLS. It also contains a particularly clear record of an abrupt change in lava composition from earlier flows after a major erosional interval. The site contains the type locality for the distinctive Preshal More type of olivine basalt, which is known to have a widespread occurrence within the BTVP and which is comparable in many respects with mid-ocean ridge basalts.

ROS A' MHEALLAIN

Highlights

The site contains excellent examples of trachyte, mugearite and benmoreite which are some of the most chemically evolved lavas in the Skye Main Lava Series. Chemical evidence shows that some (mugearite–benmoreite) formed under high-pressure conditions near the base of the crust; by contrast, others (iron-poor mugearites–trachytes) reflect lower-pressure conditions of formation high in the crust.

Introduction

Exposures between Portree and Bracadale on the hills of Ros a' Mheallain (NG 375 405), Ben Scudaig (NG 357 410) and Beinn na Cloiche (NG 366 418) display some of the most petrogenetically evolved lavas found on Skye (Fig. 2.8). The flows are members of the Bracadale Group (Table 2.2; Anderson and Dunham, 1966) and are principally porphyritic and non-porphyritic mugearites with subordinate trachytes and benmoreites. Rare basaltic/lavas and trachytic tuffs also occur.

Description

The summit of Ros a' Mheallain (Fig. 2.8) consists of a strongly feldspar-phyric mugearite which is petrologically allied to the composite flow of Roineval and Druim na Criche. The flow is underlain by scoriaceous mugearite and perhaps two trachyte flows, the lower of which is admirably exposed nearby in a small quarry and in cuttings along the Portree–Bracadale road. This trachyte is rather leucocratic and, although

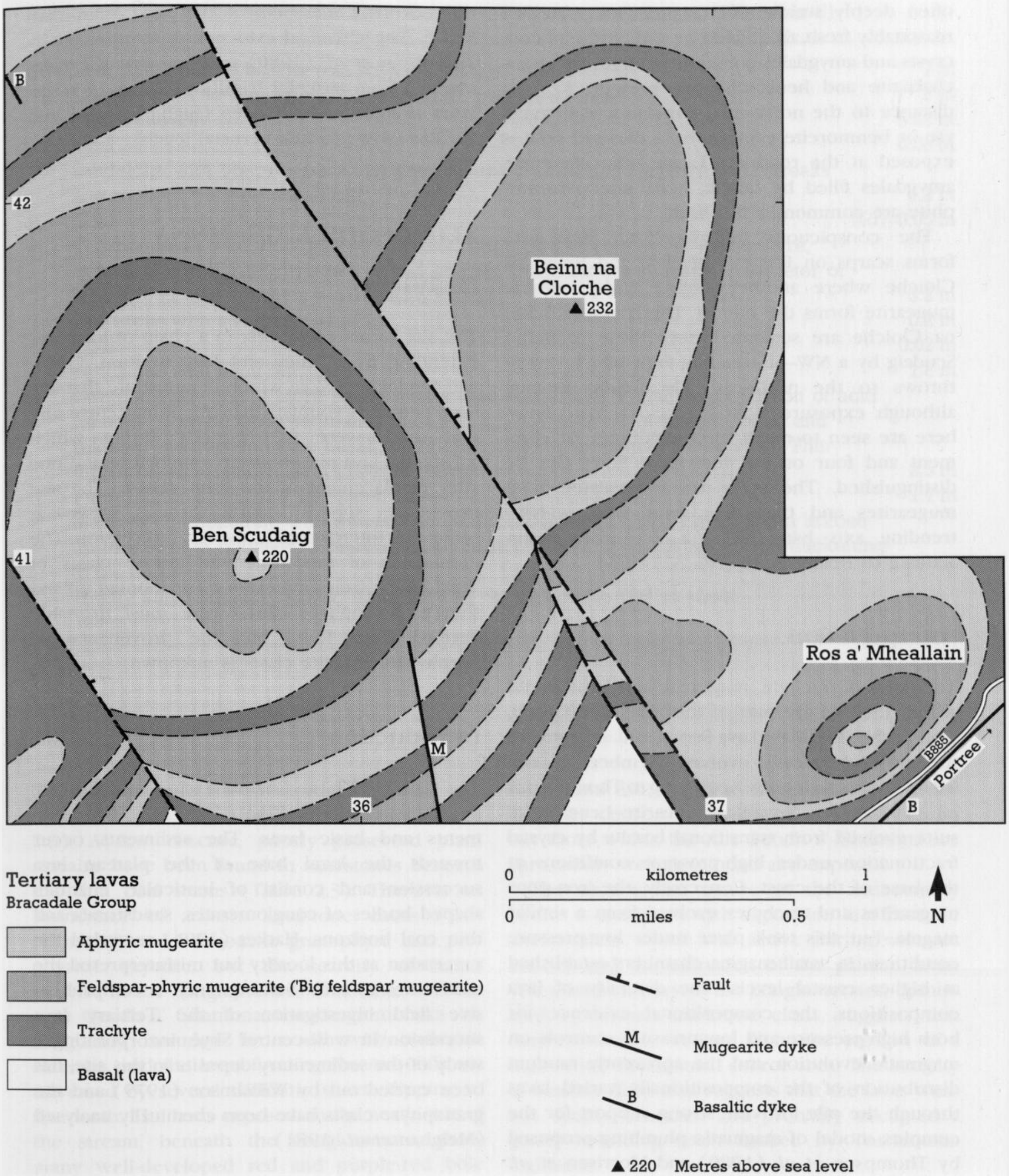


Figure 2.8 Geological map of the Ros a' Mheallain site (adapted from the British Geological Survey 'One-Inch' map, Northern Skye Sheet 80 and parts of 81, 90 and 91).

often deeply weathered, original flow banding, reasonably fresh alkali-feldspar and biotite phenocrysts and amygdales containing stilbite, mesolite, chabazite and heulandite are present. A short distance to the north-east, a melanocratic trachyte or benmoreite overlain by a thin red bole is exposed at the roadside. Large, often flattened, amygdales filled by quartz, agate and pyromorphite are common in this flow.

The conspicuous feldspar-phyric mugearite forms scarps on Ros a' Mheallain and Beinn na Cloiche where another, higher feldspar-phyric mugearite forms the hilltop. The rocks of Beinn na Cloiche are separated from those of Beinn Scudaig by a NW–SE-trending fault which downthrows to the north-east. On Beinn Scudaig, although exposure is poor, the trachytic flows here are seen to reach their maximum development and four or five individual flows can be distinguished. The lavas are intercalated with mugearites and they thin away from a NW-trending axis lying along a line from Beinn Scudaig to Beinn Aketil (NG 327 463).

Interpretation

The flows of trachyte, mugearite and benmoreite within the site are part of the Bracadale Group, high in the Skye Main Lava Series, and are some of the most chemically evolved members of this basalt-dominated series. According to Thompson *et al.* (1972), the hawaiite–mugearite–benmoreite suite evolved from transitional basalts by crystal fractionation under high-pressure conditions at the base of the crust. Conversely, the iron-poor mugearites and trachytes evolved from a similar magma, but this took place under low-pressure conditions in small magma chambers established at higher crustal levels. The diversity of lava compositions, the compositional evidence for both high-pressure and low-pressure controls on magmatic evolution and the apparently random distribution of the compositionally varied lavas through the pile, provide strong support for the complex model of magmatic plumbing proposed by Thompson *et al.* (1980) and Morrison *et al.* (1985).

Conclusions

The site is of particular value because it contains excellent examples of some of the most chemically evolved members of the Skye Main Lava Series. The chemical evidence is interpreted by Thompson *et al.* (1980) to show that the lavas evolved from parental basaltic magmas in reservoirs situated at both deep (high-pressure) and shallow (low-pressure) crustal levels.

ALLT GEODH A' GHAMHNA

Highlights

The site forms a vital link in a chain of localities extending from Muck and Eigg to Rum, Canna and Sanday and Skye which demonstrate that the Skye centre is younger than the Rum centre and that there were two periods during which substantial lava piles built up, one before and one after emplacement of the Rum centre. The site provides a superb section through water-lain sediments intercalated in the lava succession. The dominance of sandstone and arkose clasts of Torridonian facies indicates a Torridonian upland source; granophyre clasts were most probably derived from Rum, but the provenance of porphyritic rhyolite clasts is unknown.

Introduction

The Allt Geodh a' Ghamhna site contains the finest exposures on Skye of interstratified sediments and basic lavas. The sediments occur towards the local base of the plateau lava succession and consist of lenticular, channel-shaped bodies of conglomerates, sandstones and thin coal horizons. Harker (1904) recorded the succession at this locality but misinterpreted the sandstones as tuffs. Subsequently, a comprehensive field investigation of the Tertiary lava succession in west-central Skye, incorporating a study of the sedimentary deposits in this site, has been carried out by Williamson (1979) and the granophyre clasts have been chemically analysed (Meighan *et al.*, 1981).

Description

The inter-lava sedimentary deposits at Geodh a' Ghamhna are well exposed where the Allt Geodh a' Ghamhna reaches the sea cliffs immediately east of Rubha Thearna Sgurr (NG 365 197).

Table 2.3 The succession at Allt Geodh a' Ghamhna (after Williamson, 1979, table 2)

14	Thin, alkali olivine basalts with scoriaceous tops	7 m
13	Massive basaltic lava with pillow structures towards the base	5 m
12	Thin white ash	0.03 m
11	Coal	0.05 m
10	Sandstone with obscure plant remains occurring as diffuse carbonaceous streaks and rootlets, possibly seat earth	0.2 m
9	Coal	0.01–0.05 m
8	Conglomerate with well-packed, rounded pebbles and cobbles of granophyre, quartzite, porphyritic rhyolite and red arkose. Clasts have a maximum diameter of 0.10–0.15 m, and are set in a pale sandy matrix	3.2 m
7	Sandstone with micaceous partings	0.2 m
6	Coal	0.02 m
5	Sandstone with plant remains	1.8 m
4	Conglomerate with a more sandy matrix than Bed 2, and a smaller proportion of acid igneous to arenaceous sediments than Bed 8. Rare pebbles of amygdaloidal and feldspar macroporphyritic basalt. Clast size <0.30 m, averaging 0.10–0.15 m. Thin lenses of white sandstone in lower horizons	2.3 m
3	Fine-grained sandstone, laminated base	1.1 m
2	Massive conglomerate with densely packed, crudely imbricated clasts of red arkose up to 0.30 m in diameter. Contains green siltstones with a sandstone wedge thickening to the north	2.75 m
1	Highly amygdaloidal basaltic lavas forming the top of the cliff at about 125 m elevation	10 m

Williamson (1979) has recorded in detail the succession on the south side of the stream (Table 2.3). A few obscure, poorly preserved plant remains have been found in sandstones beneath the thin coal seams (Table 2.3). There is an abundance of arkosic sandstone clasts (Torridonian?) and Palaeocene granophyre and porphyritic rhyolite, but the scarcity of basalt pebbles in the conglomerates is notable.

At Geodh a' Ghamhna, the conglomerates are irregularly intruded by a sill with andesitic affinities, and the lavas forming the sea cliffs are traversed by several tholeiitic sheets dipping to the north. The lavas exposed on the north side of the stream, beneath the conglomerate, show many well-developed red and purple-red bole horizons.

Interpretation

Inter-lava sedimentary deposits are found at three main localities on Skye, namely Glen Osdale, Glen Brittle and Allt Geodh a' Ghamhna. All of these localities contain sediments of a similar nature, but those within the Allt Geodh a' Ghamhna are particularly well developed and exposed.

The channel-like nature of the sedimentary bodies is consistent with deposition in a fluviatile environment which was active during volcanic activity and the extrusion of the plateau lavas. The characteristics of the conglomerates, dominated by arkosic sandstone clasts, suggests that they are largely derived from the erosion of a high relief, Torridonian source area. The scarcity of basaltic clasts also suggests that the lavas were not deeply dissected and probably occupied a gently subsiding basin flanked by Torridonian highlands.

Williamson (1979) has suggested that the conglomerates were deposited during periods of flash flooding; probably the sandstones and certainly the coals belong to quieter periods of sedimentation. He also suggested (1979) that the source for the Torridonian clastic material may have lain to the south and that the sediments of

Skye, Rum (Fionchra) and Canna (see Sanday and Compass Hill) belong to a more-or-less penecontemporaneous fluviatile system.

The origin of the granophyre and rhyolite pebbles found in the conglomerates is problematic since they could suggest the existence of early Tertiary acid intrusions on Skye. Although the clasts are broadly similar to some of the western Red Hills granitic rocks they cannot have come from that source, for the Red Hills granites demonstrably post-date the Cuillin gabbros which, in turn, intrude the Skye Main Lava Series. Clearly, a pre-lava source is required and this could have been on Skye, in the general area of the central complex (cf. J.D. Bell, 1966, 1976; Walker, 1975). However, a study by Meighan *et al.* (1981) strongly suggests that the acid rocks may ultimately have been derived from the Rum central complex, where both granophyres and rhyolite (felsites) were deeply eroded during the early Tertiary along with Torridonian sandstones. Furthermore, detritus from Rum is known to have spread at least as far as Canna–Sanday (Emeleus, 1973). Thus, this site is an important link in a chain of sites which strongly indicates that the Skye Main Lava Series and the Skye central complex post-dated the Rum central complex (for example, Mussett *et al.*, 1988).

Conclusions

The dominance of sandstone and arkose clasts and the paucity of basalt pebbles in the conglomerates of this site indicate the former presence of a lava field traversed by streams and rivers which drained from a hilly, or possibly even mountainous, Torridonian hinterland. The additional presence of porphyritic rhyolite and granophyre clasts points to (presumably) Tertiary plutonic rocks intruding the Torridonian and also to the possibility of early acid lavas or ash flows of Tertiary age (cf. Cnapan Breaca, Rum). The provenance of the porphyritic rhyolite (felsite) cobbles and pebbles is not yet known; however, the petrography and geochemistry of the granophyre clasts singles out Rum as their most likely source. If this hypothesis is correct, this is one of the few instances where it is possible to obtain relative ages of the Tertiary central complexes. The site is thus a vital link in demonstrating that the Skye centre post-dates the central complex of Rum and that there must have been at least two periods of plateau lava eruption, one of which (the lavas of Eigg and Muck) preceded emplacement of the central complex of Rum and another (Canna–Sanday; north-west Rum; Skye Main Lava Series) which formed after the Rum volcano had been unroofed.

AN CLÈIREACH

Highlights

The site contains an excellent example of a coarse gabbroic-anorthosite (allivalite) sheet cutting the Skye Main Lava Series. The rock provides textural evidence that the sheet became choked with early-formed plagioclase megacrysts crystallized from a low-alkali, high-calcium tholeiitic basalt magma, and it demonstrates that this distinctive magma was available at a late stage in the igneous history of northern Skye.

Introduction

Substantial dyke-like bodies and occasional sills, containing coarse gabbroic anorthosite (allivalite) and gabbro (Fig. 2.9), intrude the plateau lavas of north-west Skye, following the NNW trend of the regional dyke-swarm. The characteristics of these intrusions are demonstrated by the gabbroic anorthosite intrusion at An Clèireach. The dykes are of significant petrogenetic importance in understanding the igneous activity of northern Skye.

Following their discovery by Harker (1904), they were described by Anderson and Dunham (1966). In a subsequent investigation, Martin (1969) coined the term 'Oseitic Group' for the intrusions. Donaldson (1977a) has given a detailed account of their petrology and suggested that they form volcanic plugs.

Description

At An Clèireach (NG 335 443; Fig. 2.9), a gabbroic anorthosite intrusion cuts the mugearitic and trachytic lava flows of the Bracadale Group (Anderson and Dunham, 1966). It belongs to the group of coarse-grained, basic and ultrabasic dyke and pod-like intrusions in the area between

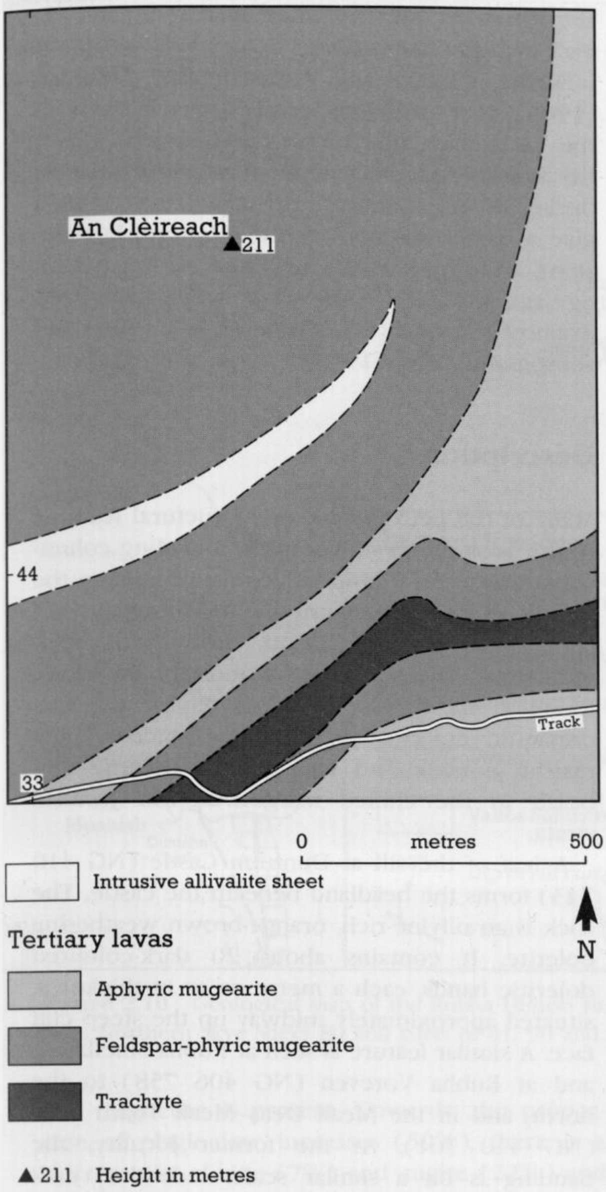


Figure 2.9 Geological map of the An Clèireach site (adapted from the British Geological Survey 'One-Inch' map, Northern Skye Sheet 80 and parts of 81, 90 and 91).

Bracadale and Beinn a Chlèirich (NG 332 451) mapped by Anderson and Dunham (1966) and collectively termed the Oseitic Group by Martin (1969) after the River Ose.

The intrusion at An Clèireach is poorly exposed, and Donaldson (1977a, Fig. 2) shows two disconnected outcrops. It is depicted on the British Geological Survey maps (Sheet 80) as a kilometre-long NNW-trending dyke, up to 150 m wide and, within the site, a sill-like apophysis skirting around the southern slopes of An Clèireach; this is one of the few sills shown to intrude the lavas (cf. Harker, 1904). The intrusion consists of coarse-grained, gabbroic anorthosite (allivalite on the BGS maps) with thin, basaltic marginal facies at the contact with the lavas. The anorthosite is dominated by calcic plagioclase megacrysts (bytownite/anorthite) subophitically enclosed by large augite crystals. Donaldson (1977a) provides detailed descriptions of the petrography and mineralogy of this distinctive group of intrusions.

Interpretation

The coarse-grained dykes lie on the axis of maximum dilation of the regional dyke swarm (Speight *et al.*, 1982). The spatially linked outcrops of the group suggest that they mark a major fissure from which the, now mostly eroded, youngest lavas on Skye (Upper Bracadale Group) were erupted.

Donaldson (1977a) has suggested that the dykes represent a concentration of solids, mainly plagioclase megacrysts, mobilized and subsequently sedimented by a basaltic liquid which erupted at the surface as lava. The plagioclase megacrysts, together with subordinate olivine, were envisaged to have crystallized in a small, shallow magma chamber from low-alkali, high-calcium olivine tholeiite liquids. The crystals were carried up by pulses of this magma into the feeder dykes, where they were concentrated and settled out, possibly by flow differentiation. The host magma subsequently erupted at the surface as low-alkali, high-calcium olivine tholeiites, the relicts of which are found in the vicinity of the dykes (Donaldson, 1977a). After the dyke had become 'choked' with crystals, the eruption site shifted to form new dykes/pods. Thus, according to Donaldson, this distinctive group of dykes represents a series of volcanic feeder plugs.

The geochemistry of these intrusions confirms the existence of low-alkali, high-calcium tholeiitic magmas, similar to those found in the Talisker site (Preshal More and Preshal Beg), towards the end of Tertiary volcanism in northern Skye. Their exact age and position in the igneous stratigraphy of Skye is not known but their petrography and chemistry suggests links with gabbros in the

Cuillin centre (see below). These rocks provide a further indication that this distinctive magma type developed widely with time in the British Tertiary Volcanic Province (see Talisker site).

Conclusions

The intrusion within this site is a representative of a group, intruding the Skye Main Lava Series of northern Skye, which demonstrates that low-alkali, high-calcium tholeiitic magmas became widely available in Skye, and elsewhere in the BTVP, after the eruption of substantial amounts of alkali-olivine and transitional basaltic magmas. The dykes are late in the igneous sequence in northern Skye, but may be coeval with intrusions in the Cuillin centre. The petrography of the dykes shows that they accumulated large amounts of early-formed crystals from the tholeiitic magmas.

RUBHA HUNISH

Highlights

The sills here show textbook examples of columnar jointing, chilled margins against sedimentary country rocks and transgressive relationships to the sediments. The thicker sills have a wide range of rock types, ranging from very olivine-enriched dolerites to pegmatitic dolerites rich in zeolites and poor in olivine. The marked variation in mineral proportions may be explained by the sinking of olivine during early crystallization of the sill magma and the subsequent redistribution of the mineral during flow of the magma.

Introduction

The Trotternish Sill Complex is one of the most remarkable features of the geology and scenery of northern Skye; excellent sill exposures lie within the Rubha Hunish site (Fig. 2.10). The complex consists of a great sheet of basic–ultrabasic rock, typically split into a number of leaves which transgress through folded Jurassic strata while retaining a constant level below the base of the Tertiary lavas. The total thickness of the sill does not depart substantially from 230 m. The sheets provide fine examples of crystal differentiation and many textbook illustrations of the relationships between sills and their host sediments, as well as columnar jointing.

Walker (1932) and Anderson and Dunham (1966) have produced detailed descriptions of the Trotternish Sill Complex and Simkin (1967) has considered the role of flow differentiation during its emplacement. Bell and Harris (1986) give a useful synthesis of the Trotternish intrusions, and the geochemistry, mineralogy, petrology and structure of the sill complex have been examined in detail by Gibson (1988, 1990) and Gibson and Jones (1990).

Description

Many of the petrographic and structural features of the Trotternish sill complex, including columnar jointing and transgressive relationships to the sediments, are demonstrated in the shore and cliff sections of this site. Inland, exposure is often indifferent. The site contains most of the facies found in these sills, including olivine dolerite, crinanitic dolerite, picro-dolerite, picrite, pegmatitic dolerite and finer-grained dolerite and basalt in the chilled margins against Jurassic strata.

A leaf of the sill at Duntulm Castle (NG 410 743) forms the headland beneath the castle. The rock is an olivine-rich, orange-brown weathering dolerite. It contains about 20 dark-coloured doleritic bands, each a metre or so in thickness, situated approximately midway up the steep cliff face. A similar feature is seen at Rubha Smellavaig and at Rubha Voreven (NG 406 758) to the north, and in the Meall Deas–Meall Tuath cliffs (NG 410 761). At the former locality, the banding is on a similar scale; individual dark bands averaging 0.3 m in thickness. Drever (*in* Brown, 1969) noted that the banding was conformable with wedging out of the sill leaf at Rubha Voreven. Gibson and Jones (1990) provide descriptions and illustrations of the layering from a number of localities and give the first detailed account of the petrography amd mineralogy of the layered rocks. The layers have well-defined mafic bases and grade upwards within centimetres (or rarely, metres) to felsic tops which are also more resistant to weathering. The layering reflects variation in the modal proportions of olivine, augite and plagioclase; at the base of layers at Rubha nam Brathairean (NG 444 758) olivine (14%) and plagioclase are poikilitically enclosed by large augite crystals (29%) and up to

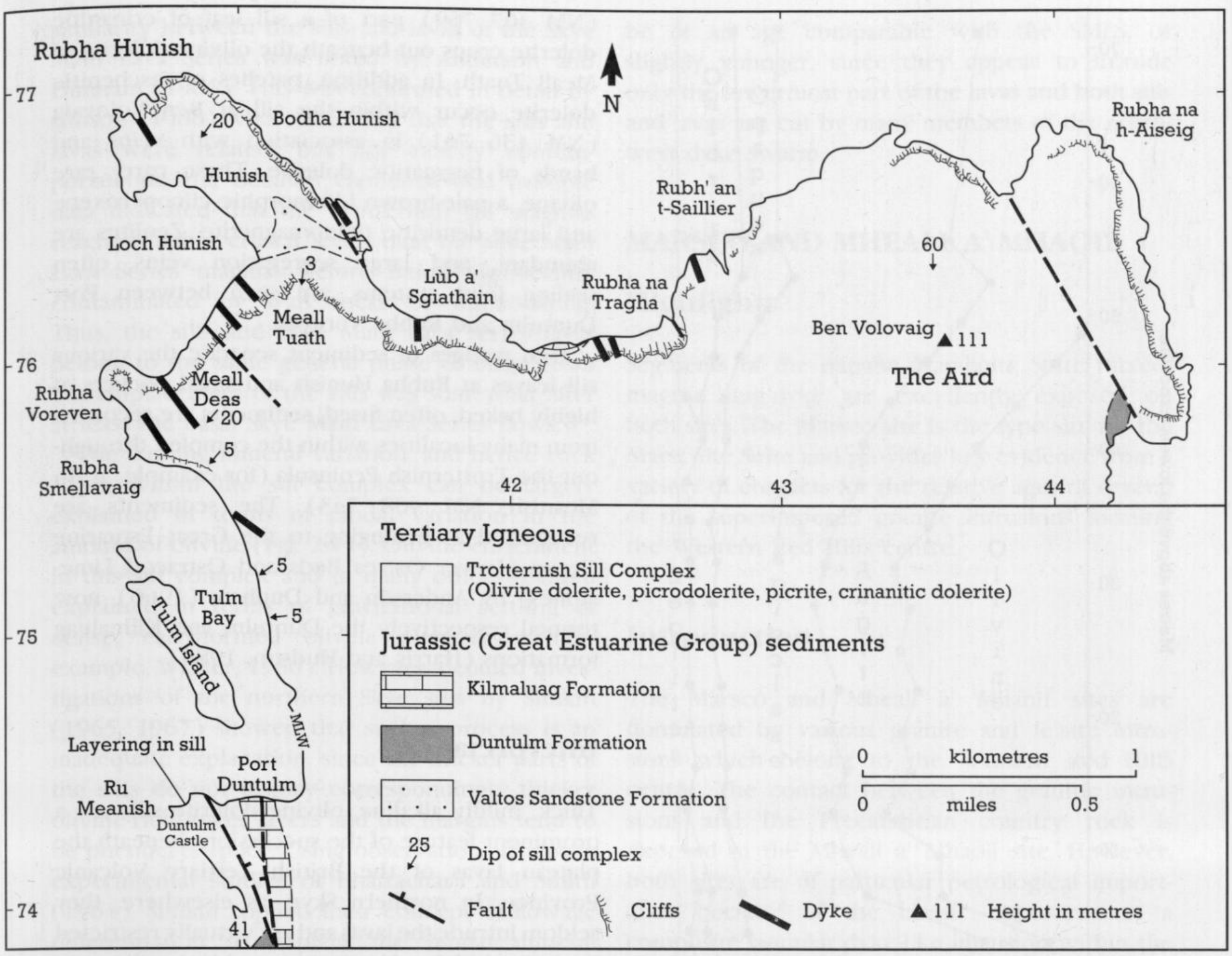


Figure 2.10 Geological map of the Rubha Hunish site (adapted from the British Geological Survey 'One-Inch' map, Northern Skye Sheet 80 and parts of 81, 90 and 91).

6% magnetite is present. Upwards, the proportion of plagioclase increases (59%), there is a decrease in olivine (7%) and augite (22%) and the habit of the pyroxene changes from large poikilitic (ophitic) crystals to small granules. No pronounced compositional variation ('cryptic layering') has been detected. Gibson and Jones consider that the layering developed *in situ*, influenced by strong thermal gradients across the contacts of the sills. It resembles layering found in other thick doleritic or fine-grained gabbroic intrusions, for example, the Camas Mòr dyke on Muck (Camas Mòr site). A thin dyke cutting the Duntulm sill exhibits banding on a centimetre scale parallel to its edges. The layering appears to be caused, in part, by alternations of bands rich in frond-like plagioclase and darker bands rich in augite; the exposure is reminiscent of the 'Mystery Dyke' exposed on the foreshore at Bornaskitaig (NG 372 715) which has been described by Drever (*in* Brown, 1969).

Immediately to the east of Rubha Voreven, the thickness of the sill complex increases substantially to over a hundred metres and is comprised of dolerite, picro-dolerite and picrite. Several distinct zones can be recognized in this exposure, banding being prominent in the lower third of the section, for which Anderson and Dunham (1966) give a comprehensive description. The basal contact of the sill is not seen here but is thought to occur just below the lowest exposures. Olivine dolerite at the base is at first succeeded upwards, through rapid gradation, by more olivine-rich dolerite (picro-dolerite) which forms the layered/banded portion. This is replaced at higher levels by olivine dolerite, the upper contact of which is missing. Simkin (1965, 1967) has described the modal mineral variation in the

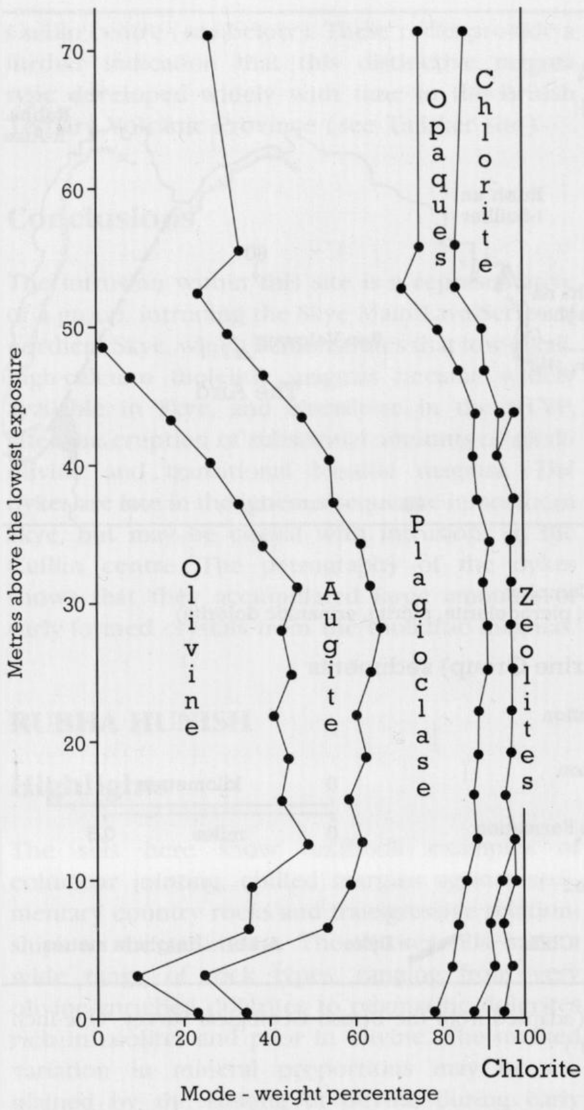


Figure 2.11 Modal variation in the Rubha Hunish sill (after Anderson and Dunham, 1966, fig. 15).

Trotternish sills, including the fine example at Meall Tuath (Anderson and Dunham, 1966, fig. 15; Fig. 2.11). Simkin attributed the distribution of olivine in the intrusions to the process of 'flowage differentiation' and on this hypothesis, some of the banding may therefore be a fluxion feature.

Much of the sill displays columnar, or prismatic jointing, fine examples occurring at Lub a' Sgiathain (NG 416 761). Here, spectacular fan jointing is observed which can be attributed to either intrusion into locally irregular bedding surfaces or unusual heat-loss conditions during cooling (Bell and Harris, 1986). At Rubha Hunish (NM 407 769), part of a sill leaf of crinanitic dolerite crops out beneath the olivine dolerite of Meall Tuath. In addition, patches of teschenitic dolerite occur within the sill at Ben Volovaig (NM 436 761) in association with veins and bands of pegmatitic dolerite. These carry rare olivine, a pale-brown idiomorphic clinopyroxene and large dendritic titanomagnetite. Zeolites are abundant, and large segregation veins, often sealing joint systems, are seen between Port Duntulm and Rubha Voreven.

Thin wedges of sediment separate the various sill leaves at Rubha Hunish and small pockets of highly baked, often fused, sediments are recorded from many localities within the complex throughout the Trotternish Peninsula (for example, at Ru Meanish, NM 408 743). The sediments are recognized as belonging to the Great Estuarine Group (Lower Ostrea Beds and Ostracod Limestones) by Anderson and Dunham (1966), now termed respectively the Duntulm and Kilmaluag formations (Harris and Hudson, 1980).

Interpretation

Thick, mildly alkaline, olivine dolerite sills are a prominent feature of the successions beneath the plateau lavas of the British Tertiary Volcanic Province. In northern Skye, as elsewhere, they seldom intrude the lavas and are virtually restricted to the underlying Mesozoic (or older) sediments. However, immediately south of the site, at Creag Sneosdal (NG 415 689), the uppermost leaf of the complex intrudes the basal tuffs and sediments of the lava succession. The sill complex is remarkable in that it remains at a fairly constant level at or near the base of the lavas and therefore behaves in a broadly transgressive manner towards the open folds in the Jurassic strata. This suggests that lithostatic loading by the lava pile was an important factor controlling sill emplacement (Anderson and Dunham, 1966) implying a fairly constant thickness of lavas over northern Skye when the sills were intruded.

The relative ages of the sill complex and the Skye Main Lava Series lavas are fairly closely defined: the sills cut tuffs at the base of the lavas and may intrude the lowermost lavas at Camas Ban on the south of Portree Harbour (NG 493 428) and at Oisgill Bay (NG 135 495) on the western edge of the lavas. Both the sill complex and the lavas are cut by numerous dykes of the NW-trending swarm. The broad geochemical similarity between the sills and lavas of the Skye Main Lava Series was noted by Anderson and Dunham (1966). This was confirmed in detail by Gibson (1988) who concluded that the sills and lavas were related, but not exactly contemporaneous; the detailed elemental and isotopic data indicated that the Trotternish sill magmas reached higher crustal levels than the Skye Main Lava Series magmas before being significantly contaminated by wall rocks or fractionating. Thus, the sills and Skye Main Lava Series lavas belong to the same general phase of magmatism but emplacement of the sills was somewhat after at least the basal Skye Main Lava Series flows.

The striking mineral variation, and hence rock types, within the sill complex can be largely explained in terms of modal variation in the amount of olivine (Fig. 2.11). Olivine enrichment in this sill complex and in many others is often explained in terms of gravitational settling of dense, early-formed olivine phenocrysts (for example, Walker, 1930). However, detailed investigations of the northern Skye sills by Simkin (1965, 1967) showed that such a process is an inadequate explanation, since the thicker parts of the sills do not display correspondingly thicker olivine-rich lower layers and the margins tend to be phenocryst poor. Using observations from the experimental studies of Bhattacharji and Smith (1964), Simkin applied their concept of flowage differentiation to explain the modal mineral variations in the Skye sills.

Conclusions

The north Skye sills result from the injection of mildly alkaline olivine basalt magmas into the Mesozoic sediments underlying the plateau lavas. The general level of sill intrusion conforms to the base of the lava pile but transgresses the folded sediments; the load imposed by the lava pile is thus seen as having exercised pressure control on the level to which the sill magmas rose.

The thick Trotternish sills show considerable internal variation in the proportions of their minerals, which is attributed to the combined effects of settling early-formed, dense minerals (olivine, possibly spinel) under gravity and their redistribution and concentration during flow of the intruding magma. The chemical composition of the less olivine-enriched facies of the sills is broadly comparable with alkali olivine basalts in the Skye Main Lava Series (SMLS). The sills must be of an age comparable with the SMLS, or slightly younger, since they appear to intrude only the lowermost part of the lavas and both sills and lavas are cut by many members of the north-west dyke swarm.

MARSCO AND MHEALL A' MHAOIL

Highlights

Segments of the narrow Marscoite Suite mixed-magma ring-dyke are excellently exposed on both sites. The Marsco site is the type site for the Marscoite Suite and provides key evidence from a variety of contacts for the relative ages of several of the superimposed granite intrusions forming the Western Red Hills centre.

Introduction

The Marsco and Mheall a' Mhaoil sites are dominated by various granite and felsite intrusions which belong to the Western Red Hills centre. The contact between the granitic intrusions and the Precambrian country rock is exposed in the Mheall a' Mhaoil site. However, both sites are of particular petrological importance because of the classic exposures of a composite, annular dyke-like intrusion within the granites containing ferrodiorite, felsite and hybrid rocks which are the product of magma mixing. These belong to the Marscoite Suite, the type locality for which is at Marsco. In addition, a gabbro forms the Marsco summit area.

Harker (1904) published the results of the first detailed survey of the central parts of Skye which included the Western Red Hills centre. He recognized the hybrid nature of some of the intrusions at Marsco, Glamaig and Mheall a' Mhaoil which he termed marscoites. Further detailed work in the area did not appear until that of Richey *et al.* (1946) followed by Wager and Vincent (1962), Wager *et al.* (1965) and Thompson (1969). These studies led to the subdivision of the Western Red Hills centre into at least 12 separate acid intrusions and provided a detailed knowledge of the petrology of the Marscoite Suite. Further work by Bell (1983) and Vogel *et al.* (1984) confirmed the hybrid character of the suite. A recent synthesis covering the sites is contained in the Skye field guide of Bell and Harris (1986) and the 1:50 000 compilation

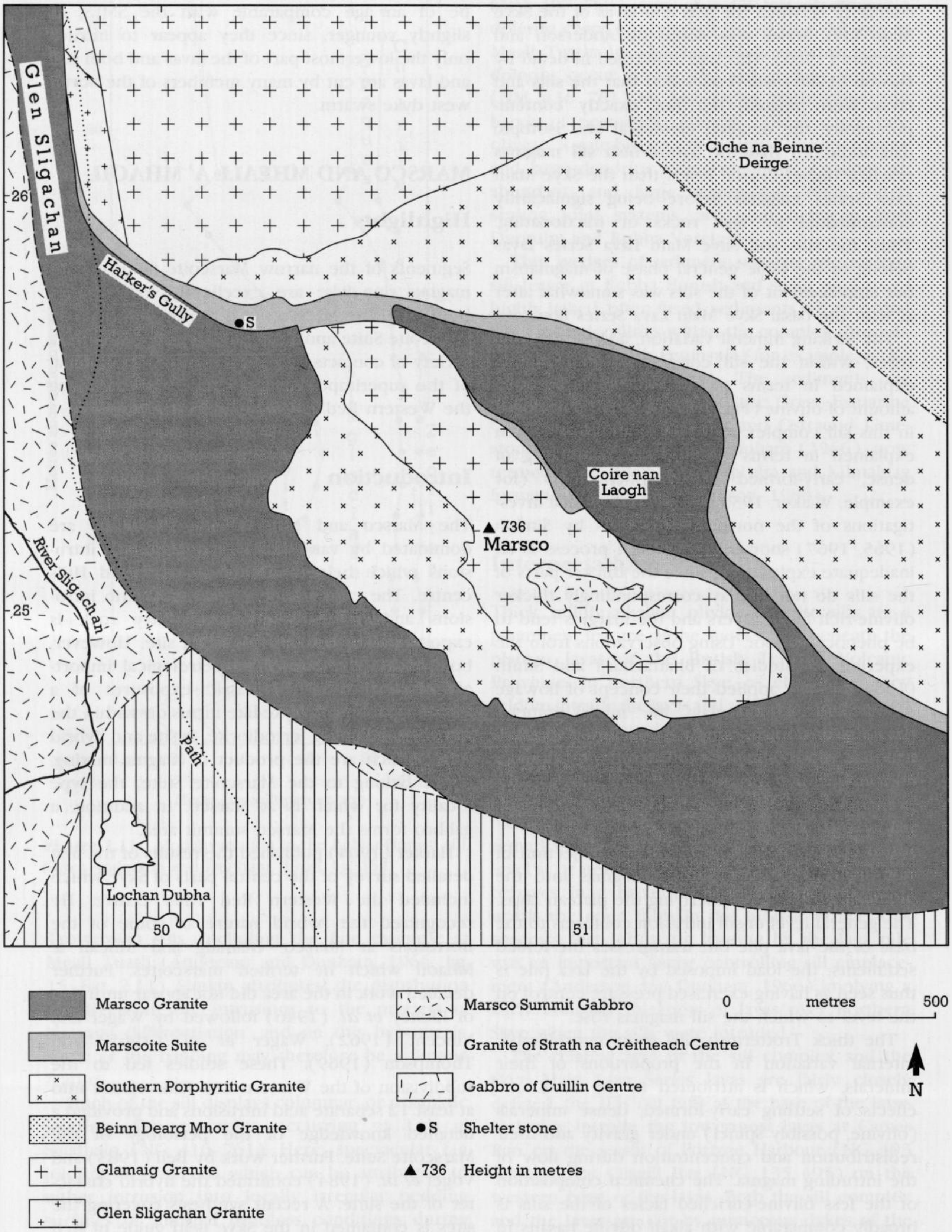


Figure 2.12 Geological map of the Marsco site (after Thompson, 1969, plate 18).

map of the Skye intrusive centres (published by the Open University) is particularly useful.

The term epigranite was introduced by Wager *et al.* (1965) to distinguish the high-level granites of the British Tertiary Volcanic Province from other, deeper-level granites such as those of Caledonian age in Scotland. The granites are characteristically found as stocks and ring-dykes emplaced into brittle crust and their chemical compositions indicate equilibration at low pressures, equivalent to one or two kilometres of cover. They are frequently drusy, or miarolitic, and the cavities indicate that a gas phase developed; they typically did not develop pegmatites. The rocks are, strictly speaking, alkali-feldspar granites, granites or alkali granites on Streckeisen's classification (1978). Although epigranite has been used widely in connection with the Skye granites, use of the term has not spread to the other centres in the Province and it is not used by Bell and Harris (1986). The term will not be used in this account.

Description – Marsco

Granites and felsites form several distinct intrusions within the site (Fig. 2.12; Wager *et al.*, 1965; Thompson, 1969). These either have steep-sided, wall-like contacts or else their margins dip at low angles, suggesting roof-like relationships. The contacts are sometimes marked by zones of crushing and are frequently fine-grained and chilled (cf. Thompson, 1969, plate 17B). This, together with veining of one acid intrusion by another has enabled their relative ages to be established; the intrusive sequence within the Western Red Hills centre is summarized by J.D. Bell (1976) and by Bell and Harris (1986).

The sequence of intrusions within the site is as follows:

(Youngest) Marsco Granite
Marscoite Suite
Ferrodiorite core
Marscoite
Porphyritic Felsite (Southern Porphyritic Felsite)
Southern Porphyritic Granite
Glamaig Granite
Marsco Summit Gabbro

The intrusive sequence may be determined at various points on Marsco; the age relationships,

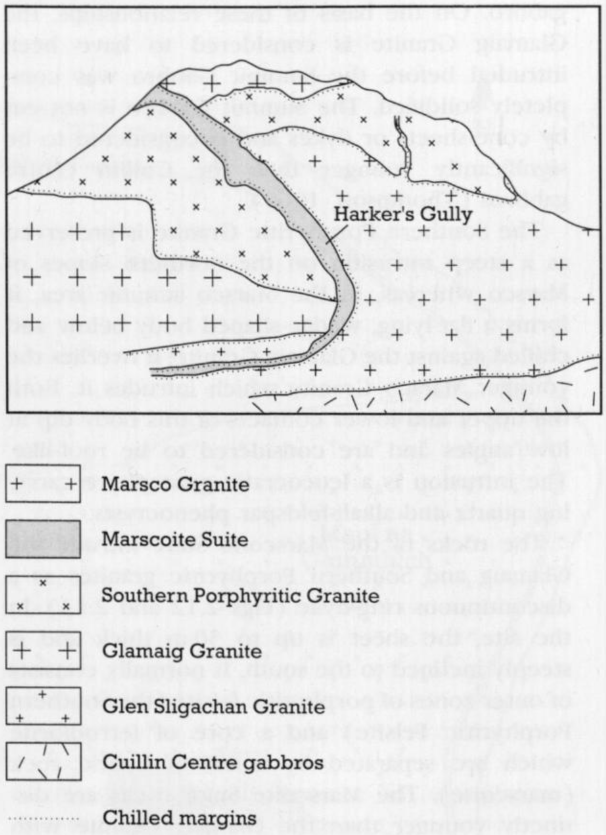


Figure 2.13 Sketch of the west side of Marsco, showing the relationships of the Marscoite Suite rocks to the granite intrusions (reproduced from Sutherland, 1982, fig. 29.5; after Brown, 1969, figure 13).

and the varied types of igneous contacts present, are shown in cartoon form in Fig. 2.13.

The Glamaig Granite, which is exposed around the summit and northern slopes of Marsco, is the earliest of the acid intrusions in the Western Red Hills centre (Wager *et al.*, 1965). The rock is characteristically medium-grained, dull-grey in colour and contains both biotite and amphibole. A persistent feature is the presence of small (0.5–5 cm diameter), partly digested mafic inclusions which constitute about 5% of the rock. Less commonly, somewhat larger (up to 0.3 m diameter) rounded and lobate inclusions of felsitic rock also occur. About 1 km to the north-west of the site, this granite is in contact with crushed gabbros of the Cuillin centre. On Marsco it is capped by the Marsco Summit Gabbro, which is fine-grained where it comes into contact with the granite. The granite, however, also 'net veins' the gabbro and is contaminated for some distance away from the contact by partly digested xenoliths of gabbro. On the basis of these relationships, the Glamaig Granite is considered to have been intruded before the Summit Gabbro was completely solidified. The Summit Gabbro is not cut by cone-sheets or dykes and is considered to be significantly younger than the Cuillin centre gabbros (Thompson, 1969).

The Southern Porphyritic Granite is preserved as a steep intrusion on the northern slopes of Marsco whereas, in the Marsco summit area, it forms a flat-lying, wedge-shaped body below and chilled against the Glamaig Granite; it overlies the younger Marsco Granite which intrudes it. Both the upper and lower contacts of this body dip at low angles and are considered to be roof-like. The intrusion is a leucocratic granophyre carrying quartz and alkali-feldspar phenocrysts.

The rocks of the Marscoite Suite intrude the Glamaig and Southern Porphyritic granites as a discontinuous ring-dyke (Figs 2.12 and 2.13). In the site, the sheet is up to 50 m thick and is steeply inclined to the south. It normally consists of outer zones of porphyritic felsite (the Southern Porphyritic Felsite) and a core of ferrodiorite which are separated by zones of hybrid rock (marscoite). The Marscoite Suite rocks are distinctly younger than the Glamaig Granite with which they are in sharp, chilled contact in Glen Sligachan just north-west of the site. The contact with the Southern Porphyritic Granite, seen just north of Harker's Gully, is again sharp but it is unchilled, suggesting that the marscoite is only slightly younger than the Southern Porphyritic Granite. The Marsco Granite intrudes the Marscoite Suite and breaks the symmetry of the latter in Harker's Gully, where it is in gradational contact with the ferrodiorite of the centre of the Marscoite Suite ring-dyke. The relationships of the several intrusions in and around Harker's Gully are shown diagrammatically in Fig. 2.13. Within the Marscoite Suite intrusion, near and above the Shelter Stone ('S' in Fig. 2.12), exposures on the east of the gully show marscoite in sharp, chilled contact with porphyritic felsite but the bulbous, crenulated contact indicates that the felsite was not consolidated when intruded by the marscoite as such a contact indicates liquid–liquid relationships. Inwards, over about 10 m, there is a complete gradation between the marscoite and the central ferrodiorite which was intruded and extensively mixed with marscoite before the former had consolidated.

The porphyritic felsite contains quartz and alkali-feldspar phenocrysts set in a fine-grained matrix; the phenocrysts are similar to those in the Southern Porphyritic Granite and the two intrusions are therefore considered to be related.

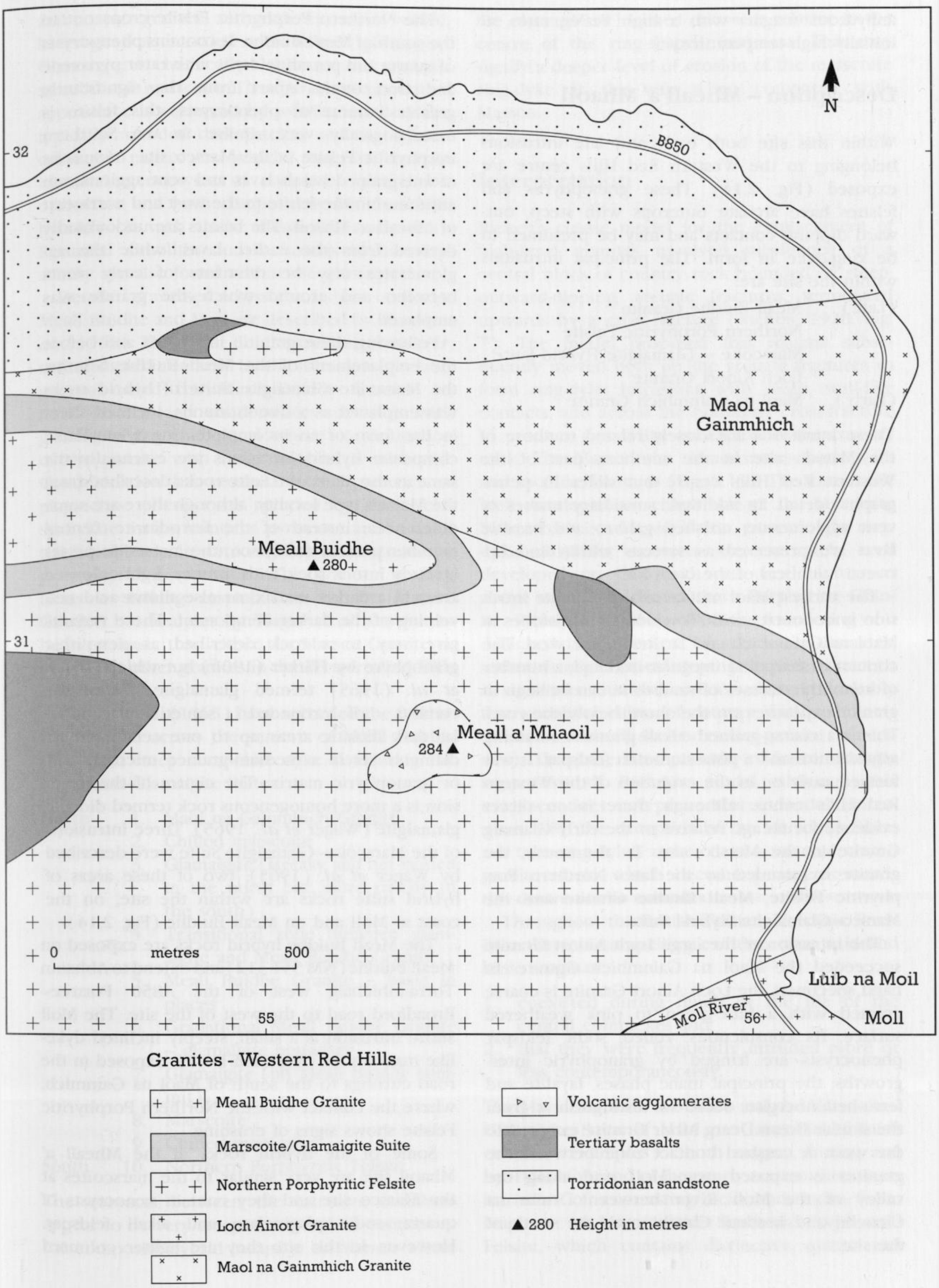
The marscoite is a fine-grained, grey rock containing xenocrysts of rounded andesine, orthoclase with embayed margins ('fingerprint' textures) and quartz rimmed by augite or amphibole. These minerals can be identified as phenocrysts in both the basic and acid rocks in the suite, suggesting that marscoite is a hybrid produced by the mingling of these contrasted types.

The ferrodiorite is variably porphyritic and non-porphyritic, having a fairly complex mineralogy consisting of andesine (as phenocrysts in the porphyritic variety), alkali-feldspar, quartz, hornblende, clinopyroxene (including inverted pigeonite), opaques, biotite and olivine (Wager and Vincent, 1962). Thompson (1969) noted the presence of quartz xenocrysts and concluded that the ferrodiorite, like marscoite, contains a component of felsite magma and that xenocrysts of alkali-feldspar have been dissolved during the slow cooling of the coarse ferrodiorite.

In the lower part of the Harker's Gully section, the later Marsco Granite has intruded along the southern margin of the ring-dyke and cut out the porphyritic felsite and marscoite members. However, the full symmetrical sequence is preserved above 500 m elevation. Within the ferrodiorites of the Marscoite Suite in Harker's Gully, below the level of the Shelter Stone, there are blocks of banded quartz–oligoclase–biotite gneiss of possible Laxfordian age. Such occurrences are also found elsewhere, for example in Coire nam Bruadaran (NM 523 254), and are important in that they provide evidence as to the nature of the deep basement beneath central Skye.

The Marsco Granite is the youngest intrusion in the site. As mentioned, it has an unchilled, completely gradational contact with the ferrodiorite of the Marsoite Suite, but develops sharp, chilled roof-like contacts against the Southern Porphyritic Granite and Glamaig Granite (Thompson, 1969). The detailed mineralogy has been described by Thompson; of particular interest is the occurrence of fayalitic olivine and hedenbergite clinopyroxene as well as calciferous amphibole, indicating crystallization in an

Figure 2.14 Geological map of the Mheall a' Mhaoil site (after Gass and Thorpe, 1976, fig. 6).


N
B850
32
31
Maol na
Gainmhich
Meall Buidhe
▲280
Meall a' Mhaoil
284 ▲
0 metres 500
55
56
Lùib na Moil
Moll River
Moll
Granites - Western Red Hills
Meall Buidhe Granite
Marscoite/Glamaigite Suite
Northern Porphyritic Felsite
Loch Ainort Granite
Maol na Gainmhich Granite
Volcanic agglomerates
Tertiary basalts
Torridonian sandstone
▲280 Height in metres

anhydrous magma with a high Fe/Mg ratio, at initially high-temperature.

Description – Mheall a' Mhaoil

Within this site both early and late intrusions belonging to the Western Red Hills centre are exposed (Fig. 2.14). These granophyres and felsites have arcuate outcrops with steep, outward dipping contacts and may be presumed to be ring-dyke in form. The principal intrusions within the site are:

(Late)	Meall Buidhe Granite
	Northern Porphyritic Felsite
	Marscoite – Glamaigite Hybrid Suite
	Loch Ainort Granite
(Early)	Maol na Gainmhich Granite

These intrusions are closely related to those of the Marsco site in the southern part of the Western Red Hills centre but differ in petrographic detail. In addition, subsidiary masses of vent agglomerate, crushed gabbro and basaltic lavas are preserved as screens within and between members of the complex.

The earliest Maol na Gainmhich Granite intrusion is in contact with Torridonian sandstones at Maol na Gainmhich and farther to the west. The contact is sharp and irregular in detail; a number of xenolithic masses of sandstone can be seen in granite exposures on the shore below the road. This is a coarse-grained, alkali granite containing arfvedsonite and a potassium-rich feldspar. It was formed early on in the evolution of the Western Red Hills centre although there is no direct evidence for its age relative to the early Glamaig Granite in the Marsco site. To the south, the granite is intruded by the later Northern Porphyritic Felsite, Meall Buidhe Granite and the Marsco–Glamaigite Hybrid Suite.

The intrusion of the large Loch Ainort Granite succeeded the Maol na Gainmhich Granite. In hand specimen, the Loch Ainort Granite is coarse grained with a blue-green to pink weathered surface. Its conspicuous, zoned, sodic feldspar phenocrysts are fringed by granophyric intergrowths; the principal mafic phases, fayalite and ferro-hedenbergite, serve to distinguish it from the similar Beinn Dearg Mhor Granite exposed to the west. A crushed contact zone between the granites is exposed near Moll, and along the valley of the Moll River between Druim na Cleochd and Leathad Chrithinn to the south of the site.

The Northern Porphyritic Felsite crops out to the south of Meall Buidhe. It contains phenocrysts of quartz and potash feldspar with rarer pyroxene and iron oxide. Apart from the significantly greater volume of phenocrysts, this felsite is mineralogically very similar to the Southern Porphyritic Felsite in the Marsco site. Inclusions of fine-grained basalt lavas and vent agglomerate are found in the felsite to the west and north-east of Mheall a' Mhaoil. The basalts are undoubtedly derived from the earlier lavas, while the agglomerates may be remnants of early vents between and around which the granite was emplaced.

Following these granitic intrusions and before the emplacement of the Meall Buidhe Granite, the Marscoite–Glamaigite Suite of hybrid rocks was emplaced as a discontinuous, inclined sheet in the form of an incomplete ring-dyke. These composite hybrid intrusions are essentially the same as the Marscoite Suite rocks described from the Marsco type locality, although there are some differences: instead of the ferrodiorite central member present at Marsco, the marscoite passes inwards into a rock with streaky, light-coloured areas in a darker matrix, or else shows acid netveining of the darker component. These variants give way to a rock described as xenolithic granophyre by Harker (1904) but which Wager *et al.* (1965) termed glamaigite. Glamaigite consists of rounded, sometimes globular dark dioritic areas up to one centimetre in diameter set in a medium-grained microgranitic or granophyric matrix. The centre of the intrusion is a more homogeneous rock termed dioritic glamaigite (Wager *et al.*, 1965). Three intrusions of the Marscoite–Glamaigite Suite were described by Wager *et al.* (1965); two of these areas of hybrid suite rocks are within the site, on the coast at Moll and on Meall Buidhe (Fig. 2.14).

The Meall Buidhe hybrid rocks are exposed on Meall Buidhe (NM 551 312) and extend to Abhainn Torra-mhichaig west of the A850 Portree–Broadford road to the west of the site. The Moll Shore intrusion is a small, steeply inclined dyke-like mass on the coast and is well exposed in the road cuttings to the south of Maol na Gainmich, where the contact with the Northern Porphyritic Felsite shows signs of crushing.

Some of the hybrid rocks in the Mheall a' Mhaoil site are very similar to the marscoites at the Marsco site and they contain xenocrysts of quartz, sodic plagioclase and alkali feldspar. However, in this site they are lighter coloured and coarser grained, and grade into a net-veined, heterogeneous mottled rock termed glamaigite. Glamaigite is chemically similar to, and contains xenoliths of, marscoite. The characteristic mottled appearance is enhanced by weathering. Both the typically rounded dark patches and the lighter-coloured matrix in which they lie contain identical xenocrysts of andesine, quartz and orthoclase and both components are marscoitic hybrid rocks with similar chemical characteristics. Rounded xenoliths and inclusions of hawaiitic affinity are also found within the glamaigites.

Detailed traverses across the hybrid bodies at Meall Buidhe and Moll are described by Wager *et al.* (1965). The Meall Buidhe traverse, however, is interrupted centrally by the intrusion of a later granite called the Meall Buidhe Granite. Its north-eastern and south-eastern contacts with glamaigite are gradational where contamination of the granite with basic material is observed. Contamination has resulted in the presence of plagioclase phenocrysts mantled by alkali feldspar. The matrix contains pyroxene and interstitial hornblende in a microgranitic, rather than a granophyric groundmass. The granite, in fact, bears a striking resemblance to the Marsco Granite, but analyses by Wager *et al.* show it to be more basic than either the Marsco Granite or any of the other granites in the Western Red Hills centre.

Wager *et al.* (1965) have recorded the following traverse across the summit of Meall Buidhe through a steep composite dyke containing the Marscoite–Glamaigite Suite.

North 1. Maol na Gainmhich Granite
2. Chilled marscoite
3. Glamaigite (streaky and net-veined in the north but more patchy in the south)
4. Transitional zone between glamaigite and Meall Buidhe Granite
5. Meall Buidhe Granite – basic in places
6. Gradational Meall Buidhe Granite – glamaigite boundary
7. Glamaigite (on Meall Buidhe summit)
8. Marscoite
9 Chilled marscoite
South 10. Northern Porphyritic Felsite

The contacts between the intrusive members appear to be very steep or vertical, in contrast to the composite hybrid intrusion on Marsco where the contacts are inclined outwards relative to the centre of the ring-shaped intrusion. This may signify a deeper level of erosion of the marscoite ring-dyke at this site when compared with Marsco.

Interpretation

Richey's classic model for the emplacement of high-level granites involved subsidence of a central block of country rock bounded by steep, outward-dipping, arcuate fractures, terminated upwards by a cross-fracture (Richey, 1928, Fig. 7). The model proposed that magma subsequently moved both up the arcuate fractures to form ring-dyke intrusions with steep, wall-like contacts, and across the bounding cross-fracture to produce a roof-like contact with the country rock. The Marsco site demonstrates both wall- and roof-like contacts (Fig. 2.13). The former are well developed on either side of the Marscoite Suite which is a classic, if thin, example of a ring-dyke. Roof-like contacts are extremely well developed on the south-west face of Marsco above and below the Southern Porphyritic Granite. Richey's model involved the foundering of a detached block several kilometres in diameter, rather than piecemeal stoping. In this respect, it is significant that the contacts show remarkably few xenoliths either of country rock sediments (Mheall a' Mhaoill site) or earlier granite (Marsco site). Thus, the sites provide evidence strongly supportive of Richey's model, although this evidence does not prove that individual intrusions, with the exception of the Marscoite Suite, are true ring-dykes rather than a suite of nested granite stocks which become younger towards the centre of the complex.

Throughout the British Tertiary Volcanic Province there is compelling evidence that acid and basic magmas:

1. coexisted during much of the life of the central complexes and
2. that they were frequently intruded more or less contemporaneously.

The Marscoite Suite of Marsco and the Marscoite–Glamaigite Suite of Maol na Gainmhich furnish excellent examples of both magma mixing and hybridization, and of the nearly contemporaneous intrusion of contrasting acid and more basic magmas. At Marsco, the Southern Porphyritic Felsite, which contains distinctive quartz and alkali-feldspar phenocrysts, was intruded first and the ferrodiorite, with its equally distinctive plagioclase phenocrysts, came last to form the core of the Marscoite Suite ring-dyke. Between these two contrasted rocks there is the marscoite which contains as xenocrysts the same minerals that form the phenocrysts in its neighbours and, furthermore, chemical analysis shows that the bulk composition of the marscoite is intermediate between the compositions of the adjoining rocks. Thus, the petrographic and chemical evidence shows that the marscoite is a mixed, hybrid rock (Wager *et al.*, 1965; Vogel *et al.*, 1984) and Bell (1983) has demonstrated that it consists of ferrodiorite and porphyritic felsite mixed in the proportions 74:26. Further evidence for mixing is provided in hand specimen by the emulsion-textured glamaigite of Mheall a' Mhaoil.

The contact relationships seen within the Marscoite Suite, and between these rocks and both the Southern Porphyritic Granite and the Marsco Granite, suggest that all were intruded in close succession: the Southern Porphyritic Felsite is in sharp but unchilled contact with the Southern Porphyritic Granite; within the Marscoite Suite the bulbous, crenulated contact between the Southern Porphyritic Felsite and the marscoite is interpreted to show that both were liquid at the same time; and the marscoite is completely gradational towards the ferrodiorite. On the ring-dyke inner contact, a similar gradation from ferrodiorite towards the Marsco Granite means that the granite intruded shortly after the Marscoite Suite. It is also evident (Fig. 2.13) that the granite exploited the ring-dyke structure during emplacement.

The Marscoite Suite thus abounds with igneous intrusive contacts showing a spectrum from those which are sharp and chilled to others which are completely gradational. From careful consideration of the contacts, it appears that the Marsco Summit Gabbro and the Glamaig Granite form an early group of intrusions and that the Southern Porphyritic Granite, the Marscoite Suite and the Marsco Granite are a later suite. Sufficient time must have elapsed between the emplacement of the Southern Porphyritic Granite and the Marsco Granite for the latter to develop a chilled contact.

Conclusions

The field relationships of the granites, Marscoite Suite intrusions and country rocks provide evidence which supports the classic ring-fracture, block subsidence model for granite emplacement proposed by Richey (1928). The sites also contain classic examples of rocks formed by magma mixing; the marscoite member of the Marscoite Suite resulted from an approximate 3:1 mixing between porphyritic magmas of ferrodioritic and granitic compositions. In the ferrodiorite end-member there is subtle evidence for the incorporation of a small amount of porphyritic acid material, and the common occurrence of small, basic inclusions in the early Glamaig Granite suggests that some basic magma was mixed in with acid magma prior to emplacement of this intrusion.

COIRE UAIGNEICH

Highlights

The distinctive mineralogy of the Coire Uaigneich granophyre indicates that it crystallized under shallow, near-surface conditions and its bulk composition shows that it received a substantial contribution from the Torridonian sediments. It is the only sizeable granitic intrusion belonging to the Cuillin centre and it is older than the other Skye granites. Basalt lavas and calcareous country rocks adjoining the Cuillin gabbros have developed distinctive high-temperature mineralogies.

Introduction

This site partly demonstrates the nature of the south-east margin of the Cuillin basic/ultrabasic centre and its effects upon the country rock and, as such, should be considered in conjunction with the Cuillin Hills site. The site contains Lower Jurassic sediments and overlying Palaeocene lavas which show the effects of thermal metamorphism and structural disturbance from the emplacement of the adjacent Cuillin layered eucrites (Fig. 2.15). In addition, the site also encompasses the Coire Uaigneich Granophyre, the only granite associated with the Cuillin centre (Fig. 2.16). This intrusion has been of significant petrological importance in the study of the origin and emplacement of the Skye granites.

The gabbros of the northern part of the Blaven Range belong to the Cuillin centre and were

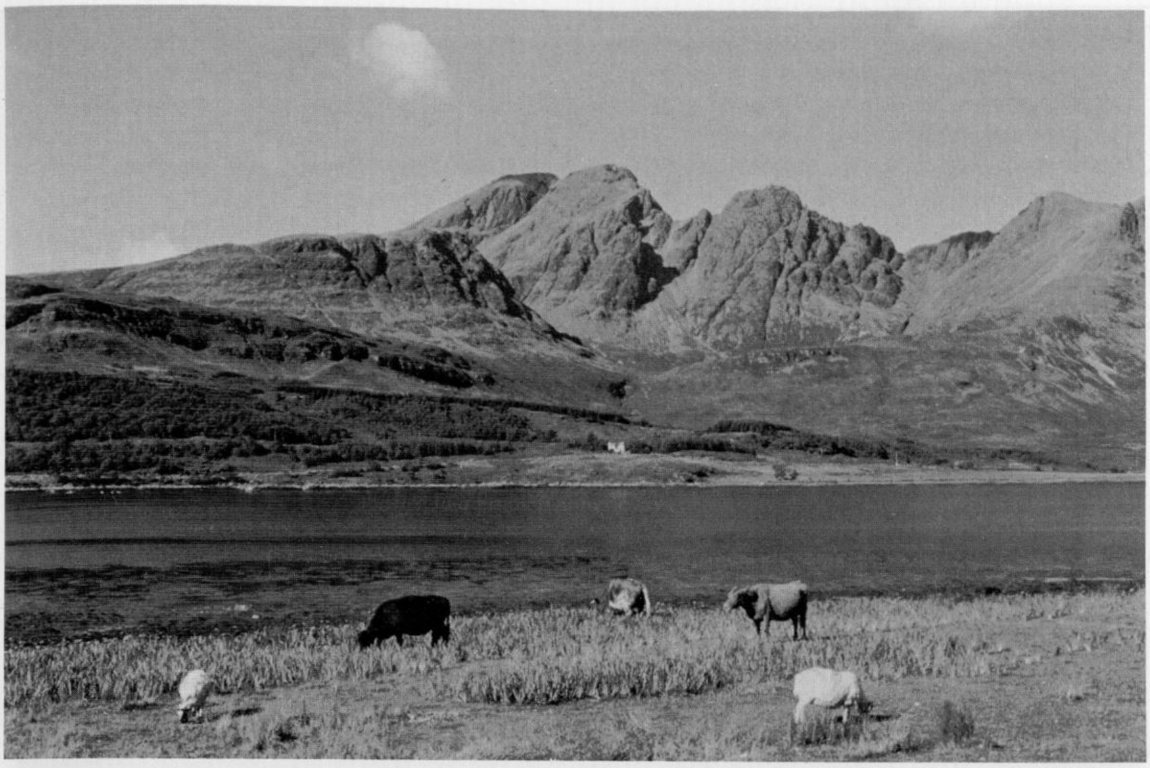


Figure 2.15 Gabbros of the Cuillin centre form the Bla Bheinn ridge in the background, Tertiary lavas on prominent ridge in top left, and Mesozoic sediments reinforced by Tertiary sill(s) in left foreground. Loch Slapin in foreground. Coire Uaigneich site, Skye. (Photo: C.H. Emeleus.)

briefly considered in a study of granites and associated rocks in the eastern part of the Western Red Hills centre by Bell (1966). The effects of the Cuillin centre on the surrounding country rocks around Strathaird were the subject of a detailed investigation by Almond (1960, 1964). Wager *et al.* (1953) and Brown (1963) have studied the origins of the Coire Uaigneich Granophyre. The contentious issue of granite petrogenesis on Skye is discussed in detail by Gass and Thorpe (1976) in the Open University's case study on the Tertiary igneous rocks of Skye and these problems were further considered by Dickin and Exley (1981). The oldest rocks within the site are Jurassic sediments. These are overlain by Palaeocene basalt lavas and both were intruded successively by layered eucrites, the Coire Uaigneich Granophyre, basaltic cone-sheets and numerous NW-trending dykes.

Description

The site comprises three principal units (in order of decreasing age):

1. The country rocks
2. Layered gabbros and other mafic intrusions of the Cuillins
3. The Coire Uaigneich Granophyre

i. Country rock

In Coire Uaigneich and along the course of Abhainn nan Leach to the south-west, Lower Jurassic strata overlain by Palaeocene lavas are in contact with the gabbros of the Cuillin centre. The emplacement of the latter has severely hornfelsed and faulted Jurassic shales, sandstones and thin limestones. Minor folding has also occurred immediately adjacent to the basic intrusion and a small anticlinal structure is present. Calc-silicate assemblages are developed in some of the dolomitic limestones and blocks of high-grade, thermally metamorphosed yellow, serpentinous marbles containing unusual calc-silicate minerals (for instance, spurrite and rankinite; Wyatt, 1952) are locally developed. Rheomorphism of the more leucocratic sediments has occurred along the contact; however, the most spectacular examples of this phenomenon

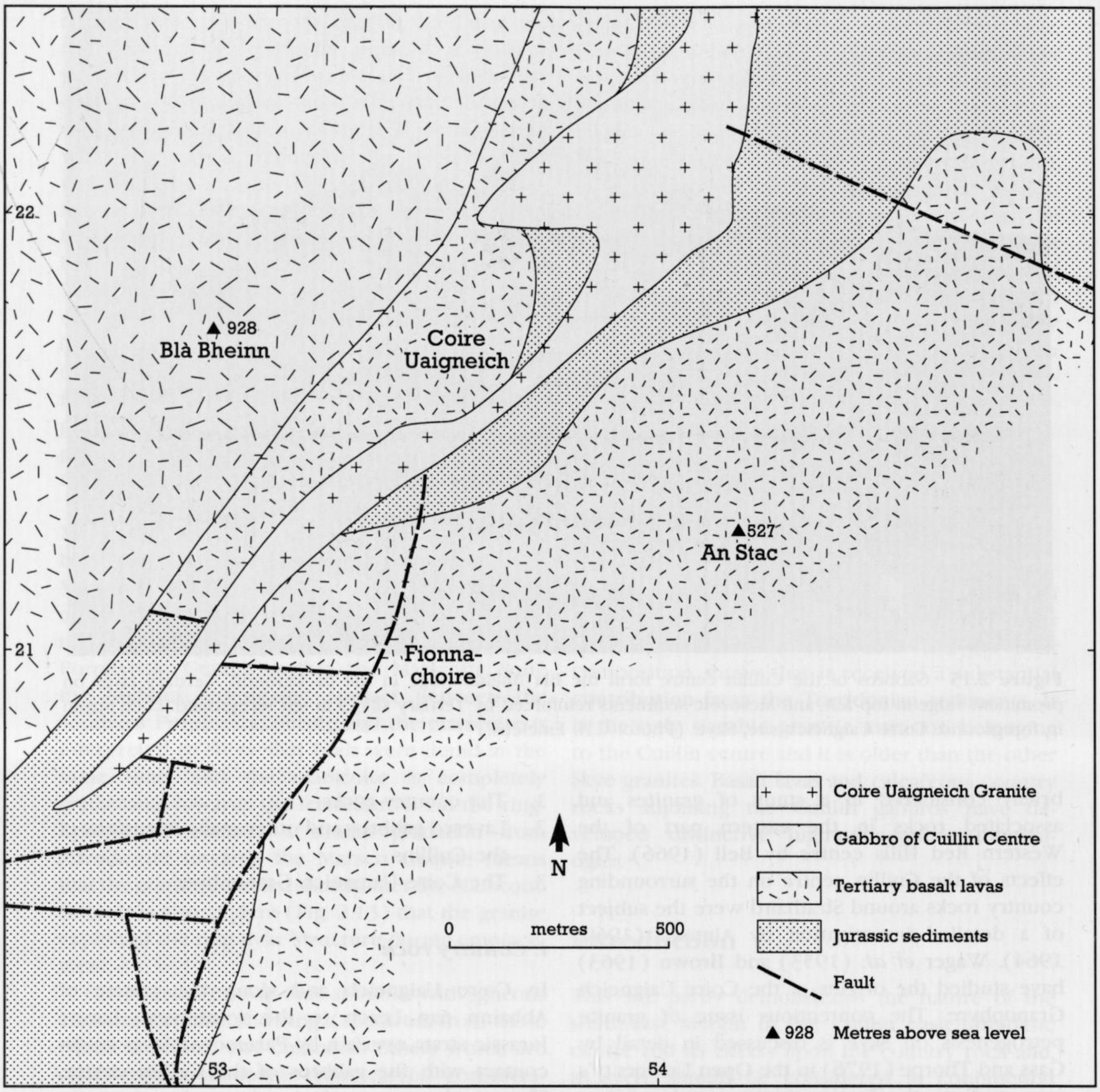


Figure 2.16 Geological map of the Coire Uaigneich site (after Gass and Thorpe, 1976, figure 6).

are found 2 km to the south-west of the site at Camasunary (NG 512 192).

The Palaeocene alkali olivine basaltic lavas are also hornfelsed, and Almond (1960, 1964) has recognized three zones of alteration.

a. Inner Zone: Granular hornfelses consisting of plagioclase, clino- and ortho-pyroxene with or without olivine – formed by complete, or partial, recrystallization. Amygdaloidal structures commonly retained as aggregates or calcic plagioclase.

b. Middle Zone: Actinolite–albite–epidote–chlorite assemblages.

c. Outer Zone: Hydrothermal alterations only.

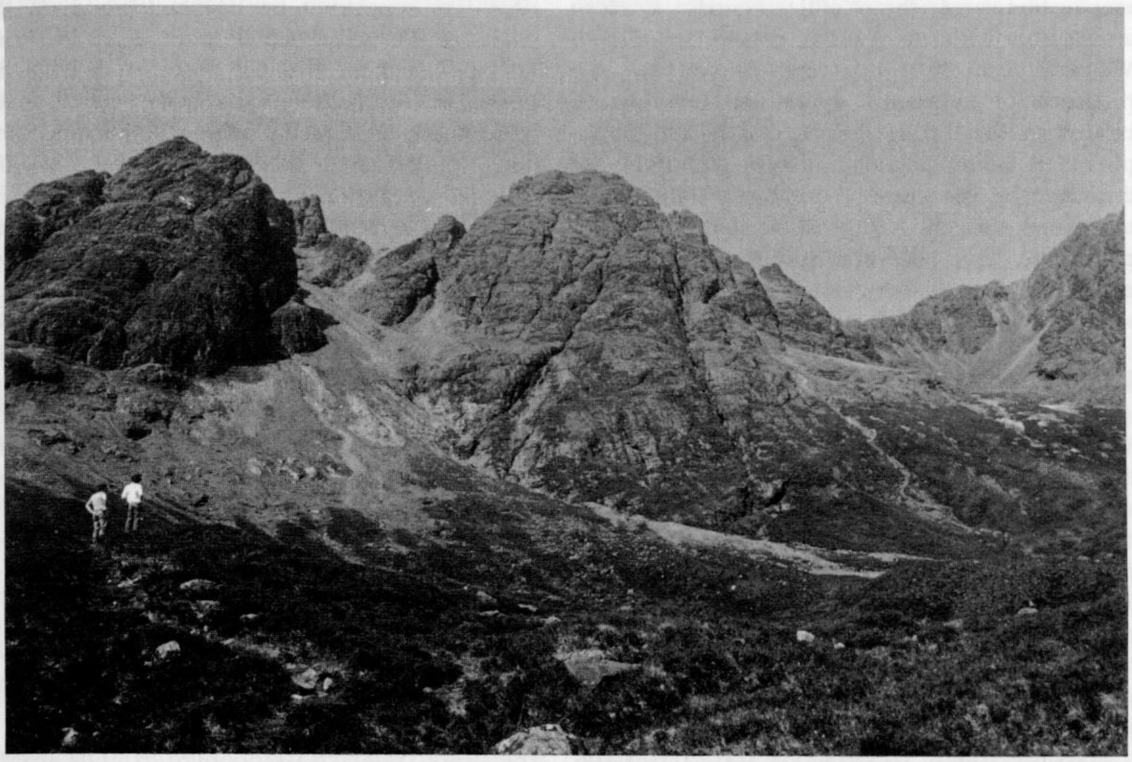


Figure 2.17 East face of Bla Bheinn formed by gabbros cut by later dykes (weathering to give notches) and cone-sheets (forming terraces on faces). Pale rocks at lower levels are the Coire Uaigneich Granite and Mesozoic sediments against the gabbros. Coire Uaigneich site, Skye. (Photo: A.P. McKirdy.)

The lavas of the Coire Uaigneich site lie in zones a and b; the lava pile forming An Stac, though, lies totally within zone b.

ii. Cuillin layered gabbros

Layered gabbros and eucritic gabbros of the Garbh Bheinn–Blaven (Fig. 2.17) range dip towards the centre of the Cuillin intrusion. They form the high serrated ridge east of Strath na Creitheach and the Cuillin Hills. These rocks can be correlated to the layered gabbros and eucrites belonging to the Outer Layered Series of the Cuillin Hills centre (Bell, 1966) and, as such, are discussed within the Cuillin Hills site report below. Essentially, the gabbro is a layered, dark-coloured rock of variable grain size containing bytownite, clinopyroxene and opaque oxides with small amounts of olivine and orthopyroxene. In addition, the gabbros also contain lensoid inclusions of hornfels and ultrabasic rock which parallel the layered structures.

iii. Coire Uaigneich Granophyre

The site has been chosen to include part of the only granitic intrusion associated with the Cuillin centre. The granophyre is exposed in Coire Uaigneich and on the col at Fionna-choire as part of a narrow, discontinuous, ribbon-like intrusion dipping steeply to the south-east at 70–80°. The granophyre is light weathering and contains fine- and coarse-grained facies bearing needles of hypersthene, together with quartz paramorphs after tridymite indicative of crystallization under low-pressure conditions (Wager *et al.*, 1953; Brown, 1963). Outside the limits of the site, on a wave-cut platform at Abhainn Camas Fhionnairigh (NG 509 187), the clean exposures of Coire Uaigneich Granophyre reveal partly digested xenoliths of sandstone.

The margins of the granophyre are chilled against Jurassic country rocks which have been deformed by the intrusion. Eucritic and basaltic xenoliths also occur along the margins of the granophyre showing that it is younger than the emplacement of the Cuillin centre. A close association with the Cuillin centre and a pre-Western Red Hills age are proved by the presence of numerous dykes and cone-sheets, related to the Cuillin centre, cutting the granophyre. In Coire Uaigneich, gabbro xenoliths are enclosed by the granophyre, but on the shore exposures there is a suggestion that the granophyre may have been remelted by the adjoining gabbros since acid net-veining is common.

Interpretation

The very high-grade thermal metamorphism of the adjoining lavas, the presence of unusual calc-silicate hornfelses in the altered Jurassic strata and the occurrence of extensive net-veining and other rheomorphic phenomena close to the site at Camasunary, all provide unequivocal evidence that the Cuillin gabbros were a major heat source on emplacement. This view is compatible with *in situ* crystallization of mafic magmas during the formation of the layered rocks.

Both the Cuillin gabbros and the Coire Uaigneich Granophyre appear to have caused varying degrees of folding and faulting in the country rocks. In the case of the granophyre, the evidence for forcible emplacement contrasts strongly with the prevailing view that the majority of the Skye granites and granophyres were essentially passively emplaced by ring-dyke and block subsidence mechanisms. However, even a cursory examination of the existing maps suggests that this view may be an oversimplification, since disturbance of the sedimentary envelopes to the granites of both the Western Red Hills and the Eastern Red Hills centres may be verified at a number of localities (for example, on the north side of Glamaig, north-east of Mheall a' Mhaoil; on the south and west of Beinn na Caillich, west of Kilchrist). The emplacement of the Skye granites should provide a fruitful field for further research.

Much of the importance of the site lies in the fact that the Coire Uaigneich Granophyre has played a significant role in the understanding of the origin of the Skye granites. Attention was focused on this granite because of the occurrence of partly digested sandstone xenoliths (just outside the site), pointing to a possible origin from the anatexis of Torridonian basement rocks. Wager *et al.* (1953) studied the intrusion in detail, concluding that the granophyre represents partially melted Torridonian sandstone. This concept was supported by Brown (1963) on the evidence of experimental melting studies. Bell (1966) calculated that the heat output from the dense basic/ultrabasic magma body beneath much of southern Skye (see Cuillin Hills) would have been adequate to produce all of the granite magmas of Skye by melting of Lewisian/Torridonian basement rocks. Since these studies, ideas on the origin of the Skye granites have advanced significantly and a detailed discussion on the continuing controversy surrounding the origin of the Skye granites is contained in the Open University's igneous case study on Skye (Gass and Thorpe, 1976) and in Thompson (1982). More recently, in a detailed study on the Coire Uaigneich Granophyre, using trace-element and isotope data, Dickin and Exley (1981) suggested that the granophyre originated from the mixing of two contrasting magmas. These magmas were envisaged to be:

1. partially melted Torridonian sediments and
2. an acid differentiate of basic (Cuillin) magma, which mixed in the ratio 2:1.

The Coire Uagneich Granophyre extends around the south-east side of the Cuillin layered mafic rocks and is obviously structurally related to the Cuillin centre. Since the majority of Skye granites are significantly younger than this centre, it is of some importance to determine its relative age as closely as possible. Probably the most conclusive evidence is provided by the cone-sheets which cut the granophyre and belong to the same suite which cuts the Cuillin layered gabbros, focusing on the Cuillin centre. None of these cone-sheets cuts the other Skye granites and rather, the reverse is true. Thus, the Coire Uaigneich Granophyre is significantly earlier than the Strath na Creitheach and Western Red Hills granites. There is also clear evidence that the granophyre post-dates the Cuillin gabbros of the Blaven area (Fig. 2.17) as xenoliths of the gabbro have been recorded in the granophyre. More importantly however, in Coire Uaigneich the granophyre lies well within the zone of high-grade thermal metamorphism developed in basalts around the gabbros but shows no sign of metamorphism itself. Had the acid intrusion pre-dated the gabbros it would have exhibited a thermal overprint and the fine-grained chilled contact, with its distinctive quartz paramorphs after tridymite, would in all probability have been obliterated. The presence of the quartz paramorphs after tridymite indicate a depth of cover of about 1 km (Brown, 1963). Nevertheless, exposures on the shore west of Abhainn Camas Fhionnairigh suggest that the xenolithic granophyre at this locality has been rheomorphically melted by the nearby gabbros, which may exhibit acid net-veining; thus, the unit mapped as Coire Uaigneich Granophyre may in fact be two separate acid bodies, one pre-gabbro, the other post-dating it.

Conclusions

There is abundant evidence in the site that the Cuillin gabbros were intruded at high temperatures. The Tertiary olivine basalt lavas have been altered to high-temperature olivine–pyroxene–plagioclase granulitic hornfelses adjacent to the contact and to rocks showing wholesale hydrous alteration at a greater distance from the contact. In the impure (sometimes dolomitic) Jurassic limestones there is alteration to high-grade calc-silicate mineral assemblages. The arcuate outcrop of the Coire Uaigneich Granophyre around the south-east of the Cuillin gabbros and intrusion of the granophyre by basic cone-sheets which focus on, and also cut, the Cuillin gabbros, shows that this granitic intrusion is structurally related to the Cuillin centre and of a significantly earlier date than the majority of the Skye/Tertiary granites. Geochemical studies show that it contains major components from melted Torridonian sandstones and from fractionated basaltic magma. The absence of any evidence of thermal overprint in the granophyre, which intrudes the severely thermally metamorphosed basalts, shows that it post-dates the Cuillin gabbros. The presence of quartz paramorphs after tridymite provides mineralogical evidence that it was intruded at 1 km or less beneath the Tertiary land surface.

BEINN AN DUBHAICH

Highlights

Spectacular calc-silicate and skarn mineral assemblages are developed in carbonate sediments at the granite contacts, along with a limited development of alkali granite. The mineralogy of the granite provides a link between the minerals of rhyolite lavas and plutonic granites. Striking deformation of the carbonate sediments and pre-granite Tertiary dykes has occurred over a limited area close to the western end of the granite intrusion.

Introduction

The site contains the major Beinn an Dubhaich granite intrusion which has been emplaced into Cambro-Ordovician limestones and dolomites overlain by Mesozoic sediments and cut by pre-granite Tertiary basaltic dykes (Fig. 2.18). The granite has caused thermal metamorphic and metasomatic alteration of the carbonate sediments and there has been a small, locally spectacular amount of structural disturbance of the sediments and dykes. The Beinn an Dubhaich Granite, with its aureole, is one of the most intensively studied small intrusions in Britain. Following the regional investigations of Harker (1904) and Richey (1932), Tilley (1951) and Hoersch (1981) investigated the contact phenomena, King (1960), Whitten (1961) and Hoersch (1979) worked on the structure of the granite, and Raybould (1973) showed the granite to be a multiple intrusion. Stewart (1965) summarized much of the earlier work and a review of current ideas is contained in the field guide by Bell and Harris (1986). The granite mineralogy was also intensively studied (Tuttle and Keith, 1954; Tuttle and Bowen, 1958).

Description

The Beinn an Dubhaich Granite is the dominant feature of the site and is one of a group of intrusions which comprise an outer granite mass in the Eastern Red Hills centre. This granite mass extends from Beinn na Cro in the west to Beinn an Dubhaich and the Allt Fearna Granite to the south and east of Beinn na Caillich respectively (Bell and Harris, 1986). The contacts of the Beinn an Dubhaich Granite with the Cambro-Ordovician sedimentary country rock are well-exposed; the sediments have been folded into a broad anticline (the Broadford anticline; Bailey, 1954) and the granite intrusion is approximately coincident with the anticlinal axis. The Cambro-Ordovician strata have also suffered earlier Caledonian tectonism and to the north-east, on the Beinn Suardal summit area on the edge of the site, Torridonian sediments have been thrust over them. To the south, the Lower Palaeozoic and Precambrian sediments are unconformably over-

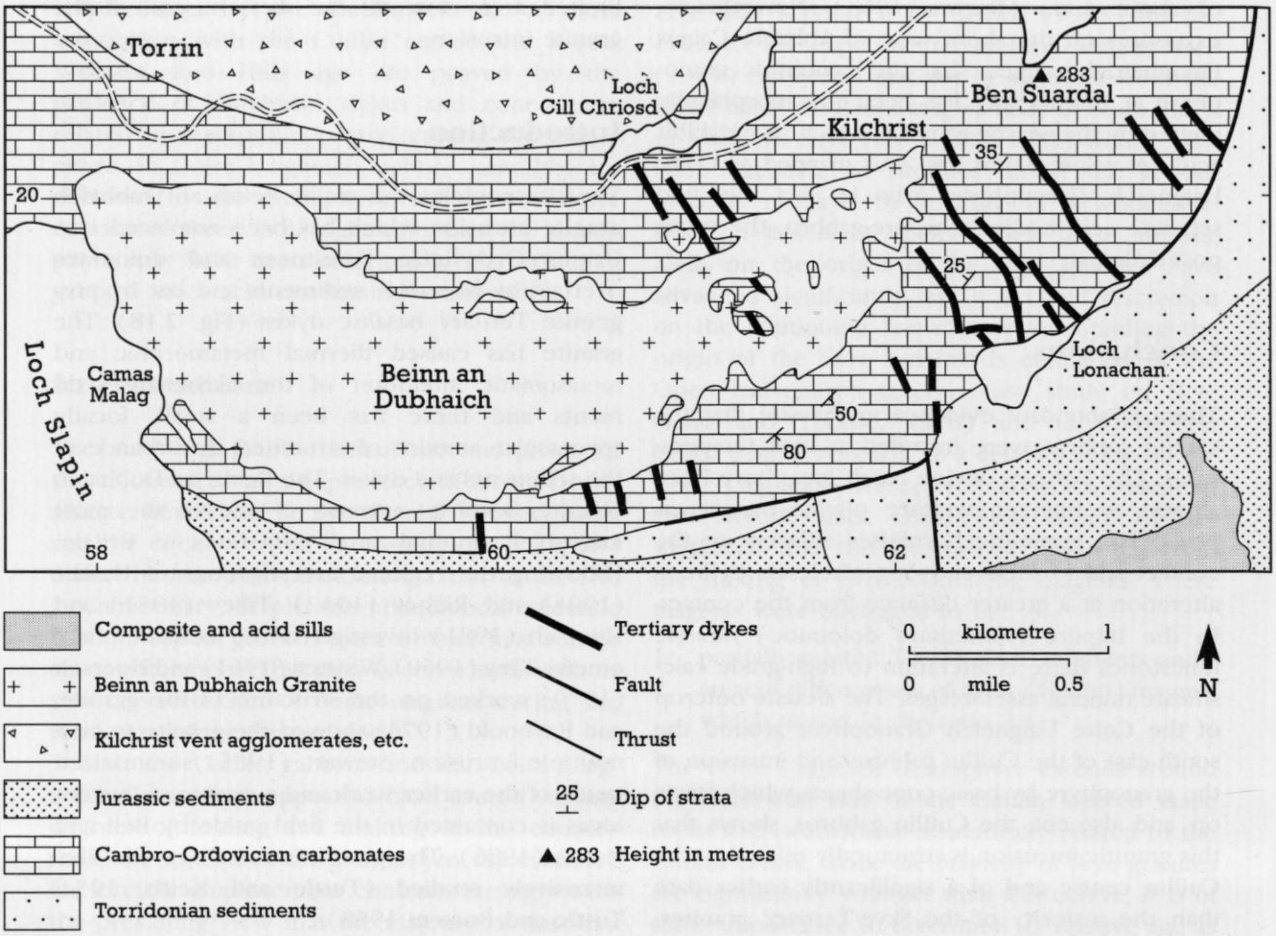


Figure 2.18 Geological map of the Beinn an Dubhaich site (after Gass and Thorpe, 1976, figure 6).

lain by Mesozoic (Triassic–Lower Jurassic) strata.

At its western end, and on the headland at the southern end of Camas Malag (NG 583 189), the granite is in steep contact with the Cambro-Ordovician sediments. However, to the east of the Beinn an Dubhaich summit area, and particularly in the vicinity of Kilchrist (NG 616 201), the relationships between the granite and metamorphosed carbonate sediments are complicated; individual contacts exposed in old quarries and pits often appear vertical, suggesting that many steep-sided rafts of limestone lie within the granite and that the granite–limestone contact is extremely irregular. The complex pattern of outcrops has resulted in numerous differing interpretations as to the form of the granite. These are discussed below.

The granite is a typical high-level Tertiary granite and has been the subject of extensive petrological investigation by Tuttle and Keith (1954) and Tuttle and Bowen (1958). It consists essentially of coarsely-perthitic alkali feldspar (including orthoclase cryptoperthite and sanidine cryptoperthite varieties), quartz and some oligoclase. Whitten (1961) examined modal variation in the intrusion and suggested that there was a definite stratification within the granite, with more basic lower parts merging upwards with more quartz-rich lithologies.

Raybould (1973) has distinguished at least four granite types forming a crude ring-structure within a small area near to the summit of Beinn an Dubhaich. In this area, the main type is a grey-coloured, porphyritic microgranite with a very fine-grained groundmass. The other types are: yellowish, sparsely quartz-phyric granophyre, greenish medium-grained pyroxene-bearing, granite and medium-grained, hornblende granite.

The intrusion of the granite into the Cambro-Ordovician country rock has resulted in sig-

Table 2.4 Minerals present in skarn zones (after Tilley, 1951, Table 1)

	Skarn zones		
Aureole beyond the skarn zones	Group 1 Primary skarns	Group 2 Boron–fluorine ore skarns	
Talc	Grossular–	Magnetite*	Grossular-
Tremolite	andradite*	Tremolite	andradite
Forsterite	Wollastonite	Forsterite*	Hydro
Diopside	solid solutions*	Diopside*	grossular
Periclase	Diopside–	Monticellite*	Idocrase
Wollastonite	hedenbergite	Cuspidine*	Bornite
Spinel	Spinel	Fluorite	Chalcosite
Idocrase	Plagioclase	Chondrodite*	Covellite
Grossular	Idocrase	Humite	Chalcopyrite
Phlogopite	Xanthophyllite	Clinohumite	Pyrite
Brucite	Phlogopite	Ludwigite	Blende
Serpentine	Orthite	Fluoborite	Galena
Chlorite	Clinozoisite–	Szaibelyite	Chessylite
Hydromagnesite	epidote	Datolite	Malachite
	Prehnite	Harkerite	
	Apophyllite		
	Pectolite		
	Xonotlite		

* most abundant minerals

nificant thermal metamorphic and metasomatic alteration of the cherty, dolomitic limestones. Within the carbonate country rocks immediately adjacent to the granite there are skarn zones up to 3 m wide which are characterized by assemblages of pneumatolytic minerals. Beyond this zone lies an aureole of marble. Tilley (1951) recognized two groups of skarns: Group 1, at the granite–country rock contact not containing boron–fluorine-bearing minerals, and Group 2 on the country rock side of Group 1 associated with boron–fluorine-bearing minerals. Table 2.4 shows the mineral assemblages recognized by Tilley within the skarn zones and in the outer aureole.

The discovery of magnetite led to the search for workable deposits, which included a ground magnetometer survey by Whetton and Myers (1949), which recorded numerous bodies of lenticular shape lying along the limestone–granite contact. Samples from these bodies proved to be relatively pure magnetite, accompanied by trace amounts of copper carbonate and sulphide.

Hoersch (1981) made a systematic study of cherty nodules in the carbonates which have reacted with the surrounding rock to produce reaction rims of calc-silicate minerals. Four mineralogically distinct zones of increasing temperature were recognized:

1. Talc-bearing, 350–425°C
2. Tremolite-bearing, 425–440°C
3. Diopside-bearing, 440–520°C
4. Forsterite-bearing, 520–600°C

At Kilchrist and Camas Malag, Tilley (1949) identified an alkali facies of the granite in contact with the skarn deposits. This rock is characterized by the presence of green alkali pyroxene (aegirine–hedenbergite) instead of the normal mafic minerals (biotite and hornblende) of the granite. At Kilchrist, the granite additionally contains metasomatized areas near the contact with veins of pyroxene (diopside–hedenbergite), plagioclase (oligoclase–andesine), fluorite, idocrase and garnet (grossular–andradite) with accessory epidote and orthite. Occasionally, phenocrysts of both microperthite alkali feldspar and plagioclase occur in the marginal facies.

At Camas Malag (NG 583 190), numerous basic and rare acidic sheets intrude near-vertical Cambro-Ordovician sediments which strike approximately parallel to the granite contact (Nicholson, 1985). Where concordant with the bedding, the sheets are clearly boudinaged and, where oblique, they are strongly folded. Individual boudins have chilled margins, even in the 'necked' portions, indicating that boudinage occurred during cooling (Longman and Coward, 1979). Nicholson (1970) considered these sheets to be of Tertiary age from their petrography; their deformation and that of the country rock is very localized and probably occurred during the initial stages of granite emplacement (Longman and Coward, 1979).

Interpretation

The form of the Beinn an Dubhaich Granite has been the subject of much controversy. Harker (1904) mapped numerous vertical contacts between the granite and limestones and concluded that the intrusion is boss shaped. Broadly similar conclusions were reached by Stewart (1965), Raybould (1973) and Bell (1982). However, radically different interpretations were advanced by King (1960) and by Whitten (1961) who considered that the granite had a sheet-like form and that the complicated contacts at the east end of the intrusion were in part caused by erosion through the granite sheet into underlying sediments. These authors suggested that the granite had been emplaced along the Kishorn Thrust Plane which separates the Torridonian and Cambro-Ordovician rocks hereabouts. However, limited borehole evidence (Raybould, 1973) and geophysical studies (Hoersch, 1979) support the interpretation that the granite is a steep-sided boss which extends to depth.

The coincidence of the granite with the Broadford anticlinal structure in the Cambro-Ordovician sediments invites the view that the fold formed in response to the forcible intrusion of the granite. This is not, however, the case as it can be shown that Tertiary dykes, intruded after the sediments had been folded but before the granite was intruded, show no signs of granite-induced deformation. The dykes intruding sediments in the large 'rafts' within the eastern end of the granite show little strike deviation from those in the country rock and, in some instances, dykes in the country rocks are seen to have once been continuous with dykes within the marble rafts. This suggests that these 'rafts' are more likely to have been attached to the roof of the granite rather than to have been 'free-floating' enclaves within the intrusion. Despite the lack of evidence for large-scale deformation around the granite, limited, but locally intense deformation of sediments and dykes occurs at the western end of the intrusion, where both Cambro-Ordovician and Mesozoic sediments have been affected by granite emplacement (Nicholson, 1970; Longman and Coward, 1979).

The calc-silicate mineral assemblages and skarns produced in the cherty dolomitic limestones along the granite contacts and within the rafts are very spectacular and internationally renowned. However, they are strictly limited to within a few metres of the contacts although marmorization is more extensive. Similarly, the chemical and related mineralogical modifications of the granite caused by reaction with the carbonate rocks or carbonate-derived metasomatizing fluids are limited; an alkali-granite facies is present but there is no suggestion from these occurrences that any large bodies of, for example, syenitic compositions, could have formed. Thus, the exposures at this site support the general view that limestone syntexis is probably of limited petrogenetic importance in the genesis of the alkali rock.

The detailed investigations of the mineralogy of the granite by Tuttle and Keith (1954) and Tuttle and Bowen (1958) demonstrated that this high-level, unmetamorphosed intrusion has mineralogical characteristics which are intermediate between those of deep-seated batholithic granites and rhyolites. In the 1950s, there was considerable controversy about the origin of granitic rocks and one school of thought held the view that granites were largely the result of metasomatic transformation of pre-existing rocks. These views were based essentially on observations made in high-grade metamorphic terranes and on large, deep-seated bodies of granite. Magmatists, who opposed this concept, maintained that granites resulted from the intrusion of granite magma and cited the evidence from small, high-level granite bodies and from rhyolite flows. Granitic rocks from these contrasted settings have different and distinct mineralogical features, which, it was argued, arose because of fundamental differences in their origins; the work by Tuttle and others on the Beinn an Dubhaich Granite, as well as other granites in the BTVP, demonstrated that some granites have mineralogical features supposedly characteristic of both settings which were, therefore, not separate and distinct but at the extremes of a series of continually varying mineralogies. Their work thus helped to pave the way for the present-day acceptance of the real existence of granite magma in the crust.

Conclusions

The granite of Beinn an Dubhaich intrudes Lower Palaeozoic carbonate sediments with limited deformation of the sediments and a group of pre-granite, Tertiary basaltic dykes. Reaction between the granites and the country rocks resulted in the production of a distinctive calc-silicate mineral assemblage in the baked carbonate rocks at the contacts, and more widespread recrystallization to form extensive tracts of marble. In addition, there are thin magnetite-rich skarns at some of the contacts, and reaction between the granite and the carbonate rocks has produced small amounts of a marginal alkali granite.

The mineralogy of the granite shows features intermediate between those of extrusive rhyolites and plutonic granites. It thus provides a vital link between these compositionally similar rocks which were formerly considered, by some, to be of fundamentally different origins.

Although it has been proposed that the granite is a sheet-like intrusion injected along a Caledonian thrust plane, the general consensus argues that it is boss shaped. The complicated contact relationships at the eastern end are due to the present level of erosion being nearly coincident with a flat, roof contact which is highly irregular in detail. Evidence for several separate granite intrusions found towards the western end of the body may indicate the presence of small, nested ring-dykes.

KILCHRIST

Highlights

At Kilchrist excellent examples of ignimbrites, tuffs and rhyolite flows are interbedded with agglomerates. Granite and gabbro fragments in the agglomerates demonstrate that a period of plutonic activity pre-dated the Eastern Red Hills centre. The lava flows and volcaniclastic rocks are preserved in a downfaulted block bounded by a ring-dyke of hybrid (mixed-magma) rocks and the Beinn na Caillich Granite.

Introduction

The site encompasses the internationally famous Kilchrist Vent which lies within the eastern part of the Eastern Red Hills centre and thus also includes part of the last major phase of igneous activity on Skye. The vent contains a highly varied association of agglomerates, ignimbrites, acidic rocks, hybrids and gabbros. The site also contains part of the large Inner, or Beinn na Caillich, Granite of the Eastern Red Hills centre (Fig. 2.19).

The Eastern Red Hills centre was, until recently, comparatively neglected. The results of the earlier investigations and some work in the immediate post-war years have been summarized by Stewart (1965). At about the same time, aspects of the Kilchrist Vent were investigated by Ray (1960, 1962, 1964, 1966 and 1972). An intensive study of the centre has since been carried out by B.R. Bell (1982, 1983, 1984a, 1984b and 1985) and these investigations are summarized in Bell and Harris (1986).

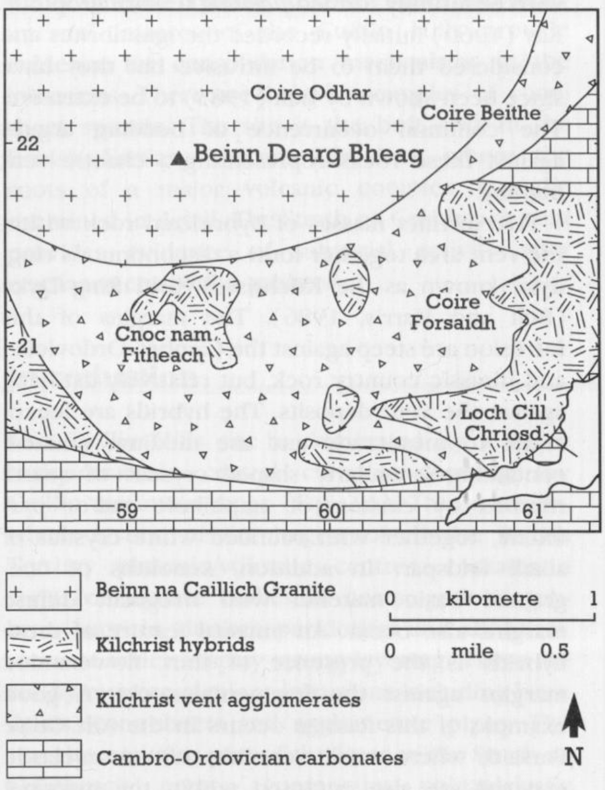


Figure 2.19 Geological map of the Kilchrist site (after Gass and Thorpe, 1976, figure 6).

Description

The volcaniclastic rocks and hybrids in the area between the middle slopes of Beinn Dearg Bheag (NG 593 219) and Loch Kilchrist are the principal features of interest in this site (Fig. 2.19). These rocks occupy the area defined in the earlier literature as the Kilchrist Vent but subsequently shown by Bell (1982) to be a downfaulted bedded volcaniclastic sequence later intruded by hybrids, rather than a chaotic vent infill. Predominant coarse agglomerates contain blocks and smaller clasts of Torridonian sandstones and shales, Cambrian carbonates and quartzites, Jurassic limestones, sandstones and siltstones and a variety of igneous rocks of probable Palaeocene age such as basalt, rhyolite, ignimbrite, granite, pitchstone and gabbro. Evidence for bedding comes from rare lateritic horizons, thin basic tuffs with lapilli, acid tuffs with wispy rhyolitic fragments, and thin rhyolites which probably represent flows (better evidence for rhyolite flows comes from exposures east of Beinn Dearg Mhor; Bell, 1985). In addition, in stream sections east of Cnoc nam Fitheach (NG 593 211), extremely well-developed ignimbrites with beautifully formed *fiamme* texture crop out. Ray (1960) initially recorded the ignimbrites and considered them to be intrusive but they have since been shown by Bell (1985) to be extrusive. The common occurrence of bedding argues against these rocks representing a chaotic vent infilling.

Five distinct masses of hybridized rock within the vent area together form a discontinuous ring-dyke known as the Kilchrist Hybrid Ring Dyke (Bell and Harris, 1986). The margins of this intrusion are steep against the Cambro-Ordovician and Jurassic country rock, but relatively flat-lying against the vent deposits. The hybrids are leucocratic to mesocratic and are medium grained, containing irregularly shaped crystals of quartz rimmed by clusters of amphibole and/or pyroxene, together with rounded white crystals of alkali feldspar. In addition, xenoliths of fine-grained basic material with irregular, diffuse margins also occur. An unusual feature of these hybrids is the presence of thin, flow-banded margins against the fragmental rocks. A good example of this feature occurs in the Allt Coire Forsaid, where small xenoliths of volcaniclastic material are also enclosed within the marginal hybrid.

The steep-sided Beinn na Caillich Granite intrusion occupies the northern part of the site. The rock is a granophyre or microgranite and contains amphibole and biotite as the main ferromagnesian phases. A fine-grained felsitic or spherulitic marginal facies, rarely more than a few metres wide, is developed at some localities, most notably in the gorge of the Allt Slapin in the extreme western tip of the site (NG 584 218). Here, fresh samples contain the iron-rich minerals ferrohedenbergite and fayalite which have been frequently replaced by hydrous alteration products. In this excellent section a succession of near-vertical basaltic and rhyolitic tuffaceous breccias strikes parallel to the granite margin and passes downstream into brecciated Jurassic sediments, which also dip steeply off the granite hereabouts. The volcaniclastic rocks are part of a narrow zone which separates the Beinn na Caillich, or Inner, Granite from Jurassic sediments and Palaeocene lavas to the west and north-west (Bell, 1985, fig. 2). Emplacement of the Inner Granite has caused severe deformation of the adjoining country rocks.

Interpretation

In the literature prior to 1980, the volcaniclastic rocks of this site were interpreted as being vent infill deposits intruded by hybrid rocks. It was termed the Kilchrist Vent (cf. J.D. Bell, 1976). B.R. Bell's detailed reinvestigation has clearly demonstrated that the fragmental rocks are not a chaotic vent infill and there is much evidence for bedded volcaniclastics, highly compacted ignimbrites and rhyolite flows (Bell, 1982). The hybrid status accorded by Harker (1904) to the highly variable intrusive rocks has been confirmed by the later studies and Bell (for example, in Bell and Harris, 1986) noted that the mixed magma nature of the rocks is very apparent in their heterogeneous field appearance. He suggested (Bell, 1982) that the Kilchrist hybrids could be produced by mixing variable proportions of basic and acid magmas similar to those which gave rise to the composite basic and acid sills of the Broadford area.

The form of the Kilchrist hybrid intrusions is important in the interpretation of the volcaniclastic rocks. The hybrids have steep outer margins against Cambro-Ordovician sediments but intrude the volcaniclastic rocks at low angles as sheet-like masses. Bell has interpreted the hybrids as a ring-dyke, the Kilchrist Hybrid Ring Dyke (Bell and

Harris, 1986), and considered that the volcaniclastic rocks form a central, downfaulted block preserved within this structure. Thus, the coarse-bedded volcaniclastic deposits, together with intercalated lava flows, may once have been more extensive, as is suggested by their occurrence on the western and north-western sides of the Beinn na Caillich (or Inner) Granite. Clearly, from the evidence within this site and that provided elsewhere around Beinn na Caillich, the emplacement of the Inner Granite involved, or was at least associated with, complex tectonic events which have not as yet been fully explained.

The varied assemblage of clasts in the fragmental rocks is of considerable interest, not least since it provides evidence for early Tertiary igneous rocks which pre-date the bedded volcaniclastics, hybrid intrusions and the Inner and Outer granites. These have been listed (see above) but attention is directed especially to the presence of blocks of granite which indicate, once again, that there may have been a distinctly early phase of plutonic acid intrusions in Skye (cf. Bell, 1976 and the evidence from Allt Geodh a' Ghamhna).

Conclusions

The site provides clear evidence that, during the Palaeocene, the Eastern Red Hills were an area of fairly extensive bedded volcaniclastic accumulations with interbedded acid and basic lava flows and excellent examples of ignimbrites. The clast content of the volcanic breccias shows that coarse-grained plutonic rocks (both gabbros and granites) were present, possibly representing a phase of central complex development on Skye which was obliterated by the emplacement of the presently exposed centres. These early volcaniclastic rocks are preserved as a downfaulted block within the Kilchrist Hybrid Ring Dyke; they may represent vent-infill material but their present margins are determined by the ring-dyke intrusion. It is therefore possible that they once formed part of an early, much more widespread cover of acid and basic lavas and volcaniclastic deposits.

The hybrid rocks provide yet another example of coexistence and mixing of acid and basic magmas found throughout the period of Tertiary magmatism on Skye. They augment the evidence from the Marscoite Suite of Marsco and elsewhere (Marsco and Mheall a' Mhaoil) and from the composite sills (Rubha' an Eireannaich). The intrusive behaviour of these mixed magmas is convincingly demonstrated in this site.

The Beinn na Caillich, or Inner Granite, is the youngest major intrusion in the site and also in the Eastern Red Hills centre. It is in sharp, chilled contact with the country rocks but does not appear to have produced very marked thermal effects on them. However, the very steeply dipping sequence of volcaniclastic rocks and Jurassic sediments, found at the granite contact in the extreme west of the site, provides convincing evidence that emplacement of this granite caused considerable tectonic disturbance of the adjoining country rocks.

CUILLIN HILLS

Highlights

Excellent exposure of a wide variety of arcuate ultrabasic and gabbroic intrusions allows the sequence of intrusion and the shape of individual bodies to be established in detail (Figs 2.20 and 2.21). Igneous layering, xenolith suites and other internal features of the Cuillin Hills provide evidence for consolidation mechanisms in the intrusions. There are superb examples of cone-sheet swarms. The site is the best area in the British Tertiary Volcanic Province where the roots of a major volcanic complex may be examined in detail. The Strath na Crèitheach vent provides evidence of subaerial activity after emplacement of the gabbros.

Introduction

The Cuillin Hills site is dominated by a major basic/ultrabasic central complex forming the Cuillin mountain range (Fig. 2.1). The intrusion, which is one of the largest of all the British Tertiary plutonic/volcanic centres, contains a series of arcuate bodies of coarse-grained gabbros, eucrites, dunites, peridotites and allivalites, some of which display strong layering. These are cut by numerous minor intrusions including basic dykes, cone-sheets and agglomerate pipes. The site also contains part of the later acidic Strath na Crèitheach centre comprising volcaniclastic deposits and several granite intrusions. The igneous succession is outlined in Table 2.5.

Figure 2.20 Gabbros of the Cuillin centre form rough ground around Loch na Crèitheach in foreground, gabbro peak of Sgurr nan Gillean on left, and smooth-weathering mass of Marsco (Western Red Hills granites) on right. Cuillin Hills and Marsco sites, Skye. (Photo: C.H. Emeleus.)

The site has attracted attention since the earliest days of geology but it was not until the latter part of the nineteenth century that the broad outlines of the geological structure were elucidated through the studies of Judd (1874), Geikie and Teall (1894) and Geikie (1897). Harker completed the first comprehensive field survey of central Skye between 1895 and 1901 which was published in his classic memoir, *Tertiary Igneous Rocks of Skye* (Harker, 1904), with accompanying maps (on both the One-Inch and Six-Inch scales). Further detailed studies were not carried out on Skye until the mid-1940s, many of which were reviewed by Wager and Brown (1968) and by Bell (1976). Further assessment of the Cuillin centre is made by Gass and Thorpe (1976), Sutherland (1982) and Bell and Harris (1986).

The term eucrite, as used in this site description, applies to a gabbro rich in bytownite plagioclase. Although the term has been criticized (Le Bas, 1959) and is not now recommended as a rock name (Le Maitre, 1989), it has been retained here as it is still commonly employed in the literature relating to the site, as well as in Rum and Ardnamurchan.

Description

The site has been selected to include much of the Cuillin basic and ultrabasic centre as well as representative parts of the later Strath na Crèitheach centre (Fig. 2.22). Exposure is generally excellent on the great ridges of the Cuillin range which rise to almost 1000 m elevation and extend in a horseshoe rampart about Loch Coruisk (Fig. 2.22).

The geology of the site is considered under three principal headings:

1. The Cuillin basic/ultrabasic centre.
   (a) The Outer Marginal Gabbros and Eucrites and their relationship with the country rock.
   (b) The layered basic and ultrabasic members of the central part of the intrusion, which are divided into the Outer Layered

Figure 2.21 Rough-weathering gabbro on Bla Bheinn (right) contrasting with smooth-weathering granites of the Strath na Crèitheach centre (left). Jurassic sediments occupy the right foreground. Cuillin Hills and Marsco sites, Skye. (Photo: C.H. Emeleus.)

Series and the Inner Layered Series.

2. The Strath na Crèitheach centre.
3. Minor intrusions.

The country rocks surrounding the Cuillin centre are almost entirely lavas belonging to the Skye Main Lava Series (Thompson *et al.*, 1972). However, on the southern edge of Sgurr na Stri (NG 501 193) Torridonian strata occur and, to the east of the site at Camasunary (NG 517 188) and to the south of Blaven (Bla Bheinn, NG 530 217), both Torridonian sediments and Jurassic limestones have been metamorphosed to high grade (Coire Uaigneich; Almond, 1960). Good examples of metamorphosed basalts occur close to a lochan to the north-east of An Sguman (NG 438 189; Harker, 1904, p. 52 and plate 16).

Outer Marginal Gabbros and Eucrites

Largely massive gabbros and eucrites extend in a broad arc from Glen Sligachan, south-west to the vicinity of Glen Brittle, and south-east to Gars Bheinn (NG 468 188) and Loch Scavaig. These intrusions are cut off to the east by the Glamaig Granite of the Western Red Hills centre in Glen Sligachan, and by younger mafic rocks to the south.

The published One-Inch geological map (Sheet 70, Minginish) and the Six-Inch sheets depict extremely irregular contacts between the Outer Marginal Gabbros and the lavas north-west of Bruach na Frithe (NG 461 253), NNE of Glen Brittle, and on the southern slopes of the Cuillin ridge near Gars Bheinn. These relationships have been interpreted as showing the gabbros fingering into the lava succession, with fairly flat-lying screens of metamorphosed basalt (and volcaniclastic rocks) caught up between (frequently fine-grained) gabbro. Harker (1904) considered that these features were a consequence of the laccolithic form of the Cuillin intrusions, but in the vicinity of Coire na Banadich (NG 435 219), at least, some of these fine-grained rocks are intrusive sheets of amygdaloidal tholeiite (Hutchison, 1966b).

Table 2.5 Succession in the Cuillin Hills site (after Bell and Harris, 1986, pp. 45–6)

Granites of the Strath na Crèitheach Centre
Volcaniclastic deposits of Strath na Crèitheach dolerite cone-sheets
Coire Uaigneich Granite
Intrusive tholeiites of the Outer and Main Ridge Complexes
Inner Layered Series
Inner Layered Gabbros
(?vent agglomerates in Harta Corrie)
Inner Layered Eucrites
Inner Layered Allivalites
Druim nan Ramh Eucrite
Agglomerates and explosion breccias of diatremes
Dykes
(Gars Bheinn ultrabasic sill?)
Outer Layered Series
Outer Layered Gabbros
Outer Layered Eucrites
Outer Layered Allivalites
Layered Peridotites
Border Group (including White Allivalite)
Cone-sheets
Dykes
Outer Marginal Gabbros and Eucrites
?Early Granites (may pre-date Palaeocene basalts of south-west Skye)
Basalt lavas
Torridonian sediments

In the Gars Bheinn area, Weedon (1961) showed that the southern margin of the Outer Unlayered Gabbros is formed by a 200 m wide, steep-sided intrusion termed the Ring Eucrite which intervenes between the wide Gars Bheinn Gabbro and the basalt lavas. To the north, the Gars Bheinn Gabbro assumes a distinctive dull matt-black appearance caused by intense clouding of the plagioclase feldspars. This clouding, caused by thermal metamorphism, was attributed by Weedon to alteration by the younger ultrabasic rocks which are in contact with the Gars Bheinn Gabbro on the south side of An Garbhchoire (NG 470 200). In this same area, south of Loch Coire a' Ghrunda (NG 452 203), an east–west striking eucrite (termed the Ghrunda Eucrite) intrudes darkened Gars Bheinn Gabbro. The eucrite has been correlated with the Border Group of allivalitic ultrabasic rocks which extend to the north and north-west (Hutchison and Bevan, 1977; Bell, 1976).

The layered basic and ultrabasic rocks of the central part of the intrusion

These intrusives may be divided into an outer, earlier sequence of layered peridotites, eucrites and allivalites known as the Outer Layered Series, and an inner later sequence of allivalites, eucrites and gabbros called the Inner Layered Series. The two are separated by the Druim nan Ramh eucrite ring-dyke. These layered rocks have been

Figure 2.22 Geological map of the Cuillin Hills site (after Gass and Thorpe, 1976, figure 6).

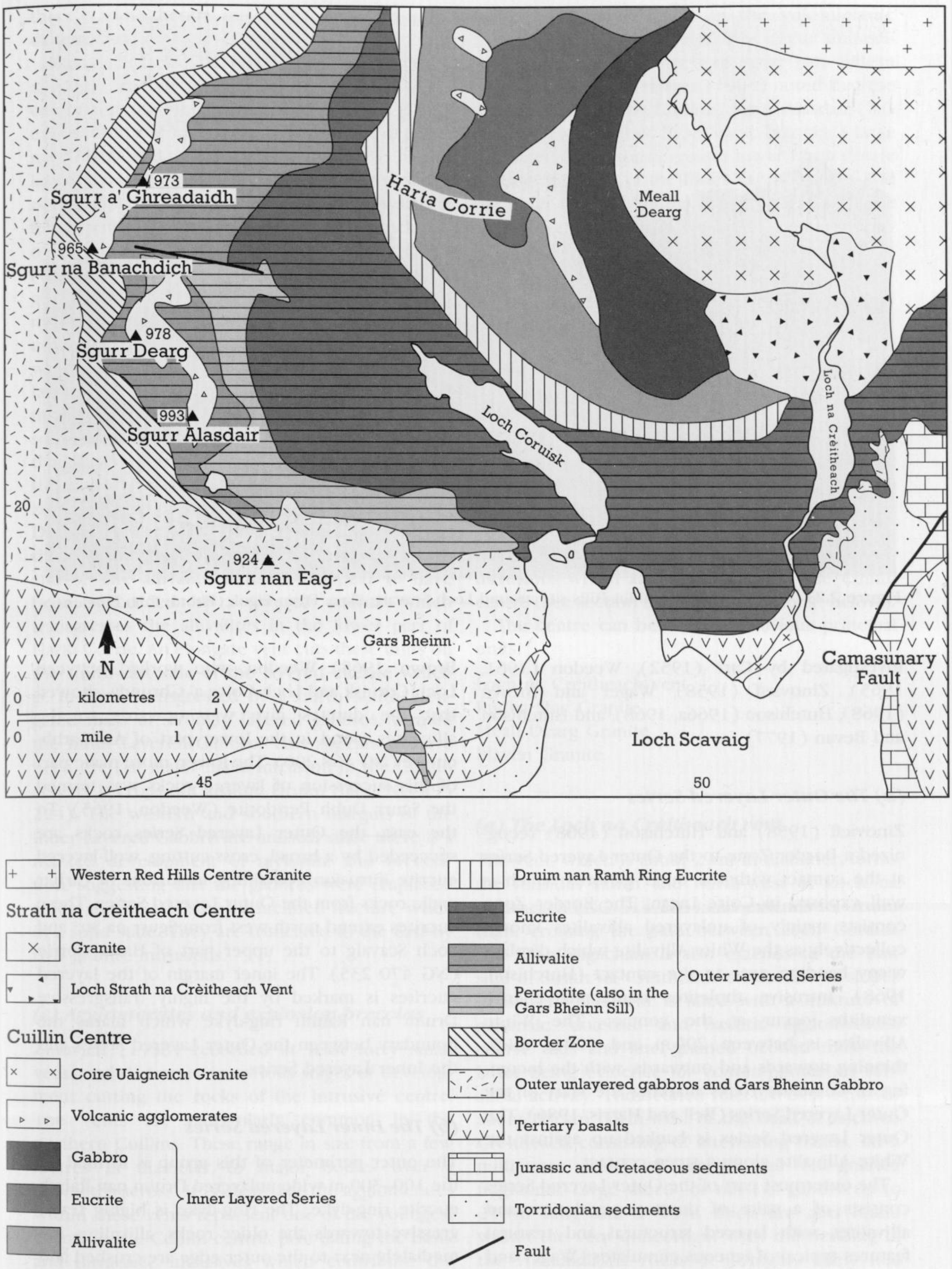

973
Sgurr a' Ghreadaidh
965
Sgurr na Banachdich
978
Sgurr Dearg
993
Sgurr Alasdair
20
924
Sgurr nan Eag
Harta Corrie
Meall
Dearg
Loch Coruisk
Loch na Crèitheach
Gars Bheinn
N
0
kilometres
2
0
mile
45
50
Camasunary
Fault
Loch Scavaig
Western Red Hills Centre Granite
Strath na Crèitheach Centre
Granite
Loch Strath na Crèitheach Vent
Cuillin Centre
Coire Uaigneich Granite
Volcanic agglomerates
Gabbro
Eucrite
Allivalite
Inner Layered Series
Druim nan Ramh Ring Eucrite
Eucrite
Allivalite
Peridotite (also in the
Gars Bheinn Sill)
Outer Layered Series
Border Zone
Outer unlayered gabbros and Gars Bheinn Gabbro
Tertiary basalts
Jurassic and Cretaceous sediments
Torridonian sediments
Fault

Figure 2.23 Gabbros of the Cuillin Hills site around Loch Scavaig, Skye. From Elgol. (Photo: C.H. Emeleus.)

investigated by Carr (1952), Weedon (1961, 1965), Zinovieff (1958), Wager and Brown (1968), Hutchison (1966a, 1968), and Hutchison and Bevan (1977).

(a) The Outer Layered Series

Zinovieff (1958) and Hutchison (1968) recognized a Border Zone to the Outer Layered Series at the contact with the outer gabbros which is well exposed in Coire Lagan. The Border Zone consists mainly of unlayered allivalites known collectively as the White Allivalite which displays wispy banding near to the contact (Hutchison, 1968). Intrusive tholeiites containing eucrite xenoliths occur at the contact. The White Allivalite is between 200 m and 600 m thick, thinning upwards and outwards, with the incoming of cumulate rocks marking the start of the Outer Layered Series (Bell and Harris, 1986). The Outer Layered Series is banked up against the White Allivalite along a steep contact.

The outermost part of the Outer Layered Series consists of a suite of dunites, peridotites and allivalites with layered structural and textural features typical of igneous cumulates (Wager and Brown, 1968). Weedon, who worked between Loch Coruisk and Loch Coire a' Ghrunda, showed that the dunites give way upwards to the allivalites found in the lower part of An Garbhchoire (NG 468 200). The lower, more mafic part of this succession of layered rocks was termed the Sgurr Dubh Peridotite (Weedon, 1965). To the east, the Outer Layered Series rocks are succeeded by a broad, cross-cutting, well-layered eucrite intrusion containing inclusions of earlier mafic rocks from the Outer Layered Series. These eucrites extend north-west from Sgurr na Stri and Loch Scavaig to the upper part of Harta Corrie (NG 470 235). The inner margin of the layered eucrites is marked by the highly transgressive Druim nan Raimh ring-dyke which marks the boundary between the Outer Layered Series and the Inner Layered Series.

(b) The Inner Layered Series

The outer perimeter of this group is formed by the 100–300-m-wide unlayered Druim nan Raimh eucrite ring-dyke. The ring-dyke is highly transgressive towards the older rocks, allivalites immediately next to the outer edge are crushed and there is some thermal metamorphism of pre-ring-dyke rocks.

Zinovieff (1958) mapped three zones of layered allivalitic rocks to the east of the ring-dyke, comprising the Inner Layered Series which is best exposed on the high ground to the east of Sgurr nan Gillean and on the summit of Sgurr Hain. The layering in these rocks, as in Outer Layered Series rocks, dips at between 20° and 40° towards a focus beneath Meall Dearg and the total thickness of allivalite has been estimated to be *c.* 500 m (Wadsworth, 1982). Different units were distinguished by Zinovieff on the basis of modal mineralogy and within each unit, basal plagioclase–clinopyroxene cumulates give way upwards to feldspar–olivine cumulates. Rhythmic layering also becomes increasingly pronounced up through the sequence. These allivalites were so similar to those in the Outer Layered Series that Zinovieff considered them all to be part of the same layered sequence and numbered two zones mapped on the main Cuillin ridge at Bidean Druim nan Raimh (NG 456 239) as units 1 and 2; those within the ring-dyke were numbered 3, 4 and 5. The allivalite units 3–5 appear to have been succeeded by a layered eucrite which transgresses the allivalites in the lower part of Harta Corrie. An elongate vent cuts these units on the south-east side of the layered eucrite which is, in turn, transgressed by a north–south elongated mass of strongly layered gabbros, termed the Inner Layered Gabbro. This appears to have been the last major mafic intrusion in the Cuillin centre. It crops out around Druim Hain (NG 495 224). The western and southern margins of the Inner Layered Gabbro are unusual since there is a marked development of mylonite and brecciation, suggesting that the gabbros were emplaced along an arcuate, steeply inclined fracture when in a solid state. They are truncated to the east by two granite intrusions.

(c) Agglomerates and explosion breccias

Zinovieff (1958) recorded at least forty small vents and diatremes in various stages of development cutting the rocks of the intrusive centre. The vents are particularly common in the northern Cuillins. These range in size from a few metres in diameter to major bodies over a kilometre across. It is clear that the agglomerates within these vents represent one of the youngest events in the Cuillin centre, post-dating the basic and ultrabasic intrusives which contribute the majority of clasts found in the volcaniclastic rocks. Small agglomerate masses occur immediately west and south-west of Sgurr nan Gillean (NG 472 253) and Harker (1904) noted that the highest point of the Cuillins, Sgurr Alasdair (NG 450 208) was formed by volcanic breccia. A large agglomerate body also crosses lower Harta Corrie cutting members of the Inner Layered Series and the Inner Layered Eucrite; it is in turn cut by the Inner Layered Gabbros and basaltic cone-sheets.

The Strath na Crèitheach Centre

The members of this small centre cut some of the youngest intrusions in the Cuillin basic and ultrabasic centre and in turn are cut by members of the Western Red Hills centre (Figs 2.20 and 2.21). The centre marks a major change in the composition of the intrusions; in contrast to the earlier basic and ultrabasic rocks of the Cuillin centre, the Strath na Crèitheach centre is acidic and the major intrusions are granophyres. The centre also post-dates the majority of minor intrusions which are so abundant in the Cuillin centre (see section on 'Minor intrusions', below).

The centre can be divided into four principal units:

Loch na Crèitheach vent
Rudha Stac Granite
Meall Dearg Granite
Blaven Granite

(a) The Loch na Crèitheach vent

The vent, which is about 2 km in diameter, forms the hillsides north and north-west of Loch na Crèitheach (NG 514 205) and extends to Druim Hain, crossing the path between Loch Coruisk and Glen Sligachan. It also extends to the east side of Strath na Crèitheach on the lower slopes of Blaven. The vent is filled with a mixture of gabbroic, doleritic and basaltic agglomerates, coarse tuffs and finer-grained bedded tuffs, the latter being evidence for contemporaneous subaerial activity. The bedded tuffs are best exposed about 0.5 km north-west of the head of Loch na Crèitheach consisting of alternating bands, on a millimetre scale, of coarse- and fine-grained fragments. Large sheets, or rafts, of gabbro up to 250 m long and 2–10 m thick are also found within the vent concordant with the bedding in the volcaniclastic rocks. It is highly likely that many of the basaltic clasts in the Loch na Crèitheach vent originated from minor basic intrusions rather than from the plateau lavas.

The vent deposits are up to 450 m thick and have contacts with older rocks which show signs of crushing and injection of basaltic magma into fractures and crush lines. It is possible that the margins mark the site of a small ring-fault and the volcaniclastic rocks may be lying within a caldera whose centre has subsided between 750 and 1000 m (Jassim and Gass, 1970).

(b) The granites

Three granite intrusions form the northern part of this centre. All are alkali granites; the Rudha Stac and Meall Dearg granites are feldspar-phyric and contain fayalite and hedenbergite or alkali amphibole; the Blaven Granite is amphibole-bearing. The Rhudha Stac Granite cuts the Loch na Crèitheach vent in the crags south of Loch an Athain (NG 512 227) and the Blaven Granite intrudes the vent on the lower north-west side of Blaven. The two granites are separated by a thin screen of gabbro along the course of the Allt Teanga Bradan, south-east of Rudha Stac (NG 515 333). Exposures on the eastern edge of this site, on the lower north-west side of Blaven, give a clear view of the pale-weathering Blaven Granite in contact with the darker, overlying (and older) gabbros and eucrites which form most of Blaven; this is one of the most visually striking igneous contacts in the BTVP.

The Meall Dearg Granite is probably the youngest of the three acid intrusions (Thompson, 1969). Its chilled contact with earlier gabbros is superbly exposed along the western edge of its outcrop. Fine-grained, flow-banded, spherulitic apophyses at the granite contacts were described by Harker (1904, p. 285) cutting the gabbros at Druim an Eidhne (Druim Hain).

There is a notable lack of minor intrusions in the Strath na Crèitheach centre, apart from a few NW-trending dolerite dykes which intrude the granites.

Minor intrusions

There are two principal types of minor intrusion associated with the Cuillin centre within this site:

1. abundant suites of centrally-focused inclined sheets, or cone-sheets, of basalt and dolerite; and
2. numerous radial dykes, generally of basaltic compositions but some ultrabasic, trachytic, felsitic examples also occur.

The minor intrusions frequently develop close-set joints which render them more susceptible to weathering than the surrounding massive intrusions, thus, many of the gullies and the serrated outlines of the Cuillin ridges owe their origins to the presence of easily-weathered dykes and cone-sheets (Figs 2.1 and 2.17).

A major NW–SE swarm of dominantly basaltic dykes crosses Skye from the Sleat Peninsula in the south-east, to the area around Waternish Point (NG 233 670). A subsidiary NE–SW swarm has been identified at Glen Brittle and on Scalpay (see Speight *et al.*, *in* Sutherland, 1982; especially figs 33.4 and 33.5) which appear to radiate about the Cuillin centre. From the field relationships of the dykes with the other intrusions in the Cuillin centre, it is clear that the injection of the NW–SE swarm occurred throughout the life of the centre and their inception probably pre-dated that of the centre. However, the majority of dykes in this swarm were intruded prior to the Strath na Crèitheach centre.

Several suites of exceptionally well-developed cone-sheets have also been recognized within the Cuillin centre, the latest of these intruding vent rocks in Harta Corrie but not the agglomerates or granites of the Strath na Crèitheach centre. The sheets focus on a centre beneath Meall Dearg and therefore have the same focus as the layering within the basic/ultrabasic cumulates of the Cuillin centre. Cone-sheets cutting the Outer Layered Series eucrites are exceptionally well exposed in the bare, glaciated slabs around the outlet to Loch Coruisk and on the southern face of Sgurr na Stri. The cone-sheets are frequently fine-grained, olivine-free dolerites and some, particularly those in the vicinity of Gars Bheinn, are strongly feldspar-phyric. The sheets dip at angles between 25° and 50° or more, with a tendency for steeper dips closer to the focus area of Meall Dearg. Bell (1976, table 1) has distinguished several generations of cone-sheets.

Ultrabasic minor intrusions represent the latest activity in the Cuillin centre and probably all belong to the same intrusive episode (Wyllie and Drever, 1963). Such intrusions include the Gars Bheinn layered peridotite sill (Weedon, 1960), an irregular body forming An Sguman (NG 436 188), and sparse ultrabasic dykes and sheets occurring in an arc from north of Sgurr nan Gillean to Sgurr nan Gobhar (NG 427 224) and

Gars Bheinn, and on Soay, to the south of the site. The dykes seem to focus on a centre towards the eastern side of the main body of the Cuillin intrusion. The Gars Bheinn sill is of significant interest as it demonstrates the presence of mineral and textural layering in feldspathic peridotite within a fairly thin intrusion, where it is difficult to envisage an origin by crystal settling. It seems likely that an explanation for layering within this sill may be one of double-diffusive convection (cf. McBirney and Noyes, 1979).

Interpretation

The Cuillin intrusion is one of the largest and most elaborately developed Tertiary central complexes in the British Isles, representing a major event in the evolution of the British Tertiary Volcanic Province. The great variety of igneous rock types gives this site its scientific importance; of particular note are the frequent, clear age relationships shown by the different intrusive members and the great variety of layered and other internal structures discussed above. The site therefore provides one of the best opportunities to establish the intrusive history of a central complex in the Province. Like many of the central complexes, the Cuillin centre has been strongly affected by structural activity during and after magmatism; the tectonics of the intrusion, however, remain poorly understood and require comprehensive reappraisal. The intrusive history of the site is summarized in Table 2.5 (based on Bell and Harris, 1986).

Reassessment of the Cuillin centre following the unrivalled field investigations of Harker (1904) has been aided by the work of Zinovieff (1958), Weedon (1960, 1961, 1965), Hutchison (1964, 1966a, 1966b, 1968), Wager and Brown (1968), J.D. Bell (1976), and Hutchison and Bevan (1977). Present interpretations of the Cuillin centre stem mainly from the syntheses of Wager and Brown (1968), Gass and Thorpe (1976) and Bell and Harris (1986). The high-level shape of the Cuillin centre is interpreted to be funnel-like, centred on Meall Dearg and intruding earlier unlayered gabbros and Tertiary lavas. The upward pressure caused by the emplacement of the centre to high structural levels probably caused inflation and doming of the overlying country rock, with the formation of cone-sheets and dykes radiating from the centre of the intrusion. Caldera-like subsidence within the intrusion probably occurred after its emplacement (Gass and Thorpe, 1976). Indications of surface or subsurface explosive volcanic activity are suggested by the prolific presence of vent agglomerates in pipes produced by gas fluidization cutting the layered rocks (Zinovieff, 1958). Some of the agglomeratic pipes may not have broken through to the surface but the presence of bedded tuffs in other pipes indicates that some were probably associated with subaerial volcanism; the bedded tuffs would represent air-fall or water-lain deposits. Variation between agglomerate bodies in respect to size, mixing and rounding of blocks and the nature and proportion of the matrix led Zinovieff to suggest that different stages in the evolution of a typical vent can be recognized:

1. country rock is brecciated and veined by the injection of basaltic material involving no movement of adjacent blocks;
2. a rise in vapour pressure results in a process of fluidization causing blocks and magma to expand and rise as one fluid-like phase;
3. blocks become rounded by attrition and mixed as the fluidized system develops with a tuffaceous matrix.

Wager and Brown (1968) proposed a relatively simple interpretation for the evolution of the centre, relating all of the layered rocks to a single episode of crystal accumulation in a basaltic magma chamber resulting in modal and cryptic layering from dunites/peridotites to gabbros. The mechanism of layering within igneous rocks is discussed in detail for the Askival–Hallival site on Rum. It was envisaged by Wager and Brown that an initial intrusion of the outer unlayered gabbro was succeeded by the intrusion of basic magmas from which the layered rocks formed at a high structural level. Complex tectonic activity during and after the emplacement and crystallization of the intrusion was suggested by Wager and Brown to be responsible for the disruption of the sequence. This explained the present configuration of the units, many of which are transgressive and have steep-sided contacts. The Druim nan Ramh Ring Eucrite was recognized by Wager and Brown (1968) to have important structural implications, separating the Outer Layered Series, towards which it transgresses, from the Inner Layered Series. It was postulated that the Inner Layered Series may either be a fault-controlled repetition of the Outer Layered Series, or the result of a later, separate intrusion of basic magma, bordered by the unlayered ring eucrite. Since a massive central uplift of *c.* 1 km is required to repeat the succession, the latter explanation is preferred (Wager and Brown, 1968; Bell, 1976; Wadsworth, 1982).

Hutchison and Bevan (1977) however, have suggested a multiple intrusion model in preference to the model of tectonic emplacement and crystallization from a single basaltic magma proposed by Wager and Brown. Several episodes of magma injection of ultrabasic and basic composition (Hutchison, 1968; Gibb, 1976) and subsequent accumulation processes have been proposed to account for the relationships between the different components of the layered intrusion. The high structural level of the formation of layered ultrabasic rocks in the intrusion precludes their accumulation from basic tholeiitic magmas as suggested by Wager and Brown, because this would require a magma chamber 9000 m thick, together with massive uplift for which there is no evidence. Hutchison (1968) has therefore suggested that the ultrabasic layered rocks accumulated from ultrabasic magmas. In addition, the dykes and ultrabasic minor intrusions of Skye and Soay have been considered by Drever and Johnston (1966) to provide unequivocal evidence for the presence of liquids appreciably more mafic than basalt, a view also advanced by Gibb (1976).

From a study of the Outer Layered Series on the western side of the Cuillin centre, Hutchison and Bevan (1977) have suggested the following sequence of events:

1. Injection of tholeiitic cone-sheets into earlier, unlayered gabbro during inflation caused by rising magma.
2. Major intrusion of ultrabasic magma producing a funnel-shaped magma chamber.
3. Outer and upper margins of the magma chamber chilled to form the allivalitic, unlayered chilled border zone. In the central part of the intrusion crystal accumulation occurred, producing dunites and peridotites followed by allivalites which banked up against the border series.
4. A second pulse of ultrabasic magma was injected into the chamber to produce an essentially allivalitic unit.
5. The cumulates were later cut by eucritic magmas injected into the chamber (Outer Eucrite Series).

Such a model of multiple magma injection is also supported by J.D. Bell (1976) who concluded that the Cuillin centre is likely to represent a series of partly confluent intrusions, each of which fractionated to varying degrees (cf. Walker, 1975). Wadsworth (1982) postulated a series of 'nested' layered intrusions, each bounded by ring fractures controlled by central subsidence of the funnel.

Gravity surveys of the Skye intrusive complex by Bott and Tuson (1973) indicated that there is a substantial volume of basic–ultrabasic rocks beneath the Cuillin centre. This study modelled an intrusive body widening downwards, from 6 km across at the top to 9 km wide at the base some 14 km below the surface. The volume of this intrusion was estimated to be in the region of 3500 km (assuming the rocks to be of gabbroic composition) with granites occupying, at most, 5% of this volume. Bott and Tuson suggested that the magma rose from the lower crust by piecemeal stoping; this is consistent with the downwards widening of the intrusion but conflicts somewhat with the funnel-shaped form postulated from surface exposure (see above).

The later intrusion of the acidic Strath na Crèitheach centre involved the emplacement of several granite bodies after the formation of a subaerial vent. The dilemma of the origin of the Skye granites is discussed in the Marsco site account.

Conclusions

The Cuillin Hills site is of special geological significance for the following reasons:

1. The Cuillins contain one of the largest and most elaborately developed of the Scottish Tertiary basic/ultrabasic intrusive complexes – the Cuillin centre. The relationships between this centre and a younger granitic centre are well demonstrated.
2. The site contains the first of the Scottish centres to be examined in detail and the Memoir (Harker, 1904) and the One-Inch and Six-Inch geological maps arising from these investigations are geological classics.
3. The intrusive relationships between the different rock types are very clearly displayed allowing unequivocal establishment of the history of intrusive activity. The Cuillin centre is thought to be composed of several superimposed phases of intrusion in associa-

tion with complex tectonic activity.
4. The systems of inclined sheets, or cone-sheets, are among the best known anywhere.
5. Geochemical investigations on the rocks from this site show, when combined with detailed field studies, that there are grounds for seriously considering the existence, at high crustal levels, of magmas significantly more mafic than basalt.
6. Geophysical studies show that this site is the surface expression of a very large, steep-sided body of dense, mafic rocks underlying central Skye and extending deep into the Earth's crust (to at least 14 km depth).

RUBHA' AN EIREANNAICH

Highlights

The site contains a fine, continuous section through a composite (felsite–basalt) sill intruded into Jurassic strata. Mixing of acid and basic magmas is demonstrated by the complete gradation from basalt at the margins of the intrusion to felsite in the core with thin, intervening hybrid zones.

Introduction

This site contains an exceptionally well-exposed example of a composite intrusion which demonstrates a virtually continuous variation from chilled upper and lower margins of basic rock, through hybrid rocks to a central felsite member. It is an excellent example of mixing between contrasting magma types. The sill lies at the northern end of a series of arcuate composite intrusions which focus on the Inner (Beinn na Caillich) Granite of the Eastern Red Hills centre. Buist (1959) has described the intrusion in some detail, and Bell (1983) worked on the geochemistry of the different components and produced a model for the formation of the intrusion. The main features of the intrusion have been summarized by Bell and Harris (1986).

Description

A sill of about 5 m in thickness intrudes sandstones and siltstones belonging to the Lower Jurassic Broadford Beds at Rubha' an Eireannaich, Broadford. In addition, two thin basic sills intrude the overlying sandstone and both sediments and the sill are intruded by basic dykes. The section through the sill can be summarized as follows (after Buist, 1959):

Upper basalt	up to 0.75 m
Hybrid zone	between 0.23 and 0.3 m
Felsite	up to 2.4 m
Hybrid zone	between 0.23 and 0.3 m
Lower basalt	up to 0.75 m

The lower and upper basic margins contain xenocrysts and phenocrysts of feldspar but the lower basic member also contains felsic stringers and small areas of fine-grained basic material, together with rare, partly resorbed gabbroic inclusions. The felsite core carries altered phenocrysts of sodic plagioclase and shows an increase in the proportion of groundmass quartz towards the centre of the sheet. The hybrid zones contain sodic plagioclase xenocrysts and phenocrysts of altered andesine and groundmass pyroxene is pigeonite, in contrast to the augite found in the basic margins. There is a complete gradation from one rock type into the other with no suggestion of chilling; this contrasts strongly with the external margins of the basic member which were chilled to (now devitrified) glass against the sedimentary rocks of the Broadford Beds.

Interpretation

The field evidence provided by the sill shows that basic and acid magmas were essentially available simultaneously. The initial injection of basic magma was followed by injection of the acid magma before the former had cooled and consolidated. The absence of a well-defined boundary between these contrasting magma types, a feature also observed in other composite intrusions (for example, in the Marscoite Suite in Harker's Gully; the composite sills of Arran, see below), led Bell (1983) to conclude that high-temperature diffusion occurred between the basic and acid members at their present level in the crust. In addition, the presence of feldspar xenocrysts in the basic margins indicates that some mechanical mixing occurred prior to intrusion.

Geochemical work by Bell (1983) has shown that for all of a range of elements determined, there is complete compositional continuity between basic and acid members of the sill, and that the chondrite-normalized, rare-earth element patterns for the basic and acid members are parallel.

From these data, Bell concluded that the basic and acid components were cogenetic. He envisaged two periods of hybridization of the acid and basic magmas. An early event involved limited addition of porphyritic acid magma to basic magma forming a basic hybrid with xenocrysts, the basic member was then intruded to form the present marginal rocks in the sill. This was rapidly followed by further porphyritic acid magma which formed the centre of the sill. At this stage, *in situ* hybridization occurred by diffusion of elements between the two contrasting magmas while they were still both close to their liquidus temperatures (Bell and Harris, 1986). This process formed the *c.* 0.30-m-thick hybrid zones which now separate the basic margins from the acid core.

Conclusions

The site provides a very clear example of a common phenomenon in the British Tertiary Volcanic Province, namely, the coexistence of basic and acid magmas. In this instance, there was limited mechanical mixing between the different magmas prior to intrusion; further limited high-temperature diffusion within the intrusion occurred during the emplacment of the basic magma, which was followed very rapidly by the central injection of acid magma. The exposures at Rubha' an Eireannaich provide a continuous section through all of the rock types which can be readily distinguished in the field.