British Tertiary Volcanic Province

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Chapter 5

Isle of Mull

INTRODUCTION

The igneous rocks of Mull are arguably the most historically significant in the British Tertiary Volcanic Province. They have been examined extensively for the past two centuries, but it was through the classic Mull Memoir of the Geological Survey of Great Britain (Bailey *et al.*, 1924) that they achieved world-wide attention. Not only was the extremely complex geology of central Mull described and illustrated by the beautiful 'One Inch' geological map (Sheet 44), but important concepts such as ring-dykes, cone-sheets, centres of igneous activity, and magma types and magma series were developed, rendering Mull important in the international context.

Mull is a mountainous island with a long, indented coastline. The coastal exposures provide good sections through the relatively early lavas (Fig. 5.1); however, the intrusions forming the central complex are largely inland where much of the countryside is mantled by peat. This is especially true of the lower ground, where tantalizing, but incomplete, glimpses of the solid geology are provided by stream sections as, for example, in the Allt Molach (see below). Exposure is, however, often good and continuous on the higher ground. The authoritative account of the field geology contained in the Geological Survey's Memoir and maps has provided the background for much subsequent work over the past thirty years. The emphasis of this more recent work has been on the geochemistry, geophysics and isotope geology of the Tertiary igneous rocks; publications have been summarized by Skelhorn (1969) and Emeleus (1983), and by several authors in Sutherland's review of the *Igneous Rocks of the British Isles* (1982). These investigations covered a range of topics, including the deep geology of the Mull volcano, the likely duration of igneous activity, the origins of the granitic and basaltic rocks and the extent to which they have received contributions from crustal as well as mantle sources, and the magnitude and likely effects of extensive hydrothermal systems established during the life of the complex.

The sequence of igneous activity on Mull is summarized in Table 5.1. The general pattern bears similarities with that found on Skye and

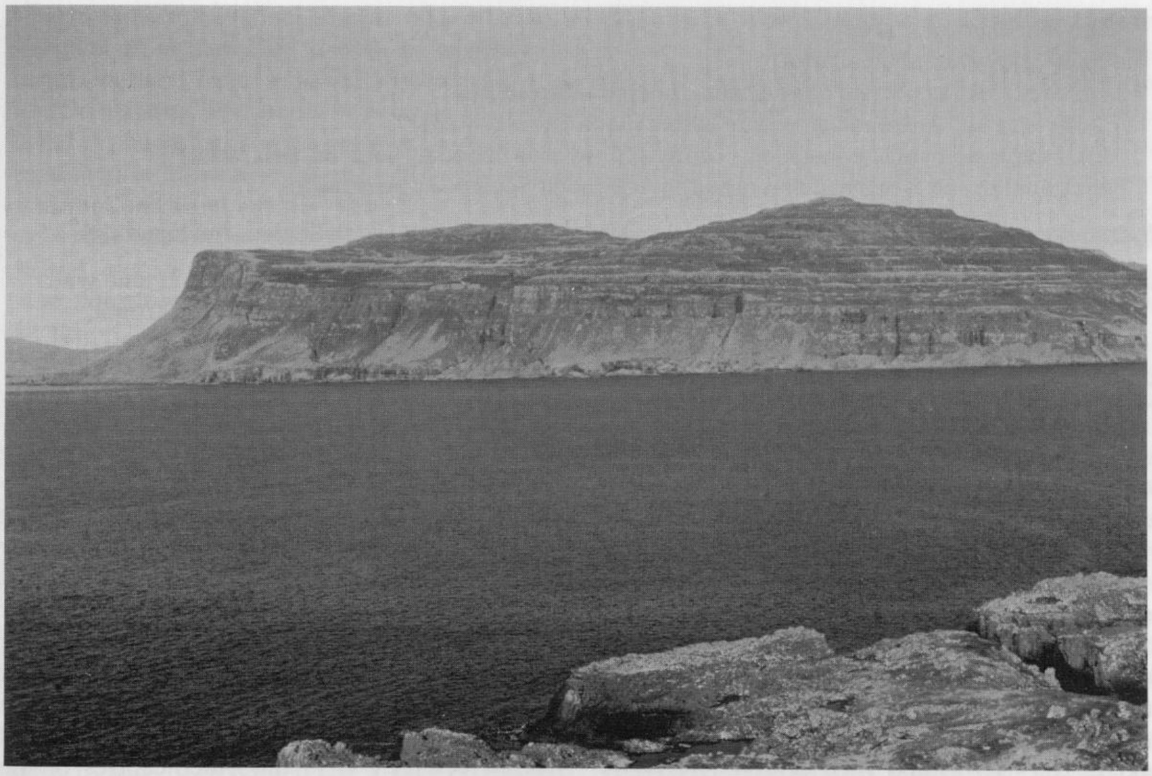


Figure 5.1 The flat-lying succession of basalt lavas of the Wilderness area, western Mull, give rise to the trap-type topography. Bearraich site, Mull. (Photo: C.H. Emeleus.)

Table 5.1 The Mull Central Complex: sequence of events (after Skelhorn, 1969, pp. 2–6)

(youngest)

Dykes were intruded throughout the sequence (Loch Bà–Ben More)

Loch Bà Centre (Centre 3; North-West or Late Caldera)

Loch Bà felsite ring-dyke (Allt Molach–Beinn Chaisgidle, Loch Bà–Ben More)
Hybrid masses of Sron nam Boc and Coille na Sroine (Loch Bà–Ben More)
Beinn a' Ghraig Granophyre (Loch Bà–Ben More)
Knock Granophyre (Loch Bà–Ben More)
Late basic cone-sheets (Loch Bà–Ben More)
Early Beinn a' Ghraig Granophyre and felsite (Loch Bà–Ben More)
Glen Cannel complex and some late basic cone-sheets (Allt Molach–Beinn Chàisgidle, Loch Bà–Ben More)

Beinn Chàisgidle Centre (Centre 2)

Glen More ring-dyke (Loch Sguabain, Cruach Choireadail)
Late basic cone-sheets (Allt Molach–Beinn Chàisgidle), Loch Scridain sheets (intruded towards middle and end of Centre 2 and start of Centre 3)
Ring-dyke intrusions around Beinn Chàisgidle
?Augite diorite masses of An Cruachan and Gaodhail (Loch Bà–Ben More)
Corra-bheinn layered gabbro (Loch Bà–Ben More)
Second suite of early basic cone-sheets
Second suite of early acid cone-sheets
Explosion vents (numerous at margin of the South-East Caldera) (Loch Bà–Ben More)

Glen More Centre (Centre 1; including the Early or South-East Caldera)

Ben Buie layered gabbro
Loch Uisg granophyre-gabbro
First suite of early basic cone-sheets (Loch Bà–Ben More)
Early acid and intermediate cone-sheets (Loch Bà–Ben More)
Acid explosion vents containing porphyritic rhyolite material (Loch Bà–Ben More)
Glas Bheinn and Derrynaculen granophyres (Loch Spelve–Auchnacraig)

Updoming and folding in south-east Mull as a result of rising diapir (Loch Spelve–Auchnacraig).

Lava eruption on to eroded surface of Mesozoic and older rocks. Latest flows overlap in time with formation of the South-East Caldera where pillow lavas are found. (Lavas: Bearraich, Ardtun, Carsaig Bay, Loch Bà–Ben More. Pillow lavas: Loch Sguabain, Cruach Choireadail)

(oldest)

Ardnamurchan, but it differs in detail. Activity commenced with the eruption of basaltic lavas fed from linear NW–SE fissures now represented by the extensive Mull dyke swarm. A thickness of up to 2 km of lava is preserved and studies of zeolite zones (Walker, 1971) indicate that the original succession may have exceeded 2.2 km in thickness. Eruption of the younger lavas overlapped the establishment of a central complex, as flows, including pillow lavas, were erupted into caldera lakes associated with central subsidence and ring-dyke formation in and around the Early or South-East Caldera (Centre 1; Table 5.1). Three distinct centres of igneous activity have been recognized within the Mull Central Complex (Table 5.1); in each, both acid and basic intrusions are present and granitic rocks may predominate at outcrop, particularly in Centre 3. However, the centres coincide with a major gravity high and it is clear that dense, gabbroic or peridotitic rocks underlie all the centres (Bott and Tuson, 1973); thus, basaltic or picritic magmas have been the driving force in the Mull central complex as in the other centres of the BTVP. The gravity surveys of Mull also show that the areally extensive granitic rocks are relatively thin, probably less than 2 km in thickness (Bott and Tuson, 1973, see also Bott and Tantrigoda, 1987). Other geophysical investigations include detailed studies of the magnetostratigraphy by Mussett *et al.* (1980) and Dagley *et al.* (1987), which suggest that the igneous activity spanned several magnetic reversals. When combined with radiometric age determinations, a sequence of reversed–normal–reversed polarities is apparent, covering about 3.5 Ma in the middle Palaeocene (between about 60 and 57 Ma; Mussett *et al.*, 1988; Table 1.1).

The arcuate, centrally-focused character of the intrusive igneous activity is strikingly demonstrated by the ring-dykes and cone-sheets of the Mull complex, particularly those of Centres 2 and 3. This feature, together with the especially clear examples of cone-sheet swarms and the perfection of individual ring-dykes such as the Loch Bà Felsite, makes Mull a classic area for these forms of intrusion, as it is also for the clear demonstration of a shifting focus of igneous activity as the complex developed.

Granite magmas were available during the activity of all three centres on Mull. Geochemical and isotopic studies (Walsh *et al.*, 1979) provide evidence that the early granites of Centre 1 contain substantial contributions of partial-melt products from Lewisian gneiss, in addition to magma derived from fractional crystallization of basaltic magmas. The granites of the later Centres 2 and 3, however, were principally derived by fractionation of basaitic magma, with only minor contributions from crustal sources. Presumably the initial rise of basaltic magmas into the crust melted out most of the available low-melting-point constituents from the gneisses, contributing to the Centre 1 granites, but leaving little available for the acid rocks in Centres 2 and 3 when subsequent batches of basalt magma rose through the, by then, extremely refractory restites. In order to make deductions about the sources of the granitic rocks it is necessary to assume that no major event has affected their compositions since their emplacement. It has been demonstrated that virtually all of the Mull central complex rocks were affected by massive circulation of heated meteoric waters (Taylor and Forester, 1971; Forester and Taylor, 1976), which clearly might have been expected to alter the rock compositions. However, the alteration appears to have been limited and it has been shown that careful sampling can provide material which has not undergone reorganization of either elemental or isotopic compositions (Walsh *et al.*, 1979).

The stratigraphy of the Palaeocene lavas of Mull is not known in the same detail as the Skye lava succession. Little has been published specifically on this topic since the appearance of the Mull Memoir (Bailey *et al.*, 1924). In this, the authors distinguished a major Plateau Group (Table 5.2) of olivine basalts overlain by another thick group of generally non-porphyritic basaltic lavas which comprised the Central Group – flows largely restricted to outcrops within the central complex or immediately adjoining areas (Bailey *et al.*, 1924, plate III and table X). Within the upper part of the Plateau Group, high on Ben More, the distinctive sequence of pale-coloured olivine basalts, conspicuously feldspar-phyric basalt (Big-Feldspar basalts) and a thick mugearite flow were mapped. A further subgroup, which closely resembled basalts of the Central Group, was found at the base of the Plateau Group around Loch Scridain and on Staffa. This was termed the Staffa Type. The majority of flows in the Plateau Group were silica-poor, olivine-phyric basalts and these voluminous basalts were held to be the products of a Plateau Magma-Type. The finer-grained, generally olivine-poor and more silica-rich Central Group lavas were distinguished as the Non-Porphyritic Central Magma-Type basalts. These and other magma types were thought to form a genetically linked group of basalts and more fractionated rocks and to constitute a Normal Mull Magma Series (Bailey *et al.*, 1924, Chapter 1). The magma types and magma series were defined on chemistry, mineralogy and petrography and therefore included both lava flows and intrusive rocks. The terminology and correlations of the Mull lavas are summarized in Table 5.2; the Mull Tertiary igneous sites are shown in Fig. 5.2.

Although little regional mapping appears to have been carried out on the Mull lavas since the publication of the Memoir, a large and valuable amount of geochemical and petrological data has built up, particularly in the last fifteen years. Using fresh samples collected outside the zone of intense pneumatolytic alteration around the central complex, Beckinsale *et al.* (1978) were able to subdivide the lavas (mainly of the Plateau Group) into three groups on geochemical criteria. The approximate positions of these groups are indicated in relation to the Memoir stratigraphy in Table 5.2. The olivine basalts of Group 1 were thought to have come from partial melting of

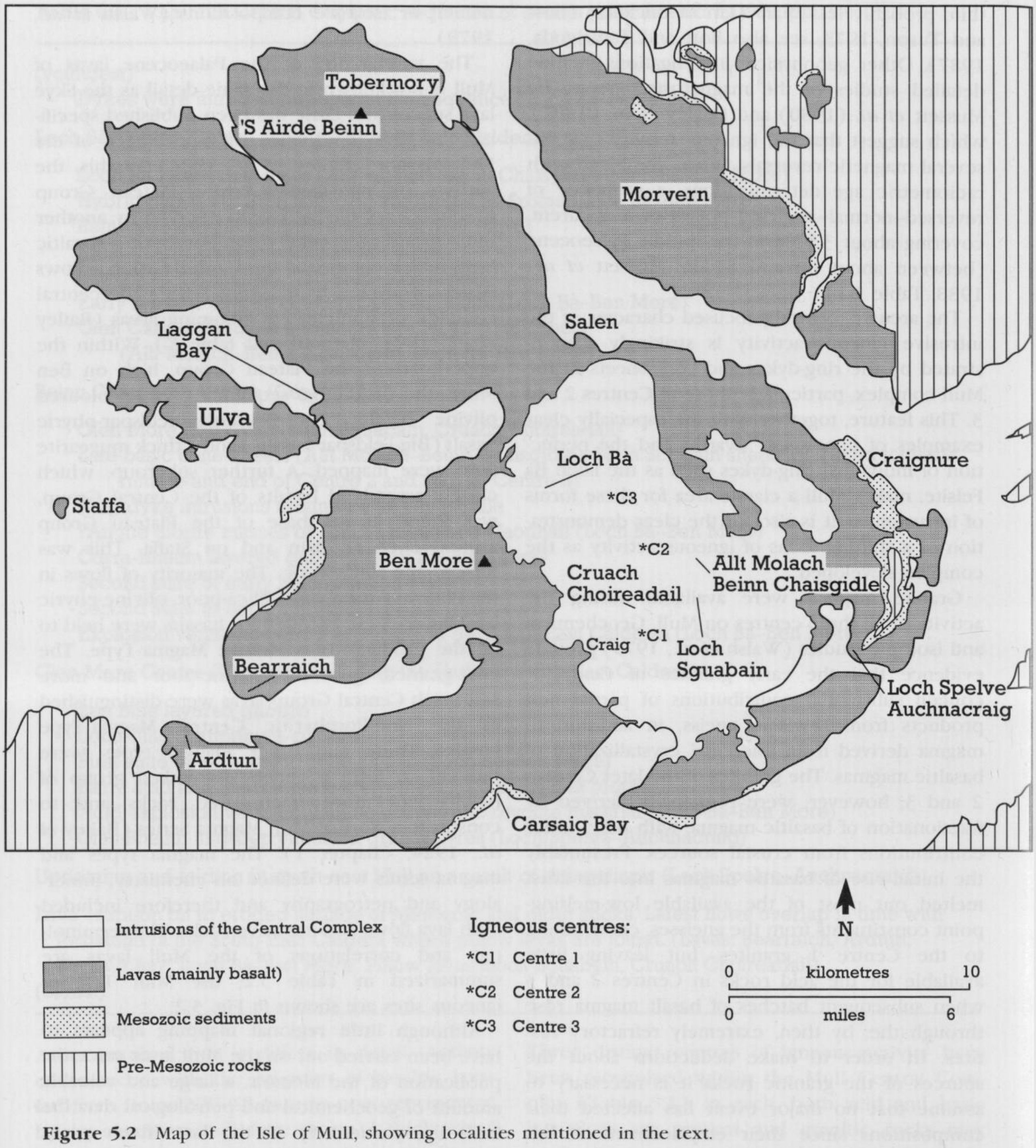


Figure 5.2 Map of the Isle of Mull, showing localities mentioned in the text.

garnet-lherzolite mantle. The Group 2 lavas, equivalent to the Staffa Type, appeared to come from a higher-level mantle source made of plagioclase lherzolite and the Group 3 flows were thought to represent mixtures of Group 1 and Group 2 magmas (or sources).

Essentially the same parts of the succession, and sometimes the same flows and localities, were examined by Morrison (1978), Thompson *et al.* (1982), Morrison *et al.* (1985) and Thompson *et al.* (1986), who came to rather different conclusions about the sources and origins of the flows. Particular attention was paid to the Staffa Type flows (Group 2 of Beckinsale *et*

Table 5.2 Classification and correlation of the Mull lavas

Mull Memoir (Bailey *et al.*, 1924)	Beckinsale *et al.* (1978)	Morrison (1978) Thompson *et al.* (1982) Morrison *et al.* (1985) Thompson *et al.* (1986)
Central Group (= NPCMT) (Includes pillow lavas in central complex)	Not dealt with in detail	Some samples analysed, all zeolitized or hydrothermally altered.
Plateau Group (majority = PMT) Pale Group of Ben More (= PMT) (with interlayered mugearite and Big-Feldspar Basalt)	Group 1 olivine basalts (mainly sampled in north-west Mull) and Group 3 olivine basalts (mainly sampled around Lochaline, Morven)	Mull Plateau Group (MPG) Note that many are transitional between alkali basalt and tholeiite, and compare closely with Skye Main Lava Series. Some lower crust contamination.
(Staffa Type at base = NPCMT)	Group 2 of south-west Mull	Staffa Magma Type (SMT) Variably enriched in lower and upper crustal contaminants.

(NPCMT = Non-Porphyritic Central Magma Type) later = tholeiitic basalt
(PMT = Plateau Magma Type) later = alkali olivine basalt but many flows are in fact transitional between alkali basalt and tholeiite
Total thickness of Mull lavas estimated about 2000 m (Bailey *et al.*, 1924)

al., 1978), where it was found that virtually each flow examined had significant chemical and/or isotopic features; that is, each was unique. This variability was attributed to differing degrees of contamination of the basaltic magmas as each followed its own unique course towards the surface. Picritic magmas were thought to have been formed by partial melting of a spinel lherzolite source, the magma ponded at the Moho and evolved to olivine-basalt magma by olivine fractionation. The fractionated batches of basalt magma pursued their own paths upwards, some were caught in density traps within the crust where they produced silicic rheomorphic magmas from the melting of the adjoining crustal rocks. Where this occurred, the basaltic magma assimilated all or some of the partial melts and became distinctively fingerprinted, taking on, in very diluted form, chemical and isotopic characteristics of that particular country rock. A few flows passed through the crust without reaction or mixing and lack the distinctive contaminated features of the majority. The actual amount of contamination undergone by the flows is estimated to have been between 5–10%, insufficient to mask features attributable to the mantle sources and equilibration at the base of the crust. However, the possible contaminants – granulite- or amphibolite-facies Lewisian gneisses and Moine rocks – have distinctive lead, neodymium and strontium isotopes and concentrations of elements such as potassium, rubidium, titanium, phosphorus and the rare earths which it is possible to analyse with extreme accuracy using modern techniques (cf. Chapter 1), thus enabling deciphering of these fingerprints, and allowing possible models for Palaeocene subcrustal plumbing to be constructed. Some possibilities are shown diagrammatically in Fig. 5.3. All the lavas except F underwent variable degrees of fractional crystallization at Moho depths; F rose directly to the surface without either appreciable fractionation or contamination. All the remainder, except E, were held at the boundary between Lewisian granulite-facies gneisses and overlying amphibolite-facies gneisses, where mixing with small amounts of melt from the granulites occurred. Subsequently, A ponded at the Lewisian amphibolite gneiss/Moine schists boundary and acquired an 'amphibolite' fingerprint from small

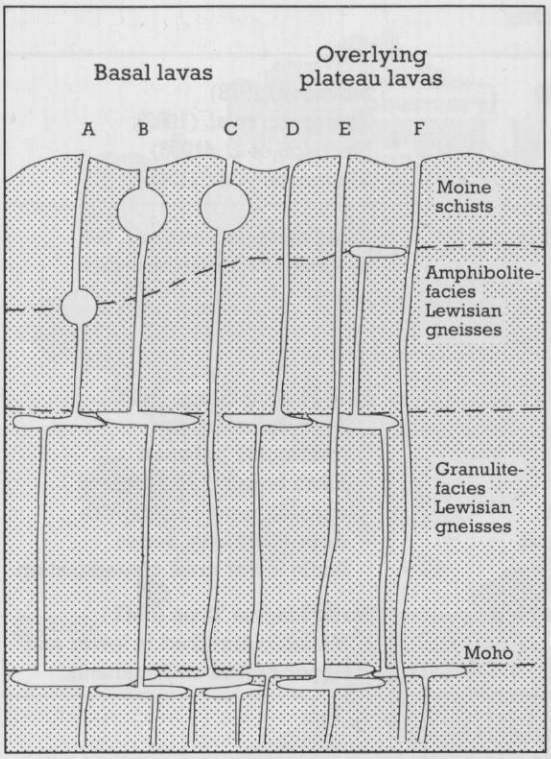


Figure 5.3 Sketch of the magmatic plumbing beneath south-west Mull during extrusion of the Palaeocene basaltic lavas (after Morrison *et al.*, 1985, fig. 4). See text for explanation.

amounts of crustal melt, whereas B was held within the Moine schists and mixed with small amounts of melt generated from the schists. C was also contaminated by Moine-derived melt but did not receive a contribution from either Lewisian gneiss source.

It is apparent that there are currently two very different views on the origin of the diversity of compositions among the Mull (and other) lavas. In one, the variability is attributed to partial melting occurring at different levels in the mantle, with the possibility of some mixing of the melt products; the mantle is thought to have had long-term vertical heterogeneity prior to the Cenozoic (Beckinsale *et al.*, 1978). A radically different viewpoint is that the magmas originated from a spinel lherzolite mantle source, formed when basaltic magmas on their way to the surface were ponded and their heat triggered localized small amounts of partial melting in the adjoining crustal rocks (Thompson *et al.*, 1982; Morrison *et al.*, 1985; Thompson *et al.*, 1986). If such events were on a sufficiently large-scale, granite-producing anatectic melts could form. The absence of rhyolite flows in the Mull lava succession therefore implies that large volumes of silicic melt were not generated at any given time during this early stage in Tertiary magmatism in Mull. However, conditions obviously changed as the central complex became established and its dense, hot, mafic root grew within the crust below Mull (cf. Bott and Tuson, 1973).

The emplacement of British Tertiary Volcanic Province central complexes was frequently accommodated by folding, faulting and other structural adjustments. On Mull some of the most spectacular examples of these features are provided by the annular folding around the early centre which is particularly well displayed in the Loch Don area (see Loch Spelve below). The significance of early folding has been examined by Walker (1975) who suggested that the deformations may be gravity structures developed in association with central updoming caused by the early diapiric emplacement of the granite magmas.

With a few notable exceptions, the researches into the Tertiary igneous geology of Mull since the publication of the Mull Memoir have been either largely geochemical or geophysical; few studies have involved intensive field-work. This is clearly a tribute to the high quality of the Survey's original field mapping and interpretation. However, the great strides made over the past 65 years in such areas as structural geology and physical volcanology, indicate that there must be considerable scope for further field-based research into many aspects of the Tertiary igneous geology of Mull. The size and complexity of the Mull centres prompts the suggestion that this should be undertaken on the basis of team-work.

BEARRAICH

Highlights

The site contains an excellent succession of basalt flows at the base of the Mull lavas, with good development of columnar jointing, pegmatitic veins and segregations, and associated lignite beds. The lavas are seen to envelop 'MacCulloch's Tree'.

Introduction

The south-western part of the Ardmeanach Peninsula at the entrance to Loch Scridain shows a representative and relatively well-exposed, continuous section through the lower lavas of the Plateau Group (Bailey *et al.*, 1924) of Mull and Morvern (Fig. 5.1) The majority of the lavas are alkaline to transitional olivine basalts belonging to the Mull Plateau Group (see Table 5.2 for lava correlations, etc.), but the flows at the base of the succession form part of the Staffa Magma Type (cf. Thompson *et al.*, 1986). The basal flow envelops 'MacCulloch's Tree' (Fig. 5.5).

The most comprehensive investigation, to date, on the lavas of Mull was published in the classic Mull Memoir by Bailey *et al.* (1924); it remains the only account with comprehensive field data. The geochemistry of the lavas was subsequently reassessed by Tilley and Muir (1962) and Beckinsale *et al.* (1978) proposed a new subdivision on the basis of preliminary trace-element and isotope data. Further detailed geochemical investigations by Morrison (1979), Morrison *et al.* (1985) and Thompson *et al.* (1986) suggest that the lavas were significantly contaminated by crustal partial melts during their passage to the surface (see also Introduction to this chapter). The distribution of zeolite minerals within the lavas of Mull, including Ardmeanach, has been studied by Walker (1971).

Description

From Tavool House (NM 437 273; Fig. 5.4) to the Wilderness (NM 405 290), the coastal cliffs provide continual exposure through lava flows which demonstrate spectacular examples of two-tier columnar jointing and complex, auto-intrusive admixtures of massive columnar and scoriaceous basalt. The majority of flows are fine-grained, aphyric basalts which have a very compact appearance. These are the Staffa Magma Type lavas of Thompson *et al.* (1986) which show transitional, tholeiitic–alkaline, olivine-basalt affinities; they were considered to be pyroxene-rich variants of the mildly alkaline Plateau basalts (Tilley and Muir, 1962). Many of the flows higher in the succession are olivine basalts belong to the Mull Plateau Group (Table 5.2), while others are basaltic hawaiites (Beckinsale *et al.*, 1978).

Thin tuff and lignite beds occur towards the base of the lava succession which are contemporaneous with the fluvio-lacustrine sediments at Ardtun. At this horizon, John MacCulloch discovered the well-known large tree fossils, the most famous of these being 'MacCulloch's Tree' at Rubha na h-Uamha (NM 402 278), (Fig. 5.5), an upright coniferous trunk some 12 m high engulfed by lava (MacCulloch, 1819).

Above the basal columnar flows of Staffa Magma Type basalt lies the main succession of Mull Plateau Group basalts. This is a thick sequence of medium- to coarse-grained olivine basalt lava flows, some of which contain glomeroporphyritic aggregates of olivine and plagioclase, but others are feldspar-phyric. Chemically, the lavas have mildly alkaline to transitional alkaline–tholeiitic olivine-basalt affinities. Between 25 and 30 flows can be identified from the base of the suite to the summit of Bearraich (432 m), each generally less than 15 m thick and forming the characteristic stepped topography of the region. Of particular note is the presence of red, scoriaceous flow tops, indicating subaerial extrusion and contemporaneous weathering.

Pegmatite segregation veins of augite, feldspar and analcite are observed in a few of the lavas of the site. The lava flow in the cliffs below Dun Bhuirg (NM 422 262) 2 km west of Tavool House on Loch Scridain contains a good example of this phenomenon. The lava, an ophitic, olivine basalt bearing violet-coloured augite and abundant fresh olivine (Plateau Magma Type) is traversed by numerous small veins of analcite and contains cavities filled by zeolites associated with analcite (see Walker, 1971 for zeolite distribution in Mull). Coarse-textured veins of euhedral pyroxene and strongly zoned plagioclase in a matrix of analcite and feldspar also occur. The alkaline nature of their matrix is shown by the presence of aegirine augite, both in the zoned margins of titanaugite crystals and forming individual crystals; segregation of this alkaline residual material could generate rocks of phonolitic, nepheline, syenite composition (cf. the Shiant Isles).

Subsidiary interests of the site include fragments of Mesozoic and basal Tertiary sediments in the small landslip at Aird na h-Iolaire (NM 403 288). Minor Tertiary intrusions include sills of the xenolithic Scridain Suite (Bailey *et al.*, 1924) and pitchstone dykes.

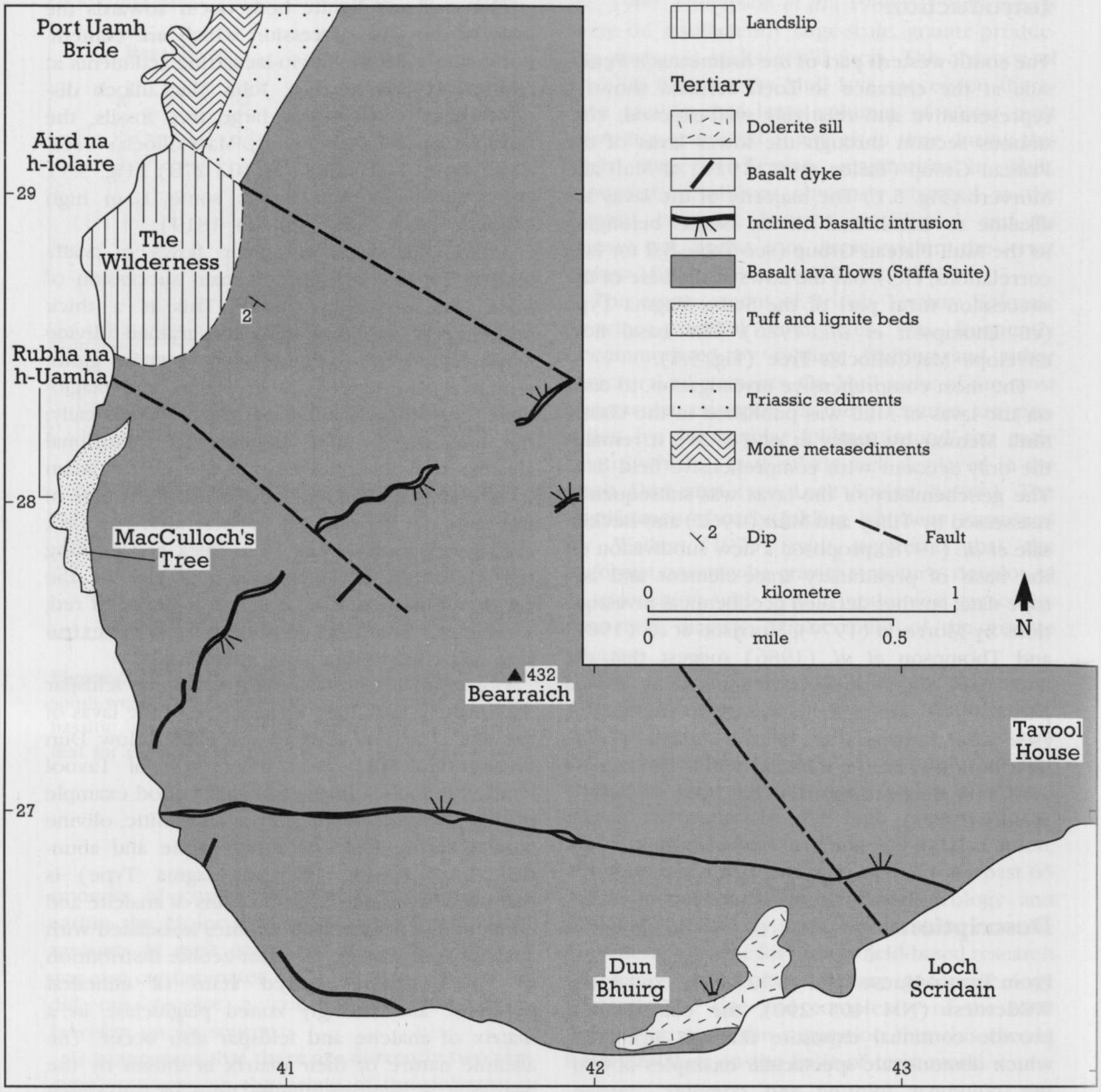


Figure 5.4 Geological map of the Bearraich site (adapted from the British Geological Survey 'One Inch' map, Sheet 43, Iona).

Interpretation

The site provides a virtually uninterrupted section through the base of the Plateau lava succession on Mull, recording the onset of Palaeocene igneous activity. The occurrence of red-weathered tops to lava flows, lignite beds and the nearby Ardtun leaf beds attest to a subaerial, warm temperate environment of lava effusion. Thick red boles above the weathered flow tops in the vicinity of the site (for example, on Aird Kilfinichen, NM 494 278) may indicate possible lava extrusion in bodies of shallow water, although conclusive evidence is lacking. Walker (1971), in a study of the regional distribution of zeolites in the Ardmeanach lavas, has shown them to have suffered burial sufficient to place them in the laumonite and mesolite zones. The systematic

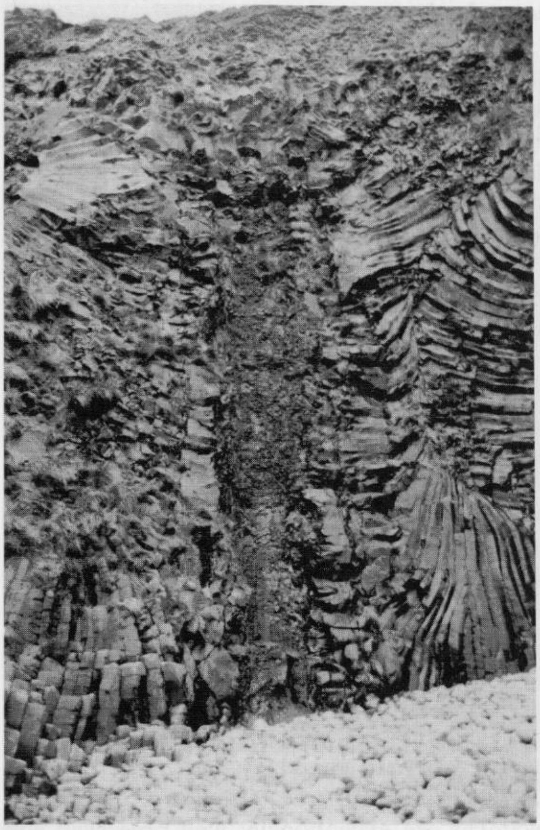


Figure 5.5 'MacCulloch's Tree' on Rubha na h-Uamha (NM 402 278), an upright coniferous trunk 12 m high engulfed by lava of Staffa Magma Type. Bearraich site, Mull. (Photo: C.J. MacFadyen.)

distribution of zeolite zones reflects the depth of burial of the lavas and, on Mull, these zones are discordant to the stratification of the flows. Walker (1971; see also Craig, 1983, Fig. 13.5) compared the Mull zonation with the more complete picture obtained from flows in Iceland, and estimated that the Mull lava succession was originally over 2200 m in thickness.

The lowermost lavas exposed on this site, including the flow enveloping 'MacCulloch's Tree', belong to the Staffa Magma Type of Bailey *et al.* (1924) and Thompson *et al.* (1986) (= Group 2, Beckinsale *et al.*, 1978). These strikingly columnar flows have provided some of the evidence used by Morrison *et al.* (1985) and Thompson *et al.* (1986) to postulate contamination by crustal partial melts – see Introduction to this chapter. At the present time, the areal distribution of these flows appears to be largely restricted to the base of the lavas either side of the entrance to Loch Scridain and to Staffa; however, there is a lack of modern stratigraphic information about the distribution of these and the other types of lavas recognized on Mull and Morvern, and their spatial distribution remains one of the outstanding problems of Tertiary igneous geology in the Hebrides, requiring a combination of modern geochemical work and careful field investigations.

'MacCulloch's Tree' is one of a number seen enveloped in the lavas within the site. It was assigned to the genus *Cupressinoxylon* by Gardner (1887). The conditions of eruption leading to preservation of this and the other trees have not been discussed in detail, but the enveloping lava must have behaved in a very fluid manner; had a typical, fragmenting flow-front advanced across the area, it is difficult to envisage that the trees remained upright. Further evidence about the environment at the start of lava eruption comes from Ardtun.

Conclusions

The site contains an important, continuous section through the lower part of the Mull lava succession. Geochemical investigation of the lowest flows shows that these were contaminated by crustal material on their path to the surface and this knowledge has been used to construct models of likely magmatic plumbing systems beneath the Mull lavas. The lowermost lavas are tholeiitic–transitional basalts, the main body of the overlying thick succession consists of alkali to transitional basalts. They were erupted subaerially and the lowermost flow engulfed growing trees.

ARDTUN

Highlights

The lacustrine sedimentary deposits between the Palaeocene lavas contain leaves of temperate plant species. The sediments and plants make up the renowned Ardtun Leaf Beds which are the prime interest of this site and are of international importance. The underlying lava contains pillows and was erupted into a shallow lake.

Introduction

The coastal cliffs and gullies within this site provide internationally important exposures of sedimentary deposits within the basal lavas of the Plateau Group in south-west Mull. These sediments are fluvial sands and gravels, which contain the renowned Ardtun Leaf Beds of important palaeobotanical value, are the prime interest of the site.

The sediments were originally discovered by a local man from Bunessan but were first fully investigated by the Duke of Argyll (1851). The discovery was of major importance in the study of the volcanic rocks of Mull since the sediments contained a rich terrestrial fossil flora and therefore allowed the associated lavas to be relatively dated. A full history of research, including a comprehensive list of the extracted plants, is given by Seward and Holttum in the Mull Memoir (Bailey *et al.*, 1924). In addition, a full description of the site is provided in a field excursion guide to the Tertiary volcanic rocks of Mull by Skelhorn (1969). Radiometric age studies on the lavas above and below the leaf beds have been carried out by Evans (1969), Mussett *et al.* (1973) and Mussett (1986).

Description

Although exposure is almost continuous along the coastal cliffs, the most accessible sections are located within small gullies leading down the cliffs (Figs 5.6 and 5.7). A sedimentary succession, which varies in thickness between 4 m and 15 m, lies upon the upper slaggy amygdaloidal zone of a thick columnar lava flow which exhibit well-developed, twisting columnar joints in the cliffs and sea stacks. Above the sediments, a second major columnar lava flow is exposed. Both lavas are olivine basalts of the Staffa Magma Type (Thompson *et al.*, 1986), or Group 2 of Beckinsale *et al.* (1978), (Table 5.2). The best section through the sediments is to be found in the ravine at Slochd an Uruisge (NM 377 248) and is described in detail by Skelhorn (1969). The sediments are predominantly flint-bearing conglomerates and grits, but contain three finer-grained horizons of silty sandstone and clay. The latter are known as the Ardtun Leaf Beds (Top, Middle and Bottom), containing an abundant leaf flora, including remains attributed to *Platanus* (plane), *Corylus* (hazel), *Quercus* (oak) and *Ginkgo* (maidenhair tree) (Skelhorn, 1969). The specimens are exceptionally well preserved and

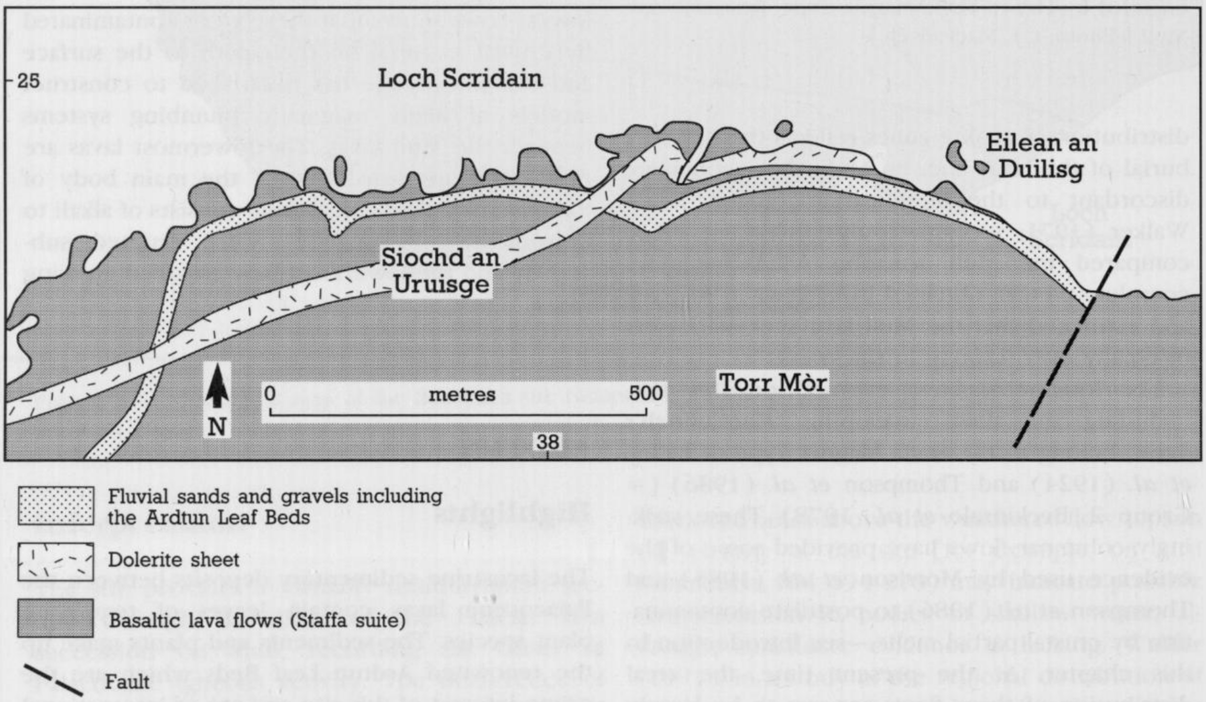


Figure 5.6 Geological map of the Ardtun site (adapted from the British Geological Survey 'One Inch' map, Sheet 43, Iona).

Figure 5.7 The best section through the Ardtun Leaf Beds at Slochd, an Uruisge (NM 377 248). Ardtun site, Mull. (Photo: C.J. MacFadyen.)

some are thirty or more centimetres in length, although they are extremely fragile. In addition, a sparse molluscan fauna has been recorded (Cooper, 1979) and fragments of a terrestrial beetle *Carabites scoticus*, a possible weevil and a ceropid insect have also been identified (Gardner, 1887; Cockerill, *in* Bailey *et al*., 1924). The lowest leaf bed is underlain by a thin coal seam which passes down into 0.15–0.20-m-thick, whitish, concretionary root clay on top of the lower basalt flow (Bailey *et al*., 1924).

The coarser-grained sediments are rich in angular quartz grains and derived flints and silicified chalk pebbles are abundant in the conglomerate. Pebbles of porphyritic igneous rocks are also present which may be of Palaeocene age and derived from nearby flows, or of Lower Old Red Sandstone age (Bailey *et al*., 1924); conclusive evidence for their source is lacking.

The gullies to the east of the main locality (NM 377 248) expose a dolerite sill transgressive towards the lavas and the intercalated sediments. Against the sediments, the sill has a well-developed tachylitic margin which has partly devitrified. The flow beneath the sediments contains pillows which may be either whole or fragmented, probably formed when the lava flowed into a small, temporary lake (Skelhorn, 1969).

A little to the south-east of Eilean an Duilisg (NM 386 249), the sedimentary horizon is downthrown below sea level by a N–S-trending fault.

Interpretation

These deposits provide valuable evidence for extended periods of sedimentation during the period of lava effusion in south-west Mull. The sediments and associated flora indicate deposition in a shallow temporary lake surrounded by marshland and which intermittently received sediment and plant debris from surrounding areas. Lava occasionally flowed into this wet environment, resulting in the development of pillow structures such as those immediately beneath the sediments. The flora in the sediments shows that a temperate climate prevailed. These conditions were established on a land surface created by the first large Palaeocene lava fields in this region. Coarse, clastic sediments were probably derived from the surrounding volcanic landscape and possibly from the tuffs containing pebbles of Cretaceous flint exposed near Malcolm's Point, Carsaig (Skelhorn, 1969). The finer-grained Leaf Beds may represent deposits formed during periods of stagnation when little sediment was washed into the lake and a limited freshwater fauna flourished. The plant material in the Leaf Beds has been correlated with other temperate northern floras and dated as early Eocene (Gardner, 1887; Seward and Holtum, *in* Bailey *et al.*, 1924), although their age is now generally accepted as being Palaeocene (but see Simpson, 1961). In addition, radiometric dates for the lavas above and below the Leaf Beds reveal an age of around 58 Ma (Evans, 1969; Mussett *et al.*, 1973, 1980). A geochemical discussion of these lavas is presented in the 'Introduction' to this chapter.

Conclusions

The rich, well-preserved flora includes temperate-climate tree species such as plane, hazel, oak and ginkgo. They were preserved during relatively quiet periods of sedimentation when muds and silts accumulated; at other times, when more vigorous sedimentation gave sands and gravels, the delicate plant debris was probably destroyed. The coarser-grained debris was largely derived from the surrounding volcanic landscape but the presence of fragments of Cretaceous flint and silicified Chalk may indicate that older rocks may also have been exposed to erosion. The sediments were laid down in shallow lakes, or from rivers flowing across the lavas; the basaltic flow underlying the plant-bearing sediments was probably erupted.

LOCH SGUABAIN

Highlights

The site contains excellent examples of pillow lavas formed when basalts were erupted into the early, South-East Caldera lake. The pillow lavas are veined by granite and thermally metamorphosed where they are intruded by the Glen More ring-dyke.

Introduction

The site encompasses the north-western slopes of Bheinn Fhada above Loch Sguabain where a representative section through lavas belonging to the Central Group within the early South-East Caldera is exposed (Table 5.1). Exceptionally well-developed pillow lavas dominate the interest of the site and other features include acid veining and thermal metamorphism of the lavas at the contact with the quartz-gabbro/granophyre Glen More ring-dyke. The lavas within this site have received no detailed investigation since Bailey *et al.* (1924) carried out the regional survey. However, the geochemical work of Beckinsale *et al.* (1978) and Morrison (1978) on the Mull lavas in general has applications to the tholeiitic Central Group lavas of this site.

Description

The lava flows exposed in the craggy outcrops above Loch Sguabain (Fig. 5.8) are sparsely feldspar-phyric and aphyric tholeiitic to transitional basalts forming part of the outer, earlier zone of lavas in the South-East Caldera (Bailey *et al.*, 1924). The basalts here lie within the zone of pneumatolysis associated with the Mull central complex; the effects of this hydrothermal alteration include the albitization of feldspar, decomposition of olivine and secondary epidote and quartz in veins and vesicles.

Excellent pillow structures are located at the summit of the first ridge on Beinn Fhada (Fig. 5.9), south-east of the loch (NM 630 304). The individual pillows here average 0.6–0.7 m in diameter and have clearly identifiable chilled margins, within which lie concentric zones rich in vesicles. Altered, fine-grained, hyaloclastite tuffs surround the pillows, and thin-bedded tuffs are occasionally present in the lava sequence.

The South-East Caldera lavas have been intruded by what appears to be an extension of the Glen More ring-dyke composed of quartz gabbro which passes upwards into granophyre. South-east of Loch Sguabain, granophyric net-veined breccia becomes progressively more evident at higher levels in the intrusion, with the uppermost portions showing a preponderance of granophyre to gabbro or coarse dolerite. Granophyric veins are also common in the lavas near the contact. The lavas have been thermally altered by the intrusion and a thin zone of granular hornfels is

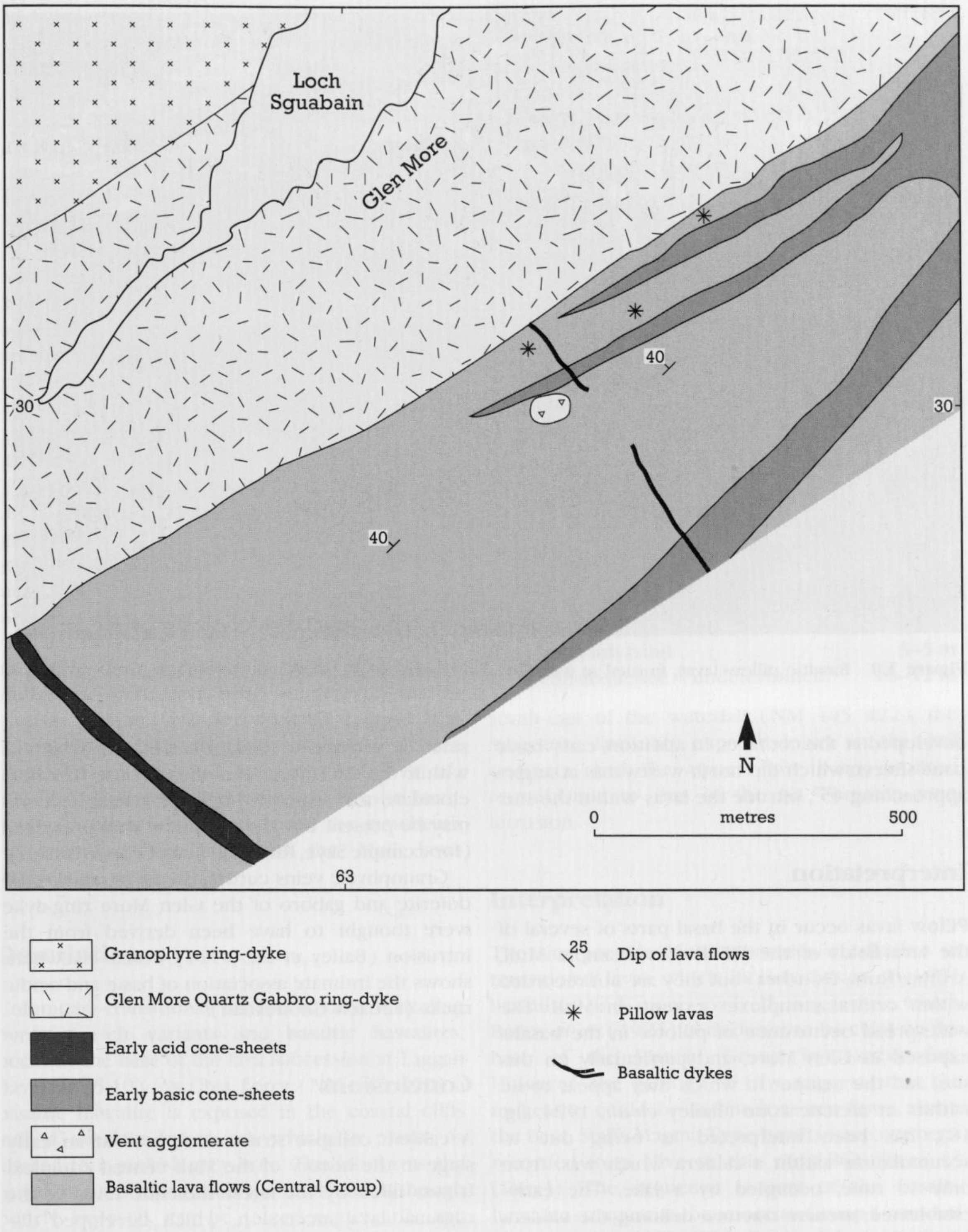


Figure 5.8 Geological map of the Loch Sguabain site (adapted from the British Geological Survey 'One Inch' map, Sheet 44, Mull).

Figure 5.9 Basaltic pillow lavas, formed in a caldera lake. Loch Sguabain site, Mull. (Photo: A.P. McKirdy.)

developed at the contacts. In addition, early basic cone-sheets, which dip north-westwards at angles approaching 45°, intrude the lavas within the site.

Interpretation

Pillow lavas occur in the basal parts of several of the lava fields of the BTVP (for example Mull, Ardtun; Rum, Fionchra) but they are not recorded within central complexes except on Mull. The widespread occurrence of pillows in the basalts exposed in Glen More, and particularly on this site, and the manner in which they appear to lie within an arcuate zone (Bailey *et al.*, 1924, fig. 18), has been interpreted as being due to accumulation within a caldera which was, from time to time, occupied by a lake. The early-established, arcuate fracture defining the caldera guided later intrusions belonging to the Glen More Centre (Centre 1, Table 5.1). This occurrence is also of importance since it records overlap between the last-preserved stages of major basalt lava accumulation on Mull and the establishment of strongly centralized igneous activity. The occurrence is of general importance since it provides a clear example of a caldera within the BTVP and can thus be used to help elucidate the structure of areas where calderas may be present but are much less well preserved (for example Skye, Kilchrist; Rum, Cnapan Breaca).

Granophyric veins cutting the lavas next to the dolerite and gabbro of the Glen More ring-dyke were thought to have been derived from the intrusion (Bailey *et al.*, 1924) which elsewhere shows the intimate association of basic and acidic rocks (Cruach Choireadail).

Conclusions

A caldera collapse structure formed at an early stage in the history of the Mull central complex. It was filled by the latest tholeiitic lavas of the regional lava succession, which developed distinctive pillow structures as they came into contact with the waters of a caldera lake. The arcuate fracture defining the caldera continued to be active after lava accumulation ceased and guided subsequent ring-dyke intrusions in the Glen More Centre. The lower, gabbroic and doleritic part of the Glen More ring-dyke intrudes and bakes the pillow lavas and is probably also the source of numerous white, granitic veins cutting the lavas near the contact.

LAGGAN BAY

Highlights

A columnar-jointed basalt flow is overlain by a well-exposed ash band and a mugearite lava flow. The mugearite flow and the ash are closely associated with mugearite which forms a volcanic plug, attesting to a phase of localized vent activity.

Introduction

The coastal and inland exposures about 1.5 km north-east of Ulva Ferry at the head of Loch Tuath provide a demonstration of columnar basaltic and mugearitic lava flows at the base of the Mull lava pile. The mugearites are associated with a volcanic plug, now infilled by ash and cut by a mugearite vent intrusion. As with most of the Mull sites, there have been no detailed studies specific to the lavas exposed at Laggan Bay, although brief descriptions of the area are contained in the Mull Memoir (Bailey *et al.*, 1924). Mugearites collected from the site have, however, been incorporated into the geochemical reconnaissance study of the Mull lavas (Beckinsale *et al.*, 1978).

Description

Columnar, transitional olivine basalts, including pyroxene-rich variants and basaltic hawaiites, occur at the base of the lava succession at Laggan Bay (Fig. 5.10). At Ulva Ferry (NM 445 400) a basaltic hawaiite is exposed in the coastal cliffs and is overlain by an ash which, in places, is altered to a pinkish-grey bole. The ash forms the lower parts of the raised sea cliffs and, although poorly exposed, can be traced northwards and westwards around Laggan Bay. Near Na Torranan (NM 452 415) it attains a thickness of 10 m in places. The ash is overlain by a fissile, mugearite lava flow and the whole sequence is intruded by a mugearite plug, 800 m in diameter. The plug displays vertical flow-banding and forms the headland of Na Torranan and the flat ground to the east. Northward, at Camas an Lagain (NM 448 418), the irregular scoriaceous and rubbly base to the mugearite is exposed above the ash which is much reduced in thickness here.

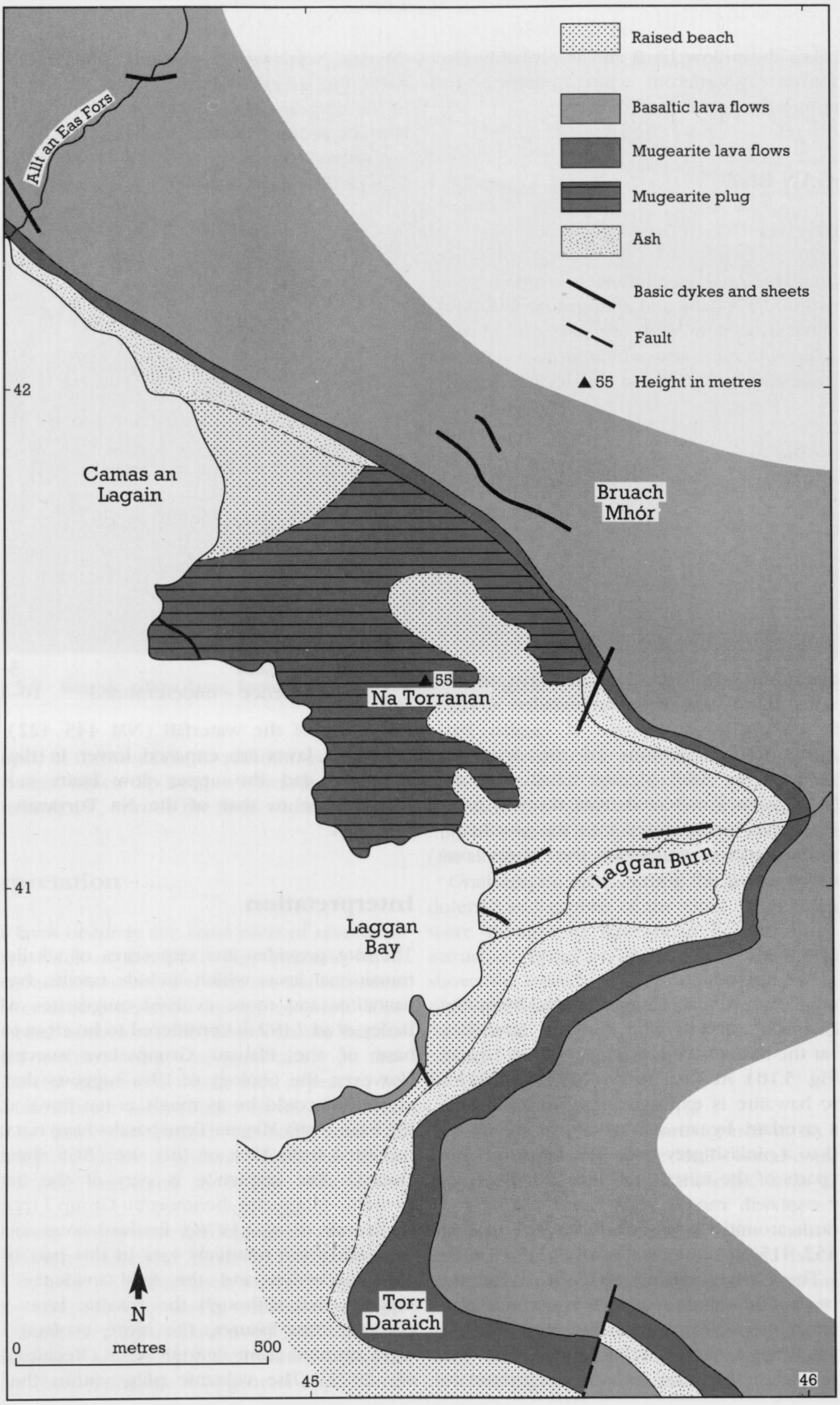
A section measured in the Allt an Eas Fors (NM 445 423) is as follows:

		thickness
10.	olivine basalt	3 m
9.	intermittently exposed bole	0.1 m
8.	massive, sparsely feldspar-phyric basalt with a vesicular, rubbly base	8–10 m
7.	red bole with banded clay-rich upper part	0.4 m
6.	scoriaceous lava with reddened top	5 m
	(gap in exposures in stream bed 8 m)	
5.	irregular, platy-jointed transgressive basic sheet	2–5 m
4.	pinkish, fissile ash with massive indurated bands	1.5 m
3.	columnar mugearite with base and pipe amygdales	12 m
2.	main ash band	3–5 m
1.	cliff sequence – undetermined	10–12 m

South-east of the waterfall (NM 445 422), the mugearite lavas are exposed lower in the cliff sequence and the upper flow bears a close resemblance to that of the Na Torranan vent intrusion.

Interpretation

The site provides fine exposures of alkaline to transitional lavas which include basalts, basaltic hawaiites and more evolved mugearites which Bailey *et al.* (1924) considered to be close to the base of the Plateau Group lava succession. However, the geology of Ulva suggests that the mugearite could be as much as ten flows above the base; Staffa Magma-Type basalts have not been recorded from Ulva or this site (BGS Sheet 43 (Iona)). The sequence is part of the basalt–hawaiite–mugearite–benmoreite Group I trend of Beckinsale *et al.* (1978). Evolved lavas such as mugearites are relatively rare in this part of the lava succession and the field evidence here suggests that, although the basaltic lavas were erupted from fissures, the more evolved lavas were erupted from central vents (Beckinsale *et al.*, 1978). The volcanic plug within the site



Raised beach
Basaltic lava flows
Mugearite lava flows
Mugearite plug
Ash
Basic dykes and sheets
Fault
55 Height in metres
Allt an Eas Fors
Camas an Lagain
Bruach Mhór
55
Na Torranan
Laggan Burn
Laggan Bay
Torr Daraich
N
0
metres
500
42
41
45
46

provides such evidence; the vent intrusion could have been the source for the associated mugearite lava and the ash the result of earlier explosive activity which established the vent (Bailey and Anderson, 1925). A significant time interval must have intervened between the eruption of the ash and the mugearite lava, as the upper surface of the ash is weathered to a bole in many places. It appears that the plugs on Mull lie in linear arrays which were probably fissure controlled. The evolved nature of the mugearites suggests that small magma chambers, in which crystal fractionation occurred, were located beneath the plugs along the fissure length. In addition, some basaltic lavas were undoubtedly erupted from vents such as that of 'S Airde Beinn. Similar vents are lacking or rare in the other Hebridean lava fields, although they are common in the Palaeocene lava fields of Antrim where there is a clear association with the regional dyke swarm (Walker, 1959).

Conclusions

The early basaltic and rarer mugearite lavas, ash and the mugearite volcanic plug within this site provide evidence that:

1. the first lavas erupted on Mull were largely basaltic;
2. the eruptive style and products were notably different at different times and more-evolved lavas and ash were erupted from explosive central vents located along the regional fissure trend.

Shallow-level magma reservoirs, in which crystal fractionation occurred, probably existed beneath the vents.

'S AIRDE BEINN

Highlights

A large, elongate dolerite plug intrudes the lava plateau along a regional structural lineament. The plug has produced a marked thermal aureole in the surrounding lavas; the aureole has been divided into three distinct zones on the basis of their mineralogy. High-temperature alteration of amygdales gave rise to larnite, rankinite and other uncommon calc-silicate minerals.

Introduction

'S Airde Beinn is a small but conspicuous rock-girt hill with a central depression occupied by a lochan (Fig. 5.11). The hill is carved from a doleritic plug which rises through the flat-lying, trap-featured lavas of the Mull Plateau. Such plugs are of restricted occurrence in the Tertiary Igneous Province and on Mull are best developed in the north of the island. It is not only the largest but also the best-known plug on Mull, having been described by Judd (1874), Geikie (1897), Bailey *et al.* (1924) and Richey and Thomas (1930). The thermal effects of the intrusion on the adjacent lavas and their amygdales have been detailed by Cann (1965); the mineralogy of the aureole is a key feature of the site.

Description

The 'S Airde Beinn plug (NM 470 540) rises as much as 60 m above the surrounding countryside and it measures 850 by 440 m. It is elongated in a NNW direction parallel to the Tertiary regional structural trend and dyke swarm. The rock is a coarse-grained dolerite composed of olivine, titaniferous augite, labradorite and magnetite and it is mineralogically identical to the lavas which it intrudes. Bailey *et al.* (1924) suggested affinities to some of the pillow lavas of the Mull complex, but Beckinsale *et al.* (1978) showed the gabbro to be quartz- and hypersthene-normative assigning it to Group 2 (Table 5.2). In thin section, the olivine is either fresh or partly altered to iddingsite and forms large irregular crystals. Large zoned feldspars are enclosed ophitically by clinopyroxene and a second generation of acicular augite associated closely with magnetite occurs interstitially in a chloritized residuum. The walls of the intrusion are close to vertical but there is no obvious abrupt contact between the plug and the adjacent lavas; the lavas appear to grade locally into the dolerite. The thermal effect of the intrusion upon the basalt country rock explains this apparent gradational contact. There is an increase in the granularity of the basalts as

Figure 5.10 Geological map of the Laggan Bay site (adapted from the British Geological Survey 'One Inch' map, Sheet 43, Iona).

Figure 5.11 A view of 'S Airde Beinn from the south. 'S Airde Beinn site, Mull. (Photo: C.J. MacFadyen.)

the intrusion is approached, accompanied by a change in amygdale compositions which normally contain minerals such as thompsonite, natrolite, analcite, heulandite, stilbite and gyrolite. The changes in basalt and amygdale composition in the thermal aureole around the plug are discussed in detail below.

Interpretation

The 'S Airde Beinn plug is one of several plugs which intrude the lavas of Mull and Morvern, most of which have NNW–SSE elongations, approximately parallel to the regional dyke swarm. It also lies on a major fault zone traceable in a similar direction from Druim Fada (NM 465 555) to the shores of Loch Frisa (NM 475 510). The numerous plugs of north Antrim are also elongate parallel to the regional dyke swarm, where the dykes and plugs are seen to merge. Like 'S Airde Beinn, many of the Antrim plugs are surrounded by pronounced thermal aureoles (cf. Tilley and Harwood, 1931; Preston, 1963); they are considered to have been long-lived feeders for lavas high in the Antrim Palaeocene lava field. A similar explanation is most likely for the Mull and Morvern plugs, which must have been coeval with the dykes and intruded as part of the same phase of magmatism, connected with Palaeocene crustal extension.

The principal value of the site is in the presence of the conspicuous metamorphic aureole associated with the plug. The apparent gradation from the coarse dolerite into the basalt at the contact was considered by Bailey *et al.* (1924) to indicate that the ascending magma which formed the plug melted and mingled with the lava wall-rock. Cann (1965), however, argued that only the most highly metamorphosed lavas have reacted with the magma. He distinguished three zones of progressive thermal metamorphism. The first is characterized initially by an increase in the amount of interstitial chlorophaeite, by the degree of alteration of pyroxene and olivine and by olivine being replaced by hypersthene and iron ore to produce a fine-grained hypersthene–augite–plagioclase–iron ore granulite. The second stage is characterized by the reappearance of olivine and an increase in granularity. Where a reaction with the magma has occurred, the third stage is reached, and olivine becomes the dominant ferromagnesian mineral.

Cann (1965) has also identified three classes of amygdale minerals on the basis of their behaviour on metamorphism. The first class consists of amygdale assemblages originally dominated by zeolite minerals such as thompsonite, natrolite and analcite with rare heulandite and stilbite. These show a consistent sequence of metamorphic change directly related to the stage of metamorphism attained by the surrounding basalts; many have been converted to plagioclase late in the first stage of metamorphism. Gyrolite is the dominant original amygdale mineral in the second class and this passes first into reyerite and then to wollastonite during metamorphism. A rim of aegirine-augite surrounds the wollastonite on its first appearance, caused by a reaction between the wollastonite and the basaltic magma. Amygdales originally filled with calcite constitute the third class. These have been altered to anhydrous calc-silicate assemblages of larnite, rankinite and wollastonite which form concentric monomineralic zones decreasing in Ca/Si outwards. The hornfelsed basalt around the amygdales has had its composition altered by the loss of Si and, at a late stage, of Mg and Al and has gained principally Ca. In places, melilite has replaced the amygdale walls and, near the amygdales, the basalt is unusually rich in augite. Metamorphosed 'amygdales' consisting largely of ferromagnesian minerals (hypersthene, olivine, hornblende) are also present and are attributed by Cann (1965) to the infilling of vesicles or voids in partly formed amygdales during the metamorphism.

Conclusions

The 'S Airde Beinn plug caused distinctive, high-temperature alteration of the surrounding basalt lavas. Three zones of thermal alteration have been recognized in the basalts and their amygdales, on the basis of mineralogy and petrography. The formation of the calc-silicate minerals larnite and rankinite provides particularly compelling evidence for high temperatures in the aureole and there has also been reaction between the basalt lavas and the marginal dolerite at the edge of the plug. This plug, in common with others in Mull and Morvern, probably acted as a long-lived feeder for lava flows since removed by erosion. It was intruded at the same time as dykes cutting the lavas.

CARSAIG BAY

Highlights

The site is notable for:

1. the presence of the thickest development of basal Palaeocene sediments on Mull, which contain debris derived from weathering of Cretaceous and earlier rocks under desert conditions;
2. a complete section through a composite (basic–acid) sill containing cognate and accidental xenoliths. Some of the latter have been partially fused and their high-temperature minerals include mullite.

Introduction

Carsaig Bay is a site of multiple interest, extending between Rubh' a' Chromain and Carsaig House, including the off-shore island of Gamhnch Mhor and the cliff at An Dunan. The interest of the site can be divided into the following categories:

1. Palaeocene sedimentary rocks, which attain their maximum development in the site and comprise sandstones and mudstones with numerous chalk clasts from the underlying Cretaceous strata.
2. The Rubh' a' Chromain composite xenolithic sill: this sill belongs to the Scridain Suite of sills which exhibit felsitic, basaltic and hybrid portions rich in cognate and accidental xenoliths.
3. The Gamhnach Mhor Syenite.

There has been no recent investigations into the geology of this site and the Mull Memoir is again the main source of information. A recent study concerned with magmatic processes which operated during the emplacement of a Scridain Suite sill to the west of the site has been made by Kille *et al.* (1986). This investigation, which has some applications to the Rubh' a' Chromain sill, demonstrated localized turbulent flow of the magma during emplacement and selective assimilation of wall rocks. The geology of the site is depicted in Fig. 5.12.

Description

Palaeocene sediments are well represented in the gully above Aird Ghlas (NM 534 212) and at

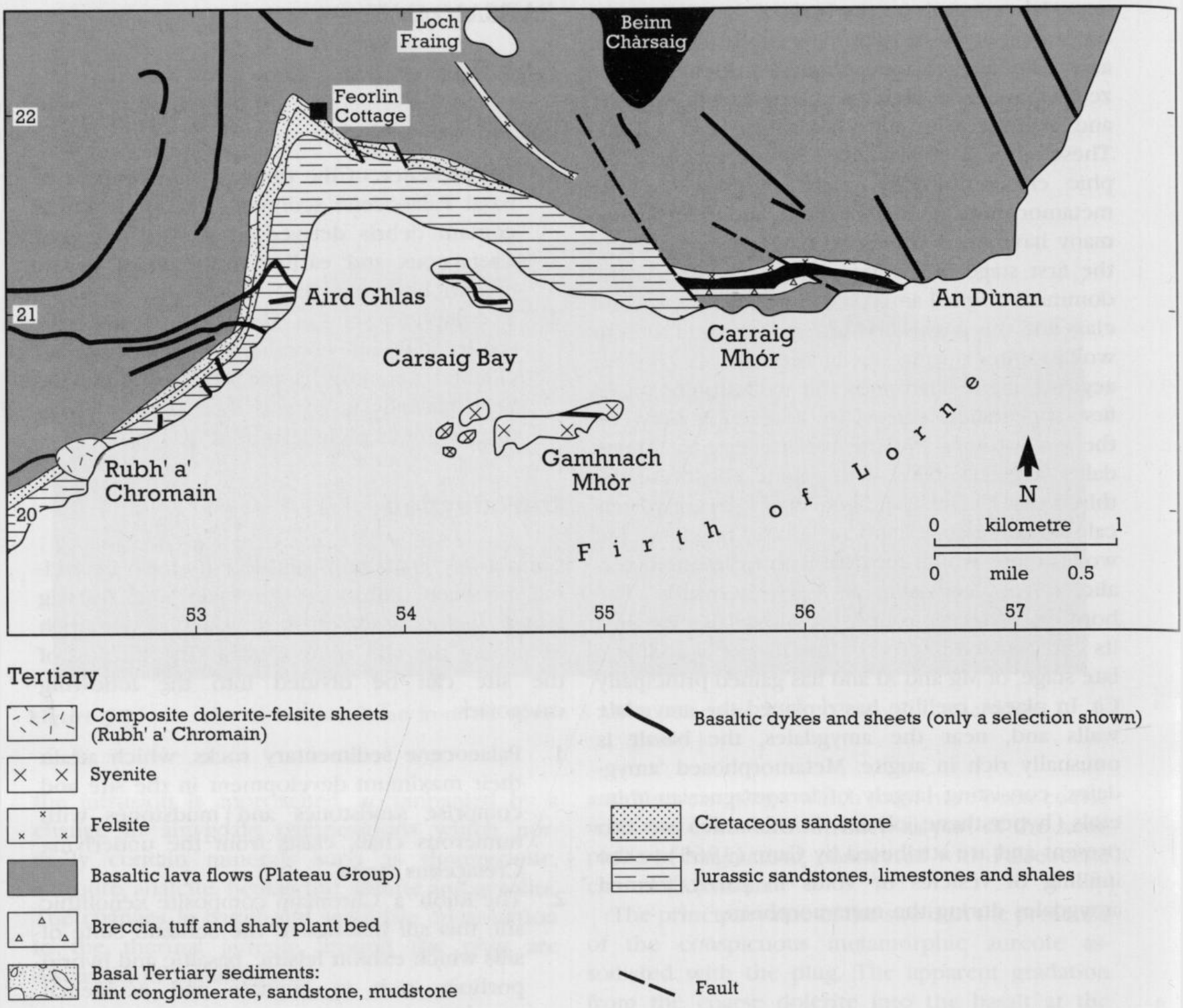


Figure 5.12 Geological map of the Carsaig Bay site (adapted from the British Geological Survey 'One Inch' map, Sheet 44, Mull).

Feorlin Cottage (NM 535 221), where they attain their maximum thickness of 1–2 m. At Aird Ghlas, Bailey *et al.* (1924) have recorded the following sequence:

6.	Basalt lava	
5.	Soft, shaly sandstone with flint fragments	0.30 m
4.	Greenish sandstone with flints and silicified chalk clasts	0.60 m
3.	Purple mudstone	0.30 m
2.	Greenish, partly glauconitic sandstone with chalk and flint fragments	1.60 m
	Gap	
1.	Cenomanian sedimentary rocks (for details see Lee and Bailey, 1925, pp. 118–20)	

The purple mudstone, which commonly occurs beneath the basal lava flow in Mull and Morvern, is interbedded with other sediments at this locality. Chalk fragments in the sandstones are hard and siliceous; their size and angularity suggests that they were derived locally, the silicification probably took place after the deposition of the sandstone (Bailey *et al.*, 1924). Abundant Cretaceous foraminifera have been identified within the chalk clasts (Jones, *in* Judd, 1878). The sandstone which underlies the mudstone consists of beautifully rounded, presumably wind-worn, quartz grains cemented by a dark, cherty matrix which also surrounds the chalk fragments. The latter are less abundant to the east, distinct horizons rich in chalk clasts being absent at Eas Mheannain (NM 538 221), where the fragments are irregularly scattered within the underlying thick, red-stained, pebbly sandstone.

The sequence within the stream section at Feorlin Cottage (NM 535 221) differs from that at Aird Ghlas and is as follows:

5.	Basalt lavas	
4.	Purple mudstone	1.0 m
3.	Chalk fragments in a black sandy matrix	0.20 m
2.	Massive, white pebbly sandstone with some iron staining and containing a lenticular bed of white flints towards the top	6.0 m
1.	Glauconitic sandstone (Cenomanian) passing down into concretionary limestones	

Still farther east in the site, no chalk is encountered within the sandstone, which grades rapidly downwards into a more glauconitic sandstone containing crushed bivalve debris thought to have been derived from the Cenomanian; the rock may or may not be of Palaeocene age. Sediments comprising 3–7 m of pale-green to buff-coloured breccia containing clasts of fine-grained vesicular basalt in a black, calcitic matrix, occur in the cliffs between Carraig Mhor (NM 555 211) and An Dunan (NM 563 212), within the lava succession. Plant remains have been located in shaly deposits a little below this horizon.

The first basalt lavas, lying immediately above the sediments, are markedly columnar – a feature characteristic of basaltic flows found elsewhere near the base of the Mull sequence. However, it is not known if these flows belong to the typically columnar Staffa Magma Type flows, examples of which occur at Ardtun. The basal lavas reach their maximum development of around 350 m, with an average flow thickness of 15 m in the Carsaig area (Bailey *et al.*, 1924).

The Rubh' a' Chromain Sill, exposed at the western edge of the site, is related to the Scridain Suite of sills (Bailey *et al.*, 1924). It is a striking and clearly exposed example of a composite intrusion having a sheet-like form and dipping to the north-west. The centre of the sheet contains felsite distinctly separated from basaltic margins which are normally chilled against the country rock (Fig. 5.13). The special interest of this composite intrusion lies in the presence of a varied suite of cognate and accidental xenoliths up to a metre in diameter; these are described below.

In detail, the intrusion cuts an earlier, irregular trachytic (bostonite) intrusion with a fine-grained, purplish-grey, aphyric appearance. Like the sill, the bostonite is xenolithic; a xenolith of black fossiliferous limestone has been tentatively assigned to the early Lias age, possibly related to the Broadford Beds (Lee and Bailey, 1925).

The lower contact of the Rubh' a' Chromain Sill abuts the Lias which appears to have been locally fused, resulting in the formation of tridymite. Kille *et al.* (1986) have described widespread fusion of pelites where doleritic Scridain sheets cut Moine metasediments to the west of the site at Traigh Bhan na Sgurra (NM 424 185). The following section through the composite intrusion at Rubh' a' Chromain is based on the work of the Survey:

	Top
Bostonite, at upper contact	
Chilled tholeiitic basalt	0.08 m
Tholeiite with cognate gabbroic xenoliths	1.20–1.80 m
Quartz dolerite with densely packed aluminous xenoliths	0.60–1.50 m
Porphyritic felsite with scattered xenoliths of sandstone at the margins and sandstone and shale xenoliths more centrally	6–9 m
Banded, possibly hybridized felsite	0.50 m
Quartz dolerite with numerous cognate xenoliths and a few accidental types	0.60–1.50 m
Chilled tholeiitic basalt	0.10 m
Lias sandstones	
	Bottom

The quartz dolerite is poor in olivine with brown, elongated, often curved crystals of augite. The interior felsite has a sharp contact with the quartz dolerite and contains sparse crystals of labradorite in a felsitic groundmass. Some chilled patches of rhyolite or acid pitchstone (Bailey *et al.*, 1924) occur in the centre of the sill; they exhibit skeletal and devitrification textures under the microscope.

The cognate xenoliths are generally dark-coloured, coarsely crystalline dolerites which

Figure 5.13 The Rubh' a 'Chromain composite sill exposed at the western edge of the Carsaig Bay site, Mull. (Photo: C.J. MacFadyen.)

appear as glomeroporphyritic patches of bytownite, hypersthene and rare greenish augite in a fine-grained variolitic matrix. A few olivine pseudomorphs are also present. Accidental xenoliths are much more variable and, although not all of the following types occur at Rubh' a' Chromain, they characterize the Scridain Suite as a whole (see Bailey *et al.*, 1924 and Kille *et al.*, 1986 for other localities where similar xenoliths are described within the Scridain sheets).

1. Micaceous gneiss
   Granulite
   Quartzite
2. Granite
   Pegmatite
3. Sandstone
   Shale
   Carbonaceous rock
   (bituminous shale/coal)
4. Basalt lava

A significant feature of the Rubh' a' Chromain Sill is the distinctive, high-temperature mineralogy of the thermally metamorphosed aluminous xenoliths. They appear to have partially fused and have a reaction rim containing anorthite, pink sillimanite, green hercynite/pleonaste spinel, corundum and cordierite. Of these, the corundum or sapphires occur isolated as small, blue, tabular crystals. The feldspars often take on a rosy hue owing to the inclusion of needles of rare pink sillimanite. The inclusions are generally completely recrystallized to granular hornfels. Shaly and sandy xenoliths are frequently fused to buchite. A fuller description of these xenoliths is given by Thomas (1922); the sillimanite was later identified as mullite ($3Al_2O_3.2SiO_2$), a common mineral in bricks (Bailey *et al.*, 1924, p. 268).

At the entrance to Carsaig Bay, the low island and surrounding reefs of Gamhnach Mhor are formed from an alkaline syenite. The body is assumed to be a sill although the contacts are not visible; it was tentatively given a Tertiary age by Bailey *et al.* (1924). The rock is yellowish to greyish-brown with a rough, irregular fracture and composed mostly of sodic orthoclase, with subordinate aegirine and pale-green aegirine-augite. Accessory minerals include a strongly blue-green, alkali amphibole, magnetite and apatite. Phenocrysts are absent, as is nepheline in hand specimen. The intrusion is traversed by numerous segregation veins, basic dykes and a tholeiitic sheet bearing cognate xenoliths belonging to the Scridain group of sills.

Interpretation

The Palaeocene sediments at Carsaig Bay are of special significance as it is here that they attain their maximum development. The sandstones, containing wind-worn quartz grains and rounded chalk fragments, were probably deposited in a desert environment, which persisted from late Cretaceous times when major uplift of the Chalk occurred and Palaeocene sedimentation commenced (Bailey *et al.*, 1924). The persistent purple mudstones at the base of the lavas and above the desert sandstones occur throughout Mull and have probably formed by the lateritic decomposition of basaltic ash in a warm and moist climate (Bailey *et al.*, 1924). The ash may have been the product of an initial volcanic explosion on Mull followed by a long repose period prior to the eruption of the first lavas.

The Scridain sheet swarm is an important and conspicuous feature of Tertiary igneous activity on Mull. The numerous sheet-like masses have intruded the lava plateau, Mesozoic sediments and Precambrian basement rocks of the Ross of Mull and Gribun peninsulas. Bailey *et al.* (1924) considered the sheets to belong to a single complex containing a wide range of rock types from basalt through to rhyolite. The sheet exposed within the site is, however, a fairly uncommon example of a Scridain sill by virtue of its composite nature (a few other examples are quoted by Bailey *et al.*, 1924, p. 287). It provides evidence for the coexistence of acid and basic magmas during Tertiary volcanism on Mull, which is in line with evidence from numerous other localities quoted in this volume. The absence of a chilled contact between the tholeiite and the felsite in the sill implies that felsitic magma was injected into the centre of the sill before the tholeiite had cooled; both were probably liquid together, as shown by the presence of banded, possibly hybridized felsite at the contact.

There have been no published, detailed, petrological investigations into the origin of the different magma types in composite sills or in the suite as a whole. Bailey *et al.* (1924) suggested that the wide range of magma types represented by the Scridain Suite were the result of crystal fractionation in a magma reservoir. This reservoir probably existed beneath the lava pile and the evidence provided by the accidental xenoliths suggests that it disrupted Precambrian and Mesozoic country rocks. The xenoliths were regarded by Bailey *et al.* as having been broken off the walls of the magma chamber and accumulated towards the base, hence the more basic parts of the sheets are richer in xenoliths. Alternatively, it is suggested that fusion of the country rock could create an acidic and intermediate melt by mixing. Ample evidence that assimilation of country rock by the basic magma is a real process comes from partly digested xenoliths, fusion of sandstone at sill margins and evidence for fusion of metasediments at Traigh Bhan na Sgurra (Kille *et al.*, 1986). However, no firm conclusion can be reached on this issue until considerable further field-work and petrological investigations have been undertaken.

The occurrence and alteration of the cognate xenoliths in this composite sill are very important features of this site since they:

1. provide information about subsurface rocks in this part of Mull; and
2. prove that the magmas of the Scridain sills were hot on emplacement, possibly over 1100°C (cf. Kille *et al.*, 1986).

Fusion of sediment at the lower contact indicates that these temperatures were sustained, thus the turbulent flow envisaged during sill emplacement elsewhere probably also applies at Rubh' a'Chromain (cf. Kille *et al.*, 1986).

Bailey *et al.* (1924) suggested that the intrusive Scridain Suite was probably contemporaneous with the emplacement of late basic cone-sheets associated with the central complex. The syenite is therefore of an earlier age; apart from this, little is known about the rock, which is a distinctly unusual type in the BTVP.

Conclusions

The site is of exceptional value as it contains several unique features of Tertiary igneous activity on Mull. Basal Tertiary sediments are well developed in Carsaig Bay and record a continuation of an arid, desert environment from the late Cretaceous into the Palaeocene. Warm, temperate conditions then prevailed when an initial explosive volcanic event marked the onset of Tertiary volcanism and spread ash over much of the region to form a basal mudstone. The Rubh' a' Chromain sill provides a clear example of a composite intrusion which belongs to the extensive Scridain Suite, emplaced during a single event along with the late basic cone-sheets associated with the central complex (Table 5.1). It provides further evidence from the BTVP for coexisting acid and basic magmas; the acid portion derived either from crystal fractionation or crustal assimilation in a shallow-level magma reservoir. Abundant accidental xenoliths appear to have been derived from Precambrian, Mesozoic and Palaeocene rocks, possibly from the walls to the magma chamber. The Gamhnach Mhor Syenite is an earlier intrusion of probable Cenozoic age and is unusual by reason of its thoroughly peralkaline character.

LOCH SPELVE–AUCHNACRAIG

Highlights

This is a classic locality of international importance for demonstrating concentric folding associated with the emplacement of an igneous central complex. Exposure of Dalradian and Moine rocks in fold cores proves the nature of the Precambrian basement beneath Mull and show that the Great Glen Fault was offset by emplacement of the central complex.

Introduction

The rocks exposed on the western shores of Loch Spelve and on the peninsula lying between its northern arm and the Firth of Lorne lie within a site of multiple interest. Principally, the exposures provide a traverse through clearly defined circumferential folds around the earliest centre (Centre 1) of the Mull central complex, which are best developed in the south and east of the island. In addition, the site contains a unique succession of Triassic strata, which is the thickest sequence in the Hebrides, together with sections through Devonian lavas, Lower and Middle Jurassic (Lias, Inferior Oolite, Great Estuarine) and Cenomanian beds unconformably succeeded by Palaeocene sedimentary rocks. Basement Precambrian rocks are also exposed as inliers. Lavas dominate the Tertiary (or other) igneous rocks present in the site but there are also exposures of the early Glas Bheinn Granophyre within the western margin of these, and basaltic dykes, especially in coastal exposures (Fig. 5.14).

The folds were first described in the Mull Memoir by Bailey *et al.* (1924), who chose the area covered by this site to be the most favourable for the demonstration of the structures. Subsequent discussions relating to the nature of the folding have been published by Cheeney (1962), Rast *et al.* (1968) and Skelhorn (1969). Most recently, Walker (1975) has related the structures of this area to the early evolution of the central complex.

Description

Bailey *et al.* (1924) have distinguished the following structural elements within the area around Auchnacraig:

1. Marginal tilt (outermost zone). A general centripetal dip of up to 50° towards the caldera of Centre 1 is easily recognizable along the coast between Grass Point (NM 748 308) and Rubha na Faoilinn (NM 729 274) where Mesozoic rocks underlie early Cenozoic sediments and lavas.
2. Duart Bay Syncline. The axis of this fold passes just east of Auchnacraig and traverses the eastern slopes of Garbh Dhoire. The Tertiary lavas, which exceed more than 300 m in thickness, have been affected by this fold; Bailey *et al.* (1924) recorded the highest lava as being Big-Feldspar basalt (Table 5.2), while Cheeney (1962) recognized lavas of the Central Group (Table 5.2) a short distance west of Gortenanrue (NM 728 279). The syncline is approximately symmetrical with maximum dips of around 45°.
3. Loch Don Anticline. The crest of this anticline extends through Loch a'Ghleannain and Meall Reamhar (NM 726 301). It is offset by over 100 m by a WNW-trending, sinistral, strike-slip fault which passes through Port Donain (NM 740 290). Immediately south of the fault the anticline bifurcates. In the north of the site, the core of the structure exposes Dalradian schists and limestones which are succeeded by Devonian lavas similar to lavas of the Lorne Plateau, Mesozoic sediments and Palaeocene lavas. The fold plunges southwards so that Dalradian and Devonian rocks pass below ground to the south of the Port Donain Fault. The Mesozoic rocks of the eastern branch of the fold do not extend beyond Carn Ban (NM 722 289) but reach the coast near the ruined chapel (NM 709 284) in the western branch. The anticline is

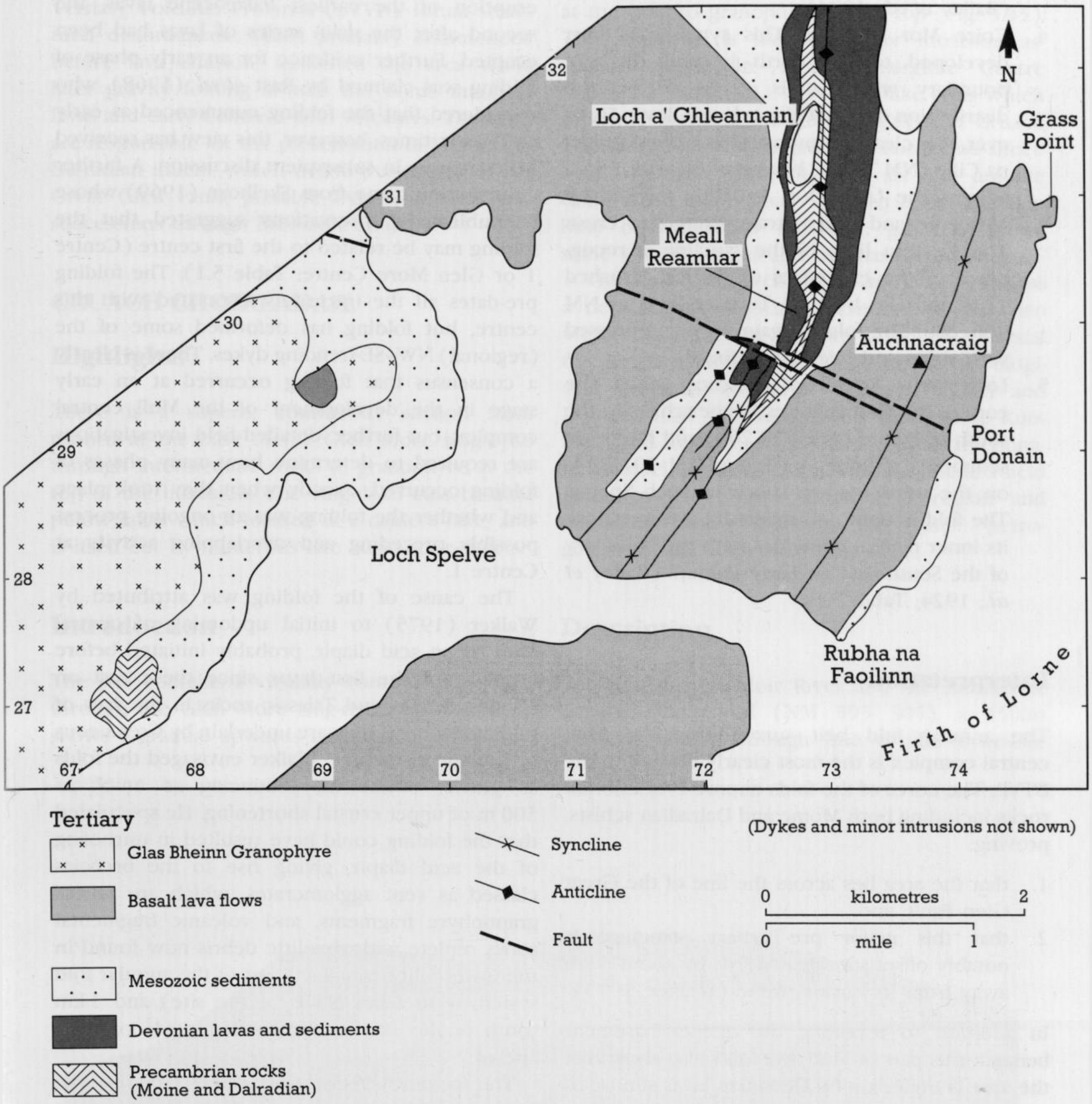


Figure 5.14 Geological map of the Loch Spelve–Auchnacraig site (adapted from the British Geological Survey 'One Inch' map, Sheet 44, Mull).

highly compressed, the eastern limb is, in places, vertical or overturned, while the western limb normally dips at between 30° and 60°, but occasional attitudes of up to 80° are recorded. The intensity of the folding has led to the brecciation of the Devonian and Tertiary igneous rocks (Bailey *et al*., 1924). The former are generally crushed while the latter show only local crushing, a difference attributed to post-Devonian but pre-Tertiary movements along the Great Glen Fault, which is coincident with the southern margin of the Mull complex. Northwards, the Loch Don Anticline weakens and passes into a faulted monocline and then into a series of *en échelon* folds of the Craignure Anticline

(Bailey *et al.*, 1924).

4. Coire Mor Syncline. This syncline is best developed to the north beyond the site boundary where it is expressed by the distribution of Big-Feldspar basalt flows. However, it is clearly demonstrated around Rubha na Cille (NM 706 283) where its eastern limb adjoins the Loch Don Anticline marked by Mesozoic and older strata along the crest. The western limb of the syncline is recognized in the exposures of vertical, crushed Trias and Lias beneath Tertiary lavas at NM 706 286. The fold is again very compressed with steep and overturned limbs.
5. Loch Spelve Anticline (innermost zone). The core of this fold contains Moine schists to the south of Balure (NM 675 268) and Mesozoic sediments at Rubha na Faing (NM 707 297) on the north-eastern shore of Loch Spelve. The fold is tight and markedly asymmetrical; its inner margin coincides with the boundary of the South-East, or Early Caldera (Bailey *et al.*, 1924; Table 5.1).

Interpretation

The annular fold belt surrounding the Mull central complex is the most clearly defined in the BTVP. The cores of the folds expose Precambrian rocks including both Moine and Dalradian schists, proving:

1. that the area lies across the line of the Great Glen Fault; and
2. that this major pre-Tertiary structure is notably offset south-eastwards by about 5 km away from its normal trend (Walker, 1975).

In addition to revealing the deeper basement beneath this part of Mull, the folds also show that the area is underlain by Devonian lavas similar to those of Lorne and by Triassic and Jurassic rocks.

Formation of the arcuate folds was tentatively regarded by Bailey *et al.* (1924) as one of the earliest events in the Mull central complex. Their origin was ascribed to the intrusion of the early granophyres of Glas Bheinn and Derrynaculen; thus, forcible intrusion of acid magmas was clearly envisaged at this early stage in research on Mull. Cheeney (1962) observed an angular discordance of about 60° between Mesozoic sediments and overlying lava flows near Auchnacraig, leading him to recognize two periods of folding, the first post-late Cretaceous, but before eruption of the earliest Palaeocene lavas, the second after the main series of lavas had been erupted. Further evidence for an early phase of folding was claimed by Rast *et al.* (1968), who considered that the folding commenced as early as Triassic times; however, this view has received little support in subsequent discussion. A further contribution came from Skelhorn (1969) whose (unpublished) observations suggested that the folding may be related to the first centre (Centre 1 or Glen More Centre; Table 5.1). The folding pre-dates all the intrusions associated with this centre, but folding has deformed some of the (regional) NW–SE-trending dykes. There is clearly a consensus that folding occurred at an early stage in the development of the Mull central complex, but further, detailed field investigations are required to determine how many phases of folding occurred, exactly when they took place and whether the folding was an ongoing process possibly preceding and overlapping activity at Centre 1.

The cause of the folding was attributed by Walker (1975) to initial updoming of central Mull by an acid diapir, probably initiated before eruption of the first lavas since these rest on Moine gneisses and Triassic rocks in the area of folding, whereas they are underlain by Cretaceous or Jurassic elsewhere. Walker envisaged the folds as gravity structures, producing as much as 500 m of upper crustal shortening. He speculated that the folding could have resulted in unroofing of the acid diapir, giving rise to the breccias classed as vent agglomerates, which are full of granophyre fragments, and volcanic fragmental rocks replete with rhyolitic debris now found in the Coire Mhor syncline (part of the annular fold system 4 to 8 km NNW of the site) and 1 km south of the site on the southern side of Loch Spelve.

The tectonic effects of the emplacement of the Mull central complex are the finest developed in the BTVP and are regarded as textbook examples of international importance. They are, however, still poorly understood in detail and would merit a thorough reinvestigation.

Conclusions

Clearly defined concentric folds associated with the early emplacement of Centre 1 on Mull are the finest expression of this type of deformation associated with igneous activity in the British

Tertiary Volcanic Province (BTVP). Initial structural disturbances, which probably commenced before lava effusion, updomed the area while later gravity folding around the dome involved lavas and early Centre 1 acid volcanics. The folds are responsible for the preservation of Moine and Dalradian inliers, which define the course of the Great Glen Fault, possible Devonian lavas and successions through Mesozoic strata.

CRUACH CHOIREADAIL

Highlights

There is a superb, continuous section from gabbro at the base of the Glen More ring-dyke through intermediate rocks to granophyre at the top of the intrusion. The ring-dyke cuts basaltic pillow lavas which formed in a caldera lake, and is itself cut by numerous late basic cone-sheets.

Introduction

The site contains a virtually continuous section through the Glen More ring-dyke which clearly shows a gradual upwards transition from gabbro at the base to granophyre at the top (Fig. 5.15). The ring-dyke is the last major intrusion associated with the Beinn Chaisgidle Centre (Centre 2, Table 5.1). Two dyke-like arms which protrude upwards from the ring-dyke at Cruach Choireadail are connected by a horizontal sheet. Also exposed within the site are the arcuate Coire 'an t-Sailein quartz gabbro body, the Ben Buie olivine-gabbro intrusion, gabbroic plugs, some volcanic rocks and late basic cone-sheets.

The Mull Memoir (Bailey *et al.*, 1924) contains a detailed petrological description of the Glen More ring-dyke. The authors advanced a crystal fractionation model to account for the petrological variations. However, Holmes (1936) and Fenner (1937) challenged this view, while Koomans and Kuenen (1938) favoured the fractionation model. Skelhorn (1969) has produced a field guide to the Cruach Choireadail region and discusses the models for the petrogenesis of the Glen More ring-dyke.

Description

Between the Coladoir River and the summit of Cruach Choireadail (NM 595 305), a 450 m vertical section through one of the dyke-like

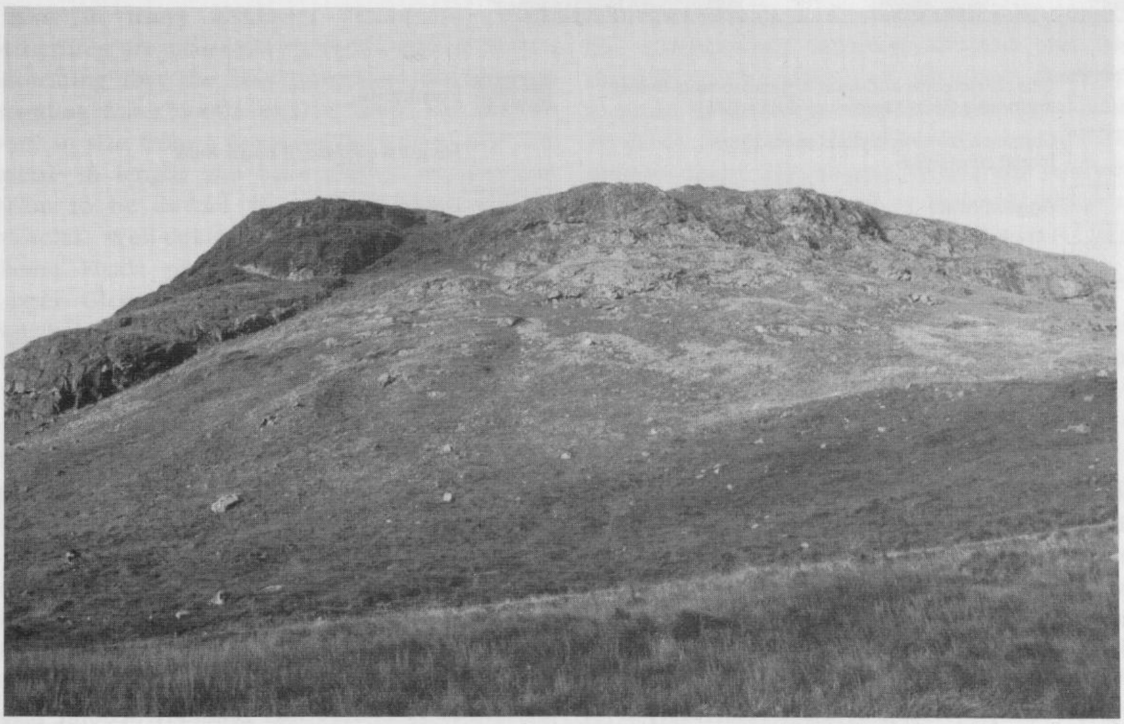


Figure 5.15 Cruach Choireadail, viewed from the Coladoir River, exposing gabbro/granophyre of the Glen More ring-dyke. Cruach Choireadail site, Mull. (Photo: C.J. MacFadyen.)

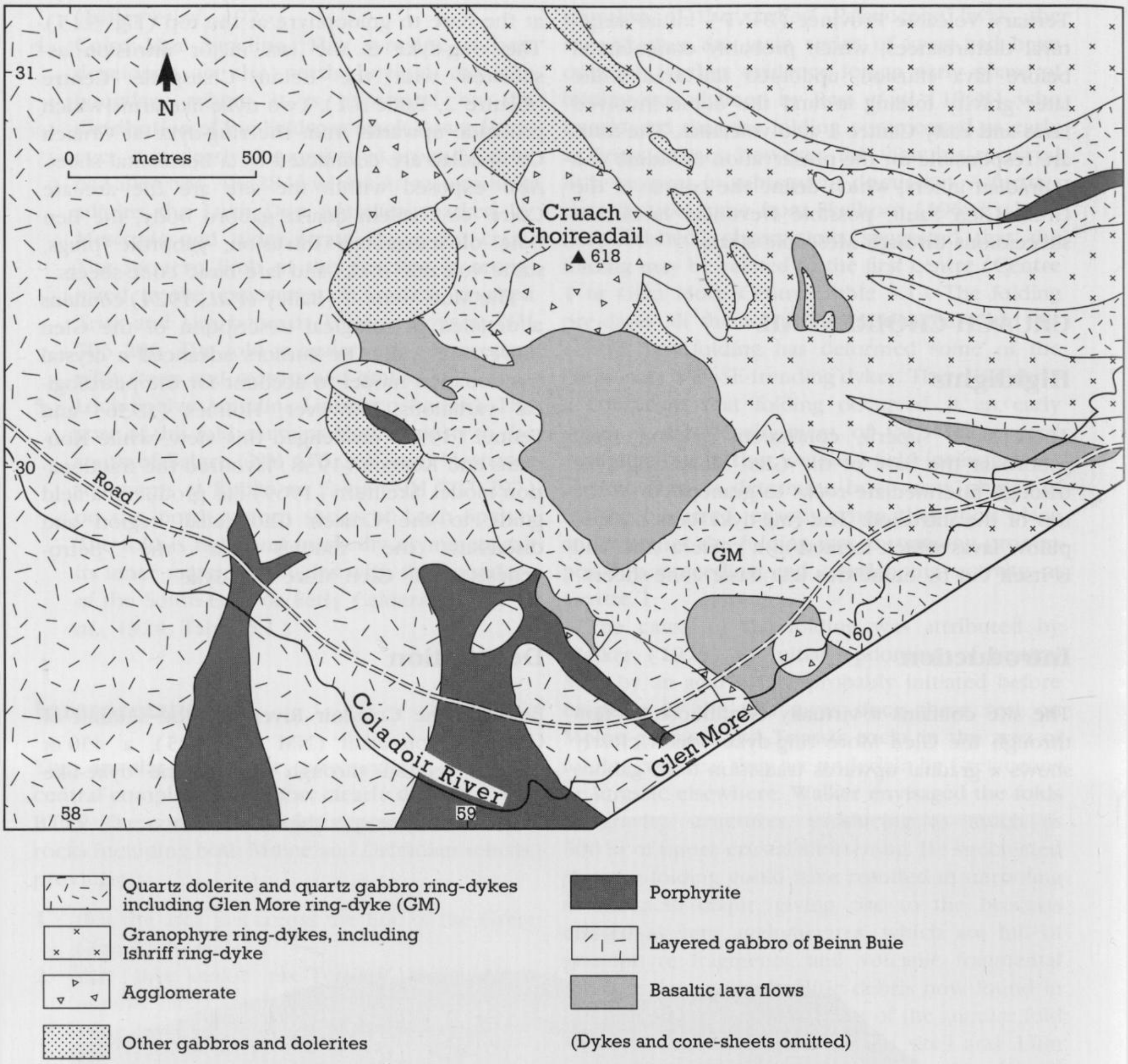


Figure 5.16 Geological map of the Cruach Choireadail site (adapted from the British Geological Survey 'One Inch' map, Sheet 44, Mull).

apophyses of the Glen More ring-dyke is exposed (Fig. 5.16). The lowermost rocks are the most basic, containing about 44% silica (Koomans and Kuenen, 1938), and are moderately coarse-grained, speckled quartz gabbros/dolerites containing labradorite (40%), augite (40%), ilmenite + magnetite (12%) and minor amounts of quartz + alkali-feldspar intergrowths. Pseudomorphs of chlorite after olivine also occur but form less than 5% of the modal mineralogy (Koomans and Kuenen, 1938). The distribution of feldspar is sometimes uneven, resulting in leucocratic segregations and horizontal segregation veins of an acidic residuum up to a metre in thickness. These are common in the basic portion of the intrusion. There is a gradual and remarkably regular decrease in grain size upwards through the intrusion as the rocks generally become paler and more leucocratic. The proportion of acid mesostasis likewise increases upwards, olivine completely disappears, plagioclase becomes less calcic and the habit of augite changes from ophitic to acicular. The quartz gabbro passes upwards into a pinkish-grey, augite diorite with a hybridized appearance and finally into pinkish leucocratic 'granophyre'. The summit 'granophyre' is a fine-grained, quartz-microporphyritic, spherulitic, sodic felsite essentially composed of albite, orthoclase, quartz and alkali-feldspar intergrowths, and quartz and fibrous green hornblende replacement after acicular augite.

In the Coladoir River, the Glen More ring-dyke is separated from the earlier Ishriff Granophyre ring-dyke by a narrow screen of basalt and dolerite. These thermally metamorphosed rocks are probably early members of the late, basic, cone-sheet complex (Table 5.1). This screen is traceable for some distance up the slopes of Cruach Choireadail. The numerous NW-trending sheets traversing the lavas are truncated by the Glen More ring-dyke and form the main wall rocks; however, the ring-dyke is itself cut by late basic cone-sheets (Bailey *et al.*, 1924) in the north-west, showing that it has been bracketed by the late basic cone-sheet emplacement episode. Examples of the lavas associated with the South-East Caldera (Centre 1) are located to the south of Cruach Choireadail and the small lochans and are notably packed with large feldspar phenocrysts in many instances. Occasional pillow structures are observed in these altered basalts indicating that the lava sometimes flowed into standing water within shallow lakes. The pillows vary in size from a few centimetres to over one metre in length and have chilled margins but seem to be devoid of concentrically arranged vesicles. Well-developed pillow lavas along the Beinn Fhada plateau above Loch Sguabain in upper Glen More, are described in the Loch Sguabain report (see above).

Between the two dyke-like parts of the Glen More intrusion, a small gabbroic plug is exposed, cut by late basic cone-sheets. Identical plugs are found around Cruach Choireadail having chemical affinities with the caldera lavas and they may be regarded as potential feeders for them. Other features of interest within the Cruach Choireadail site include the agglomerates or breccias towards the summit and an exceptionally large xenolith of the Ben Buie layered gabbro (exposed at the western end of the site) at a height of about 250 m. This gabbro is the youngest intrusion of the earlier Glen More Centre (Centre 1; Table 5.1).

Interpretation

The continuous vertical section through the Glen More ring-dyke, showing an unbroken transition from basic rocks at low levels in the intrusion to acid rocks at high levels, is one of the most clearly demonstrated examples of such compositional variation in the BTVP. The close association of basic and acid rocks, and by implication magmas, in the same intrusion is a common feature of intrusions in the Province. The fine exposures in this site provide an excellent opportunity to study the problem.

The gradual change in rock type at different levels in the intrusion was attributed by Bailey *et al.* (1924) to *in situ* differentiation involving crystal settling towards the base and migration of residual, progressively more evolved magma into the upper parts of the ring-dyke. Objections have been raised to this mechanism. Skelhorn (1969) pointed out that the gabbros at the base lack rhythmic layering, igneous lamination and other features characteristic of cumulate rocks. Further evidence against a model involving fractionation of basaltic magma by crystal settling is the lack of marginal border rocks representing the parental basaltic magma (cf. Wager and Deer, 1939) and the observation that granophyre is in direct contact with the country rocks, against which it is chilled. Another possible mechanism involves the simultaneous intrusion of acid and basic magmas, with mixing of the two contrasted magmas to give intermediate rock types which certainly have the textural attributes of hybrid igneous rocks. The magma mixing and hybridization model was advanced by Holmes (1936) and Fenner (1937), but Koomans and Kuenen (1938) argued against it on the grounds that:

1. there was an absence of biotite, hornblende and orthopyroxene which they claimed were characteristic of a 'hybrid series';
2. the predominantly curved trends on the chemical variation diagrams (as opposed to straight-line relationships produced by magma mixing); and
3. the lack of intrusive breccias or sharp contacts between the various rock types.

They suggested that gravitative separation and settling of augite and iron oxides (+ plagioclase) resulted in the formation of the granophyre, and that subsequent 'pneumatolytic emanations from the lower reaches of the column' were responsible for the textural features of the intermediate rocks.

Clearly, the close association of basic and acid rocks, and the apparent height control on their occurrence in the intrusion, have important petrogenetic implications. However, it is obvious from a cursory glance at the literature that a thorough petrological investigation of the Glen More ring-dyke is long overdue. This would have to take into account modern work on magma mixing and zoned magma chambers; until this is done the site will not attain the international status which it almost certainly merits.

Conclusions

The Glen More ring-dyke shows continuous variation from gabbroic rocks in its lower levels through intermediate rocks to granophyre in the highest parts of the intrusion. This variation may have been caused by:

1. settling of early-formed crystals (augite, magnetite, calcic plagioclase, plus some olivine) towards the base of the intrusion, allowing the remaining magma, enriched in silica, potassium and sodium, to crystallize as granophyre at the top of the ring-dyke; or, alternatively,
2. basaltic magma may have been injected into the base of the ring-dyke at the same time as granitic magma entered the top; the two magmas then mingled to give the rocks of intermediate composition now found between the gabbro and granophyre.

Pillow lavas in the site formed when basaltic magma flowed into a caldera occupied by a lake (see also Loch Sguabain).

ALLT MOLACH – BEINN CHÀISGIDLE

Highlights

Continuous stream sections expose acid and basic ring-dykes and numerous cross-cutting cone-sheets associated with Mull Centre 2. Extensive acid veining of basic rocks occurs where these intrude acid rocks. Screens of country rock (earlier volcanic and igneous rocks) are present between the ring-dykes. Acid intrusions of Mull Centre 3, including the classic Loch Bà ring-dyke, truncate the earlier Centre 2 intrusions.

Introduction

The geological significance of the Allt Molach–Beinn Chàisgidle site lies in the exposure of various members of the second intrusive centre on Mull – the Beinn Chàisgidle Centre (Centre 2) (Table 5.1). The intrusions are predominantly ring-dyke structures of felsite and quartz dolerite/gabbro compositions and the screens between them are formed by earlier volcanics erupted into the South-East Caldera. The Loch Bà felsitic ring-dyke, together with granophyre bodies belonging to the Glen Cannel complex, truncate the ring intrusions and are associated with the third, and last, Loch Bà Centre (Centre 3).

The classic Mull Memoir (Bailey *et al.*, 1924) remains the main reference source for this site, although a field guide to the area has been published by Skelhorn (1969), which contains a more detailed petrological description of the intrusions than is presented here.

Description

The site is conveniently divided into three geographical sections (Fig. 5.17):

1. The stream section and valley sides of the Allt Molach from the head of Loch Sguabain at Ishriff to Sgulan Beag (NM 610 320).
2. The bleak upland plateau between Sgulan Beag and Beinn Chàisgidle.
3. Beinn Chàisgidle and northwards to Glen Cannel.

(a) The Allt Molach–Sgulan Beag

The section along the Allt Molach contains 14–15 separate, subvertical intrusions of felsite, granophyre and quartz dolerite/gabbro. These are cut by a suite of cone-sheets inclined towards either Centre 2 or Centre 3. Composite dykes are also present in this section. Bailey *et al.* (1924, p. 308) have recorded the following sequence of ring-dyke intrusions striking NE–SW across the stream from Loch Sguabain, the detail of which is not shown on the accompanying site map (but see Skelhorn, 1969, fig. 3): (No time sequence is implied here; sequence commences at Loch Sguabain.)

1. Glen More ring-dyke – gabbro merging to granophyre
2. Ishriff ring-dyke – granophyre

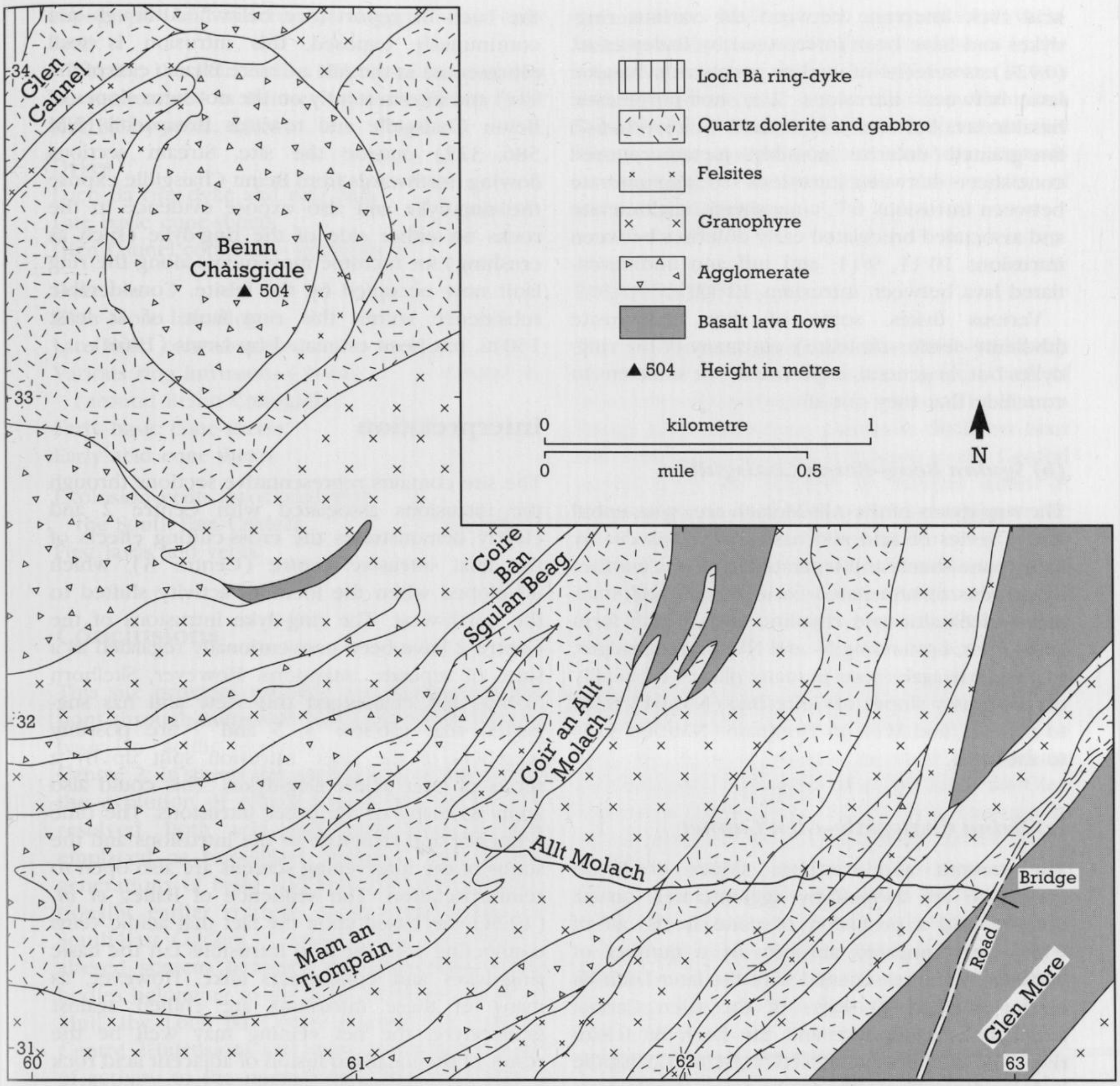


Figure 5.17 Geological map of the Allt Molach–Beinn Chàisgidle site (adapted from the British Geological Survey 'One Inch' map, Sheet 44, Mull).

3. Quartz gabbro cut by quartz + alkali feldspar segregation veins
4. Granophyre–feldspar-phyric felsite
5. Acidic quartz gabbro merging to granophyre
6. Xenolithic feldspar-phyric felsite
7. Quartz gabbro
8a. Granophyre
8b. Felsite
9. Quartz gabbro passing uphill into granophyre
10. Quartz dolerite possibly merging uphill into granophyre
11. Non-porphyritic granophyre
12. Feldspar-phyric granophyre
13. Vesicular quartz dolerite

Acidic net-veining is common in the basic intrusions which are often chilled against the acidic ones. Late basic cone-sheets cut most of the ring-dykes and also show net-veining by rheomorphic acidic material.

Discontinuous arcuate patches of basic and acid rock intervene between the various ring-dykes and have been interpreted by Bailey *et al.* (1924) as screens of: earlier porphyritic basaltic lava between intrusions 2/3; non-porphyritic basaltic lava between intrusions 3/4, 5/6, 4/6, 6/7; fine-grained dolerite possibly metamorphosed cone-sheets between intrusions 6/7; agglomerate between intrusions 6/7; cone-sheets, agglomerate and associated brecciated early dolerites between intrusions 10/11, 9/11; and tuff and undifferentiated lava between intrusions 12/13.

Various dykes, some of them composite (tholeiite–felsite–tholeiite), cut many of the ring-dykes but, in general, exposure is not sufficient to conclude that they cut all.

(b) Sgulan Beag–Beinn Chàisgidle

The ring-dykes of the Allt Molach area pass uphill into a series of acid and basic intrusions cut by many cone-sheets and separated from one another by screens of brecciated basic sheets, agglomerates and basaltic and rhyolitic lavas which form prominent, upstanding N- and NW-dipping ridges. Exposure is again poor in many places, especially on the grassy slopes of Coire Ban (NM 613 328) to the east, and Mam an Tiompain (NM 604 315) to the west.

(c) Beinn Chàisgidle–Glen Cannel

The summit and northern slopes of Beinn Chàisgidle are formed by agglomerates, quartz dolerite and a profusion of cone-sheets, all of which are truncated abruptly by a number of intrusive bodies associated with the later Loch Bà centre (Centre 3). Parts of the Glen Cannel peralkaline granophyre and the Loch Bà felsite ring-dyke are poorly exposed on Beinn Chàisgidle and in the valley. The granophyre forms low, smooth, striated knolls within the arcuate caldera fault intruded by the Loch Bà ring-dyke. It has a uniform appearance, weathering to a pale-pink colour and is moderately coarse-grained, consisting of perthitic orthoclase, quartz, aegirine-augite, magnetite and sphene. Occasionally the granophyre may appear spherulitic or more obviously granophyric as it is immediately south of the old burial ground at Gortenbuie (NM 599 345), just north of the site.

The Loch Bà felsite ring-dyke is arguably the most spectacular of its kind in the Province and was the first complete steep-sided ring-dyke to be described in the world. It is described in detail in the Loch Bà report (see below). Although not continuously exposed, this intrusion is well represented in the Allt a Choire Bhain (east of the site) and intermittently on the northern slopes of Beinn Chàisgidle and towards Breapadail (NM 586 328) outside the site. Stream sections flowing northwards from Beinn Chàisgidle expose the ring-dyke and also expose evidence in the rocks on either side of the ring-dyke (such as crushing) for tectonic movements along the ring fault now occupied by the felsite. Considerable subsidence within this ring fault, of at least 150 m, has been estimated by Lewis (1968).

Interpretation

The site contains representative sections through the intrusions associated with Centre 2 and clearly demonstrates the cross-cutting effects of the final intrusive centre (Centre 3), which developed when the focus of activity shifted to the north-west. The ring-dyke intrusions of the Centre 2 have been conventionally regarded as a suite of separate intrusions. However, Skelhorn (1969) has challenged this view and has suggested that gabbros 3, 5 and 7 are possibly members of the same intrusion split up by a series of later acidic ring-dykes. This could also apply to many of the other intrusions. The time sequence and structure of the intrusions and the status of the intervening screens are also open to reinterpretation. The sequence of Bailey *et al.* (1924) was based upon the fact that acidic veins connecting with the acid intrusions cut the basic ring-dykes and cone-sheets alike. However, as many of these intrusions are chilled against granophyre, the net veining may well be the result of the localized fusion of adjacent acid rock by the basic intrusions which generated rheomorphic magmas resulting in the acid back-veining of the basic rocks. Many of the late basic cone-sheets are also back-veined and chilled against the intrusions, although others apparently truncate the veining, indicating several distinct episodes of cone-sheet emplacement.

Skelhorn (1969) has thrown some doubt on the interpretation of some of the granophyres as ring-dyke structures; for example, intrusion 4 has subvertical contacts which dip at 60°–90° towards Centre 2 and should perhaps be considered as a cone-sheet. As exposure is rather poor in some parts of the site, this problem is not fully resolvable but the relationships between topography and outcrop do suggest steep contacts.

Finally, the Palaeocene history of the site can be summarized as follows (after Skelhorn, 1969 and Bailey *et al.*, 1924):

Dykes Loch Bà ring-dyke and ring fault Late basic cone-sheets Glen Cannel complex – granophyre	Centre 3
Dykes Glen More Intrusion Late basic cone-sheets Various ring intrusions (2–14) (around Beinn Chàisgidle) Early basic cone-sheets Early acid cone-sheets	Centre 2
Explosion vents associated with the South-East Caldera First lavas and vents	Centre 1

Conclusions

This site provides valuable and informative sections through numerous intrusions of dominantly basic to acidic compositions associated with Centre 2. It shows the complexity of the centre, the evolution of which has, as yet, to be fully resolved. Both acid and basic magmas were emplaced as ring-dykes, together with several generations of basic and acid cone-sheets. Additionally, earlier volcanic rocks erupted into the South-East Caldera (Centre 1) are preserved as altered screens between the ring-dykes. Acidic bodies belonging to the final intrusive centre on Mull, the Loch Bà Centre (Centre 3), truncate Centre 2 intrusions and mark a shift in the focus of activity to the north-west. Clear examples of rheomorphic acid net-veining occur where basic intrusions cut and chill against lower-melting-point acidic rocks.

LOCH BÀ–BEN MORE

Highlights

The Loch Bà Felsite ring-dyke is the international type example of a ring-dyke intruding arcuate faults within which central subsidence has taken place. The ring-dyke and the hybrid intrusions provide evidence that acid and basic magmas coexisted on Mull and the compositional variation shown by porphyritic glassy inclusions in the ring-dyke suggests that the Mull Centre 3 was underlain by a zoned magma chamber. There is a coastal section across the Mull dyke-swarm axis where 12% crustal dilation has been demonstrated. These features make this a site of international importance.

Introduction

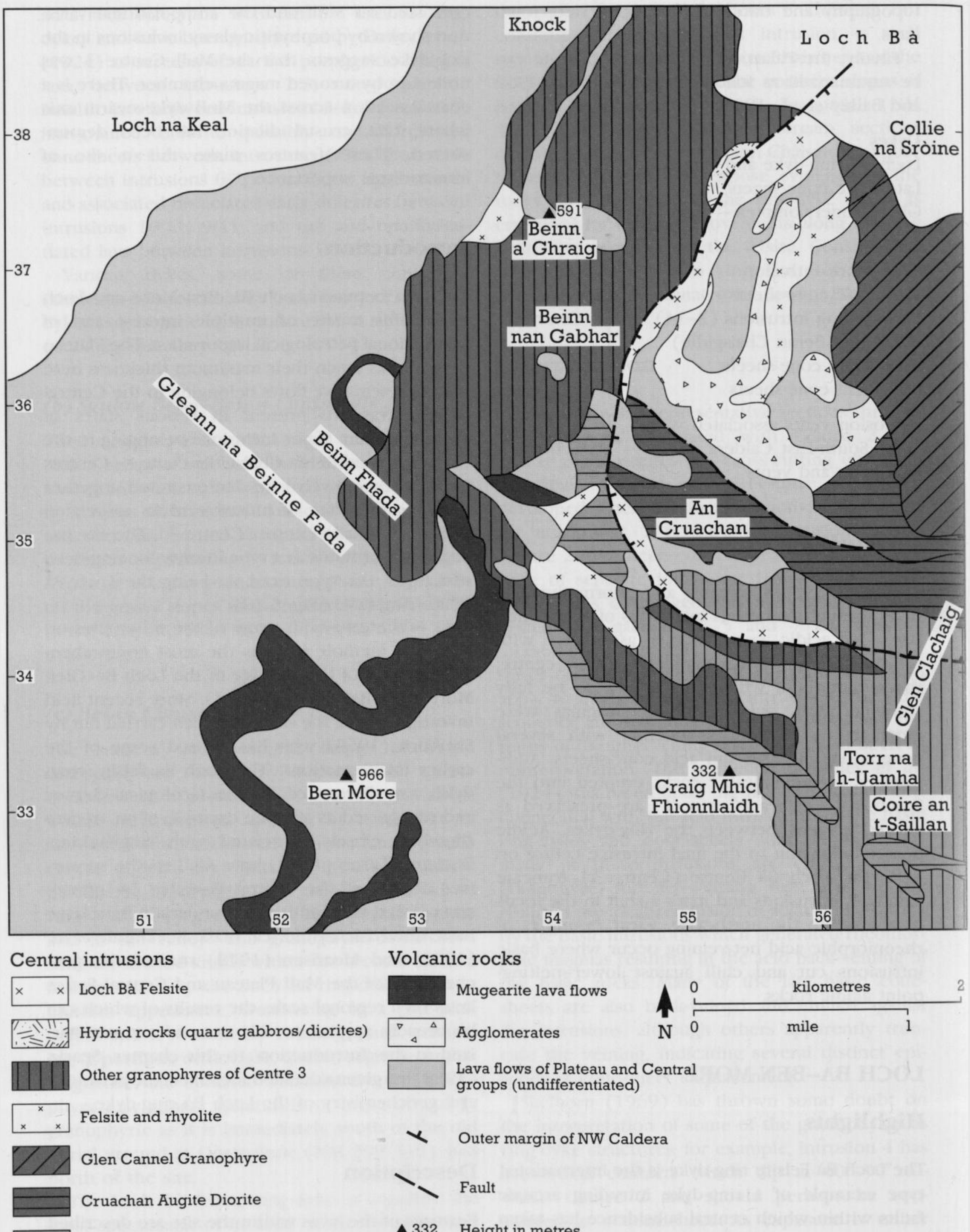
The area between Loch Bà, Ben More and Loch na Keal is a site of multiple interest and of international petrological importance. The Plateau Group lavas attain their maximum thickness here and representative flows belonging to the Central Group lavas are present in various states of metamorphism. Major intrusions belonging to the Glen More and Beinn Chàisgidle centres (Centres 1 and 2 respectively) are demonstrated, together with the full suite of intrusive rocks associated with the Loch Bà Centre (Centre 3). The site has international status as a type locality for ring-dyke structures, the type example being the Loch Bà felsite ring-dyke (Fig. 5.18).

As is the case with many of the other sites on Mull, the Memoir remains the most comprehensive account of the geology of the Loch Bà–Glen More area (Bailey *et al.*, 1924). More recent field investigations in the site have been carried out by Skelhorn (1969) who has revised some of the earlier interpretations. The Loch Bà felsite ring-dyke was discovered by the Geological Survey and recognized as a prime example of an arcuate ring-dyke closely associated with ring-faulting. Bott and Tuson (1973) have studied the subsurface extent of the central complex by gravity surveys and showed it to be underlain by a large basic/ultrabasic cylindrical mass. Beckinsale *et al.* (1978) and Morrison (1978) studied the geochemistry of the Mull Plateau and Central Series lavas on a regional scale, the results of which can be broadly applied to this site and are summarized in the 'Introduction' to this chapter. Sparks (1988) has given a detailed account of the petrology and geochemistry of the Loch Bà ring-dyke.

Description

Features of the lavas within the site are described first; these are followed by an account of central complex intrusions.

Isle of Mull



Knock
Loch Bà
Loch na Keal
Collie na Sròine
591
Beinn a' Ghraig
Beinn nan Gabhar
Gleann na Beinne Fada
Beinn Fhada
An Cruachan
Glen Clachaig
966
Ben More
332
Craig Mhic Fhionnlaidh
Torr na h-Uamha
Coire an t-Saillan
38
37
36
35
34
33
51
52
53
54
55
56
Central intrusions
Loch Bà Felsite
Hybrid rocks (quartz gabbros/diorites)
Other granophyres of Centre 3
Felsite and rhyolite
Glen Cannel Granophyre
Cruachan Augite Diorite
Quartz Gabbro
Corra-bheinn Gabbro
Volcanic rocks
Mugearite lava flows
Agglomerates
Lava flows of Plateau and Central groups (undifferentiated)
Outer margin of NW Caldera
Fault
332 Height in metres
0 kilometres 2
0 mile 1
N

(a) The lavas

The Plateau Group lavas (Table 5.2) attain their maximum thickness of over 900 m on Ben More (NM 526 331). They lie within the limit of pneumatolysis around the central complex and the alteration is most severe in the east of the lava outcrop, where the flows adjoin the major intrusions. As a consequence, basalt flows in this area no longer carry fresh olivine and generally contain epidote in amygdales and veins. Trap featuring, reflecting the different weathering properties of the resistant flow centres and the crumbling, amygdaloidal tops, is still discernible and a few recognizable boles are present, attesting to subaerial weathering between successive eruptions.

The lowest division of the Plateau Group, the Survey's Staffa Type basalts, do not crop out in the site as the gentle easterly dip of the lavas has taken the earlier flows below sea-level. The lowest flows preserved are mildly alkaline to transitional basalts which are either aphyric or contain olivine pseudomorphs. These are succeeded by pale-weathering, alkali-olivine basalts belonging to the Survey's Pale Group of Ben More which contains a prominent horizon of mugearite and feldspar-phyric basalt near the base (Table 5.2). The Pale Group forms the upper part of Ben More and isolated outcrops cause the north-western terminations of the ridges of Beinn Fhada and Bheinn a' Ghraig (NM 542 373).

Many of the flows are amygdaloidal and the amygdale minerals are of considerable interest, both in their own right and also in studies concerned with the hydrothermal effects associated with the emplacement of the central complex. A full description of these minerals is contained in the Memoir and zeolite zones in the lavas have been delineated by Walker (1971). Numerous basaltic dykes and sheets, and some of felsite and craignurite compositions, cut the Plateau Group lavas.

The basaltic lavas of the overlying Central Group are exposed outside the central complex and as isolated masses among the intrusions of the complex. South of Creag Mhic Fhionnlaidh (NM 554 333) these lavas are separated from the Plateau Group to the west by a fault and are terminated to the north and east by intrusions associated with Centre 2. Large, detached masses of Central Group lavas occur on the slopes west of Glen Clachaig, within the North-West or Late Caldera of Centre 3 (Table 5.1). Smaller masses are preserved as screens between the intrusions of Centre 2. The lavas to the south of Creag Mhic Fionnlaidh, outside the caldera, are cut by early acid and basic cone-sheets whereas the flows preserved within the caldera are virtually free from cone-sheets. A few basic dykes also intrude the lavas. The Plateau Group and Central Group lavas to the west of the central complex are pierced by volcanic vents which, in turn, are cut by early basic cone-sheets, the Corra-bheinn gabbro and granophyre veins. The largest vent (at NM 558 324) is about 700 m in length. The agglomerate in this and other smaller vents contains fragments of Moine gneiss (Fig. 5.19). Gneiss fragments occur in vents outside the calderas, but are not found in the numerous agglomerates within these structures (Bailey *et al.*, 1924, fig. 29) where subsidence has presumably brought the gneisses and schists below the level at which the magmas were liable to rapid vesiculation and explosion.

Towards the later, major intrusions of the central complex, all lavas show progressive effects of thermal metamorphism. These changes are particularly well demonstrated by alteration in the low-temperature amygdale mineral assemblages and successively higher-temperature phases are found as the later intrusions are approached. The lavas also show signs of thermal metamorphism and have been hornfelsed up to pyroxene-granulite facies near to the intrusions.

(b) The Central Complex

Three major intrusions of somewhat uncertain age occupy a 2-km wide, NW-trending tract of ground extending from the south-eastern extremity of the site to the southern slopes of Beinn Fhada and Beinn nan Gobhar (NM 538 317). These bodies separate the lavas from the intrusions of Centre 3 and form the margin of the Central Complex (Fig. 5.18).

The Corra-bheinn Gabbro is one of the intrusions in the extreme south-east of the site, forming the eastern slopes of Sleibhte-coire. Its western and southern contacts are intrusive against Central Group lavas, vent agglomerate and (outside the site) the Derrynaculen Granophyre. To the north-east it is split up by late, basic cone-sheets and probable continuations of the Glen

Figure 5.18 Geological map of the Loch Bà–Ben More site (adapted from the British Geological Survey 'One Inch' map, Sheet 44, Mull).

Figure 5.19 Vent agglomerate containing fragments of Moine gneiss (NM 558 324). Loch Bà–Ben More site, Mull. (Photo: C.J. MacFadyen.)

More ring-dyke. The Corra-bheinn Gabbro is probably an early intrusion of Centre 2 (Skelhorn, 1969; but see Bailey *et al.*, 1924). The gabbro exhibits rhythmic layering, igneous lamination and other structures characteristic of cumulate rocks. Layers dip to the north-east between 15° and 75° (but averaging 40°) towards Centre 2. Skelhorn (1969) has identified nine major rhythmic units in the gabbro to the south-west of Coir' an t-Sailein (NM 566 326) and recorded horizons of tabular pyroxene-granulite xenoliths, some of which disrupt the layering which is also banked up against some xenoliths (Skelhorn, 1969).

An interrupted chain of composite quartz-gabbro masses, changing internally to granophyre towards their tops, extends from Coir' a' Mhàim (NM 580 318) to the south of the site, through Coir' an t-Salein and Torr na h-Uamha (NM 560 332) and terminates on Beinn Fhada. These are probably continuations of the Glen More ring-dyke of Centre 2 (Bailey *et al.*, 1924) and cut the Corra-bheinn Gabbro and the lavas north of Creag Mhic Fhionnlaidh.

The Cruachan Augite Diorite intrusion occurs within and outside the Loch Bà felsite. It is cut by numerous late, basic cone-sheets and, although its outcrop is restricted to narrow screens between the sheets, it is mapped as an entity. The composition of the intrusion becomes progressively more acidic upwards and the highest parts are granophyre or felsite rather than diorite. The mass is assigned to Centre 1 and is probably the equivalent of the Gaodhail Augite Diorite (Bailey *et al.*, 1924), although Skelhorn (1969) has suggested that it could be the earliest member of Centre 3.

The main interest of this site derives from the exposure of the western quadrant of Centre 3, the Loch Bà Centre. A complete and unique suite of intrusions and associated rocks is demonstrated and Skelhorn (1969) has revised the sequence of events for the evolution of this centre as follows:

6. The Loch Bà Felsite ring-dyke
5. The hybrid masses of Sron nam Boc and Coille na Sroine
4. The Beinn a' Ghraig Granophyre
3. The Knock Granophyre
2. The early Beinn a' Ghraig Granophyre and Felsite
1. The Glen Cannel Complex: This consists of an early quartz dolerite plug, vents, intrusive rhyolites, and a late felsite and granophyre.

A mass of pyroxene granophyre dominates the Glen Cannel complex and this forms a low dome elongated along a north-west to south-east axis. It thermally alters a felsite mass (also part of the complex) on the south side of Glen Clachaig. The granophyre has yielded a Palaeocene age (58 ± 3 Ma, Beckinsale, 1974). To the west and south of Glen Clachaig, two quartz-dolerite plugs belonging to the complex have been metamorphosed by the granophyre. Other members of the complex occupy ground between Allt Beithe and Coille na Sroine and include agglomerate-filled vents into which a rhyolite dome has been intruded, along with tuffisite dykes containing fragments of Moine schist (which the agglomerates hereabouts do not, see above). These small masses have intruded Central Group lavas.

The early granophyre and felsite of Beinn a' Ghraig is exposed on the ridge immediately east of the summit. It is chilled on both its east and west contacts against Plateau Group lavas at the base of the Pale Group of Ben More, and a screen of lavas occurs between the Beinn a' Graig and Knock Granophyres at its eastern tip.

The Knock Granophyre has a dyke-like outcrop 100–300 m wide, extending north-eastwards for 3 km from the western edge of the Beinn a' Ghraig ridge. The granophyre characteristically develops shearing and cataclastic textures which have been attributed to the emplacement of the Beinn a' Ghraig Granophyre. These two granophyre intrusions are separated by a particularly clear example of a screen: this is composed of highly metamorphosed basaltic lavas and cone-sheets, it extends for about 3 km, has a vertical range of over 500 m and a width of between 3 m and 100 m. The screen rocks have been recrystallized to fine-grained granulites consisting of plagioclase, augite, hornblende and magnetite and the adjoining granophyres have been contaminated with basic material derived from the screen. Screens are abundantly developed in the Mull Central Complex and elsewhere in the BTVP: this example is one of the clearest since the topography of the site, coupled with reasonable exposure, shows the three-dimensional form to best advantage, and the rocks forming the screen have been thoroughly altered by the adjoining igneous intrusions.

A small mass of hybrid rocks consisting of acid-veined quartz gabbros and diorites lies between the Beinn a' Ghraig Granophyre and the Loch Bà Felsite south of Coille na Sroine (at about NM 553 376). The hybrids are chilled against the Beinn a' Ghraig Granophyre which has been partially melted and back-veins the chilled, marginal hybrid rocks (Rast, 1968).

The site contains the western quadrant of the Loch Bà Felsite ring-dyke (Fig. 5.20), including the historic exposures where its association with a fault and its annular outcrop were first described. The ring-dyke is well exposed and both its outer and inner contacts can be seen to dip outwards at angles of 70°–80°. Between Loch Bà and Beinn nan Gabhar the felsite separates the Beinn a' Ghraig Granophyre from various members of the Glen Cannel Complex and Central Group lavas. On the western slopes of Beinn nan Gabhar, shortly after 'entering' the intrusions of Centre 2 cut by a profusion of late basic cone-sheets, the felsite fails. However, the fault into which it was intruded can be traced southwards until, after a gap of several hundred metres, the felsite reappears and can be traced across the slopes of An Cruachan and the River Clachaig. On the south side of the river its outcrop narrows and disappears once more just beyond the site boundary.

Compositionally, the ring-dyke varies from an apparently flow-banded rhyolite to felsite and typically contains phenocrysts of alkali feldspar and mafic minerals. A particularly striking feature is the common occurrence of dark, fine-grained, elongate wispy xenoliths. The basic character of the xenoliths was first reported by Blake *et al.* (1965); however, Sparks (1988) has shown that these dark, aphanitic rocks vary continuously in composition from basaltic andesite to andesite, dacite and rhyolite. The phenocrysts in the enclosing rhyolite include plagioclase (An_{32} to An_{24}), sanidine, hedenbergite, fayalite, magnetite, ilmenite, apatite and zircon. The phenocrysts are often aggregated; however, it is unusual to find hedenbergite and fayalite in the same cluster. The dark wispy inclusions are usually aphyric; where phenocrysts occur they include plagioclase (An_{65} to An_{30}), a continuous range of clinopyroxenes from augite to pure hedenbergite, pigeonite, magnetite, ilmenite and rare apatite (Sparks, 1988, p. 446). The significance of this range of phenocrysts, and particularly the compositional spectrum of glassy inclusions, is discussed subsequently.

The site includes an excellent section through the axis of the Mull dyke swarm on the southern shores of Loch na Keal, to the west of Eilean Feoir (NM 531 389). The majority of the dykes are basaltic and many are multiple, comprising as

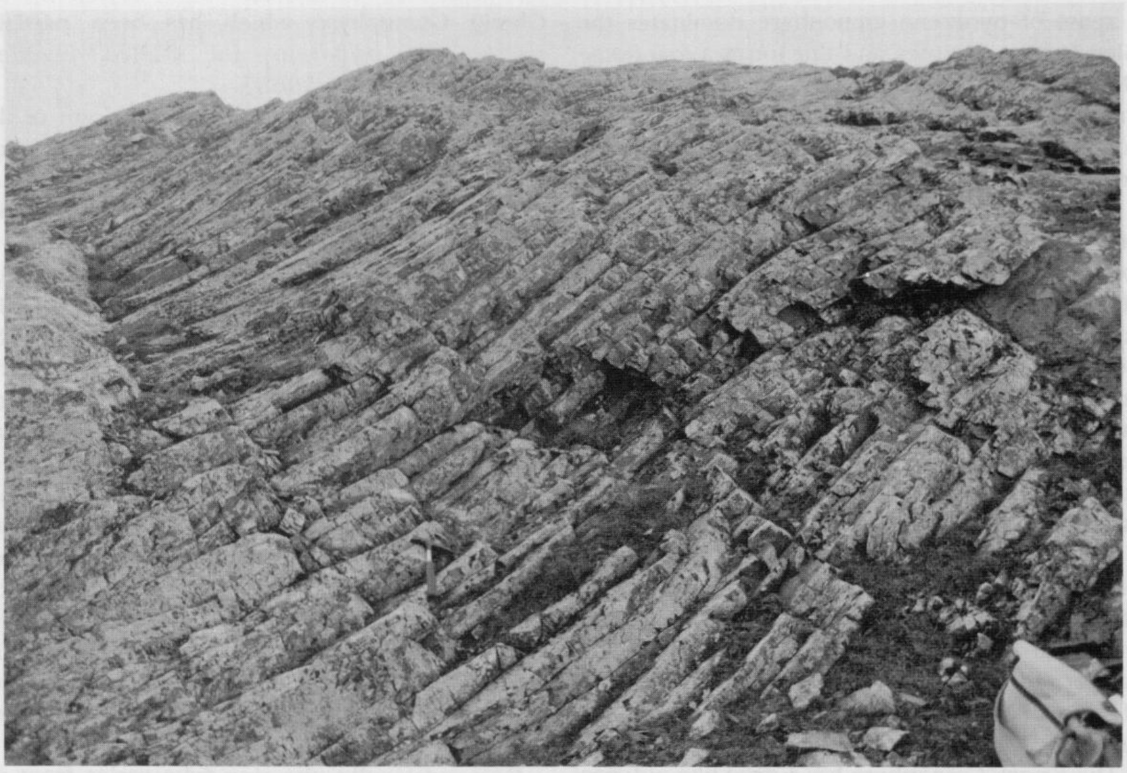


Figure 5.20 Columnar jointing in the Loch Bà Felsite ring-dyke (NM 552 371). Loch Bà–Ben More site, Mull. (Photo: C.J. MacFadyen.)

many as four or five intrusions, which may show cross-cutting relationships. Some 142 dykes have been recorded, with an aggregate thickness of 249 m along a 2-km traverse of the Loch na Keal shore (Bailey *et al.*, 1924). The average dyke thickness is 1.8 m and a total crustal dilation of 12.4% has been calculated. The dykes show the same effects of alteration as the lavas within the zone of pneumatolysis, although often to a lesser extent.

Interpretation

The Loch Bà–Ben More site supports some of the most spectacular geology and scenery on Mull, and is arguably the most important locality as it demonstrates representative rocks from every major Tertiary igneous event on the island. Centre 3 is fully represented and marks a final shift of intrusive activity to the north-west as a possible result of the elongation of the magma chamber in this direction, parallel to the axis of the regional dyke swarm (Skelhorn, 1969). According to Skelhorn, the Centre 2 Glen More ring-dyke, represented in this site by the quartz-gabbro masses, is the earliest intrusion to reflect this elongation. The arcuate, fragmented ring-dykes of Centres 1 to 3 have intricate intrusive relationships from which the history of the complex is determined. They also exhibit a large compositional range from acid to basic rock types. Acidic intrusions, despite their wide aerial extent, represent only a small proportion of the total igneous mass of the Mull central complex, as shown by the gravimetric work of McQuillin and Tuson (1963) and Bott and Tuson (1973). A gravity survey of the Glen Cannel granophyre revealed that it is no more than 1220 m thick and must have a sheet-like form. Walker (1975), however, suggested that the granophyre mass once formed the upper part of a large body of acid magma which had migrated into a curved, flange fracture and thus caused the north-west transfer of the igneous centre to the Loch Bà area, and that further portions of this acid magma migrated to form the younger Knock, Beinn a' Ghraig and Loch Bà intrusions.

The site provides evidence which supports the view that acid and basic magmas probably coexisted in a compositionally zoned magma chamber beneath Mull, and that this mixed magma was injected into fractures associated with ring-faulting and central block subsidence. The Coille na Sroine hybrids provide good evidence for magma mixing, as well as the rheomorphic generation of acid melts. Within the magnificently exposed Loch Bà felsite ring-dyke, there is also excellent evidence for coexisting magmas of contrasted compositions: the dark, glassy inclusions in the felsite (which make up about 15% of the rock) often have lobate, cauliflower-shaped margins and are frequently wisp-like and convoluted. Marshall and Sparks (1984) considered that the inclusions were liquid when they were incorporated into the felsite magma and they explained the heterogeneous, mixed-magma intrusion by envisaging incomplete mechanical mixing between different components in a vertically zoned magma chamber, triggered off by subsidence of the central block. Subsequently, Sparks (1988) made a detailed examination of the rhyolite and inclusion compositions, together with the compositions of phenocrysts in both. The really striking feature to emerge is the compositional range of the glassy inclusions and their phenocrysts (which appear linked by crystal–liquid equilibria). The mafic glasses vary continuously in composition from basaltic andersite through to dacite and rhyolite suggesting that the Loch Bà centre was underlain by a zoned magma chamber, capped by rhyolite magma. Crystals were precipitating from all levels of this chamber, which covers the compositional range of the Middle and Upper zones of the Skaergaard Intrusion in East Greenland (Wager and Deer, 1939; Wager and Brown, 1968; McBirney, 1975), when this structurally ordered sequence was catastrophically disrupted to form the heterogeneous Loch Bà ring-dyke. Sparks' (1988) discoveries and interpretation have obvious implications for the subsurface geology of Mull – the gravity high (Bott and Tuson, 1973; Bott and Tantrigoda, 1987) indicates subsurface, dense, gabbroic rocks which may include a Skaergaard-like body. They also shed further light on the possible mode of crystallization of layered basic intrusions: the evidence from Loch Bà suggests that the compositionally contrasted layers could have built up essentially simultaneously, rather than sequentially as envisaged in the classic models of layering (for example, Wager and Brown, 1968). Sparks (1988) regards the felsite as an intrusive, banded, rhyolitic, welded tuff.

The Loch Bà site provides sound evidence for the frequent suggestion that emplacement of the Mull Central Complex (and others) has involved subsidence of a central block, or blocks, bounded by arcuate ring-faults. Richey (1932) calculated that the downthrow on the block circumscribed by the Loch Bà ring-dyke and associated fault was about 1000 m. Lewis (1968), however, pointed out that much of the displacement could have occurred on two NW-trending faults which transect the block and suggested that the maximum downthrow on the ring-fault, now occupied by felsite, was only about 150 m.

Conclusions

The thick succession of basalt lavas on Ben More and surroundings has been extensively altered by the later intrusions of the central complex, with the result that original minerals (for instance, olivine) were replaced and new ones (for example epidote, chlorite) formed by circulating heated waters and gases. The site lies astride the Mull dyke swarm which locally produced crustal dilation of over 12%; the dykes mostly pre-dated the central complex and thus also are generally altered. A variety of basic, granitic and hybrid intrusions belongs to the youngest centre, Centre 3 of Mull. They provide compelling evidence for the mingling of basic and acid magmas. The Loch Bà felsite ring-dyke is the type example of a ring-dyke. It intruded along a ring-fault bounding a central block which may have subsided by as much as 1 km in aggregate. The ring-dyke intrusion provides spectacular evidence for the explosive disintegration of a crystallizing, zoned magma chamber in which rhyolite liquid passed by continuous compositional variation downwards through intermediate compositions to basaltic liquids. These discoveries are of major scientific importance as they provide a glimpse of the details of the dense rocks known from gravity surveys to underlie Mull; they are of more general importance since they suggest ways in which layered igneous intrusions may crystallize.