British Tertiary Volcanic Province

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Chapter 6

Isle of Arran

INTRODUCTION

Arran has long been known as an area of complex and diverse geology and outstanding natural beauty (Fig 6.1). It is the most accessible of the Scottish Cenozoic igneous centres and is used extensively as a training ground for geologists. Interest in the geology of Arran goes back over more than 200 years to the writings of Pennant (1774), Hutton (1795), MacCulloch (1819), Boué (1820) and others, but the first detailed survey of the island, other than that by Ramsay (1841), was not carried out until the start of the present century by Gunn (1903) and this was subsequently completed by Tyrrell (1928, reprinted 1987). The sites selected as illustrating Arran's varied igneous geology are indicated on Fig. 6.2.

The Tertiary igneous interest is concerned mainly with the varied intrusive rocks; remnants of a former lava cover now only exist as subsided blocks within the Central Igneous Complex. The largest body of intrusive rocks is formed by the granites of the scenically spectacular Northern Mountains (Fig. 6.1). Two distinct biotite granites; one a coarse-grained rock forming the outermost parts and the other a younger, finer-grained rock within the first, are present (see Harker *in* Gunn, 1903; Tyrrell, 1928; Flett, 1942). These two units comprise the Northern Granite. Their significance to the British Tertiary Volcanic Province (BTVP) as a whole lies in the fact that they demonstrably pre-date the Central Ring Complex and, additionally, that emplacement of the outer granite caused updoming and faulting of the enveloping Palaeozoic sediments and Dalradian schists (Bailey, 1926; Woodcock and Underhill, 1987; England, 1988, 1990). Clear examples of the distortion of the country-rock envelope during granite emplacement are often difficult to demonstrate in the Province although predicted by Walker (1975); special significance thus attaches to the north Arran granites. The Glen Catacol site has been selected to represent both granites, their relationships to one another, to the country rocks and to later minor intrusions.

The Central Igneous Complex, between Brodick and Blackwaterfoot, is well known as an area of highly variable geology (Necker de Saussure, 1840; Ramsay, 1841; Gunn, 1900, 1903; Tyrrell, 1928). Its true complexity was realized by King

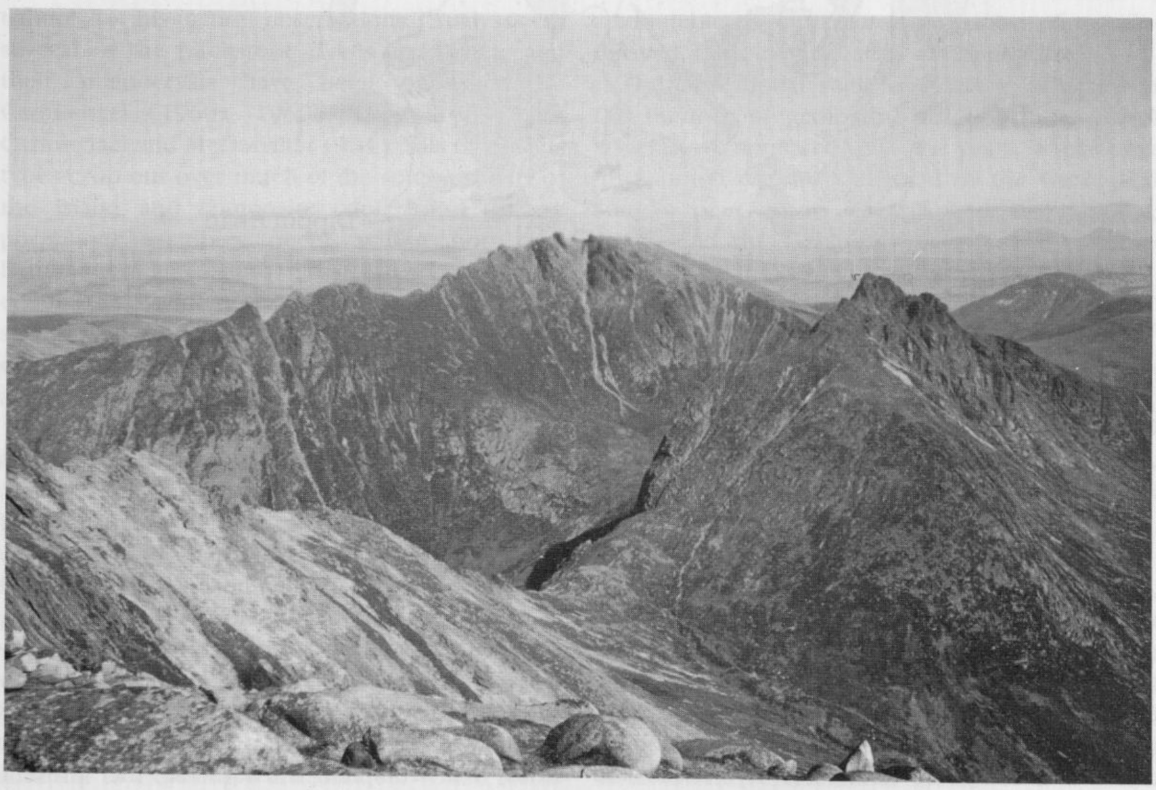


Figure 6.1 The Northern Granite Mountains of north Arran. Cir Mhor, Arran. (Photo: C.H. Emeleus.)

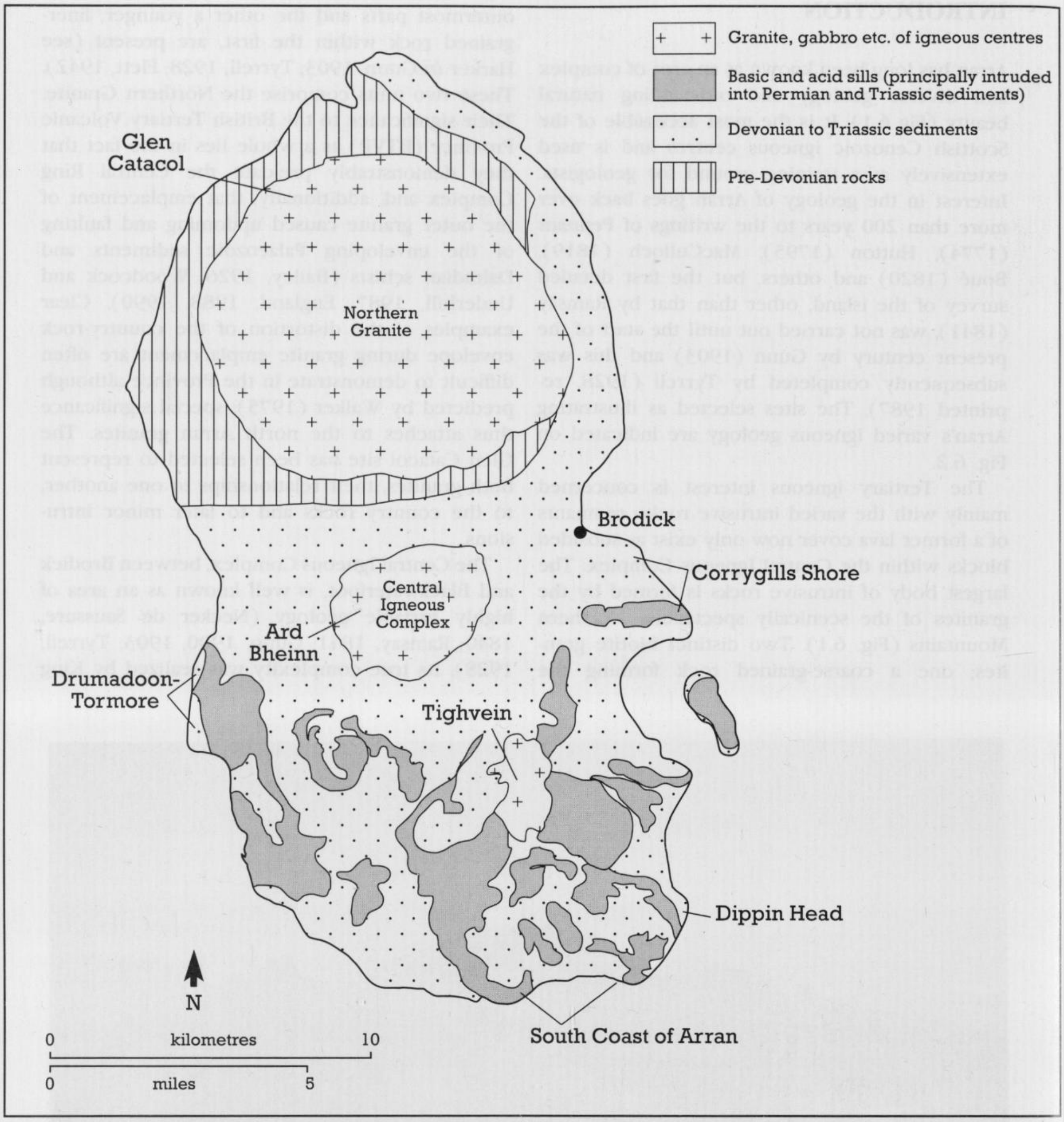


Figure 6.2 Map of the Isle of Arran, showing localities mentioned in the text.

(1955) who demonstrated that the varied rock types were grouped round four discrete foci, each interpreted as the eroded remains of a volcanic cone. These volcanoes built up on the floor of a caldera. Within this caldera there are large, subsided masses, the remains of Palaeocene basalt and Mesozoic sediments by which the complex is relatively dated. The complex thus preserves features of a comparatively high level of volcanicity that may be lacking, or ill exposed, in the other central complexes of the Province. The 'volcanic' part of the complex is more or less encircled by granites, sparse gabbros and some remarkable gabbro–granite hybrid rocks. The strata the complex intrudes at the present erosion level range from Devonian to Permian.

These sediments were already domed around the Northern Granites and were subsequently cut and tilted by the Central Ring Complex, which thus establishes the Northern Mountains granites as an early event in the Tertiary intrusive sequence of Arran. The site chosen to represent the features of the Central Ring Complex is the Creag an Fheidh–Beinn na h-Uaimh–Ard Bheinn area, simply denoted as the Ard Bheinn site (see below).

Despite the interest generated by these major intrusions, it is perhaps the minor intrusions of Arran which lend it most significance in the Province. The major Arran dyke swarm is magnificently exposed on the southern coast of the island, which cuts across the NNW–SSE-trending basaltic dykes from Bennan Head eastwards to Kildonan and beyond. This shore section, the South Coast site, has been chosen to represent this feature of the BTVP.

Dykes also figure prominently in the west coast site at Drumadoon and Tormore. These dykes are composite (dolerite + felsite + pitchstone) intrusions which, although present elsewhere in the Province, are especially prevalent and well exposed in Arran; having been described in the classic works of Judd (for example, 1893), they are usually referred to as 'Judd's Dykes' as a tribute to his acute observations. Analyses of several of the pitchstone dykes and sheets and their phenocrysts have been published by Carmichael (1960a, 1960b, 1962, 1963) and Carmichael and McDonald (1961). Sills of various types crop out over much of the southern part of the island and composite (dolerite + quartz porphyry) examples occur within both the Drumadoon and South Coast sites. These sills encompass a wide range of the compositions and structures associated with such bodies (for example, Tyrrell, 1928; Rao, 1958, 1959; Rogers and Gibson, 1977; Kanaris-Sotiriou and Gibb, 1985) and greatly enhance the significance of these sites. Basic sills are also a prominent feature and are either olivine-analcite dolerites (crinanites) or quartz dolerites. They form important members of the Dippin Head and Corrygills Shore sites. Recent studies on the Dippin Head sill (Henderson and Gibb, 1977; Gibb and Henderson, 1978a, 1978b) have added valuable information on the petrogenesis of the mildly alkaline basalt magma type which characterizes much of the Province. The Corrygills Shore site, in addition to exposing a crinanite sill which forms part of a possible cone-sheet system around Lamlash Bay (Tomkeieff, 1961), contains numerous other minor intrusions including the well-known Corrygills Pitchstone. The Tertiary igneous succession on the Isle of Arran is summarized in Table 6.1.

The Tertiary igneous rocks of the island have been the subject of geophysical studies and radiometric age determinations. The Northern Granite and Central Igneous Complex are the site of a positive Bouguer gravity anomaly, indicating that both centres are probably underlain by a considerable body of dense, mafic rock (McQuillin and Tuson, 1963). Palaeomagnetism investigations of the Arran dykes by Dagley *et al.* (1978) showed the majority to have reversed magnetization, although a substantial number of the dykes on the north-east coast showed normal magnetization; some of the sills and the Northern Granite sites also yielded normal magnetization. Age determinations on the Northern Granite range from *c.* 60 Ma (Dickin *et al.*, 1981) to *c.* 58 Ma (Evans *et al.*, 1973); a Palaeocene age (*c.* 58 Ma) was also obtained from the Central Igneous Complex (Evans *et al.*, 1973). Geochemical investigations by Dickin *et al.* (1981) included isotopic determinations on a variety of the Tertiary igneous rocks. From these the authors concluded that the isotopic variation is attributable to crustal contamination of mantle-derived, basic magma after differentiation.

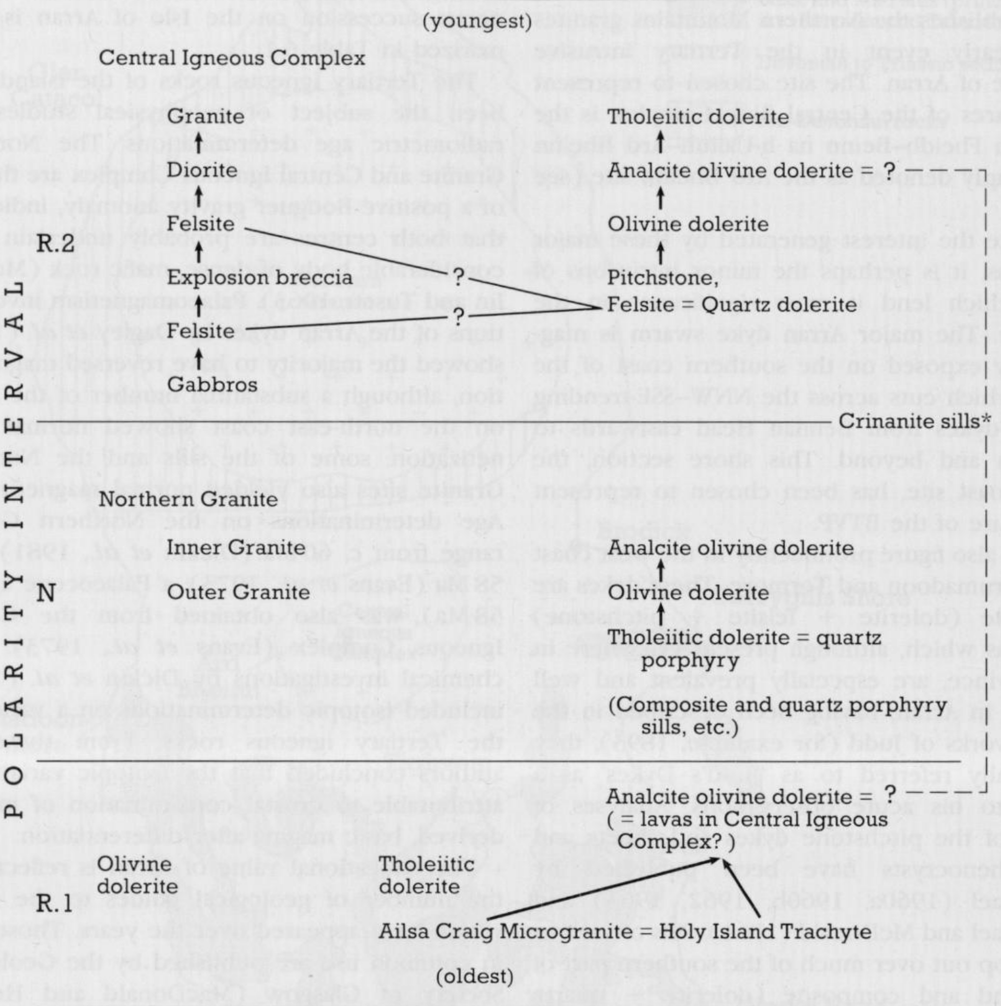
The educational value of Arran is reflected in the number of geological guides to the island which have appeared over the years. Those now in common use are published by the Geological Society of Glasgow (MacDonald and Herriot, 1983) and the Geologists' Association (McKerrow and Atkins, 1985).

ARD BHEINN

Highlights

This site exposes some of the best evidence for the eroded remains of a caldera in the British Tertiary Volcanic Province. Collapsed blocks of basalt lavas and fossiliferous Mesozoic rocks have been preserved within the caldera; the mapping of lavas and volcaniclastic rocks has shown that several volcanic cones grew on the caldera floor.

Table 6.1 Tertiary igneous succession in the Isle of Arran (after Hodgson *et al.*, 1990, figure 8)



R.1, R.2 = reversed polarity intervals, N = normal polarity interval.
*Crinanite sills could be in either R.1 or R.2.
Arrows indicate probable sequence.

Introduction

The Ard Bheinn site demonstrates the characteristic features of the Central Igneous Complex of Arran. A large variety of rocks is exposed in the complex which are of both intrusive and effusive origin; they are compositionally highly variable. These include agglomerates, gabbros, felsites and granites which crop out as arcuate masses. In addition, blocks of Mesozoic sediments and Tertiary lavas are preserved within the complex. Volcanic rocks of intermediate and acidic composition are associated with several eruptive centres which developed on the caldera floor.

The foundations for our understanding of the geology of this complex area can be attributed to the Geological Survey (Peach *et al.*, 1901; Gunn, 1903; Tyrrell, 1928). These workers recognized the complex, volcanic nature of the area and demonstrated a Tertiary age by the identification of *remanié* blocks of Mesozoic sediments and similarities to ring intrusions found elsewhere in the BTVP. However, credit for our present detailed knowledge of the site is owed to King (1955) who mapped the area in considerable detail. King demonstrated that there were four, independent but overlapping, centres of volcanic activity in the Ard Bheinn area situated within a subsidence caldera (1955, Figs 1 and 2).

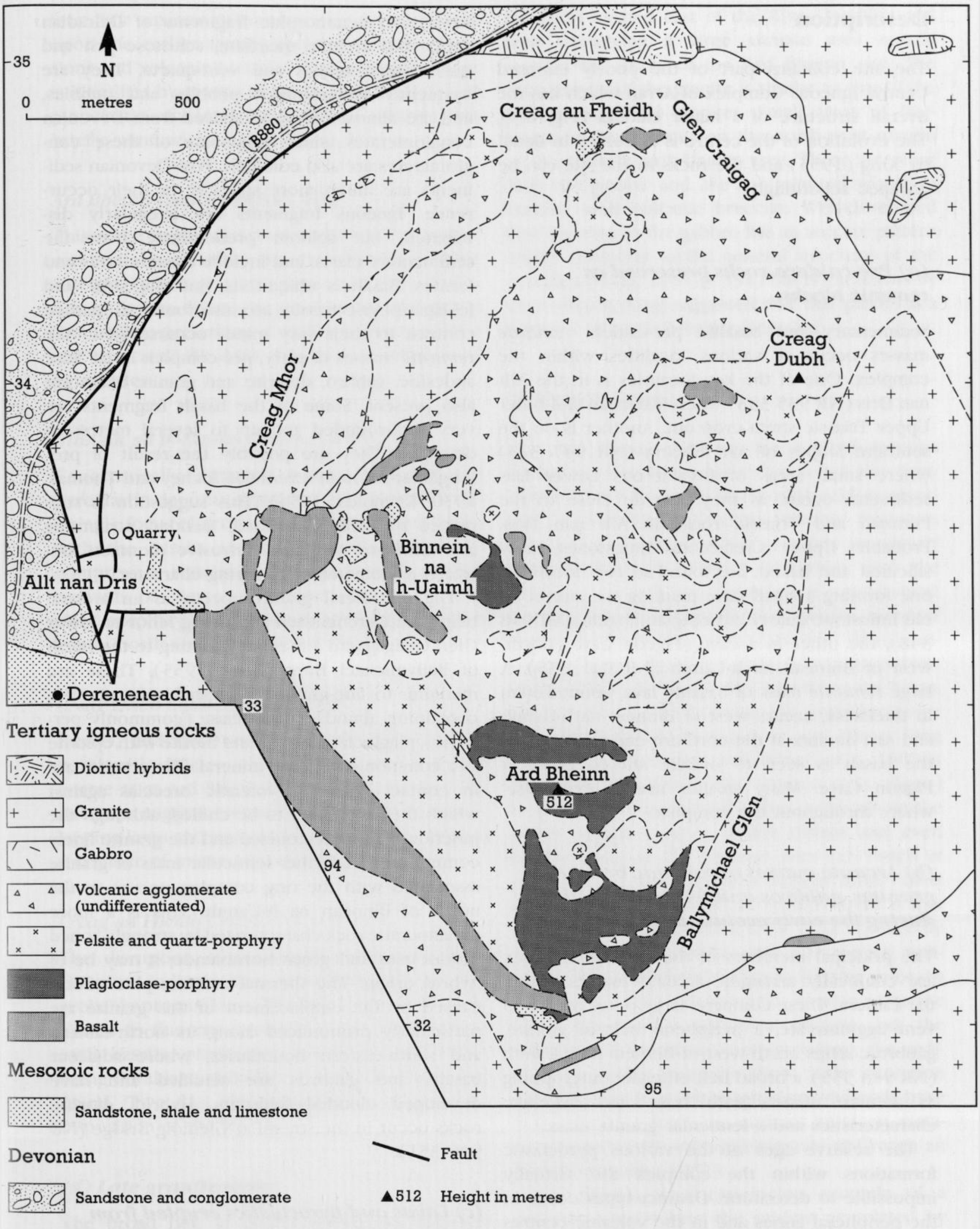


Figure 6.3 Geological map of the Ard Bheinn site (adapted from King, 1955, plate XVI).

Description

The site contains part of the poorly exposed Central Igneous Complex of Arran which has the overall structure of a major caldera (Fig. 6.3). The evolution of the centre is discussed in detail by King (1955) and the rocks in the site can be grouped accordingly:

(a) Pre-caldera rocks preserved as remanié *blocks.*

Sedimentary and basaltic pre-caldera *remanié* masses occur at various localities within the complex. One of the key localities is in the Allt nan Dris (NR 935 333) where Rhaetian and other Upper Triassic strata crop out. Another is on the southern slopes of Ard Bheinn (NR 947 323) where small areas of fossiliferous Lower Lias sediments occur, as they also do close to the Permian and Triassic rocks in Allt nan Dris. Probable Upper Cretaceous limestones, now silicified and baked, are found in two localities, one forming a small cave marking the site of an old limestone quarry at Creag an Fheidh (NR 948 348), the other in a cave (Pigeon Cave) north-west of Binnean na h-Uaimh (NR 941 335). A large *remanié* mass of basaltic lava, about 100 m in thickness, occurs west of Binnein na h-Uaimh and Ard Bheinn; at the northern end of this mass; the basalt is seen to overlie altered chalk at Pigeon Cave. Many smaller masses exist elsewhere throughout the complex.

(b) Arcuate masses of volcanic breccias, granites, gabbros and felsites formed during the early evolution of the complex.

The principal members of the igneous complex are confocally arranged, arcuate masses within the caldera. These comprise large outer masses of vent agglomerate, a peripheral belt of granite, gabbroic strips north-west of Binnein na h-Uaimh (NR 943 335), a broad belt of felsite outcropping as arcuate masses with boss- and dyke-like characteristics and a lenticular granite mass.

The relative ages of the various pyroclastic formations within the complex are virtually impossible to determine. Distinct types occur in the peripheral zones and in the volcanic centres distinguished by King (1955). The peripheral caldera volcanic breccias are relatively uniform, the dominant inclusions being sedimentary and low-grade metamorphic fragments of Dalradian rocks and include quartzite, schistose grit and quartz–mica schists and vein-quartz. They are frequently well-rounded pebbles and cobbles, and are almost certainly derived from Devonian conglomerates, since fragments of these conglomerates are also common. Post-Devonian sediments are much more sporadic in their occurrence. Igneous fragments are irregularly distributed, but seldom predominate over the sedimentary clasts, and include basaltic lavas and felsites. Basalt is ubiquitous, but mugearite and feldspar-phyric basalts are also found in marked contrast to their very minor occurrence in the *remanié* masses of early, pre-complex lavas. Rare andesitic, gabbro, dolerite and granite clasts are also present. Some of the basalt fragments are very well-rounded and up to several metres in diameter. They are possibly the result of prolonged attrition in a vent (cf. Richey and Thomas, 1930; Reynolds, 1954). This suggestion is supported by steeply inclined, 'bedded' structures and intricate, sinuous, 'intrusive' contacts between agglomerates of varying character.

The peripheral granites occur as an arcuate belt from Dereneneach and Creag Mhor to lower Glen Craigag and a mass terminating to the north of Ballymichael Burn (King, 1955). These are medium- to fine-grained, pinkish biotite granites containing abundant orthoclase (commonly perthitic), plagioclase, quartz and biotite with epidote as a common secondary mineral. The granites are in contact with the volcanic breccias against which they are found to be chilled, although the junction is often tectonized and the granite finely comminuted. A further lenticular mass of granite associated with the ring complex occurs to the north of Binnean na h-Uaimh. This is a more melanocratic rock characterized by strongly zoned plagioclases and green hornblende; it may be of hybrid origin. The thermal metamorphic effects caused by the emplacement of this granite are particularly pronounced along its north-eastern and south-eastern boundaries, where adjacent basalts and gabbros are acidified and have developed clouded feldspars. Hybrid, dioritic rocks occur in the stream at Glenloig Bridge (NR 946 351).

(c) Lavas and pyroclastics erupted from discrete volcanic centres developed within the confines of the caldera.

The central, higher part of the area contains at least four separate volcanic centres superimposed upon the earlier steeply inclined, arcuate intrusions and volcanic breccias. Each volcanic centre is identified by groups of gently inclined lavas and pyroclastic accumulations. These centres are briefly summarized below (King, 1955).

Ard Bheinn Centre (NR 945 329)

This is the largest and least eroded of the centres and contains abundant basaltic andesite, andesite and plagioclase porphyry lavas and pyroclastics. The andesites dip to the south and south-east at low angles, presenting a confocal pattern. They are truncated by later felsites and felsitic agglomerates.

Binnein na h–Uaimh Centre (NR 943 335)

Concentrically arranged basalts and andesitic pyroclastic deposits appear to be arranged about a single focus of activity. Agglomerates associated with the basalts are exceptionally varied and comprise a succession of layers with varying amounts of coarse sedimentary, basaltic, plagioclase porphyry and felsitic debris in the form of gently north-westerly inclined sheets.

Creag Dubh Centre (NR 952 338)

Basalts, andesites and associated breccias and porphyritic felsites are well represented at this centre as at Ard Bheinn. The arcuate form of the outcrops suggests several intersecting and overlapping lavas and pyroclastic layers attributable to a number of minor volcanic vents.

Creag an Fheidh Centre (NR 948 347)

The disruption of peripheral structures of the complex indicate that a volcanic centre was probably present here. The lithology is varied and similar to that encountered in the other centres with basalts, plagioclase porphyries and felsite being dominant, although no andesites have been found. Two foci are suggested by the arcuate disposition of the felsites.

(d) Late granite mass.

The broad belt of granite extending from the source area of the Ballymichael Burn to mid-Glen Craigag is later than all of the other members of the complex. It is part of a late central granite intrusion located east of the Ring Complex and now occupying a large arcuate area mostly outside the limits of the Ard Bheinn site. The petrography of the granite is similar to that of the earlier peripheral granites. Small areas of fine-grained gabbro occur on the north-west margin of the Binnein na h-Uamha area. These are older than the granite and are comminuted where in contact with volcanic breccias. Well-developed flow layering in the gabbro has an arcuate pattern which conforms to the general structure of the complex (King, 1955, p. 331) but is cut across by the contacts; King suggested that this gabbro is a remnant of a much larger intrusion.

Interpretation

The Ard Bheinn area of the Central Igneous Complex contains probably some of the best-preserved evidence for an eroded caldera structure in the British Tertiary Volcanic Province. The arcuate outlines of the complex are clearly defined by later granitic intrusions and the evidence for central subsidence is unequivocal: the numerous, occasionally fossiliferous, *remanié* masses of Mesozoic sediments and closely associated lavas, similar to plateau lavas elsewhere in the BTVP, do not occur elsewhere on Arran, the country rocks adjoining the complex range from Devonian to Permian in age. Thus, King (1955) estimates that subsidence of *c.* 1000 m may have occurred. The nearest (on shore) exposures of similar fossiliferous rocks are on the North Antrim coast *c.* 60 km distant and even further afield in the Western Isles (cf. Peach *et al.*, 1901). The inference drawn from their presence, together with the Tertiary lavas, is that Arran and the surrounding areas were covered by Rhaetian, Lower Jurassic and Cretaceous sediments and Palaeocene plateau basalts prior to post-Eocene and Pleistocene erosion. Despite their preservation within a caldera and the presence of numerous later intrusions, the sedimentary rocks generally show little alteration beyond induration, although skarn minerals have been recorded from the contact between metamorphosed chalk and agglomerates at Creagh an Fheidh (Cressey, 1987).

Ard Bheinn is a convincing example of a volcanic cone within the caldera postulated by King (1955). Here, and at Binnein na h-Uamha, there are well-defined flows of andesite and dacite, and associated pyroclastic rocks. The high proportion of rocks derived from magmas of intermediate compositions is unusual in the BTVP, where compositions are generally distinctly basaltic or granitic. From the evidence of hybrid dioritic rocks at Glenloig Bridge and of mixing of basic and acid magmas (as at 'Hybrid Hill', *c.* NS 978 980–outside the site), a hybrid origin for these rocks is a possibility but this would imply very thorough homogenization of the contrasted, mixed magmas prior to eruption. The origin of these rocks must remain open, for no detailed geochemical work has been published on them since King's account (1955); they were not included in the radiochemical and geochemical investigations made by Dickin *et al.* (1981).

The coarser-grained granitic rocks of the complex appear to have been intruded along the margins of the caldera, possibly in association with the caldera collapse, although King's (1955) identification of crushing along the margins indicates post-consolidation movements. Emplacement of the granitic rocks may also have resulted in doming of the country rocks; this is particularly clear from the Survey's mapping to the south and south-east of the site, whereas the relationships along the northern and north-western margins of the complex suggest that the intrusions cut across the domed structure around the earlier Northern Granite.

The particular value of this site lies in the preservation of features of surface and near-surface volcanicity within a caldera collapse structure. Elsewhere in the BTVP, the present level of erosion is between 1–2 km (or even more) below what was the Palaeocene land surface, so that we are usually dealing with the eroded roots of the volcanoes. In this site much of the volcanic superstructure is preserved, and through the observations made here it is becoming increasingly recognized that some of the relicts of surface volcanism found in other central complexes (for example, Beinn na Caillich–Kilchrist on Skye) may also owe their preservation to subsidence within calderas. A positive gravity anomaly over the area indicates that it is underlain by mafic rocks at depth (McQuillin and Tuson, 1963).

The sequence of events within the Central Igneous Complex, and in particular this site, may be summarized as follows: after emplacement of the Northern Granite, a major igneous centre developed to the south. The initial activity involved formation of a caldera with central block subsidence of about 1 km and a diameter of at least 5 km. In the north-west, wall rocks collapsing into the caldera included olivine basalts from Tertiary lavas, which probably covered Arran and surrounding areas in the Palaeocene, and masses of fossiliferous Rhaetian and Lower Jurassic sedimentary rocks, together with Permian and Cretaceous rocks. At least four volcanic cones became established on the caldera floor and built up through the effusion of intermediate and acid lavas and pyroclastic deposits. Subsequently, granite and dioritic rocks were intruded along the ring fracture around the margins of the caldera. The status of gabbroic rocks in the north-west of the site, near Binnein na h-Uamha, is uncertain, but it may be a relict of a larger, pre-granite mass; the presence of the positive Bouguer gravity anomaly over the complex indicates that there are appreciable amounts of dense gabbroic rocks beneath the area.

Conclusions

The Ard Bheinn area contains a wide range of intrusive and extrusive igneous rocks with which are associated masses of fossiliferous and non-fossiliferous sediments, ranging in age from the Permian to the Cretaceous. This perplexing mixture of rock types is the result of surface and near-surface rocks being downfaulted within a major volcanic collapse structure, or caldera, which was subsequently intruded along its margins by granitic and other ring-dykes.

GLEN CATACOL

Highlights

The Northern Granite intrusions of Arran include a spectacular example of a diapir, uniquely well preserved in the British Tertiary Volcanic Province. The Dalradian country rocks have undergone extensive ductile deformation, with concentric folds formed around the granite. Excellent sharp intrusive contacts of the latter with the Dalradian are common within the site.

Introduction

The north-western part of the Northern Granite and adjoining updomed and metamorphosed

Dalradian metasediments lie within this site, which includes the glacially eroded and deepened Glen Catacol and much of the higher ground of the Bheinn Bharrain-Meall nan Damh ridge. Two distinct biotite granites comprise the Northern Granite, a coarse-grained Outer Granite often in chilled, intrusive contact with the Dalradian, and a younger fine-grained Inner Granite which has sharp intrusive contacts towards the Outer Granite. The Outer Granite forms the spectacular mountainous scenery of northern Arran (Fig. 6.1), whereas the Inner Granite is less resistant to weathering and is characterized by lower, more rounded hills. Granite–granite and granite–metasediment contacts are generally steep, a feature well displayed within the site which has over 700 m of relief. Post- and pre-granite basaltic dykes and post-granite felsitic dykes also occur throughout the site.

Early investigations on the Northern Granite (MacCulloch, 1819; Ramsay, 1841; Zirkel, 1871; Smith, 1896) were succeeded by those of the Geological Survey with the publication by Gunn (1903) and Tyrrell (1928) of the standard works on the geology of Arran. The form of the Northern Granite was considered by Bailey (1926) and subsequent work by Flett (1942) detailed the nature of the contact between the coarse- and fine-grained granites. More recently, the structures associated with the intrusion of the granite have received detailed attention from Woodcock and Underhill (1987) who have produced a new model for the high-level emplacement of the pluton; this topic has been further pursued by England (1988, 1990).

Description

The Outer Granite is a coarse-grained rock dominated by quartz and alkali feldspar accompanied by minor amounts of plagioclase and biotite. It is well exposed in the mountainous areas of the site and in the lower reaches of the River Catacol. Coarse granite, with characteristic rough weathering and widely spaced, subhorizontal and subvertical joint sets, is well-exposed on Meall nan Leac Sleamhuinn (NR 916 479), Madadh Lounie (NR 925 487) and Creag na h-Iolaire (NR 926 475) in close proximity to Dalradian country rocks (Fig. 6.4). The strong jointing, which often parallels the valley floors and sides, has been attributed to the unloading effects during the weathering of the granite. The Inner Granite has a similar mineralogy to the Outer Granite but is much finer grained and is frequently conspicuously drusy; the small cavities become especially numerous near the contacts with the earlier Outer Granite. The Inner Granite is occasionally granophyric, as at the confluence of the Allt nan Calman (NR 918 454). The intrusive relationship of the Inner Granite towards the Outer Granite has been well documented by Flett (1942). Intrusive contacts are exposed close to the confluence of the Diomhan and Catacol rivers (*c.* NR 923 469) on the south-east side of Meall nan Damh, in the col between that hill and Mheall Bhig, where thin sheets and veins of fine-grained granite cut the Outer Granite, and some 3 km south of Glas Choirein. The contacts are generally steeply dipping, with the Inner Granite passing under the Outer Granite.

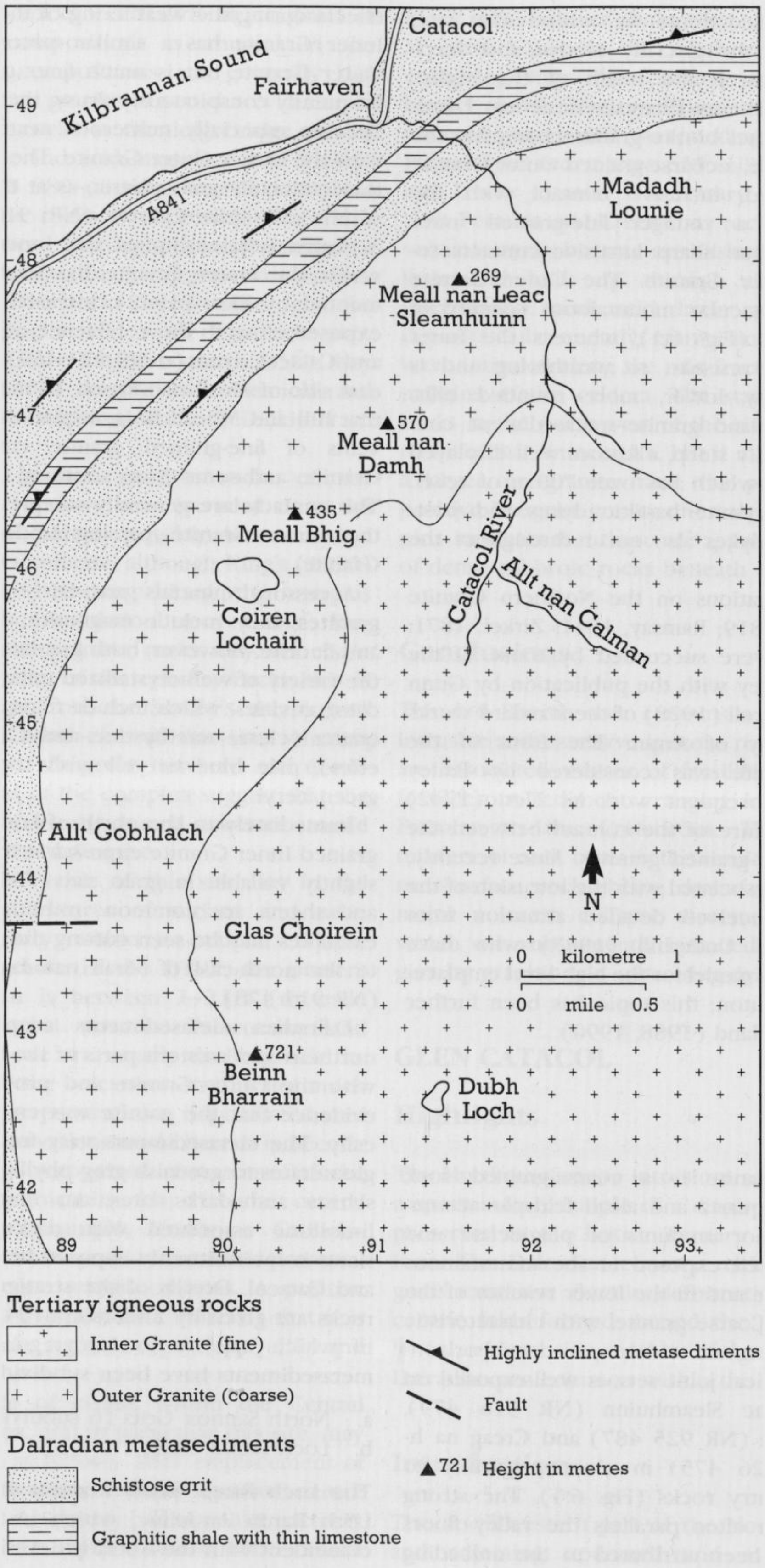
Accessory minerals are fairly rare in both granites; they include magnetite, apatite, zircon and fluorite. However, both granites are noted for the variety of well-crystallized minerals lining the drusy cavities, which include feldspar, dark mica, quartz (clear, amethystine and Cairngorm varieties), pale blue to yellowish topaz and blue-green beryl.

Immediately to the north of Loch Tanna, fine-grained Inner Granite exposed in the river bed is slightly variable in grain size. Thin aplite veins and sheets are common in both granites and examples may be seen cutting the Outer Granite to the north-east of Meall nan Leac-Sleamhuinn (NR 915 478).

Dalradian metasediments crop out in the northern and western parts of the site in contact with the Outer Granite and provide important evidence that the granite was emplaced diapirically. The metasediments vary from coarse conglomerates to greenish-grey phyllites, arenaceous schists and dark slates. An impure schistose limestone associated with dark-grey graphitic slates is intermittently exposed between Pirnmill and Catacol. Details of the stratigraphy of these rocks are given by Anderson (1945), a summary of which appears in Macgregor (1965). The metasediments have been subdivided into:

a. North Sannox Grits (6 subdivisions); and
b. Loch Ranza Slates.

The Loch Ranza Slates occupy the core of the Loch Ranza Anticline, which is thought to be coincident with the Aberfoyle Anticline (also see


Catacol
Kilbrannan Sound
Fairhaven
A841
Madadh
Lounie
269
Meall nan Leac
Sleamhuinn
570
Meall nan
Damh
435
Meall Bhig
Catacol River
Allt nan Calman
Coiren
Lochain
Allt Gobhlach
Glas Choirein
N
0 kilometre 1
0 mile 0.5
721
Beinn
Bharrain
Dubh
Loch
49
48
47
46
45
44
43
42
89
90
91
92
93
Tertiary igneous rocks
Inner Granite (fine)
Outer Granite (coarse)
Dalradian metasediments
Schistose grit
Graphitic shale with thin limestone
Highly inclined metasediments
Fault
721 Height in metres

Johnston, *in* Craig, 1965) and lies within the Barrovian chlorite zone. The Catacol Synform to the north-east, on the other hand, has resulted from the deformation of the Dalradian rocks by the forcible emplacement of the granite and the steeply inclined Dalradian metasediments are frequently deflected into parallelism with the granite contacts.

Within 50–100 m of the granite, the Dalradian rocks become almost vertical in attitude and are often seen to have been considerably metamorphosed thermally, with resultant overprinting of their cleavage. At Fairhaven, Madadh Lounie, on the Allt Gobhlach and along the coast to the west of the site, the schists provide evidence for the updoming effects of the granite and dip north-westwards away from the granite, with minor folding parallel to strike of the contact. On the east side of Glen Catacol at Madadh Lounie, fine-grained Outer Granite is in sharp contact with schists in the prominent spurs along the cliff face. Dark schists are thermally altered in a zone of about 75 m at the contact and they take on a bluish hue. Occasionally, fine-grained veins and offshoots of granite penetrate the country rock and blocks of Dalradian, probably detached by stoping, are sometimes completely engulfed by granite (McKerrow and Atkins, 1985). In the Allt Gobhlach (at NR 888 439) granite is in steep contact with indurated quartzose schists and the metasediments within a few metres of the granite have developed epidote, biotite, cordierite and andalusite. West of Glen Catacol, the contact of granite and schist is well exposed on the northern side of Meall nan Leac Sleamhuinn (NR 913 483) where the marginal granite contains several metasedimentary xenoliths.

Minor intrusions, widely scattered throughout the site, include basic dykes which were intruded before and after the emplacement of the Northern Granite. A good example of a pre-granite dyke is seen near to the granite contact in the stream issuing from Lochan a'Mhill (NR 908 482). It has been substantially baked and the original clinopyroxene has been replaced by hornblende and accessory biotite (Gunn, 1903). Basaltic dykes intrusive into both varieties of granite trend NW–SE and can be observed in the Catacol River, some of its tributaries and along the better-exposed parts of Beinn Bharrain (NR 898 423). Felsitic dykes are less common but do intrude both granites, and examples occur near to the basic dyke at Lochan a'Mhill and within the granite of Glen Catacol. A small pitchstone sheet cuts the Inner Granite 500 m north-west of Dubh Loch (NR 908 428). It appears that the majority of acid dykes within the granite are younger than the basic dykes.

Figure 6.4 Geological map of the Glen Catacol site (adapted from the British Geological Survey 1:50 000 Special District Sheet, Arran).

Interpretation

The Northern Granite is the most spectacular pre-central complex granite pluton in the British Tertiary Volcanic Province and is thus a very significant feature in the geology of Arran. The site is chosen in preference to the more scenically spectacular eastern part of the mass because both granites, numerous minor intrusions and granite contacts with upturned Dalradian metasediments, are exposed to advantage here. The area around Catacol provides a clear demonstration of the local tectonics associated with the diapiric emplacement of the pluton, such as the pronounced updoming of the Dalradian country rock and accompanying annular Catacol Synform. The intrusion has a cylindrical, plug-like form with outwardly dipping steep margins. Its margins have unusual characteristics for an intrusion of this size (McKerrow and Atkins, 1985): features such as the limited, sometimes very narrow thermal aureole, the poorly developed or absent chilled margin, a general absence of veins of late-stage residua in the country rock and the total lack of mineralization in the country rock. These features and the presence of many faults on the eastern side of the intrusion which downthrow away from it, suggest that the final emplacement of the diapir occurred when the granite was nearly solid. The diapir therefore caused brittle and ductile deformation in the country rock and was too cool and too 'dry' to effect substantial thermal metamorphism and mineralization in the country rock. However, the contacts in the Catacol area differ from this overall interpretation in that the junction is highly irregular and the veining of the country rock, together with evidence for stoping, suggest that here at least the granite was still at, or near to, liquidus temperatures when it was emplaced. An alternative model for the emplacement of the pluton has been suggested by Woodcock and Underhill (1987), based on detailed investigations of the deformation of the country rock. A two-stage ballooning model is suggested, following the arrest of the uprising pluton at the Dalradian–New Red Sandstone unconformity (exposed on the eastern side of the pluton). Initially the arrested pluton steadily inflated, causing radial stretching and normal faulting. This was followed by continued ballooning of the pluton, resulting in updoming of the country rocks, with further upwards and outwards movement following the intrusion of the Inner Granite. This model, however, does not explain the unusual contact features discussed above, in particular the irregular veining of the Dalradian rocks and the evidence for stoping. England (1990) contends that the Outer Granite has most of the characteristics of a diapir and some of a ballooning pluton.

Walker (1975) considered that the emplacement of granite diapirs preceded the development of all of the BTVP central complexes, that of Arran being the only one which is fully exposed for study. He envisaged a sequence of events, starting with emplacement of hot, basaltic magma into the base of the crust. This gave rise to low-density acid magma which rose as a diapir, closely followed by basalt channelled into a magma trap below the diapir. The diapir was augmented by new magma formed by fractionation of the basalt, by partial melting of crustal rocks or, most probably, a combination of the two (see 'Introduction', Chapter 1). In the brittle, upper crust, the country rocks were deformed by folding and faulting and later events included the formation of cone-sheet swarms and 'confluent cone-sheet type' bodies of gabbro beneath the diapirs (Walker, 1975, Figs 5 and 6). Basalt eventually broke through the diapir to form ring-dykes of gabbro which may be so numerous as to obliterate much of the evidence for the original diapir (for example, Mull, Skye). In north Arran the later stages did not develop, and in this area there are relatively few basaltic intrusions which post-date the granites, although the gravity data suggest that there is underlying, dense (gabbroic) rock (Tuson, 1959).

The sharp, steep contacts of the Inner Granite with completely undeformed coarse Outer Granite suggest that the later Inner Granite was emplaced in a permissive manner by ring-faulting and block subsidence.

Conclusions

The Outer Granite of the Northern Granite of Arran is the most spectacular diapiric intrusion of granite in the British Tertiary Volcanic Province. Intrusion of the Outer Granite has deformed the country rocks, causing them to develop steep, radial dips off the intrusions and also to become folded parallel to the granite contact. The granite probably moved upwards as a nearly solid body in the final stages, although some mobile granite magma did remain and formed veins in the country rocks. The Inner Granite was intruded without any deformation of the earlier, coarse-grained, Outer Granite.

DRUMADOON–TORMORE

Highlights

Five major pitchstone dykes ('Judd's Dykes') are excellently exposed in coastal outcrops. These dykes and other sills and sheets are exceptionally clear examples of composite (basic–acid) intrusions, where coexisting acid and basic magmas have interacted to produce hybrid rocks. Petrographic and chemical evidence indicates that the basic rocks were also hybridized before they were intruded.

Introduction

The coastal section between Drumadoon Point and Tormore provides good sections through a number of dykes and sills of quartz–feldspar porphyry, felsite and pitchstone. Many of these intrusions are composite and contain tholeiitic basaltic components. The 4-km-long shore section has two principal interests – the composite dykes in the King's Cave (NR 884 309) to Leacan Ruadh area (NR 887 322) and composite and acid sills at Drumadoon.

The composite dykes around Tormore were first systematically described by Judd (1893) in the now classic publication on these intrusions. Further work on these dykes and the sills at Tormore was carried out by the Survey (Tyrrell, 1928). McKerrow and Atkins's guide (1985) contains useful discussions on the origin of the Drumadoon intrusions, and a recent study on the hybridization and petrogenesis of the composite dykes, in particular the one at An Cumhann, has

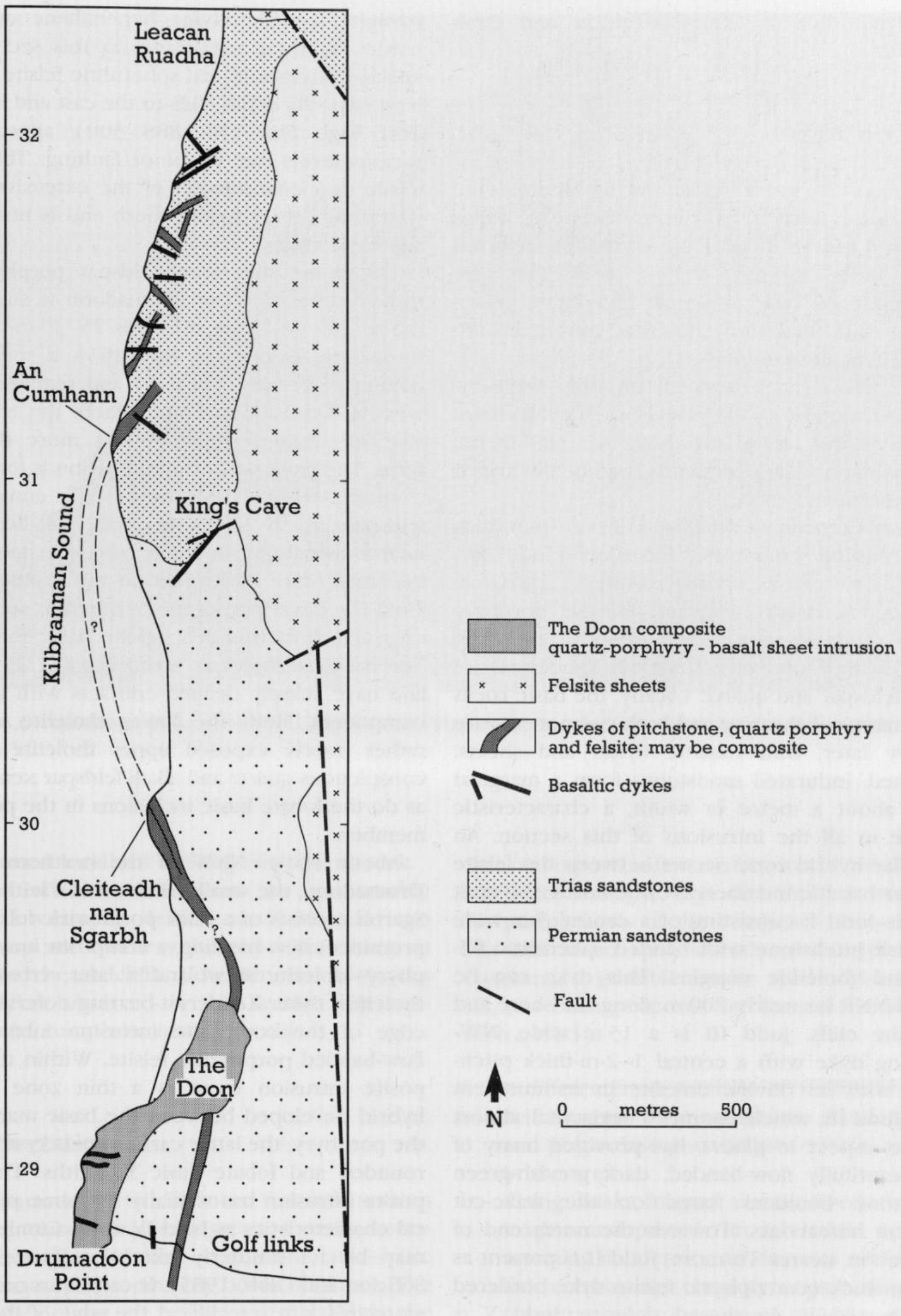


Figure 6.5 Geological map of the Drumadoon–Tormore site (adapted from the British Geological Survey 1:50 000 Special District Sheet, Arran, with additional information from McKerrow and Atkins, 1985, figure 11a).

been published by Kanaris-Sotiriou and Gibb (1985).

Description

Five major composite dykes on the shore some 2 km south-west of Tormore, between Kings Cave and Leacan Ruadha, are commonly referred to as Judd's Dykes I–V (Fig. 6.5). They are composed of quartz–feldspar porphyry, pitchstones and tholeiitic dolerite intruded into Permo-Triassic sediments.

The dykes are exposed on the wave-cut platform and also in the raised beach cliffs where the pitchstone and felsite dykes and sills in the soft sediments are frequently highly devitrified and spherulitic.

At An Cumhann (NR 884 312), a 30-m-thick NNE-trending composite intrusion (Judd IV) forms a low cliff (see Kanaris-Sotiriou and Gibb, 1985). It consists of quartz-feldspar porphyry flanked, and also intruded centrally by tholeiitic basalt which contains rounded xenocrysts of alkali feldspar and quartz. Locally, the basic rocks show marginal shearing and both components are cut by later, thin basaltic dykes and sheets. Bleached, indurated sandstones form a marginal ridge about a metre in width, a characteristic feature in all the intrusions of this section. An irregular hybrid zone occurs between the felsite and the basaltic members. To the north, the next dyke is Judd I, consisting of a central 5-m-wide greenish pitchstone with banded spherulitic felsite and tholeiitic margins. This dyke can be traced NNE for nearly 200 m along the shore and into the cliffs. Judd III is a 15 m wide, NW-trending dyke with a central 1–2-m-thick pitchstone with an olivine dolerite in its northern edge. Judd III, which assumes a horizontal, almost sill-like, aspect in places, has provided many of the beautifully flow-banded, dark greyish-green pitchstone boulders found on the wave-cut platform hereabouts. Towards the north end of the section, nearer Tormore, Judd II is present as a 10 m thick quartz-phyric felsite dyke bordered by spheroidally weathered dolerite; Judd V is exposed nearby, being a conspicuous pitchstone dyke on the shore. Both Judd II and V trend east–west and cannot be traced far inland. The felsites contain phenocrysts identical to those in the pitchstones and are most probably their altered, devitrified equivalents. Fresh pitchstones contain phenocrysts of quartz, andesine, ferroaugite, fayalitic olivine, hypersthene and Fe–Ti oxides. Running subparallel to this section, devitrified pitchstone and spherulitic felsite form at least two sills in the cliffs to the east and inland at Torr Righ Mor (NR 888 300), appearing at various levels due to minor faulting. The upper felsite is a continuation of the extensive Blackwaterfoot Felsite to the south and is not cut by any basic dykes.

The composite quartz-feldspar porphyry and tholeiitic basalt sill at Drumadoon is situated at the south end of the site. This 25–30-m-thick sill forms The Doon (NR 885 293), a spectacular columnar feature (Fig. 6.6) and extends south-west to Drumadoon Point, where the transgressive sill changes attitude to a more dyke-like form. The main part of the intrusion is formed by a quartz–feldspar porphyry with conspicuous feldspars up to 20 mm long, and smaller, glassy quartz crystals set in a pale felsitic matrix which becomes more basic next to the tholeiite margins. The lower part of the porphyry is sometimes crowded with rounded, lobate basic inclusions. The marginal tholeiitic sheets are 1–1.25 m thick and have sharply defined contacts with the acid component. Both the lower tholeiite and the rather poorly exposed upper tholeiite contain conspicuous quartz and alkali-feldspar xenocrysts, as do the lobate basic inclusions in the porphyry member.

About 400 m NNW of the northern end of Drumadoon, the small headland of Cleithadh nan Sgarbh consists of a thick porphyritic felsite with prominent flow-banding, a composite quartz porphyry–dolerite sheet and a later, cross-cutting tholeiitic dyke. Xenocryst-bearing dolerite at the edge of the composite intrusion intrudes the flow-banded porphyritic felsite. Within the composite intrusion there is a thin zone of acid hybrid developed between the basic margin and the porphyry; the latter carries xenocryst-bearing, rounded and lobate basic xenoliths. The composite intrusion has virtually the same petrological characteristics as Judd IV at An Cumhann and may be its southerly extension (see Kanaris-Sotiriou and Gibb, 1985). It can be traced south-eastwards into sea cliffs at the edge of the raised beach and may link with the porphyritic felsite exposed on the beach south of Blackwaterfoot golf course, about 400 m east of Drumadoon Point. The xenocryst-free dolerite dyke is a multiple intrusion cutting the composite sheet and the flow-banded felsite. The dyke splits into several sheets in the felsite where it appears to

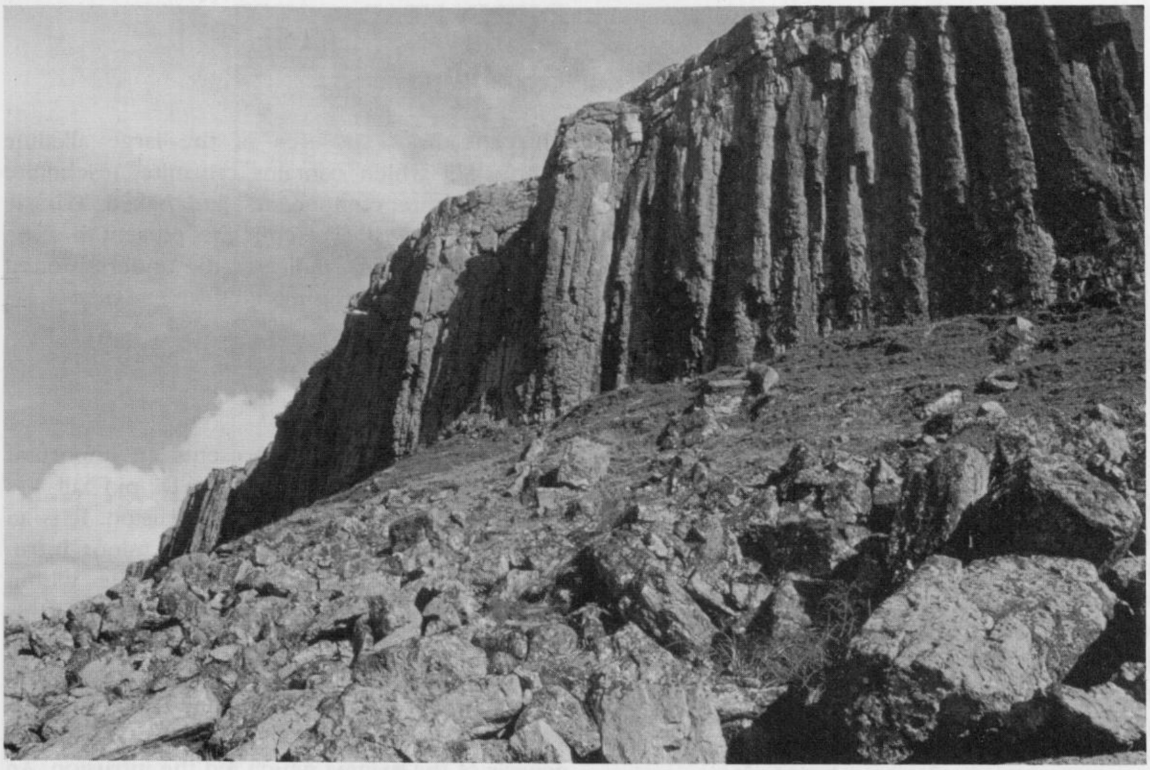


Figure 6.6 Columnar jointing in the composite sill, The Doon. Drumadoon–Tormore site, Arran. (Photo: A.P. McKirdy.)

have caused localized melting of the acid rock.

Minor intrusions fail to cut the (presumably later) flow-banded felsite at Cleitheadh nan Sgarbh and are absent within the felsite sheets in the raised beach cliffs. However, the numerous basic dykes observed in this section cut sediments and composite intrusions alike.

Interpretation

The Drumadoon to Tormore coastal section provides classic, well-exposed and easily accessible examples of the composite acid–basic intrusions which commonly occur on Arran. The importance of the site has been realized since the early studies of Judd (1893) and, as a consequence, the section is frequently visited and has unfortunately suffered heavy damage through indiscriminate hammering of the attractive glassy pitchstones.

The site clearly demonstrates that acid and basic magmas existed in this area at the same time, an important feature frequently noted in the BTVP (for example, Skye and Mull). A model for the petrogenesis of the composite intrusions in this area based upon a study of the dyke at An Cumhann, a possible feeder to the Drumadoon Sill, has been proposed by Kanaris-Sotiriou and Gibb (1985):

a. A differentiated, partially crystallized body of acid magma, bearing quartz, alkali feldspar and plagioclase phenocrysts existed at depth in the area.
b. Rising basic magma encountered the acid magma and passed through while generally retaining its identity; mixing was inhibited by the contrasting viscosity, composition and temperature properties of the two magmas. The basic magma, however, was partly hybridized by the incorporation of matrix and phenocrysts from the acid magma as xenocrysts.
c. The basic hybrid magma rose to higher levels and intruded Triassic sediments as dykes and sills of dolerite. Xenocrysts (especially alkali

feldspar) were resorbed. Flow differentiation in the dykes/sills resulted in the concentration of xenocrysts towards the centre.

d. Acid magma was subsequently emplaced along planes of weakness into the unconsolidated centres of the hybrid basic dykes/sills. Contamination of the acid porphyritic magma occurred at the contacts with the dolerite, by *in situ* assimilation of the basic rock and the incorporation of the basic rock as xenoliths.
e. The acid magma continued to fill the centres of the intrusion and became progressively more acidic as more evolved magma was tapped from the reservoir.

Kanaris-Sotiriou and Gibb (1985) suggested that all of the composite intrusions in this area formed in this way and all are related to a common source. They point out that composite sheets with cores of quartz–feldspar porphyry and dolerite margins are also developed in the immediate vicinity of other major granite bodies in the BTVP and cite Skye and the Mourne Mountains as examples. The inescapable conclusion seems to be that the composite sheets are formed by a single fundamental mechanism rather than by the chance association of partly crystallized acid magma and basalt magma. They do not consider that the acid magma was derived from the basic magma by differentiation. Possibly it was generated by remelting, or partial melting, of an earlier Tertiary granite.

Conclusions

The site contains excellent examples of glassy, flow-banded pitchstones some of which form the central parts of composite acid–basic dykes. The composite dykes, sheets and sills provide clear evidence that basaltic and granitic liquids were in existence at the same time in this area and were intruded in quick succession (basaltic magma, followed by acid magma). The crystals found as phenocrysts in the pitchstones, and particularly in the quartz–feldspar porphyries, are also present as xenocrysts in the enclosing, earlier dolerites. This indicates that the basalt magma mingled with partially crystallized acid magma before it was intruded; the basaltic and doleritic margins thus have some of the features of hybrid (mixed magma) rocks.

DIPPIN HEAD

Highlights

This site has exposures of the large alkaline Dippin Sill which contains crinanite, teschenite and pegmatite components and baked Triassic country rock. Primary nepheline, present in some of the components, indicates the undersaturated nature of some of the margins.

Introduction

The Dippin Head site represents an important locality for the exposure of the Dippin Sill – a basic, compositionally variable intrusion. It is an important member of the suite of minor intrusions seen in south-east Arran. The sill lies within baked Triassic marls and is intruded at this locality by a large doleritic dyke (Fig. 6.7).

The petrology of the sill has been described in a detailed study by Gibb and Henderson (1978a; 1978b), who proposed a model for the petrogenesis of the magma which fed the intrusion. An earlier description of the sill is also contained in the Arran Memoir (Tyrrell, 1928).

Description

The Dippin Sill crops out at Dippin Head (NS 050 222) and extends beyond the limits of the site between Cnoc na Comhairle (NS 036 240) and Cnocan Biorach (NS 034 222) and beneath much of the ground to the west. At Dippin Head, the sill attains a thickness of approximately 36 m and overlies highly baked Triassic marls. Here the sill is intruded by a thick, sparsely feldspar-phyric dolerite dyke with conspicuous tachylitic margins. Both intrusions display columnar jointing, which is vertical in the sill and horizontal in the dyke. The sill has the structure of a slightly transgressive sheet dipping to the south-east and thinning to the south-west, west and north. A thickness of 42.8 m was recorded from a borehole, in a stream at NS 043 228 (Gibb and Henderson, 1978a), which intersected both the roof and the floor of the intrusion.

Gibb and Henderson (1978a) described four main rock types within the sill, each variety having sharp, but unchilled, internal contacts, suggesting that the sill was probably intruded as a single event. These varieties and their petrologi-

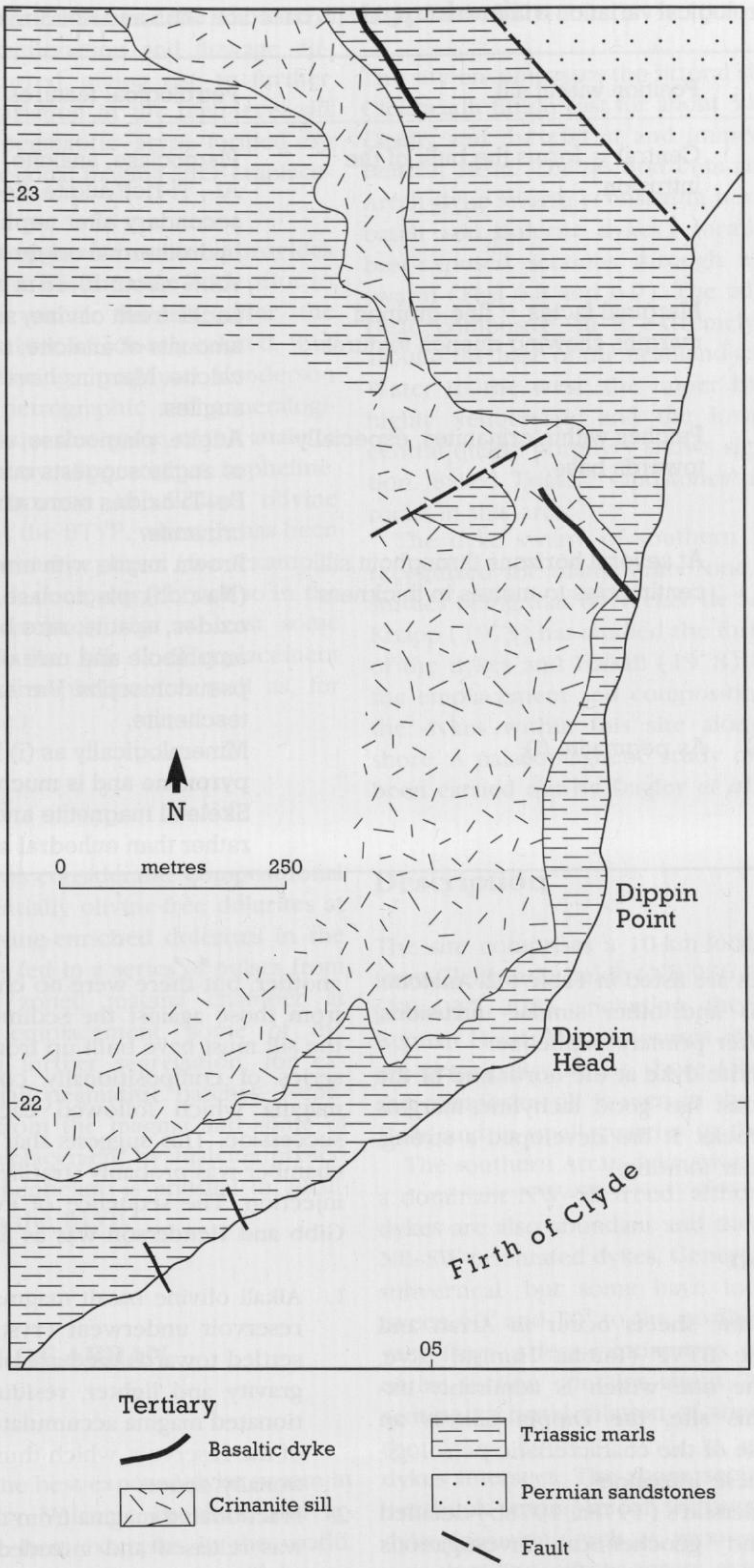


Figure 6.7 Geological map of the Dippin Head site (adapted from the British Geological Survey 1:50 000 Special District Sheet, Arran).

Table 6.2 Petrological variation within the Dippin Sill (based on Gibb and Henderson, 1978b, figure 4)

Rock type	Position within sill	Petrological features
(a) Crinanite	Central = forms the bulk of the intrusion	Plagioclase, analcite, olivine, ophitic Al-, Ti-rich augite. Zeolites. Analcite, secondary after nepheline and of hydrothermal origin. Olivine up to 12 vol.% about 10–15 m above base.
(b) Teschenite	Marginal facies = fine-grained margins showing quench textures	Lacks fresh olivine, substantial amounts of analcite, zeolites and calcite. Margins have skeletal Ti-augites.
(c) Augite teschenite	Patches within crinanites, especially towards base.	Augite, plagioclase, analcite. Alignment of augite suggests cumulate texture. Fe–Ti oxides more abundant than in crinanite.
(d) Pegmatite(i)	At several horizons throughout sill, centimetres to metres in thickness	Brown augite with emerald-green rims (Na-rich), plagioclase, analcite, Fe-oxides, apatite, rare blue riebeckitic amphibole and rare olivine pseudomorphs. Variant of augite teschenite.
(e) Pegmatite (ii)	As pegmatite (i)	Mineralogically as (i) but has less pyroxene and is much coarser grained. Skeletal magnetite and ophitic augite, rather than euhedral as in (i).

cal characteristics are listed in Table 6.2. Analcite, common in this and other similar intrusions, occurs in part after primary nepheline.

The large dolerite dyke at the north end of the cliff near the coast has good tachylitic margins against the sill rocks. It has developed a strong, flat-lying, columnar jointing.

Interpretation

Large basic alkaline sheets occur in Arran and elsewhere in the BTVP (Rubha Hunish, Skye, Shiant Isles). The one which is admirably exposed within this site, the Dippin Sill, is an excellent example of the characteristic petrological features of these intrusions.

Gibb and Henderson's (1978a; 1978b) detailed mineralogical and geochemical investigations were carried out on continuous drill-core samples obtained from a locality inland from the site. They showed that the distinctive rock types were generally sharply defined against one another, but there were no chilled contacts apart from those against the sediments; consequently, the sill must have built up from the injection of a series of compositionally contrasted pulses of magma which followed each other in rapid succession. This suggests that the source magma chamber was probably stratified at the time of sill injection. The sequence of events envisaged by Gibb and Henderson was as follows:

1. Alkali olivine basalt magma in a deep crustal reservoir underwent crystallization. Olivines settled towards the base of the magma under gravity and lighter, residual and more fractionated magma accumulated towards the top of the reservoir, which thus became compositionally zoned.
2. Fractionated magma from the top of the body was released and intruded at a high crustal level to form a sill. Reaction with the sediments modified the first-injected magma.
3. Successively less-fractionated, increasingly olivine-rich magmas were subsequently in-

jected into the central parts of the sill, where some *in situ* fractionation and flowage differentiation occurred, giving rise to further compositional variation in the high-level sill intrusion. The pegmatitic areas formed by segregation of residual magma after emplacement.

The sill is therefore important because it provides evidence for magmatic fractionation both prior to intrusion and also within the sill, after the injection of the pulses of closely-related, but compositionally differing, magmas. Henderson and Gibb's (1977) petrographic and mineralogical studies clearly show that some of the analcite in the sill is secondary after original nepheline. Analcite is very common in alkaline olivine dolerites throughout the BTVP, where it has been considered as a primary phase (for example, Harker, 1904). This is demonstrably not so in the Dippin Sill and it is likely that at least some analcite in other similar sills is of replacement origin, after original nepheline (as well as, for example, plagioclase).

Conclusions

The Dippin Sill shows considerable compositional variation from essentially olivine-free dolerites at the margins to olivine-enriched dolerites in the central parts. It was fed in a series of pulses from a compositionally zoned magma chamber at depth and, after emplacement, some of the magma underwent further segregation, for example, forming small pegmatitic patches. Nepheline crystallized from the magma and some of this has survived replacement by analcite; preservation of original nepheline is unusual in alkali-olivine dolerites in the BTVP.

SOUTH COAST OF ARRAN

Highlights

The site contains the best-exposed dyke swarm in the British Tertiary Volcanic Province and arguably one of the best examples in the world. The nearby Bennan Head composite sill has an exceptionally thick lower margin, and both its margins contain excellent examples of xenocrysts derived from granitic magma.

Introduction

The site encompasses the littoral shore zone from Cleitheadh Buidh east for about 5 km to Kildonan Castle, and the cliff at and immediately west of Bennan Head. The section cuts across the south Arran dyke swarm (consisting here of about 200 basalt and dolerite dykes), forming one of the best-exposed sections through a Tertiary dyke swarm (Figs 6.8 and 6.9). The adjoining Bennan Head composite sill is extremely well exposed around the base of the headland and in the Struey Water to the west; the upper basic member is highly xenocrystic and the lower part of the central quartz porphyry shows signs of hybridization. Baked Triassic sandstones are the country rocks in this area.

The dyke swarm of southern Arran has been recognized for many years, one of the earliest studies being that of Necker de Saussure (1840). Knapp (1973) has studied the form and structure of the dykes and Halsall (1978) has investigated the emplacement and compositional variation of the dykes within this site along the Kildonan shore. A palaeomagnetic study of the swarm has been carried out by Dagley *et al.* (1978).

Description

The site comprises a 10-km-long coastal section from Cleitheadh Buidh (NR 956 208) to Kildonan (NS 037 208), including the sea cliffs near Bennan Head. The exposures of the dyke swarm are principally on the shore (Figs 6.8 and 6.9); the composite sill is seen in the cliffs at Bennan Head and in small quarries to the north.

The southern Arran dyke swarm in this area has a dominant NW–SE trend, although north–south dykes are also abundant and there are subsidiary NE–SW-orientated dykes. Generally, the dykes are subvertical, but some have inclinations of between 60° and 70° to the north-east. Thicknesses vary from a few centimetres up to 30 m. The entire section contains about 200 dykes, representing a crustal dilation of about 10%. Some of the dykes bifurcate and, in several instances, dykes intersect. The shore section reveals clear, 'textbook' examples of features associated with dyke intrusion, such as prominent chilled margins, bedding offsets across dykes, flow-banding, vesicles and amygdales, jointing and dyke offsets.

Various rock types are represented by the dyke swarm, the commonest being: transitional alka-

Figure 6.8 Dyke swarm on the foreshore at Kildonan. The dykes weather out to form reefs; the softer Triassic sandstone in between has been eroded back. South Coast of Arran site, Arran. (Photo: C.H. Emeleus.)

Figure 6.9 Dolerite dykes forming part of the Arran dyke swarm on the shore below Kildonan Castle (NS 037 209). South coast of Arran site, Arran. (Photo: C.J. MacFadyen.)

line olivine dolerite, alkali olivine dolerite (crinanite and teschenite), tholeiitic olivine dolerite and quartz dolerite.

Red and white Triassic sandstones and coarser clastic rocks are the country rocks; they are often bleached and even occasionally metamorphosed to form tough, grey hornfelses which may contain quartz paramorphs after tridymite. The baked margins sometimes stand up as low walls along the dyke margins.

The major, thick composite sill of Brennan Head, with a central quartz–feldspar porphyry component, is flanked above and below by tholeiite. The sill is similar in many respects to the Drumadoon Sill. The base of the intrusion contains some large xenoliths, or rafts, of sandstone and, in the lower part of the porphyry, dark xenolithic bands of dolerite occur near to a small waterfall above the main Struey Falls (NR 993 203). The sections in and near Struey Burn (NR 994 205) show the acidic component to be more melanocratic than normal, and there is evidence for hybridization both by magma mixing and assimilation of xenolithic material. The marginal tholeiitic members, particularly the upper one, carry abundant quartz and alkali-feldspar xenocrysts (cf. Drumadoon Sill) and also scattered hypersthene crystals; the lower marginal tholeiite is exceptionally thick (>10 m).

Interpretation

The site contains the best example of a dyke swarm in the BTVP, including many of the 'textbook' features of dykes and a considerable range in compositions. Consequently, it is a classic section, with international status, and is frequently visited for educational purposes.

Halsall (1978) distinguished ten episodes of dyke and sill emplacement, based on successive, cross-cutting phases of intrusion. He showed that there was a general trend from alkali-basaltic to tholeiitic magmas with time, possibly attributable to increased partial melting of a mantle source as the swarm was intruded. However, superimposed on this simple pattern there was also random intrusion of olivine dolerite, tholeiitic olivine dolerite and tholeiitic dolerite dykes throughout the entire period, suggesting crustal magmatic plumbing similar to that envisaged for the Mull and Skye lavas (Chapter 1).

A palaeomagnetic study of the dykes (Dagley *et al.*, 1978) showed the majority to have reversed magnetization (>75%) and that the proportion showing reversed polarity increased from west to east. There is no simple correlation between polarity and petrography and neither is there a significant difference between mean pole directions of the alkali-basalt and tholeiitic intrusions. Overall, it appears that the dykes span three or four magnetic polarity episodes, reversed–normal–reversed or (more probably) reversed–normal–reversed–normal (Dagley *et al.*, 1978), during a period of about three million years, or four if four polarity periods were involved. Reliable radiometric age determinations are not as yet available for the dykes, but they pre-date the Holy Island trachyte which has been dated at about 58.5 Ma (Macintyre, 1973).

The high percentage of crustal dilation represented by the dykes indicates that Arran lay on a zone of crustal extension and possible thinning during the Palaeocene. Speight *et al.* (1982) consider that the dyke swarms formed above ridge-like, basaltic, magma chambers situated in the lower crust and extending into the mantle. They regard the ridges as fundamental structures in the BTVP, forming in the crust beneath the region in response to shearing stresses associated with the opening of the North Atlantic, and they compare the pattern of dyke swarms in the BTVP with similar, but smaller-scale patterns formed by quartz-filled tension gashes (cf. Speight *et al.*, 1982, Fig. 33.5).

The Bennan Head composite sill intrusion has many features in common with the composite intrusions of the Drumadoon–Tormore site. The principal differences are the thick, lower basaltic and doleritic member at Bennan and the occurrence of fairly numerous baked sedimentary xenoliths near the floor of the intrusion. Intrusion of the mafic rocks appears to have disturbed the country rocks to a much greater extent than at Drumadoon–Tormore. Although no quantitative modal data are available, the Bennan Head sill contains many more obvious examples of quartz and feldspar xenocrysts in its mafic members than are found at Drumadoon–Tormore, particularly towards the top, suggesting mixing with greater amounts of porphyritic acid magma.

Conclusions

The large number of well-exposed dykes and the wealth of intrusive features which they show, make the dyke swarm exposed on the south

Arran shore the best example to be found within the Province. The site was thus selected as the type section of a dyke swarm. The intrusion of the dykes has extended the crust by about 10%: this was achieved during the course of as many as ten phases of dyke injection.

Measurements of the remanent magnetization of the dykes show that the swarm was probably emplaced over a period of between three and four million years, spanning three or four episodes of magnetic polarity.

The Bennan Head composite sill provides additional evidence from Arran for the coexistence of basic and acid magmas and that mingling between these occurred both before intrusion and after emplacement of the intrusion.

CORRYGILLS SHORE

Highlights

The early, thick Clauchlands crinanite (analcite–olivine dolerite) sill forms part of a possible cone-sheet system focused on Lamlash Bay. The Corrygills Pitchstone is an outstanding example of a natural glass, representing a quenched granitic magma.

Introduction

The site comprises the coast and adjoining cliffs for about 1.5 km north from Clauchlands Point and extends as far inland as the hill of Dun Dubh. Excellent exposures of variably textured crinanite in a thick sill form Clauchlands Point, to the north, the Corrygills pitchstone sill crops out. The site also contains good examples of dolerite, basalt and felsite dykes. Permian sediments, including coarse breccias, conglomerates and dune-bedded sandstones, are the country rock in this area (Fig. 6.10).

Description

The 30–35 m thick Clauchlands Sill is well exposed on the scarp below Dun Fionn (NS 047 338) and at Clauchlands Point. The rock is a coarse-grained analcite olivine dolerite (crinanite) which is generally deeply weathered to give a spheroidal surface. The sill is traversed by veins of fine-grained basalt and contains segregations of pegmatite containing titaniferous augite crystals up to several centimetres in length. The rock characteristically has a speckled appearance caused by the presence of areas of altered analcite in the groundmass: this is a feature of all facies of the sill. Olivine-rich segregations are present and apatite is a common accessory mineral.

The sill is in the form of a sheet dipping to the west and south-west, towards Lamlash Bay. Its upper margin is transgressive towards the Permian sediments, but the lower contact is partly conformable with the sandstones which dip at between 30° and 50° SW or WSW. At Clauchlands Point there is a steep, almost vertical contact with the sediments and the sill has developed a 0.3-m-thick marginal zone of vertically flow-banded basalt. The steep margin at this point may be due to intrusion along an earlier fault.

Some way below the Clauchlands Sill there are 3- to 4-m-thick exposures of the Corrygills pitchstone sill which intrudes Permian sediments, and dips at about 30° SSW (Fig. 6.11). The pitchstone is a beautiful, dark-green, glassy rock with pale streaks and bands which define flow lines. It is nearly phenocryst free, the glassy base containing microlites and delicate branching growths of crystallites (probably pyroxene and/or plagioclase) which have figured in textbooks since the early days of microscopic petrography (for example, Teall, 1888; plate 34, fig. 4). The rock is closely comparable in composition with the more silica-rich granites of the BTVP (Carmichael, 1962).

Between Clauchlands Point and Corrygills Point the wave-cut sandstone platform is traversed by several dykes and sills which are only fully visible at low tide. The Mile Dyke is a prominent dolerite dyke exposed on the platform. It is between 1 and 2 m wide, trends in a NW–SE direction, and is bordered by indurated and bleached sandstone. Another pitchstone sheet, sometimes termed the Small Corrygills Pitchstone to distinguish it from the thicker one described above, crops out at the base of a thick felsite sheet exposed about 0.5 km SE of Corrygills Burn (NS 043 348). The pitchstone is about one metre in outcrop width and both it and the overlying felsite show well-defined flow-banding; the pitchstone is glassy and bottle-green in colour, whereas the felsite is distinctly spherulitic, greenish-grey rock. The sheet crosses the shore in a WNW direction and dips between 25° and 35° SSE.

Along the Corrygills shore section, which is

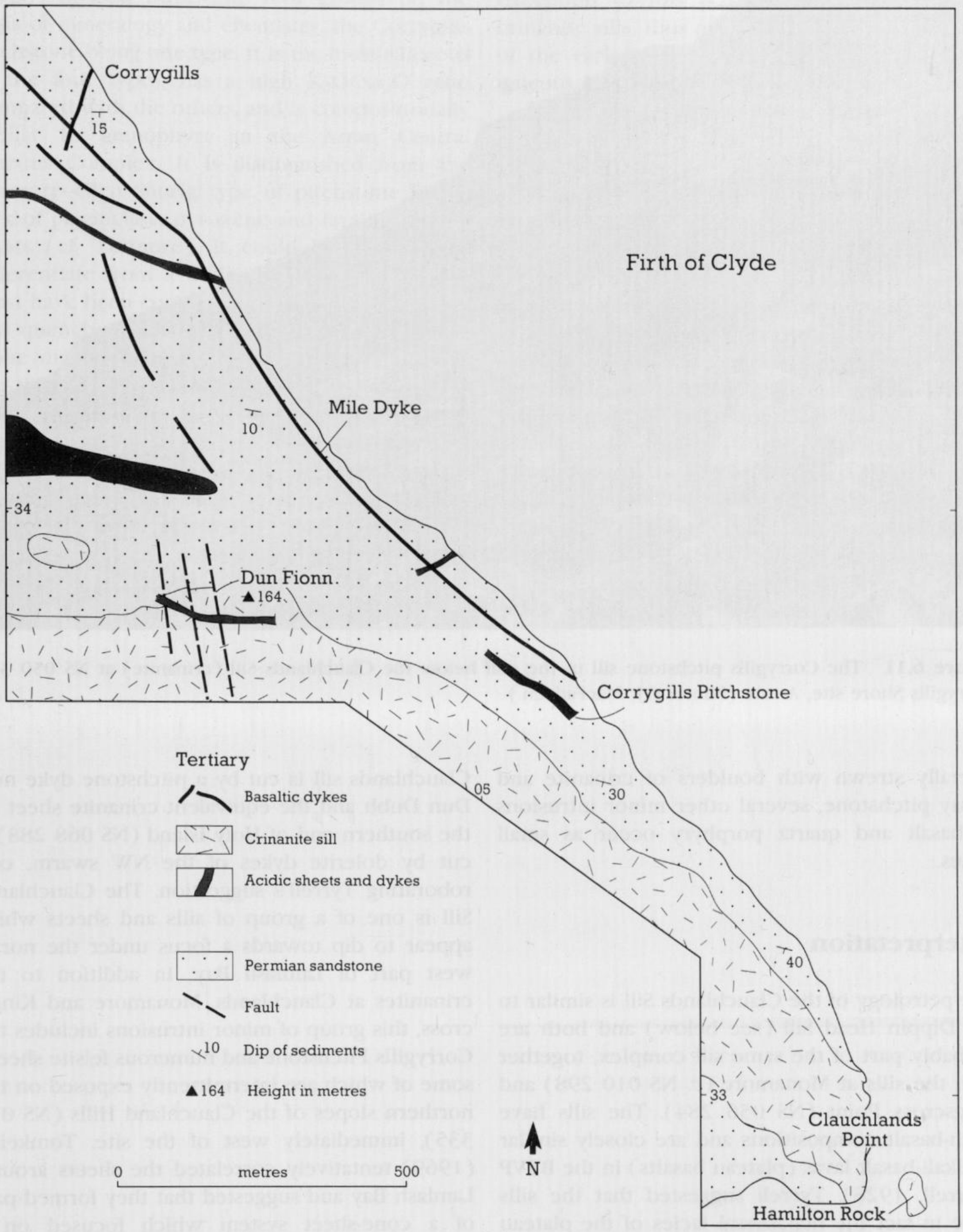


Figure 6.10 Geological map of the Corrygills Shore site (adapted from the British Geological Survey 1:50,000 Special District Sheet, Arran).

Figure 6.11 The Corrygills pitchstone sill in the cliff below the Clauchlands Sill (crinanite) at NS 050 337. Corrygills Shore site, Arran. (Photo: C.J. MacFadyen.)

liberally strewn with boulders of crinanite and glassy pitchstone, several other minor intrusions of basalt and quartz porphyry occur as small dykes.

Interpretation

The petrology of the Clauchlands Sill is similar to the Dippin Head Sill (see below) and both are probably part of the same sill complex, together with the sills at Monamore (*c.* NS 010 298) and Kingscross Point (NS 056 284). The sills have alkali-basalt compositions and are closely similar to alkali-basalt lavas (plateau basalts) in the BTVP (Tyrrell, 1928). Tyrrell suggested that the sills were in fact the hypabyssal facies of the plateau lavas, if this correlation is correct they could be equivalent to the large, subsided masses of basalt present within the Central Igneous Complex (Ard Bheinn) and could therefore be early members of the extensive suite of Palaeocene intrusions on Arran. An early date is supported by the manner in which they are freely cut by other minor intrusions (Tyrrell, 1928, pp. 112–3). The Clauchlands sill is cut by a pitchstone dyke near Dun Dubh and the equivalent crinanite sheet on the southern end of Holy Island (NS 068 288) is cut by dolerite dykes of the NW swarm, corroborating Tyrrell's suggestion. The Clauchlands Sill is one of a group of sills and sheets which appear to dip towards a focus under the northwest part of Lamlash Bay. In addition to the crinanites at Clauchlands, Monamore and Kingscross, this group of minor intrusions includes the Corrygills Pitchstone and numerous felsite sheets, some of which are intermittently exposed on the northern slopes of the Clauchland Hills (NS 035 335), immediately west of the site. Tomkeieff (1969) tentatively correlated the sheets around Lamlash Bay and suggested that they formed part of a cone-sheet system which focused on a 'magmatic hearth' (that is, an igneous centre) beneath Lamlash Bay (Tomkeieff, 1969, figs 3 and 4). He also suggested that the Holy Island riebeckite trachyte (NS 060 300) and the small quartz-porphyry intrusion at Dun Dubh (NS 038 343) were embryonic ring-dykes associated with the postulated Lamlash Bay igneous centre.

The essentially aphyric Corrygills Pitchstone is one of numerous pitchstones in Arran. Tyrrell (1928) divided these into four groups on the basis of mineralogy and chemistry, the Corrygills Pitchstone being one type. It is the most siliceous of the four types, has a high K_2O/Na_2O ratio compared with the others, and is compositionally similar to granophyre in the Arran Central Igneous Complex. It is distinguished from the Tormore–Glen Shurig type of pitchstone by its lack of plagioclase, pyroxene and fayalite phenocrysts (cf. Tormore). It could be an extreme differentiate from a tholeiitic basalt magma and must have been completely liquid when intruded and quenched against the sediments. The pitchstone magma appears to have received little in the way of crustal contributions: it has a fairly low $^{87}Sr/^{86}Sr$ ratio (0.70855 at 59 Ma, Dickin *et al.*, 1981) and also only minor amounts of lead of crustal origin (Dickin *et al.*, 1981, table 2 and fig. 7). In common with most of the Arran Palaeocene intrusions there appears to have been little alteration due to circulating heated meteoric waters (Dickin *et al.*, 1981). The principal exception to this is the altered facies of the crinanite sills, thus providing a further indication of the early position of these intrusions in the igneous sequence.

Conclusions

The Clauchlands Sill was intruded at an early stage in the Palaeocene igneous activity in Arran and may have a similar age to large masses of basalt caught up in the Arran Central Igneous Complex. Together with other alkali-dolerite (crinanite) sills near Lamlash Bay and the numerous felsite and pitchstone sheets in this area, it may form part of a cone-sheet system with a focus beneath the bay. The Corrygills Pitchstone was intruded as a nearly crystal-free magma which quenched against Permian sedimentary rocks. It probably originated as an extreme differentiate of tholeiitic basaltic magma.